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10 Microsecond Time Resolution Studies of Cygnus X-1

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H. C. Wen

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10 Microsecond Time Resolution Studies of Cygnus X-1 *

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Abstract

Time variability analyses have been applied to data composed of event times of X-rays emitted from the binary system Cygnus X-1 to search for unique black hole signatures. The X-ray data analyzed was collected at ten microsecond time resolution or better from two instruments, the High Energy Astrophysical Observatory (HEAO) A-1 detector and the Rossi X-ray Timing Explorer (XTE) Proportional Counter Array (PCA). HEAO A-1 and RXTE/PCA collected data from 1979-79 and from 1996 on with energy sensitivity from 1-25 keV and 2-60 keV, respectively. Variability characteristics predicted by various models of an accretion disk around a black hole have been searched for in the data. Drop-offs or quasi-periodic oscillations (QPOs) in the Fourier power spectra are expected from some of these models. A re-examination of an analysis of the Cygnus X-1 data from HEAO A-1 by Meekins, et. al. indicates that the reported excess variability at the ten millisecond time scale can be attributed to instrumental effects.

The Fourier spectral technique was applied to the HEAO A-1 and RXTE/PCA data with careful consideration given for correcting the Poisson noise floor for instrumental effects. The resulting noise-subtracted Fourier power spectrum is described by a $\sim 1/f$ power-law with a break at 3 Hz in the HEAO A-1 data and between 10-20 Hz in the RXTE/PCA data. Evidence for a drop-off may be interpreted from the faster fall off in variability at frequencies greater than the observed breaks. Both breaks occur within the range of Keplerian frequencies associated with the inner edge radii of advection-dominated accretion disks predicted for Cyg X-1. The break between 10-20 Hz is also

near the sharp rollover predicted by Nowak and Wagoner's model of accretion disk turbulence. Evidence is seen in the RXTE/PCA data for marginal excess power at frequencies from 100–4000 Hz with 33% of the power spectrum at those frequencies exceeding the 95% confidence level upper limit for detecting a signal in the presence of Poisson noise. No QPOs were observed in the data for quality factors $Q > 9$ with a 95% confidence level upper limit for the fractional rms amplitude at 1.2% for a $16 M_{\odot}$ black hole.

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INTRODUCTION AND SUMMARY

1.1 Standard Models

Over the last three decades, the field of X-ray astronomy has yielded significant advances in understanding the end states of stars. Central to this progress was the observation and study of close binary systems in which a compact object orbits tightly about a companion star. The compact objects are believed to be stars that have reached the end of their lives or end states. By observing how a companion star's behavior is affected by the compact object, properties of the compact object can be indirectly determined. Measurements of the orbital motion of the companion star about the compact object lead to a lower limit for the compact object's mass. One type of compact object, a black hole, is by itself observationally invisible. Indirect observation is the only means whereby information about the object may be extracted.

In addition to affecting the companion's orbital motion, the compact object also strips the companion of its matter. The matter, with a specific angular momentum equal to that of the companion, gradually falls towards the compact object as the angular momentum is removed by viscosity. The flow encircles the compact primary and forms a quasi-stationary structure around it commonly known as an accretion disk, as illustrated in Figure 1.1. The process of accreting matter onto the compact object generates observable X-ray emissions.

Fig. 1.1 Illustration of a close binary system (not to scale). The critical surface is the innermost self-intersecting equipotential surface commonly referred to as the Roche lobe. The compact object accretes matter that has overflowed the companion's Roche lobe through the Lagrange point, L_1 and onto its accretion disk.

In our current standard model, three types of compact objects are believed to exist in close binary systems. All three compact objects are gravitationally bound. When a star has exhausted its nuclear fuel, the loss of thermal pressure leads to the star's gravitational collapse. One of the possible outcomes of the remaining core is a white dwarf with typical radii of $10^{-2} R_{\odot}$ and densities of 10^6 g cm^{-3} , where $R_{\odot}$ is the radius of the sun. For white dwarfs, the Fermi electron-degeneracy pressure balances the object's self-gravitation.

Above 10^7 g cm^{-3} , the density is high enough that all the Fermi levels are filled beyond the energy of the electrons from neutron-beta decay, and inverse beta decay is favored,

$$e^{-} + p \rightarrow n + \nu \quad [1.1]$$

When the density exceeds $10^{11} \text{ g cm}^{-3}$ the neutron population begins to dominate both in number and in its contribution to the total pressure by its Fermi degeneracy pressure. The

compact object at such densities is called a neutron star with typical radii of $10^{-5} R_{\odot}$.

At nuclear densities ($10^{14} \text{ g cm}^{-3}$) and higher the equation of state for matter is incomplete. Beyond a certain density no known repulsive force of nature can balance the object's tremendous gravitational attraction. It is currently believed that the remaining core continues to collapse to a gravitational singularity called a black hole, one of the most startling predictions of general relativity. The exact density separating a neutron star and a black hole is not known, but should be less than $10^{16} (M_{\odot}/M)^2 \text{ g cm}^{-3}$, the effective density of a black hole.

Cygnus X-1 is a close binary system where the compact object is believed to be a black hole. Discovered by Bowyer et. al.^[1] in 1965, Cyg X-1 is one of the brightest X-ray sources in the sky and one of the best studied X-ray sources. The compact object has^[2] a mass greater than $7 M_{\odot}$ and a best estimate of $16 \pm 5 M_{\odot}$ with a 5.6 day orbital period. The companion star is a supergiant (O9.7 Iab) with a mass greater than $20 M_{\odot}$ and a best estimate of $33 \pm 9 M_{\odot}$.

The binary system is additionally characterized by frequent transitions it undergoes between two states^[3]: a "low" state, where it spends about 90% of its time, and a "high" state. The two states are distinguished by their energy spectra shown in Figure 1.2 and their total luminosity. During the low state, the source emits primarily a hard X-ray component, described by a single power-law spectrum over the range 1–250 keV:

$$dF/dE = bE^{-\alpha} \quad [1.2]$$

where dF/dE is the differential flux [$\text{photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$], E is the energy, b is the proportionality constant and α is a constant called the spectral index. For Cyg X-1 in the low state, α ranges from 1.3–2.3 and the total X-ray luminosity^[4] is about $3 \times 10^{37} \text{ erg s}^{-1}$.

The rarer high state makes its transition over periods of days and lasts for about a month. An intense, ultrasoft spectral component appears in the 3–6 keV band, followed

Fig. 1.2 X-ray energy spectra of Cyg X-1 in the a) high state and the b) low state. The low state is characterized by a single power law while the high state is described by a ultrasoft component plus a weaker hard power law tail.

by a weaker power-law above 10 keV with $\alpha \sim 1.6\text{--}2.3$. The total luminosity in the high state increases by a factor of about 2 to over $6 \times 10^{37} \text{ erg s}^{-1}$.

The Cyg X-1 data analyzed in this Thesis were collected from two instruments, the High Energy Astrophysical Observatory (HEAO) A-1 and the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA), described further in Section 1.3 and Chapters 3 and 4. During the HEAO A-1 observations, Cyg X-1 was in the low state^[5], with a mean energy flux of $1.25 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1}$ from 1–30 keV assuming a power law with a spectral index of 1.56. An estimated distance to Cyg X-1 of 2.5 kpc^[6] yields a mean source luminosity of $9.4 \times 10^{36} \text{ ergs s}^{-1}$. The RXTE observation occurred while Cyg X-1 was in the high state^[7]. The energy spectrum was fit to a 0.34 keV soft blackbody component plus a power law between 3–200 keV with a spectral index of 2.5. During the time of the RXTE observation, the bolometric luminosity was estimated to be $\sim 4.7 \times 10^{37} \text{ ergs s}^{-1}$ from observations of Cyg X-1^[7] using the All-Sky Monitor/RXTE and BATSE/Compton Gamma Ray Observatory.

A black hole, as the name suggests, is a region of spacetime in which nothing, not even light, can escape. Predicted by general relativity, a black hole arises when the

gravitational potential of matter becomes so high that nothing can stop self-gravitation from collapsing the matter into a singularity.

The mass distribution of a black hole distorts its surrounding vacuum spacetime geometry. For a non-rotating black hole in a vacuum, the spacetime geometry is described by the Schwarzschild metric^[8]

$$ds^2 = -(1 - 2M/r) dt^2 + (1 - 2M/r)^{-1} dr^2 + r^2 d\Omega^2 \quad [1.3]$$

where M is the black hole mass. The quantity r is the radius of a two-dimensional spherical surface whose proper circumference is $2\pi r$. Unless otherwise specified, the units for this Chapter are chosen such that c (speed of light) = G (gravitational constant) = 1. Schwarzschild derived this metric by solving the Einstein field equations in a vacuum assuming spherical symmetry. The surface of the black hole or *event horizon* lies at $R_s = 2M \equiv 3(M/M_\odot)$ [km], commonly called the Schwarzschild radius.

For a test particle of mass m and angular momentum L , the effective potential in the spacetime geometry defined by the Schwarzschild metric is^[9]

$$V(r) = m \left[(1 - 2M/r) \left(1 + L^2 / (mr)^2 \right) \right]^{1/2} \quad [1.4]$$

such that the equation of motion for the test particle is given by

$$m^2 (dr/d\tau)^2 = E^2 - V(r)^2 \quad [1.5]$$

where E is the energy of the particle and τ is the proper time of a comoving observer.

The effective potential is shown in Figure 1.3 for several values of the test particle's angular momentum. The local minima are represented by dots, corresponding to radii of stable circular orbits. Such orbits exist only for $L > 2\sqrt{3}M$. The innermost or marginally stable circular orbit occurs for a test particle with angular momentum $L = 2\sqrt{3}M$ at $r_{ms} = 3R_s = 9 (M/M_\odot)$ [km], corresponding to the point of inflection of the effective potentials.

Fig. 1.3 The effective potential for a test particle of mass m of various angular momenta L , orbiting a Schwarzschild black hole of mass M . The horizontal lines mark various energies of the test particle. The dots at the local minima of the effective potential curves identify radii of stable circular orbits. For comparison, the effective Newtonian potential is shown by the dashed line for one of the angular momenta.

When rotation of the black hole is considered, the radius of the marginally stable circular orbit becomes dependent on the black hole's angular momentum. For a chargeless rotating black hole, the spacetime geometry is described by the Kerr metric^[10]. In Boyer-Linquist coordinates^[11], the Kerr metric is given by

$$\begin{aligned}
 ds^2 = & -(1 - 2Mr/\Sigma) dt^2 - (4arM^2 \sin^2 \theta/\Sigma) dt d\phi + (\Sigma/\Delta) dr^2 \\
 & + \Sigma d\theta^2 + (r^2 + a^2 M^2 + 2a^2 r M^2 \sin^2 \theta/\Sigma) \sin^2 \theta d\phi^2
 \end{aligned}
 \tag{1.6}$$

where $a \equiv cJ/(GM^2)$, $\Delta \equiv r^2 - 2Mr + a^2 M^2$ and $\Sigma \equiv r^2 + a^2 M^2 \cos^2 \theta$. The dimensionless angular momentum parameter, a is defined here explicitly in terms of c and G for clarity.

Setting $a = 0$ in Equation [1.6] gives the Schwarzschild metric. Solved by Bardeen et al.^[12], the radius of the marginally stable circular orbit for the Kerr metric is given by

$$\begin{aligned} r_{ms} &= M \left(3 + Z_2 \mp \left[(3 - Z_1)(3 + Z_1 + 2Z_2) \right]^{1/2} \right) \\ Z_1 &\equiv 1 + (1 - a^2)^{1/3} \left[(1 + a^2)^{1/3} + (1 - a^2)^{1/3} \right] \\ Z_2 &\equiv (3a^2 + Z_1^2)^{1/2} \end{aligned} \quad [1.7]$$

The upper sign refers to corotating or direct orbits where the orbiting test particle and black hole angular momenta are parallel, the lower sign to counterrotating or retrograde orbits. For non-rotating black holes ($a = 0$), Equation [1.7] reduces to $r_{ms} = 6M$. At maximum rotation ($a = 1$), $r_{ms} = M = 1.5 (M/M_\odot)$ km for direct orbits and $r_{ms} = 9M = 13.5 (M/M_\odot)$ km for retrograde orbits.

The radius of the marginally stable orbit defines the inner edge of the accretion disk around a black hole. The amount of gravitational binding energy at the inner edge of the disk is the total energy that is radiated by matter as it drifts inward through the disk. For a non-rotating black hole binary, the radiation efficiency for matter accreting onto the surface of the disk is 5.7%, increasing to up to 42% for a maximally rotating black hole. For a white dwarf or a neutron star binary, the inner edge of the accretion disk may extend all the way down to the compact object's surface, leading to radiation efficiencies of 0.01% and 10%, respectively. Comparing these efficiencies to that of nuclear burning, 0.9%, the conversion of rest mass to other forms of energy for accretion onto disks around black holes and neutron stars is considered highly efficient.

Most of the radiation from accreting matter originates from the innermost regions of the accretion disk. A thin, Keplerian accretion disk around a black hole has an integrated flux emitted from the top and bottom faces of the disk of^[13]

$$F(r) \approx \frac{3}{4\pi} \frac{L}{r^2} \left(\frac{r_{ms}}{r} \right) \left[1 - \left(\frac{r_{ms}}{r} \right)^{1/2} \right] \quad [1.8]$$

Fig. 1.4 The radial distribution of the integrated flux emitted from the faces of a thin, Keplerian accretion disk. Most of the radiation originates from the innermost parts of the disk. The peak of the distribution occurs at $1.4 r_{ms}$, where r_{ms} is the radius corresponding to the innermost stable orbit.

where L is the total luminosity of the disk. As Figure 1.4 shows, the integrated flux distribution is strongly peaked at $1.4 r_{ms}$. Accreting matter is drawn to the inner disk regions due to interactions with viscous stresses in the disk that transport angular momentum outward from the inner to the outer regions of the disk. The narrow peak of flux distribution observed in Figure 1.4 reflects the viscous stress that is seen by the accreting matter as it falls towards the compact object.

The standard thin disk models obtained by Shakura and Sunyaev^[14] and by Novikov and Thorne^[15] successfully characterize some of the energy spectra of radiation seen from binary systems. If the disk is optically thick, the expected emitted radiation is a modified black body spectrum described by the differential flux F_ν ,

$$F_\nu \propto \frac{x^{3/2} \exp(-x/2)}{(e^x - 1)^{1/2}} \quad [1.9]$$

where $x \equiv h\nu/kT_s$ and $T_s \approx 10^9$ K is the characteristic temperature of the accretion disk surface at which the emergent photon spectrum is formed. Equation [1.9] successfully describes the ultrasoft spectrum observed in the high state of Cyg X-1.

However, the standard thin disk models cannot produce the hard X-rays (~ 100 keV) observed from Cyg X-1^[15]. Other disk models have been proposed to explain the hard X-rays by adding Comptonization mechanisms to the existing standard thin disk models. Thorne and Price^[16] have argued that the instability in the inner region of a disk could swell the usual optically thick, radiation-pressure dominated region to a hotter ($\sim 10^9$ K), gas-pressure dominated, optically thin region. This would result in a "Compton cloud" occupying the inner region of a disk. By Compton scattering soft X-ray photons into hard X-rays, the Compton cloud model predicts a power-law for the spectral curve from 8 to ~ 500 keV, which compares well with the observed hard X-ray spectrum from Cyg X-1.

Another disk model first proposed by Ostriker^[17], Liang and Price^[18], and Bisnovatyi-Kogan and Blinnikov^[19], consists of an optically thick disk surrounded by a hot corona. The high temperatures in the corona are produced by acoustic and Alfvén waves and magnetic dissipation. The hot, thermal electrons in the corona Comptonize the soft photons into hard X-rays.

Recent advective-dominated accretion disk models proposed by Chakrabarti and Titarchuk^[20] and Narayan^[21] provide a self-consistent explanation for both the ultrasoft and hard power law tail energy spectra of Cyg X-1. The Two-Component Advective Flow (TCAF) model^[20] consists of an optically thin sub-Keplerian halo sandwiching an optically thick Keplerian disk, as illustrated in Figure 1.5. The disk component consists of viscous, predominantly Keplerian gases accreted through the Lagrange point from the companion star. As in the standard thin disk models of Shakura and Sunyaev, soft X-ray photons are expected to dominate the distribution of radiation emitted from the Keplerian disk. The surrounding halo component consists of a low viscosity, sub-Keplerian gas that is fed from the Keplerian disk far away and contributed to by companion winds.

The low angular momentum, sub-Keplerian gas flows advectively towards the black hole with roughly constant angular momentum, building up ram pressure due to its radial motion as it nears the centrifugal barrier. Where the ram pressure of the pre-shock flow roughly matches with the thermal pressure of the rotation dominated post-shock

Fig. 1.5 Schematic diagram of the two component advective disk model. A Keplerian disk component is enveloped by a sub-Keplerian halo component. A standing shock forms near where the sub-Keplerian gas hits the centrifugal barrier. Jets emitted from the post-shock region are predicted for supermassive black holes ($M > 10^7 M_\odot$).

flow a standing shock wave is formed. For matter with marginally bound angular momentum, $2\sqrt{3}M$, the shock forms around $\sim 10\text{--}30 R_s$. The location of the standing shock defines the effective inner edge of the accretion disk for both the disk and halo components. The post-shock thermalizes the accretion kinetic energy from the sub-Keplerian halo and creates a hot, optically slim and geometrically thick post-shock region. The post-shock halo intercepts soft photons from the Keplerian component and reradiates them as hard X-rays after Comptonization.

Figure 1.6 shows how the TCAF model describes the spectral index of the low and high states of black hole binary systems as a function of the accretion rate of the disk $\partial_i m_d = \partial_i M_d / \partial_i M_{Edd}$ and the accretion rate of the halo $\partial_i m_h = \partial_i M_h / \partial_i M_{Edd}$. The Eddington accretion rate $\partial_i M_{Edd}$ is proportional to the Eddington luminosity^[22],

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} = 1.3 \times 10^{38} (M/M_\odot) \text{ erg s}^{-1} \quad [1.12]$$

which is derived by balancing the gravitational attraction from the compact object's mass to the radiation pressure from the photons emitted from the disk. For a $16 M_\odot$ black hole in Cyg X-1, the Eddington limit is $2 \times 10^{39} \text{ erg s}^{-1}$.

Fig. 1.6 Variation of the energy spectral index α (observed slope in the 2–50 keV region) for the TCAF model^[20] as functions of the disk and halo accretion rates. Halo rates are marked on the curve. Computed spectral index in soft states due to convergent pre-shock inflow from the sub-Keplerian halo is also provided. Dashed curves indicate regions where both components could contribute. $M = 5 M_{\odot}$ is chosen.

During the low state the soft photons emitted from near the inner edge of the Keplerian disk (i.e. at the standing shock) are reradiated as hard X-rays by the post-shock halo through Comptonization. This accounts for the observed hard power-law energy spectrum. During the high state, when the accretion rate is higher, the additional flux of soft photons cools the post-shock region through inverse Compton scattering. This leads to a suppression of the hard power-law tail and an enhancement of the ultrasoft spectrum.

All of the accretion disk models described are steady state models that provide little temporal information about the X-ray emissions from the accretion process. However, there are several models that attempt to describe the time variability of X-ray emissions from a black hole binary.

Bao and Østgaard^[23] have numerically modelled orbiting blobs in a geometrically thin accretion disk around a black hole including all relativistic effects. The blobs or “hot spots” were simulated to radiate photons isotropically in their proper rest frames. For various assumed blob distributions and different inclination angles, they find that the time variability power spectra exhibit drop-offs at the Keplerian frequency of the

Fig. 1.7 Power spectrum of many simulated optically thick blobs orbiting about a black hole. Units for power are arbitrary and units of frequency are in $-1.5 \log(r/M)$. The drop-off in power occurs at the innermost orbit of the blobs corresponding to the Keplerian frequency $-1.5 \log(6) = -1.2$. The inclination of the accretion disk is 40° and the number distribution for the blobs, $n(r) \sim r^{-0.5}$.

inner edge of the accretion disk. These drop-offs are present whether the disk is optically thick or optically thin. Figure 1.7 shows an example of one of their power spectra that exhibits such a drop-off. The drop-off signifies an end of the self-similar $1/f$ structure of the variability. While Figure 1.7 shows a sharp drop-off in the power spectra, Bao and Østgaard recognized that noise in the observation data may smooth out this feature.

A model of accretion disk turbulence by Nowak and Wagoner^[24] also predicts a sharp drop-off in the Fourier power spectrum as shown in Figure 1.8. Three-dimensional hydrodynamic turbulence was considered as the mechanism driving accretion disk viscosity, affecting the observed flux by coupling to acoustic modes. In addition, low-frequency variability was modelled by weak fluctuations on viscous/thermal time-scales. For a $6 M_\odot$ black hole and a detector bandpass from 1.2 to 15.7 keV, their model predicts a sharp rollover in the Fourier power spectrum that starts between ~ 20 – 60 Hz and falls as f^{-5} for frequencies $f \geq 100$ Hz.

Fig. 1.8 Combination of viscous/thermal timescale and acoustic mode power from a model of accretion disk turbulence by Nowak and Wagoner^[24]. The detector bandpass = 1.2–15.7 keV; the luminosity = 0.1 times the Eddington limit; the viscosity parameter $\alpha = 0.3$; and the mass of the black hole = $6 M_{\odot}$.

In contrast to drop-offs in variability, Kato and Fukue^[25] realized that normal modes of oscillations can be trapped by general relativity near the inner edge of accretion disks around black holes. These modes do not exist in Newtonian gravity. Recent progress has been made in quantitatively identifying these modes. Nowak and Wagoner^[26] used a modified Newtonian potential to identify and characterize two of these modes. Perez, et. al.^[27] reanalyzed these modes by applying the relativistic fluid perturbation formalism of Ipser and Lindblom^[28] to thin accretion disks about a Kerr black hole. These studies of adiabatic oscillations that are trapped in the inner regions of accretion disks by non-Newtonian gravitational effects of a black hole have been called relativistic diskoseismology^[27].

Three types of trapped adiabatic oscillations have been identified and characterized by Nowak and Wagoner and Perez, et. al.^{[26],[27]}: internal gravity (g) modes, acoustic (p) modes and corrugation (c) modes. The lowest g-mode oscillations result from vertical displacements of the disk. Small radial displacements trapped near the inner

radius characterize the lowest p-mode. The c-mode oscillations are nonradial incompressible waves that slowly precess about the angular momentum of the black hole.

These trapped oscillations are expected to manifest themselves in the observed X-ray fluctuations as quasi-periodic oscillations (QPOs). The quality factor, Q of these QPOs can range from ~ 1 to ~ 100 depending on the disk viscosity and the number of radial and vertical modes excited. Nowak and Wagoner^[26] obtained an estimation of the fractional modulation of the disk luminosity to be $\sim 1\%$.

A prominent observed characteristic in black hole binaries such as Cyg X-1 is the power law shape of its variability power spectra (PSD). Attempts have been made to explain this power law using phenomenological models. The shot-noise model^[29] in particular, has been very successful in reproducing power law spectra. Each shot consists of an exponential rise and decay and the shots are distributed randomly in time. Variants of the shot model have also been proposed, such as the self-organized criticality (SOC) model proposed by Bak et al.^[30] and later applied to black hole objects by Mineshige, Ouchi and Nishimori^[31]. Here it is assumed that the regions near the inner edge of the disk are populated by numerous small reservoirs. If a critical mass density is reached at some reservoir, an unknown instability becomes established and accumulated material drifts inward as an avalanche, thereby emitting X-rays. The size of the X-ray shot is proportional to the number of reservoirs involved in an avalanche.

1.2 Searching for Black Hole Signatures in Cygnus X-1

Cygnus X-1 has been studied extensively for over 30 years because of several observed characteristics that indicate that its compact object is a black hole. Finding these characteristics or signatures is important in determining if black holes really exist. Signatures may also help determine one or more of the three physical properties of the black hole: its mass, angular momentum and charge. If black hole and neutron star binaries can be distinguished from each other, then observational characteristics unique to either a black hole or a neutron star may be identified. Finally, searching for expected

black hole signatures tests models of the accretion process and its underlying physics, general relativity.

Currently, the most popular and easiest method for identifying a compact object as a potential black hole is if its mass exceeds the Rhoades & Ruffini limit^[32] of $3.2 M_{\odot}$. The mass limit results from integrating over the volume of a gravitationally bound compact object in general relativistic hydrostatic equilibrium assuming an equation of state with the greatest possible stiffness. Matter cannot be so stiff that the speed of sound exceeds the speed of light, and this sets an upper limit on how strongly repulsive nuclear forces can become at ultrahigh densities. The Baym-Pethick-Sutherland equation of state^[33] is assumed below nuclear densities, but the resulting mass contribution amounts to only a few percent of the total mass limit. However, the Rhoades & Ruffini limit assumes that the compact object is bound gravitationally and that the nuclear physics of normal matter can be extrapolated to compact objects where the number of nucleons can exceed 10^{57} . Other equations of states have been proposed^[34] that circumvent these two assumptions, leading to much larger mass limits for compact objects.

Additional evidence for the existence of black holes in close binary systems has been sought by studying the characteristics of the X-ray emissions. Initial studies of the X-ray spectral data showed much promise for such evidence. Observed blackbody and power law energy spectra may be understood from standard^{[14],[15]} or advection-dominated^{[20],[21]} accretion disk models. However, these spectral characteristics appear to be mostly independent of the nature of the compact object since they are observed in both black hole and neutron star binary systems^[35].

The challenge remains to find X-ray characteristics that are unique to black hole binary systems. One of the physical properties that distinguishes a black hole from a neutron star is the absence of a solid surface. A non-rotating black hole's "surface" is characterized by an event horizon at the Schwarzschild radius, R_s . Nothing within this surface can be emitted to the outside observer. Nothing from the outside can reflect off this surface. These properties are in stark contrast to those of a neutron star. In close binary systems, X-ray bursts can be emitted from a neutron star's surface due to

thermonuclear flashes^[36]. Isolated neutron stars called pulsars have intense magnetic fields that can beam X-rays out along their magnetic poles^[37].

The dynamic timescale associated with a black hole is defined by the proper circumference at its surface, $2\pi R_s$. Light emitted from this spatial region should have a dynamic timescale $t_d \approx 2\pi R_s/c$. For a $16 M_\odot$ black hole, the dynamic timescale is roughly one millisecond. Since t_d corresponds to light emitted from the smallest spatial region around a black hole, no variability is expected at timescales below this characteristic value. In terms of frequency, this dynamic timescale becomes

$$f_d = c (2\pi R_{s_\odot})^{-1} (M_\odot/M) = 16 (M_\odot/M) \text{ kHz} \quad [1.13]$$

where $R_{s_\odot}$ is the Schwarzschild radius of a black hole with a mass of the sun. For Cyg X-1, the range of possible black hole masses, 7 to $21 M_\odot$, correspond to dynamic frequencies 2.3 kHz to 758 Hz, respectively. At the most probable mass, $16 M_\odot$, the dynamic frequency is < 1 kHz.

The dynamic frequency sets a rough upper limit to measuring variability in excess of Poisson noise. However, for close binary systems variability is expected to drop-off near the Keplerian frequency of the marginally stable circular orbit, as shown by Bao and Østgaard^[19]. The motion of a test particle about a central mass is characterized by its orbital frequency. The Keplerian frequency refers specifically to circular equatorial orbits. It is determined by finding the local minimum of the effective potential for radial motion introduced by the spacetime metric. For a rotating black hole governed by the Kerr metric the Keplerian frequency is^[13]

$$f_k = 31.8 (M_\odot/M) ((2r/R_s)^{3/2} \pm a)^{-1} \text{ kHz} \quad [1.14]$$

where the upper and lower signs refer to direct and retrograde orbits, respectively. In the limit of a non-rotating black hole ($a = 0$), with a mass of $16 M_\odot$, a test particle at the marginally stable orbit rotates with a Keplerian frequency of 135 Hz.

By substituting the radius of marginally stable circular orbit for the Kerr metric, equation [1.7] into equation [1.14], the Keplerian frequency can be expressed as a

Fig. 1.9 The dependence of the Keplerian frequency at the marginally stable circular orbit on the black hole angular momentum parameter $a = cJ/GM^2$. Positive and negative values of a represent direct and retrograde orbits, respectively. The boundaries of each band are defined by the mass limits of Cyg X-1's black hole.

function of the black hole's mass M and angular momentum parameter a . Figure 1.9 shows the dependence of the Keplerian frequency over the ranges of possible a and black hole masses of Cyg X-1. Positive and negative values of a correspond to direct and retrograde orbits, respectively. The shaded band in Figure 1.9 covers frequencies from 58 Hz to 2.3 kHz.

For the advection-dominated TCAF disk model, the effective inner edge of the disk lies farther out from the marginally stable orbit at the edge of an expected standing shock. The location of the standing shock is a function of the black hole's angular momentum and several properties of the accretion disk. Viscosity, the efficiency for transferring heat, and the specific energy and angular momentum of the accreting gas all contribute to determining the location of the shock. These properties are insensitive to the accretion rate^[20], so the location of the standing shock is expected to remain unchanged whether the binary system is in the high or low state.

For accreting gas with marginally bound angular momentum, the location of the standing shock ranges from $\sim 10\text{--}30 R_s$ to $\sim 5 R_s$ for a non-rotating ($a = 0$) and maximally

rotating ($a = 0.99$) Kerr black hole, respectively^[20]. At these radii, the Keplerian frequencies for the range of black hole masses, $7\text{--}21 M_{\odot}$ are from $51\text{--}3.3$ Hz for $a = 0$, and from $139\text{--}46$ Hz for $a = 1$, respectively. For a non-rotating $16 M_{\odot}$ black hole the Keplerian frequency is 22 Hz if the shock lies at $\sim 10 R_g$.

Unlike the radius of a marginally stable circular orbit, the effective inner edge of an advection-dominated accretion disk may not be as sharply defined. Several shock characteristics such as its strength may affect how well the shock obscures the Keplerian disk component behind the centrifugal barrier^[20]. A partial obstruction of this Keplerian disk component may smear this effective edge.

Other possible signatures of a black hole in a close binary system are the non-Newtonian quasi-periodic oscillations (QPOs) predicted by relativistic diskoseismology.^{[26],[27]} The QPOs result from modes of oscillations trapped near the inner edge of the accretion disk. Of the three types of identified trapped oscillations, the g-modes are the most robust and observable. The lowest radial ($m = 0$) g-modes have a frequency given by^[27]

$$f_g = 714 (1 - \epsilon_{nj}) (M_{\odot}/M) F(a) \text{ Hz}, \quad \epsilon_{nj} \approx \left(\frac{n+1/2}{j+1} \right) \frac{h}{r_0} \quad [1.15]$$

The dependency of f_g on the properties of the accretion disk is limited to one small term, ϵ_{nj} , in which r_0 is the radius of the mode, $2h(r_0)$ is the disk thickness, and n and j are the radial and vertical mode numbers, respectively. A radiation-pressure dominated optically thick disk region has typical geometrical fractional thickness $h(r_0)/r_0 \sim 0.1 L/L_{Edd} \sim 10^{-3}$ for Cyg X-1. $F(a)$ depends on the black hole angular momentum parameter $a = cJ/(GM^2)$, increasing from $F(-0.99) = 0.60$ to $F(0.99) = 3.44$. For a non-rotating, $16 M_{\odot}$ black hole, Equation [1.15] gives ~ 45 Hz for the lowest g-mode frequency.

Using [1.15], the frequencies of the g-modes of oscillations are plotted in Figure 1.10 for the same three black hole masses chosen for the Keplerian frequency profile. The g-mode frequencies range from 20.4 Hz at $a = -1$ to 351 Hz at $a = 1$. The frequency

Fig. 1.10 The dependence of the frequency of the lowest radial ($m = 0$) g-modes on the black hole angular momentum parameter $a = cJ/GM^2$. Positive and negative values of a represent direct and retrograde orbits, respectively. The boundaries of the band are defined by the mass limits of Cyg X-1's black hole.

band for these g-modes lies just underneath the frequency band for direct marginally stable orbits shown in Figure 1.9.

A summary of all the different characteristic frequencies predicted from these accretion disk models of Cyg X-1 are shown in Figure 1.11, spanning from roughly 3 Hz to 2.5 kHz. For each shaded region, the range of frequencies covers the ranges of possible black hole mass (7 to $21 M_\odot$) and angular momenta ($a = 0$ to 1).

To search for these variability characteristics, the Fourier spectral technique is employed. The finite Fourier transform of a time series of length T divided into N equal-length bins is

$$a_j = \sum_{k=0}^{N-1} x_k e^{2\pi i j k / N} \quad (j = 0, 1, 2, \dots, N/2) \quad [1.16]$$

where x_k is the number of events in the k th time bin, and a_j is the Fourier coefficient at frequency f_j ($f_j = j/T$). The squared magnitude of the j th Fourier coefficient, $|a_j|^2$, is a measure of the variability power in the source at frequency f_j .

Fig. 1.11 Summary of the frequencies where drop-offs or QPOs are predicted in Cyg X-1 over the range of possible black hole mass and angular momentum. The dashed vertical line in each shaded region marks the predicted frequency for a non-rotating, $16 M_{\odot}$ black hole.

The distribution of the variability power over all possible frequencies forms the Fourier power spectrum. With the Leahy normalization, this power spectrum is given by^[38]

$$P_j = \frac{2 |a_j|^2}{N_\gamma} \quad [1.17]$$

where N_γ is the total number of photons observed in the interval from 0 to T . (N_γ equals the value of the zeroth Fourier coefficient, a_0).

For a steady source, the power given by [1.17] is not zero because of noise introduced by Poisson counting statistics. However, Poisson noise introduces the same amount of power at all frequencies, and the power introduced can be readily calculated from the count rate. Excluding any instrumental effects, the power in [1.17] due to Poisson noise is 2 at every frequency^[38], forming what is usually called the Poisson noise floor.

At a given frequency, the powers introduced by Poisson noise are normally distributed by the central limit theorem. Namely, P_j is distributed as χ^2 with 2 degrees of freedom, where the mean is equal to the standard deviation. Fourier transforming a longer time series simply extends the frequency range where power is calculated. The power at each frequency is still distributed with the same standard deviation.

To improve the signal-to-noise, it is necessary to sum a large number of power spectra of independent segments of data. In addition, the powers are usually summed over adjacent frequency bins in a narrow interval. The actual procedure consists of first dividing the data into sequential time segments of equal length. The Fourier power spectra are then calculated for all of these segments and then averaged together over equal logarithmic frequency intervals. If the power spectrum is averaged over S independent data segments and M adjacent frequency bins then the distribution of averaged power due to Poisson noise approaches a Gaussian with standard deviation $2/\sqrt{SM}$. An intrinsic average power spectrum may be determined by subtracting the Poisson noise floor from the average power spectrum. The standard error on the average noise-subtracted power at a given frequency is determined by adding in quadrature the standard errors of the average power spectrum and the Poisson noise floor.

1.3 Experimental Results

Results from analysis of Cyg X-1 data from HEAO A-1 and RXTE/PCA, detailed in Chapter 3 and 4, are presented here. HEAO A-1 and RXTE/PCA have time resolution capabilities of 10 microseconds or better. Such capabilities are useful to search for black hole characteristics predicted at the frequencies summarized in Figure 1.11. Studies of the HEAO A-1 data were motivated by evidence for the inner edge of an accretion disk found in one of its observations of Cyg X-1. An analysis of that observation by Meekins, et. al.^[6] showed evidence for excess intrinsic variability between the 1 - 10 millisecond timescales that cut off at the one millisecond timescale. For a $16 M_{\odot}$ black hole, the marginally stable orbit lies at a timescale of ~ 7 milliseconds and the dynamic timescale of equation [1.13] is expected at one millisecond.

Encouraged by this possible black hole signature, this evidence was first reproduced by applying the same analysis to the same observation. Figure 1.12a shows good agreement between the original and reproduced analyses. In their analysis of the HEAO A-1 data, Meekins, et. al. neglected the effects due to dead time and other possible instrumental effects. After an extensive analysis of all the high time resolution HEAO A-1 data and a comparison to Monte Carlo models of the detector response, a previously undetected instrumental effect was found. This instrumental effect has been observed in all the high time resolution pointed observations. A HEAO A-1 module-electronics malfunction is suspected of causing these distortions. Chapter 3 describes this instrumental effect in further detail. Figure 1.12c shows the result of correcting the Meekins, et. al. analysis for dead time and other instrumental effects using a Leahy normalized Fourier power approximation to the relative power described in Chapter 3. After correcting for instrumental effects, the excess intrinsic variability between the 1–10 millisecond timescale is no longer present.

The Fourier power spectral technique was then applied to all the high time resolution Cyg X-1 data from HEAO A-1. Figure 1.13 shows the resulting noise-subtracted Fourier power spectrum. The noise floor due to Poisson statistics was corrected for instrumental effects before the subtraction, described further in Chapter 3. To measure the significance of the noise-subtracted power, the 95% confidence level for detecting a signal above the Poisson noise floor is overlaid in Figure 1.13 as a solid curve. Excess power is observed at frequencies less than 20 Hz at greater than a 95% confidence level above the Poisson noise. At frequencies greater than 40 Hz, the noise-subtracted spectrum was forced to be consistent with the null hypothesis in order to correct the Poisson noise floor for HEAO A-1's instrumental effects.

Between frequencies 0.1 and 20 Hz, the spectrum follows power laws with a break to a steeper index at 3 Hz. Power laws were fit separately to the frequency region before and after the break. As Table 1.1 shows, the power spectrum roughly follows a $1/f$ spectrum before the break and then falls more steeply afterwards.

Fig. 1.12 The relative integral power defined by Meekins, et. al. for Cyg X-1, using a) the original Meekins definition, b) the Leahy power approximation, and c) the Leahy approximation corrected for dead time and additional instrumental effects. The two sets of relative integral power in a) are from the original Meekins, et. al. analysis and a reanalysis by Wen, et. al. using the general theoretical framework of Meekins, et. al.

Detector	Power Law Before Apparent Break			Power Law After Apparent Break		
	Frequency Range [Hz]	Photon Index	χ^2/dof	Frequency Range [Hz]	Photon Index	χ^2/dof
HEAO A-1	0.1 – 3	1.20 ± 0.08	15/13	3 – 40	1.7 ± 0.2	18/19
RXTE/PCA	0.1 – 3	1.24 ± 0.04	28/14	14 – 40	2.1 ± 0.5	4/8

Table 1.1 Summary of power law fits to the noise-subtracted Fourier power spectrum. The breaks between the two effective power laws occur at 3 Hz and 10 – 20 Hz for the HEAO A-1 and RXTE/PCA data, respectively.

The RXTE/PCA data was Fourier analyzed in the same manner as the HEAO A-1 data in the attempt to both verify the HEAO A-1 results and resolve some of the uncertainties in those results that remained even after correcting for instrumental effects. The RXTE/PCA lacked evidence for any other instrumental effect except that due to dead time. Correcting the Poisson noise floor for dead time is discussed further in Chapter 4.

The resulting noise-subtracted power spectrum also shows two power laws in the spectrum as shown in Figure 1.14. The break between the two power laws is seen at a higher frequency between 10 to 20 Hz, and features a more rounded shape. Table 1.1 summarizes the results of fitting power laws to the regions before and after this break.

The effect of approaching the Poisson noise floor is clearly demonstrated by the flattened spectrum at frequencies greater than 50 Hz. It is an artifact introduced by limited counting statistics. The downward slope results from more statistics at higher frequencies. Despite the limiting statistics, evidence for marginal excess power is seen at frequencies between 100–4000 Hz. Over 33% of the excess power at frequencies greater than 100 Hz exceeds the 95% confidence level curve.

No evidence is seen in this analysis of the Cyg X-1 data for the QPOs. A 95% confidence level upper limit is shown in Figure 1.15 for detecting QPOs of a given fractional root-mean-square (rms) amplitude over a given logarithmic frequency interval. The QPOs for this limit are contained within a given logarithmic frequency interval, giving a quality factor, $Q > 9$. The best upper limits are obtained from RXTE/PCA

Fig. 1.13 The noise-subtracted Fourier power spectrum of Cygnus X-1 from the HBR data in a) full and b) close-up views. The Poisson noise floor was corrected for instrumental effects before the subtraction. The solid curve represents the 95% confidence level for detecting a signal above the Poisson noise floor.

Fig. 1.14 The noise-subtracted Fourier power spectrum of Cygnus X-1 from the RXTE/PCA data in a) full and b) close-up views. The Poisson noise floor was corrected for dead time before the subtraction. The solid curve represents the 95% confidence level for detecting a signal above the Poisson noise floor.

Fig. 1.15 The 95% confidence level upper limit for detecting QPOs in Cyg X-1 with a quality factor, $Q > 9$ for a given fractional rms amplitude. The shaded region spans the range of expected frequencies for g-mode QPOs, with the horizontal line marking the expected g-mode QPO amplitude and the dashed vertical line marking the frequency for a non-rotating, $16 M_{\odot}$ black hole.

since that observation contained six times more data than HEAO A-1 on Cyg X-1. Over the frequency range from 20.4 to 351 Hz where diskoseismic QPOs are predicted for Cyg X-1, the fractional rms amplitudes are less than 1.9% at a 95% confidence level. For a $16 M_{\odot}$ black hole, the limit is 1.2%. As Figure 1.15 shows, the 95% confidence level upper limit curve in the shaded region lies above the $\sim 1\%$ fractional rms amplitude predicted for diskoseismic QPOs.

1.4 Summary

The study of X-ray time variability of close binary systems appears to be a promising method of searching for predicted black hole features. Evidence for a smooth drop-off may be interpreted from the faster fall off in variability at frequencies greater than the observed break from the $\sim 1/f$ power law behavior. The break occurs in the HEAO A-1 and RXTE/PCA data at roughly 3 Hz and between 10–20 Hz, respectively. Both breaks occur at frequencies within the range of drop-offs expected from the advection-dominated TCAF model. The break between 10–20 Hz is also near the sharp

rollover predicted by Nowak and Wagoner's model of accretion disk turbulence. More RXTE/PCA data is needed to determine how the drop-off behaves at frequencies greater than 50 Hz, by lowering the expected variance in the Poisson noise floor (the solid curve in Figure 1.14). As Figure 1.16 shows, the noise-subtracted spectra from the HEAO A-1 and RXTE/PCA data are consistent with each other within their given error bars at frequencies greater than ~ 10 Hz. The drop-off starting at 3 Hz in the HEAO A-1 data matches smoothly to the start of the drop-off at ~ 10 Hz in the RXTE/PCA data.

At frequencies less than 10 Hz, the variability in the HEAO A-1 data is 2–3 times greater than the RXTE/PCA data with the same approximate $\sim 1/f$ power law behavior. These differences may be attributed in part to the different states Cyg X-1 was in for the two periods of observations: low state for HEAO A-1 and high state for RXTE/PCA. In addition, the two instruments have different detector efficiencies and are thus sensitive to detecting X-rays in different energy ranges. As described in Chapter 2, the HEAO A-1 and RXTE/PCA detectors are sensitive to detecting photons at 15% efficiency with energies of 1 keV and 2.5 keV, respectively. Assuming a power law with a spectral index of 1.5, the photons from 1–2.5 keV comprise about 17% of the total number of photons detected by HEAO A-1. Unfortunately, individual photon energy information was not available to the HEAO A-1 detector. The USA detector, which is sensitive to detecting 1.1 keV X-rays at 15% efficiency will be able to test if photons from 1–2.5 keV exhibit greater variability than photons with energies greater than 2.5 keV.

The locations of the apparent breaks in the two power spectra occur at frequencies too low to be evidence of drop-offs near the marginally stable orbit. Instead, they may indicate the location of the shock formed from advection-dominated accretion or for the HEAO A-1 data, the outer edge of the Compton cloud.

The interpreted drop-offs exhibit a lower degree of steepness than predicted by Bao and Østgaard. Such drop-offs may be smoothed by other physical processes not explicitly included in their model. The X-ray emissions from Cyg X-1 may suffer from interference from a Compton cloud or hot corona believed to surround the black hole. In

Fig. 1.16 The noise-subtracted Fourier power spectra of Cygnus X-1 from the HEAO A-1 and RXTE/PCA data shown together a) from 1–100 Hz on a log scale and b) from 10–100 Hz on a linear scale. The two spectra are consistent with each other within their given error bars for frequencies greater than ~ 10 Hz.

Fig. 1.17 Total integrated RXTE/PCA observation time required to detect diskoseismic QPOs in Cyg X-1 with a Fourier power amplitude a given number of sigma above Poisson noise. A fractional rms amplitude $\sim 1\%$ and quality factor, $Q > 9$ are assumed for the QPOs.

the alternative advection-dominated disk model, the shock formed by sub-Keplerian flows can strongly interfere with the X-ray emissions near the inner edge of the accretion disk.

Given the amount of Cyg X-1 data analyzed from RXTE/PCA, diskoseismic QPOs with 1% fractional rms amplitudes can be excluded for frequencies ≤ 25 Hz at a 95% confidence level. The excluded frequencies contained within the shaded region in Figure 1.15 correspond to retrograde orbits with black hole angular momenta parameter $a \leq -0.5$. As discussed in Chapter 3, the QPO amplitude is proportional to the square root of the standard error of the average Fourier power. This standard error as described in Section 1.2 is inversely proportional to the square root of the number of data segments averaged, namely, the length of the data. Therefore, the QPO amplitude is inversely proportional to the fourth root of the length of data. A 95% confidence level upper limit for detecting diskoseismic QPOs in Cyg X-1 at a 1% fractional rms amplitude over the entire range of predicted frequencies, requires a total of five hours of integrated RXTE/PCA observation time.

If we instead assume that diskoseismic QPOs are present in Cyg X-1, then an important experimental quantity is the amount of data needed to detect the QPOs at a given confidence level above the Poisson noise. Figure 1.17 shows the total integrated RXTE/PCA observation time required to detect diskoseismic QPOs with a Fourier power amplitude a given number of sigma above Poisson noise. A quality factor, $Q > 9$ and a 1% fractional rms amplitude over the range of predicted frequencies were assumed. To detect 4-sigma diskoseismic QPOs in Cyg X-1, a total integrated RXTE/PCA observation time of 21 hours or about a day is required.

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SUMMARY OF X-RAY MISSIONS

2.1 Introduction

X-ray time variability characteristics unique to black hole binary systems are expected at frequencies spanning several orders of magnitude depending on the properties of the black hole and the accretion disk. For Cyg X-1, the frequency range spans from tens of Hertz to several kiloHertz. A search for such variability characteristics in Cyg X-1 requires an instrument with time resolution of 50 microseconds or better. Three astronomical instruments that have flown, are flying or will soon fly currently satisfy this requirement, the High Energy Astrophysical Observatory (HEAO-1), the Rossi X-ray Timing Explorer (RXTE) and the Unconventional Stellar Aspect Experiment (USA). All three of these instruments have 10 microsecond time resolution capabilities or better. This Chapter will describe these instruments in greater detail.

2.2 High Energy Astrophysical Observatory (HEAO-1)

2.2.1 *Mission*

The first of NASA's three High Energy Astrophysical Observatories, HEAO-1 was launched aboard an Atlas Centaur rocket on 12 August 1977 and operated until 9 January 1979. During that time, it scanned the X-ray sky almost three times in

HEAO Instruments **NRL & NASA (b)
1977-79****HEAO A-1** **Fig. 2.1**

a) The High Energy Astrophysical Observatory-1 HEAO-1 satellite shown with its four major experiments identified. b) An exploded view of the HEAO A-1 detector.

Name	Mission	Instrumentation
A1 - Large Area Sky Survey experiment (LASS) ^[1]	All-sky survey of X-ray sources	Array of seven proportional counters with 1350 cm ² , 1650 cm ² and 1900 cm ² open areas covering 0.25 to 25.0 keV.
A2 - Cosmic X-ray Experiment (CXE) ^[2]	Study the large scale structure of the galaxy and the universe (diffuse X-ray background)	Array of six proportional counters with 400 cm ² and 800 cm ² open areas covering 0.15 - 60 keV
A3 - Modulation Collimator (MC) ^[3]	Measure the positions of X-ray sources with sufficient precision to identify optical and/or radio counterparts.	Two four-grid modulation collimators with 300 cm ² effective area covering 0.9 - 13.3 keV. Positional accuracy was projected to be ~2'.
A4 - Hard X-Ray / Low Energy Gamma Ray Experiment ^[4]	Observe hard X-rays / low-energy gamma-rays	Seven scintillators with 45 cm ² and 100 cm ² areas covering 15 keV - 10 MeV.

Table 2.1 Brief summary of the four experiments in HEAO 1.

the energy range 0.2 keV - 10 MeV, provided nearly constant monitoring of X-ray sources near the ecliptic poles, as well as more detailed studies of a number of objects through pointed observations. HEAO-1 was primarily a survey mission, dedicated to systematically mapping the X-ray sky every 6 months. The satellite was launched into a nearly circular orbit with apogee 445 km and inclination 22.75°. HEAO-1 had a 93 minute orbital period, and, while in scanning mode, spun with a nominal period of 33 minutes. Each spin traced out a great circle of constant ecliptic longitude. Every twelve hours, the spin axis was moved approximately 0.5° in order to keep it pointed at the Sun; thus, after 6 months, the entire sky had been observed. After the first ~ 100 days of the mission, scanning was interrupted from time to time to point the detectors at particular objects of interest. These pointing times became more frequent until 9 January 1979, when the gas used to control the spacecraft attitude ran out. The systems were shutdown, and HEAO-1 drifted in a decaying orbit until March 1979, when it burned up

Sensor Module	FWHM	View Direction	Open Area (cm ²)	Comments
1	1° × 4°	-Y	1650	Failed 9/23/77
2	1° × 4°	-Y	1650	Failed 9/22/77
3	1° × 4°	-Y	1650	Single Detector Case
4	1° × 4°	-Y	1650	Failed 1/26/78
5	1° × ½°	-Y + 1/3° Z	1350	Not used in this analysis
6	1° × ½°	-Y - 1/3° Z	1350	
7	2° × 8°	+Y	1900	Intermittent severe noise

Table 2.2 Summary of HEAO A-1 Module properties. Modules 5 and 6 were tilted a third of a degree either towards or away from the Z (Sun-pointed) axis.

on re-entry into the atmosphere.

2.2.2 Instrumentation

HEAO-1 carried four instruments all used primarily in a scanning mode, with a small number of pointed observations. Table 2.1 briefly describes each of these four experiments. Of special interest is the A1 instrument, also known as the NRL Large Area Sky Survey Experiment (LASS) or HEAO A-1^[1].

As Figure 2.1 shows, the HEAO A-1 instrument consisted of seven sensor modules, six mounted on the -Y side of the spacecraft, the seventh on the +Y side. Each sensor module had a collimator constructed of rectangular molybdenum tubes of various dimensions. Table 2.2 summarizes their properties. The experiment had sufficient sensitivity to detect sources as faint as 0.25 μ Jy at 5 keV for sources with a Crab-like spectrum. Data was typically collected in either a 5 or a 320 millisecond timing resolution mode. Full sky coverage for both time resolutions was achieved before the mission's end.

Each sensor module consisted of a 2' × 3' proportional counter body frame on which was mounted support structures, a collimator assembly and electronic subassemblies.

Fig. 2.2 HEAO A-1 effective area for a single Module (1,2,3 or 4) for the sum of both wire layers as a function of photon energy. Cyg X-1 data used in this analysis collected from Module 3 only.

The proportional chamber contained three wire layers, where the top layer usually served as the X-ray sensor while the lower two layers provided anticoincidence protection against charged particle events. Additional anticoincidence protection was provided on the ends and sides.

The gas in the chamber was supplied by a central gas system consisting of two 524 psi spherical tanks filled with a gas mixture of 77.5% Xenon and 22.5% Methane. Each tank was separately valved to a gas distribution system, supplying gas to any or all of the seven sensor modules.

A 2.5 μm layer of mylar contained the gas volume. To maintain electrical conductivity on the inward surface, the mylar was coated with a thin film of Nichrome, 45 Å thick. In addition to the collimator face, a stainless steel wire mesh was placed in-between the collimator and the mylar window to provide additional support and protect against any small burrs on the collimator face. To protect against overheating from the sun, the collimator was covered with a 2 μm aluminized Kimfol heat shield that had an

effective transmission of 91.2%. Figure 2.2 shows the resulting effective X-ray acceptance for HEAO A-1 module 1, 2, 3 or 4.

Each sensor module had its own independent electronics consisting of preamplifiers, high voltage filter and logic and digitizing circuitry. The circuitry was composed of a remote serial magnitude command decoder, a data analog-to-digital converter and a housekeeping multiplexer.

Processing the digitized data from the modules was a task left to the central electronics. It sorted the module data according to either a 16-channel or a 40-channel nonlinear energy scale and routed it to scalar accumulators. Depending on the telemetry format chosen (320 msec/5 msec) additional processing may have been applied to the data with the accumulated counts saved into the appropriate data format.

One special telemetry mode consisted of utilizing the Random Encoder unit to transmit events at a 1- 8 μ s time resolution in real time at a high-bit-rate (HBR) of 128 kps. Events received originated from either the sum of sensor modules 1-4 or singly from module 7, depending on which side of the satellite the X-ray source was located. Since modules 1, 2 and 4 had failed by the time most of these HBR telemetry modes were commanded, most of the resulting data in this mode originated only from either sensor module 3 or 7.

2.3 Rossi X-Ray Timing Explorer (RXTE)

2.3.1 Mission

The Rossi X-ray Timing Explorer is a NASA mission with instruments built by the NASA Goddard Space Flight Center (GSFC), Massachusetts Institute of Technology (MIT) and the University of California, San Diego (UCSD) that was launched on December 30, 1995. RXTE is designed to facilitate the study of time variability in the emission of X-ray sources with moderate spectral resolution. Time scales from microseconds to months are covered in an instantaneous spectral range from 2 to 250 keV. It is designed for a required lifetime of two years, with a goal of five years.

Fig. 2.3 The Rossi X-Ray Timing Explorer satellite.

The spacecraft was designed and built by the Engineering Directorate at GSFC. The launch vehicle was a Delta II rocket that put RXTE into a low-earth circular orbit at an altitude of 580 km, corresponding to an orbital period of about 90 minutes, with an inclination of 22.75°.

2.3.2 Instrumentation

The mission carries two pointed instruments, the Proportional Counter Array (PCA)^[5] developed by GSFC to cover the lower part of the energy range, and the High Energy X-ray Timing Experiment (HEXTE)^[6] developed by UCSD covering the upper energy range. These instruments shown in Figure 2.3 are equipped with collimators yielding a 1° FWHM. RXTE also carries an All-Sky Monitor (ASM)^[7] from MIT that scans about 80% of the sky every orbit, allowing monitoring at time scales of 90 minutes or longer. Data from the PCA and the ASM are processed on board by the Experiment Data System (EDS)^[8], also built by MIT.

The PCA is an array of five proportional counters shown in Figure 2.4 with a total collecting area of 6500 cm². Sensitive to a spectral range from 2 - 60 keV at an energy resolution < 18% at 6 keV, the X-rays can be recorded to 1 microsecond resolution. The effective X-ray acceptance for RXTE/PCA is shown in Figure 2.5. Each PCA unit has a

a) PCA Assembly (5 units)

b) Proportional Counter (1 unit)

Fig. 2.4 a) Layout of the Proportional Counter Array (PCA). b) Cross section of a PCA unit showing the various components of its operation.

Fig. 2.5 RXTE/PCA effective area for all PCUs and all anodes as a function of photon energy.

collimator constructed of a honeycomb of hexagonal tubes with 1° FWHM. An additional “single-cell” rectangular tube sits on top of the collimator to serve as a sun shade.

Sitting below the collimator, a thin proportional chamber is filled with propane gas and netted down its center with a single layer of wires to serve as an anticoincidence layer. Below this thin chamber is the main proportional chamber surrounded along its perimeter by anticoincidence chambers with a single layer of wires running through. The main proportional chamber contains three signal layers and shares a mixture of 78% Xenon and 22% Methane gas with the anticoincidence chambers. To contain the propane gas in the anticoincidence layer, two layers of $25\ \mu\text{m}$ thick mylar are positioned, one above and the other below the layer's boundaries. Figure 2.4 summarizes the components of this PCA unit.

Fig. 2.6 The Advanced Research and Global Observation (ARGOS) satellite.

2.4 Unconventional Stellar Aspect Experiment (USA)

2.4.1 Mission

The Unconventional Stellar Aspect Experiment (USA)^[9] is a joint collaboration of the Naval Research Laboratory (NRL) and the Stanford Linear Accelerator Center (SLAC) to develop and operate a pointing X-ray observatory. The expected launch date is December 1997. USA is designed to collect large amounts of high resolution X-ray timing data with moderate spectral resolution on 30 of the most luminous sources in the X-ray sky. Each X-ray source will be observed at roughly one microsecond time resolution in the spectral range from 1 to 25 keV for a total collected duration of about one month. The experiment is designed for a required lifetime of three years, with a goal of five years.

As one of several experiments on the Air Force's Advanced Research and Global Observation Satellite (ARGOS), the USA experiment will be mounted on the aft or antivelocity face of ARGOS, shown in Figure 2.6. ARGOS will be launched by a Delta II rocket into a low-earth orbit at an altitude of 834 km or a nominal orbital period of 102 minutes with an orbital inclination of 98.7°. Onboard gyros will keep the orbit sun-synchronous so that in a period of a year, the orbital plane will sweep the entire celestial sky.

Fig. 2.7 USA effective area for both detector units and all three wire layers as a function of photon energy.

2.4.2 Instrumentation

Two independent detector units (DU) with a total collecting area of 2000 cm² comprise the primary components of the USA experiment. Each detector unit consists of a collimator, a proportional counter, gas system and central electronics. Figure 2.7 shows the effective X-ray acceptance for the USA detectors. The collimator is a honeycomb of hexagonal copper tubes (1.2° FWHM) formed into eight separate modules to facilitate their construction. Each module is 4½" deep with a 3" × 11" face. They are stacked along the longest dimension in groups of four to form the two segments that fill its support structure, an aluminum collimator frame.

Construction and testing of the USA collimator modules were performed at SLAC. The acceptance of each module to X-rays incident at given relative angles were measured. The X-ray beam consisted of an ⁵⁵Fe source placed at the end of a long evacuated pipe that was assembled in the PEP Machine tunnel. A detector apparatus was designed and constructed to position the modules and detect the X-rays transmitted through the module. Further details of this testing are given in Appendix D.

Fig. 2.8 Layout of a USA detector unit with an exploded view of the collimator.

The collimator frame was bolted onto a proportional chamber with a thin window in between to contain the gas volume. The window's thickness was chosen to be 5 μm mylar to lower the energy spectrum of detected X-rays to the 1 keV region. A fine wire mesh is placed between the window and the collimator to give the window additional structural support and protection against any small burs on the collimator face. Along the junction of two stacked collimator modules, the two supporting bridge sheets formed a thin separation. At the end of a thermal-vac cycle during preflight testing, the window burst along one of these thin separations, causing a catastrophic collimator failure. Additional details about this incident are provided in Appendix D.7. After this incident, all of the junctions between collimator modules and between the modules and the support frame were taped over to protect against the window expanding into and possibly breaking this junction.

Refurbished from the Spartan shuttle mission, the multi-wire proportional chamber contains one perimeter veto wire and three wire layers. The chamber is filled with P-10 gas (90% Argon, 10% Methane). A spherical titanium gas bottle bolted to the detector backplane supplies the P-10 gas at 2700 psi. The pressure regulation system

a) USA front view, rotated

b) USA front view, straight-on

Fig. 2.9 Front views of the Unconventional Stellar Aspect Experiment shown here a) rotated with its collimator face exposed and b) straight-on with its sun shield in place, but without its Multi-Layer Insulation (MLI) thermal blanket.

a) USA rear view, rotated

b) USA rear view, straight-on

Fig. 2.10 Rear views of the Unconventional Stellar Aspect Experiment shown here without its MLI thermal blanket a) rotated and b) straight-on. The gas tanks are indicated by the two metal spheres, one for each detector unit. The two views are rotated from each other by 180° about the yoke and the pylon axes.

maintains the chamber at 14.7 psi.

A 2.5 μm layer of aluminized kapton is suspended above the collimator by an aluminum heat shield frame. The layer serves as a heat shield to keep the sun heat input through the face of the collimator to a minimum. Figure 2.8 summarizes the geometry of a USA detector unit.

The two detector units are supported together by a two-axis gimbal system^[10]. As Figure 2.9 and 2.10 shows, the two detector units are first supported by a yoke along an axis that enables rotations of $\pm 90^\circ$ in yaw. The yoke, in turn is supported by two pylons along an axis perpendicular to the first that enables $+70^\circ/-100^\circ$ rotations in pitch. With this two-axis gimbal system any source within the limits in pitch and yaw as described may be tracked by the USA detector during its orbital motion.

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HEAO A-1 HIGH-BIT-RATE DATA STUDIES

3.1 Introduction

The HEAO A-1 High-Bit-Rate (HBR) data is the highest time resolution data available from the A-1 instrument. It was obtained by commanding a special telemetry mode to transmit event times in real time at a one or eight microsecond time resolution. The HBR data were recorded periodically from 1977 to 1979 at time resolutions higher than any other X-ray detector before or after the HEAO-1 mission. HEAO A-1 held this distinction until 1995 when XTE was launched.

Given that distinction, the HBR data represented a unique opportunity to measure the X-ray time variability of astronomical objects at submillisecond timescales. In 1984, Meekins, et. al.^[1] analyzed an HBR pointed observation of Cyg X-1. They reported evidence of a cutoff in the time variability at the one millisecond timescale, described further in Section 3.6. Motivated by this finding as evidence for a black hole, the HBR data were recovered in 1995 by a joint effort of the Stanford Linear Accelerator Center (SLAC) and the Naval Research Laboratory (NRL). This Chapter will describe the recovery of the HBR data, the development of a data archive at SLAC, and the subsequent processing and data analysis.

Mode	Time Resolution [μ s]	Maximum Data Rate [$\times 10^3$ events/sec]	Description
Bit	7.8125	128	Characterized by a change in level of the bit stream to signify an event.
Word	7.8125	12.8	Characterized by the occurrence of a 10 bit sync word to signify an event.
Frame	1	11	Consists of 11 x 10 bit words, 17 bits of sync and one overflow bit, for a frame length of 128 bits. The 10 bit data words represent the time from the beginning of the frame to an event. This time is in binary counts of the 1.024 MHz spacecraft clock.

Table 3.1 Description of the telemetry modes available for the HBR data. Only the Bit mode was used.

3.2 Description of the HBR Data

During the normal workhorse mode, the A-1 instrument^[2] accumulated X-ray events in sequential 320 or 5 millisecond time bins and stored the resulting data on its onboard tape recorders. The stored normal telemetry data were then downloaded during the spacecraft's next pass over a ground station. For historic reasons, the normal telemetry data are referred to as the Non-Return-to-Zero (NRZ) data. For the HBR data, the onboard tape recorder was not available. The HBR data were instead obtained by preempting the transmission of the normal telemetry data and using the spacecraft's entire 128 kbps data channel to downlink the data in real time. This restricted observations at the HBR time resolutions to 11 minute periods, four times per orbit, when the spacecraft was in direct radio contact with a ground station.

The time resolution of the HBR data varied between one and eight microseconds depending upon which of the three HBR telemetry modes was selected. The majority of the HBR observations were collected at an eight microsecond time resolution in the Bit mode, described in Table 3.1. This is the only mode whose data format is understood. For a detailed description of Bit mode data format see Appendix A.1.

At the ground stations, the HBR and NRZ data were recorded together onto analog magnetic tapes on separate tracks. The tapes were then forwarded to NRL under an arrangement with NASA, whereby NRL assumed the responsibility for their digitization. At NRL the analog tapes were read with a video tape drive, digitized using a NOVA 800 and the data were written onto 9-track 6250 bpi magnetic tapes.

Except for the Meekins, et. al. analysis in 1984, these magnetic tapes lay primarily in storage at NRL for eleven years. In 1995, a joint effort of SLAC and NRL led to the recovery of these data. This process was made difficult by the paucity of documentation and the dispersion of the personnel familiar with the data, by-products of the extended period of time since the HEAO-1 mission. Nevertheless, with the guidance of K. Wood and D. Yentis, the two resident experts on the HBR data, the magnetic tapes were successfully located and read by a Data General Eclipse. The data were written to disk, one file for each observation. Log book records identified the observations on each tape. The size of the total data sample is 2 gigabytes.

The HBR data were then stored permanently in the SLAC cartridge silo facility onto high density magnetic cartridges. First, the data files were transmitted to SLAC over the internet and written to disk. These files were then transferred and staged to the SLAC staging farm. UNIX shell scripts^[3] were written to automate this process. Once in the staging farm, the files were written to one of the cartridges in the SLAC silos.

With the data readily accessible, the next task was understanding the data format. A search of documentation at NRL yielded a few routines that were used in the preliminary data processing and in the Meekins, et. al. analysis. Only one of the routines found described the HBR data format of only one of the telemetry modes, the Bit mode. To process the data with an acceptable performance using the hardware at the time, this routine was written in Data General Assembly. This routine was deciphered after considerable effort with generous assistance from D. McNutt and T. Crandall, and translated into an Interactive Data Language (IDL)^[4] routine. The data format of the HBR Bit mode is described in detail in Appendix A.

DATA PROCESSING STEPS	
1) MKHBRECS	Produce "Quick Look" light curves
2) HBRFMT	Re-format raw data into the Photon Time Interval (PTI) format
3) CTIFMT	Simplify PTI format data into the Concatenated Time Interval (CTI) format

Table 3.2 The major data processing steps for creating the HBR data archive.

3.3 Processing the HBR Data

The construction of the HBR data archive at SLAC is summarized by the three major production steps shown in Table 3.2. In general, each step reduces the data set size and simplifies the retrieval of event times. All of the production routines were developed at SLAC and the relevant source listings are provided in Appendix A.4. The first step in the data processing examined a quick look of the data. The MKHBRECS routine extracted the light curves from the data. Plots of the light curves revealed that counts near the ends were too high to be interpreted as real count rates, as Figure 3.1 shows. These numbers occur during the periods when either an acquisition is lost or gained over a ground station or when the telemetry mode is switching between HBR and NRZ. The data records corresponding to these regions were cut from further processing.

A product of the real time acquisition of the HBR raw data is a highly inefficient data format. One bit is recorded for each sequential 8 microsecond interval. Namely, information is stored for every time bin. A bit is set if one or more events occur in that 8 microsecond interval or is otherwise cleared. The resulting data is sparsely populated with set bits, even at Crab intensities ($\sim 6\%$). The second production step improves the data storage efficiency by storing information for every event instead of every time bin. The HBRFMT routine reformats the HBR raw data into storing the time intervals or *waiting times* between sequential events. This HBRFMT routine was originally developed at NRL in skeletal form and later rewritten and expanded at SLAC. The format of the reformatted data is called the Photon Time Interval (PTI) format. Further description of the PTI

Fig. 3.1 Typical light curve for a HBR raw data file. The ends contain numbers $>$ Crab intensity ~ 2300 counts/320 ms/ $1^\circ \times 4^\circ$ Module and were cut from further data processing.

format can be found in Appendix A.2. The resulting PTI files are on average 4 times smaller than their raw data predecessors.

Although the PTI format stored photon times efficiently, retrieving those photon times is somewhat cumbersome. The data format was designed for sequentially accessing data in 40.96 second sections. These sections of time, called Major Frames, originate from the format of the normal 320 or 5 millisecond binned NRZ data that delimited sections by Major Frames. The CTIFMT routine concatenates all the Major Frame data segments in the PTI format into arrays, greatly simplifying the retrieval of photon event times. These arrays are stored into a single Interactive Data Language (IDL) structure variable named *cat*. For a complete description of this IDL structure variable, see Appendix A.3. This IDL structure variable is then saved to an IDL save session file. An IDL save session file is written in a platform independent format called the eXternal Data Representation^[5].

Since NASA neither checked nor corrected the HBR data for possible errors, those tasks were left to the data processing at SLAC. Several diagnostic tools were available to help identify errors in the HBR data. Flags associated with downlink errors were included in the HBR data format every 80 microseconds. If any of these error flags was set, then the associated data were cut from further processing. The NRZ data were

also included in the data stream. Since the NRZ and HBR data collected events over the same period of time, their light curves could be compared and checked for differences. Appendix B describes the procedure for comparing the two light curves in greater detail. Finally, the distribution of waiting times from the HBR data served as another quick look of the data. Anomalous number of occurrences at particular waiting times could be readily identified by examining these waiting time distributions.

Using the diagnostic tools described, a source of noise was identified in the HBR data and was subsequently corrected for. Erroneous waiting times occurred when two adjacent 8 microsecond time bins both recorded an event, called an adjacent pair. However, the detector dead time was 19 microseconds, as discussed later in Section 3.4.1, corresponding to a minimum possible waiting time of two 8 microsecond time bins. These adjacent pairs were found to occur only at a specific location in the raw data format and at a rate that represented only 0.6% of the total number of events. Comparison of the HBR and NRZ data showed that only one of the two adjacent pairs was present in the NRZ data. Evidence indicates that this noise was a property unique to the HBR data and possibly a product of the digitization process. The HBR data were corrected by randomly removing one of the events in every adjacent pair. This correction was applied during the CTIFMT data processing step and is further described in Appendix B.

3.4 Instrumental Effects

In addition to data format errors, instrumental effects can also introduce distortions in the data. Some instrumental effects are unavoidable by-products of detection, such as dead time, while other instrumental effects are due to instrument malfunctions. In the HEAO A-1 detector, both types of instrumental effects were present. We suspect that an electronics malfunction produced systematic distortions in all of the HBR data. The identification and correction of these instrumental effects are necessary elements for separating real and artificial features in time variability analyses. As discussed later in Section 3.5.2, the instrumental effects in HEAO A-1 introduced distortions in the Meekins, et. al. analysis that completely account for many of the features they attributed to Cyg X-1.

Dead Time Type	Observed Count Rate R_{obs}	Observed Waiting Time Density for a Poisson process f_{obs}
Non-paralyzable	$\rho/(1 + \rho\tau)$	$U(t - \tau)\rho e^{-\rho(t-\tau)}$
Paralyzable	$\rho e^{-\rho\tau}$	$\sum_{j=1}^K U(t - j\tau) \left[(-1)^{j-1} / (j-1)! \right] \rho^j (t - j\tau)^{j-1} e^{-j\rho\tau}$ $\approx [\rho/(1 - \rho\tau)] e^{-\rho t}, \quad t \gg \tau$

Table 3.3 Summary of the properties of two types of dead time models. ρ is the true count rate, t is the waiting time, K is the largest integer smaller than t/τ and U is the unit-step function.

3.4.1 Dead Time

For any detector or electronic circuit there exists a minimum “waiting time” between two events to allow each to be detected. This is referred to as the dead time τ , the length of time that an apparatus is insensitive to additional pulses after the arrival of an accepted event. Two types of dead time are traditionally considered^[6], a non-paralyzable dead time and an paralyzable dead time. They differ in how the apparatus responds to the arrival of pulses during a dead time. For a non-paralyzable dead time, the instrument is dead for a fixed amount of time even if another event arrives during the dead time interval. An paralyzable dead time reacts by extending the dead time by τ from the last pulse arrival time. The properties of these two types of dead time models are summarized in Table 3.3.

For small dead times (i.e. $\rho\tau \ll 1$, where ρ is the true count rate) the distinction between the two types of dead times becomes negligible. To first order in $\rho\tau$, the observed count rate formulae listed in Table 3.3 are identical, $R_{obs} \approx \rho(1 - \rho\tau)$ and the relative error between the two waiting time distributions is $\approx \rho\tau$. For the A-1 instrument, the dead time was 19 microseconds as discussed later in this Section, which gives a $\rho\tau \sim 0.06 \ll 1$ at Crab intensities. Thus, the differences between the two types of dead time are negligible in the HBR data analysis and a non-paralyzable dead time is assumed in

HEAO A-1 Module	3	7
Non-paralyzable Dead Time [$\pm 0.1 \mu\text{s}$]	18.8	19.3

Table 3.4 Dead times for Modules 3 and 7 determined from fitting [3.1] to the HBR waiting time distributions.

subsequent analysis for its simpler waiting time distribution.

The observed waiting time distribution is additionally distorted by the binning introduced by the time resolution of the telemetry mode. Namely, the probability of detecting two events within some number of waiting time bins is not simply the integral of the waiting time density over that interval. An event may occur any time within the smallest possible time bin, the length of the time resolution. For the HBR data this time bin is eight microseconds. This information loss must be accounted for in the observed probability distribution. The resulting probability function for a Poisson process

$$P(n, \rho) = \begin{cases} 0, & 0 \leq n \leq \kappa - 1, \\ 1 - \varepsilon - (1 - e^{-\mu(1-\varepsilon)})/\mu, & n = \kappa, \\ \varepsilon + (1 + e^{-\mu(1-\varepsilon)}(e^{-\mu} - 2))/\mu, & n = \kappa + 1, \\ \left(\frac{\sinh(\mu/2)}{\mu/2}\right)^2 \mu e^{-\rho(nT-\tau)}, & n > \kappa + 1 \end{cases} \quad [3.1]$$

is derived in Appendix C.1, where ρ is the count rate of the Poisson process; n is number of waiting time bins; κ is the largest integer $\leq \tau/T$; ε is the residual $\tau/T - \kappa$; T is the time resolution; τ is the dead time; and μ is the mean number of counts per bin, ρT .

The dead times for HEAO A-1 Modules 3 and 7 were determined by fitting [3.1] to the HBR waiting time distribution at small waiting times (< 1 millisecond). The method of non-linear least squares was used. A summary of the fit results is shown in Table 3.4. The dead time is bounded below by the smallest waiting time recorded, two time bins. The dead time is bounded above by three time bins, otherwise three time bins

would be the smallest waiting time recorded. These lower and upper limits of two and three time bins correspond to dead times, 15.6 and 23.4 microseconds, respectively.

3.4.2 HEAO A-1 Module Electronics Malfunction

A reset problem involving coincidence events was known to exist in the HEAO A-1 module electronics. The X-ray energy spectrum was contaminated by the charge particle spectrum because the charge held in the electronics circuitry was not properly reset when a coincidence event (i.e. charged particle) occurred. The pulse amplitude recorded for the next X-ray event would be the larger of the current X-ray event or the held pulse height of the charged particle.

An exhaustive inspection of the HBR data has revealed another systematic distortion, this time of the Fourier power spectrum. A strong suspect for this previously undetected problem was modelled as a malfunction of the HEAO A-1 module electronics. The distortion resulting from modelling this suspected detector malfunction for a Poisson source is shown in Figure 3.2. The noise floor at lower frequencies is raised above the floor at higher frequencies. A broad "knee" from 100 to 1000 Hertz joins the two levels. These features sharply contrast to the flat spectrum expected for a Poisson source. The waiting time distribution for a Poisson source also showed a systematic distortion from its expected form. As Figure 3.2 shows, a smooth "kink" is introduced into its exponential at approximately one millisecond.

Neither of these distortion features could have been detected in the well-studied NRZ data. This may explain why this problem remained undetected. The highest time resolution for the NRZ data is 5 milliseconds, corresponding to a Nyquist frequency of 100 Hz. This is just where the "knee" distortion starts in the Fourier power spectrum. The NRZ data were binned. Therefore, waiting time distributions that require individual photon times could not be obtained.

Similar distortions were discovered by my colleague at SLAC, G. Shabad, in preflight USA calibration data. After extensive modelling and examination of the USA electronics, G. Shabad and G. Godfrey of SLAC determined that the cause of the USA

Fig. 3.2 The a) Fourier power spectrum and the b) waiting time distribution of a Poisson source, Cas A. Distortions from the expected Poisson characteristics are seen by the bi-level spectrum and a “kink” in the exponential. The solid curves in both plots are the result of fitting an offset hyperexponential distribution to the waiting time distribution shown. Goodness of fit is: $\chi^2/\text{dof} = 115/85$ for the Fourier spectrum and $\chi^2/\text{dof} = 1061/993$ for the waiting time distribution.

distortions was a faulty reset of the perimeter veto electronics. Normally, when a charged particle traverses the USA detector, it generates a coincidence between the perimeter veto wire and one or more chamber wires. For such events, the perimeter veto is reset properly. However, for some charge particle trajectories only the perimeter veto wire fires. For such events, the perimeter veto fails to reset. The only way it can be cleared is if another perimeter veto event occurs or if a chamber wire fires. If the next event is an incident X-ray, it will be vetoed regardless of when it arrives. This amounts to vetoing asynchronous coincidences between charged particle and X-ray events. This faulty perimeter veto logic introduces an effective variable dead time. The resulting waiting time density, f_{pvm} for the perimeter veto model (PVM) is given by

$$f_{vx}(T) = \binom{v-1}{x-1} \frac{(\rho_v T)^v (\rho_\gamma T)^x}{(v+x)!} \rho_\gamma e^{-(\rho_v + \rho_\gamma)T} \quad [3.2]$$

$$f_{pvm}(T) = \sum_{v=1}^{\infty} \sum_{x=1}^v f_{vx}(T)$$

where T is the waiting time, ρ_γ is the X-ray source rate and ρ_v is the perimeter veto rate. The $f_{vx}(T)$ term is the probability density for a waiting time T between two photons if v perimeter veto events and x photons arrive within that interval of time. Appendix C.2 gives a detailed derivation of Equation [3.2]. Fortunately, the USA electronics have since been modified before launch to correct this perimeter veto reset problem.

If we assume that a problem similar to that discovered in preflight USA electronics existed in the HEAO A-1 module electronics, then [3.2] provides a reasonable model for fitting the data. However, this scenario could not be confirmed nor denied for HEAO A-1 due to the inaccessibility and lack of archival records of the electronics diagrams. In addition, perimeter veto rates were not recorded in the HBR nor in the NRZ data.

The distortions in the data can be approximated with sufficient accuracy by using an offset hyperexponential distribution^[7],

$$f_H(t) = U(t - \tau) \left(p_1 \rho_1 e^{-\rho_1(t-\tau)} + (1 - p_1) \rho_2 e^{-\rho_2(t-\tau)} \right) \quad [3.3]$$

where τ is the non-paralyzable dead time, ρ_1 and ρ_2 are the count rates from two Poisson processes and p_1 is the probability of generating a waiting time from the first process. The convention chosen here will be that $\rho_1 > \rho_2$. Within the context of the perimeter veto model, the ρ_1 and ρ_2 parameters may be interpreted as “effective” Poisson rates.

Equation [3.3] is the linear combination of the waiting time densities for two Poisson processes with the same non-paralyzable dead time. The resulting probability function for this offset hyperexponential process is

$$P_H(n) = p_1 P(n, \rho_1) + (1 - p_1) P(n, \rho_2) \quad [3.4]$$

where the $P(n, \rho)$ are given by [3.1]. The solid curves in Figure 3.2 show the result of a non-linear least squares fit of [3.4] to the Cas A data set.

3.5 Data Analysis

A challenge for any time variability analysis is to differentiate real features from instrumental effects. For the HEAO A-1 HBR data, this is underscored by significant distortions to the Fourier power spectrum, characterized by a “knee” as previously described. Two types of time variability analyses will be explored with the Cyg X-1 data: the Meekins, et. al. analysis and the Fourier spectra technique. As later discussed, instrumental effects play a significant role in both analyses.

3.5.1 Correcting the Poisson Noise Floor

The Poisson noise floor is defined as the Fourier power spectrum of a Poisson process. In the absence of any instrumental effects, the Poisson noise floor is frequency independent with a value of 2 using the Leahy normalization^[8]. In the HEAO A-1 instrument, the detector dead time and the suspected HEAO A-1 module electronics malfunction each introduced a distortion to this Poisson floor. The dead time lowers the Poisson floor by a small and approximately constant value ($\sim 2\%$) over the frequencies of

HBR Data File	τ [μ s]	ρ_1 [Hz]	ρ_2 [kHz]	p_1
086_7_7	18.8	935	2.05	0.53
015_2_3	18.8	991	2.18	0.52

Table 3.5 The offset hyperexponential distribution parameters that defined the effective Poisson noise floor for two Cyg X-1 data files.

interest (0.1 Hz to 4 kHz). The suspected electronics malfunction introduces a strong frequency dependent distortion of the Poisson noise floor. As Figure 3.2 shows, the noise floor is distorted into a bi-level spectrum with a broad knee from 100 to 1000 Hertz that joins the two levels. The frequency width and position of this knee vary from source to source.

While the distortions to a Poisson source are readily modelled by fitting [3.4] to the waiting time distribution, the same procedure does not necessarily apply for a non-Poisson source such as Cyg X-1. Excluding any instrument effects, the waiting time distribution for a non-Poisson source is a non-exponential. The effects on non-exponential distributions due to the suspected electronics malfunction are not well understood. However, the Fourier spectra for non-Poisson sources are observed to also have knees characteristic of Poisson sources. The beginning of the knee region is defined as the frequency where the power spectrum has an inflection. For the Cyg X-1 data, this inflection point occurs at 40 Hz. To determine the effective Poisson noise floor for a non-Poisson source, the offset hyperexponential distribution, [3.4] is used to fit to the data's power spectrum from the beginning of the knee region to the Nyquist frequency.

The procedure for determining the effective Poisson noise floor for Cyg X-1 consists of first fitting [3.4] to the waiting time distribution. Random waiting times are drawn from [3.4] as defined by the fitted parameters and accumulated into absolute times. The Fourier spectrum of the simulated event times is calculated in the same manner as the data. Finally, the chi-squared of the fit to the data is calculated at frequencies above 100 Hertz. This procedure is repeated for a grid of parameter values whose origin is defined by the initial fit of [3.4] to the data's waiting time distribution. Table 3.5 summarizes the

set of parameters that minimized the chi-squared for the Cyg X-1 data. The resulting Fourier power spectrum from these parameters defined the effective Poisson noise floor.

3.5.2 Correcting the Meekins, et. al. Analysis

Meekins, et. al.^[1] attempted to quantify the aperiodic variability of Cyg X-1 by defining a new statistical quantity called the *relative* integral power. This new statistic was defined by Meekins, et. al. as the total discrete Fourier transform power of the mean subtracted time series divided by the square of total number of counts, N^2 in the time series,

$$P_{\text{rel}} \equiv \frac{\sum_{j=-m/2}^{j=m/2-1} |a_j|^2 - a_0^2}{N^2} = \frac{\chi^2}{N} \quad [3.5]$$

where a_j are the standard Fourier coefficients defined in Section 1.2 and m is the number of bins in the time series. The chi-squared, χ^2 , here is constrained by the sample mean, N/m , substituted for both the expected value and the variance of the counts. The timescale associated with [3.5] is defined by the range of Fourier frequencies allowed, namely the Nyquist and the smallest non-zero frequency.

To improve the signal-to-noise, the relative integral power had to be averaged over a large number of independent segments of data. A given time series is first divided into equal length segments. Each segment contained m bins. The relative integral power was calculated for each segment and then the resulting quantities were averaged.

The relative integral power defined by [3.5] contains contributions from both intrinsic variability and extrinsic noise. Meekins, et. al. separated out these two contributions in a formal derivation that showed that

$$\langle P_{\text{rel}} \rangle = \left[\langle \chi^2 \rangle - \langle \chi^2 \rangle_{\text{noise}} \right] / (\langle N \rangle - 1) \quad [3.6]$$

where $\langle P_{\text{rel}} \rangle$ is the average relative power due to intrinsic variability, and $\langle \chi^2 \rangle$ and $\langle \chi^2 \rangle_{\text{noise}}$ are the average chi-squareds of the data and the expected extrinsic noise,

Fig. 3.3 The average relative integral power for Cygnus X-1 from Meekins, et. al. and a reanalysis by Wen, et. al. using the general theoretical framework of Meekins, et. al.

respectfully. The same constraints defined for χ^2 in [3.5] also applied to these two averaged quantities. $\langle N \rangle$ is the average total number of counts in one data segment of m bins. This average relative integral power intrinsic to a source will be subsequently referred to as the *relative power* for brevity.

Equation [3.6] was applied to nine minutes of HBR data on Cyg X-1 observed by HEAO A-1 on May 7, 1978, while Cyg X-1 was in its low state, (observation 086_7_7 listed in Table B.2). The resulting relative power is shown in Figure 3.3. Cyg X-1 exhibits excess power between the 1 - 10 millisecond timescales that cutoff at the 1 millisecond timescale. Meekins, et. al. attributed these features to activity near the inner edge of an accretion disk. In 1996, the Meekins, et. al. result was reproduced using the Meekins, et. al. theoretical framework¹ with good agreement² as shown in the plot in Figure 3.3.

¹A value of 9 for χ^2 for sets with no counts was chosen instead of 0 as reported by Meekins, et. al. because using a value of 0 could not reproduce the relative integral power at the 0.6 - 3 ms timescale.

²Remaining discrepancies may be attributed to differences in bin offset and analyzing data from a separate digitization of the original analog tape from Meekins, et. al.

The impact of possible instrumental effects on this result was not quantitatively addressed. Meekins, et. al. neglected the effects of dead time in their analysis and additionally, did not detect the suspected HEAO A-1 module electronics malfunction. To allow a more straightforward correction of dead time and other instrumental effects, the definition of the relative power is first re-examined.

As in [3.5], we define χ^2 in terms of the sum of all the Leahy normalized Fourier powers, P_j

$$\chi^2 = \sum_{j=1}^{m/2-1} P_j + \frac{1}{2} P_{m/2} \quad [3.7]$$

$$P_j = 2 |a_j|^2 / N$$

where m is the total number of time bins in each data segment, (chosen as 10 for the Meekins, et. al. analysis). The average of the chi-squared in [3.7] over the entire ensemble of m bin data segments can be approximated by,

$$\langle \chi^2 \rangle \approx \left(\frac{m-1}{2} \right) \langle P \rangle \quad [3.8]$$

where $\langle P \rangle$ is the average Leahy normalized power over the entire ensemble of m bin data and the set of frequencies ($f_j = 1/T, 2/T, \dots, m/2T$). T is the length of an m bin data segment. Using [3.8] to substitute for the average chi-squared in [3.6] yields,

$$\langle P_{\text{rel}} \rangle \approx \left(\frac{m-1}{2} \right) \left[\langle P \rangle - \langle P \rangle_{\text{noise}} \right] / (\langle N \rangle - 1) \quad [3.9]$$

The average chi-squared of the expected intrinsic noise is simply proportional to the usual Poisson noise floor. By ignoring any instrumental effects, the Meekins, et. al. analysis effectively chose a value of 2 for the expected noise floor. The average Fourier power, $\langle P \rangle$ in [3.9], is approximated by the Fourier power described in Section 1.2 at the logarithmic frequency interval that spans the set of frequencies ($f_j, j=1..m/2$). This approximation ignores possible contamination of variability from other timescales. The

Fig. 3.4 The average relative integral power for Cyg X-1 approximated by using Leahy normalized Fourier power. As in the Meekins, et. al. analysis, dead time and instrumental effects were ignored here.

result of applying [3.9] to the data and ignoring instrumental effects is shown in Figure 3.4. Good agreement is seen between Figures 3.3 and 3.4 using the two methods for calculating the relative power, [3.6] and [3.9]. Any contamination of variability from other timescales is negligible in this data compared to the sharply peaked feature in the relative power from the one to ten millisecond timescale.

By using [3.9] to approximate the relative power, the procedure for correcting instrumental effects in the HEAO A-1 data is straightforward. First, the Poisson noise floor is calculated with the instrumental effects taken into account by applying the technique discussed in Section 3.5.1. The average Fourier power over the m bins of a given timescale is again approximated by the usual Fourier power spectrum as previously described.

3.6 Results

The relative power distribution of Figure 3.4 can now be corrected for instrumental effects. Figure 3.5 shows the relative power after correcting the Poisson noise floor for dead time and then additionally for the suspected HEAO A-1 module

Fig. 3.5 The average relative integral power for Cyg X-1 after the Poisson noise floor is corrected for a) dead time and b) dead time and the suspected HEAO A-1 module electronics problem. The Fourier power are used to approximate the average relative integral power, as described in Section 3.5.2.

electronics malfunction. The peak in relative power is actually broadened and enhanced after correcting the Poisson noise floor only for dead time. This is due to the slight lowering of the Poisson floor in the presence of dead time. However, this larger peak in relative power is eliminated once the corrections due to the suspected electronics malfunction have been additionally applied to the Poisson noise floor. This analysis indicates that the excess relative power between the 1 - 10 millisecond timescales that was previously reported by Meekins, et. al. can be attributed to previously undetected instrumental effects.

Using the approximation [3.9], the statistic that defines the relative power can be reinterpreted from the perspective of Fourier power. The numerator of [3.9] is the total noise-subtracted Fourier power. The denominator in [3.9] scales linearly with timescale since the width of each time bin is proportional to the timescale. The relative power is proportional to the total intrinsic Fourier power per timescale. Figure 3.5b shows that this total power per timescale steadily decreases with smaller timescales.

The HEAO-1 spacecraft made a total of two pointed observations of Cyg X-1 using the high-bit-rate telemetry mode. Meekins, et. al. analyzed the first of these observations. The second observation occurred on November 9, 1978, (observation 015_2_3 listed in Table B.2), while Cyg X-1 was again in its low state based on its mean count rate. Both observations each lasted 8.5 minutes and were made while Cyg X-1 was in its low state based on its average count rate of 1071 cts s^{-1} .

The Fourier power spectra technique was applied to both of these pointed observations. For each observation, the Poisson noise floor was corrected for instrumental effects as described in Section 3.5.1. To further improve the statistics, the Fourier power spectra from the two observations were averaged together. Figure 3.6a shows the resulting power spectra of Cyg X-1 and the simulated Poisson noise floor corrected for instrumental effects. Their difference is shown in Figures 3.6b and 3.6c.

To measure the significance of the noise-subtracted power, the 95% confidence level for detecting a signal above the Poisson noise floor is overlaid in Figures 3.6b and

Fig. 3.6 The a) raw and noise-subtracted Fourier power spectrum of Cyg X-1 from the HBR data in b) full and c) close-up views. The solid curve represents the 95% confidence level for detecting a signal above the Poisson noise floor. Excess power at frequencies greater than 20 Hz (shaded region) may be contaminated by residual instrumental effects.

Detector	Power Law Before Apparent Break			Power Law After Apparent Break		
	Frequency Range [Hz]	Photon Index	χ^2/dof	Frequency Range [Hz]	Photon Index	χ^2/dof
HEAO A-1	0.1 – 3	1.20 ± 0.08	15/13	3 – 40	1.7 ± 0.2	18/19

Table 3.6 Summary of power law fits to the noise-subtracted Fourier power spectrum. The break between the two different power laws occurs at 3 Hz.

3.6c. The overlaid curve is 1.96 times the standard deviations of the corrected Poisson noise floor based on the same total number of counts as the data. Excess power is observed at frequencies less than 40 Hz with greater than a 95% confidence level. At greater frequencies the noise-subtracted spectrum is consistent with the null hypothesis as expected. The Poisson noise floor was corrected for HEAO A-1's instrumental effects by fitting to the power spectrum of Cyg X-1 for frequencies greater than 40 Hz.

Between frequencies 0.1 and 20 Hz, the spectrum follows power laws with a break to a steeper photon index at frequencies greater than 3 Hz. Power laws were fit separately to the frequency region before and after the break, and the results are presented in Table 3.6. The power spectrum follows a $\sim 1/f$ spectrum before the break and then falls more steeply afterwards.

No evidence was seen in the HBR data on Cyg X-1 for QPOs. A 95% confidence level upper limit was calculated for detecting QPOs of a given fractional root-mean-square (rms) amplitude over a given logarithmic frequency interval. The fractional rms normalization is the Leahy normalization divided by the mean X-ray intensity, and can be thought of as a mean amplitude of the intensity variations expressed as a fraction of the average intensity^[10]. The QPO amplitude is plotted in Figure 3.7 as the square root of the area in one logarithmic frequency interval, $\sqrt{\Delta P \Delta f}$, where ΔP is 1.96 times the standard error of the average Fourier power over the logarithmic frequency interval, $\log(\Delta f)$. The QPOs for this limit are contained within a given logarithmic frequency interval, giving a quality factor, $Q > 9$. Over the frequency range from 34 to 357 Hz where diskoseismic

Fig. 3.7 The 95% confidence level upper limit for detecting QPOs in Cyg X-1 from HEAO A-1 with a quality factor, $Q > 9$ for a given fractional rms amplitude. The shaded region spans the range of expected frequencies for g-mode QPOs, with the horizontal line marking the expected g-mode QPO amplitude and the dashed vertical line marking the frequency for a non-rotating, $16 M_{\odot}$ black hole.

QPOs are predicted for Cyg X-1, the fractional amplitudes are less than 1.8% to 3.3%, respectively at a 95% confidence level. For a $16 M_{\odot}$ black hole, the limit is 2.2%. The amount of HBR data on Cyg X-1 is insufficient to detect QPOs at the 1% fractional rms amplitudes predicted by relativistic diskoseismology^[9].

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RXTE/PCA DATA STUDIES

4.1 Introduction

The RXTE/PCA instrument is capable of collecting X-ray data at time resolutions down to 1 μ s and up to 256 energy channels covering 2 - 60 keV. The time resolution capability of the instrument is the finest for all current and previous astronomical X-ray detectors. The data collected from this instrument represents the opportunity to explore the time variability of X-ray objects to unprecedented submillisecond time scales.

4.2 Description of the RXTE/PCA Data

Under guest observation proposal D0889, P.I. P. Hertz, the RXTE/PCA instrument^[1] observed Cygnus X-1 in its high state on June 8, 1996, for 23 minutes. The data mode for the Proportional Counter Array (PCA) was set to the E_4us_4B_0_1s configuration, giving a time resolution of 4 microseconds and 4 energy channels: (1.6 - 6.4 keV), (6.4 - 10.1 keV), (10.1 - 14.6 keV) and (14.6 - 99.6 keV).

The resulting data were written in Flexible Image Transport System (FITS)^[2] format. The components of this FITS file are described in Table 4.1 and further documented at the High Energy Astrophysics Science Archive Research Center (HEASARC)^[3]. There are only two basic FITS formats for the RXTE/PCA science data:

Name	Description
Primary Header	Information about the mission, the instrument, the observation and the initial processing.
Primary Image	Array is blank.
First Extension Header	Description of the contents of the first extension. For convenience, it also contains some of the same information as the primary header.
First Extension	Contains the scientific data. In the case of science array files, the first extension is called XTE_SA. In the case of science event files, it is called XTE_SE.
Second Extension Header	Description of the contents of the second extension. For convenience, it also contains some of the same information as the primary header.
Second Extension	Lists the standard good time intervals, i.e. the start and stop times of all the potentially useable data in the file.

Table 4.1 Description of the RXTE FITS format.

science array and science event. The science array format is used for data binned at regular intervals by the spacecraft electronics. For unbinned data (e.g., individual events collected in this observation), the science event format is used.

The science data occupy the XTE_SE extension as event words - binary-encoded descriptions of the individual events. In the XTE_SE extension the science data is arranged in rows (one per event) and in two columns: time and event word. Event words define the properties of each event with respect to a template of all possible properties within the data mode configuration (e.g. E_4us_4B_0_1s). This template is broken up into sections that, depending on the particular configuration, refer to items such as Proportional Counter Unit (PCU) Identification Number (ID), Pulse Height Analyzer (PHA) channel band, event overflow, etc. A detailed description of these templates can also be found at the HEASARC^[4].

4.3 Processing the RXTE/PCA Data

The tasks for the off-line analysis software are two-fold: extract good event times and save those event times in an easily retrievable manner. Table 4.2 summarizes the

OFF-LINE DATA PROCESSING STEPS	
1) FITSHDR	Extract the FITS headers
2) E4US4B01	Decipher the Event words
3) XTETIMES	Filter event times according to PCU ID and Energy channel

Table 4.2 The major off-line processing steps for the RXTE/PCA data.

steps followed to complete these tasks. The RXTE/PCA data are written in a well-documented FITS format, greatly simplifying the job of extracting good event times. The primary and extension headers are first extracted from the FITS file using the FITSHDR routine. In particular, the first extension header describes the templates used to encode the event words in the XTE_SE extension. The E4US4B01 routine uses this description to decipher the bits in the event word into various items such as the PCU ID and energy channel. This information is used to filter events according to their PCU ID and energy channels in the XTETIMES routine. All of the routines listed in Table 4.2 were written in the Interactive Data Language (IDL)^[5]. In addition, several FITS routines from IDL Astronomy User's Library^[6] were also called to interpret the FITS file format.

The event times were separated according to their PCU ID and saved as 5 separate IDL Save Session files^[5], one for each PCU. Another processing run selected events from PCU 0 and separated events according to their energy channel.

Invalid events were removed in the XTETIMES routine by selecting various criteria in the first and second (XTE_SE) extensions of the FITS file. Any event times not within the good time intervals specified in the second extension were cut. For each row of the XTE_SE extension, the event word was checked for a valid time, PCU ID and energy channel. If any of those items was invalid, (e.g. because the row contained overflow information) the time recorded in the first column would be eliminated from the returned event times array. Finally, the event times from the first column were checked by verifying that the time encoded in its event word agreed.

PCU	0	1	2	3	4
Dead Time [$\pm 0.03 \mu\text{s}$]	8.77	8.74	8.87	8.81	8.81

Table 4.3 Non-paralyzable dead times for each PCU determined from fitting [3.1] to the RXTE/PCA waiting time distributions.

4.4 Instrumental Effects

Distortions caused by instrumental effects dominated the time variability of the HEAO A-1 HBR data. Given that proven example of how important instrumental effects can be, emphasis was placed on searching for possible instrumental effects in the RXTE/PCA data. The dead times were first determined by separately fitting [3.1] to the waiting time distribution of each PCU using the method described in Section 3.4.1. As in the HEAO A-1 HBR data, the differences between the two types of dead time, non-paralyzable and paralyzable, were negligible. A non-paralyzable dead time was chosen in the fits because of its mathematical simplicity. The results of these fits, shown in Table 4.3 give an average dead time of 9 microseconds.

Additional instrumental effects were searched for by analyzing RXTE/PCA data on a Poisson source, the Crab Nebula. The data archive in the RXTE Guest Observer Facility^[4] was searched for public data on observations of the Crab. Several such observations at a one millisecond time resolution were located and subsequently analyzed for instrumental effects. The Fourier power spectra were summed and averaged over all observations and over all five PCUs. Figure 4.1 shows the final averaged Fourier power spectrum of all the Crab data analyzed. The Fourier powers at the harmonics of the Crab pulsar frequency $(33 \text{ ms})^{-1}$ were excluded from the plot. As discussed in the next Section, the expected Poisson noise floor shown by the solid horizontal line fits the Fourier power spectrum of the Crab exceptionally well. No distortions of the power spectrum beyond those due to dead time were detected in this Crab data for all frequencies up to the Nyquist value, 500 Hz.

Fig. 4.1 The Fourier power spectrum of the RXTE/PCA data on the Crab, excluding values at the harmonics of the Crab pulsar frequency. The solid horizontal line is the expected Poisson noise floor corrected for RXTE/PCA dead time. The fit of the expected Poisson noise floor to the Crab spectrum shown gives a goodness of fit: $\chi^2/\text{dof} = 173/178$.

4.5 Data Analysis

The time variability analysis of the RXTE/PCA data was greatly facilitated by the limited number of instrumental effects introduced by the detector. The analysis of Crab data gave no indication of any other instrumental effect besides that due to detector dead time. Correcting the Poisson noise floor only for dead time is straightforward and well understood. Given confidence that all of the instrumental distortions of the Poisson noise floor are understood, an upper limit to measuring noise-subtracted power can be determined.

4.5.1 Correcting the Poisson Noise Floor

In the presence of dead time, the Poisson noise floor is affected by the length of the dead time and the observed count rate of the X-ray source^[7]. This Poisson noise floor can be determined by first generating simulated Poisson data distorted by dead time, and then calculating the Fourier spectrum of that simulated data. The dead time and the true

count rate are input parameters into [3.1] to define the probability function of waiting times between successive Poisson events. The true count rate is determined from the observed count rate and the dead time by using the formula listed in Table 3.3. Random waiting times are drawn from this probability function until the total number of events equals that of the data. The generated waiting times are accumulated into event times and then the simulated event times are Fourier analyzed in the same manner as the data. The resulting average Fourier spectrum defines the Poisson noise floor in the presence of dead time for that data.

4.5.2 Frequency Upper Limit on Detected Intrinsic Variability

Poisson noise in the presence of dead time is well understood in terms of a binned offset exponential, [3.1] that describes the probability of waiting times between events. Given this understanding, the highest frequency that Fourier power can be detected above the Poisson noise can be determined for a given confidence level. Signal is detected above the noise at a 95% confidence level or greater when the noise-subtracted power exceeds 1.96 times the standard deviation of the power defining the corrected Poisson noise floor. The frequency upper limit is defined as the highest frequency where signal is detected over the noise at a given confidence level.

4.6 Results

Given the technique described in the previous Section, the RXTE/PCA data can now be corrected for instrumental effects. For each PCU, the data were summed over all energy channels and then the resulting light curves were Fourier analyzed. The corrected Poisson noise floor was simulated for each PCU using the average count rate and dead time specific to that PCU. To further improve the statistics, the Fourier spectra of all the PCUs were averaged together. Figure 4.2 shows the resulting power spectra for Cyg X-1. The corrected Poisson noise floor is flat with a small frequency dependency near the Nyquist frequency. The level is lowered by 2% from its value when no instrumental effects are present.

Fig. 4.2 The a) raw and noise-subtracted Fourier power spectrum of Cyg X-1 from the RXTE/PCA data in b) full and c) close-up views. The Poisson noise floor was corrected for instrumental effects. The solid curve represents the 95% confidence level for detecting a signal above the Poisson noise floor.

Detector	Power Law Before Apparent Break			Power Law After Apparent Break		
	Frequency Range [Hz]	Photon Index	χ^2/dof	Frequency Range [Hz]	Photon Index	χ^2/dof
RXTE/PCA	0.1 – 3	1.24 ± 0.04	28/14	14 – 40	2.1 ± 0.5	4/8

Table 4.4 Summary of power law fits to the noise-subtracted Fourier power spectrum. The break between the two different power laws occurs between 10 – 20 Hz.

As in the HEAO A-1 data, the noise-subtracted power spectrum also shows two power laws in the spectrum. The break between the two power laws occurs at a higher frequency than the previous data set, between 10 to 20 Hz. In addition, the break is more rounded. Table 4.4 summarizes the results of fitting power laws to the regions before and after this break.

The 95% confidence level for detecting a signal above the Poisson noise floor is also plotted in Figures 4.2b and 4.2c. At frequencies greater than 50 Hz, the effect of approaching the Poisson noise floor is demonstrated by a flattening of the spectrum. It is an artifact introduced by limited counting statistics. Sensitivity to measuring intrinsic variability is limited by the variance of the noise floor. With additional data, the 95% confidence level curve will be lowered to reveal how the spectrum continues beyond 50 Hz.

The downward slope seen at frequencies greater than 50 Hz is a consequence of averaging over equal logarithmic frequency intervals. The number of frequencies, M averaged over in an equal logarithmic frequency interval is proportional to the central frequency of that interval. Thus, M increases while the standard deviation decreases as $1/\sqrt{M}$. Despite the limiting statistics, evidence for marginal excess power is still seen at frequencies between 100–4000 Hz. Over 33% of the excess powers at frequencies greater than 100 Hz exceed the 95% confidence level curve.

Again, as in the HEAO A-1 data, no evidence is seen for QPOs. A better 95% confidence level upper limit can be obtained with the RXTE/PCA data since the data set

Fig. 4.3 The 95% confidence level upper limit for detecting QPOs in Cyg X-1 from RXTE/PCA with a quality factor, $Q > 9$ for a given fractional rms amplitude. The shaded region spans the range of expected frequencies for g-mode QPOs, with the horizontal line marking the expected g-mode QPO amplitude and the dashed vertical line marking the frequency for a non-rotating, $16 M_{\odot}$ black hole.

contained 6 times as many photons as in the HEAO A-1 data. Figure 4.3 shows fractional rms amplitudes ranging from 0.96% to 1.9% over the frequencies where QPOs are predicted by relativistic diskoseismology^[8]. Diskoseismic QPOs with 1% fractional rms amplitudes can be excluded for frequencies ≤ 25 Hz at a 95% confidence level. The excluded frequencies contained within the shaded region in Figure 4.3 correspond to retrograde orbits with black hole angular momenta parameter $a \leq -0.5$. At frequencies greater than 25 Hz, the QPO amplitude limits are higher than the 1% fractional rms amplitudes predicted for diskoseismic QPOs over the range of expected frequencies for Cyg X-1.

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Format of the HEAO A-1 High-Bit-Rate Data

A.1 Bit Telemetry Mode Format

The HEAO A-1 HBR data in the Bit telemetry mode can be basically described as a continuous stream of bits, each bit representing a $7.8125 (\approx 8) \mu\text{s}$ time bin set if one or more events occurred in that interval. The normal (NRZ) telemetry data was written along with the HBR data onto analog tapes that were later digitized at NRL. The format of the digitized data was described in a Data General assembly routine developed at NRL. This routine was later translated to an IDL routine with the same name, HBRSYNC.

The digitized data consists of fixed length records of 8220 bytes. Each file record spans a minor frame, a period of 320 ms. Table A.1 gives a breakdown of a file record where a word is defined as 2 bytes or 16 bits. The majority of the file record forms an HBR data record, a continuous block of 4096 words. Each word of an HBR data record spans an $80 \mu\text{s}$ period, one bit for each $8 \mu\text{s}$ time bin. A set bit represents data presence in that corresponding time bin. Table A.2 describes the bit format for each of these words.

The start of an HBR data record is offset from the start of a minor frame of the NRZ data. This offset is typically 65 words. However, this offset may vary from file to file and even between HBR data records if any errors are present.

Word(s)	Description
0	Time information. The minor frame number can be extracted from this word.
1 - 4096	HBR data record.
4097	NOVA tape sequence number
4098	NOVA tape run number
4099	Number of NOVA files
4100	NOVA tape file number
4101	Copy error flag
4102	NOVA input record size
4103 - 4105	Date of copy (year, day, month)
4106 - 4108	Time of copy (hour, minutes, seconds)
4109	Undefined

Table A.1 Contents of a HBR File record.

Bit(s)	Description
0 - 5	HBR photon data at corresponding relative time bins: [9, 8, 7, 6, 5, 4]
6	6.4 kbs synch lock flag (1 = lost)
7	Frame synch flag from the DCS ground station. (0 = DCS ground station is locked on and has found the minor frame synch word. For each minor frame, this bit = 0 for 16 sequential words and = 1 for all other words.)
8 - 11	HBR photon data at corresponding relative time bins: [3, 2, 1, 0]
12	6.4 kbs NRZ data (There are two copies of 128 NRZ data words that are embedded into each HBR data record. Each copy is formed from concatenating bit 12 of every other word in an HBR data record, starting at the Most Significant Bit of the NRZ word. For example, if HBR data words 20, 22 and 24 contain bits 15, 14 and 13 of a NRZ word then HBR data words 21, 23 and 25 would also contain these same three NRZ bits.)
13	Tick tock bit for copies of NRZ data (Namely, this bit "tick-tocks" between 0 and 1 for sequential HBR data words. The words where this bit is set to 0 or 1 have the first or second copy of the NRZ data, respectively)
14	High bit rate lock (1 = lost)
15	Analog lost data bit (1 = lost)

Table A.2 Format of the bits in a given HBR data word. Bit 0 = Least Significant Bit.

Name	Number of records	Description
MJF header	1	Overall accounting statistics and errors for this MJF.
NRZ Data block	32	The normal 6.4 kbps telemetry data for this MJF.
HBR Data block	Dynamic	The 128 kbps HBR data for this MJF.

Table A.3 Structure of a Major Frame segment.

Several steps are taken to determine this offset. In an HBR data word, the frame synch bit (bit 7) is cleared when the DCS ground station has found the minor frame synch word and is locked on. The HBR data record is searched for the first word where the frame synch bit is cleared. This typically occurs at the last word of the HBR data record.

The actual start of the minor frame occurs at an additional offset of typically, -64 words. Namely, a minor frame usually starts at word 4031 of the HBR data record, (starting from word 0). To verify that the minor frame starts at this offset, a synch pattern is searched for in the first 24 bits of the NRZ data starting from the given offset. Since a copy of the NRZ data occurs in bit 12 of every other HBR word, these 24 bits actually span 48 words of the HBR data record. The synch pattern searched for is:

111 110 101 111 001 100 100 000

where the right-most bit represents the Least Significant Bit.

If the 24 bits of NRZ data match the synch pattern then we have found the beginning of the minor frame for both the NRZ and the HBR data. Otherwise, this negative offset is varied between 0 and -100 with the 24 bit synch pattern searched for at each offset until a match is found.

A.2 Photon Time Interval Format

The Photon Time Interval (PTI) format organizes the HBR data into sequential segments of data, 40.96 seconds long. This period of time is called a major frame, MJF and each major frame may be divided into 128 minor frames. Each major frame segment consists of fixed-length records of 1024 bytes and each record may be read into a 512

Word Offset	Pointer Name	Description
0	MJF	MJF number calculated (32-bit integer)
2	MJFNZR	MJF number read (32-bit integer)
4	MJFLAGS	MJF flags (16 bits) (see Table A.5)
5	SYNLOSS	Total number of HBR sync loss errors (32-bit integer)
7	CLKERRS	Total number of Clock TicToc errors (32-bit integer)
9	MJFCNTS	Total counts (32-bit integer)
11	MNFMIS	Number of Missing MNF's
12	MNFLAGS	MNF flags (duplicated)
139	MNFNDTS	Number of photon time intervals (Counts-1)/MNF
266	DATRECS	Total number of data records written
267	DATRECN	Data record number for each MNF
394	PARERRS	Total number of parity errors
395	SYNMNFS	Number of MNF's with HBR sync loss errors
396	NOSYNCH	Number of buffers with no DCS synch bit transition error(s)
397	BADSYNC	Number of buffers with bad or missing synch pattern error(s)
398	TIKTOK	Number of buffers with Clock TicToc errors
399	BUMSIZ	Number of buffers with MNF is not 4096 words long error(s)
400	BITSBAD	Number of buffers with DCS bit lock lost somewhere in MNF
401	OBOUNDS	Number of buffers with MNF extends beyond buffer size error(s)
448	MJFMARK	MJF marker (64 words)

Table A.4 Description of the Major Frame Header.

element, 16-bit integer array. The time interval or waiting times between events are stored in this data format instead of the absolute times as in the A-1 Bit mode data format.

The data structure of a MJF segment is broken into three sections: a header, a block of normal telemetry data (NRZ) and a block of HBR data as illustrated in Table A.3. The header provides an overall description of the current major frame segment with overall statistics ranging from the number and types of errors found to the number of

Bit	Bit Name	Description
0	MJF_GDVS	Global data validity (0=ok)
1	MNF_MISS	MNF(s) missing
2	NO_DATAS	No events (data) detected
3	SYN_ERRS	HBR sync loss error(s)
4	PAR_ERRS	Tape parity error(s)
5	HBR_FMTS	HBR format (0=bit,1=word)
6	NOSYN_ERRS	No DCS synch bit transition error(s)
7	BADSYN_ERRS	Bad or missing synch pattern error(s)
8	CLK_ERRS	Clock tictoc error(s)
9	BUMSIZ_ERRS	MNF is not 4096 words long error(s)
10	BITBAD_ERRS	DCS bit lock lost somewhere in MNF error(s)
11	OBOUND_ERRS	MNF extends beyond buffer size error(s)

Table A.5 Bit assignments for the MJF flags word, MJFLAGS. (0=LSB)

events detected. A complete description of this header is given in Tables A.4 and A.5.

Although these headers maintain the bookkeeping of errors found in the HBR data, safeguards are needed to check the integrity of the PTI data itself. Data integrity may be breached by file corruption or read errors. To address this issue a marker is placed in the last 64 words of every MJF header. This marker is the number sequence: [66, 79, 75, 83, 84, 69, 86, 69] repeated 8 times.

Even if there are no events in a given MJF or if a MJF is missing, a MJF header is still written out. Information in the header will reflect this by indicating that there are no counts and additionally, for the case of a missing MJF that there are 128 missing minor frames.

The NRZ Data block follows the MJF header and contains 32 records (512 words/record) of normal 6.4 kbps telemetry data from all four HEAO 1 instruments. This block contains a total 16384 or 128^2 words. Each sequential 128 words represents a sequential minor frame of NRZ data. There is a caveat in the case when there are one or more missing minor frames in the HBR data. If a missing minor frame occurs, then by

Fig. A.1 Example of two MNF sections in the an HBR Data block.

definition there is no corresponding NRZ data. Namely, 128 words of the NRZ Data block are zero. This and any additional sections of zero NRZ data are positioned at the end of the NRZ Data block regardless of which minor frames are missing.

Unlike the MJF header and the NRZ Data block, the size of the HBR Data block is dynamic in terms of its total number of records. While the HBR Data block may be divided into minor frame (MNF) sections as in the case of the NRZ Data block, each of these minor frame sections may have different numbers of records. Each minor frame section consists of a 16-word minor frame header followed by a list of successive waiting times between events. Therefore, the number of records for a minor frame section depends on the number of waiting times in that minor frame. The situation is further illustrated in Figure A.1.

Each minor frame header also has a marker. This provides another means of testing the integrity of the PTI data. The number sequence: [-11337, 2179] is placed in the last two words of the header.

Missing minor frames are also accounted for in the HBR Data block. A MNF header is written out for each range of missing minor frames. The remaining 496 words in the record that holds such a MNF header are flushed to 0. The missing MNF bit is set and the range of missing MNFs is stored in the MNF header. For further descriptions of the MNF header, see Tables A.6 and A.7.

Word Offset	Pointer Name	Description
0	MNF	MNF number calculated/first missing
1	MNFNZR	MNF number read/last missing
2	MNFLAG	MNF flags (16 bits) (see Table 7)
3	MNFCNT	Counts this MNF
4	NRZOFF	NRZ data offset in buffers
5	SYNLOS	Number or HBR sync loss errors
6	CLKERR	Number of Clock TicToc errors
7	DATREC	Data record number
8	MNFNDT	Number of photon time intervals in this MNF
9	MNFLDT	Number of photon time intervals in the last MNF
10	DELBEG	Time between beginning of MNF to first photon
11	DELEND	Time between last photon to end of MNF
12	SYNFLG	HBRsync flags (16 bits)
13	ERROFF	Error offset in buffers
14	MNFMARK	MNF marker (32-bit integer)

Table A.6 Description of the MNF Header

Bit	Bit Name	Description
0	MNF_GDV	Global data validity (0=OK)
1	MNF_MIS	MNF missing
2	NO_DATA	No events (data) detected
3	SYN_ERR	HBR sync loss error(s)
4	CLK_ERR	Clock tictoc error(s)
5	PAR_ER1	Tape parity error buffer 1
6	PAR_ER2	Tape parity error buffer 2
7	SUSPECT	Current MNF suspect due to one or more sync errors between current and previous MNFs

Table A.7 Bit assignments for the MNF flags word , MNFLAG. (0=LSB)

Tag Name	Description
Name	Name associated with this HBR data file, SSS_TT_FF, [string].
Origin	Structure describing the origins of this save file. It tags are as follows: Routine : Name of the IDL routine, 'CATPTI.PRO' Date : Date of creation, SYSTIME(), [string] Version : Version of IDL, copy of !VERSION File : Filename of the PTI file, including path, [string].
MJFH	Array of all the MJF headers, [intarr(512, nMJF)].
NRZ	Array of all the NRZ blocks, [intarr(128, nNRZ)].
MNFH	Array of all the MNF headers, [intarr(16, nMNF)].
PTI	Array of all the Photon Time Intervals with the Adjacent Photon Events removed, [intarr(nPTI)].
ts	Array of all absolute photon times, [lonarr(nPTI+1)]. ts(0) = time of the first photon relative to the beginning of it MNF.
MJFs	Array of MJF numbers, [lonarr(nMJF)].
nMJF	Total number of MJFs, [fix].
nMNF	Total number of MNFs, [fix].
nPTI	Total number of PTIs, [long].
nAPE	Number of Adjacent Photon Events found/MJF, [intarr(nMJF)].
DBS	Structure containing the HEAO HBR database information on this target.
GDV	Overall Global Data Validity flag (0=Ok), [fix].

Table A.8 Description of the *cat* structure variable.

There is a caveat with regard to the values of the waiting times. The largest positive number a 16-bit integer can hold is 32767. This is smaller than the largest possible waiting time within a minor frame, 40960. However, the MSB (the sign bit) effectively expands the range of numbers to [0-65535]. Therefore, any waiting times > 32767 overflow to their negative complement, namely, $-2^{16} + \text{waiting time}$. All waiting times in the range $\in [32768, 40960]$ are mapped to their negative overflow values, [-32768, -24576].

A.3 Concatenated Time Interval Format

The HBR data that has been reformatted into the Photon Time Interval (PTI) format is organized into sequential blocks of Major Frames. This imposes a strong preference to analyze the event times in 40.96 second segments. To eliminate this bias and simplify access to all the event times, these Major Frame blocks of data are concatenated into arrays that are stored into one IDL structure variable.

Each array stored into an IDL structure variable must have a name or tag. A properly chosen tag name provides self-documentation of the data stored in that array. The IDL structure variable is then saved as an IDL Save Session file into a platform independent data format called eXternal Data Representation.

The routine needed to restore these files is built into IDL so the user is not dependent on a specific external routine that can properly interpret the data format. The name of the structure variable saved is called *cat*. Table A.8 lists the tags defined in this structure variable and provides a description of each.

A.4 Relevant IDL Routines

The following are listings of IDL routines that were developed at SLAC to read in the various HBR data formats described in the last three Sections.

A.4.1 Bit Telemetry Mode Format

```

;+
; NAME:
;   HBRSYNC
;
; PURPOSE:
;   This routine processes the HBRB data (High-Bit-Rate in Bit telemetry
;   mode) and extracts the 128 kbps and 6.4 kbps datastream for a
;   minor frame.
;
; CATEGORY:
;   HEAO HBR.
;
; CALLING SEQUENCE:
;
;   HBRSYNC, Buf [, HBR, NRZ, MJF, MNF, Flags]
;

```

; INPUTS:

; Buf : A concatenation of two HBR records, the earlier one
; first. Namely, a 2*4096 element 2-byte array, intarr(8192).

; INPUT KEYWORD PARAMETERS:

; INIT : Set this keyword to initialize various parameters used in
; subsequent calls to this routine.

; OPTIONAL OUTPUTS:

; HBR : The 128 kbps datastream packed into 4096 words, intarr(4096)
; containing a minor frame (320ms) of data.

; NRZ : The 6.4 kbps datastream packed into 128 words, intarr(128)
; containing a minor frame (320ms) of data.

; MJF : The major frame number, long.

; MNF : The minor frame number, integer [0-127].

; Flags: A 3-element integer array containing possible error flags:

; Flags(0) : Error code
; 0, Success.
; 2, Failure to find 6.4 kb DCS lock.
; 3, Bad or missing synch pattern.
; 4, Alternate failure(s) in NRZ clock.
; 5, Minor frame is not 4096 words long.
; 6, DCS bit lock lost somewhere in frame
; 7, Minor frame is out of Buf array boundary.

; Flags(1) : if Flags(0) =
; 3, Word offset to the start of the minor
; frame with a bad or missing synch
; pattern. This offset is relative to
; the next DCS synch bit transition to 0.
; 4, Number of tick tock errors.
; 5, Word offset to the next DCS synch bit
; transition to 0.
; 6, Word offset to the lost DCS bit lock.
; 7, Word offset to the end of the minor frame.

; ** Unless stated otherwise, all word offsets are
; relative to the start of the buffer.

; Flags(2) : Word offset in Buf array to the "real" start of
; the minor frame for the NRZ data.

; COMMON BLOCKS:

; HBRSYNC: This common blocks holds various parameters and static
; variables used in repeated calls to this routine.

; PROCEDURE:

```

;   You must call first this routine with the INIT keyword set to define
;   various parameters.
;
;
; MODIFICATION HISTORY:
;
; MODIFIED 3 31 83 TO CORRECT FOR OBSERVED TICKTOCK ERRORS ON SOME TAPES
; INIT ENTRY ADDED.
; MODULE TO CONTAIN BIT SHOVING STUFF FOR HEAO HIGH BIT RATE DATA
; D P MCNUTT 1 26 83 - NO RIGHTS RESERVED
;
; THE FOLLOWING ASSEMBLY PARAMETER AFFECTS THE TIMING OF THE
; MINOR FRAME DATA RETURNED. FAZEF=0 WILL USE THE EARLIER OF
; THE TWO AVAILABLE COPIES OF A MINOR FRAME, FAZEF=1 WILL USE
; THE LATER.
;
; **** I will use the convention that BIT 0 is the LEAST significant bit.
; **** All numbers will be in base 10, unless stated otherwise.
;
; We will assume that the data is in BIG Endian convention since this
; routine was written for the Data Generals which used this convention.
;
; "Ported" to IDL from Data
; General Eclipse assembly : Han Wen, April 1995.
; 23-APR-1995      Bugfix: NRZ was returning as a long integer (4-byte)
;                  instead of a (2-byte) integer.
; 08-JUL-1995      Changed word offset (Flags(1)) for BITSBAD error
;                  relative to start of buffer instead of start of minor
;                  frame.
;-
pro HBRSYNC, Buf, HBR, NRZ, MJF, MNF, Flags, INIT=Init

  common HBRSYNC, B_, E_, V_, C_
;
  if keyword_set(INIT) then begin

    ; Define various bit parameters

    B_ = { $
      LOSS:15,$ ; Analog lost data bit
      HLOK:14,$ ; High bit rate lock
      TIKT:13,$ ; Tick tock FAZEF bit for copies of NRZ data
      LNRZ:12,$ ; 6.4kb NRZ data
      FSYN:7,$ ; Frame synch flag from the DCS ground station
      LLOK:6,$ ; 6.4kb bit synch lock flag
      HBR1:11,$
      HBR2:8,$ ; Bit locations in source words of HBR data bytes
      HBR3:5,$
      HBR4:0 }

    ; Define error codes for the Flags array

    E_ = { $
      NOSYNCH :2,$ ; Failure to find 6.4 kb DCS lock
      BADSYNCH:3,$ ; Bad or missing synch pattern

```

```

        ; second word is SLIP value
TIKTOK :4,$ ; Alternate failure(s) in NRZ clock
        ; second word is count thereof
BUMSIZ :5,$ ; Minor frame is not 4096 words long
        ; second word is ordinal of next synch
        ; bit transition if it occurred early.
BITSBAD :6,$ ; DCS bit lock lost somewhere in the frame
OBOUNDS :7 } ; Minor frame is out of Buf bounds
        ; second word is end of minor frame offset

; Define other miscellaneous constants

SLIPR   = 100
LBUF    =8192      ; Length of double buffer in 16 bit words
LIMBF   =LBUF/2-SLIPR

C_ = { $
    SLIPR: SLIPR,$    ; +/- range allowed for slip checking
    LIMBF: LIMBF,$    ; = -4196, limiting address in search for
        ; DCS synch
    LIMB2: -4095+16,$ ; = -4079, Length of scan to find second
        ; synch flag.
    LOKC9: -4096,$
    TTMSK: 8192,$    ; Mask for tick tock bit (6.4kb clock)
        ; 0010 0000 0000 0000

    TTERR: -16384,$  ; Fill word in case of ticktock failure
        ; 1100 0000 0000 0000

    ; BARKER CODE 24: 111 110 101 111 001 100 100 000
    PTRNH: -1293,$   ; 1 111 101 011 110 011
    PTRNL: 8192 }    ; 0 010 000 000 000 000

; Define various STATIC variables

V_ = { $
    SLIP :-64,$      ; Offset required to give earlier minor frame
        ; this value requires that TTSAV be initialized
        ; to 0
    TTSAV:0,$        ; Storage for 'last' ticktock value
    TTCNT:0,$        ; Counter for ticktock failures
    INITF:0,$        ; Init/reinit flag, zero means init
    TTTRY:0,$        ; Try counter for ticktock phasing
    TTINI:0 }

    return
endif

; Leftover stuff from HBRSYNC.SR
;
; FAZEF=0
; BANANA=0 ; Set so that slip will not be reset on synch fail ; on 3/31

; Initialize/define output arguments

```

```

if N_ELEMENTS( MJF ) eq 0 then MJF = 0L

HBR    = intarr(4096)
NRZ    = intarr(128)
Flags  = intarr(3)

V_.TTTRY = 0      ; Set try count for ticktock phasing
SLIPS   = V_.SLIP ; Save beginning value for loop test

;
; Search for the first word in the buffer in which the frame synch word is
; set. this means that the DCS ground station is locked on and has found
; the minor frame synch word.
;
bitsets = (BUF(C_.SLIPR:8191) and 2^B_.FSYN) ; Bump C_.SLIPR words
        ; ahead to avoid
        ; early synch pattern

here0   = WHERE( bitsets eq 0, nzero ) ; The first word where
        ; the B_.FSYN bit is NOT
        ; set points to the first
        ; DCS frame synch

if (nzero eq 0) then begin
    Flags(0) = E_.NOSYNCH ; DCS never found frame synch
    return    ; Exit with error flag
endif

; Check next synch transition to see if it is 4096 words away.
; For each minor frame (i.e. 320ms time interval), there are 16 sequential
; words where bit B_.FSYN is 0. So the 17th word where bit B_.FSYN is 0
; should contain the next synch transition.

if (nzero gt 16) then begin ; If nzero eq 16, then next
    ; synch transition is out of buffer.
    ; Assume it's okay.

    if ((here0(16) - here0(0)) ne 4096) then begin
        Flags(0) = E_.BUMSIZ ; Error code
        Flags(1) = C_.SLIPR + here0(16) ; Word offset of
        ; offending bit
        return
    endif
endif

RENTRE: ; Possible reentry if SLIP value is bad

START   = C_.SLIPR + here0(0) ; Offset of the first DCS sync bit
START   = START + V_.SLIP ; Position to "real" start of minor
        ; frame
Flags(2) = START ; Send start offset to caller *-*
        ; In third word of flags *** 3-8-83

;
; Check to see if minor frame is within buffer

```

```

;
; if START gt 4096 then begin
;   Flags(0) = E_.OBOUNDS
;   Flags(1) = START + 4095 ; Return out of bound offset
;   return
; endif

;
; Now pack up the minor frame into caller's buffer.
;
; BNRZ = BUF(START + 2*indgen(128*16)) ; Get every other word
; BNRZ = (BNRZ and 2^B_.LNRZ) ne 0 ; Pick out 6.4kb NRZ bits
; BNRZ = REFORM( BNRZ,16,128,/OVERWRITE ) ; Each 16 element array represents
; ; the bit pattern of one minor frame,
; ; where the 0th element corresponds
; ; to the MSB, 2^15.
;
; bbase= REVERSE(indgen(16))
; bbase= 2^bbase ; i.e. [2^15, 2^14, ... 2^0]
;
; NRZ = FIX(TRANSPPOSE( bbase#BNRZ ))
;
; Now see if we got a synch pattern at the right place
;
; SYBAD = 0
;
; if (NRZ(0) eq C_.PTRNH) then begin ; Synch pattern HI
;   AC0 = C_.PTRNL
;   AC1 = NRZ(1) and -256 ; Only keep upper 8 bits
;
;   if AC0 ne AC1 then SYBAD = 1
; endif else SYBAD = 1 ; No match

;
; SYBA1 = 0 ; Date: 3/31
; if SYBAD then begin ; If at beginning allow slip to
;   if V_.INITF eq 0 then begin ; adjust, otherwise fail on no
;     AC0 = V_.SLIP - 1 ; synch
;     AC1 = AC0 + C_.SLIPR ; Limiting value
;     ; See if there, and if so,
;     if AC1 eq 0 then AC0 = 0 ; replace w/ other limit.
;     V_.SLIP = AC0
;     if (SLIPS ne V_.SLIP) then $ ; See if we have gone full
;       goto, RENTR ; circle
;     SYBA1 = 1
;   endif else SYBA1 = 1
; endif

; if SYBA1 then begin
;   Flags(0) = E_.BADSYNCH
;   Flags(1) = V_.SLIP
;   return
; endif

;
; Check DCS bit lock bit - if zero anywhere we will fail

```

```
;
bitsets = (BUF(START:START+4095) and 2^B_LLOCK) ; Pick out DCS
; bit lock

here_bad = WHERE( bitsets ne 0, nbad )

if (nbad gt 0) then begin
    Flags(0) = E_.BITSBAD ; Set error flags for caller
    Flags(1) = START + here_bad(0)
    return
endif

;
; CELL = 1 byte = 8 bits
;
; Pick up the subframe ID and pass to caller
; 20 bits of the spacecraft clock are contained in cells 128,129,130
; of each minor frame, the upper 4 bits of 128 being garbage. eight more
; bits of clock are transmitted in cell 81 of minor frame 118.
;

AC1 = NRZ(65) ; CELLS 130 AND 131
AC0 = NRZ(64) ; CELLS 128 AND 129
AC0 = AC0 and 4095 ; Clear out bits 12 thru 15
CARRY= (AC1 and -32768) ne 0 ; Shift bit 15 into the CARRY
if CARRY then $
AC1 = (AC1 xor -32768 )
AC1 = ISHFT(AC1,-8) ; Get rid of garbage CELL 131.
AC0 = ISHFT(AC0,1) ; Shift and put CARRY into
AC0 = AC0 + CARRY ; bit 0.
MNF = AC1
if (MNF ne 118) then begin ; Get callers MJF bits
    ACL = ISHFT(MJF,3)
    AC1 = ISHFT(ACL,-16) ; Get upper 16 bits of ACL
endif else AC1 = NRZ(40) ; Cell 81 plus garbage in high bits

DUM = AC0
AC0 = AC1
AC1 = long( DUM )
AC0 = long( AC0 and 255 ) ; Lower 8 bits, 255=0000 0000 1111 1111
AC1 = ISHFT( AC1, 3 ) ; Left justify low order bits
MJF = ISHFT( AC0, 16 ) + AC1
MJF = ISHFT( MJF, -3 ) ; and merge with the hi

;
;
; Now we need to pack the high bit rate bits into the caller's output buffer
; we will pick up one word at a time and shift the bits around. In the output
; the sign bit will be set if the HBR lock bit was set or if we had a tick-tock
; sequence error.
;
; There are 10 bits of HBR data for each BUF word, namely there are
; ten 7.8125 microsecond time intervals where one or more photons may have
```



```
; been detected. Each bit that is set represents a detection of one or
; more photons. (We are assuming that the data is in the HBRB or High Bit
; Rate BIT format.)
;
```

```
    HBRwrds = (BUF and 63)           or $ ; Bits 0 - 5
              (ISHFT(BUF,-2) and 960) or $ ; Bits 8 - 11
              (ISHFT(BUF and 2^B_.HLOK,15-B_.HLOK))
```

```
HBM_0:
```

```
    V_.TTSAV= V_.TTINI    ; Value varies with assembly parameter "FAZEF"
    INC1 = 0 - 1          ; Set auto incrementer for destination buffer
    INC0 = START - 1      ; Set auto incrementer for source buffer
    COUNT= 4096           ; Set number of words to move
```

```
;
; The bit picked up by TTMSK should be "tick-tock"ing between values
; 0 and 1 for sequential BUF words.
;
```

```
    for i=1,COUNT do begin
```

```
        INC0 = INC0 + 1
        AC1 = BUF(INC0)    ; Load up next source word
        AC2 = AC1 and C_.TTMSK ; Pick up NRZ clock bit only
        AC0 = V_.TTSAV
        V_.TTSAV= AC2
```

```
        HBRfill = HBRwrds(INC0)
```

```
        if (AC2 eq AC0) then begin ; If next "tick" is a "tock"-> error
            V_.TTSAV= C_.TTMSK xor AC2
            AC0 = C_.TTERR
            INC0 = INC0 - 1          ; Move back in the source
            if INC0 ne 0 then HBRfill = AC0 ; and go store the fill data
        endif
```

```
        INC1 = INC1 + 1
        HBR(INC1) = HBRfill
```

```
    endfor
```

```
;
; Now calculate the number of words actually loaded from the buffer. should
; be 4096 - if not we had a ticktock error.
;
```

```
    AC0 = START + 4095
    AC0 = AC0 - INC0
    if AC0 ne 0 then begin ; Will be zero if no tick tock errors
```

```
        if (V_.TTTRY ne 0) or $ ; Have tried both phases - just fail
            (V_.INITF ne 0) then $ ; See if we ever had a good one
            begin ; yes so fail now
                Flags(0) = E_.TIKTOK ; Return with error
                Flags(1) = AC0
                return
            endif
```

```

V_.TTINI = C_.TTMSK xor V_.TTINI ; Otherwise invert the
V_.TTTRY = V_.TTTRY + 1 ; initializer and try again.
goto, HBM_0

endif

Flags(0) = AC0
Flags(1) = V_.TTINI ; Pass the initial value to DJY if he wants it
V_.INITF = 1 ; Adjust the innitializer flag
; to show a successful pass
return ; Return with no errors
;
;
; A known problem with this code can occur when and if the synch pattern
; occurs before the beginning of the buffer and the DCS frame synch bit
; comes true right at the beginning of the buffer. If this happens a simple
; fix is to save some data in storage space before the beginning of the
; buffer. It happened: MURPHY'S RULE IS PROVEN; it's been fixed.
;
;
end

```

A.4.2 Photon Time Interval Format

```

;+
; NAME:
;   DEF_HBRH
;
; PURPOSE:
;   This routine defines all the pointers and bits to the Major Frame
;   and Minor Frame headers for the Photon Time Interval (PTI) format.
;
; CATEGORY:
;   HEAO HBR.
;
; CALLING SEQUENCE:
;
;   DEF_HBRH
;
; OUTPUTS:
;   A common block gets filled with pointer and bit values. See below
;   for definition of the common block.
;
; COMMON BLOCKS:
;   DEF_HBRH: This common block holds all the pointers and bits to the
;   MJF and MNF headers.
;
;   NWMJFH: Length of a MJF header in WORDS
;   MJFptr_: A structure containing the index values and their
;   associated names of all the pointers to the MJF
;   header.
;   MJFbit_: A structure containing the bit values and their
;   associated names of the MJF Flags variable.
;   MJFmark: Value of the MJF marker.

```

```

;
;      NWMNFH: Length of a MNF header in WORDS
;      MNFptr_: A structure containing the index values and their
;               associated names of all the pointers to the MNF
;               header.
;      MNFbit_: A structure containing the bit values and their
;               associated names of the MNF Flags variable.
;      MNFmark: Value of the MNF marker.
;
;      (*Note: For a description of each pointer or bit, see DEF_HBRH.pro)
;
; MODIFICATION HISTORY:
;   Written by:  Han Wen, July 1995.
;-
pro DEF_HBRH

    common DEF_HBRH, NWMJFH, MJFptr_, MJFbit_, MJFmark, $
           NWMNFH, MNFptr_, MNFbit_, MNFmark, $
           NWNRZB, NWPTIR

    NWPTIR =512      ; Number of words/record for PTI format.

; *****
;
;      MJF Header
;
; *****

    NWMJFH =NWPTIR   ; Words/MJF Header

    MJFptr_ = { $
        MJF      : 0,$ ; MJF number calculated (32-bit integer)
        MJFNrz   : 2,$ ; MJF number read (32-bit integer)
        MJFLAGS  : 4,$ ; MJF flags (16 bits) (see below for definition)
        SYNLOSS  : 5,$ ; Total number of HBR sync loss errors (32-bit)
        CLKERRS  : 7,$ ; Total number of Clock TicToc errors (32-bit)
        MJFCNTS  : 9,$ ; Total counts (32-bit)
        MNFMISS  : 11,$ ; Number of Missing MNF's
        MNFLAGS  : 12,$ ; MNF flags (duplicated)
        MNFNDS  : 140,$ ; Number of Deltat's (counts-1)/MNF
        DATRECS  : 268,$ ; Total number of data records written
        DATRECN  : 269,$ ; Data record number for each MNF
        PARERRS  : 397,$ ; Total number of parity errors
        SYNMFNS  : 398,$ ; # MNF's with HBR sync loss errors
        NOSYNCH  : 399,$ ; # buffers with no DCS synch bit transition error(s)
        BADSYNC  : 400,$ ; # buffers with bad or missing synch pattern error(s)
        TIKTOK   : 401,$ ; # buffers with Clock TicToc errors
        BUMSIZ   : 402,$ ; # buffers with MNF is not 4096 words long error(s)
        BITSBAD  : 403,$ ; # buffers with DCS bit lock lost somewhere in MNF error(s)
        OBOUNDS  : 404,$ ; # buffers with MNF extends beyond buffer size error(s)
        MJFMARK  : 448 } ; MJF marker (64 words)

;
; MJF FLAG BITS (F77 Convention: 0=LSB)

```

```

;
MJFbit_ = { $
  MJF_GDVS : 0,$ ; Global data validity (0=ok)
  MNF_MISS : 1,$ ; MNF(s) missing
  NO_DATAS : 2,$ ; No events (data) detected
  SYN_ERRS : 3,$ ; HBR sync loss error(s)
  PAR_ERRS : 4,$ ; Tape parity error(s)
  HBR_FMTS : 5,$ ; HBR format (0=bit,1=word)
  NOSYN_ERRS : 6,$ ; No DCS synch bit transition error(s)
  BADSYN_ERRS : 7,$ ; Bad or missing synch pattern error(s)
  CLK_ERRS : 8,$ ; Clock tictoc error(s)
  BUMSIZ_ERRS : 9,$ ; MNF is not 4096 words long error(s)
  BITBAD_ERRS : 10,$ ; DCS bit lock lost somewhere in MNF error(s)
  OBOUND_ERRS : 11 } ; MNF extends beyond buffer size error(s)

;
; MJF Marker (Use to recover from any read errors)
;
MJFmark =reform(byte(['B','O','K','S','T','E','V','E']))
MJFmark =MJFmark#replicate(1,8)
MJFmark =fix(REFORM(MJFmark,64))

;
; *****
;
; MNF Header
;
; *****
;
; Added DPM's HBRSYNC flags (07/08/95, H.C. Wen)
;
NWMNFH =16 ; Words/MNF Header

MNFptr_ = { $
  MNF : 0,$ ; MNF number calculated/first missing
  MNFNZR : 1,$ ; MNF number read/ last missing
  MNFLAG : 2,$ ; MNF flags (16 bits) (see definitions below)
  MNFCNT : 3,$ ; Counts this MNF
  NRZOFF : 4,$ ; NRZ data offset in buffers
  SYNLOS : 5,$ ; Number of HBR sync loss errors
  CLKERR : 6,$ ; Number of Clock TicToc errors
  DATREC : 7,$ ; Data record number
  MNFNDR : 8,$ ; Number of Dt's this MNF, this record
  MNFLDR : 9,$ ; Number of Dt's this MNF, last record
  DELBEG : 10,$ ; Time from beginning of MNF to first event
  DELEND : 11,$ ; Time from last event to end MNF
  SYNFLG : 12,$ ; HBRsync flags (16 bits)
  ERROFF : 13,$ ; Error offset in buffers (see HBRsync.pro, flags(1),
  MNFMARK : 14 } ; MNF marker (32-bits)

;
; MNF flag bits (F77 convention: 0=LSB) (MNFLAG)
;
MNFbit_ = { $
  MNF_GDV : 0,$ ; Global data validity (0=OK)
  MNF_MIS : 1,$ ; MNF missing
  NO_DATA : 2,$ ; No events (data) detected

```

```

SYN_ERR: 3,$ ; HBR sync loss error(s)
CLK_ERR: 4,$ ; Clock tictoc error(s)
PAR_ER1: 5,$ ; Tape parity error buffer 1
PAR_ER2: 6,$ ; Tape parity error buffer 2
SUSPECT: 7 } ; Current or previous buffer(s) have one or
              ; more fatal HBRSYNC errors.
;      : 8,$ ; Unassigned
;      : 9,$ ; Unassigned
;      : 10,$ ; Unassigned
;      : 11,$ ; Unassigned
;      : 12,$ ; Unassigned
;      : 13,$ ; Unassigned
;      : 14,$ ; Unassigned
;      : 15 } ; Unassigned

;
; MNF Marker (Use to recover from any read errors)
;
      MNFmark =142857143L

; *****
;
;      NRZ Block
;
; *****

      NWNRZB =128*128 ; Words/NRZ block (128 words/MNF)
end



---


;+
; NAME:
;   OPENPTI
;
; PURPOSE:
;   This routine opens a Photon Time Interval (PTI) file.
;
; CATEGORY:
;   HEAO HBR.
;
; CALLING SEQUENCE:
;
;   OPENPTI, LU, File
;
; INPUTS:
;
;   LU:   The logical unit to be associated with the opened PTI file.
;         If LU is undefined then the GET_LUN procedure is automatically
;         used to set its value.
;
; OPTIONAL INPUTS:
;
;   File: A string containing the name of the PTI file to be opened.
;         If this parameter is not provided, then the PICKFILE routine
;         is used to allow the USER to interactively select the name

```

```

;         of the PTI file.
;
; OPTIONAL INPUT KEYWORD PARAMETERS:
;
;   GET_LUN: Force the GET_LUN procedure to be called to defined LU if
;             LU is undefined or redefine LU if it is.
;
; OPTIONAL OUTPUT KEYWORD PARAMETERS:
;
;   NRECORDS: The total number of 512 byte records in the opened PTI file.
;
; COMMON BLOCKS:
;   DEF_HBRH:  Holds all the MJF and MNF PTI pointers, (see def_hbrh.pro).
;   PTI_ENDIAN: Holds variable that determines whether or not to swap bytes.
;
; PROCEDURE:
;   Opens a PTI file and reads in the first record to determine the byte order.
;
; MODIFICATION HISTORY:
;   Written by:  Han Wen, August 1995.
;   29-SEP-1995  Added GET_LUN keyword.
;   08-OCT-1995  Eliminated XDR and BINARY keywords; check for byte order;
;                 made compatible with vers 4.0.1.
;   09-OCT-1995  Moved Win 4.0.1 specific keywords to WINOPEN function.
;-
pro OPENPTI, LU, File, NRECORDS=NRECORDS, GET_LUN=Get_LUN_set

  common DEF_HBRH    ; Defined in def_hbrh.pro
  common PTI_ENDIAN, endian_swap_

  NP = N_PARAMS()
  if (NP eq 0) or (NP gt 2) then $
    message,'Must be called with 1-2 parameters: LU [, File]'

  if (N_ELEMENTS(LU) eq 0) or keyword_set(Get_LUN_set) then GET_LUN, LU

  if (NP eq 1) then File = pickfile()

  def_hbrh

  openr, LU, File, _EXTRA=WINOPEN( /BINARY )

  iss    = fstat(LU)
  NRECORDS = iss.SIZE/(NWPTIR*2)

; Determine the byte order

  endian_rec= intarr(NWPTIR)
  endian_ck = indgen(NWPTIR)
  readu, LU, endian_rec

  diff = TOTAL( abs(endian_rec - endian_ck) )
  if (diff eq 0) then endian_swap_ = 0 $
  else begin
    endian_rec= SWAP_ENDIAN(endian_rec)
  end

```

```

        diff = TOTAL( abs(endian_rec - endian_ck) )
        if (diff eq 0) then endian_swap_ = 1 $
        else message,'Unrecognized PTI format.'
    endelse
end

;+
; NAME:
;   READPTI
;
; PURPOSE:
;   This routine reads in the next MJF block of Photon Time Interval (PTI)
;   file and supplies it to the USER in a structure variable.
;
; CATEGORY:
;   HEAO HBR.
;
; CALLING SEQUENCE:
;
;   READPTI, LU, Block
;
; INPUTS:
;
;   LU:   Logical unit associated with the current PTI file.
;
; OUTPUTS:
;
;   Block: Structure variable holding the next MJF block of PTI data.
;          The tags are defined as follows:
;
;          MJFH:  An array holding the MJF header, intarr(512).
;          MNFH:  An array holding the MNF header for each MNF
;                 present in this MJF block, intarr(16,nMNFH*).
;          NRZ:   An array holding the NRZ data**, intarr(128,nMNF*).
;          PTI:   An array holding all the photon time intervals** in
;                 7.8125 usec bins in this MJF block, lonarr(ndt).
;                 (E.g. A value of 1 means that two photons occurred
;                 within adjacent 7.8125 usec bins.)
;
;   * (see PROCEDURE below for definitions).
;   ** (see PROCEDURE below for caveats).
;
; OUTPUT KEYWORD PARAMETERS:
;
;   ERROR: Error status code:
;           0, Success.
;           1, End of File.
;           2, Could not find MJF marker.
;           3, Could not find MNF marker.
;           !error, I/O error.
;
; COMMON BLOCKS:
;   DEF_HBRH: Holds all the MJF and MNF PTI pointers, (see def_hbrh.pro).
;
; PROCEDURE:

```

```

; * There are several HBR data files where there are one or more missing
; MNFs. For each contiguous section of missing MNFs (e.g. missing
; MNFs = [23,24,25]) one MNFH header is written out. No PTI or NRZ data
; is associated with this header. Therefore,
;
; nMISS          , Number of missing MNFs in this MJF.
; nsect          , Number of contiguous section(s) of
;                missing MNFs, (e.g. missing MNFs =
;                [23,24,25, 100] => nMISS_sec = 2)
; nMNFH = 128 - nMISS + nsect , Number of actual MNF headers written out
; nMNF = 128 - nMISS          , Number of MNFs present (i.e. NOT missing)
;                in the MJF of data.
;
; ** If there are NO photons in a MJF then NRZ = PTI = -1. This can
; happen if an entire MJF is missing or if NO counts are actually detected
; in a MJF.
;
; MODIFICATION HISTORY:
;   Written by:  Han Wen, August 1995.
;   31-AUG-1995  Let PTI=-nMNFw if no photons in entire MJF.
;   28-SEP-1995  Added negative numbers due to overflow comments; check
;                for PTIs > 32767 across adjacent MNFs.
;   29-SEP-1995  Eliminated any negative PTIs due to overflows or
;                missing MNFs by converting the PTI array output to a
;                long integer array.
;   30-SEP-1995  Eliminated non-existent NRZ data from Block.NRZ due
;                to one or more missing MNFs.
;
;-
pro READPTI, LU, Block, ERROR=Error

  common DEF_HBRH ; Defined in def_hbrh.pro
  common PTI_ENDIAN, endian_swap_

  overflow = 65536L

  Error = -1 & ON_IOERROR, ERROR_

  NP = N_PARAMS()
  if (NP lt 1) or (NP gt 2) then $
    message, 'Must be called with 1-2 parameters: LU [, Block]'

; Check for End-of-File

  Error = 1 & if EOF(LU) then goto, ERROR_

  PTIrec = intarr(NWPTIR) ; Define PTI record

; Read/Check/Search for Major Frame Header

  repeat begin
    readu, LU, PTIrec
    if (endian_swap_) then byteorder, PTIrec, /SSWAP
    i = MJFptr_MJFMARK
    marker = PTIrec(i+63) ; Check for MJF marker
  
```



```

    diff = TOTAL(abs(marker - MJFmark))
    endrep until (diff eq 0) or EOF(LU)

    Error = 2 & if EOF(LU) then goto, ERROR_

    MJFH = PTIrec

; Read in NRZ (6.4 kps) Data block

    NRZ = intarr(NWNRZB) ; NRZ block
    nMNF = 128 ; Number of Minor frames/MJF
    NWNRZ = NWNRZB/nMNF ; = 128 words of NRZ data/MNF

    readu, LU, NRZ
    if (endian_swap_) then byteorder, NRZ, /SSWAP
    NRZ = REFORM(NRZ, NWNRZ, nMNF, $ ; NRZ record/MNF
                /OVERWRITE)

; Read in all Minor Frame data records

    nrecMNFs = MJFH( MJFptr_.DATRECS )
    DATArecs = intarr(long(nrecMNFs)*NWPTIR)

    readu, LU, DATArecs ; Read in all data records
    if (endian_swap_) then byteorder, DATArecs, /SSWAP
    DATArecs = REFORM( DATArecs, $ ; DATA record/MNF
                      NWPTIR, nrecMNFs, $
                      /OVERWRITE )

; Determine MNF record numbers

    mrkstr = 'MNF'
    i = MJFptr_.DATRECn
    MNFrecn = MJFH( i:i+nMNF-1 ) ; Eliminate any missing MNFs
    here = WHERE( MNFrecn ne 0, nne0 ) ; not reported by HBRFMT
    Error = 3 & if (nne0 eq 0) then goto, ERROR_
    MNFrecn = MNFrecn(here)

    here = UNIQ( MNFrecn ) ; Removing redundant missing
    MNFrecn = MNFrecn(here) ; MNFs record numbers
    nMNFw = N_ELEMENTS( MNFrecn ) ; Number of MNFs written to PTI file

; Extract MNF headers

    rec_offset = MNFrecn - MNFrecn(0)
    MNFh = DATArecs( 0:NWMNFH-1, rec_offset )

; Check MNF marker

    i = MNFptr_.MNFMARK
    markint = MNFH( i:i+1, * )
    markers = lonarr( nMNFw )
    EQUIV, markers, markint

```

```

here = WHERE( markers ne MNFMARK, nne0 )
Error = 3 & if (nne0 gt 0) then goto, ERROR_

; Extract number of DATA record numbers written for each MNF

if (nMNFw eq 1) then nrecDATA = nrecMNFs - rec_offset(0) $
else begin
    nrecDATA = [rec_offset(1:nMNFw-1), nrecMNFs]
    nrecDATA = nrecDATA - rec_offset(0:nMNFw-1)
endelse

; and the Photon Time Intervals

ntot = MJFH(MJFptr_.MJFCNTS) ; Total number of photons in this MJF
k = 0 ; Number of MNFs with photons present
npho = REFORM(MNFBH(MNFptr_.MNFCNT,*)) ; Number of photons in the MNF
ndt = npho - 1 ; Number of PTIs in the MNF
for i=0,nMNFw-1 do begin

    ; See if this is a MISSING MNF block
    MNFmiss_bit = MNFBH(MNFptr_.MNFLAG,i) and 2^MNFbit_.MNF_MIS
    if (MNFmiss_bit ne 0) then goto, SKIP_MISS

    case 1 of

    ; Two or more photons in MNF
    (npho(i) gt 1) : begin
        k = k+1
        nrec = nrecDATA(i)
        j = rec_offset(i)
        data = DATArecs( *, j:j+nrec-1 )
        data = REFORM( data, nrec*NWPTIR, /OVERWRITE )
        data = long(data( NWMNFBH: NWMNFBH + ndt(i)-1 ))

        ; Check for 16-bit overflows

        hovr = where( data lt 0, novr )
        if (novr gt 0) then $
            data(hovr) = data(hovr) + overflow

        if (k eq 1) then PTI = data $
        else begin

            ; Extract time interval from beginning of MNF
            ; to 1st photon. With dt_EOMNF, construct the
            ; time interval between last and first photons
            ; of "adjacent" MNFs.

            dt_SOMNF = long(MNFBH( MNFptr_.DELBEG,i ))
            if (dt_SOMNF lt 0) then dt_SOMNF = dt_SOMNF + overflow

            dt_pho1 = dt_EOMNF + dt_SOMNF

            ; If there are missing MNFs between current and
            ; previous MNFs, then we must add that time interval

```

```

; to dt_pho1

mnf_skip = MNFH(MNFptr_.MNFNRZ,i) - $
          MNFH(MNFptr_.MNFNRZ,i_last) - 1
if (mnf_skip gt 0) then $
  dt_pho1 = dt_pho1 + mnf_skip*40960L

; Finally add this 1st and remaining time intervals for
; this MNF to the PTI array.

PTI = [PTI, dt_pho1, data]
endelse

; Extract time interval from last photon
; to end of MNF

dt_EOMNF = long(MNFH( MNFptr_.DELEND,i ))
if (dt_EOMNF lt 0) then dt_EOMNF = dt_EOMNF + overflow

i_last = i
end

; One photon in MNF
(npho(i) eq 1) : begin
  k = k+1
  if (k gt 1) then begin
    dt_SOMNF = long(MNFH( MNFptr_.DELBEG,i ))
    if (dt_SOMNF lt 0) then dt_SOMNF = dt_SOMNF + overflow
    dt_pho1 = dt_EOMNF + dt_SOMNF
    PTI = [PTI,dt_pho1]
  endif
  dt_EOMNF = long(MNFH( MNFptr_.DELEND,i ))
  if (dt_EOMNF lt 0) then dt_EOMNF = dt_EOMNF + overflow
end

; NO photons in MNF
(npho(i) eq 0) : if (k gt 1) then dt_EOMNF = dt_EOMNF + 40960L

endcase
SKIP_MISS:
endfor

if (N_ELEMENTS(PTI) eq 0) then PTI=-1

; MNF headers describing missing MNFs have NO associated NRZ data.
; The actual amount of NRZ data contained in a (128,128) NRZ block is
; (128,nMNF-nskip), where nskip is the number of MNF headers with
; missing MNFs.

b_MNFmiss = MNFH(mnfptr_.MNFLAG,*) and 2^MNFbit_.MNF_MIS
hdata = where(b_MNFmiss eq 0,ndata) ;i.e. ndata = nMNF-nskip
if (ndata gt 0) then NRZ = NRZ(*,0:ndata-1) $
else NRZ = -1

block = { MJFH : MJFH, $

```

```
NRZ : NRZ, $  
MNFH : MNFH, $  
PTI : PTI }
```

```
Error = 0 & return
```

```
ERROR_: fptr = FSTAT(LU)
```

```
nbytes = fptr.CUR_PTR
```

```
nrec = nbytes/(2*NWPTIR)
```

```
case Error of
```

```
1 : ; End of File
```

```
2 : BEGIN ; MJF marker error
```

```
message,'Could NOT find MJF marker!'/INF
```

```
message,'Number of records searched: '+strtrim(nrec,2),/INF
```

```
END
```

```
3 : BEGIN ; MNF marker error
```

```
message,'Could NOT find MNF marker!'/INF
```

```
message,'Number of records searched: '+strtrim(nrec,2),/INF
```

```
END
```

```
else : BEGIN
```

```
message,'Error reading PTI data file at RECORD: '+strtrim(nrec,2),/INF
```

```
print, strmessage(!error)
```

```
Error = !error
```

```
END
```

```
endcase
```

```
end
```



```

;           0 - scanning/spinning
;           1 - pointing
;
; MJFH:  Major frame headers* created by HBRFMT,
;        intarr(512,nMJFH)
; MNFH:  Minor frame headers* created by HBRFMT,
;        intarr(16,nMNFH)
; nMJFH:  Number of major frame headers in the PTI file.
; nMNFH:  Number of minor frame headers in the PTI file.
; nNRZ:   Number of NRZ block in the PTI file.
; nPTI:   Number of time intervals in the CTI file.
; nbad:   Number of time regions with BAD minor frames.
; nAPE:   Number of Adjacent Photon Events (APE) found
;         in each MJF, intarr(nMJFH).
; MJFs:   Major frame numbers, lonarr(nMJFH).
; GDV:    Overall Global Data Validity flag (0=Ok, NO
;         HBRSYNC errors found in entire data file).
; NRZ:    Normal 6.4 kbps telemetry data (NRZ),
;         intarr(128, nNRZ).
; PTI:    Corrected photon time intervals, lonarr(nPTI).
; ts:     Corresponding photon time relative to the
;         beginning of the minor frame containing the
;         first photon, lonarr(nPTI+1).
; tbad:   The beginning and end of time regions where
;         one or more HBRSYNC error were detected,
;         lonarr(2,nbad). The times are relative to the
;         beginning of the MNF containing the 1st photon.
;
; *For a complete description of the headers, see DEF_HBRH.PRO.
;
; RESTRICTIONS:
;
; The def_hbrh.pro routine must be previously compiled.
;
; COMMON BLOCKS:
; DEF_HBRH: Holds all the MJF and MNF PTI pointers, (see def_hbrh.pro).
;
; MODIFICATION HISTORY:
; Written by:  Han Wen, October 1995.
;-
pro READNSWAP, LU, A, SWAP=Swap

    readu, LU, A
    if keyword_set(Swap) then A = SWAP_ENDIAN(A)
end

pro READCTI, Name, Cat

    common def_hbrh

    NP = N_PARAMS()
    if (NP ne 2) then message,'Must be called with 2 parameters: '+$
        'Name, Cat'

    openr, lu, Name, /GET_LUN, _EXTRA=WINOPEN(/BINARY)

```

; Determine the byte order

```

endian_rec= intarr(NWPTIR)
endian_ck = indgen(NWPTIR)
readu, LU, endian_rec

diff = TOTAL( abs(endian_rec - endian_ck) )
if (diff eq 0) then swap = 0 $
else begin
    endian_rec= SWAP_ENDIAN(endian_rec)
    diff = TOTAL( abs(endian_rec - endian_ck) )
    if (diff eq 0) then swap = 1 $
    else message, 'Unrecognized PTI format.'
endelse

```

; Read in the string headers

```

nbyte  = 0L
strhdr = strarr(7)
for i=0,6 do begin
    readnswap, lu, nbyte, SWAP=swap & input= bytarr(nbyte)
    readnswap, lu, input, SWAP=swap
    strhdr(i) = string(input)
endfor

name    = strhdr(0)
target  = strhdr(1)
routine = strhdr(2)
ctitime = strhdr(3)
file    = strhdr(4)
vers    = strhdr(5)
sattime = strhdr(6)

```

; Read in miscellaneous HEAO info

```

readnswap, lu, nbyte, SWAP=swap & rev = 0
readnswap, lu, rev, SWAP=swap
readnswap, lu, nbyte, SWAP=swap & mode = intarr(nbyte/2)
readnswap, lu, mode, SWAP=swap

```

; Extract the MJF and MNF headers

```

readnswap, lu, nbyte, SWAP=swap & nMJF = nbyte/4 & MJFs = lonarr(nMJF)
readnswap, lu, MJFs, SWAP=swap
readnswap, lu, nbyte, SWAP=swap & MJFH = intarr(512,nMJF)
readnswap, lu, MJFH, SWAP=swap
readnswap, lu, nbyte, SWAP=swap & nMNF = nbyte/32 & MNFH = intarr(16,nMNF)
readnswap, lu, MNFH, SWAP=swap
readnswap, lu, nbyte, SWAP=swap & GDV = 0
readnswap, lu, GDV, SWAP=swap

```

; Get the 6.4 kbps data and the photon info

```

readnswap, lu, nbyte, SWAP=swap & nNRZ = nbyte/256 & NRZ = intarr(128,nNRZ)

```

```

readnswap, lu, NRZ, SWAP=swap
readnswap, lu, nbyte, SWAP=swap & nPTI = nbyte/4 & PTI = lonarr(nPTI)
readnswap, lu, PTI, SWAP=swap
readnswap, lu, nbyte, SWAP=swap & nts = nbyte/4 & ts = lonarr(nts)
readnswap, lu, ts, SWAP=swap
readnswap, lu, nbyte, SWAP=swap & nbad = nbyte/8 & tbad = lonarr(2,nbad)
readnswap, lu, tbad, SWAP=swap
readnswap, lu, nbyte, SWAP=swap & nAPE = intarr(nbyte/2)
readnswap, lu, nAPE, SWAP=swap

```

```

if (nPTI eq 1) and (PTI(0) eq -1) then nPTI=0L

```

```

if (nbad eq 1) and (tbad(0) eq -1) then nbad=0L

```

```

free_lun,lu

```

```

; Pack the IDL structure variables

```

```

IDL = { routine : routine, $
       date   : ctitime, $
       version : vers, $
       file   : file }
heao = { rev   : rev, $
       mode   : mode, $
       date   : sattime }
cat = { name   : name, $
       target  : target, $
       idl     : idl, $
       heao    : heao, $
       MJFH    : MJFH, $
       MNFH    : MNFH, $
       nMJFH   : fix(nMJF), $
       nMNFH   : fix(nMNF), $
       nNRZ    : fix(nNRZ), $
       nPTI    : nPTI, $
       nbad    : nbad, $
       nAPE    : nAPE, $
       MJFs    : MJFs, $
       GDV     : GDV, $
       NRZ     : temporary(NRZ), $
       PTI     : temporary(PTI), $
       ts      : temporary(ts), $
       tbad    : temporary(tbad) }

```

```

end

```


A.4.4 NRZ Format

```

;+
; NAME:
;   NRZUNPAK
;
; PURPOSE:
;   This function "unpacks" the raw 6.4 kbps NRZ data by extracting
;   its 2.1 kbps HEAO A-1 component and storing it into a structure
;   variable.
;
; CATEGORY:
;   HEAO.
;
; CALLING SEQUENCE:
;
;   Result = NRZUNPAK( NRZblock, Mode )
;
; INPUTS:
;   NRZblock: An array holding a block of NRZ data, intarr(128,nMNF).
;             Each Minor Frame (MNF) of NRZ data contains 128 bytes.
;
;   Mode:    An integer describing the telemetry mode of the data in
;            MILLISECONDS, (=5 or 320).
;
; OUTPUTS:
;   This function returns a structure containing the HEAO A-1 component
;   of the NRZ data. Its tags depends on the Mode specified and are
;   defined as follows:
;
;   Mode = 320 ms
;
;       nMNFs  : Number of Minor Frames
;       MNFs   : Minor frame numbers, intarr(nMNFs)
;       TCnt1_6 : Total counts for Modules 1-6, intarr(6,nMNFs)
;       TCnt7  : Total counts for Module 7, intarr(nMNFs)
;       SChT   : Counts in 16-Channels for Mods 1-4, intarr(16,nMNFs)
;       SCh5   : Counts in 16-Channels for Mod 5, intarr(16,nMNFs)
;       SCh6   : Counts in 16-Channels for Mod 6, intarr(16,nMNFs)
;       SCh7   : Counts in 16-Channels for Mod 7, intarr(16,nMNFs/8)
;       FCh    : Counts in 40-Channels, intarr(40,nMNFs/2)
;       Chmask : 16-Channel MASKS, intarr(16,no. MNF #s = 119)
;       AGC    : Auto Gain Control structure:
;               HV : Monitor HV/Module, fltarr(7,nMJFs)
;               Loop : Loop setting/Module, fltarr(7,nMJFs)
;               Gain : Gain/Module, fltarr(7,nMJFs)
;       Data   : HEAO A-1 2.1 kbps data, intarr(256,nMNFs)
;
;   Mode = 5 ms
;
;       nMNFs  : Number of Minor Frames
;       MNFs   : Minor frame numbers, intarr(nMNFs)
;       PtMd   : Counts for Modules 1-4, intarr(64,nMNFs)
;       FCh    : Counts in 40-Channels, intarr(40,nMNFs/2)

```

```

;      Data      :  HEAO A-1 2.1 kbps data, intarr(256,nMNFs)
;
; RESTRICTIONS:
;   This routines assumes that the block of NRZ data is contiguous in
;   time. Namely, there are no MISSING MNFs.
;
; MODIFICATION HISTORY:
;   Written by:  Han Wen, June 1995.
;   21-SEP-1995  Added comments; replaced POINT and SCAN keywords
;                 with Mode parameter.
;   22-SEP-1995  Changed Chmask tag to MskS and added Msk7 tag.
;-
function NRZUNPAK, NRZs1, Mode

  NP = N_PARAMS()
  if (NP ne 2) then message,'Must be called with 2 parameters: '+$
    'NRZblock, Mode'

  Scan_mode = 0
  Point_mode = 0
  case Mode of
    320 : Scan_mode = 1
    5 : Point_mode = 1
    else : message,'Invalid Telemetry Mode: '+strtrim(Mode,2)
  endcase

; Define all BYTE offsets to all HEAO A-1 NRZ Data

; Scan Mode Telemetry Format

iSchT = 4*indgen(16)+7 ;16-Channels Mods 1-4
iTcnt = [4*indgen(4)+71,159,227,251] ;Tot. Count Mods 1-7
iFch = [ 5, 21, 26, 37, 53, 69, 85, 90,101,117,$ ;40-Channels
        133,149,154,165,181,197,213,218,229,245 ]
iSch5 = [4*indgen(10)+91,4*indgen(6)+135] ;16-Channels Mod 5
iSch6 = [4*indgen(16)+163] ;16-Channels Mod 6
iSch7 = [231,247] ;16-Channels Mod 7

; Point Mode Telemetry Format

iFch = [ 5, 21, 26, 37, 53, 69, 85, 90,101,117,$ ;40-Channels
        133,149,154,165,181,197,213,218,229,245 ]
iPtMd = 4*indgen(64)+3 ;5ms MODs 1-4

if keyword_set( Scan_mode ) then Sarr = [iSchT, iTcnt, iFch, iSch5, iSch6, iSch7 ]
if keyword_set( Point_mode ) then Sarr = [iFch, iPtMd]
Type = strarr(256)
Type(Sarr) = 'S'

; Convert to byte array

nMNFs = n_elements(NRZs1)/128
NRZs = REFORM( NRZs1, nMNFs*128 )

i = 0

```

```

j      = 2*indgen(128)
k      = j+1
NRZb   = bytarr(256,nMNFs)

NRZb(j,*) = ISHFT(NRZs,-8)    ;Upper 8 bits fill the "first" bytes
NRZb(k,*) = NRZs and '377'O   ;Lower 8 bits fill the "second" bytes

```

; Convert quasi-logarithmic numbers for Science data

```

Data    = fix(NRZb)
here    = where(Type eq 'S')
Data(here,*) = ACNVRT(Data(here,*))

```

; Extract MNF numbers (Taken from HBRSYNC)

```

AC1 = REFORM(NRZs1(65,*))          ; CELLS 130 AND 131
here = WHERE((AC1 and -32768) ne 0,nCARRY) ; Shift bit 15 into the CARRY
if (nCARRY gt 0) then AC1(here) = AC1(here) xor -32768
AC1 = ISHFT(AC1,-8)                ; Get rid of garbage CELL 131.
MNFs = AC1
h0 = WHERE(MNFs eq MNFs(0),nMJFs)

```

; Extract NRZ depending on USER specified telemetry mode

```

i0 = 0
if (MNFs(0) and 1) eq 1 then i0=1 ; Odd MNF
CASE 1 OF
  keyword_set(Scan_mode): BEGIN          ; A-1 Scan Telemetry Mode

```

; Extract the COUNTS

```

TCnt1_6 = Data(iTCnt(0:5),*)          ; Total Cts, Mods 1-6
SchT     = Data(iSchT,*)                ; 16-Channels, Mods 1-4
Sch5     = Data(iSch5,*)                ; 16-Channels, Mod 5
Sch6     = Data(iSch6,*)                ; 16-Channels, Mod 6
Fch      = Data(iFch,*)                 ; 40-channel counts collected
                                           ; every 640 ms.
if (MNFs(0) and 1) eq 1 then begin      ; If first MNF is Odd then
  Fch = TRANSPOSE(Fch)                  ; fill first 20 channels
  Fch = [intarr(1,20),Fch]              ; with 0's
  Fch = TRANSPOSE(Fch)
endif
if (MNFs(nMNFs-1) and 1) eq 0 then begin ; If last MNF is Even then
  Fch = TRANSPOSE(Fch)                  ; fill last 20 channels
  Fch = [Fch,intarr(1,20)]              ; with 0's
  Fch = TRANSPOSE(Fch)
endif
Fch = REFORM( Fch, 40,n_elements(Fch)/40,/OVERWRITE)

j0 = MNFs(0) MOD 8
j0 = (8 - j0) MOD 8

j1 = MNFs(nMNFs-1) MOD 8
if (j1 eq 7) then j1 = nMNFs-1 $
else
  j1 = (nMNFs-1) - (j1+1)

```

```

nk      = (j1 - j0)/8 + 1
i       = j0 + 8*indgen(nk)
TCnt7   = Data(iTCnt(6),i+7)      ; Total Cts, Mod 7
TCnt7   = REFORM(TCnt7,/OVERWRITE)

SCh7    = intarr(16,nk)           ; 16-Channels, Mod 7
for j=0,15 do begin               ; Module 7 data collected
    k    = (j gt 7)               ; every 2.56 ms
    SCh7(j,*) = Data(iSCh7(k),i+j)
endfor

```

; See which energy channels are masked off for Modules 1-4

```

imsk_MNF = 119      ; MNF index
imsk_word = 255     ; NRZ word index

hmask    = where(MNFs eq imsk_MNF)
MSBs     = Data(imsk_word,hmask)
LSBs     = Data(imsk_word,hmask+1)
masks    = ISHFT(MSBs,8) + LSBs
MskS     = intarr(16,n_elements(hmask))
for i=0,15 do MskS(i,*) = (masks and 2^i)/2^i

```

; See which energy channels are masked off for Module 7

```

imsk_MNF = 117      ; MNF index
imsk_word = 255     ; NRZ word index

hmask    = where(MNFs eq imsk_MNF)
MSBs     = Data(imsk_word,hmask)
LSBs     = Data(imsk_word,hmask+1)
masks    = ISHFT(MSBs,8) + LSBs
Msk7     = intarr(16,n_elements(hmask))
for i=0,15 do Msk7(i,*) = (masks and 2^i)/2^i

```

; See what the AGC MONITOR, LOOP and GAIN is for each module

```

iAGC_word = [87, 87, 87, 87, 255, 255, 255] ; NRZ word index for
                                                ; each module
iHV_MNF   = [16, 48, 80, 112, 16, 48, 80]   ; MNF index for
iAGC_MNF   = [27, 59, 91, 123, 27, 59, 91]   ; each module
iAGC_Lbit = 1                                ; LOOP Bit index of
                                                ; the NRZ word
iAGC_Gbit = 2                                ; GAIN Bit index of
                                                ; the NRZ word

AGC_Vmin = -1.56                             ; min. Voltage [V]
AGC_Vmax = 1700.00                           ; max. Voltage [V]

HV = fltarr(7,nMJFs)
Loop = fltarr(7,nMJFs)
Gain = fltarr(7,nMJFs)

```

```

for i=0,6 do begin
  here = where(MNFs eq iHV_MNF(i),nh)
  AGCwords = REFORM( Data(iAGC_word(i),here))
  AGCvolts = (AGC_Vmax-AGC_Vmin)*(AGCwords/255.) + AGC_Vmin
  HV(i,0:nh-1) = AGCvolts

  here = where(MNFs eq iAGC_MNF(i),nh)
  AGCwords = REFORM( Data(iAGC_word(i),here))
  AGCbits = (AGCwords and 2^iAGC_Lbit)/2^iAGC_Lbit
  Loop(i,0:nh-1) = AGCbits

  AGCbits = (AGCwords and 2^iAGC_Gbit)/2^iAGC_Gbit
  Gain(i,0:nh-1) = AGCbits
endfor

result={ nMNFs :nMNFs, $ ; Number of Minor Frames
        MNFs :MNFs, $ ; Minor frame numbers
        TCnt1_6 :TCnt1_6,$ ; Total Cts, Mods 1-6
        TCnt7 :TCnt7, $ ; Total Cts, Mod 7
        SChT :SChT, $ ; 16-Channels, Mods 1-4
        SCh5 :SCh5, $ ; 16-Channels, Mod 5
        SCh6 :SCh6, $ ; 16-Channels, Mod 6
        SCh7 :SCh7, $ ; 16-Channels, Mod 7
        FCh :FCh, $ ; 40-Channels
        MskS :MskS, $ ; 16-Channel MASKS for Mods 1-4
        Msk7 :Msk7, $ ; 16-Channel MASKS for Mod 7
        AGC :{ $ ; Auto Gain Control parms:
            HV:HV, $ ; Monitor HV/Module
            Loop:loop, $ ; Loop setting/Module
            Gain:Gain},$ ; Gain/Module
        Data :Data }

return, result
END

keyword_set(Point_mode):BEGIN ; A-1 Point Telemetry Mode

Fch = Data(iFch,*) ; 40-channel counts collected
; every 640 ms
if (MNFs(0) and 1) eq 1 then begin ; If first MNF is Odd then
  Fch = TRANSPOSE(Fch) ; fill first 20 channels
  Fch = [intarr(1,20),Fch] ; with 0's
  Fch = TRANSPOSE(Fch)
endif
if (MNFs(nMNFs-1) and 1) eq 0 then begin ; If last MNF is Even then
  Fch = TRANSPOSE(Fch) ; fill last 20 channels
  Fch = [Fch,intarr(1,20)] ; with 0's
  Fch = TRANSPOSE(Fch)
endif
Fch = REFORM( Fch, 40,n_elements(Fch)/40,/OVERWRITE)

PtMd = Data(iPtMd,*) ; 5ms, Mods 1-4

result= { nMNFs :nMNFs, $ ; Number of Minor Frames
        MNFs :MNFs, $ ; Minor frame numbers
        PtMd :PtMd, $ ; 5ms, Mods 1-4

```

```

        FCh   :FCh, $      ; 40-Channels
        Data  :Data }
    return, result
    END
    ELSE: message,/INF,'No Telemetry Mode specified.'
    ENDCASE

```

```
end
```

```

;+
; NAME:
;   ACNVRT
;
; PURPOSE:
;   This function converts the HEAO A-1 quasi-logarithmic numbers
;   to HEAO A-1 Science Data and vice versa.
;
;   HEAO A-1 quasi-logarithmic number format:
;   (8 BITS) - CCCMMMMM (C=CHARACTERISTIC, M=MANTISSA)
;
;   These quasi-logarithmic numbers are the result of the onboard
;   HEAO A-1 quasi-logarithmic scalars and are present in the raw
;   2.1 kbps A-1 portion of the NRZ data.
;
; CATEGORY:
;   HEAO.
;
; CALLING SEQUENCE:
;
;   Result = ACNVRT( Data )
;
; INPUTS:
;   Data:  Array of any dimensions containing either the HEAO A-1
;          quasi-logarithmic numbers OR the HEAO A-1 Science
;          Data.
;
; OPTIONAL INPUT KEYWORD PARAMETERS:
;
;   INVERSE: Set this keyword to convert A-1 Science Data to
;            HEAO A-1 quasi-logarithmic numbers, (0=Default).
;
; OUTPUTS:
;   This function returns A-1 Science Data converted from the input
;   Data array or A-1 quasi-logarithmic numbers, if the INVERSE keyword
;   is set.
;
; MODIFICATION HISTORY:
;   Written by:  Daryl J. Yentis, Naval Research laboratory, SSD 1980.
;   13-JUN-1994  H.C. Wen - Adapted to IDL; added INVERSE keyword.
;-
function ACNVRT, Data, INVERSE=Inverse

```

```
    IEXP2=[1,2,4,8,16,32]
```

```
    ND = N_ELEMENTS(Data)
```

```

if keyword_set(INVERSE) then begin
    ID = FIX(Data)
    h64 = where(Data gt 64, n64)
    if (n64 gt 0) then begin
        D64 = FIX(Data(h64))
        char = REPLICATE(2,n64)
        h127 = where(D64 gt 127, n127)
        while (n127 gt 0) do begin
            D64(h127) = ISHFT(D64(h127),-1)
            char(h127)= char(h127)+1
            h127 = where(D64 gt 127, n127)
        endwhile
        mant = ISHFT(D64-64,-1)
        ID(h64)= ISHFT(char,5) + mant
    endif
    return, ID

endif

ID = FIX(Data)      ; convert to 16-bit words

; FINISHED IF D=0 OR C=0 OR 1
here = WHERE( ID ge '100'O, nconvert )

if (nconvert gt 0) then begin

; CHARACTERISTIC (3-BITS)
; IC=ISHIFT(ID,-5).AND.7K
ICs=ID(here)/'40'O

; MANTISSA (5-BITS)
IMs=ID(here) and '37'O

; D = (2*(M+32)+1)*(2**(C-2))
; DATA(I)=ISHIFT(2*IM+65,IC-2)
ID(here)=(2*IMs+65)*IEXP2(ICs-2)

endif

return, ID

end

```

HEAO A-1 High Bit Rate Data Archive

B.1 Summary of the HBR Data

A summary of all the useable HEAO A-1 HBR data is shown in Table B.2. Each row represents a different scanned or pointed observation. A total of 23 separate observations from November 1977 to January 1979 are listed. Most of these observations were pointed and a total of 13 different X-ray targets were observed. Details of the instrument configuration are provided in columns 11-12, specifying which Modules collected the data in which telemetry and data format modes. The list of observations in Table B.2 is restricted to those collected in the Bit mode, since the data formats of the other two modes, Word and Frame are not understood. The raw HBR data file locations at NRL and at SLAC are specified by the information listed in the first four columns. All of the data processing steps described in Chapter 3 have been applied to each observation listed.

Any observations that are subsequently referenced will follow the following naming convention: the NRL sequence number, tape copy and file number, as described in columns 3-5 of Table B.2. For example, there are two pointed observations of Cygnus X-1. The first observation, analyzed by Meekins' et. al., is listed on row 12 of Table B.2 and will be referenced as 086_7_7. The second observation listed on row 8 will be referenced as 015_2_3.

Column	Heading	Description		
1	SLAC Vol Ser	Volume serial number of the SLAC silo cartridge.		
2	SLAC Seq	The sequence number on the SLAC silo cartridge		
3	NRL Seq	The sequence number on the NRL magnetic tapes containing the original analog HBR data.		
4	COPY Tape	One of the NRL magnetic tapes containing a copy of the digitized HBR data.		
5	File	The file number on that NRL magnetic tape.		
6	Rev	HEAO satellite revolution number.		
7	Pass	Ground station pass, abbreviation.		
8	Time			
9	Day	Day of the year.		
10	Date			
11	Configuration	HBR h PM mh MOD n FCON mf	HBR mode Modules selected for HBR data NRZ mode Modules selected for 40-channel analyzer	h = (B)it, (F)rame or (W)ord mh = (SCA) - mods 1-4, = (SEV) - module 7 n = (P0) - 5 ms, = (SC) - 320 ms mf = List of modules, 1-4
12	Sat Mode	HEAO satellite mode, (P) = point, (S) = scanning.		
13	Min	Length of the processed HBR data in minutes.		
14	Target	Description of the celestial object; the character(s) in parentheses (e.g. (U)) follows the van Paradijs' Catalogue of X-ray Binaries letter code, e.g. U - ultra-soft X-ray spectrum).		

Table B.1 Description of the column headings in Table B.2.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	SLAC Vol Ser	SLAC Seq	NRL Seq	COPY Tape	File	Rev	Pass	Time	Day	Date	Configuration	Sat Mode	Min	Target
1	RY2071	23	20	2	8	6250	H	4:32:00	262	19-Sep-78	HBRB, PMSCA, MODP0	P	8.3	4U1728-34, 1728-337, LMXB, NS, (BA)
2	RY2071	10	10	1	9	5507	G	12:58:00	214	2-Aug-78	HBRB, PMSEV, MODP0	P	9.0	Cas A, 2321+585, SNR
3	RY2071	9	36	4	2	5470	H	3:33:39	212	31-Jul-78	HBRB, PMSEV, MODP0	P	5.6	Cen X-3, 1119-603, HMXB, NS, (P)
4	RY2071	16	12	1	11	5776	Q	19:22:00	231	19-Aug-78	HBRB, PMSEV, MODP0	P	2.7	Cir X-1, 1516-569, LMXB, NS, (TB)
5	RY2070	16	25	3	3	5775	I	17:40:12	231	19-Aug-78	HBRB, PMSEV, MODP0	P	7.3	Cir X-1, 1516-569, LMXB, NS, (TB)
6	RY2072	5	79	7	3	8000	G	17:48:00	8	8-Jan-79	HBRB, PMSCA, (MODP0)	P	8.5	Cir X-1, 1516-569, LMXB, NS, (TB)
7	RY2069	12	2	1	2	531	H	14:49:00	258	15-Sep-77	HBRB, PMSCA, FCON1 2 3 4, (MODSC)	S	6.7	Crab, 0531+219, NS, (P)
8	RY2071	29	15	2	3	7056	I	17:26:00	313	9-Nov-78	HBRB, PMSCA, MODP0	P	8.5	Cyg X-1, 1956+350, HMXB, BHC, (U)
9	RY2069	28	38	14	4	1331	H	9:54:50	310	6-Nov-77	HBRB, PMSCA, FCON3 4, (MODSC)	S	5.7	Cyg X-1, 1956+350, HMXB, BHC, (U)
10	RY2069	29	38	14	5	1331	H	9:54:50	310	6-Nov-77	HBRB, PMSCA, FCON3 4, (MODSC)	S	5.7	Cyg X-1, 1956+350, HMXB, BHC, (U)
11	RY2070	3	42	12	6	1349	G	12:14:50	311	7-Nov-77	HBRB, PMSCA, FCON3 4, (MODSC)	S	5.5	Cyg X-1, 1956+350, HMXB, BHC, (U)
12	RY2070	26	86	7	7	4147	I	2:47:40	127	7-May-78	HBRB, PMSCA, MODSC	P	8.5	Cyg X-1, 1956+350, HMXB, BHC, (U)
13	RY2071	1	8	1	7	4542	H	12:29:00	152	1-Jun-78	HBRB, PMSEV, MODP0	P	7.4	Cyg X-3, 2030+407, HMXB, BHC
14	RY2071	17	24	3	2	5834	I	12:18:10	235	23-Aug-78	HBRB, PMSCA, MODSC	P	8.1	Gamma Cas, 0053+604, HMXB
15	RY2071	13	1	1	1	5713	H	18:26:45	227	15-Aug-78	HBRB, PMSEV, MODP0	P	8.2	Her X-1, 1656+354, LMXB, NS, (P)
16	RY2071	12	11	1	10	5688	G	3:43:50	226	14-Aug-78	HBRB, PMSEV, MODP0	P	7.7	Her X-1, 1656+354, LMXB, NS, (P)
17	RY2070	21	26	3	4	3102	H	18:00:50	59	28-Feb-78	HBRB, PMSEV, MODP0	P	8.2	Her X-1, 1656+354, LMXB, NS, (P)
18	RY2071	15	91	7	9	5759	I	17:00:47	230	18-Aug-78	HBRB, PMSEV, MODP0	P	8.1	Her X-1, 1656+354, LMXB, NS, (P)
19	RY2071	24	18	2	6	6338	I	19:49:00	267	24-Sep-78	HBRB, PMSEV, (MODP0)	P	8.7	MX 1730-63
20	RY2071	18	23	3	1	5308	G	18:17:00	201	20-Jul-78	HBRB, PMSEV, MODP0	P	7.9	New Nova, 0115+634, HMXB, BHC, (TP)
21	RY2071	5	77	7	1	5106	H	18:43:00	188	7-Jul-78	HBRB, PMSCA, MODP0	S	10.6	Nova, Mag. Clouds
22	RY2071	20	13	2	1	6018	H	7:19:00	247	4-Sep-78	HBRB, PMSEV, MODP0	P	7.8	OAO 1653-40
23	RY2071	25	19	2	7	6367	I	16:17:00	269	26-Sep-78	HBRB, PMSCA, MODP0	P	7.3	OAO 1653-40

Table B.2 Summary of all usable HBR data files. Columns 1-2 identifies the file location in the SLAC silos. Columns 2-4 identifies the file location among the digitized NRL tapes. Columns 6-10 provides date and time information. Columns 11-14 describes the telemetry mode, length of data and target name. For a more detailed description of each column heading, see Table B.1.

Fig. B.1 Waiting time distribution for an uncorrected HBR data file showing an anomalous number of pairs of events with a waiting time of 1.

B.2 Data Screening

The process of data screening involves identifying artifacts in the data and correcting for them. One such artifact as described below was found in the HBR data and subsequently corrected for. The HBR data is checked for additional artifacts by comparing the HBR and NRZ data over periods when they simultaneously observed a target.

B.2.1 Correcting for Adjacent Pairs

An examination of the waiting time distributions of the HBR data showed an anomalous excess of occurrences at the 8 microsecond waiting time, as Figure B.1 demonstrates. These waiting times correspond to events that are recorded in two sequential 8 microsecond time bins and will be called *adjacent pairs*. Before these adjacent pairs can be identified as anomalous, binning effects must be first considered. If the data are binned at an 8 microsecond resolution, the location of an event in such a bin is unknown. In units of 8 microsecond bins, a binned waiting time of n corresponds to an uncertainty in the actual waiting time of $[n-1, n+1]$. Given a dead time of 19 μs , as described in Section 3.4.1, the smallest binned waiting time possible is 2. However, the

adjacent pairs have a binned waiting time of 1. For each observation, these adjacent pairs represent about 0.6% of the total number of observed events.

The adjacent pairs have been found to occur at same position in the data format of the raw digitized data. As described in Appendix A.1, the data format of the raw 8 microsecond data consists of 4096 16-bit words for each 320 ms record. Ten of the bits from each word represent 10 sequential 8 microsecond time bins, with a bit set if a photon is detected in that time bin. The adjacent pairs occur only across adjacent words, the last time bit of one word and the first time bit of the next word.

To determine which events in an adjacent pair should be removed, waiting time distributions were made for two possibilities. When one event is removed, the resulting distribution of waiting times between the remaining event and its nearest neighbor is exponential. When both events are removed, the distribution of waiting times between the adjacent pair's nearest neighbors follows a gamma distribution

$$f(t; \lambda, k) = \frac{t^{k-1} \lambda^k e^{-\lambda t}}{(k-1)!} \quad [\text{B.1}]$$

at $k=2$. Here, t is the waiting time and λ is $k\rho$. Equation [B.1] is the distribution for a Poisson process of waiting times from a particular event to the following k^{th} event. Namely, distributions for both possibilities are consistent with identifying only one event from the adjacent pair as artificial.

The HBR data were corrected by removing one event from each adjacent pair present. For a given adjacent pair, the event removed was chosen pseudo-randomly by selecting the event with the closest neighboring event outside the adjacent pair. The KILLAPE routine performed this data correction and was called within the CTIFMT routine.

Fig B.2 The average of the absolute valued differences between the corrected HBR and NRZ time series as a function of various offsets. The minimum occurs at an offset of 5.82 ms. (Data file: 015_2_3)

B.2.2 Data Integrity Check

After applying corrections to the adjacent pairs, the HBR data were then compared to the NRZ data of the same period. The first part in this check was finding the correct offset between the start of the HBR and NRZ data. The NRZ data lagged the HBR data by approximately the length of the NRZ telemetry resolution (5 or 320 ms). This length of time is required to collect one time bin of NRZ data and then additional time is needed to process it. An offset was added to the event times of the HBR data and the resulting offset times were histogrammed at the same time resolution as the NRZ data. The two time series were compared by averaging the absolute value of their difference. The offset was varied until a minimum was found. For the Cygnus X-1 data set, 015_2_3 the NRZ time resolution was 5 ms, and as Figure B.2 shows, this minimum occurs at a 5.82 ms offset.

The difference between the NRZ and corrected HBR time series with the latter adjusted for a 5.82 ms offset is shown in Figure B.3 for a sample of time bins. Discrepancies of ± 1 count/bin are observed for $\sim 0.3\%$ of the entire data set. The

Fig. B.3 The difference between the 5 ms resolution time series of the corrected HBR and NRZ data for the data set, 015_2_3. The adjacent pairs have been corrected and a 5.82 ms offset has been added. The dashed vertical lines mark the locations in time of the adjacent pairs. There are 27 bins with ± 1 count discrepancies and 18 bins with an Adjacent Pair out of a total of 10,162 counts.

locations of adjacent pairs are show in Figure B.3 to be uncorrelated with the remaining discrepancies.

A measure of the significance of the remaining discrepancies is the average and rms average of the residuals,

$$R = \frac{HBR - NRZ}{\sigma_{HBR-NRZ}} = \frac{HBR - NRZ}{\sqrt{HBR + NRZ}} \quad [B.2]$$

where HBR and NRZ are the number of counts/bin in HBR and NRZ time series, respectively. For the 015_2_3 data set, $\langle R \rangle = -2 \times 10^{-4}$ and $\langle R \rangle_{rms} = 0.04$, indicating a uniform distribution of ± 1 count/bin discrepancies at a level much smaller than the uncertainties due to Poisson statistics.

Dead-Time-Distorted Waiting Time Distributions

C.1 Probability Distribution of Binned Waiting Times

Let T be the time resolution or width of the time bins in a given apparatus. The dead time of the apparatus is non-extended and greater than T for this derivation. All events originate from a Poisson process with a true count rate ρ . Assume an event is detected in the 0^{th} time bin. The probability of the next event occurring n time bins away is

$$P(n) = \int f_1(s)P_2(s)ds \quad [\text{C.1}]$$

where s is the period from the start of the 0^{th} bin, $f_1(s)$ is the density of the first event occurring at s and $P_2(s)$ is the probability of detecting the second event in the n^{th} bin if the first event occurs at s . The location of the first event in the 0^{th} time bin is random, so the density function is simply

$$f_1(s) = \frac{1}{T} \quad [\text{C.2}]$$

and the probability for the second event is given by the integral of waiting time density in the presence of a non-extended dead time τ ,

$$P_2(s) = \int U(s' - \tau) \rho e^{-\rho(s' - \tau)} ds' \quad [C.3]$$

where s' is the waiting time between the two events and U is the unit-step function.

The limits in equations [C.1] and [C.3] depend on how close the n^{th} bin is to the dead time τ . Defining κ as the largest integer $\leq \tau/T$, there are four cases to consider.

$$\text{case 1) } n \in [0, \kappa - 1], \quad s' \in [0, 0], \quad s \in [0, 0]$$

$$\text{case 2) } n = \kappa \quad s' \in [\tau, (n+1)T - s], \quad s \in [0, (n+1)T - \tau]$$

$$\begin{aligned} \text{case 3) } n = \kappa + 1 \quad s' \in [nT - s, (n+1)T - s], \quad s \in [0, nT - \tau] \\ s' \in [\tau, (n+1)T - s], \quad s \in [nT - \tau, T] \end{aligned}$$

$$\text{case 4) } n > \kappa + 1 \quad s' \in [nT - s, (n+1)T - s], \quad s \in [0, T]$$

Inserting these limits into equations [C.1] and [C.3] yields the following solution

$$P(n) = \begin{cases} 0, & 0 \leq n \leq \kappa - 1, \\ 1 - \varepsilon - (1 - e^{-\mu(1-\varepsilon)})/\mu, & n = \kappa, \\ \varepsilon + (1 + e^{-\mu(1-\varepsilon)}(e^{-\mu} - 2))/\mu, & n = \kappa + 1, \\ \left(\frac{\sinh(\mu/2)}{\mu/2} \right)^2 \mu e^{-\rho(nT - \tau)}, & n > \kappa + 1 \end{cases} \quad [C.4]$$

where $\mu = \rho T$ and $\varepsilon = \tau/T - \kappa$. Equation [C.4] is the probability distribution of binned waiting times for a Poisson process in the presence of a non-extended dead time τ and a time resolution T .

C.2 Waiting Time Density of the USA Perimeter Veto Problem

The preflight USA perimeter veto logic failed to properly reset itself for non-coincidence charged particle events. The first photon event following any perimeter veto event that had not self-cleared is vetoed. This resulted in an effective variable dead time in addition to the normal detector dead time.

Before proceeding, several definitions are in order to facilitate the derivation of the waiting time density for a Poisson source in the presence of this electronics malfunction. Let ρ_γ and ρ_v represent the count rates of the Poisson source and the perimeter veto events that were not self-cleared, respectively. The normal detector dead time will be neglected in this derivation to simplify the calculation. Let $P_0(x, T)$ represent the probability that no events of type x (γ or v) occur in an interval of time T and $f_x(T)$ represents the probability density of events of type x arriving a waiting time T later.

The waiting time density for this problem is the sum of the waiting time densities for all possible ways that veto and photon events could have arrived between the waiting time between two detected photon events. The first possibility is that no veto events had arrived. The waiting time density for this configuration is

$$f_{00} = P_0(v, T) f_\gamma(T) \quad [C.5]$$

where T is the waiting time between the two detected photon events. The second possibility is that one veto event had arrived during the interval T . Since a second photon was detected at the end of the interval T , that means one other photon event must have arrived between the veto event and the second photon. The waiting time density for this configuration is

$$f_{11} = \int P_0(\gamma, x_1) f_v(x_1) P_0(v, T - x_2) f_\gamma(x_2) f_\gamma(T - (x_1 + x_2)) \quad [C.6]$$

Repeating this logic for additional veto events arriving between two observed photons events, the general waiting time density for v veto events and x photon events arriving between two observed photon events can be derived to be

$$f_{vx}(T) = \binom{v-1}{x-1} \frac{(\rho_v T)^v (\rho_\gamma T)^x}{(v+x)!} \rho_\gamma e^{-(\rho_v + \rho_\gamma)T} \quad [C.7]$$

The actual waiting time density for this perimeter veto model (PVM) is the sum off all the waiting time densities defined by [C.7] over all possible combinations of veto and photon events that can occur between two observed photon events.

$$f_{pvm}(T) = \sum_{v=1}^{\infty} \sum_{x=1}^v f_{vx}(T) \quad [C.8]$$

Testing of the USA Collimators

D.1 Introduction

As part of the development of the USA instrument, SLAC has assumed responsibility for the design, construction and testing of the USA collimator. The collimator is a honeycomb of narrow tubes that restricts the solid angle of detected X-rays to directions within the collimator's field of view. To facilitate construction and testing, a modular design was adopted, dividing the collimator into eight identical modules for each detector. Each module was manufactured from layers of rolled, half-hexagonal copper sheets that were epoxied and cured together to form honeycomb tubes. Figure D.1 shows an image of one of the constructed USA collimators.

The testing of the USA collimators consisted of measuring the acceptance of each module to X-rays incident at given relative angles. Rotations about a vertical Y-axis (*yaw* or ϕ) and a horizontal X-axis (*pitch* or θ) described these relative angles. All angles are relative to the axis normal to the module's face (i.e. the Z-axis). The module's acceptance as a function of pitch and yaw will be called the *response function*. For each module, an elliptical cone was fitted to the measured response function to determine its full width half-maximum (FWHM) and the location of its peak in pitch and yaw. These parameters

Fig. D.1 One of three USA collimators constructed at SLAC. Eight modules can be seen in the collimator frame stacked in two groups of four. An additional module separate from the collimator is also shown. Each module is framed by thin aluminum (copper anodized) bridge sheets to help support the honeycomb structure.

were used to help select/match the modules that would form the three final collimators (2 flight, 1 spare) by simulating the response function expected for a given configuration of eight modules.

A small experiment nicknamed X-Ray Cannon (XRC) was performed at SLAC to individually measure each collimator module response function. Each module was set into a miniaturized USA detector with a goniometer supporting the entire assembly. Counts from an X-ray beam were then measured at different pitch and yaw. The following Appendix will describe the setup, calibration, data acquisition and analysis of the XRC experiment.

D.2 XRC Setup

The setup of the X-Ray Cannon experiment consisted of two major components: a source and a detector assembly. The source assembly consisted of building an apparatus that would deliver an X-ray beam. To detect those X-rays a simple detector was assembled along with the supporting apparatus, electronics and data acquisition.

D.2.1 Source Assembly

The X-ray beam delivered to the detector satisfied several criteria. A thin $4" \times 4"$ sheet of ^{55}Fe with an activity of 25 mC was chosen for the X-ray source. Its energy (6 keV K_{α}) lies within USA's energy sensitivity, 2 - 15 keV. Its surface area covered a significant portion of the $3" \times 11"$ collimator module face. A long pipe then collimated this source into a beam of X-rays. The length was chosen to give a beam divergence (0.07° FWHM) that was smaller than the resolution which was chosen to measure the response function, 0.1° .

Other methods for delivering an X-ray beam with a higher intensity were also considered. However, the development of extensive radiation safety infrastructure required for sources with significant activity (~ 0.1 -1 C) dictated a practical limit to the source strength. The source chosen was the hottest source available that required minimal radiation safety precautions.

With the given source area and beam divergence, a 200' long pipe or "cannon" was assembled with an effective 1.5" inner radius. A straight section of the PEP Machine tunnel, adjacent to IR12 was chosen to contain this pipe. The cannon was constructed from 20' segments of 2" inner radius PVC pipe and supported every 10' by two $5/8"$ diameter steel rods clamped to cable tray support beams above and threaded into a pipe hanger below. As Figure D.2 shows, one rod was vertical and the other at 45° to provide rigid support in both vertical and horizontal directions. To eliminate any small angle scattering of X-rays off the PVC surface, aluminum baffle discs with a 1.5" inner radius were positioned at the end of each PVC pipe segment.

Fig. D.2 Layout of the XRC experiment.

A roughing pump evacuated the pipe volume to 200 μHg of pressure to help minimize the attenuation of the X-rays over the length of the pipe. To contain this vacuum, a 5 mil mylar window sealed the detector end while an end cap with the source positioned inside sealed the other. The mylar window was supported between two aluminum discs epoxied together along with a thin bar across the diameter.

D.2.2 Detector Assembly

The detector assembly was designed about the geometry defined by the X-ray beam and the collimator modules. For the X-ray detector, a small single-wire proportional wire chamber (PWC) was constructed to allow a collimator module to be mounted on it. A goniometer was designed and machined to enable relative orientations between the collimator and beam axes. In addition, a 4-sided scintillator was built to help veto cosmic ray events.

To mount a collimator module onto the PWC, the 3" x 11" x 4 $\frac{1}{2}$ " module was first set into an aluminum frame and then bolted against the PWC with a $\frac{1}{2}$ mil mylar window in between. An evaporated aluminum film covered the PWC side of the mylar window, insuring a uniform ground over the entire inner surface of the PWC. A single 30 μm gold-plated wire stretched across the longest dimension of the proportional wire chamber's 3" x 11" x 2 $\frac{1}{2}$ " active volume. Two gas couplings allowed P-10 gas (10% CH_4 , 90% Ar) to flow continuously through the chamber's active volume at $\sim 1 \text{ cm}^3 \text{ s}^{-1}$.

Supporting the PWC and collimator unit was a goniometer that was designed with two perpendicular axes of rotation. As shown in Figure C.2, a double layered "T"-shaped geometry provided the two independent degrees of freedom. Two small aluminum blocks fastened to the bottom "T" layer provided gimbals support to the top "T" layer, enabling rotations in the vertical plane. A pivot at the "T" intersection of the bottom layer allowed rotations in the horizontal plane. Rotations of the goniometer in the horizontal and vertical planes will be referred to by the variables ϕ and θ , respectively. In relation to the USA instrument, a rotation in the ϕ and θ directions correspond to yaw and pitch, respectively.

Fig. D.3 Geometry of the XRC goniometer.

A triangular aluminum baseplate supported the two "T"-layers and an iron table in turn supported the baseplate's three legs. An adjustable length pipe connector formed each leg, allowing the leveling of the baseplate. To insure stability and position reproducibility, each leg was bolted to the iron table and the iron table was loaded at its base with over 500 lb. of lead bricks.

Two stepper motors controlled rotations in ϕ and θ by turning bolts through threaded fixtures on the moment arms of the top and bottom "T" layers. We chose the distance from the pivots to satisfy the simple conversion, $1 \text{ turn} = 50 \text{ steps} = 0.2^\circ$.

To veto cosmic ray background, a 4-sided scintillator "box" was assembled to surround all exposed sides of the detector except for the collimator face. The scintillator from each side was cut and polished before epoxied together. Two phototubes were glued to the scintillator with translucent RTV, one along the y-axis and the other along the x-axis as the axes are defined in Figure D.3. The scintillator was wrapped with aluminum foil to reflect scintillated light and then wrapped again with black mat board and black photographic tape seal against light leaks.

Managing all this detector apparatus was the electronics, the final component of the detector assembly. The electronics processed the signals from the detector components into actual X-ray counts and sent signals to the stepper motors to control the goniometer's movements. The PWC and the phototubes were the sources of input signals.

A pre-amplifier preprocessed charge collected on the PWC into a viable signal for the discriminator. The pre-amplifier was fabricated from a circuit consisting of two emitter-followers in series as shown in Figure D.4. The rise time of the output signal was 300 nsec.

The amplified analog signals from the PWC and the phototubes were then digitized by discriminators with a 10 ns rise time and a -30 mV threshold. A logic unit summed the discriminated phototube pulses and then a gate generator increased the width of the summed pulse to 250 μs to allow for any accidental double-counting in the PWC.

Fig. D.4 Circuit diagram of the pre-amplifier used in the XRC electronics. All units are in Ω or μF unless indicated otherwise.

Another gate generator narrowed the discriminated PWC pulse to $10\ \mu\text{s}$ and time-delayed it to lie at the center of a scintillator pulse generated from the same event. This inhibited over-vetoing of cosmic rays due to any multiple misfiring in the chamber.

Finally, a logic unit used the gate generated pulses from the scintillator to veto any corresponding pulses from the PWC. Output from this logic unit translated into counts in a scalar reset and read through the parallel port of a PC. The electronics for counting X-ray events as described here is summarized in Figure D.5.

To control the stepper motors, a simple driver circuit was assembled using LM18293 chips. The PC communicated commands to the circuit through its parallel port. A step commanded by the PC translated into 4 rotations of the motor windings or 0.004° of the goniometer arms. A simple FORTRAN program enabled complete automation of the goniometer movements and data collection.

Fig. D.5 Flow chart for the XRC electronics.

D.3 XRC Calibration

Several source and detector assembly components of the XRC experiment were calibrated. The XRC cannon was aligned to minimize occultation losses of the X-ray beam. To define the collimator pointing axes relative to the beam direction, the goniometer arms were calibrated. Finally, the two phototubes and the PWC were plateaued.

D.3.1 Alignment of the XRC Cannon

Before the XRC cannon was placed into its support apparatus, the positions of the vertical support rods were determined by using a string suspended across the length of the pipe as a horizontal reference. To mark the position of each pipe hanger along the vertical rods, the string was pulled taut and the ends positioned to the same desired height.

Final vertical and horizontal alignments were made after the cannon was positioned in the pipe hangers. The vertical reference originated from a suspended bucket of water with a plastic tube attached at the bottom. The height of the water at the other end of the tube was used as a vertical reference. For the horizontal reference another string was tied taut to the pipe hangers at the ends of the cannon. An L-shaped ruler with a leveler was

used to measure the distance between the pipe and the string. Any minor misalignments were then corrected by adjusting the nuts that held the two rods to an angle bracket.

The accuracy of the final alignment was limited by the poorest reference, the string that defined the horizontal reference. Repeated measurements at each support point along the cannon indicated that the resulting horizontal alignment was good to $\pm 1/8''$.

D.3.2 Calibration of the Goniometer

The goniometer apparatus, shown in Figure D.3 rested on top of an iron table that was weighed down by +500 lb. of lead bricks. The table was needed in order to bring the detector apparatus to the same height as the X-ray beam. Using two levelers, the baseplate of the goniometer apparatus was first leveled through its adjustable legs. When the adjustments were completed, the legs were then bolted to the iron table.

The zero angle positions of the horizontal and vertical arms were calibrated to the peak transmission of one of the collimator modules. To mark these positions, metal tips were glued to the end of the horizontal arm and to the vertical stepper motor's turning shaft. Each pointed to a fixed reference mark that defined the goniometer's rotation origin.

D.3.3 Plateauing of the Detector

The voltage setting on a detector unit is determined by increasing its voltage until its efficiency for detecting counts 'plateaus'. This is usually exhibited as a function of voltage by a rapid rise in the number of counts detected followed by a sharp 'knee' and then a plateau. A continued increase of the voltage along this plateau will eventually lead to a breakdown of the detector resulting in a runaway in the number of counts detected.

Three detector units were plateaued: two phototubes and one proportional wire chamber (PWC). The cosmic rays were used as the source to plateau the phototubes. Coinciding the scintillator signals with the PWC, the resulting veto counts were accumulated as a function of the phototube voltage as shown in Figure D.6. The operating voltages were set to 2300V and 2200V for phototube 1 and 2, respectively. As defined in Figure D.3, phototubes 1 and 2 were oriented along the x-axis and y-axis respectively.

Fig. D.6 Plateau curves for phototubes 1 and 2 and PWC. The operating voltages were set to 2300V, 2200V and 2300V, for phototubes 1 and 2 and PWC, respectively.

The X-ray beam from the XRC cannon was used as the source to plateau the PWC. The cosmic rays were first vetoed by coinciding the outputs of the PWC and the scintillator. In addition, to eliminate the effects from the residual isotope activity of the chamber (described later in Section D.4.1), the signal counts with no X-ray source was subtracted from the signal counts with the X-ray source. The difference represented the "actual" detected source rate. From the resulting plateau curve for the PWC shown in Figure D.6, the operating voltage was set to 2300 V.

D.4 XRC Experiment

The collimator response measurements began on September 9, 1993, and continued for 3 months. In that period of time, all 28 collimator modules were measured, (8 flight units and 20 spares). In addition, module 18 was re-measured several times to test the reproducibility of the detector apparatus.

D.4.1 Backgrounds

The veto system of the detector apparatus was successful in identifying coincidence events with rate of $\sim 3 \text{ cts s}^{-1}$. These events are due to cosmic rays. At sea level, the total flux from cosmic rays crossing a unit horizontal area from above is estimated at $0.02 \text{ cm}^{-2} \text{ s}^{-1}$. The PWC was on its side facing the X-ray beam, exposing a surface area of 177 cm^2 . Therefore, the expected rate of cosmic rays was 3.5 cts s^{-1} .

After the veto counts were removed, a residual PWC count rate of $\sim 4 \text{ cts s}^{-1}$ remained. The output pulses of the pre-amplifier and the phototubes were observed on a scope to verify that these residual counts were not caused by double-pulsing in the chamber nor due to incorrect time delays between the PWC and the scintillator signals. To insure that this residual rate was not due to unvetoes cosmic four sides of the detector were covered by scintillator material with two phototubes attached. Evidence indicates that the source of these residual counts originates from within the PWC, probably from radioactive impurities in the chamber's aluminum walls.

D.4.2 X-Ray Beam Intensity

In designing the source assembly, the expected rate of X-rays detected by the PWC was estimated to insure that the resulting beam would be useful. The scattering and adsorption through the various materials and physical obstructions (e.g. the cannon's solid angle) were considered and are summarized in Table D.1. For a ^{55}Fe source with 25 mC activity the expected count rate in the PWC is 4.5 cts s^{-1} .

To measure this rate, the goniometer was set to the peak of a collimator response ($0^\circ, 0^\circ$) and counts were collected in both the presence and the absence of the X-ray beam. The latter measurement was needed to subtract the residual background discussed in the previous section. The difference of these two measurements yielded an observed count rate of $4.29 \pm 0.02 \text{ cts s}^{-1}$.

The small discrepancy between the observed and expected count rate may be attributed to a smaller transmission through the collimator face than dictated by an idealized geometry. While the amount of area covered by the collimator material over its face accounts for only 2% of the total area, the effective area is slightly larger due to small imperfections and misalignments between different hexagonal cells.

To measure this effect, counts were collected again at ($0^\circ, 0^\circ$) in both the presence and the absence of the X-ray beam with the collimator module removed from the detector apparatus. The difference of these two measurements yielded an observed count rate of $4.6 \pm 0.1 \text{ cts s}^{-1}$. The ratio between the rates with and without the collimator in the apparatus gives $93 \pm 2\%$ as the transmission through the collimator, compared to 98% due to the collimator's surface area alone. Taking into account this measured transmission through the collimator, the expected count rate is 4.27 cts s^{-1} which agrees with the observed rate within 1σ .

	Transmission
Transmission through the pipe (Air, 200 μ Hg)	0.98
Transmission through the pipe window (5 mil mylar)	0.75
Transmission through gap between pipe window and PWC (Air, 1 atm)	0.70
Transmission through PWC window (1/2 mil aluminized mylar)	0.97
Absorption efficiency of PWC gas (P10 gas, 90% Ar, 10% CH ₄)	0.97
Fraction of Source Area (3.75" $\times$ 3.75") within pipe cross section	0.97
Fraction of solid angle unobstructed by pipe ($\pm$ 1/8" misalignment)	0.50
Fraction of collimator face area unobstructed by collimator material	7.85×10^{-8}
Total Transmission	4.85×10^{-9}

	Count Rate [cts s ⁻¹]
Source: 55Fe, Activity: 25.0 mC, Date: 9-1-93 Spectrum: K α fraction = 0.26, Energy = 5.9 keV	9.25×10^8
Expected Rate observed by PWC	4.48
Measured Rate observed by PWC	4.29 ± 0.02

Table D.1 Summary of the transmissions through the various materials and obstructions and the expected and measured count rates in the PWC.

D.4.3 Measurement Run

The procedure for measuring the response function for a collimator module began with placing the unit in an aluminum frame and bolting the frame to the PWC with a $\frac{1}{2}$ mil mylar window in between to contain the gas. The detector was then positioned on the goniometer base. Since the X-ray beam covered only $\sim \frac{1}{3}$ of the collimator face, three positions were defined along the goniometer base such that the beam was incident at the center or near either end of a collimator face. Holes were drilled at these positions and an aluminum peg filled one of them to define the reference edge for the collimator module.

Name	ϕ Range [degrees]	θ Range [degrees]	Step Size [degrees]	No. of points	Total time [hrs]
Origin	0°	0°	0.0°	1	0.1
Horizontal Scan	[-2.4°, 2.4°]	0°	0.1°	49	6.2
Origin	0°	0°	0.0°	1	6.4
Vertical Scan	0°	[-2.4°, 2.4°]	0.1°	49	12.5
Origin	0°	0°	0.0°	1	12.6
Coarse Grid	[-0.6°, 0.6°]	[-0.6°, 0.6°]	0.2°	49	18.7
Background	2.4°	2.4°	0.0°	1	18.9
Fine Grid	[-0.2°, 0.2°]	[-0.2°, 0.2°]	0.1°	25	22.0
Background	2.4°	2.4°	0.0°	1	22.1
Origin	0°	0°	0.0°	1	22.2

Table D.2 List of measurements made for each run.

For each collimator, this position was chosen randomly.

Once the detector was fully assembled on the goniometer, the PWC was flushed with P10 gas for ~ 20 minutes to remove air in the chamber. In addition, once the measurements began, a pressure regulator insured that a steady stream of P10 gas flowed through the chamber ($\sim 1 \text{ cm}^3 \text{ s}^{-1}$) to flush out any air that may have leaked in.

The measurements of X-rays at different angles relative to the beam axis was fully automated. Commands were read sequentially from a file and sent to the stepper motor through a serial port on a PC. As listed on Table D.2, the measurement run consisted of a horizontal scan in ϕ , a vertical scan in θ , a coarse $1.2^\circ \times 1.2^\circ$ grid and a fine $0.4^\circ \times 0.4^\circ$ grid. Counts were collected at each angular position for 7.5 minutes. Each measurement run lasted 22 hours.

Fig. D.7 Definition of ϕ and θ in the xyz-coordinate system. The X-ray beam lies along the $-z$ -axis. At $\phi = \theta = 0^\circ$ the collimator module rests on the xz -plane with its collimator face is parallel to the xy -plane. The shaded region indicates the rear collimator face.

D.5 XRC Data Analysis

D.5.1 Coordinate Systems

In this experiment, three rotational coordinate systems are identified: one from the goniometer and two from the collimator module. The first is defined by the goniometer arms. When the arms are rotated to its origin, the direction the arms are pointing defines the goniometer g -axis. This axis will lie along the z -direction of the *goniometer* coordinate system.

For a perfect collimator module, all the hexagonal tubes are aligned and are parallel to the bridge sheets that support them. The direction that the tubes are pointing towards (i.e. peak of the response function) defines what will be referred to as the z -axis. This is the *inertial* coordinate system of a perfect collimator module. In terms of an actual module, this coordinate system is defined by the collimator bridge sheets.

The third coordinate system is that of the actual collimator module. Here, small misalignments of the hexagonal tubes may cause the effective pointing direction to be offset from the z -axis. The effective direction that the actual collimator module is pointing towards is identified as the c -axis. This axis defines the z -direction of the *body* coordinate system.

The angles referred to in the text as ϕ and θ are illustrated in Figure D.7. For a given coordinate system, a unit vector $\mathbf{r}$ is defined in terms of these two angles as

$$\mathbf{r} = \cos \theta \sin \phi \mathbf{x} + \sin \theta \mathbf{y} + \cos \theta \cos \phi \mathbf{z} \quad [\text{D.1}]$$

where $\mathbf{x}$, $\mathbf{y}$, $\mathbf{z}$ are defined relative to one of the three coordinate systems discussed.

D.5.2 Method for Determining Collimator Response Characteristics

The data from each measurement run was analyzed to determine the center and width (FWHM) of the response function for that collimator module. An elliptical cone was chosen as the functional form to interpolate the 2 variables that determine the collimator module characteristics relevant to USA performance, acceptance in ϕ and θ . Its expression is given by

$$f_s(\phi, \theta, t) = -m\sqrt{(\phi - \phi_0)^2 + a^2 (\theta - \theta_0)^2} + b \quad [\text{D.2}]$$

where ϕ_0 , θ_0 , m , a and b are fit parameters. (ϕ_0, θ_0) defines the center, b/m defines the FWHM along ϕ (horizontal axis) and $b/(ma)$ defines the FWHM along θ (vertical axis). [D.2] is constrained to points within the ellipse

$$(\phi - \phi_0)^2 + a^2 (\theta - \theta_0)^2 = (b/m)^2 \quad [\text{D.3}]$$

where $f_s(\phi, \theta, t) > 0$. For all points outside this ellipse, $f_s \equiv 0$.

In addition to the signal from the X-ray beam, a residual background contributed to the overall observed count rate. As discussed in Section D.5.1, this background was probably due to impurities in the proportional chamber aluminum walls. To account for this systematic offset the background was modeled by a polynomial in time,

$$f_B(t) = \sum_{j=0}^N c_j t^j \quad [\text{D.4}]$$

Run	Response Function Centers		Response Function FWHM	
	ϕ (g-axis) [$\pm 0.005^\circ$]	θ (g-axis) [$\pm 0.004^\circ$]	ϕ [$\pm 0.02^\circ$]	θ [$\pm 0.02^\circ$]
1	0.057°	0.135°	1.21°	1.19°
2	0.045°	0.124°	1.20°	1.20°
3	0.048°	0.128°	1.27°	1.20°
4	0.049°	0.123°	1.23°	1.19°
5	0.048°	0.125°	1.22°	1.20°
Average	0.049°	0.125°	1.23°	1.196°
$\sqrt{\text{Variance}}$	0.005°	0.005°	0.03°	0.005°

Table D.3 Summary of the fit results to five separate measurement runs with Collimator 18. The response function centers are angles relative to the goniometer axis (g-axis). The overall variance for each parameter is consistent with its statistical uncertainty for each run.

The sum of [D.2] and [D.4] was applied to the fit of the entire data set in a measurement run. The MINUIT89 program¹ was employed to minimize the χ^2 of the parameters in the fit using the SIMPLEX algorithm. The degree of the polynomial in [D.4] was varied from 0 to 4 and the fit with the smallest χ^2 per degree of freedom, ν was selected.

D.5.3 Accuracy of the Detector Apparatus

To make a meaningful comparison of the centers from different modules, the detector apparatus must be able to consistently reproduce the same response function for repeated measurements of a given module. Several measurement runs were performed on collimator module 18. The data from each run was fit for its response function center and width using the method described in the previous section. The results of these fits, summarized in Table D.3, show that the overall variance of the centers and widths are

¹ Application Software Group (1992), *Minuit, Function Minimization and Error Analysis*, CERN Program Library Entry D506, CERN Geneva, Switzerland.

consistent with the statistical uncertainty in determining each parameter. Namely, the detector apparatus produces reproducible measurements within the resolution of counting statistics. The accuracy of the detector apparatus is estimated conservatively to be 0.005° .

D.5.4 Determination of the Goniometer Axis

All of the response functions were measured at angles relative to the g-axis of the goniometer coordinate system. However, the g-axis itself may be rotated from the true collimator z-axis. This true z-axis defines the collimator's *inertial* coordinate system, described in Section D.5.1.

The center of a response function is the location of its peak. This response function *center* is quantified by parameters ϕ_0 and θ_0 of the elliptical cone in [D.2]. The goniometer g-axis can be expressed in the inertial coordinate system in terms of these fitted parameters. The response function centers can then be transformed into the inertial coordinate system to determine the absolute misalignment of a collimator module.

Assume the goniometer g-axis is rotated from the inertial coordinate system by 3 small Euler angles, ϵ_1 , ϵ_2 and ϵ_3 . The rotation matrix to second order in these angles is

$$\begin{pmatrix} 1 - \frac{1}{2}(\epsilon_1 + \epsilon_3)^2 & \epsilon_1 + \epsilon_3 & \epsilon_2 \epsilon_3 \\ -(\epsilon_1 + \epsilon_3) & 1 - \frac{1}{2}(\epsilon_1 + \epsilon_3)^2 - \frac{1}{2}\epsilon_2^2 & \epsilon_2 \\ \epsilon_1 \epsilon_2 & -\epsilon_2 & 1 - \frac{1}{2}\epsilon_2^2 \end{pmatrix} \quad [\text{D.5}]$$

which gives the coordinates of the g-axis in terms of the z-axis coordinate system as

$$\mathbf{g} = \mathbf{x}_g + \mathbf{y}_g + \mathbf{z}_g \quad [\text{D.6}]$$

$$\mathbf{x}_g = \begin{pmatrix} 1 - \frac{1}{2}(\epsilon_1 + \epsilon_3)^2 \\ -(\epsilon_1 + \epsilon_3) \\ \epsilon_1 \epsilon_2 \end{pmatrix}, \quad \mathbf{y}_g = \begin{pmatrix} \epsilon_1 + \epsilon_3 \\ 1 - \frac{1}{2}(\epsilon_1 + \epsilon_3)^2 - \frac{1}{2}\epsilon_2^2 \\ -\epsilon_2 \end{pmatrix}, \quad \mathbf{z}_g = \begin{pmatrix} \epsilon_2 \epsilon_3 \\ \epsilon_2 \\ 1 - \frac{1}{2}\epsilon_2^2 \end{pmatrix}$$

For the collimator c-axis, let (ϕ, θ) denote its direction with respect to the inertial coordinate system and (ϕ_g, θ_g) its direction with respect to the goniometer coordinate

	Value [$\pm 0.005^\circ$]
ϵ_1	-0.117°
ϵ_2	-0.104°
ϵ_3	-0.183°

Table D.4 Euler angles needed to rotate goniometer axis to the direction observed from the inertial z-axis.

system. The c-axis may be expressed in terms of the these two coordinate systems as

$$\begin{aligned} \mathbf{c} &= \cos \theta \sin \phi \mathbf{x} + \sin \theta \mathbf{y} + \cos \theta \cos \phi \mathbf{z} \\ &= \cos \theta_g \sin \phi_g \mathbf{x}_g + \sin \theta_g \mathbf{y}_g + \cos \theta_g \cos \phi_g \mathbf{z}_g \end{aligned} \quad [\text{D.7}]$$

Replacing the goniometer unit vectors $\mathbf{x}_g$, $\mathbf{y}_g$, $\mathbf{z}_g$ by their representation in the inertial coordinate system [D.6], and then equating the components for each of the unit vectors $\mathbf{x}$, $\mathbf{y}$, $\mathbf{z}$ gives (ϕ, θ) in terms of (ϕ_g, θ_g) and the Euler angles $\epsilon_1, \epsilon_2, \epsilon_3$ to second order as

$$\begin{aligned} \phi &\approx \phi_g + \theta_g (\epsilon_1 + \epsilon_3) + \epsilon_2 \epsilon_3 \\ \theta &\approx \theta_g - \phi_g (\epsilon_1 + \epsilon_3) + \epsilon_2 \\ \theta^2 + \phi^2 &\approx \phi_g^2 + (\theta_g + \epsilon_2)^2 \end{aligned} \quad [\text{D.8}]$$

The three equations in [D.8] can solve three of the 5 unknowns $(\phi, \theta, \epsilon_1, \epsilon_2, \epsilon_3)$ for a given collimator c-axis. To solve for the remaining parameters, perform a π -rotation of the collimator module about the x-axis of the inertial coordinate system.

$$\mathbf{c}' = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} \cos \theta \sin \phi \\ \sin \theta \\ \cos \theta \cos \phi \end{pmatrix} = \begin{pmatrix} \cos \theta \sin \phi \\ -\sin \theta \\ -\cos \theta \cos \phi \end{pmatrix} \quad [\text{D.9}]$$

Namely, $\phi \rightarrow -\phi$ and $\theta \rightarrow \theta + \pi$. Another measurement of the collimator c-axis in the goniometer coordinate system gives (ϕ'_g, θ'_g) . This procedure amounts to replacing $\phi_g \rightarrow \phi'_g, \theta_g \rightarrow \theta'_g, \theta \rightarrow -\theta$ in the first two equations of [D.8] which gives the two additional equations needed to solve all of the 5 unknowns for a given collimator c-axis.

To actually perform this measurement, the collimator module is flipped 180° about its long x-axis, the collimator response function is re-measured and then the center is determined using the fitting algorithm described in Section D.5.2. Table D.4 shows the values for the Euler angles obtained using this procedure. Using these values in [D.8] and setting $\phi_g = \theta_g = 0$ gives for the goniometer axis,

$$(\phi, \theta)_{g\text{-axis}} = (0.019^\circ, -0.104^\circ) [\pm 0.005^\circ] \quad [\text{D.10}]$$

D.5.5 Monte Carlo Simulation

Simulations of the response functions for each module are used to estimate the total response function expected by combining two or more of the modules. The simulation is performed in two stages. In the first stage, photons are generated at uniform random positions along a square region and emitted at uniform random solid angles. The photon is projected down the length of the XRC cannon and if it lies within the pipe's effective radius, then the photon is permitted to enter the collimator face.

The second stage projects each photon through the collimator. The collimator axis is first rotated to the direction of the response function center for the collimator module being simulated. If a photon crosses one or more hexagonal cell boundaries as it traverses the depth of the collimator, then that event is discarded. The simulation is repeated using the same angles as in the experiment measurement run to generate simulated data.

D.6 XRC Results

D.6.1 Characterization of the Collimator Modules

For each of the 28 collimator modules constructed, the center and FWHM of its response function were determined using the fitting technique described in the previous section. Table D.5 summarizes the results of these fits, where the response function centers listed have been corrected by [D.8] so that they are relative to the inertial

coordinate system. In the inertial coordinate system, the average offset of the response function centers is observed to be

$$(\langle\phi\rangle, \langle\theta\rangle) = (0.036^\circ, -0.015^\circ) [\pm 0.001^\circ] \quad [\text{D.11}]$$

with a $\sqrt{\text{variance}}$ or spread of the centers as

$$(\phi, \theta)_\sigma = (0.03^\circ, 0.06^\circ) \quad [\text{D.12}]$$

The overall widths of the response functions are

$$(\phi, \theta)_{FWHM} = (1.237^\circ, 1.185^\circ) [\pm 0.004^\circ] \quad [\text{D.13}]$$

with a relatively smaller $\sqrt{\text{variance}}$ as

$$(\phi, \theta)_{\sigma(FWHM)} = (0.02^\circ, 0.02^\circ) \quad [\text{D.14}]$$

An additional fit was performed on each module using the results from the simulations of its response function. The elliptical cone used to fit the center and width of each response function was replaced with the simulated data. The background was then fit as a polynomial in time for degrees from 0-4. The fit giving the smallest χ^2/ν was selected and its corresponding confidence level is displayed in the last column of Table D.5.

The results of this additional fit are also shown at the end of this Appendix. There, the data from the ϕ -scan and the θ -scan for each module are displayed along with overplots of the fits using the simulated data. The difference between the data and the fit is displayed below each scan.

D.6.2 Final Selection of Collimator Modules

Twenty-four modules are selected to construct three full collimators (2 flight, 1 spare). The final selection of modules is shown in Table D.6. The selection of modules and their orientations $\phi = (0 \text{ or } \pi)$ in the collimator frame was based on several criteria. Modules with the larger confidence levels ($>1\%$) to the fit to the simulations of the

Module	Center of Response Functions				FWHM		Cone	MC	
	ϕ $\pm [0.005^\circ]$ (g-axis)	θ $\pm [0.004^\circ]$ (g-axis)	ϕ $\pm [0.005^\circ]$ (z-axis)	θ $\pm [0.004^\circ]$ (z-axis)	ϕ $\pm [0.02^\circ]$	θ $\pm [0.02^\circ]$	χ^2/v	χ^2/v	CL (%)
1	0.070	0.016	0.084	-0.067	1.25	1.17	1.40	1.12	15
2	0.019	0.042	0.025	-0.056	1.24	1.20	1.41	1.00	49
3	0.037	0.106	0.024	0.014	1.24	1.16	1.53	1.29	0.6
4	-0.015	0.054	-0.012	-0.054	1.23	1.19	1.55	1.32	0.3
5	0.037	0.175	0.004	0.083	1.24	1.16	1.51	1.19	4
6	0.068	0.131	0.048	0.048	1.21	1.19	1.58	1.31	0.3
7	0.010	0.040	0.017	-0.061	1.26	1.17	1.44	1.40	0.03
8	0.021	0.130	0.001	0.033	1.25	1.20	1.26	1.12	14
9	0.012	0.140	-0.011	0.040	1.25	1.19	1.70	1.42	0.02
10	-0.007	0.038	0.001	-0.068	1.19	1.19	1.37	1.21	3
11	0.038	0.046	0.043	-0.046	1.20	1.20	1.66	1.30	0.4
12	0.031	0.111	0.017	0.017	1.28	1.18	1.46	1.44	0.01
13	0.037	0.088	0.030	-0.004	1.23	1.20	1.66	1.31	0.4
14	0.043	0.191	0.005	0.100	1.28	1.17	1.50	1.30	0.5
15	0.073	0.174	0.040	0.092	1.25	1.19	1.47	1.17	6
16	0.048	0.044	0.054	-0.045	1.21	1.20	1.56	1.22	2
17	0.063	0.089	0.055	0.004	1.22	1.18	1.73	1.37	0.08
18	0.057	0.135	0.036	0.049	1.21	1.19	1.31	1.10	18
19	0.100	0.053	0.103	-0.021	1.23	1.20	1.17	0.94	72
20	0.084	0.065	0.083	-0.013	1.25	1.19	1.30	1.15	8
21	0.040	0.073	0.037	-0.019	1.22	1.14	1.43	1.35	0.1
22	0.017	0.028	0.028	-0.070	1.23	1.19	1.34	1.16	7
23	0.045	0.085	0.038	-0.005	1.27	1.21	1.47	1.30	0.5
24	0.046	-0.042	0.078	-0.132	1.23	1.18	1.25	1.11	16
25	0.024	0.032	0.033	-0.064	1.23	1.19	1.33	1.21	3
26	0.008	0.058	0.010	-0.043	1.27	1.19	1.37	1.27	0.8
27	0.052	0.006	0.069	-0.082	1.23	1.17	1.04	0.99	54
28	0.016	0.034	0.025	-0.065	1.24	1.18	1.54	1.50	0.001
Avg.	0.04	0.08	0.03	-0.02	1.24	1.18			
σ	0.03	0.06	0.03	0.06	0.02	0.02			

Table D.5 Characterization of all the collimator modules by fitting an elliptical cone to the data (columns 2-8). The centers of the response functions are given relative to the goniometer coordinate system (columns 2-3) and the inertial coordinate system (columns 4-5). Monte Carlo simulation of each module with a background polynomial in time was also fit to data. The resulting χ^2/v and confidence levels are given in the last two columns. The last two rows represent the average and the $\sqrt{\text{variance}}$ of the fitted quantities in columns 1-4.

Collimator	Segment	Module	Relative Rotation	Status
C-1	1	5	0°	Flight Collimator
		20	180°	
		8	0°	
		14	180°	
	2	1	180°	
		7	180°	
17		180°		
26		180°		
C-2	1	3	180°	Destroyed in thermal-vac test by burst window
		4	0°	
		12	0°	
		18	0°	
	2	6	180°	
		19	0°	
10		0°		
22		0°		
C-3	1	2	0°	Flight Collimator
		13	0°	
		23	0°	
		27	180°	
	2	11	180°	
		16	180°	
		21	180°	
		25	180°	

Table D.6 Collimator modules selected for the three assembled full collimators. The fourth column represents the orientation of each selected collimator module about its short z-axis.

response functions were favored. Combinations of modules were selected based on constructing a full collimator response function with different degrees of flat top. This flat top arises from small misalignments between the collimator modules' axes. The width of the flat top for a full collimator is proportional to the $\sqrt{\text{variance}}$ of module response function centers.

The number of combinations for arranging the modules was increased by allowing a π -rotation about the module's short z-axis. For such rotations the collimator c-axis flips $\phi \rightarrow -\phi$ and rotates $\theta \rightarrow \theta + \pi$. Namely, θ effectively remains unchanged.

The response functions for the three full collimators constructed were simulated by combining the simulated response functions of each of its modules listed in Table D.6. The contour plots of the simulated response functions for the three full collimators are

Collimator	Response Fcn. Maximum	Flat Top	
		$\Delta\phi$	$\Delta\theta$
C-1	0.88	0.08°	0.14°
C-2	0.90	0.08°	0.10°
C-3	0.93	0.02°	0.04°

Table D.7 Results of fitting the simulations of the response functions of collimators C-1, C-2 and C-3 for a flat top or plateau at the response function apex.

shown in Figure D.8. Their shapes follow the hexagonal geometry of the collimator tubes. As the response function gets closer to its apex, this hexagonal shape smears into an ellipse.

These simulations also show that collimators C-1 and C-2 have larger flat tops than collimator C-3. The width of these flat tops in ϕ and θ , may be measured by fitting the simulated data of a ϕ -scan and a θ -scan. First, the simulated data along a scan is fit for a triangle. The difference between area under this triangle and the simulated data with a flat top is another triangle with area A . The width of the flat top is then simply given by

$$\Delta_{\text{Flat Top}} = 2\sqrt{A \tan \theta_t} \quad [\text{D.15}]$$

where $\tan \theta_t$ is defined by the fitted triangle, namely, base/2 divide by the height. Table D.7 shows the resulting widths and heights of the flat tops of collimators C-1, C-2 and C-3. Collimator C-3 shows a flat top 3-4 times narrower than the other two collimators.

Collimators C-2 and C-3 were originally selected as the flight units for USA. While collimators C-1 and C-2 have very similar response functions, collimator C-3 was chosen over C-1 because its smaller flat top gave it the better angular resolution. Collimator C-2 was later replaced by C-1, after C-2 was damaged after a window break, as discussed in the next Section. Figures D.10 - D.25 show the measured scans of each module in collimators C-1 and C-3 with their fitted response functions overplotted.

Simulation of C-1 (installed in USA)

Simulation of C-2 (destroyed in thermal test)

Simulation of C-3 (installed in USA)

Fig. D.8 Simulated collimator response functions for collimators C-1, C-2 and C-3 from data taken in XRC test.

D.7 USA Collimator Failure

In May of 1996, at the end of the last thermal-vac cycle of that series of tests, the window behind collimator C-2 burst, causing a catastrophic collimator failure. The window failure occurred between modules 10 and 22 and resulted in an large eye-shaped opening 2 1/4" wide at its center. As shown in Figure D.9, the bridge sheets between the two modules were left bowed into the copper tubes, collapsing a significant portion of the honeycomb structure.

The consensus after extensive discussion and analysis is that this collimator damage originated from a breach in the window that contained the proportional chamber gas volume. At the union of two collimator modules are two bridge sheets affixed together by a narrow bead of epoxy. The epoxy was intended to prevent relative movements between the modules, not to withstand substantial loads. The loads that were expected were along the collimator face due to the gas pressure.

This union formed a slit and the two bridge sheets that defined its aperture had semi-sharp edges. The gas is believed to have pushed the window into these slits, where the sharp edges eventually breached the integrity of the window. As the gas then leaked into the space between the modules, the pressure between the two bridge sheets rose rapidly until the epoxy failed and a runaway of pressure from the remaining gas volume collapsed the surrounding honeycomb. An engineering calculation was able to reproduce the general character of this model quantitatively.

To prevent this type of failure from reoccurring, all of the slits between adjacent collimator modules were subsequently taped over for remaining USA collimators C-1 and C-3. The tape helps prevent the window from being cut by the semi-sharp edges of the bridge sheets and from letting the window push into the slits. The thermal-vac tests were then repeated on the USA instrument containing collimators C-1 and C-3 and no additional collimator failures occurred.

Fig. D.9 Damage from burst PWC window behind USA collimator C-2 resulting in a large eye-shaped opening. The top image shows the hole relative to the USA instrument, and the bottom image shows a close-up of collimator C-2.

Fig. D.10 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-1

Segment: 1

Module: 5

Simulated response
function using parameters

(ϕ) , (θ)

FWHM: 1.24° , 1.16°

Centers: 0.037° , 0.175°

from fit to data are shown
in solid curve. Difference
between data and simula-
tion shown in lower curves.

Fig. D.11 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-1

Segment: 1

Module: 20

Simulated response
function using parameters

(ϕ) , (θ)

FWHM: 1.25° , 1.19°

Centers: 0.084° , 0.065°

from fit to data are shown
in solid curve. Difference
between data and simula-
tion shown in lower curves.

Fig. D.12 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-1

Segment: 1

Module: 8

Simulated response
function using parameters

$(\phi), (\theta)$
FWHM: $1.25^\circ, 1.20^\circ$
Centers: $0.021^\circ, 0.130^\circ$

from fit to data are shown
in solid curve. Difference
between data and simulation
shown in lower curves.

Fig. D.13 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-1

Segment: 1

Module: 14

Simulated response
function using parameters

(ϕ) , (θ)

FWHM: 1.28° , 1.17°

Centers: 0.043° , 0.191°

from fit to data are shown
in solid curve. Difference
between data and simula-
tion shown in lower curves.

Fig. D.14 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-1

Segment: 2

Module: 1

Simulated response
function using parameters

(ϕ) , (θ)
FWHM: 1.25° , 1.17°
Centers: 0.070° , 0.016°

from fit to data are shown
in solid curve. Difference
between data and simula-
tion shown in lower curves.

Fig. D.15 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-1
Segment: 2
Module: 7

Simulated response
function using parameters

$(\phi), (\theta)$
FWHM: $1.26^\circ, 1.17^\circ$
Centers: $0.010^\circ, 0.040^\circ$

from fit to data are shown
in solid curve. Difference
between data and simula-
tion shown in lower curves.

Fig. D.16 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-1

Segment: 2

Module: 17

Simulated response
function using parameters

(ϕ) , (θ)
FWHM: 1.22° , 1.18°
Centers: 0.063° , 0.089°

from fit to data are shown
in solid curve. Difference
between data and simula-
tion shown in lower curves.

Fig. D.17 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-1

Segment: 2

Module: 26

Simulated response
function using parameters

(ϕ) , (θ)

FWHM: 1.27° , 1.19°

Centers: 0.008° , 0.058°

from fit to data are shown
in solid curve. Difference
between data and simulation
shown in lower curves.

Fig. D.18 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-3
Segment: 1
Module: 2

Simulated response
function using parameters

$(\phi), (\theta)$
FWHM: $1.24^\circ, 1.20^\circ$
Centers: $0.019^\circ, 0.042^\circ$

from fit to data are shown
in solid curve. Difference
between data and simula-
tion shown in lower curves.

Fig. D.19 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-3
Segment: 1
Module: 13

Simulated response
function using parameters

(ϕ) , (θ)
FWHM: 1.23° , 1.20°
Centers: 0.037° , 0.088°

from fit to data are shown
in solid curve. Difference
between data and simulation
shown in lower curves.

Fig. D.20 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-3
Segment: 1
Module: 23

Simulated response
function using parameters

(ϕ) , (θ)
FWHM: 1.27° , 1.21°
Centers: 0.045° , 0.085°

from fit to data are shown
in solid curve. Difference
between data and simulation
shown in lower curves.

Fig. D.21 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-3
Segment: 1
Module: 27

Simulated response
function using parameters

(ϕ) , (θ)
FWHM: 1.23° , 1.17°
Centers: 0.052° , 0.006°

from fit to data are shown
in solid curve. Difference
between data and simulation
shown in lower curves.

Fig. D.22 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-3
Segment: 2
Module: 11

Simulated response
function using parameters

(ϕ) , (θ)
FWHM: 1.20° , 1.20°
Centers: 0.038° , 0.046°

from fit to data are shown
in solid curve. Difference
between data and simulation
shown in lower curves.

Fig. D.23 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-3

Segment: 2

Module: 16

Simulated response
function using parameters

(ϕ) , (θ)

FWHM: 1.21° , 1.20°

Centers: 0.048° , 0.044°

from fit to data are shown
in solid curve. Difference
between data and simulation
shown in lower curves.

Fig. D.24 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-3
Segment: 2
Module: 21

Simulated response
function using parameters

(ϕ) , (θ)
FWHM: 1.22° , 1.14°
Centers: 0.040° , 0.073°

from fit to data are shown
in solid curve. Difference
between data and simula-
tion shown in lower curves.

Fig. D.25 :

Scans in a) ϕ (yaw) and
in b) θ (pitch) for unit:

Collimator: C-3

Segment: 2

Module: 25

Simulated response
function using parameters

(ϕ) , (θ)

FWHM: 1.23° , 1.19°

Centers: 0.024° , 0.032°

from fit to data are shown
in solid curve. Difference
between data and simulation
shown in lower curves.

Charged Particle Backgrounds in the USA Detector

E.1 Introduction

The time available for X-ray observations in Earth-orbit is limited by regions of high charged particle flux, where the background counting rates are too high for X-ray detectors to operate. An estimate is made of this available time or *uptime* for the USA detector. Phenomenological models are first utilized to estimate the flux of charged particles at USA's altitude for a given longitude and latitude. The charged particles are made incident on the USA detector by Monte Carlo simulation and then propagated through the various materials to determine the observed counting rate. The USA orbit is then simulated to estimate the fraction of orbital time with counting rates below a detector cutoff.

E.2 Monte Carlo Simulation

The active X-ray detecting volume of the USA detector is defined by its proportional chamber. There are two detector units with identical proportional chambers. All simulations and counting rate estimates will refer to one detector unit. The rate of charged particles penetrating into the proportional chamber is given by

$$\frac{dN}{dt} = \sum_{n=e^-,p} \int dE \int d\Omega \oint_S da \left(\frac{d^2\Phi}{d\Omega dE} \right)_n t_{n,S}(\mathbf{r}, E) \quad [\text{E.1}]$$

where the surface integral is performed over all faces of the detector unit, $(d^2\Phi/d\Omega dE)_n$ is the differential flux [particles/(cm²·ster·sec)/MeV] and $t_{n,S}(\mathbf{r}, E)$ is the probability (0 or 1) that a charged particle incident on surface S at position and direction $\mathbf{r}$ and kinetic energy E will be recorded in the USA proportional chamber

The charged particle fluxes were determined from phenomenological models that provided omnidirectional estimates

$$\frac{d\Phi}{dE} = 4\pi \frac{d^2\Phi}{d\Omega dE} \quad [\text{E.2}]$$

which factor out of the solid angle and surface integrals in [E.1]. The closed surface integral in [E.1] can be rewritten as the sum of surface integrals over all the faces of the detector unit S_i

$$\oint_S da = \sum_{S_i} \int_{S_i} da = \sum_{S_i} A_i \int_{S_i} \frac{da}{A_i} \quad [\text{E.3}]$$

Finally, defining the total transmission probability for particles of type n incident on face S_i with kinetic energy E as

$$T_{n,S_i}(E) \equiv \int \frac{d\Omega}{4\pi} \int_{S_i} \frac{da}{A_i} t_{n,S_i}(\mathbf{r}, E) \quad [\text{E.4}]$$

and substituting it with [E.2] and [E.3] into [E.1] gives the final expression for the charged particle rate observed in the proportional chamber of a USA detector unit,

$$\frac{dN}{dt} = \sum_{n=e^-,p} \sum_{S_i} A_i \int dE \left(\frac{d\Phi}{dE} \right)_n T_{n,S_i}(E) \quad [\text{E.5}]$$

The total transmission probabilities were evaluated by approximating the integrals in expression [E.4] by sums

Fig. E.1 Typical differential flux distribution of electrons trapped in the van Allen radiation belts. Model: AE8 (NSSDC) at an altitude of 834 km.

$$T_{n,S_i}(E) \approx \sum \frac{\Delta\Omega}{4\pi} \sum \frac{\Delta a}{A_i} t_{n,S_i}(\mathbf{r}, E) \quad [\text{E.6}]$$

and evaluating the sums by method of Monte Carlo simulation. Charged particles at kinetic energy E were generated at random incident positions and solid angles onto one of the detector unit faces S_i . The trajectory of each particle was then propagated through the detector materials. If the trajectory penetrated the proportional chamber volume and the energy lost traversing the materials was less than the particle's initial kinetic energy then that particle was recorded as an event. The total transmission probability is the fraction of incident particles that are recorded as events in the proportional chamber.

E.2.1 Sources of Charged Particle Background

The charged particle background originates primarily from the solar wind and the galaxy. The Earth's magnetosphere interacts with the solar wind by trapping solar particles (electrons and protons) in doughnut-shaped van Allen radiation belts. At a given altitude, these torroidal belts intersect a sphere by forming two rings or bands at high and low latitudes with high charged particle flux. Another region of high charged particle flux is known as the South Atlantic Anomaly (SAA), an elliptical region centered

above Brazil, spanning roughly 130° in longitude and 50° in latitude (see Figure E.4). In the SAA, the magnetic flux is anomalously low, allowing particles from the inner belt to brush the top of the atmosphere.

Phenomenological models¹ of the flux of trapped particles have been developed by the U.S. National Space Science Data Center (NSSDC) at NASA's Goddard Space Flight Center. They are based on almost all available satellite data. The models, AP8 for protons² and AE8 for electrons³ provide omnidirectional estimates of differential flux down to 1 particle $\text{cm}^{-2} \text{sec}^{-1}$ at an energy spectrum ranging from 0.1 to 400 MeV for the protons and from 0.04 to 7 MeV for the electrons. A typical differential flux distribution is shown in Figure E.1 for electrons in the radiation belts. The electron flux dominates over the proton flux by several orders of magnitude.

Galactic cosmic rays are focused at the Earth's poles where the density of magnetic field lines is the highest. Developed at the Naval Research Laboratory (NRL), the Cosmic Ray Effects of Microelectronics (CREME) model⁴ was used to estimate the differential flux from cosmic rays. Consisting primarily of protons, the CREME model estimates the differential flux at an energy spectrum ranging from 10 MeV to 30 GeV for various interplanetary and magnetic weather conditions. Figure E.2 shows a typical differential flux distribution for cosmic rays near the poles.

E.2.2 Detector Physics

Once the flux of charged particles incident on the USA detector is estimated, the task of translating that flux into an actual detector count rate is left to the detector physics simulation. Charged particles that penetrate into the detector's chamber volume must traverse either the collimator or the proportional chamber walls. The trajectory of the incident particle must project into the chamber volume with more incident energy than is

¹ Bilitza, D. (1988), "Radbelt, Trapped Radiation Models", NSSDC ID:PT-14A.

² Sawyer, D. W. & Vette, J. I. (1976), "AP-8 Trapped Proton Environment for Solar Maximum and Minimum", NSDDC/WDC-A-R&S 76-06.

³ Teague, M. J., Chan, K. W., & Vette, J. I. (1976), "AE-8: A Model Environment of Trapped Electrons for Solar Maximum", NSSDC/WDC-A-R&S 76-04.

⁴ Adams, J.H. (1986), "Cosmic Ray Effects on Microelectronics, Part IV", NRL Report 5901.

Fig. E.2 Typical differential flux distribution of galactic cosmic rays. Model: CREME (NRL) at an altitude of 834 km.

lost while traversing these materials.

Most of the energy lost is due to ionization. The dE/dx curves for this process were determined using the Berger-Seltzer formula⁵ for the electrons and the restricted energy loss formula⁶, a modification of the Bethe-Bloch equation, for the protons. Although both of these formulae allow for the explicit generation of delta rays, the energy loss for both particle species was treated as continuous.

Special treatment was given to the calculation of energy loss through the collimator. A uniform effective density was chosen to represent the collimator honeycomb material. This density was the ratio of the total collimator mass divided by the total collimator volume. However, particles incident on the top face with angles less than 0.75° from the normal were passed through the collimator without interacting with the material.

⁵ Berger, M. J. & Selzer, S. M. (1964), NASA SP 3012.

⁶ Particle Data Group (1992), Review of Particle Properties, p. III.14.

Fig. E.3 Transmission probabilities through the various faces of the collimator and the proportional chamber walls. The top and bottom rows are transmissions through the collimator and proportional chamber, respectively. The left and right columns specifies the particle species, electrons and protons, respectively.

Applying the simulation as previously described in conjunction with the dE/dx curves, the total transmission probabilities, [E.6] were determined through each of the 3 different faces of the collimator and the proportional chamber. Figure E.3 summarizes these transmission probabilities covering energy ranges with significant differential flux of electrons or protons.

E.3 Results

E.3.1 Charged Particle Background Counting Rates

Combining the transmission probabilities with the differential flux of electrons and protons, the charged particle background counting rates, [E.5] were estimated for all longitudes and latitudes in 1° increments at the altitude of the USA detector, 834 km. Figures E.4, E.5 and E.6 shows the contour maps of counting rates due to charged

Region	Average Expected Background Counting Rate [counts sec ⁻¹]
Equatorial	$\sim 1.5 \times 10^3$
Polar	$\sim 6 \times 10^3$
Radiation Belts	$\sim 2 \times 10^5$
South Atlantic Anomaly	$\sim 2 \times 10^6$

Table E.1 Average expected counting rate in a USA detector unit from all estimated particle backgrounds. The equatorial region lies between the two radiation belt bands and outside the SAA.

particles trapped by the Earth's magnetosphere, galactic cosmic rays and all charged particles, respectively. As Figure E.4 shows, rates in the two radiation belt bands and the South Atlantic Anomaly dominate the trapped charged particle background. For the galactic cosmic rays, Figure 3.5 shows a smooth distribution of counting rates rising to maxima at the polar regions. The averages for various regions of Figure E.6 are summarized in Table E.1.

E.3.2 X-ray Observation Uptime

A USA detector unit shuts down when the counting rate in its proportional counter exceeds 10^4 counts sec⁻¹. The fraction of USA's orbit spent with background rates below this cutoff is defined as the *uptime*. To calculate this uptime, the orbit of the ARGOS satellite was simulated with an expected orbital inclination of 98.7° and a period of 102 minutes. The Earth's rotation was also included in the simulation. The uptime was averaged over 1800 orbits or 127 days using contour maps of the total charged particle counting rates as the one shown in Figure E.6. Table E.2 summarizes the uptimes calculated from this simulation.

Solar Epoch	Magnetic Weather Condition	Interplanetary Weather Index	% Uptime
Maximum	Stormy	1	61.8
		2	60.9
		3	46.2
		4	46.2
Minimum	Stormy	1	61.1
		2	60.7
		3	45.8
		4	45.8

Table E.2 The percentage of uptime below a 10^4 counts sec^{-1} cutoff for several scenarios in the trapped charged particle and cosmic ray models. The interplanetary weather index is defined as follows: 1 - galactic cosmic rays only (quiet period), 2 - worst-case galactic cosmic rays allowing for uncertainty in flux data and solar activity, 3 - peak ordinary flare flux and mean composition and 4 - peak 10% worst-case flare flux and mean composition.

Fig. E.4 Contour map of the expected background rates in one USA detector unit due to charged particles trapped by the Earth's magnetosphere. The numbers in the legend represents the $\log_{10}$ (Counting rates [counts sec⁻¹]). The two bands due to the radiation belts and the South Atlantic Anomaly are the most notable features.

Fig. E.5

Contour map of the expected background rates in one USA detector unit due to galactic cosmic rays. The numbers in the legend represents the $\log_{10}(\text{Counting rates} [\text{countssec}^{-1}])$. The rates are highest at the poles where the density of the Earth's magnetic field lines is the highest.

Fig. E.6

Contour map of the expected background rates in one USA detector unit due to all charged particles. The numbers in the legend represents the $\log_{10}$ (Counting rates [counts sec^{-1}]).

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