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A Balloon Investigation of Galactic γ-ray Lines with a High Resolution Ge(Li) Spectrometer

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Abstract

Galactic γ-ray lines have been investigated with a balloon-borne Ge(Li) spectrometer. The galactic plane was surveyed over the longitudinal interval 40°–210°, but upper limits only were obtained for the intensities of γ-ray lines from positron annihilation at 0·511 MeV and the nuclear decays of $^{20}Ne^*$ (1·634 MeV), $^{24}Mg^*$ (1·369 MeV), $^{28}Si^*$ (1·779 MeV) and $^{56}Fe^*$ (0·847 MeV). These upper limits are of the order of 10^{-3} photons $cm^{-2}\,s^{-1}\,sr^{-1}$, which are consistent with measurements for other lines observed so far. A possible γ-ray line feature at 400 keV, with a flux of $(7\cdot4 \pm 5\cdot4) \times 10^{-3}$ photons $cm^{-2}\,s^{-1}$, was detected when the Crab Nebula was in the field of view. This line seems to be identical with one reported by Leventhal *et al.* (1977), who suggested that it may originate from a gravitational redshift of the 0·511 MeV annihilation line produced near the surface of the neutron star.

Introduction

Since galactic γ-ray lines are produced by interactions between low energy cosmic rays and the interstellar medium, the observation of these lines can provide information on the galactic distribution, the energy spectrum and the composition of both of the interacting components. Theoretical studies of galactic γ-ray lines have been made by Ramaty *et al.* (1969), Rygg and Fishman (1973), Yoshimori (1975), Meneguzzi and Reeves (1975) and Lingenfelter and Ramaty (1976). Several lines have been suggested as being suitable for observation. These include the positron annihilation line at 0·511 MeV and the nuclear decay lines of $^{12}C^*$ (4·439 MeV), $^{16}O^*$ (6·131 MeV), $^{20}Ne^*$ (1·634 MeV), $^{24}Mg^*$ (1·369 MeV), $^{28}Si^*$ (1·779 MeV) and $^{56}Fe^*$ (0·847 MeV). The detectability of these lines has been discussed in the above-mentioned works.

Recently, the galactic distribution and the composition of the interstellar gas and dust have been studied by means of galactic surveys of the 2·6 mm radio line emission from the $J = 1 \rightarrow 0$ transition of CO molecules (Burton *et al.* 1975; Scoville and Solomon 1975; Burton and Gordon 1976; Gordon and Burton 1976), the IR emission from the interstellar dust (Hayakawa *et al.* 1976; Okuda *et al.* 1977) and the high energy γ-ray emission from π^0 decays (Bennett *et al.* 1977; Fichtel *et al.* 1977), as well as surveys of the 21 cm atomic hydrogen line emission (Westerhout 1973, 1976). However, the galactic distribution and the energy spectrum of low energy cosmic rays have not been studied. Thus, the detection of galactic γ-ray lines could reveal the existence of large intensities of hitherto undetected low energy cosmic rays and give unique information on their galactic distribution and their energy spectrum. A comparison between the galactic distribution of low energy cosmic rays and those of supernova remnants, pulsars, high energy γ rays and interstellar matter could also provide important information on the origin and propagation of cosmic rays.

Positron annihilation leads to a γ-ray line emission at $0 \cdot 511$ MeV. The principal mechanism for positron production is inelastic collisions between low energy cosmic rays and the interstellar medium, which produce nuclei that decay by positron emission, such as ^{11}C, ^{13}N, ^{15}O etc. Since nuclear reactions producing positron emitting nuclei involve relatively low threshold energies (of the order of 10 MeV), positrons from β-particle decays have maximum energies of the order of 1 MeV. Such positrons will be easily decelerated by ionization loss, and then annihilate with ambient electrons to emit two $0 \cdot 511$ MeV γ rays. Yoshimori (1979, present issue pp. 383–404) has calculated the galactic intensity distribution of the $0 \cdot 511$ MeV line, and predicts line intensities in the galactic centre and anticentre directions of 3×10^{-5} and 6×10^{-6} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{rad}^{-1}$ respectively.

Nuclear reactions between low energy cosmic rays and the ambient interstellar medium also lead to γ-ray line emission via the decay of excited levels in nuclei found in both cosmic rays and the ambient medium. Lines of this type have been observed in large solar flares (Chupp *et al.* 1973). Three line components due to nuclear deexcitation can be distinguished in the galactic γ-ray spectrum: a broad component with a width of the order of 1 MeV arising from the deexcitation of excited cosmic ray nuclei which have energies of a few MeV per nucleus or more; a narrow line component with a width of the order of 100 keV arising from the deexcitation of excited ambient nuclei which pick up recoil energies of a few tens of keV per nucleus; a very narrow line component with a width of the order of a few keV arising from the deexcitation of excited nuclei which have effectively come to rest prior to deexcitation. The broad lines merge into the underlying continuum on which the narrow and very narrow lines are superimposed. In the interstellar medium, the narrow lines are likely to be produced by nuclei within the interstellar gas and the very narrow lines are likely to be produced by nuclei within the interstellar dust. The strongest lines from cosmic ray interactions are expected at $4 \cdot 438$ MeV from $^{12}C^*$ and at $6 \cdot 129$ MeV from $^{16}O^*$. Their intensities are estimated to be comparable with that of the $0 \cdot 511$ MeV line.

Several observations of galactic γ-ray lines have been made so far. Gamma-ray lines at $0 \cdot 511$, $1 \cdot 9$ and $4 \cdot 4$ MeV have been detected from the galactic centre (Haymes *et al.* 1975; Leventhal *et al.* 1978) and from Cen A (Hall *et al.* 1976). A 20 min burst of γ-ray lines at $0 \cdot 41$, $1 \cdot 79$, $2 \cdot 22$ and $5 \cdot 95$ MeV was reported by Jacobson *et al.* (1978), and an interpretation of this very exciting event has been given by Lingenfelter *et al.* (1978). A possible 400 keV line feature from the Crab Nebula was observed by Leventhal *et al.* (1977). However, for the diffuse γ-ray lines, only upper limits to the intensities have been obtained (Metzger *et al.* 1964; Dyer *et al.* 1977; Ling *et al.* 1977; Imhof and Nakano 1977).

In the present paper we describe a long duration balloon experiment designed to search for diffuse γ-ray lines. A high resolution Ge(Li) detector surrounded by a plastic scintillator shield was employed. Only upper limits were obtained for intensities of γ-ray lines. The results are compared with other available data.

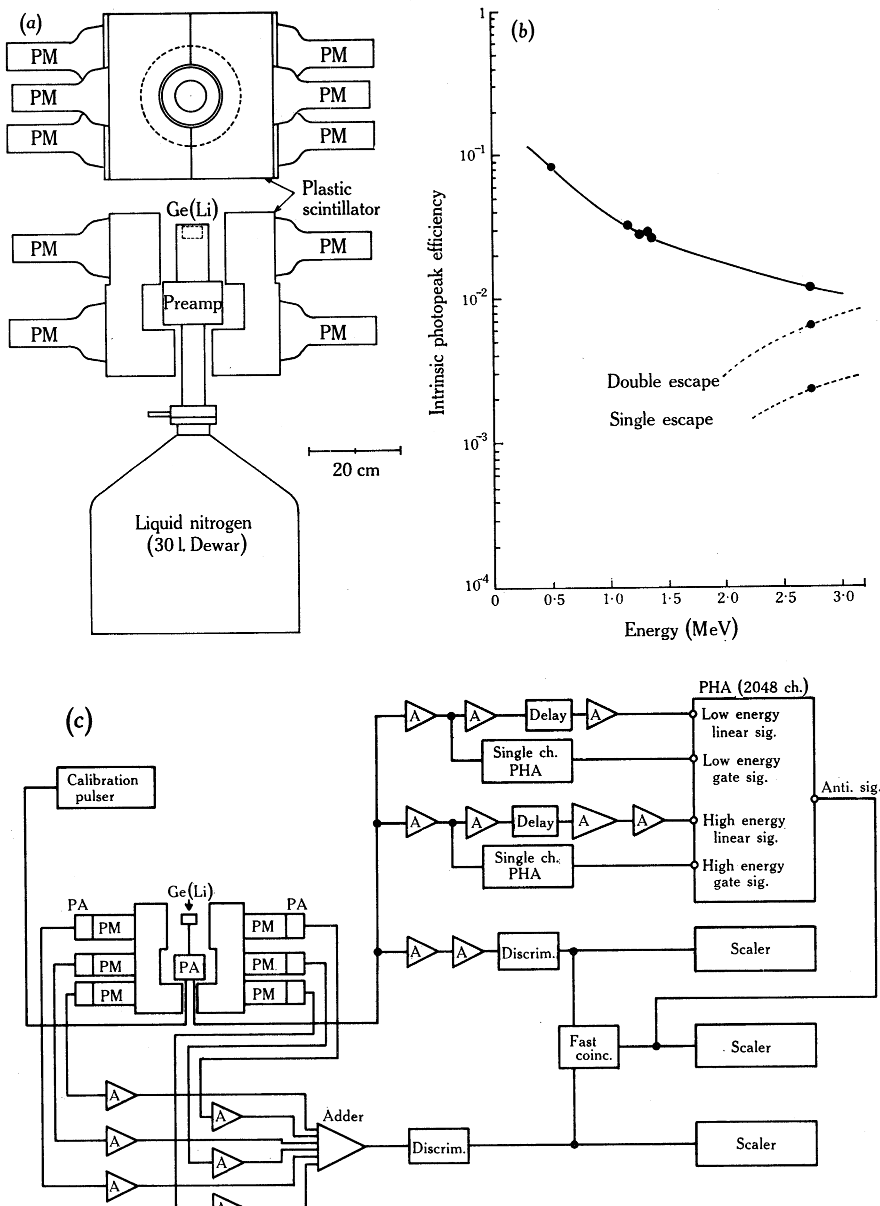

Fig. 1. Ge(Li) detector showing: (*a*) schematic diagram of a cross section through the balloon-borne detector; (*b*) plot of the full energy peak efficiency of the detector as a function of the γ-ray energy, with the single- and double-escape efficiencies given for comparison; (*c*) block diagram of the electronics of the balloon-borne detector.

Instrumentation

We used a high resolution Ge(Li) detector to search for diffuse γ-ray lines in the energy range of 0·2–6 MeV. The Ge(Li) detector was surrounded by a well-type plastic scintillator shield, as shown in Fig. 1*a*. The detector was of coaxial construction, being 39 mm in diameter and 26 mm in length. It was maintained at a pressure of 10^{-7} mmHg ($\sim 10^{-5}$ Pa) and was cooled to 77 K by liquid nitrogen, the coolant's lifetime being estimated as 100 h at balloon altitudes. The detector operated with a bias of 1800 V, and it possessed an energy resolution of 3 keV (FWHM) at 1·333 MeV. The full energy peak, and the single- and double-escape peak efficiencies were measured using γ-ray sources ^{22}Na (0·511 and 1·275 MeV) and ^{24}Na (1·369 and 2·754 MeV). The resulting efficiency curves are shown in Fig. 1*b*, where it can be seen that the full energy peak efficiency is 9% at 0·511 MeV and decreases to 3% at 1·333 MeV. For energies above 3 MeV, the double-escape peak efficiency predominates over the full energy peak efficiency. Electrical connections between the Ge(Li) detector and the charge sensitive preamplifier and bias supply are made via feed-throughs welded into the back wall of the cryostat. The detector is DC-coupled to the preamplifier input (FET) stage.

Surrounding the Ge(Li) detector is a plastic scintillator anticoincidence shield with a minimum thickness of 100 mm. The function of this plastic scintillator shield is twofold: Since the interactions between γ-rays and the central Ge(Li) detector produce secondary radiation which may escape the Ge(Li) detector, the energy deposition within the Ge(Li) detector may be only a fraction of the energy of the incident γ-ray. One function of the scintillator shield is to detect this escaping radiation and thereby cancel (veto) the initial Ge(Li) detector event. The second function of the scintillator shield is to collimate and define the γ-ray acceptance cone, i.e. to reduce the contributions of diffuse atmospheric and cosmic background sources to the observed γ-ray rate in the Ge(Li) detector. The plastic scintillator shield defines an aperture of 110° (FWHM) and is viewed by six RCA 2065 photomultiplier tubes. Optical coupling to the plastic scintillator is made via transparent silicon rubber. The shield-associated preamplifiers and high voltage suppliers are attached directly to the shield housing. The shield veto channel has a lower level discrimination at 200 keV.

A block diagram of the electronics of the Ge(Li) detector is shown in Fig. 1*c*. The Ge(Li) detector is connected to a pulse shaping amplifier and a 2048 channel pulse height analyser. The detector electronics are configured to analyse the pulse heights of pulses corresponding to energy losses between 0·2 and 6 MeV in the Ge(Li) detector which are not vetoed by a coincident event in the plastic scintillator. The energy range 0·2–6 MeV is divided into two energy sub-bands: a low energy sub-band (0·2–2 MeV) and a high energy sub-band (2–6 MeV); the energy width per channel being 0·88 keV for the former and 1·95 keV for the latter. The pulse height channel of each event is digitized into an 11 bit binary number, which is telemetered to the ground recording station via PCM with a bit rate of 16 384 bits per second. In order to correct electronics drifts in the amplification factor and discrimination level during the balloon flight, four test pulses corresponding to γ-ray energies of 610, 1370, 2243 and 3719 keV were fed to the charge sensitive preamplifier. Information needed to monitor the total, shield and anticoincidence counting rates, and the temperature of the instrument were telemetered on additional PCM channels. The total weight of the instrument was 175 kg.

Balloon Experiment and Results

The Ge(Li) detector was flown on a balloon from Sanriku Balloon Center (geomagnetic latitude 29°) on 30 September 1977. The balloon was launched at 0812 h

(UT) and reached a float altitude of $7\cdot8\ \mathrm{g\,cm^{-2}}$ at 1050 h (UT), which it maintained for about 26 hours before cutdown. During the balloon flight the galactic plane over the longitudinal interval 40°–210° was surveyed. The region of the sky, in galactic coordinates, covered by the present experiment is shown by the hatched area in Fig. 2*a*. The interesting discrete sources of Her X-1, Cyg X-1, Cas A and the Crab Nebula were scanned during the flight. Unfortunately, owing to changes in the internal temperature of the gondola during flight, an electronic fault developed which prevented the use of the high energy sub-band (2–6 MeV). Only data for the low energy sub-band (0·2–2 MeV) were analysed.

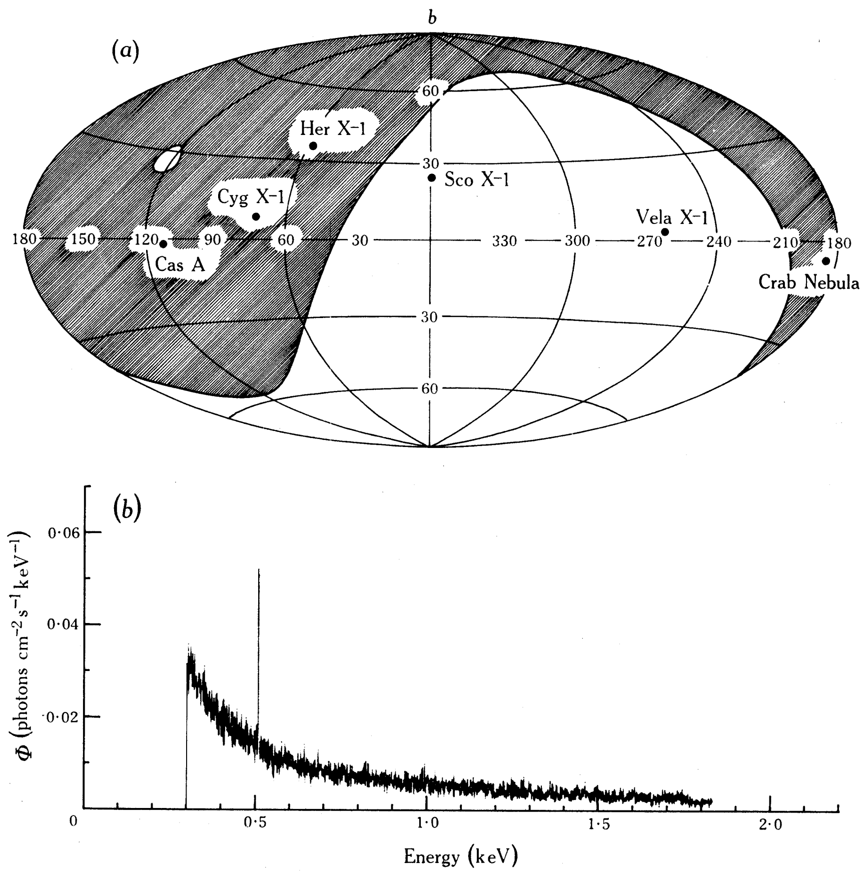

Fig. 2. Summary of balloon observations: (*a*) region of sky, in galactic coordinates, scanned during the flight (hatched area); (*b*) γ-ray energy spectrum, showing the flux Φ as a function of γ-ray energy, along the galactic plane.

The γ-ray spectrum measured during the galactic plane scan is shown in Fig. 2*b*. A strong γ-ray line from positron annihilation at 0·511 MeV was detected, as can be seen. The flux of the line is $1\cdot2\times10^{-1}$ photons $\mathrm{cm^{-2}\,s^{-1}}$, which is consistent with that previously obtained by Nakagawa *et al.* (1971), but is many orders of magnitude larger than the 0·511 MeV line of galactic origin. We conclude that the observed line arises from positron annihilation within the Earth's atmosphere.

In general, the intensity of the γ-ray line emission from the galactic plane can be obtained by differencing the line intensities measured in the galactic plane and galactic halo scans. However, no statistically significant difference could be found between these scans. Thus we were only able to set upper limits to the intensity of γ-ray line emission from the galactic plane. The upper limits set by us to galactic plane emission from the $0 \cdot 511$ MeV positron annihilation line and the $^{20}Ne^*$ ($1 \cdot 634$ MeV), $^{24}Mg^*$ ($1 \cdot 369$ MeV), $^{28}Si^*$ ($1 \cdot 779$ MeV) and $^{56}Fe^*$ ($0 \cdot 847$ MeV) nuclear deexcitation lines are 4×10^{-3}, $1 \cdot 5 \times 10^{-3}$, $2 \cdot 0 \times 10^{-3}$, $1 \cdot 0 \times 10^{-3}$ and $1 \cdot 2 \times 10^{-3}$ photons $cm^{-2} s^{-1} sr^{-1}$.

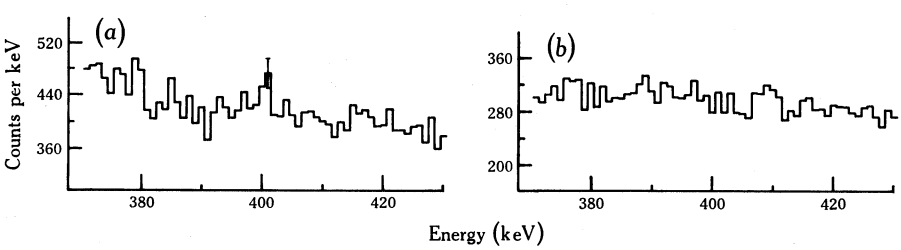

Fig. 3. Gamma-ray energy spectra obtained during scans of the Crab Nebula, showing: (*a*) the target scan, which includes a possible γ-ray line at 400 keV; (*b*) the corresponding background scan.

A possible γ-ray line at 400 keV was detected when the Crab Nebula was in the field of view. The Crab target (1524–2150 h, 30 September) and Crab background (0100–0407 h, 1 October) spectra in the vicinity of 400 keV are shown in Figs 3*a* and 3*b* respectively. As can be seen, the weak line feature appears at 400 keV in the spectrum shown in Fig. 3*a*. This line feature represents a $1 \cdot 4\sigma$ deviation above the continuum, and corresponds to a line flux of $(7 \cdot 4 \pm 5 \cdot 4) \times 10^{-3}$ photons $cm^{-2} s^{-1}$ incident on the Earth with a width of not more than 3 keV. This line feature may be identical with that detected by Leventhal *et al.* (1977).

Discussion

The present balloon experiment places upper limits only on intensities of diffuse γ-ray lines from the galactic plane over the longitudinal interval 40°–210°. So far, a few upper limits have been obtained for the intensity of the $0 \cdot 511$ MeV line by Metzger *et al.* (1964), Dyer *et al.* (1977), Imhof and Nakano (1977) and Ling *et al.* (1977). Metzger *et al.* obtained the first upper limit to the intensity of 10^{-3} photons $cm^{-2} s^{-1} sr^{-1}$ with an omnidirectional NaI detector on board the Ranger 3 spacecraft, while Dyer *et al.* obtained that of 3×10^{-3} photons $cm^{-2} s^{-1} sr^{-1}$ with an Apollo-borne NaI detector. Recently, high resolution Ge(Li) detectors have been employed for balloon and satellite experiments. Ling *et al.* obtained an upper limit of $9 \cdot 2 \times 10^{-3}$ photons $cm^{-2} s^{-1} sr^{-1}$ with a balloon-borne Ge(Li) detector, while Imhof and Nakano obtained 5×10^{-3} photons $cm^{-2} s^{-1} sr^{-1}$ with a satellite-borne Ge(Li) detector. Our value for the upper limit is 4×10^{-3} photons $cm^{-2} s^{-1} sr^{-1}$, which is of the same order of magnitude as the previous determinations. However, these upper limits are at least one order of magnitude larger than the predicted intensity of 10^{-4} photons $cm^{-2} s^{-1} sr^{-1}$ (Ramaty 1978). In order to detect a 3σ deviation of the $0 \cdot 511$ MeV line intensity above the continuum, it is necessary to make an observation of 160 hours duration using a Ge(Li) detector of $100\ cm^2$ area and 3 keV energy resolution. Upper limits to the intensities of γ-ray lines from the nuclear decay of $^{20}Ne^*$, $^{24}Mg^*$, $^{28}Si^*$ and $^{56}Fe^*$ have not been reported so far. Since predicted intensities of these lines are of the order of 10^{-5} photons $cm^{-2} s^{-1} sr^{-1}$, a detection of these lines will be more difficult.

When the Crab Nebula was under observation, a possible γ-ray line feature at 400 keV was detected. A 400 keV line from the Crab Nebula has previously been reported by Leventhal *et al.* (1977), who gave its flux as $(2 \cdot 44 \pm 0 \cdot 65) \times 10^{-3}$ photons $cm^{-2} s^{-1}$. The present line intensity agrees with that of Leventhal *et al.* within statistical errors. This 400 keV line has been interpreted in terms of the gravitational redshift of the 511 keV positron annihilation line produced near the surface of the neutron star with a gravitational redshift of 0·28.

Gamma-ray line astronomy adds a whole new dimension to our investigation of astrophysics, because of the nuclear and astronomical information that it uniquely conveys. While we now know that γ-ray lines of galactic origin do exist with detectable intensities, there remain two vital experimental needs: the need for a better detection instrument and the need for a better space vehicle. Increases in the exposure time and the detection sensitivity are needed if we are to detect low intensity γ-ray lines. The present authors plan to observe γ-ray lines from discrete sources with a balloon-borne high sensitivity Ge(Li) detector in the near future.

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