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GAMMA RAY LINES FROM SUPERNOVAE, SUPERNOVAE REMNANTS, AND THE INTERSTELLAR MEDIUM

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RESUMEN

Se discuten las primeras observaciones, la situación y las perspectivas de la astronomía de líneas de rayos gama. Las observaciones iniciales fueron llevadas a cabo por Bob Haymes y su equipo de la Universidad de Rice, con la primera detección de una línea espectral astronómica de rayos gama —una línea cercana a 0.5 MeV— asociada con la línea de aniquilación del positrón en la región central de la galaxia. El campo ha progresado lentamente debido a los bajos flujos. Sin embargo, ha habido resultados emocionantes en las observaciones de líneas de rayos gama de supernovas, en la detección de ^{26}Al radioactivo del plano galáctico y en la evidencia de emisión difusa de Orión. Con las perspectivas de mejoras sustanciales en sensitividad, es claro que la astronomía de líneas en rayos gama tiene un importante futuro.

ABSTRACT

The early observations, status and future prospects of gamma ray line astronomy are discussed. The initial observations were achieved by Bob Haymes and his team at Rice University with the first detection of an astronomical gamma ray spectral line —a feature near 0.5 MeV— associated with the positron annihilation line from the galactic center region. The field has progressed slowly due to the low fluxes. Nevertheless, exciting results have been achieved on gamma ray line observations of supernovae, the detection of radioactive ^{26}Al from the galactic plane, and evidence for diffuse emission from Orion. With prospects for significant improvement in sensitivity, it is clear that gamma ray line astronomy has an important future.

Key words: **GAMMA RAYS: OBSERVATIONS — NUCLEAR REACTIONS, NUCLEOSYNTHESIS, ABUNDANCES — SUPERNOVAE: GENERAL**

1. INTRODUCTION

The early 1960s witnessed the birth of X-ray and gamma ray astromony. The first detection of a celestial X-ray source was obtained on a rocket flight by Giacconi et al. (1962) when they observed X-ray emission toward the galactic center (Sco X-1 was the source being observed). Using a lunar occultation of the Crab Nebula in 1964, the NRL team led by Herb Friedman proved the Crab was an X-ray source and also showed that the bulk of the emission originated from the nebula rather than a hypothetical compact remnant of the explosion of 1054 A.D. (Bowyer et al. 1964).

The Crab Nebula was also the first objective of gamma ray line astronomy. Burbidge et al. (1957) laid the framework for nucleosynthesis of the heavy elements in supernovae. They also suggested that the exponential decay of Type Ia supernovae might be powered by the radioactive decay of a freshly-synthesized element and suggested ^{254}Cf as a candidate. Wade Craddock, Bob Haymes' first graduate student, and Don Clayton calculated the spectrum of gamma radiation from the Crab Nebula (Clayton & Craddock 1965), arriving at optimistic fluxes for lines from ^{249}Cf and ^{251}Cf that might be detectable by Rice's new balloon-borne gamma-ray experiment. A June 1967 observation of the Crab revealed a power-law spectrum, but no gamma ray line features (Haymes et al. 1968). This flight did, however, provide the data with which Fishman et al. (1969) discovered hard X-ray emission from the Crab pulsar. Clayton, Colgate, & Fishman (1969) identified ^{56}Ni-decay gamma rays from supernovae as a prime target for gamma ray astronomy.

These first attempts to search the heavens for gamma ray line emission foretold the difficulties to be experienced by a generation of gamma ray astronomers. The Rice group did make the pioneering observation of 0.5 MeV emission from the galactic center region (Johnson & Haymes 1973). The Sun was soon to provide impetus to the field with the detection of gamma ray lines from solar flares (Chupp et al. 1973). In this paper we discuss the painstaking progress, the current status, and also comment on future prospects.

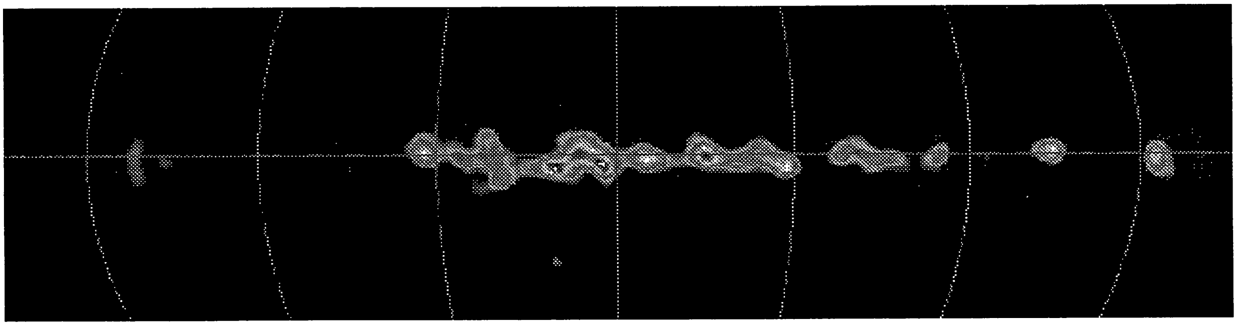

Fig. 1. *COMPTEL* map of ^{26}Al in the Galaxy. Lines of constant latitiude are shown every 30 degrees. Positive longitude is to the left. The emission is concentrated along the galactic plane with enhancements correlated with spiral arm structure.

2. GALACTIC ^{26}AL

Radioactive ^{26}Al was discovered in the Galaxy by the germanium spectrometer flown on HEAO-3 (Mahoney et al. 1982). This important discovery was the first gamma-ray evidence for continuing synthesis of heavy nuclei in the Galaxy, and indicated about 3 $M_{\odot}$ of ^{26}Al residing in the Galaxy. The gamma ray spectrometer on the Solar Maximum Mission extended these observations (Share et al. 1985). The *COMPTEL* instrument on NASA's *COMPTON Gamma Ray Observatory* (*CGRO*) has provided the first maps of ^{26}Al in the Galaxy. (See Oberlack et al. 1996 for recent discussion of the *COMPTEL* results). Figure 1 shows the ^{26}Al distribution of the inner Galaxy.

Figure 2 shows the spectrum of the galactic center region observed by *OSSE* from the accumulation of data from several *CGRO* viewing periods. *OSSE* also detects the 1.809 MeV ^{26}Al line from the galactic center region. The measured intensity corresponds to a flux of about 3×10^{-4} γ cm^{-2}s^{-1}rad^{-1}. This is in agreement with the integrated emission from this region observed by *COMPTEL* (Diehl et al. 1995) and the SMM gamma ray spectrometer (Share et al. 1985). Analyses of the combined *CGRO* data sets are in progress with the goal of optimizing the maps of this important radioactivity as data from *CGRO* continue to be collected during the remainder of the mission.

3. GALACTIC POSITRON-ELECTRON ANNIHILATION RADIATION

The other strong gamma ray line feature in the galactic center spectrum (Figure 2) is the positron-electron annihilation line at 511 keV and the associated positronium continuum which extends to lower energies. Purcell et al. (1997) discuss the distribution of the positron annihilation radiation in the galactic center region. Briefly, models of the 0.511 MeV emission require several components including a central core component with an intensity of about 6×10^{-4} γ cm^{-2}s^{-1} that can be represented as a spheroid centered on the galactic center and with scale size of about 1.2 kpc. There is also a narrow disk component with a flux of $\sim 3 \times 10^{-4}$ γ cm^{-2}s^{-1} that is observed out to ~30° galactic longitude. The total flux measured by large field-of-view instruments (e.g., Share et al. 1988) suggests a third "extended halo" component with a flux of about 1.0×10^{-3} γ cm^{-2}s^{-1}. No contribution from a discrete source of 0.511 MeV emission is required by the data and no evidence of time-variable emission has been observed. Initial efforts to map the emission with the entire data base of *OSSE* observations in the galactic center region confirm the central bulge and plane components, and also suggest an enhancement in a region several degrees above the center of the Galaxy (Cheng et al. 1997; Purcell et al. 1997)

4. SUPERNOVAE

SN1987A, a core collapse SN in the Large Magellanic Cloud at a distance of 55 kpc, provided gamma ray astronomers with their first good opportunity to test theoretical predictions about nucleosynthesis in supernovae. The gamma ray spectrometer on the Solar Maximum Mission satellite, which had been launched seven years earlier and then repaired and re-deployed at a higher altitude in 1984, made the seminal discovery of ^{56}Co (Matz et al. 1988). The ^{56}Co emission was detected earlier than expected for standard Type II SN models.

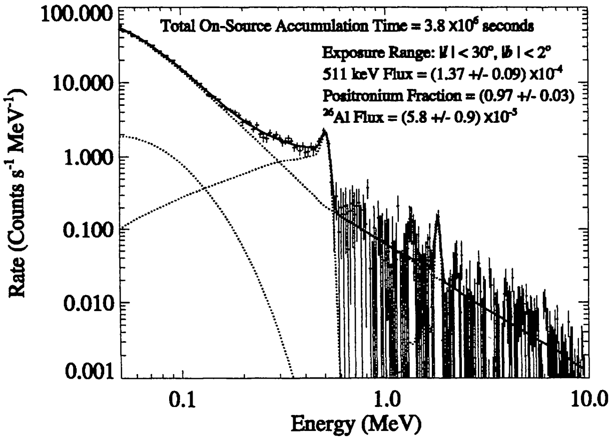

Fig. 2. *OSSE* spectrum of the galactic plane accumulated over several viewing periods and covering galactic longitudes from −30° to + 30°. The fit includes the 0.511 MeV line and associated positronium continuum, the ^{26}Al line, a broken power law for the cosmic ray continuum, and an exponential component for discrete source contributions at low energies.

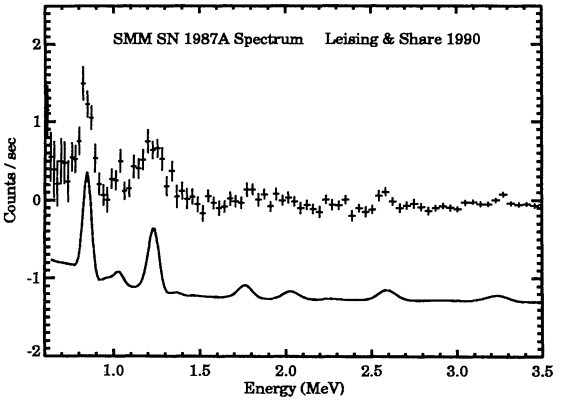

Fig. 3. Count spectrum of SN 1987A obtained by SMM. The solid curve indicates the expected spectrum for the ^{56}Co-decay gamma rays (offset from the data for clarity).

This indicated that a considerable amount of the freshly produced ^{56}Co was mixed into the outer envelope of the expanding remnant. Leising & Share (1990) analyzed the full SMM data base and reported the spectrum and time history of the individual ^{56}Co lines. Figure 3 shows the summed spectrum obtained by SMM. Several balloon-borne spectrometers confirmed the ^{56}Co emission (Sandie et al. 1988; Cook et al. 1988; Mahoney et al. 1988; Teegarden et al. 1989). Tueller et al. (1990) reported a surprising red shift for the 847 keV emission which may be associated with material mixed into the outer envelope by fragmentation or a non-spherical explosion.

OSSE observations of SN 1987A provided the first detection of ^{57}Co γ–rays (Kurfess et al. 1992). The spectrum observed in *CGRO* viewing period 6 is shown in Figure 4. The ratio of ^{57}Ni/^{56}Ni produced in the supernovae was 1.5±0.5 times solar. These data constrained the late time energy input into the supernova remnant and, coupled with the previous observations of ^{56}Co, the nucleosynthetic processes in Type II supernovae (Clayton et al. 1992).

An important objective of low-energy gamma ray astronomy is to use observations of ^{44}Ti ($\tau_{1/2} \sim 60$ yrs.) decay gamma rays to search for recent supernovae in the Galaxy. The decay of ^{44}Ti produces gamma ray lines at 68, 78 and 1156 keV. *COMPTEL* results (Iyudin et al. 1997) indicate a flux in the 1156 keV line of 4.8±0.9 × 10^{-5} γ cm^{-2}s^{-1}. At a distance of 2.8±0.2 kpc, the *COMPTEL* observations imply the production of 1.5–3 × 10^{-4} $M_\odot$ of ^{44}Ti, at the upper end of the expected range for Type II (core collapse) supernova. The et al. (1996) have analyzed the combined *OSSE* observations by jointly fitting the spectrum for the three ^{44}Ti decay lines at 68, 78 and 1156 keV. Fitting the summed spectrum of all *OSSE* data yields a flux of 1.7±1.5 × 10^{-5} γ cm^{-2}s^{-1} in each of the three ^{44}Ti lines. Thus *OSSE* and *COMPTEL* appear to be in marginal disagreement. The recently launched *XTE* and *SAX* carry new hard X-ray instruments that can search for the 68 and 78 keV lines and help resolve the current situation with regard to Cas A.

SN 1991T, a Type Ia supernovae in NGC 4527 at a distance of ~ 13 Mpc, was observed early in the *CGRO* mission. A marginal detection of ^{56}Co has been reported by Morris et al. (1995) with a flux in the 847 keV

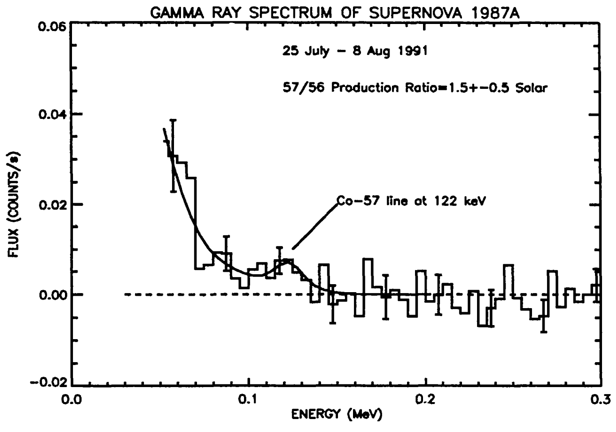

Fig. 4. Count spectrum of the LMC and SN1987A acquired in July 1991. The solid curve is the best fit exponential plus a model 10HMM ^{57}Co template. The continuum below 80 keV is from LMC X-3.

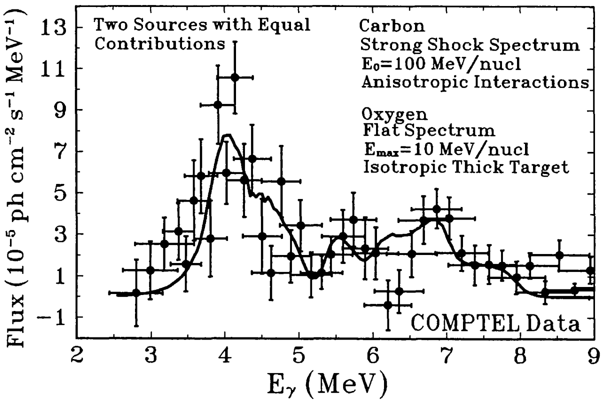

Fig. 5. Spectrum of the Orion region observed by the *COMPTEL* instrument on *CGRO* .

line of 5.3 × 10^{-5} γ $cm^{-2}s^{-1}$. *OSSE* does not detect the ^{56}Co emission (Leising et al. 1995). The *OSSE* data are in agreement with previous *COMPTEL* limits (Lichti et al. 1994) and appear to rule out those models for Type Ia supernovae which produce close to 1 $M_\odot$ of ^{56}Ni. A clear observation of ^{56}Ni- and ^{56}Co-decay gamma radiation from Type Ia supernovae remains an important milestone for gamma ray astronomy.

5. MEV LINES FROM ORION

Bloemen et al. (1994) reported the discovery, using *COMPTEL* data, of gamma ray emission in the 3 – 7 MeV energy range from the region of Orion. By including all data obtained between 1994 and 1996, Bloemen et al. (1997) recently reported a more sensitive measurement of this emission at (1.28±0.15) × 10^{-4} γ cm^{-2} s^{-1}. The spectrum obtained by *COMPTEL* is shown in Figure 5. Bloemen et al. (1997) interpret the features in the spectrum as doppler-shifted ^{12}C and ^{16}O features which result from the interactions of accelerated ^{12}C and ^{16}O ions with the ambient medium. The accelerated ions must be very overabundant in C and O. Bykov & Bloemen (1994) discuss the origin of the doppler shifts. Kozlovsky, Ramaty, & Lingenfelter (1997) have investigated in detail the shape of the broad nuclear line emission resulting from several distributions of accelerated ions. The solid line in Figure 5, which is a reasonable fit to the observed data, is a two-source model. One source has a pure C composition with a hard energy spectrum, and the other source is pure O with a soft spectrum.

OSSE has searched the Orion region for evidence of the gamma ray line emission reported by *COMPTEL* during a 5-week observation from April to June in 1995 (Murphy et al. 1996). The *OSSE* detectors were pointed midway between the Orion A and B radio sources in three different viewing configurations. No compelling evidence for line emission near 4.4 or 6.1 MeV was found, with a total flux in narrow lines of (1.9±1.4) × 10^{-5} γ $cm^{-2}s^{-1}$. Because of the narrow field-of-view (3.8° × 11.4°) of the *OSSE* detectors, however, this measured flux is consistent with the reported *COMPTEL* flux if the source is sufficiently spatially extended, such as that of the CO emission from the Orion region measured by Maddelena et al. (1986). The entire set of *COMPTEL* observations (Bloemen et al. 1997) do indeed suggest that the emission is spatially extended as

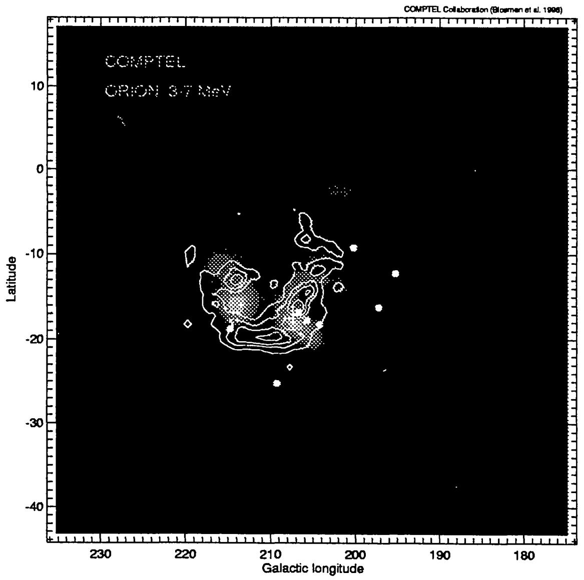

Fig. 6. Map of the Orion region obtained by the *COMPTEL* instrument on *CGRO* . The flux distribution observed of 3–7 eV gamma rays is shown along with contours of the OH emission from the region. Bright stars are also indicated.

shown in Figure 6. Harris et al. (1997) have combined all *OSSE* data from observations of the Orion region obtained through the end of 1996, with pointings distributed across the whole region. Again, no significant line emission was detected. They were able to exclude the possibility that the flux was due to narrow 4.4 and 6.1 MeV lines with 90% confidence from most of the cloud. They were also able to exclude the possibility that it arises from a single point source with 95% confidence.

6. THE FUTURE

Substantial progress has been made in gamm ray line astronomy by a large number of groups flying balloon-borne instruments, and a number of satellite missions leading to the currently operational *CGRO* mission. *CGRO* has clearly made significant advances in gamma ray line astronomy. The observatory is currently being re-boosted to a higher altitiude which could provide up to 10 years of additional mission lifetime. This would greatly improve the chances for important target of opportunity observations of nearby novae and supernovae. It will also extend the opportunity to continue mapping the galactic emissions of ^{26}Al and positron annihilation radiation, and other features such as ^{60}Fe, ^{44}Ti, and cosmic ray interactions on the ISM.

In 2001–2002 ESA's *INTEGRAL* mission will be launched. This is the next major gamma ray mission, and will carry a germanium spectrometer (Lichti et al. 1996) and a CdTe hard X-ray imager (Ubertini et al. 1996). Both instruments use coded aperture techniques, with the spectrometer providing improved sensitivities for narrow line features (esp. if they are point sources) and also having an angular resolution of 2–3 degrees for mapping the stronger diffuse galactic features. In general, the sensitivities for the *INTEGRAL* instruments will not represent a significant improvement over those obtained with *CGRO* .

It is clear that the highest priority for future gamma ray missions is to obtain much improved sensitivity relative to *CGRO* and *INTEGRAL*. This can be achieved with a high spectral resolution compton telescope for which concepts are being developed (Johnson et al. 1995; Tümer et al. 1995), and with the novel Laue focussing optics. The latter technique (von Ballmoos & Smither 1994) brings to gamma ray spectroscopy the high signal to noise advantages of focussing optics, albeit only at well defined lines and for narrow bandpasses. These techniques hold promise for a factor 100 improvement in sensitivity for many gamma ray objectives. Just to take a single example, sensitivities approaching 10^{-7} γ cm^{-2}s^{-1} will bring Type Ia supernovae out to 50–100 Mpc within gamma ray range. This will enable observations of several such supernovae per year, and over an extended mission provide class studies of these events. Such understanding could prove essential for the use of Type Ia supernovae in measuring the cosmological paramaters H_0 and q_0.

In summary, the pioneerring work of Bob Haymes and his many outstanding students at Rice Unversity established gamma ray astronomy as an important field of astronomical research. Progress has been slow, but steady, and the future looks bright for a new generation of gamma ray astronomers.

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Bob William takes questions at the conclusion of his Marlar Award lecture.