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An Optical and Near Infrared Search
for a Pulsar in Supernova 1987A

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By

Timothy Paul Sasseen

Abstract

We describe a search for an optical pulsar in the remnant of Supernova 1987A. We have performed over one hundred separate observations of the supernova, covering wavelengths from 3500 angstroms to 1.8 microns, with sensitivity to pulsations as faint as magnitude 22.7. As of September 26, 1990, we have not seen evidence for pulsations due to a pulsar in the supernova. We discuss the implications of this result on predictions of pulsar optical luminosity.

We have constructed for the search two photodiode detectors and a data system. We describe their design, calibration and performance. These detectors have allowed us to increase our sensitivity as much as a factor of 5 over standard photomultiplier tubes, and extend this search to near infrared wavelengths.

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Chapter I. Motivation for Search

Introduction

The discovery of Supernova 1987A in the Large Magellanic Cloud by Shelton and Duhalde (IAU Circular No. 4316) has provided a wealth of excitement and data for astronomers, astrophysicists, and physicists from a variety of sub-disciplines. This event has been well-chronicled both by primary articles too numerous to list here, and many reviews (see for example, Arnett *et al.* 1989 and references therein).

Supernova 1987A was the nearest supernova event in modern times. Its proximity has allowed not only intensive observation at many wavelengths, but may also invite the most immediate connection between the fields of study of supernovae and pulsars. It is safe to say that at this time, more is known about SN1987A than any other supernova in history. Therefore, the appearance and character of its collapsed remnant may be most directly associated with theories and observation of the supernova. Additionally, the detection of the collapsed remnant of this supernova would be only the second extragalactic neutron star to be discovered (after PSR 0540-69 by Seward *et al.* 1986). These qualities make a search for a neutron star a natural undertaking.

The neutron star may be discovered by more than a single method of observation. In some sense, the neutrino events detected with the Kamiokande II (Hirata *et al.* 1987) and the Irvine-Michigan-Brookhaven (IMB) (Bionta *et al.* 1987) neutrino detectors are the first discovery observations of the collapsed object. These events have been interpreted as arising from the formation and cooling of a neutron star (see *e.g.* Bludman and Schinder 1988). Another way in which the neutron star might be observed is by its contribution to the total energy output of the supernova explosion. By monitoring the total light output of the supernova and comparing this with models for the expected energy input from radioactive elements created in the explosion, one might determine that energy input from a

pulsar is present. A recent analysis by Woosley *et al.* 1989 discusses the possibilities and problems with this technique.

Finally, there is the possibility of directly measuring radiation from a rapidly rotating neutron star. The Crab pulsar was detected in optical photographs by Baade and Minkowski in 1942, 26 years before radio pulses were first observed (Staelin and Reifinstein 1968), or modulation of the optical light was observed (Cocke *et al.* 1969). However, the background light from the expanding shell of SN1987A and the distance to the LMC make direct optical detection difficult in the present case. One way to defeat the large steady state background from supernova is to look for a time varying signal. This is best done at wavelengths where the output from the collapsed object is large, and the opacity of the envelope is small.

We have chosen to use ground-based optical telescopes to search for a modulated optical signal. This strategy offers the advantage that much of the necessary instrumentation is available at optical observatories. However, the convenience of using existing instruments must be balanced against the opacity and background of the supernova envelope, and the expected brightness of the pulsar at these wavelengths. For example, unpublished results from Stan Woosley and Phil Pinto of the University of California at Santa Cruz showed that the optical depth of the supernova envelope at day 400 was a factor of 10^7 lower at 1 micron than at 0.4 microns. This factor led us to build new infrared-sensitive detectors for this search.

To provide an estimate of the sensitivity needed to detect a pulsar in SN1987A, we investigate the expected apparent magnitude of a pulsar in the LMC as a function of the intrinsic brightness of the pulsar. Figure 1.1 shows the apparent visual magnitude which would be measured at the Earth as a function of the absolute magnitude of an object at the distance to the LMC (taken to be 55 kpc), through 0.6 magnitudes of visual extinction (Middleditch *et al.* 1987). The different curves on the graph represent the effects of optical depth in the supernova envelope, shown at values which may apply for the several years

after the explosion. The arrow in the figure indicates what the magnitude of the Crab pulsar would be, if it were at the distance of the LMC (and using the corresponding extinction correction). An observation to a given limiting magnitude would be represented by a horizontal line in this graph, and the combinations of pulsar brightness and supernova envelope opacity lying below this line are then ruled out at the time of the observation. Theoretical estimates of the brightness of a pulsar in SN1987A are discussed in Chapter 4, where the results of this search are presented.

Figure 1.1 The apparent magnitude of an optical pulsar, vs. the intrinsic brightness at the distance of the LMC, including 0.6 magnitudes of intervening extinction. Different curves are shown representing different amounts of extinction within the supernova envelope itself.

The next question may be phrased, "What is the probability that there will be a pulsar bright enough at optical wavelengths to be above our detection threshold within the remnant of SN1987A?" This question may be broken down into a number of conditions, and the answer is the product of the probabilities that each condition holds true. These include the probability that a neutron star was actually formed in the explosion; that the neutron star is emitting energy via some pulsar mechanism; that enough of this energy is emitted at optical or near infrared wavelengths; that the putative pulsar beam points at the Earth; that the envelope is sufficiently optically thin at these wavelengths; and that the emission is turned on often enough that a sporadic search will see it. This situation is reminiscent of the Drake equation, which attempts to predict the probability that there are other technological civilizations in the galaxy; each factor is uncertain by such a degree that the final answer can range from near certainty to fantastically improbable. Some discussion of scientific estimates of these probabilities may be found in Pennypacker *et al.* (1989). However, a clear answer to the question posed is unlikely to emerge in the near future, except by the discovery of the pulsar.

Other Searches for the Pulsar

Searches for pulsations from the supernova have been made since the supernova was discovered. The first set of searches were timing analyses of the neutrino arrival-time data (Harwit, *et al.* 1987, Ogelman and Buccheri 1987, deJager 1987, Bludman and Schinder 1988). These analyses are confounded both by the small number of events (8 from IMB and 11 from Kamiokande), and the fact that the arrival time of the Kamiokande events, while known relatively to better than milliseconds, have an overall timing uncertainty of one minute. Harwit *et al.* (1987) claim evidence for 8.9 ms pulsations, but authors using different statistical tests find only chance significance to this period (Schaefer 1987, and Buccheri and Ogelman 1987). Ogelman and Buccheri (1987) claim evidence

for a period of 202.4 ms at the 99.9% confidence level. To date, there has been no confirmation of this result or any other neutrino periodicity by an independent test.

Since its discovery, Supernova 1987A has been targeted for observations with detectors sensitive over regions of the electromagnetic spectrum from radio to gamma-ray wavelengths. In the vast literature resulting from these observations, there have been no confirmed reports of pulsations from the supernova. Negative reports have been published in response to a particular claim for pulsations, rather than reporting general results from a comprehensive search. We include here a survey of recent observations which could have detected periodic emission from the pulsar.

Radio emission from Supernova 1987A died out a few months after the explosion. Turtle *et al.* 1990 report in I.A.U. Circular 5086 that SN1987A had reappeared at radio wavelengths, with a signal strength of a few millijanskys in bandpasses near 1 GHz. No periodic emission was reported.

There have been several groups making systematic optical observations looking for the pulsar with ground-based telescopes. Aside from our collaboration, R. N. Manchester of CSIRO Division of Radiophysics, Epping NSW and B. A. Peterson of Siding Spring Observatory in Canberra have been searching for the pulsar since the supernova discovery, with the Anglo-Australian 4 meter Telescope and the New Technology Telescope at the European Southern Observatory (ESO) in La Silla, Chile. H. Ogelman of the Max Planck Institute, F.R.G., and R. W. Hanuschik of the Bochum Institute for Astrophysics, F.R.G., have also been searching with telescopes at ESO. Upper limits from the Ogelman search have recently been published (Ogleman *et. al* 1990). Their observations were sensitive to wavelengths between 0.35 and 0.9 μm , and resulted in 95% confidence upper limits of 10 μJy (magnitude 21.5) for pulsations up to 5000 Hz. A Brazilian group, led by F. J. Jablonsky of the National Space Research Institute, Sao Paulo, have searched for the pulsar using the 1.6 meter telescope of the Brazilian National Astrophysical Laboratory. This group sent a communique reporting optical pulsations in October 1990 which was

widely distributed in the astronomical community. However, the group retracted this report a week later, attributing the signal to terrestrial background sources. Null results for signals near 1968 Hz in response to the report by Kristian, *et al.* 1989 were published in 1989 by Ogelman *et al.* and Dieters, *et al.* (IAU Circulars 4743 and 4773). There have been no other published results at the time of this writing; however, these searches continue.

The x-ray continuum from 10 keV to 300 keV from Supernova 1987A was detected at by satellite-borne detectors (Sunyaev, *et al.* 1987 and Dotani, *et al.* 1987) soon after the supernova discovery. The x-ray emission from the supernova has faded since then, and in recent months it has not been detected by the Japanese GINGA, the Soviet GRANAT, or the West German ROSAT satellites (Murdin 1990). The ROSAT observation limits x-ray luminosity to less than 5×10^{34} ergs s⁻¹, considerably lower than the typical x-ray luminosity for Galactic x-ray accretion-powered pulsars of 10^{35-36} ergs s⁻¹, but greater than the Crab pulsar's x-ray luminosity of $\sim 5 \times 10^{33}$ ergs s⁻¹.

Searches for gamma rays from supernova 1987A have yielded either detection at the few σ level (see *e.g.* Bond *et al.* 1988), or upper limits. The possibility of detecting a periodic signal at these energies is hampered by the low sensitivity of the detectors, the low number of photon events and the background from cosmic rays and radioactive decays in the supernova remnant.

The following chapters describe some aspects of our search at optical and near infrared wavelengths which has been carried on in collaboration with researchers from Los Alamos, the Carnegie Institute of Washington, the University of Toronto, Mt. Stromlo – Siding Springs Observatory, Nasa – Ames Research Center, the University of Oregon at Eugene, and Cerro Tololo Interamerican Observatory. In Chapter 2 we describe the instruments used, and their calibration. In Chapter 3 we describe the observations and

some qualities of the data. Chapter 4 contains the results of these observations to date, and a comparison with theoretical predictions of the luminosity of an optical pulsar.

Chapter II. Instrumentation

We have utilized several generations of detectors and instrumentation in this search. Much of it was custom-built, in order to gain in quantum efficiency, signal-to-noise, and greater spectral coverage. The three main types of detectors used were photomultiplier tubes, a Silicon photodiode, and a Germanium photodiode. Photomultiplier tubes and their use in astronomy have been well described in the literature (see *e.g.* Landolt-Bornstein 1981), and hence will not be described here. The two photodiode instruments were built specifically for this experiment, and will be discussed in detail.

A. Photodiodes vs. Phototubes

The two photodiode detectors were built to take advantage of their greater quantum efficiency, their red sensitivity, and their ability to withstand higher count-rates than photomultiplier tubes. They both have the disadvantage, however, of higher instrumental noise rates. Nonetheless, we will demonstrate that photodiodes are superior to photomultiplier tubes for fast sampling of bright astronomical sources.

We consider the signal-to-noise ratio achieved with both types of detectors, for a given target brightness, and observation length. The signal-to-noise ratio for a detector at a particular telescope may be written in terms of the signal S photons $\text{s}^{-1} \text{\AA}^{-1}$, the quantum efficiency of the detector q photoelectrons per photon, an filter attenuation factor r , a bandpass $\Delta\lambda$ $\text{\AA}$, and the noise sources. The noise sources are the sky background, the background light from the supernova itself, and instrumental background. It is useful to express the background sources in terms of the equivalent number of photoelectrons per second light falling on the detector would generate. The noise contribution from a particular background source is then just the square root of the product of its rate and the length of the observation. We indicate by S_{sky} , SN , and IB the square root of the number

of photoelectrons per second from the background sources. The signal-to-noise ratio may then be written:

$$SNR = \frac{S q r \Delta\lambda}{\sqrt{S k y^2 + S N^2 + I B^2}} \quad (2.1)$$

We will compare the ratio of the signal-to-noise which would be achieved by a standard RCA S-20 photomultiplier tube and the Silicon photodiode detector for a hypothetical observation of Supernova 1987A on day 350, approximately when the Silicon photodiode was first used. At this time, the visual magnitude of the supernova was about 6.5. The countrate of the S-20 must be limited to about 15 million counts per second to avoid overheating the anodes; therefore, for the photomultiplier tube, the numerator of (2.1) cannot exceed this value. This is accomplished in practice using filters. For this hypothetical observation with the photomultiplier tube, the appropriate value of r is 0.75, and $SN = \sqrt{1.5 \times 10^7}$ photoelectrons s^{-1} . The dark count rate (IB) of the S-20 is about 500 s^{-1} . The sky background at the position of SN1987A is about $m_v=17$, due to the positional coincidence of a 17th magnitude star and the supernova, rather than the fainter surface brightness of the nebula. Hence, the sky background is negligible compared to the background from the supernova until the supernova has faded to magnitude 17. The ratio of quantum efficiency times the bandpass for the two detectors may be inferred from Figure 2.1 (see below); it is approximately 15. In an observation with the Silicon detector near day 350, we counted about 2.5×10^8 photoelectrons s^{-1} from the supernova. Hence SN for this detector is 1.5×10^4 . The instrumental background of the Silicon detector (IB) is about 5×10^3 electrons per second. Putting these numbers into equation 2.1 shows that the signal-to-noise ratio for the photodiode detector exceeds that for the S-20 by a factor of 5 near day 350.

As the supernova fades, we reach an epoch when the two detectors would give the same signal-to-noise ratio, if the detector spectral responses were equally tuned to a pulsar signal. A simple calculation using equation 2.1 shows that this point is reached when the supernova visual magnitude is about 12. The new Germanium photodiode detector had lower instrumental noise, equivalent to 10^3 photoelectrons per second. At this rate, the crossover point occurs at a visual magnitude of 15.5. However, as described in Chapter I, we expect the pulsar signal to be stronger in the infrared; hence there is advantage to using the Germanium diode even when the supernova is fainter than magnitude 15.5.

The photodiode detectors have higher quantum efficiency and better infrared response than photomultiplier tubes. Both of these advantages are shown in Figure 2.1, in which we plot the radiant sensitivity¹ as a function of wavelength for the the photodiodes and an RCA S-20 photocathode. All three curves are adapted from the specification literature from the manufacturers.

B. The Photodiodes

For photodiode detectors to be useful with the low source intensities expected in this experiment, it is necessary to reduce the instrumental noise sources as much as possible. The primary contributors are leakage current from the diode, Johnson noise from the feedback resistor, and transistor (FET) noise from the preamplifier. Several techniques were used in the construction of the two detectors to minimize these noise sources. In these non-doped semiconductor diodes, the leakage current is the number of electrons thermally excited to the conduction band per second. This is proportional to $\exp(-E_{gap}/2kT)$ ², where E_{gap} is the band gap energy. For Silicon, the reduction of the

¹ Radiant sensitivity is the current generated when the detector is illuminated. The units are amperes per watt of incident light.

² The law of mass action in the case where $E_{gap} > E_{Fermi} \gg kT$ states that the product of the the density of electrons, and density of holes in a semiconductor is proportional to $\exp(-E_{gap}/kT)$. Since pure Silicon is an intrinsic semiconductor, the two densities are equal, and hence the factor of two in the denominator with kT above.

Figure 2.1 The relative responses of the three detectors. The photodiode instruments show both higher quantum efficiency and response to infrared wavelengths.

leakage current by reducing the diode temperature from room temperature to -30°C is a factor of about 250. At LN temperature, this factor is 6×10^4 . Hence a large reduction in leakage current is possible with moderate cooling. The operating temperatures were chosen such that the leakage current would be less than 10% of the on-source current, even after the supernova had faded to $m_v=17$. The Silicon and Germanium diodes were operated at -30°C and -77°C respectively.

We now consider noise from the detector/preamplifier circuit. The preamplifier circuit is a standard transimpedance amplifier, in which the voltage generated at the output V_{out} varies with the current input I , and the total impedance Z as $V_{out} = I Z$. The impedance will be due to the feedback resistor R and the capacitance of the components. At frequencies where resistive impedance is dominant over capacitive impedance (they are equal at about 40 Hz in the photodiodes), the output voltage is given approximately by $V_{out} = I R$. A measure of the gain of the circuit is V_{out}/I_{in} ; this is just the value of the resistor. The primary noise sources are Johnson noise from the resistor, and shot noise from the current source (the photodiode). The formula for Johnson noise is

$$V_{johnson} = \sqrt{4 k T R \Delta f} \quad (2.2)$$

where k is Boltzmann's constant, T is the temperature, and Δf is the sampled bandwidth. For a photodiode signal current i , the shot noise i_{shot} is

$$i_{shot} = \sqrt{2 e i \Delta f} \quad (2.3)$$

We now consider the signal-to-noise ratio after the preamplifier, with these noise sources. The signal-to-noise ratio SNR is

$$\begin{aligned} SNR &= \frac{(i R)^2}{R^2 i_{shot}^2 + V_{johnson}^2} \\ &= \frac{i^2}{2 e i \Delta f + \frac{4 k T \Delta f}{R}} \end{aligned} \quad (2.4)$$

From this equation, it is clear that we can maximize the signal-to-noise ratio if the value of the resistor is large enough such that $2 e i \gg 4 k T / R$. For this condition to hold true for the lowest source currents we expected, we needed a resistor with $R \gtrsim 10^{11}$ ohms. The actual resistors used in the Silicon and Germanium photodiodes had resistances of 10^{12} and 4×10^{11} ohms respectively. When the Silicon photodiode was first used near day 350, the signal-to-noise from equation 2.4 was 10^5 in a bandpass of 1000 Hz .

The FET makes a contribution to the noise, and its capacitance affects the overall circuit performance. As is typical for low noise applications, we used a bare FET in the preamplifier circuit, rather than an op-amp. This is because we want to cool the circuit element to LN temperatures to reduce voltage and current noise, and this rules out standard monolithic integrated circuits. Additionally, the capacitance of the smaller package is lower, which reduces the FET noise contribution in the following way. The r.m.s. voltage noise from the preamplifier (V_{FET}) is given approximately by

$$V_{FET} = e_n \left(\frac{C_{FET}}{C_f} \right) \quad (2.5)$$

where C_f is the capacitance of the feedback network including the detector capacitance, C_{FET} is the capacitance of the FET, and e_n is the equivalent voltage noise of the FET. e_n is basically the sum of Johnson and shot noise from the innards of the transistor, and is characteristic of the particular model and unit used.³ The capacitive term is merely the two capacitive impedances acting as a voltage divider. In order to reduce the FET capacitance, the FET was removed from its package (de-canned) before installing. This procedure reduced the FET capacitance by about a factor of three. For the data shown in this thesis, other noise sources were greater than FET noise.

Although it appears from equation 2.5 that the FET noise can be reduced by increasing the capacitance of the feedback network, this would also increase the RC time constant, and hence decrease the rolloff frequency of the filter. For example, with the

³ Our FET (2N4416) had a manufacturer specified e_n of 4×10^{-9} V Hz^{-1/2}.

Germanium diode's 0.01 pf capacitance, and a feedback resistor of 4×10^{11} ohms, $1/RC$ is 250 Hz, in good agreement with the rolloff frequency of ≈ 300 Hz inferred from Figure 2.5 (explanation for this figure is given in section 3, below). Since the FET was a minimal contributor to the overall noise budget (less than 1%), there was no reason to increase the detector capacitance to reduce further FET noise. This allowed us to keep the higher rolloff frequency, which increased our sensitivity to fast pulsar signals.

The two photodiode instruments were similar in design. The changes and upgrades for the Germanium diode are described in section 2. below.

1. The Silicon Photodiode

a. Electronics

The principal component of this detector system was a Hamamatsu model S1188-06 Silicon photodiode. Current output from the diode was amplified by an FET (2N4416) preamplifier and feedback network. The actual circuit used is shown in Figure 2.2. The primary function of this circuit was to amplify the detector signal, using a two-stage feedback loop. The gain comes primarily from the first stage, which consists of the FET, and the large (10^{11} ohm) feedback resistor. The second stage (OP-27) was to provide compensation for the first stage rolloff, and to offset the center voltage. These latter two effects were to adjust the signal voltage to the linear region of the voltage-to-frequency converter. To minimize electronic interference from other instruments and avoid ground-loop problems, the detector, amplifiers, and power supply were all electrically isolated, and battery powered. The batteries we used were rechargeable, lead-acid 6 V storage cells.

Figure 2.2 The actual circuit used for the Silicon photodiode and preamplifier. Unit was thermoelectrically cooled, with secondary preamplifier not cooled. The functions of the circuit are described in the text. (Drawing courtesy of Don Landis.)

To minimize leakage current from the photodiode, it was cooled by a thermoelectric cooler (Marlo, model MI 3040). We determined that an operating temperature of -30°C would limit the leakage current to a fraction of the expected supernova light background, and not place an unacceptable current burden on the battery-powered power supply.

To maintain the operating temperature without additional refrigeration required evacuation of the detector housing to approximately 10^{-6} Torr. We maintained continuous vacuum at this pressure with an ion pump, which was permanently attached to the detector

housing. The ion pump offered the advantages of being compact, transportable, and relatively inexpensive. Following an initial evacuation by laboratory pumps to 10^{-6} Torr, the ion pump had to operate continuously. If the internal pressure of the detector exceeded about 10^{-4} Torr, a potentially damaging arc could have been established in the vacuum-detector chamber. The disadvantages to this pump were twofold. One was that it required a constant 3 kV operating power at all times, which was troublesome to provide during intercontinental transport. The second problem was that the internal oscillating electric field contaminated the detector signal, albeit at discrete and identifiable frequencies.

To make the photodiode signal compatible with the original data system, we utilized a multi-stage voltage-to-frequency converter. The amplified photodiode current was integrated for the sampling period, held on a secondary latch circuit, and then converted by a voltage-to-frequency IC (RCA CD4046)⁴. The output pulses were shaped to emulate negative photomultiplier tube pulses, for which the data counter had been designed.

b. Mechanical Design

The mechanical design for the detector had several functional goals. The structure had to be sufficiently rigid to keep the target image on the detector as the orientation of the detector changed due to telescope tracking. It had to accommodate the detector cooling and vacuum units. Finally, it needed to include some fine positioning adjustments. A picture of the assembly is shown in Figure 2.3. Optical and infrared light were admitted through a sapphire window.

Since it is generally easier to move light than machinery, we settled on a simple, movable lens for the fine positioning system. A 25.0 mm f/1 lens was mounted in an x-y stage, where the z-axis was the optical axis of the telescope. Adjustment knobs on the stage allowed final positioning of the target object on the detector without further motion of

⁴ RCA CD4046 is a phase-locked loop amplifier. We used only the V-to-F converter IC from this system.

Figure 2.3 The Silicon photodiode detector.

XBB-900-9622A

the telescope or instrument. This design also provided a reduced lever arm for the attachment of the detector to the telescope. The interface mounting for this purpose was constructed from aluminum of sufficient thickness to keep flexure at all telescope angles within tolerance. This latter behavior was tested during normal operation by monitoring the detector output.

2. The Germanium Photodiode

The electronics for the Germanium detector were similar to the Silicon detector. Both systems used the same basic preamp-amplifier design, although the components were refabricated. The main difference was the digitization of the photodiode signal, which was a straightforward analog to parallel eight-bit digital conversion. In a few cases, faster components were used to allow the higher sampling speeds we desired with this unit. Additional circuitry was also needed for an internal heater, and temperature sensitive diode, which were used to stabilize the temperature of the detector. A schematic diagram of the circuit is shown in Figure 2.4.

The circuit shown in Figure 2.4 has several functions. One is to amplify the detector signal. This part of the circuit is similar to the Silicon diode preamplifier, but has one additional gain stage (OP 27). Additionally, no rolloff compensation was necessary. The two 2N3904 transistors and the two 1N4148 diodes form a push-pull amplifier for the zero-biased signal. Another function of the circuit is to conduct power, including a 300 V offset voltage to the diode. Leads from the external power supply are connected as indicated, and further smoothed by low pass filters ($\approx$ few Hz). The last functions are a temperature sensitive diode, a heater, and a too-much-light-on-diode warning.

The mechanical design goals for this unit were similar to the Silicon photodiode unit. However, some modifications were required because of the infrared sensitivity of the detector. A liquid-nitrogen dewar with capacity approximately 1 liter was needed to cool an aperture wheel and filter wheel, as well as the electronics. The heat load to the internal parts

3. Calibration Procedure

Early estimates for the characteristics of an optical pulsar (Ho, 1987, Michel *et al.* 1987) were not able to predict with certainty the date optical pulsations would emerge from the supernova shell. Since we wished to discover pulsations as soon as they became bright enough to detect, it was advantageous to begin observations with the more sensitive photodiode detectors as soon possible. We began to observe with each new instrument as soon as a minimum standard of functionality was achieved. Hence the instruments were intended to discover any pulsations, rather than be suited initially for precisely measuring all of their characteristics.

One consequence of this speedy approach was that certain calibrations were not performed before their first use in the field. Because observations were being made in the Southern Hemisphere, follow-up calibration was difficult. This was due to the danger and expense of transporting the instruments, the lack of laboratory facilities available at the observatories, and the financial inability of observatories to support such activities. Out of a sample of possible calibrations, Table 2.1 shows which measurements were actually performed in the laboratory. These procedures are discussed below.

Table 2.1 Calibrations

Measurement	Si	Ge
Measured spectral response (quantum efficiency vs. wavelength)	NO	NO
Measured preamplifier gain	YES	YES
Measured preamplifier rolloff	NO	YES
Measured amplifier rolloff	NO	NO
Measured linearity of detector response	YES	YES
Measured Noise Characteristics		
FET noise	NO	NO
Discrete spectral noise sources	NO	NO
Microphonics	YES	YES
Studied interactions with environment (RFI , etc.)	NO	NO
Measured frequency stability of system	NO	YES

Unfortunately, we did not detect a pulsar as a consequence of the early use of the photodiode detectors. Rather, when an interesting signal was seen, the lack of certain calibrations frustrated attempts to process the data rapidly. In particular, the sources of background noise in the laboratory and from the telescope and their coupling to the instruments were not well-studied prior to use of the instruments. Since just such a background later lead to a mistaken report of a real signal, it is possible, although by no means certain, that more extensive calibration in this area could have avoided this error.

The preamplifier gain and capacitance were measured by depositing a known amount of charge in the diode, and measuring the output pulse of the preamplifier. For this purpose, the detector was exposed to Americium ²⁴¹, a source of 59.57 keV x-rays. Those x-rays stopped completely within the detector liberate a number of electrons approximately equal to their energy divided by average energy required to produce a conduction electron. For Germanium at liquid-nitrogen temperature, this energy is 2.96 eV

per electron-hole pair. From the voltage of the largest pulses, we deduced the detector capacitance $C = Q/V$. The capacitance of the Germanium detector was found to be about 0.01 pf. The decay time, equal to RC , was read from the pulse shape to be approximately 4 ms. Thus R is 4×10^{11} ohms. The gain of current sources like a photodiode is often expressed as $\text{gain} = V_{out}/I_{in}$. At frequencies well below $1/RC$, this is simply the value of the resistor.

The preamplifier rolloff was measured in a simple procedure. The diode was illuminated with an optical light emitting diode. The light emitting diode was powered with both a steady-state voltage of about 5 V, and an oscillating sinusoidal voltage which was smaller by a factor of 100. This allowed us to maintain nearly constant brightness while varying the frequency of the illumination. Since we calculated that the secondary amplifier would rolloff at a much higher frequency than the preamplifier (above 10 kHz), in fact the output of the secondary amplifier was monitored. This amplifier output was connected to a spectrum analyzer, and the voltage of the output signal was measured as a function of frequency. These data points are shown in Figure 2.5. Also shown in the figure is the curve of a theoretical low pass single pole RC -filter, where $1/RC = 482$ Hz. The fair agreement between the data and the curve show that the feedback circuit behaves like the simple low pass filter. While such a filter does attenuate the signal at higher frequencies, it has exactly the same effect on source shot noise, and Johnson noise from the feedback resistor. Therefore, the signal to noise ratio is unchanged where these noise sources are dominant. Noise from the FET (e_n) is not attenuated, begins to dominate other sources at frequencies above approximately 1000 Hz; it is the largest source of high frequency noise at low light levels.

The frequency stability of the system was of critical importance for the pulsar system; the main distinguishing characteristic of a pulsar signal is that it should be narrow in frequency (i.e. is emitted at a nearly constant frequency). If the timekeeping mechanism of the detector or data system drifted with respect to the source, a narrow frequency signal

Figure 2.5 The amplifier response for Ge detector. Measured points are shown as black diamonds. The solid curve is a theoretical RC rolloff with $1/RC = 482$ Hz.

would be indistinguishable from a broad one. Therefore, we designed each part of the system to operate from the same standard frequency source. A pure sine-wave at about 1 kHz (from the same frequency standard which ran the data system, Hewlett-Packard Frequency Counter model 5350) was applied to the DC-biased light emitting diode described above, and we used this to illuminate the detector. Data were accumulated at 50 kHz for three hours, and Fourier-transformed. The signal in the resulting frequency spectrum had 90% of its spectral power in the two frequency bins nearest the central frequency, consistent with no drift with respect to an exactly constant frequency. The frequency resolution of a three hour data set is 9×10^{-5} Hz. Hence we were sensitive to frequency drifts of 8.5×10^{-9} Hz s⁻¹ with this test. We showed that our data system did not drift at this level, which was sufficient for our search.

Nonlinearities in the detector response would have shown up as higher harmonics of the 1 kHz signal in the test above. The total power in all higher harmonics was less than 5% of that seen at 1 kHz. We also directly measured the linearity of the A/D converter in the Germanium detector data system. We applied a fixed DC voltage with values throughout the rated input range, and recorded the output of the device. The results are shown in Figure 2.6. A straight line is shown for comparison. No significant deviation from linearity is seen, except at the extreme ranges of the data.

The test for microphonic noise was performed with the detector mounted on the Cerro Tololo four meter telescope. This test was performed during the day, when

Figure 2.6 The output of the analog-to-digital converter as a function of input voltage, showing excellent linearity. A straight line is shown for comparison.

electronic noise in the environment was at a minimum. We first acquired one set of data as the control set. Then a second set of data was taken while thumping on the detector with sharp and with muted blows. Each data set was then Fourier analyzed, and the resulting frequency spectra inspected for additional noise in the second spectrum. No significant differences were seen in the two data sets. However, since mechanical vibrations may differ in amplitude from run to run, the most effective use of this calibration was to compare with it potentially interesting signals seen in later runs.

C. The Data System

The original data acquisition and storage system used for this experiment was designed and built by Jerome Kristian and Richard Lucinio of the Carnegie Institute of Washington. The system counted photomultiplier tube pulses, and stored them on 12" magnetic reel tapes. While the system worked very well for the purpose for which it was designed, there were several reasons not to use it with the photodiode detectors. The maximum sampling rate was 10 kHz. The amount of data storage allowed by the magnetic reel tapes with the available tape drive was only 40 MB per tape. Hard disks currently available for microcomputers offer capacities up to 700 MB, and magnetic tapes now can hold 2 GB (GB = 10^9 bytes) per tape. Using these media would allow longer continuous operation, and easier data transportation and archiving. The remaining disadvantage of the older system was that it counted pulses. With the photodiode detectors there are no pulses, so they had to be created artificially by a current-to-frequency circuit. While such an arrangement was constructed for the Silicon photodiode detector, a direct analog-to-digital (A/D) conversion is easier to design and construct, and proved more reliable in this experiment.

There were several design goals for the data system developed for this experiment. The most important of these was that it should maintain time continuity of data samples,

and any losses should be detectable, and correctable. We also wanted a higher maximum sampling rate, to allow measurement of the higher harmonics of millisecond period pulsars; a large data-storage capacity; and the ability for real-time data analysis. The existence of commercially available data input and output (I/O) boards for microcomputers complemented our need to sample and digitize the photodiode signals. This led us to consider and finally construct a data acquisition system based on a personal computer (PC). The actual PC we selected was a 20 MHz IBM 386 clone made by AST Research, Inc. This system proved largely successful, and much easier and cheaper to construct than an equivalent custom-designed system. However, to fulfill all of the design goals, some additional custom hardware had to be designed and built.

The new data acquisition system is shown schematically in Figure 2.7. The discussion below follows the signal path from the detector to the storage unit, and discusses each element of the data chain in turn. The amplified signal from the detector was first passed through a unit containing an additional adjustable amplifier stage, the integrator, and the analog-to-digital converter. A dial on this unit set the sampling speed to either 10 kHz, 20 kHz, or 50 kHz. The frequency response of the amplifier was not dependent on the sampling speed. The digitized signal was then fed into the "Tick Mark Maker" (TMM) unit. The TMM unit also isolated and shaped the stable clock input. The purpose of this device was to insert into the data stream record markers at fixed intervals, such that timing continuity could be tested. To keep the same data record size as the earlier data storage system, a timing byte was inserted after every 8192 data bytes. The timing byte was alternately 255 and an incrementing counter value. The value of 255 was chosen to be a conspicuous and otherwise unlikely number to search for as an end-of-record in the data stream. The counter value allowed us to check for continuity in the data stream, and told us exactly how much data, if any, was lost.

Figure 2.7 Block diagram of data acquisition system developed for pulsar search. Components are shown in boxes, while data flow is indicated with arrows. The "transfer acknowledge" was only used for diagnostics.

Since we were not approaching the maximum acquisition rate of our data I/O board (by Metrabyte, model PDMA-32) of 100 kHz, we chose to insert the timing byte between two data values rather than replace a data value. This required additional timing circuitry in the TMM, and a separate switch on the unit indicating the sampling speed. It is not clear whether not losing a single datum out of every 8192 was worth the development time and the "something-else-to-go-wrong" cost.

We used a self-contained Rubidium Frequency Standard to drive all units of the system. This unit had a manufacturer specified stability of 1 part in 10^{11} per day. The absolute frequency rate was set by the reseller. Since we had no other clock with as good stability or accuracy conveniently available, we did not recalibrate this source. Although drifts in frequency (df/dt) would be detrimental to the search, it was insensitive to errors in the absolute frequency of the standard.

The TMM unit was expected to be physically separated from the PC, which we wanted in the telescope control room. For convenience, we chose to put all of the start and stop controls for the data system near the PC. We built a hardware unit to house a system reset, and both mechanical and electronic start inputs. The system reset was to insure that we acquired an integral number of data records, and that the counter start from unity. The electronic start pulse allowed synchronization with appropriate standard time. Absolute synchronization was accurate to about 3 microseconds, the time it took the A/D converter to "turn on", and considerably better than the minimum sampling period of 20 microseconds.

Each byte of data was presented at the parallel input of the I/O board in the PC along with a "Data ready" bit. Bytes were then stored in hardware memory located on the board, and would be written to internal PC disk in one or two kilobyte sections. This disk write was done using special purpose "Streamer" software written by Metrabyte. This software used direct memory access, eliminating DOS overhead and allowing a higher maximum sampling rate. The software required a 80387 math coprocessor to process data at the 100 kHz sampling rate. The maximum amount of data we could continuously

accumulate was set by the size of the PC hard disk. At the time of construction, the largest disk with adequate access time was 760 MB. A formatted size of 630 MB allowed a total acquisition time of 3.5 hours when sampling at 50 kHz, and proportionately longer at slower sampling rates.

For permanent storage of the data, we copied it to 8 mm videotape cassettes, using the Sony Exabyte drive, in a chassis package by Summus, and Summus's proprietary software. Each tape holds 2 GB of data. The backup procedure was time-consuming, taking about three hours for the entire 630 MB disk. In practice, this meant that once the PC disk was filled up, observations using this system were pretty much over for that night. This situation rarely caused difficulty.

Chapter III. Observations

A. Strategy

There is a certain brute force nature to this experiment. We wish to observe as often and as long as possible SN1987A using the largest available telescopes, and then analyze the data collected in the largest sections allowed by accessible computer resources. This approach meant enlisting a number of different observers, to provide maximum coverage. From March 1987 until January 1988, all data were taken with photomultiplier tubes. The Silicon photodiode detector was first used in January 1988, and continued to be used until approximately January 1990. The Germanium photodiode has been used since January 1990. In this chapter, we describe the data, the analysis procedure, and how we formulate an upper limit.

B. Data Analysis and Sensitivity

The basic data analysis procedure we use is to search the Fourier transform of time series data for a signal appearing in one bin, or two adjacent bins. Once a certain threshold power is found, more sophisticated tests may be invoked to reject noise and artifacts, including examination of higher and lower harmonics, and the behavior of the signal over time. Discussions of some aspects of these techniques may also be found in Middleditch 1975, and Pennypacker *et al.* 1989.

If time series data is normally distributed, the Fourier transform will produce an exponential distribution of power samples in frequency space (for a derivation, see Middleditch 1975). If the primary sources of noise in the time domain are shot noise and Johnson noise, these will accumulate to produce a Gaussian distribution of the sample data if there are sufficient counts per sample. Sources of noise which are not random, such as

interference from oscillators, wall current, etc., will not produce Gaussian noise. However, these sources may be identified in the frequency spectrum and eliminated; hence they will not enter statistical calculations based on the assumption of Gaussian noise. We can easily check that our time series data is Gaussian by examining the data sets themselves. Due to the large amount of data, the tests which follow are not performed on every section of data, except where specified.

At the same time, it is appropriate to check that the data points are uncorrelated as well as normally distributed.

1. Gaussian Data

We have accumulated a histogram of approximately 16,000 consecutive raw data points from observations on January 18, 1989, and January 19, 1990. These data sets were chosen to be typical, and show the general behavior of the data. These data were acquired at the four meter telescope at CTIO with the Silicon photodiode (from 1989), and the 100" telescope at Las Campanas Observatory with Germanium photodiode. The two detector/data systems had no hardware in common. The results are shown in Figures 3.1 and 3.2. The best fit three-parameter Gaussian for each of these distributions is also shown in the figures. Qualitatively, the figures show the data to be well-described by a Gaussian distribution. To investigate further the accuracy of this appearance, we calculated the chi-square of the Gaussian fit. For the CTIO data, the chi-square is 173, for 148 non-zero histogram points. For the Las Campanas data, the chi-square is 171 for 105 non-zero histogram points. These chi-square values indicate that the data is not exactly Gaussian-distributed, revealing the presence a small component of non-Gaussian interference.

Figures 3.1 and 3.2 A histogram of count values from the Silicon (3.1) and Germanium (3.2) detectors. A best-fit Gaussian is shown as a solid line, and provides a good approximation to the data distribution. Error bars shown are $\pm$ square root of count value.

Figure 3.3 Data from the Silicon photodiode, where each Cartesian point consists of sequential values in the data stream. A slight skew is evident, showing minimal correlation of these points. (The hatched appearance is due to the printer resolution.)

2. Correlation of Data Points

To investigate whether successive data points are correlated, we plot pairs of data values as cartesian points in Figure 3.3. Here, the x-coordinate is one data value and the y-coordinate is the following data value. Although a very slight skew is evident along the $y = -x$ direction, there is no large trend. To study this correlation further, we apply Pearson's test for correlation to sequential data points. Pearson's " r " parameter is defined as

$$r = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^N (y_i - \bar{y})^2}} \quad (3.1)$$

Pearson's r may range in value from -1.0 to 1.0, and is close to zero for non-correlated data. The distribution of r values for uncorrelated data is approximately normal, with mean of zero, and a standard deviation of $1/\sqrt{N}$, where N is the number of points. For this application, we set $y_i = x_{i-1}$, and $y_1 = x_N$. The value for the r parameter for 2048 of the points plotted in Figure 3.3 is -0.2. This implies correlation of adjacent points with high statistical significance. An effect which could give a negative correlation is a wrap-around counter, in which samples over a maximum counter value are rescaled starting again at zero. In fact, we were using such a counter when this data was taken. In any event, the amount of correlation does not appear from Figures 3.1 and 3.2 to be a large source of non-Gaussian noise.

3. Fourier transform search technique

Before we can conclude this study of the data, we need first to explain how we use the fast Fourier transform (FFT) in our analysis procedure. For a general reference on FFT's, see *e.g.* Brigham 1974, and references therein. The advantages and disadvantages of using FFT's versus other techniques to search for pulsar signals have been discussed elsewhere (Middleditch 1975, Leahy, *et al.* 1983). Except for extremely small duty cycle signals, and with data that contains no gaps, the FFT is the preferred method, since it affords maximum sensitivity and efficient computer usage.

Each observation results in a time series of data points. The number of data points is the product of the rate of sampling and the length of the observation. For the observations presented here, the sampling rates range between 5 kHz and 200 kHz, and contiguous observation periods from about one to four hours. Hence a single observation may result in a total of 18 million to 2 billion points. For our FFT analysis, we can show that the spectral power divided by the local spectral power for a signal narrow in frequency

space grows linearly proportional to time. Therefore, there is a benefit to transforming the longest contiguous data set possible. The practical limits for analyzing this amount of data arise from three separate areas: (1) memory available in CPU or disk-virtual memory, (2) machine computation and disk access speed, and (3) the Nyquist (highest frequency) limit one is willing to accept. The first two considerations lead one to use the fastest and largest computer available. Since the computers used for the data analysis could transform all but the largest data sets, it was rarely necessary to re-bin the data. Hence our Nyquist limit was generally set by the sampling rate used when the data was acquired.

After Fourier transforming the time series data, we searched the resulting transform for bins with significant power above a local average. We describe this averaging process in detail to show that we do not have uniform sensitivity at all frequencies. This loss of sensitivity is due to three separate effects. One effect is electronic interference appearing as relatively narrow peaks in the frequency spectrum. Another is the increase in power at low frequencies due to scintillation by the Earth's atmosphere of the light from the supernova. The final effect is due aliasing of noise power from frequencies above the Nyquist frequency to frequencies below it. Some additional discussion may be found in Middleditch (1975).

The atmosphere has the effect of a rising increase in the power seen towards low frequencies (below about 10 Hz) compared to a mean level calculated at higher frequencies. This reduces our sensitivity to pulsars with periods greater than 100 ms. Electrical oscillations from either the photodiode detector unit or the telescope environment also produced excess power at certain frequencies. These sources of interference usually occurred at a small number of frequencies, and rarely extended beyond a few hertz region about the central value. However, the large number of frequency bins affected, and the variability of these sources make it impossible to set a global threshold for spectral power.

These two effects may be seen in Figures 3.4 and 3.5, which show the transform of data from the Silicon photodiode detector sampled at 5 kHz. Figure 3.4 shows the

increase in noise power at very low frequencies, and Figure 3.5 shows discrete noise sources throughout the full range of the positive frequencies. In the latter figure, each bin with spectral power well over the average is indicated with a marker. The units of spectral power corresponding to counts per second in the time domain are counts squared per Hz. The average spectral power for the data in Figure 3.5 is approximately $7 \times 10^8 \text{ counts}^2 \text{ Hz}^{-1}$ for the data in the figure. A similar figure for data taken with the Germanium photodiode detector is shown in Figure 3.6. The Silicon photodiode has at least four narrow background sources in this frequency range with spectral power in excess of one thousand times the mean, and other sources with less power. In comparison, the highest noise peaks in the Ge diode spectrum are 60 and 120 Hz sources. The 60 Hz noise is due to capacitive pickup of the wall current, and the 120 Hz noise is from stray light. The amount of power seen at these frequencies varied by about 10^3 in different observations. There are some other narrow sources evident at lower frequencies, but none above 200 Hz. It is clear there is less noise from narrow sources in the Germanium instrument.

Noise from frequencies above the Nyquist frequency is aliased to appear at frequencies below the Nyquist frequency. Fortunately, this noise is attenuated by two effects. The first is the preamplifier, which is shown in Chapter II, section 3 to behave similar to an RC low-pass filter, with $1/RC \approx 500 \text{ Hz}$. Thus, preamplifier gain is falling at 6 dB/octave at the Nyquist frequency, and the average spectral power is falling as 12 dB/octave. Near the Nyquist frequency, the average spectral power is doubled; we are half as sensitive to a given signal as we would be with no power aliased from higher frequencies. The contribution to the average spectral power at lower frequencies is lower than the contribution at the Nyquist frequency by 12 dB/octave. The next effect is arises from the integration of current over the sampling period. Signals or noise with frequencies above the sampling frequency complete more than one cycle during one sample period; complete cycles contribute no power at their frequency. The proper formula to account for this effect is given by Middleditch (1975). These attenuation effects make this additional

noise negligible except near the Nyquist frequency. For example, at a sampling rate of 10 kHz, the additional noise at 1 kHz from frequencies greater than 5 kHz is 1 part in 10^3 .

To allow a simple threshold search, we first normalize the spectral power seen at a bin to an average level calculated from the surrounding bins. In practice, about 200 bins excluding the nearest ten bins were used to calculate this average. If a noise peak is included in the calculation of the average, our sensitivity at the target frequency is reduced by a factor roughly proportional to the ratio of the sum containing the average noise to the sum containing the noise peaks. For the data in Figure 3.5, this ratio can be as much as two thousand.⁵

We can now finish our general examination of the data. Once we have produced a normalized distribution of spectral power divided by the "local power," we should test to see if this looks exponential. An exponential distribution in frequency space would be more evidence that our statistics are not significantly influenced by non-Gaussian noise. The original data is from a 15 minute observation of the Crab Pulsar taken February 7, 1990 with the CTIO 4 meter telescope. We have selected a section of a Fourier transform where we expect to find little or no signal from the pulsar. We show for 1.6×10^4 consecutive transform points between 500 Hz and 520 Hz the histogram of the spectral power in each bin divided by the local spectral power. This data is plotted on a log scale in Figure 3.7. An exponential curve is also shown in the figure. It is clear that the observed distribution of normalized power values does not differ significantly from an exponential. We conclude that at frequencies not contaminated by discrete noise sources, the distribution of spectral power is exponential.

⁵ The actual frequencies with significant background sources for the Si photodiode system at Cerro Tololo are 534 Hz and the next four higher harmonics, 1147, 1267, 1691, 1811, and 1931 Hz.

Figures 3.4 and 3.5. Spectral noise from Silicon detector at low (3.4) and higher (3.5) frequencies. In figure 3.5, each bin with spectral power well above average is indicated by a +. Signals broad in frequency are characteristic of instrumental noise.

Figure 3.6 Spectral noise from Germanium diode. The right hand axis is for data above 500 Hz. (note scale change), and individual bins are shown by dots rather than crosses. The overall noise level is approximately 3 times lower than the Silicon detector, and has fewer narrow noise sources at frequencies of interest.

Once we have derived a normalized frequency spectrum, it is straightforward to calculate the expected level of noise peaks. The probability for a noise peak of power level P at one frequency is e^{-P} , and the expectation power is unity. For instance, if there is a peak with a normalized spectral power of 20, the probability that this is due to noise is e^{-20} ,

or 2×10^{-9} . This probability is approximately equivalent to a 6σ fluctuation if the distribution were gaussian. A noise peak with this level of spectral power or greater will occur on average once every 5×10^8 frequency points. Therefore, a measure of the likelihood of finding a peak at spectral power level P from random noise is the exponential function of negative P , times the number of frequencies searched. For this analysis, the parts of the frequency spectrum known to be contaminated with instrumental noise should be considered separately or eliminated.

Figure 3.7 A histogram of 16,000 consecutive local power levels, plotted on semi-log scale. A straight line is shown for comparison

To obtain a confidence limit on our assertion that no pulsations are present in the data to a given magnitude, we need to know the probability that a real signal of spectral power P_o will fluctuate downward to the level of the highest peaks attributed to noise in the frequency spectrum. Note that the actual power seen in the frequency spectrum is $P_o + 1$, since there is the noise contribution as well. Middleditch (1975) shows the variation in the signal is approximately Gaussian about the central value $P_o + 1$, with a σ of $\sqrt{2P_o}$. To obtain 90% confidence limits, we wish to identify the level of a signal whose spectral power would remain above the level of the noise 90% of the time.

Suppose the highest noise power we decide is not a pulsar signal is P_1 . We wish to identify the power level P_o which obeys⁶

$$\frac{\int_{P_1}^{\infty} \exp\left(-\frac{(P - P_o)^2}{4 P_o}\right) dP}{\int_0^{\infty} \exp\left(-\frac{(P - P_o)^2}{4 P_o}\right) dP} = 0.9 \quad (3.2)$$

Changing variables to $u = (P - P_o)/2\sqrt{P_o}$,

$$\frac{\int_{\frac{(P_1 - P_o)}{2\sqrt{P_o}}}^{\infty} e^{-u^2} du}{\int_{-\frac{\sqrt{P_o}}{2}}^{\infty} e^{-u^2} du} = 0.9 \quad (3.3)$$

⁶ There is an approximation in using $\sigma = \sqrt{2P_o}$, since the error in power in the complex plane is a bivariate gaussian. If one does not use this approximation, the final answer is 27.3, instead of from 29.8.

or

$$\operatorname{erfc}\left(\frac{P_1 - P_o}{2\sqrt{P_o}}\right) = 0.9 \operatorname{erfc}\left(\frac{-\sqrt{P_o}}{2}\right) \quad (3.4)$$

From this formula, it is straightforward forward to solve for P_o , given P_1 . For example, if $P_1 = 20$, plotting each side of the equation as a function of P_o reveals that $P_o = 29.8$.

When a real signal is present, the above procedure for estimating its significance is more complicated. One must take into account additional effects of the discrete Fourier transform on real data. These include the fact that the signal is actually integrated rather than sampled; the signal may not be a pure sinusoid; the actual frequency of the signal may not fall exactly on one of the discrete frequencies output by the transform process; and that the observation is of finite length, leading to a distribution of the real signal power over multiple frequency bins. We can find appropriate formulas which account for these effects in Middleditch (1975) and Leahy *et al.* (1983).

We now convert spectral power level to the equivalent amplitude for a *sinusoidal* signal of the form $a \sin(2\pi ft)$. The formula for this is given in Middleditch (1975, p. 30); we refer the reader to this source for the derivation. The formula is⁷

$$a = \sqrt{\frac{4 \cdot MSD \cdot LL(f) \cdot P_o}{T}} \quad \text{counts s}^{-1} \quad (3.5)$$

where P_o is the spectral power, MSD is the average variance of the raw data in $\text{counts}^2 \text{s}^{-1}$, $LL(f)$ is the local deviation from the mean variance, and T is the time of the observation in seconds. The factor of 4 is due to the dividing of a sine wave into positive and negative frequencies; if we look at only the positive frequencies, we find only one half the original amplitude. Since P_o is the normalized power, the factors MSD and $LL(f)$ are the

⁷ Middleditch uses P_o to be the raw spectral power, where we use it to mean the excess spectral power. Hence his formula reads $(P_o - 1)$ where we use P_o .

appropriate factors to unnormalize it and get back to counts. Once the flux in counts per second is known, it is straightforward to determine the magnitude by comparing this rate to the flux received from a standard star. Since the detectors were not designed for DC measurements, we used the Crab pulsar as the standard source.

4. Calibration Observations

Calibration observations were performed with each instrument to determine the noise background, and the overall sensitivity. This was done once per observation run. The noise calibration consisted of observing a star which does not pulse, and was approximately as bright as the supernova at the time. The frequency spectrum of the observation showed contaminating noise sources. This observation was performed at least once per night.

To calibrate the absolute sensitivity of an observation at a given telescope, we observed the Crab Pulsar. The magnitude of the Crab Pulsar has been measured in standard visible and near infrared passbands (Middleditch *et al.* 1983, Middleditch *et al.* 1987). We compare spectral power we measure from the Crab Pulsar to the known magnitude of the Crab pulsar in the same passband. We can use either the integrated brightness at all harmonics, or use the fractional contribution of a single harmonic. From these results, we can calculate the magnitude of the background level. Knowing this level, we derive the appropriate limit on the appearance of a pulsar signal above the background level.

As an example of this procedure, we show how we calculate the limiting magnitude from the observation of the Crab Pulsar described above, for February 7, 1990, using the Germanium detector. A long pass filter with a cutoff wavelength of about 0.9 microns was used for this observation. A Fourier transform of 210 seconds of this data is shown in Figure 3.8. The Crab pulsar signal is easily visible at harmonics of its approximately 30

Hz spin frequency. The spectral power at the fundamental frequency is $617 \text{ counts}^2 \text{ Hz}^{-1}$, summing the two frequency bins with highest spectral power. The fraction of the spectral power in the Crab pulsar's first harmonic with this filter is 0.08 (Middleditch, private communication). We take the integrated magnitude to be 15.0 (Middleditch *et al.* 1983), and calculate that the corresponding magnitude for just the first harmonic is 17.7. The highest noise peaks in this observation have a spectral power of approximately 14. Solving equation 3.4, we find the appropriate upper limit on spectral power is $P_o = 22.6$. Inserting these values into the magnitude equation, we find the upper limit for the magnitude of a single harmonic of another pulsar in this observation:

$$\begin{aligned} m_{\text{upper limit}} &= 17.7 - 2.5 \log_{10} \sqrt{\frac{22.6}{617}} \\ &= 19.5 \end{aligned} \tag{3.6}$$

To use this procedure with a different observation, appropriate values of MSD and $LL(f)$ would be calculated for the new observation, and used in equation 3.5.

Figure 3.8 The near-infrared frequency spectrum of the Crab Pulsar, uncorrected for instrument response. Data values with less than four times the local power are not shown. The Crab pulsar's double-peaked pulse profile leads to the second harmonic having more power than the fundamental.

Chapter IV. Results of Observations

The result of this experiment has been to set limits on the brightness of an optical pulsar in Supernova 1987A in the first few years after the explosion. A consequence of this experiment has been work done by a number of researchers to explain, or make sense of the report of a detection of a 0.5 millisecond pulsar in Supernova 1987A (Kristian *et al.* 1989). We discuss this work following our results.

Upper limits

The lack of power at points in the Fourier transform frequency spectrum significantly higher than the background allows us to set upper limits on the strength of a narrow pulsar signal within the bandpass of our detector or filter. A summary of results from observations through day 553 was reported in Pennypacker *et al.* 1989. Since then, we have made 83 separate observations, and used the Germanium photodiode detector to observe the window between 1.2 and 2 μm . We have now set limits as faint as magnitude 22.7. A complete list of search observations with a summary of findings are presented in Appendix A.

We present both a magnitude and a luminosity limit on the pulsed light from the supernova. In Figure 4.1 we plot the magnitude upper limit for each observation of the experiment over the day since the supernova explosion. The calculation of the magnitude limits is described in Chapter III. The magnitude limits are derived from the magnitude of the Crab pulsar in the same instrumental bandpass. For the data shown in Figure 4.1, the magnitude of the Crab pulsar was considered to be 16.6. The magnitude limits vary depending on the brightness of the supernova at the time of the observation, and on the detector, telescope, and filter used. We indicate in the figure the different detectors used with different marker styles. We also include for reference the apparent visual magnitude of Supernova 1987A through day 800 (Middleditch 1990, private communication).

Figure 4.1 Upper limits on pulsed magnitude. Different detectors are indicated with different marker styles. Magnitudes are in appropriate filter or detector passband. Si II indicates duplicate silicon diode detector used in Australia. Other detectors were phototubes, mainly an EMI Ga/As, with various optical filters.

We also use the Crab pulsar as a reference for our pulsed luminosity limits for Supernova 1987A. The flux from the Crab pulsar has been measured in standard visual and infrared bandpasses by Middleditch *et al.* (1983) and Becklin *et al.* (1973). The uncertainty in the flux values of Middleditch *et al.* is given as 15%. However, the flux quoted by Middleditch *et al.* differ with those of Becklin *et al.* in the same bandpasses by about 30%. These uncertainties in the flux from the Crab pulsar lead to the largest uncertainty in our calculation of pulsed flux limits from Supernova 1987A. We infer a flux for the Crab pulsar at wavelengths in this region based on best linear fit to the three flux values given by Middleditch *et al.* for bandpasses V, J, and H. Interstellar extinction in the visual band (A_V) is lower towards the Large Magellanic Cloud than towards the Crab pulsar by the ratio 0.6:1.6 (Middleditch *et al.* 1987). We infer a value for extinction towards the LMC at longer wavelengths by scaling the values of Middleditch *et al.* 1983 by the same ratio. We use 55 kpc for the distance to the LMC.

In Figure 4.2 we plot limits on the pulsed luminosity from Supernova 1987A versus frequency. In this figure we show our faintest limits from observations between days 1030 and 1121. A black diamond marks the 90% confidence limit on pulsed emission from the supernova at the midpoint of the bandpass. A signal with equal energy per hertz measured in the bandpass would arise half each from frequencies above and below the midpoint. The horizontal bar extends to the frequencies at which the transmission function for the bandpass falls to 50% of the peak value. The vertical bars indicate 25% systematic errors, reflecting the uncertainty in the published flux values for the Crab pulsar, and to allow for uncertainties in the spectral shape of a pulsar luminosity. We plot as open diamonds the luminosity inferred for the Crab pulsar from the extinction-corrected flux measurements of Middleditch *et al.* (1983), using a distance of 2 kpc. The flux values shown for the Crab pulsar are best fit by a spectral index of -0.4 , although no single power law describes well the ultraviolet, visible and infrared fluxes (Middleditch *et al.* 1983). The actual luminosity of a pulsar in SN1987A could differ from the plotted value by more than

Figure 4.2 The limits and spectral coverage of observations between days 1030 and 1131. The black diamonds mark the 90% confidence limit on the pulsed luminosity. Vertical error bars are a fixed 25% of this limit (see text). Horizontal bars indicate frequencies where the bandpass transmission is 50% of the peak. The open diamonds indicate V, J and H measurements of Middleditch et al (1983), shown with 15% error bars.

25% in the widest bandpass shown in the figure when the spectral index of the pulsar luminosity lies outside the range -0.4 ± 1 . In the other bandpasses shown in the figure, this point is reached near a spectral index of -0.4 ± 2 . We list in Appendix A, Table A.2 the observation date, the filter, and the bandpass parameters for each of the limits plotted in Figure 4.2.

We have reached limits on the pulsed optical luminosity for a pulsar in SN1987A fainter than magnitude 22. Typical measurements place limits on the pulsar luminosity about 10 magnitudes fainter than the supernova, implying a sensitivity of better than 1 part

in 10^4 . The sensitivity of our best measurements was to 1 part in 10^5 . Our measurements to September 26, 1990 (day 1340) rule out a region of steady state optical luminosity from a pulsar and optical depth of the supernova envelope shown shaded in Figure 4.3. We discuss in the next section the implications of this result on theoretical predictions of the optical luminosity of a pulsar.

Figure 4.3 Regions of absolute magnitude and optical depth covered by our limits are indicated by shading.

Discussion

We compare our upper limits with theoretical predictions for the optical luminosity of a pulsar in Supernova 1987A. Pacini (1971) formulates the scaling law for the bolometric luminosity of a pulsar L

$$L \propto B_o^4 P^{-10} \Delta r \quad (4.1)$$

where B_o is the surface magnetic field on the neutron star, P is the period of the pulsar, and Δr is the radial extent of the emitting region. This scaling law has been successful in predicting the optical luminosity of the Vela pulsar, and the secular decrease in the optical luminosity of the Crab pulsar (Pacini and Salvati 1983). We use equation 4.1 to predict the optical luminosity from a hypothetical pulsar in Supernova 1987A (PSR1987A) by scaling from the optical luminosity of the Crab pulsar. As a starting point, we assume that the magnetic field B_o and emitting region Δr of PSR 1987A are equal to those of the Crab pulsar. The initial spin period of the Crab pulsar is predicted lie in the range 17 ms to 22 ms (Manchester and Taylor 1977). Considering a 17 ms period for PSR1987A and 33 ms for the Crab's current spin period leads to a factor of ~ 750 difference in the bolometric luminosity of the two pulsars, using equation 4.1. A period of 22 ms for PSR1987A yields a difference of ~ 60 in the luminosity of the two pulsars. The optical luminosity of the Crab pulsar is approximately 10^{34} ergs s^{-1} (Middleditch *et al.* 1983). Therefore, PSR1987A would have an optical luminosity in the range 6×10^{35} to 8×10^{36} ergs s^{-1} .

Figure 4.2 shows that broad-band optical pulsations escaping the supernova are fainter than about 5×10^{20} ergs s^{-1} Hz $^{-1}$. In a bandpass of width $\sim 10^{14}$ Hz, this corresponds to a luminosity of 5×10^{34} ergs s^{-1} . This upper limit is lower than we predicted using equation 4.1 by a factor between 10 and 150. We note that equation 4.1 predicts the optical output of PSR0540-69.3 to be 20 times *lower* than the measured value (Pacini and Salvati 1987). Pacini and Salvati discuss how this pulsar's duty cycle, the energy spectrum of the radiating electrons, and their pitch angle in the magnetic field could explain the factor of 20. However, our measurements show that for PSR1987A, the deviation from the prediction of equation 4.1 may be more than a factor of 20, and it has the opposite sign from the deviation of the light output from PSR0540-69.3.

It is possible that optical output from the pulsar is being absorbed by the nebula. If the supernova envelope's optical depth to radiation in our bandpasses was equal to 5, it would dim the pulsar's light from that predicted by equation 4.1 to below our measured limits. An optical depth near 1 mm as high as 5 due to absorption by atomic species is unlikely after day 500 (Pinto, 1989, private communication). Condensates could be much more effective at absorbing a pulsar's optical output (Dwek 1988). However, uncertainties in the formation and survival rates leave uncertain whether condensates can be responsible for dimming sufficiently an optically bright pulsar. Current estimates from the light curve of Supernova 1987A limit energy input from a pulsar to $\sim 10^{38}$ ergs s^{-1} (Woosley *et al.* 1989), roughly equivalent to the total spin-down energy of the Crab pulsar. Extracting a limit on the optical output of a pulsar from this limit is highly sensitive to assumptions of the pulsar's spectrum, and the fraction of spin-down energy output as pulsed radiation.

It is also possible that the PSR1987A is emitting less energy than we predict above. Equation 4.1 would predict a luminosity of 5×10^{34} ergs s^{-1} for PSR1987A if either its magnetic field strength or spin frequency, or both were lower than we supposed. The magnetic field would need to be lower by a factor of 2-3, or the period as long as 28 ms. While this magnetic field is typical for neutron stars (Shapiro and Teukolsky 1983), a period of 28 ms is inconsistent with the initial period inferred for the Crab pulsar. Narayan (1987) and Chevalier and Emmering (1986) have argued that initial spin periods of neutron stars as slow as 500 ms are indicated by the distribution of current pulsar periods. There is also evidence for a ~ 200 ms periodicity discovered from the neutrino timing data from Supernova 1987A (Ogelman and Buchieri 1987). A period longer than ~ 28 ms may be indicated for PSR1987A.

The Mistaken Pulsar Report

On February 24, 1989, a telegram signed by fourteen members of the experiment collaboration was sent to the I.A.U. (Middleditch *et al.* 1989). The telegram reported optical pulsations seen in January 1989 from Supernova 1987A, and attributed them to a sub-millisecond pulsar formed by the supernova explosion. The group then published analysis of this signal, which appeared to corroborate the detection (Kristian *et al.* 1989), and suggested that the pulsar was in a binary orbit, with a Jupiter-sized companion. Almost one year later, this group found that the signal originated not from a pulsar, but from a television camera at Cerro Tololo observatory. A retraction of the original detection was subsequently published (Kristian *et al.* 1990). The text of this retraction, and additional analysis of this false report are contained in Appendix A.

Theory

The false pulsar report resulted in a substantial body of theoretical work. These investigations clarified previous assumptions about spin rates and neutron star interiors. One of the most intriguing suggestions was the possibility that strange matter might be found in collapsed stellar remnants. Additionally, interesting hypotheses about the immediate environment of a newborn pulsar were formulated to explain the disappearance of the "pulsar" signal, and the companion object. What follows is a short review of this work.

Even before the discovery of the pulsar in the Crab Nebula, (Hewish *et al.* 1968) models had been advanced for the equation-of-state (EOS) for neutron stars as early as 1939 (Oppenheimer and Volkoff 1939; for a brief history, see Shapiro and Teukolsky 1983). However, actual observations of glitches in the Crab and Vela pulsars, and the spin-down of the Crab pulsar, provided data which could constrain the relatively crude models. Pines and Shaham (1972) studied glitches in the Crab and Vela pulsars, and

suggested a model attributing the glitches to strain buildup in the crust of the pulsars. While the details of their results have not stood up to further observations, they did establish that predictions of glitch frequency and magnitude should follow from an assumed EOS and strain model.

In the period between 1972 and 1989, a variety of equations of state were studied (for a review see Arnett and Bowers 1977, or Friedman *et al.* 1986a). At the same time, the observational discoveries of the first millisecond pulsar (Backer *et al.* 1982), and the Hulse-Taylor binary pulsar (1975) provided a real possibility of discerning tests for these models. An acceptable EOS must accommodate a slowly rotating pulsar of $1.4 M_{\odot}$ (PSR 1913+16, Taylor and Weisberg 1982) without collapsing to a black hole, and also a pulsar period of 1.6 ms (PSR 1937+21) without flying apart. A number of authors have used the millisecond pulsar to test EOS models (Shapiro *et al.* 1983 and Friedman *et al.* 1988). Their results are that even the millisecond pulsar did not rule out any of the standard EOS. However, it is nearly useful in this regard. Shapiro, *et al.* (1983) write

... we find that the rapid period found for PSR 1937+214 cannot be invoked to rule out any of the currently viable equations of state. However, the discovery of a single pulsar with $P \lesssim 0.5$ ms would either (1) rule out all currently viable equations of state or (2) require substantial differential rotation in rapidly rotating neutron stars.

If this a fair representation of the theoretical environment at the time of the supposed discovery of the SN1987A 0.5 millisecond pulsar, then such a discovery is indeed very significant for neutron star science.

In the wake of the report, a new round of papers on this subject was published (Friedman *et al.* 1989, Haensel and Zdunik 1989, Sato and Suzuki 1989). These examine what new constraints on the EOS are imposed by the reported pulsar. In agreement with

the prophesy of Shapiro *et al.*, these authors find that none of the standard EOS can explain both the reported pulsar, and PSR 1913+16. The problem lies in the stiffness or softness of the star for a given equation of state. (A stiffer EOS has a larger pressure for a given density than a soft EOS.) The danger of a soft equation of state is that a slowly spinning $1.4 M_{\odot}$ mass pulsar like PSR1913+16 will collapse to a black hole. The problem with a stiff EOS is that a neutron star will be physically larger, and hence the centrifugal force of a half-millisecond star could cause it to fly apart. The stiffness also influences the neutron star's response to perturbations by radiating gravitational waves; the stiffer star is more prone to instability at high spin rates (Friedman *et al.* 1984).

There are two qualifications to these conclusions. One is that Friedman *et al.* do find two EOS which can explain a 0.5 ms pulsar. However, since these soft EOS do not allow for a slowly spinning pulsar, they imply that a 0.5 ms pulsar would eventually collapse to a black hole after it lost rotational energy. This is in agreement with Finn and Shapiro (1989), who find that in one model, the spin frequency of such a pulsar could actually increase as it loses energy. Second, the authors agree that estimates for the onset of non-axisymmetric gravitational instabilities are complicated by uncertainties in damping viscosity of the stellar material. In some cases, this could reduce the maximum spin rate allowed otherwise by a given EOS, including those considered to allow a 0.5 ms pulsar.

Because of the difficulties imposed by rotation models on the EOS, Wang, *et al.* (1989) suggest that the pulsar could be vibrating at 1968 Hz, rather than rotating at this frequency. Ruderman *et al.* (1989) examine this and other models, and point out that the proposed vibration model does not explain in detail the formation and acceleration of ions proposed as the emissive particles.

Another puzzling datum about the SN1987A pulsar was the disappearance of the pulsar signal. The supernova was observed by the same group the night following the "discovery" run, albeit with a less sensitive detector, and again two weeks later. In neither of these observations, nor in any in the months that followed was the same 1968 Hz signal

seen. Several explanations were put forth to explain this disappearance, including simple skepticism of the original detection. Among the physical models were the suggestion that the opacity of the supernova envelope had changed (Kristian *et al.* 1989), Nakamura 1989); that the pulsar might have turned off, due to accretion of nearby material (Woosley and Chevalier 1989); models for precession of the pulsar beam away from the line of sight (Glendenning 1989a); and collapse to a black hole (Glendenning 1990) or quark star (Glendenning 1989b), Glendenning 1989c). Of these, the reported pulsar may have been the first astrophysical system to support the theory in the last two cases. We discuss these in more detail.

Glendenning (1989b and c) points out that considering the normal EOS library in the context of a 0.5 ms pulsar is contradictory. Glendenning argues that the central density implied by the a standard model is in excess of typical nuclear density by a factor of 15. The predicted central density is 9.4 times greater than the density of protons packed as classical spheres of the proton charge radius. He suggests that the expected state of such dense matter is instead an approximately equal mixture of u, d, and s quarks. This follows from the suggestion of Witten (1984) that at this energy density the lowest energy state may include strange quarks. A pulsar consisting of strange matter would have a different mass-radius relationship than purely hadronic pulsars. This leads to the coincidence that the conversion of the core of a normal pulsar to strange matter would speed up the rotation rate by about a factor of 3 – 4, roughly the same factor by which a 0.5 ms pulsar is faster than the fastest previously discovered pulsar. With the retraction of discovery of PSR1987A, there is again little evidence for this scenario.

As a final puzzle about the report of Kristian *et al.*, the 1968 Hz signal had a sinusoidal modulation, reminiscent of other pulsars in binary systems, but with a period of about 8 hours. Modelling the pulsar-companion system reveals that the companion orbit would be well within the radius of the original progenitor star. To explain this circumstance, it is suggested by Nakamura (1989) and Nakamura and Fugita (1989) that

either the original iron core fragmented into two pieces upon collapse, or that an aggregation of material in an accretion disk could produce such an object. The obvious problems with both these scenarios are discussed in the referred papers.

Chapter V. Conclusions

Null results are rarely as exciting as making new discoveries. Further, it is difficult to infer any but a narrow conclusion from a null measurement. Since few expected to see an optical pulsar in Supernova 1987A by this time, these measurements have not yet formed a conclusive test of standard theories. However, it is very possible that as time goes on and the nebula thins, an optical pulsar may be detected. There are many scenarios one could imagine which would render the present set of observations of great interest. Only time will tell. In any event, we have developed new and more sensitive instruments for this search than were previously available, and used them to make observations of unprecedented sensitivity.

We have set upper limits for the appearance of an optical pulsar in Supernova 1987A in the first three and one half years after the core collapse. We have observed with bandpasses between 3000 angstroms and 1.8 microns, at sampling rates from 10 kHz to 200 kHz. As of September 26, 1990, we have seen no evidence for pulsations due to a neutron star within the supernova remnant. We expect that this search will continue.

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Appendix A: A Complete List of Search Observations

Table A1 presents a summary all of the observations since this search began.

Explanation and definitions for the entries are after the table.

Table A.1 Complete List of Search Observations

Date (days since core collapse)	Detector	Sampling Speed (kHz)	Observatory/ Telescope (m)	Filter	Observers	Magnitude Limit		
21.87	17 Mar 87	S20	1	CTIO	0.9	JG	16.9	
22.89	18 Mar	S20	1	CTIO	0.9	GG495	JG	15.4
30.83	26 Mar	S20	1	CTIO	1.0	ND 1.0	CP RM	16.4
30.82	26 Mar	S20	10	CTIO	1.0	ND 1.0	CP RM	15.6
30.84	26 Mar	S20	10	CTIO	1.0	ND 1.0	CP RM	14.9
31.81	27 Mar	S20	1	CTIO	1.0	GG495	CP RM	16.6
32.70	28 Mar	S20	10	LCO	0.61		IS CP RM	14.9
47.81	12 Apr	S20	10	LCO	0.61	ND 1.0	IS	15.2
52.87	17 Apr	S20	1	CTIO	1.0	ND 2.5	MH	13.8
54.80	19 Apr	S20	10	LCO	0.61	ND 1.0	IS	15.1
69.75	04 May	S20	10	LCO	0.61	ND 1.0	IS	15.0
76.70	10 May	S20	1	CTIO	1.0	ND 2.5	MH	14.8
87.68	21 May	S20	1	CTIO	1.0	ND 2.5	MH	14.8
114.66	17 Jun	S20	1	CTIO	1.0	ND 2.5	JM JI	13.5
116.66	19 Jun	S20	1	CTIO	1.0	B	JM JI	16.0
118.66	21 Jun	S20	1	CTIO	1.0	CuSO4	JM JI	16.4
147.08	20 Jul	S20	10	LCO	0.61		IS	16.2
157.05	30 Jul	S20	10	LCO	0.61	CuSO4	IS	16.2
176.02	18 Aug	S20	10	LCO	0.61	BG12,38	WK JF	12.7
176.10	18 Aug	S20	10	LCO	0.61		WK JF	16.3
206.08	17 Sep	S20	2	LCO	0.61	BG12,38	JF	12.3
227.04	08 Oct	S20	20	LCO	0.61		JF	15.7
260.99	11 Nov	S20	10	LCO	0.61		JF	16.2
291.03	11 Dec	S20	10	LCO	0.61		JF	14.7
303.01	23 Dec	S20	10	LCO	0.61		JF	14.8
317.81	07 Jan 88	S20	10	LCO	0.61		BH	14.8
332.87	22 Jan	Si	1	CTIO	4.0		JM CP	20.2
333.98	23 Jan	Amp	1	CTIO	4.0		JM CP	18.4
333.75	23 Jan	Si	10	CTIO	4.0		JM CP	19.8
333.83	23 Jan	Si	10	CTIO	4.0		JM CP	19.7
334.75	24 Jan	Amp	10	CTIO	4.0		JM CP	18.4
345.72	04 Feb	S20	10	LCO	0.61		JF	15.0
354.78	13 Feb	S20	10	LCO	0.61		JF	15.1
365.77	24 Feb	S20	10	LCO	0.61		JF	16.5
408.75	07 Apr	S20	10	LCO	0.61		JF	16.6
414.71	12 Apr	S20	10	LCO	0.61		JF	16.8
438.77	07 May	S20	10	LCO	0.61		JF	16.8

Table A.1 (*continued*)

Date (days since core collapse)	Detector	Sampling Speed (kHz)	Observatory/ Telescope (m)	Filter	Observers	Magnitude Limit
443.78	12 May	Si	10	LCO	2.5	WK TS 20.1
492.12	29 Jun	Si	20	LCO	1.0	WK TS 17.8
493.11	30 Jun	Si	20	LCO	1.0	WK TS 17.8
526.10	02 Aug	Si	20	LCO	1.0	WK 17.8
526.41	02 Aug	S20	10	MS	0.76	IT 18.8
552.89	29 Aug	S20	10	CTIO	4.0	JM TS 20.6
553.03	29 Aug	Si	10	CTIO	4.0	JM TS 21.4
589.29	04 Oct	S20	10	MS	0.76	IT SR 18.2
592.03	07 Oct	Si	10	LCO	1.0	WK 18.4
592.29	07 Oct	S20	10	MS	0.76	IT SR 18.3
614.06	29 Oct	S20	10	MS	0.76	IT SR 17.9
659.19	13 Dec	S20	10	MS	0.76	SR 18.8
694.81	18 Jan 89	Si	5	CTIO	4.0	JM TS 21.8
694.95	18 Jan	Si	5	CTIO	4.0	JM TS 21.8
694.76	19 Jan	GaAs	10	CTIO	4.0	JM TS 20.1
707.36	30 Jan	Si II	10	MS	0.76	SR IT 17.6
707.85	31 Jan	Si	10	LCO	2.5	WK 20.4
707.94	31 Jan	Si	10	LCO	2.5	WK 20.4
723.91	16 Feb	Si	10	LCO	2.5	WK 20.2
721.33	13 Feb	Si II	10	SSO	2.3	SR 19.9
725.86	18 Feb	Si	10	LCO	1.0	TS 18.4
727.88	20 Feb	Si	10	LCO	2.5	TS WK SP 20.4
727.94	20 Feb	Si	10	LCO	2.5	TS WK SP 19.6
728.80	21 Feb	Si	10	LCO	2.5	TS SP 20.4
728.86	21 Feb	Si	10	LCO	2.5	TS WK SP 19.9
728.89	21 Feb	Si	10	LCO	2.5	TS WK SP 20.1
729.06	21 Feb	Si	10	LCO	2.5	TS WK SP 19.8
732.78	25 Feb	Si	10	CTIO	4.0	WK DM 21.2
736.72	01 Mar	Si	10	CTIO	4.0	WK AG 21.1
738.15	02 Mar	Si II	10	SSO	2.3	SR IT 19.9
739.74	04 Mar	Si	10	CTIO	4.0	JK AG 21.1
741.73	06 Mar	Si	20	CTIO	4.0	AG DM 20.7
741.75	06 Mar	Si	20	CTIO	4.0	AG DM 20.3
756.75	21 Mar	Si	10	CTIO	4.0	DM AG SH 21.0
759.71	24 Mar	Si	10	CTIO	4.0	DM SH 21.1
762.70	27 Mar	Si	10	CTIO	4.0	DM SH 20.9
771.21	04 Apr	Si II	10	SSO	2.3	SR IT 19.9
775.61	08 Apr	Si	10	CTIO	4.0	DM 20.8
786.69	18 Apr	Si	10	CTIO	4.0	DM 20.9
799.08	02 May	Si II	10	SSO	2.3	SR 19.9
808.71	12 May	Si	10	CTIO	4.0	SH 21.2
820.71	24 May	Si	10	CTIO	4.0	JK 21.2
879.84	22 Jul	Si	10	CTIO	4.0	JM JK TS 21.4
879.92	22 Jul	Si	10	CTIO	4.0	JM JK TS 21.4
880.00	22 Jul	Si	10	CTIO	4.0	JM JK TS 21.4
880.08	22 Jul	Si	10	CTIO	4.0	JM JK TS 21.1
881.77	24 Jul	GaAs	10	CTIO	4.0	JM JI JK TS 22.6

Table A.1 (continued)

Date (days since core collapse)	Detector	Sampling Speed (kHz)	Observatory/ Telescope (m)	Filter	Observers	Magnitude Limit
881.84	24 Jul	GaAs	10	CTIO	4.0	JM JI JK TS 22.6
881.92	24 Jul	GaAs	10	CTIO	4.0	JM JI JK TS 22.7
882.08	24 Jul	GaAs	10	CTIO	4.0	JM JI JK TS 22.5
927.44	07 Sep	Si II	10	SSO	2.3	SR 19.1
928.45	08 Sep	Si II	10	SSO	2.3	SR 19.9
929.44	09 Sep	Si II	10	SSO	2.3	SR 19.9
958.38	08 Oct	Si II	10	SSO	2.3	SR 19.9
958.44	08 Oct	Si II	10	SSO	2.3	SR 19.7
969.82	20 Oct	S20	10	LCO	2.5	WK 21.4
969.87	20 Oct	S20	10	LCO	2.5	WK 21.3
969.92	20 Oct	S20	10	LCO	2.5	WK 21.3
969.96	20 Oct	S20	10	LCO	2.5	WK 21.2
970.02	20 Oct	S20	10	LCO	2.5	WK 21.2
970.06	20 Oct	S20	10	LCO	2.5	WK 20.7
999.88	19 Nov	GaAs	50	LCO	2.5	.8 μ mLP JK 21.7
1002.38	21 Nov	Si II	10	SSO	2.3	SR 19.9
1002.45	21 Nov	Si II	10	SSO	2.3	SR 19.9
1003.25	22 Nov	Si II	10	SSO	2.3	SR 19.9
1003.33	22 Nov	Si II	10	SSO	2.3	SR 20.0
1003.40	22 Nov	Si II	10	SSO	2.3	SR 20.0
1029.75	19 Dec	GaAs	10	LCO	2.5	RG610 WK 21.4
1029.80	19 Dec	GaAs	10	LCO	2.5	RG610 WK 21.4
1029.85	19 Dec	GaAs	10	LCO	2.5	RG610 WK 21.4
1029.90	19 Dec	GaAs	10	LCO	2.5	RG610 WK 21.3
1029.95	19 Dec	GaAs	10	LCO	2.5	RG610 WK 21.4
1030.00	19 Dec	GaAs	10	LCO	2.5	RG610 WK 21.4
1045.30	03 Jan 90	Si II	10	SSO	2.3	SR 19.9
1045.37	03 Jan	Si II	10	SSO	2.3	SR 19.7
1060.97	19 Jan	Ge	20	LCO	2.5	LP TS WK 19.0
1061.00	19 Jan	Ge	20	LCO	2.5	LP TS WK 19.0
1061.82	20 Jan	Ge	20	LCO	2.5	LP TS WK 19.6
1062.92	21 Jan	Ge	20	LCO	2.5	LP TS WK 19.4
1062.97	21 Jan	Ge	20	LCO	2.5	J TS WK 18.8
1062.99	21 Jan	Ge	20	LCO	2.5	H TS WK 18.6
1063.77	22 Jan	Ge	20	LCO	2.5	LP TS WK 19.5
1063.96	22 Jan	Ge	20	LCO	2.5	J TS WK 19.5
1064.02	22 Jan	Ge	20	LCO	2.5	TS WK 18.7
1079.90	07 Feb	Ge	50	CTIO	4.0	LP JM TS 20.7
1080.90	08 Feb	Ge	50	CTIO	4.0	LP JM TS 20.8
1088.89	16 Feb	GaAs	50	LCO	2.5	RG690 JK 22.2
1090.95	18 Feb	GaAs	50	LCO	2.5	.8 μ mLP JK 21.6
1120.81	20 Mar	GaAs	50	LCO	2.5	RG690 WK 22.3
1285.80	01 Sep	Ge	20	LCO	2.5	LP TS WK 20.0
1310.95	26 Sep	Ge	50	LCO	2.5	LP JK RL WK 19.9

Explanation for Table A.1:

Date This is the time in days since February 23.316 UT, 1987, the time neutrinos from the explosion were observed (Hirata *et al.* 1987 and Bionte *et al.* 1987). The calendar day is also shown.

Detector

The spectral response and other characteristics of the photodiode and RCA S-20 detectors are described in Chapter II. The spectral response curves for the Ga-As and Amperex photomultiplier tube may be found in Landolt-Bornstein (1981).

Si: The Silicon photodiode detector

Si II: A duplicate of the original Silicon photodiode detector, used in Australia

Ge: The Germanium photodiode detector

S20: RCA (or EMI) S-20 photomultiplier tube. The spectral response is shown in Chapter II.

Amp: Amperex photomultiplier tube, with biakali photocathode. This spectral response of this tube extends from 350 nm to 600 nm.

GaAs: Gallium-Arsenide photocathode, used with RCA C31034 photomultiplier. The spectral sensitivity of this tube is similar to S20, but red-sensitivity extends to 900 nm.

Observatory / Telescope:

CTIO: Cerro Tololo Inter-American Observatory, Chile

LCO: Las Campanas Observatory, Chile

MS: Mount Stromlo Observatory, Australia

SSO: Siding Spring Observatory, Australia

The telescope diameter is shown in meters.

Filters

GG495 - Long pass filter, from 495 nm

ND 1.0 - Neutral density; 1 magnitude reduction

ND 2.5 - Neutral density; factor of 10 reduction

CuSO₄ - Short pass filter, cutoff approximately 500 nm

BG12,38 - similar to B filter

RG 690, 665, 610: Long pass filters. Number is cutoff wavelength in nm.

LP - Long pass filter for Ge system; cutoff wavelength .8 μ m; cooled with LN.

B, J, H - Standard astronomy passbands

A blank space indicates that no filter was used.

Observers

JM - Middleditch, J.	CP - Pennypacker, C. R.	JK - Kristian, J.
MH - Hamuy, M. A.	JI - Imamura, J. N.	WK - Kunkel, W. E.
RM - Muller, R. A.	SP - Perlmutter, S.	SR - Rawlings, S.J.
TS - Sasseen, T. P.	IS - Shelton, I.K.	IT - Tuohy, I. R.
AG - Gomez, A.	DM - Maturana, D.	SH - Heathcote, S.
JF - Filhaber, J.	BH - Herbst, W.	

Magnitude Limit

This is the upper limit on the apparent magnitude of pulsations in the particular passband used. The calculation of this magnitude is described in Chapter III.

Table A.2 Spectral Coverage Data

The following table contains additional data for the limits shown in Figure 4.2.

Day	Date	Detector	Filter	Bandpass Blue	Wavelengths (nm) Central	Red	Flux Limit (mJ)
1030.00	19 Dec 89	GaAs	RG610	600	750	850	0.03
1045.30	03 Jan 90	Si II		550	850	1100	0.1
1063.96	22 Jan	Ge	J	1100	1250	1400	0.4
1064.02	22 Jan	Ge		950	1300	1600	0.6
1080.90	08 Feb	Ge	LP	800	1300	1600	0.08
1090.95	18 Feb	GaAs	.8 μ mLP	800	850	900	0.03
1120.81	20 Mar	GaAs	RG690	700	800	850	0.01

Explanation of the column headings for Table A.2 are the same as for Table A.1, except for the bandpass and flux limit information. The central wavelength of the bandpass is chosen such that half of the absorbed energy is at longer wavelengths, and half is at shorter wavelengths. The "Blue" and "Red" column headings denote the wavelengths at which the transmission of the bandpass is 50% of the peak value. Wavelength values shown are in nanometers, and are rounded to nearest 50 nm.

The calculation of the flux limit (shown in milliJanskys) is described in Chapter IV.

Appendix B: The false pulsar report

While occasionally false reports and claims are published in science journals, these same journals are rarely a forum for discussion and didacticism of such issues. Rather, these discussions are left to oral folklore, seldom discussed, and then infrequently openly. It may be worthwhile therefore to record here some of the events which lead to the mistaken pulsar report, and suggest which contributors were mistakes, or carelessness, and which were an inevitable part of forefront research. For the graduate student on the project, this false report, the accompanying analysis, and concomitant discussions have provided a unique opportunity to witness and learn from experiences which if encountered later, could be purchased only at a much dearer cost.

An attempt to explain what lead to the false report is more history than physics. Since this is a physics thesis, we will instead concentrate on those aspects of the experiment on which crucial judgements rested. Since schooling such judgement is a vital part in the development of any physicist, we hope to capture in this section some of the lessons learned from these events.

The arguments for believing the original pulsations were due to a pulsar were summarized in Kristian *et al.* (1989). Here is the relevant paragraph:

In view of the lack of confirmation so far of the pulsations reported here, it seems useful to summarize the evidence for their proposed origin. They are extremely strong, and are clearly real; the question is whether they originate in the supernova or are merely instrumental. They are unlike anything seen in 36 previous runs using the same instrumentation over the preceding two years; a number of artefacts in the data have been seen over this period, but these pulsations are unprecedented in their strength and their behavior. Taking into account the 8-h sinusoidal variation, they are phase-coherent over the entire 7 h of observation, so that an integral number of cycles for the fundamental frequency can be counted unambiguously between sets of data. The pulsations are as narrow in $(f, df/dt)$ space as

would be a δ -function for such a discrete Fourier transform, which implies an extremely good time-keeping mechanism. In addition to the fundamental frequency, evidence is seen for two higher harmonics, which track the fundamental in frequency and intensity. The pulsations are not seen in data taken on another object immediately following the supernova observation. The observed frequency modulation is a good fit to a sine wave only when transformed to barycentric coordinates. The ratio of harmonics is similar to that seen in the Crab pulsar.

As indicated in this paper, since the pulsations were definitely real (i.e. present in the data), the real issue was whether or not they were instrumental in origin. The reasons to believe they were not instrumental were indeed compelling. These are modified in retrospect by the recollection that the TV camera found later to be the source of the pulsations was switched off in between the two observations that night. However, puzzling still are the sinusoidal behavior of the signal after transforming to the barycentric frame, and the similarity in the ratio of harmonics to that of the Crab pulsar.

Despite the power of the reasons to believe the source of the signal was not instrumental, there were serious reasons why the signal was unlikely to be due to a pulsar. These included the brightness of the signal, the disappearance of the signal, and the frequency modulation of the signal. Despite a number of papers anticipating the pulsar's discovery, certainly none of these behaviors had been predicted for the pulsar. The matter came down to deciding which of two unlikely options one preferred; there seemed to be no third alternative. In this situation, the collaboration of primarily experimentalists and observers found it easier to ascribe the difficulty to the theoretical camp.

An interesting aspect to the publication was that another group was observing the supernova looking for the pulsar the very same night. Although this work was known to our group, no inquiry was made of their results, for two reasons. The first was the fear that so-called confirmation of either group's result could discourage a thorough examination of all of the experimental facts. It is difficult not to be rendered less cautious

by a "We see something there too!" However, for the final analysis, each experimental result should be judged only on the experiment from which it was derived. The second reason the other group was not consulted was the desire of members of our group not to share credit for the discovery. This attitude may be endemic to scientists, and there is a tendency to tolerate this as "Boys will be boys." However, the public does not fund science for the private amusement of scientists. Many nights on big telescopes at public observatories were devoted to looking for this pulsar as a result of this report. When the advancement of knowledge is held up or public funds wasted, one must ask if this tolerance has extended too far. However, in this case, the judgement of other scientists on our group's conduct has been approving.

Communication was a vital aspect of this experiment, and one which formed one of the shortcomings of the collaboration, regardless of one's final judgement of the outcome. The common education received by most physicists forms a trap for the belief that communication takes place on secure ground. In fact, the conduct of experimental research is taught in an individual research group, each having its own particular philosophy and idiosyncrasies. In the course of a day, a researcher may make many tens of small decisions, calculations, or judgements. When an exciting development breaks, is it possible that all of these preceding judgements are identified, understood, and discussed? Of course they are not. We reconcile ourselves with the thought that at least the critical issues will out. Springing from a milieu in which learning to communicate effectively may drown in a sea of equations and computer printouts, it seems unlikely that even as many as a dozen researchers will be party to all necessary information.

One very important development in this experiment was the ability to do near real-time analysis of the data to look for a signal. When the 1968 Hz signal reappeared in January of 1990, we knew this while we were still observing. This allowed us to adjust our observing schedule accordingly. If we had had a similar ability during the original observation, it is possible that we could have used this information to search immediately

for sources of interference. One thing which had previously discouraged us from developing an on-site analysis program was our belief that any interesting signal would be barely detectable, even by our most sensitive computer analysis, and therefore impossible to see using the limited computer resources at the observatory. However, our experiences showed that reasoning was in error.

What follows is the text of the retraction letter sent to Nature (Kristian *et al.* 1990).

There is No Half-Millisecond Pulsar in SN 1987A

We previously reported an observation of what appeared to be an optical pulsar in the remnant from supernova 1987A 1. This observation has proved to be spurious. Despite repeated intensive searches by us and others for a year following the original observation in January, 1989, the putative pulsar was not confirmed. In new data obtained in February, 1990, however, we again detected the signal, not only in data from the supernova, but also in comparison data taken on the Crab pulsar at the same time. From this, it is clear that the signal did not originate in the supernova, and we retract our reported discovery of the pulsar.

We believe that the observed signal is electrical noise from a closed circuit television camera used for acquisition and guiding at the Cassegrain focus of the 4-meter telescope at Cerro Tololo Interamerican Observatory (CTIO), where both sets of data were taken. The observed frequency of 1968.627 Hz is close to the 16th subharmonic of the nominal horizontal sync pulse of the camera (1968.75 Hz); the coincidence seems too close to be accidental.

We do not know how the signal coupled into our detector, nor have we been able to totally reconstruct events during the observations. However, we think there are plausible

explanations for some of those things that made the original observation appear real. The most important of these are:

(1) The signal disappeared when the telescope was pointed at a different object immediately after the run on the supernova. As best we can reconstruct events, it is likely that the offending guider camera was turned off between the two sets of observations in order to prevent it being damaged by the increasing light of twilight.

(2) The signal was not observed with the same equipment on the same telescope either before or after the detection run, until the run in February, 1990. It is impossible after the fact to determine why this is so, but a number of plausible explanations come to mind, any one or more of which might have occurred; for example, there may have been subtle differences in the mounting of the detector system, or changes in the adjustment of components, or a different guider camera (one without the 1968 Hz problem) may have been used (there are two such cameras at the telescope, which are used interchangeably), etc.. It should be noted in this context that the system is extremely sensitive, and the detected signal was very small by normal standards: the equivalent interference current was of order 10-15 amps.

(3) Several highly suggestive properties of the observed frequency were totally fortuitous. The stability of the frequency over the 7 hour run was quite high (10^{-6}), which indicated a good time-keeping mechanism. This is about a factor of 100 better than the stability specification for the time base of the camera. Furthermore, the observed small frequency change was quite smooth, and when the data were corrected for the earth's motion, they were well fit by a sine wave, which suggested an external origin. (When a sine wave was subtracted from the data, the frequency residuals decreased by an order of magnitude. This was the basis for considerable speculation: for example, that the pulsar might be in a binary orbit.) Likewise, the fact that the first two higher harmonics were in the same proportions as those seen in the Crab pulsar was a coincidence. All of this was undoubtedly a combination of bad luck (although Divine malice has also been suggested),

misplaced pattern-finding skills, and the common human tendency to over-interpret a limited amount of data.

Searches for the pulsar continue, so far unsuccessfully.

END

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