A TUNABLE CRYSTAL DIFFRACTION TELESCOPE FOR THE INTERNATIONAL SPACE STATION*

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ABSTRACT

Even though technically innovative, a tunable crystal diffraction telescope for use in nuclear astrophysics has become feasible today. The focusing gamma-ray telescope we intend to propose for the space station consists of a tunable crystal diffraction lens, focusing gamma-rays onto a small array of Germanium detectors perched on an extendible boom. While the weight of such an instrument is less than 500 kg, it features an angular resolution of 15", an energy resolution of 2 keV and a 3 σ sensitivity of a few times 10^7 photons^{-1}cm^{-2} (10^6 sec observation) for any individual narrow line at energies between 200 - 1300 keV.

This experience would greatly profit from the continuous presence of man on the station. Besides of the infrastructure for maintenance and servicing of the various innovative techniques used for the first time in space, the available extra-vehicular robotics will facilitate deployment of the required boom structure.

INTRODUCTION

Present telescopes for nuclear astrophysics make use of geometrical optics (shadowcasting in modulating aperture systems) or quantum optics (kinetics of Compton scattering). Because the collecting area of such systems is identical to the detector area, nuclear astrophysics has come to an impasse where "bigger is not necessarily better": with the background noise being roughly proportional to the volume of a detector, a larger photon collection area is synonymous with higher instrumental background - consequently, the signal to noise ratio does not improve with the larger collectors.

The telescope we intend to present for the International Space Station will, for the first time, use a gamma-ray lens. The signal/noise ratio will be dramatically improved as gamma-rays are collected on the large area of a lens from where they are focused onto a small detector. As a result, this instrument can overcome the mass-sensitivity impasse and reach outstanding performances.

Until recently, focusing of gamma-radiation was regarded as an impracticable task. Today, gamma-ray lenses exist (Figure 1) and have been tested in the laboratory at energies up to 700 keV (Smither 1989, von Ballmoos and Smither 1994, Naya et al. 1996). Besides an unprecedented sensitivity, such an instrument features very high angular and energy resolution.

Fig. 1 The prototype gamma-ray lens and the 3x3 Germanium matrix during the ground based system tests at ANL. When operating in the focal spot of the lens, the Ge detector was located 10-20 m behind the lens.

SCIENTIFIC POTENTIAL

The characteristics of crystal diffraction telescopes can be exploited for a variety of observational aims: precise source localization, two-dimensional intensity mapping of sources with arc minute extent, the observation of narrow spectral lines, measurement of pulsar light curves in a narrow energy band...

The concept of diffracting a narrow energy band is ideally matched to the observation of the narrow lines in the domain of nuclear transitions. Besides the supernovae 1987A (Matz et al 1988) and 1991T (Morris et al 1995) the evidence for point like sources of narrow gamma-ray line emission has been mostly implicit at this point. Yet, various objects like galactic novae and extragalactic supernovae are predicted to emit detectable gamma-ray lines. These sources should have small angular diameters but very low fluxes - mostly because such objects are relatively rare and therefore are more likely to occur at large distances.

The instrumental requirements for exploring this kind of sources match with the anticipated performance of a crystal diffraction telescope (Figure 2).
supernovae: Deeper insight in the explosive nucleosynthesis using the usual key isotopic decay chains identified for supernovae might be used to constrain the models (at this time, detonation or deflagration) and to understand the dynamics of the explosion through the shape and red (blue) shifts of the gamma-ray lines.

The expected fluxes are highly dependent on the models of the different types of SN explosions (especially the convection processes which could remove synthesized materials from the high temperature burning regions). The study of the explosive nucleosynthesis represents a crucial input to better understand the chemical history of the Galaxy. The nuclear gamma-ray lines from a supernova that could be observed by a crystal lens are the 847 keV and 1238 keV line from the decay chain \(^{56}\text{Ni} ightarrow ^{56}\text{Co} ightarrow ^{56}\text{Fe}\), the 1156 keV line from \(^{44}\text{Ti}\), and the 1173 keV line from \(^{56}\text{Fe}\). The photons produced by the nuclei in the shell have noticeable Doppler-shifts due to the motion of the expanding supernova ejecta (a few 10000 km/s).

A large broadening of the lines - up to 40 keV at 847 keV is expected for SN type I where the shell gets transparent relatively early. At this energy the bandwidth of a crystal diffraction telescope is about 16 keV FWHM which corresponds to > 35% of the flux in the SN line. Tuning parts of the lens to different energy bands or scanning the line profile in energy will provide a complete coverage of these potentially broad features.

For supernovae of type II (core collapse SN - the gamma-ray flux is initially obstructed by the massive shell), the broadening is much less accentuated than for SNIa's as the observations of SN1987A have shown. A volume of a few Mpc should be accessible to an instrument with a sensitivity of \(10^{-7}-10^{-6} \text{ ph cm}^{-2}\text{s}^{-1}\) (T_{obs} \(10^5\) seconds) - this will make their detection possible for events occurring within our local cluster.

It has been suggested that the observability of SNIa can be expressed independently of the distance of the host galaxy since the optical peak magnitude of the SN should be directly correlated to the gamma-ray line flux (Arnett 1982). Indeed, the decay of the ejected gamma-ray isotopes actually is the energy source of the optical light curve.

Here, SN1991T has been used to establish a relation between gamma-ray flux f_{847} and optical peak magnitude m_v (the COMPTEL detection of SN1991T gives f_{847}=(5.3 \pm 2.0) \times 10^{-5} \text{ ph cm}^{-2}\text{s}^{-1} for an optical peak magnitude of m_v = 11.6)

\[
\log(f_{847}/10^{-4} \text{ ph cm}^{-2}\text{s}^{-1}) = 0.4(10.9-m_v)
\]

Thus a detectable flux of \(\sim 10^{-6} \text{ ph cm}^{-2}\text{s}^{-1}\) is expected from SNIa's with optical peak magnitudes m_v < 16. In recent years (2/1987-6/1996), events of this magnitude and brighter were observed at a rate of about three per year (Tsvetkov et al. 1996).

**THE PRINCIPLE OF A DIFFRACTION LENS**

Our gamma-ray lens consists of a frame on which concentric rings of germanium single crystals are mounted (Fig. 3).

In order to get diffracted, an incoming \(\gamma\)-ray must satisfy the Bragg-relation

\[
2d \sin(\theta) = n \lambda
\]  

where d is the crystal plane spacing, \(\theta\) the incident angle of the photon, n the reflection order, and \(\lambda\) the wavelength of the \(\gamma\)-ray.

Each ring uses crystals with a different set of crystalline planes. The radius R of each ring is optimized so that all crystals diffract the incident radiation to the same focal point. R, is given by the relationship:

\[
R = D \tan 2\theta
\]

where D is the focal distance.

Thus the lens concentrates the radiation collected from a large area into a small focal spot. This allows a modest size, well shielded detector to register a much larger signal than it would have intercepted if it was exposed to the radiation field directly.

In order to take maximum advantage of the particular properties of a focused gamma-ray beam, a novel gamma-ray detector, consisting of a high-purity 5x3 germanium matrix housed in a single cylindrical aluminum cryostat will be used. A prototype lens
CONCLUSION

A tunable crystal diffraction telescope for nuclear astrophysics has become feasible today: 1) A monochromatic prototype lens suitable for an astronomical instrument exists and has been tested in the laboratory at energies up to 700 keV. 2) The energy-tuning of single crystals is possible using today's piezotechnology; a first tunable lens including 20 closed-loop system is presently being tested. 3) Germanium detector arrays are manufactured today and have demonstrated their advantages in conjunction with the prototype lens. 4) Various space experiments have been carried out using extendible booms. The weight of such an instrument is less than 500 kg, yet it features an angular resolution of 15°, an energy resolution of 2 keV and a 3 σ narrow line sensitivity of a few times 10⁻⁷ photons s⁻¹ cm⁻² (10⁵ sec observation) at energies between 200 - 1300 keV. (Fig. 5). The energy bandwidth will be of 1-50 keV over this range (increasing with energy).

The concept of diffracting a narrow energy band is ideally matched to the narrow lines in the domain of nuclear transitions. A tunable space borne crystal telescope will permit the observation of any identified source at any selected line-energy in a range of typically 200 keV to 1300 keV. The sites of explosive nucleosynthesis are in fact a natural target for such an instrument: The nuclear lines of extragalactic supernovae (⁵⁶Ni, ⁴⁴Ti, ⁶⁰Fe) and galactic novae (p+p line, ⁷Be) are accessible to observation, one at a time, since different decay times and changing opacity to gamma-rays give rise to different lines being dominant at different times after the explosion. Other scientific objectives include the narrow 511 keV line from galactic broad class annihilators (such as 1E1740-29, nova musca), possible redshifted annihilation lines from AGN's but also two-dimensional intensity mapping of strong continuum sources with unprecedented angular resolution. Because of the various innovative techniques used for the first time in space this experience would greatly profit from the continuous presence of man. While the station's infrastructure will enable maintenance and servicing of the lens-nanotechnology and cryogenic Ge-detector arrays, the extra-vehicular robotics available on the station will facilitate deployment of the required boom structure. The ATV is a natural choice to carry out the transfer to/from a closeby orbit where observations with the gamma-ray lens will be made.

As an R&D project, the tunable gamma-ray lens project is supported by the French Space Agency CNES since 1994. Also, our Laue Crystal Telescope (LCT) is under study as a part of the Hard X-Ray Telescope (HXT) which has been selected by NASA for a mission concept study in 1995 (NRA 94-OSS-15, CoI's LCT: B. Smither, P. von Ballmoos).

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