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Jacob Trombka, Carl Fichtel, Jonathan Grindlay and Robert Hofstadter

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Goddard Space Flight Center
Greenbelt, Maryland 20771

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GAMMA-RAY ASTROPHYSICS — A NEW LOOK AT THE UNIVERSE

Dr. Jacob Trombka
Laboratory for Astronomy and Solar Physics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

Dr. Carl Fichtel
Laboratory for High Energy Astrophysics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

Dr. Jonathan Grindlay
Center for Astrophysics
Harvard College Observatory
Smithsonian Astrophysical Observatory
60 Garden Street
Cambridge, MA 02138

Dr. Robert Hofstadter
Physics Department
Stanford University
Stanford, CA 94305

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

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GAMMA-RAY ASTROPHYSICS—A NEW LOOK AT THE UNIVERSE

Jacob Trombka, Carl Fichtel
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Introduction

A new window on the universe is being opened at the high energy end of the electromagnetic spectrum as γ-ray astronomy* has finally come of age with the detection of sources, observation of the general galactic emission, and the measurement of a diffuse background. Gamma-ray astronomy permits investigation of the most energetic photons originating in our galaxy and beyond. These observations provide the most direct means of studying the largest transfers of energy occurring in astrophysical processes. Of all the electromagnetic spectrum, high-energy γ-ray astronomy measures most directly the presence and dynamic effects of the energetic charged cosmic ray particles, element synthesis, and particle acceleration. Further, γ rays suffer negligible absorption or scatterings as they travel in straight paths; hence they may survive billions of years and still reveal their source. Studies of the spatial, temporal and energy distribution of cosmic γ rays will, therefore, provide fundamental new information for resolving some of the major problems in astrophysics today. The high energy processes in stellar objects (including our Sun), the dynamics of the cosmic-ray gas, the formation of clouds and nebulae, galactic evolution and

*γ-ray astronomy may be defined to include the spectral region from above ~100 keV to ≥1000 GeV.

even certain aspects of cosmology and the origin of the universe may be explored by γ-ray observations.

Progress in this field of astronomy has, however, been slower than in some other fields such as x-ray astrophysics because γ-ray production cross-sections are smaller with corresponding lower fluxes. Relatively large sophisticated instruments are therefore required. In the lower energy portion of the γ-ray spectrum, nuclear activation with subsequent γ-ray decay further complicate the detector design.

Except for observations at energies greater than 100 GeV which can be performed on the Earth's surface, most of this work must be carried out above the terrestrial atmosphere and outside the trapped radiation belts. First order information on differential energy spectra (both discrete and continuous) and angular distributions from solar, planetary, and galactic sources have already been obtained largely from satellite experiments. There is also evidence that extragalactic radiation possibly of cosmological origin may have been detected. The progress within the last seven years has been particularly encouraging. The first detailed results for the extended γ-ray emission from the galactic plane are now available and great interest is developing in the interrelationship between galactic structure, cosmic ray origin, the cosmic ray distribution in the galaxy and γ-ray emission. Point sources of cosmic γ-rays with energies above 100 MeV and even up to 1000 GeV have been detected with one of the great surprises being the identification of several γ-ray pulsars with their radio counterparts. Emission from a galaxy other than our own, Centaurus A, has been detected at both the lowest (~1 MeV) and highest (~300 GeV) γ-ray energies. The differential energy spectrum of a possible diffuse cosmic background γ-ray flux has been observed over five decades in energy, from 10 keV to 100 MeV. The first evidence of γ-ray line emission associated with solar fluxes has been obtained. Discrete line γ-ray emission from the Moon has also been observed and used to infer the elemental composition over about 20% of the lunar surface. Finally, there has been the exciting discovery of γ-ray bursts with a typical duration of several seconds and photon energies of approximately 1 MeV. The observed bursts generally have complex temporal behavior and often contain what appear to be multiple emission peaks. None of the observed bursts have been associated with any known celestial objects.

The results obtained thus far are important not only because of their astrophysical significance, but also because of the impact that they have had on development of the next generation of instrumentation, the technology for which now exists. Future missions carrying detectors of significantly improved sensitivity will permit γ-ray astronomy to make its potentially significant contribution to our understanding of the nature of our universe.

Some of the results already obtained in γ-ray astronomy from observations made of our own solar system, of other γ-ray sources in our own Galaxy, and of objects beyond our Galaxy are described in the following sections.

Gamma-Ray Observation of our Solar System

In the last two decades, significant observational data have been obtained from both space flight programs and meteorite studies allowing certain constraints to be imposed on the theoretical models for the origin and evolution of the solar system. Further, various theoretical approaches can now be evaluated in terms of their observational tests, and more rigorous models can be developed. Both chronology and present day dynamics of the Sun and solar system can be examined critically with γ-ray astronomical observations. First let us consider the study of the Sun which, in addition to appealing to our natural interest in its formation and dynamics, is the only star that an astronomer has any reasonable hope of studying in detail.

Gamma-ray astronomy, as applied to the observation of the Sun, has the specific objective of considering high energy processes that take place in the Sun's atmosphere and the relation of these phenomena to the basic problems of solar activity. To illustrate the nature of the information that can be obtained from γ-ray spectroscopic observations during solar flares, three problems will be briefly described.

The γ-ray lines at 0.51 MeV in solar flares result from either the free annihilation of positrons with electrons or from the formation and decay of positronium. In the case of free annihilation, the formation of the 0.51 MeV line depends on the source of the positrons, on the propagation of the positrons in the solar atmosphere, and on the density and temperature of the ambient medium in which the positrons decelerate. Next, γ-ray line emission is evidence that the particular nuclear species with a corresponding nuclear level has been excited by particles with energies above the excitation threshold. Elemental composition of excited species can also be inferred. Two or more lines from the same nuclear species provide information on the spectrum of exciting particles. For example, the relative intensities of the 15.1 MeV γ-ray line to that of the 4.4 MeV γ-ray line from the excitation and subsequent deexcitation of the corresponding states of ^{12}C can be used to determine the spectral distribution of the energetic particles (1). Finally, Doppler shifts in selected γ-ray lines can be used to study the anisotropic propagation of charged particles during solar flares. Protons with energies greater than 10 MeV will excite the 4.4 MeV and 6.1 MeV γ-ray lines of ^{12}C and ^{16}O, respectively. Since γ-rays are emitted in a time short compared with the slowing down time of the nucleus, any directional anisotropy in the primary exciting particles would cause a Doppler shift in the central energy of the observed lines (2).

That such observations are indeed possible was confirmed when γ-ray lines associated with solar emission were observed during two flares in 1972 from the OSO-7 satellite (3, 4). There was evidence of significant enhancement of the 0.51 MeV and 2.2 MeV spectral regions. Line features at 4.4 MeV and 6.1 MeV were also evident. All the lines except the 2.2 MeV line from deuterium formation are attributable to interactions with energetic protons. The fact that the 2.2 MeV line was observed implies the presence of a significant thermal neutron flux, not absorbed by other processes.

Gamma-ray astronomy observations also find important application in studying the development of the planets out of the primitive solar nebula. For those planets where the atmosphere and trapped radiation environment do not interfere significantly with the γ-ray emission, orbital measurements can be carried out. Some of the so-called terrestrial planets are examples of such systems. Asteroids and comets can also be studied. Elemental surface composition can be inferred from observations of γ-ray line emission. This emission can be attributed mainly to natural radioactivity (Th, U, and K) and to the primary and secondary cosmic-ray induced activity producing identifiable emission from H, O, Si, Al, Mg, Fe, and Ti.

In acquiring an understanding of the geology of a planetary body, a knowledge of the total chemical composition and of the variation of the surface composition of the body are of fundamental importance. The overall composition will be related to the mechanism of accretion and accumulation leading to planetary formation. The distribution of elements also has been affected by geological processes which have been operative during planetary evolution.

A number of missions have been flown to the Moon and Mars from which such information has been obtained, for example in the American space program, Apollo 15 and Apollo 16 and in the Russian program, a number of lunar missions, the Mars 4 and Mars 5 missions and the Venera mission. The distribution of the radioactive elements Th, U, and K measured by the γ-ray spectrometer during the Apollo 15 and Apollo 16 missions are shown in Figure 1. The concentration increase is indicated by a darkening in the orbital path outlined in the figure. The data from the Apollo 15 and the Apollo 16 x-ray and γ-ray spectrometers have been most thoroughly analyzed (5, 6, 7, 8, 9). These measurements indicate that the Moon has a global Al or plagioclase rock crust whose formation was the major geochemical event of the Moon's geologic evolution after its formation. By outlining variations of the distribution of uranium, thorium, and potassium, the γ-ray information suggest that large basin-forming events were capable of creating the geochemical provinces by the ejection from depths of ten or more kilometers. The depletion of volatile materials relative to refractory materials was found to hold true on a global basis, since the K/Th ratio determined from the Moon remained significantly lower over most of the Moon compared to that on Earth. The measurement of radioactive elements Th, U, and K obtained from Mars 4 and Mars 5 (10) indicate that the soil overflown on the surface of Mars is basaltic in nature.

Stellar Objects

Gamma-ray astronomy is directly related to the most energetic processes occurring in stellar objects, and is therefore expected to play a particularly valuable role in the study of supernovae and compact objects such as neutron stars and black holes. Of the dozen point sources of γ rays identified outside our solar system, four are associated with radio pulsars and are pulsing at the radio period, whereas only one radio pulsar has been seen in the x-ray range. It was less than a decade ago that the discovery of radio pulsars provided the first observational evidence for the existence of collapsed stellar objects. These pulsars are now generally accepted as neutron stars primarily on the basis of their short pulse periods, high period stability, and very large energy release.

The luminosities of the γ-ray pulsars already observed are in the range from 10^{33} to 10^{35} ergs sec^{-1} above about 30 MeV (11-19). Because these γ rays almost certainly owe their origin to extremely relativistic particles interacting with intense magnetic fields, the observation of these large amounts of energy being released in the form of very high energy photons implies that an extraordinarily efficient particle acceleration process exists at the pulsar. Gamma-ray spectral measurements particularly at higher energies would provide information about the particle acceleration process and very possibly about the magnetic field configuration around the neutron star. A variable spectral component has already been observed from the Crab pulsar above 800 GeV (20). In at least one case, that of PSR 0833-45, the γ radiation is shifted in phase by 45° from the radio pulse (21). On the other hand for the Crab pulsar, the pulses at the two energies are in phase, suggesting that more than one radiation mechanism may be involved in some cases. Further support for this concept is given by the difference in the emission character of the pulsed radiation between the radio and γ-ray regions for PSR 0833-45. As shown in Figure 2, two pulses of nearly equal size separated by about half a period were observed in the γ-ray region with the SAS-2 γ-ray telescope and subsequently by the COS-B satellite whereas only a single pulse is seen in the radio region for this same source.

The most luminous galactic γ-ray source observed thus far is Cygnus X-3 (22) with a flux above 30 MeV observed by SAS-2 implying a luminosity of more than 10^{37} ergs/sec if the radiation is confined to a cone of one steradian. The γ-ray emission is observed to have the same 4.8^h periodicity seen in the x-ray and infrared regions. This source is thought to be either a precessing neutron star or a neutron star in a binary system; further γ-ray observations may clarify this question.

Gamma-ray sources have also been observed by SAS-2 and COS-B with no apparent counterpart at other wavelengths (22, 24, 25) suggesting the possibility of a whole class of stellar objects not known previously. Further, it is certainly expected that γ rays will prove to be a valuable probe of black holes since the intense gravitational field near a black hole subjects in-falling matter to extreme conditions. Recent theory has also predicted the existence of relatively small primordial black holes which may signal the evaporation of their last $\sim 10^{14}$ g by emitting $\sim 10\%$ of this rest mass energy in a short, 2×10^{-7} second, burst of high energy γ rays with energies of approximately 250 MeV (26).

Whereas bursts with this short time period have not been seen, low energy γ-ray bursts, whose origin remains a mystery, have been observed (cf., 27-31). With the sensitivity of current detectors, these bursts are detected several times a year with photons whose energies appear to be concentrated below a few

MeV. They generally last a few seconds to half a minute and some, such as the one shown in Figure 3 (30 and 31), are observed to have substantial fine structure. As yet the sources of these bursts have not even been precisely located on the celestial sphere, but it is anticipated that some accurate source locations will be forthcoming over the next two years. Recent results do indicate that these bursts are of galactic origin (32).

The search for the origin of cosmic rays is a problem particularly suited to γ-ray astronomy. If the acceleration of these particles should occur in objects such as pulsars or supernovae, they will reveal their presence by interacting with the surrounding matter. Supernovae have been expected to be one of the more likely γ-ray emitters, and indeed the Crab nebula was the first individual γ-ray source seen.

A very important prospect for γ-ray astronomy is the detection of γ-ray spectral lines, and the direct evidence they provide on nucleosynthesis through the decay of unstable nuclei. Nucleosynthesis has long been postulated to occur in the outer envelopes of supernovae, and a particularly important test that this has occurred in these objects would be the detection of γ rays from the decay of the more abundant unstable resulting nuclei such as ^{56}Ni, ^{56}Co, ^{48}V, and ^{44}Sc (33). Identification of more than one nucleus will provide a quantitative test of the theory which would not be possible by any other means. The first attempts to search for γ-ray lines with high-resolution spectrometers were conducted by the Lockheed group (34); further searches will be pursued on STP78-1 and on HEAO-C (35).

Diffuse Gamma-Ray Emission from our Galaxy

When considering the interstellar medium of our Galaxy, the tenuous gas consisting largely of atomic and molecular hydrogen and interstellar dust often come to mind first. However, there are two other very important constituents that are believed to account for about two-thirds of the expansive pressure of the galaxy; they are the cosmic rays and the magnetic fields. It is now realized that the density of the thermal gas in the galactic disk is only marginally capable of holding down the cosmic-ray gas and magnetic fields against their dynamic pressures, and therefore that the latter play a very important role in the Galaxy.

Gamma-ray astronomy can provide information on the density distributions of both the galactic cosmic-ray nuclei, which contain the great bulk of the energy, and independently on the cosmic-ray electrons. The latter could be combined with continuum radio measurements to obtain a much more quantitative picture of the galactic magnetic fields than currently exists.

The most complete picture of the large scale structure of the γ-ray sky which exists at present is that obtained by the SAS-2 high energy γ-ray telescope (23, 36, 37). The most striking feature of the celestial sphere when viewed in the 100 MeV energy range is the emission from the galactic plane, which is particularly intense in the galactic longitude region from almost 300° to 50°. This enhancement corresponds in longitude extent to a region of extended 21 cm radio emission, but compared to other regions of the galactic plane it is relatively more intense. When examined in detail the longitude and latitude distributions appear to be generally correlated with galactic structure features as shown in Figure 4. In particular, the γ-ray emission appears to be associated with spiral-arm segments and the enhancement of matter near five kiloparsecs from the galactic center; however, the sensitivity of the γ-ray instruments shown thus far does not yet permit a discussion of fine detail. Analysis of these data shows that the cosmic rays are correlated with the matter on the scale of galactic arms, supporting the galactic nature of the cosmic rays. Because of this correlation between the cosmic rays and the matter, a very high contrast picture of the Galaxy should ultimately be forthcoming from γ-ray studies. In addition, future γ-ray experiments with improved sensitivity and angular resolution should, for example, be able to answer the question of whether cosmic rays play a major role in cloud formation, since very definite predictions can be made about the relative γ-ray intensity expected from clouds compared to the intercloud region for different models of the interrelationship between cosmic rays and clouds.

Other Galaxies and Cosmology

At present, because instruments of sufficient sensitivity have not existed, only the closest active galaxy, Centarus A (CEN-A), has been detected in γ rays (40). The study of other galaxies in high energy γ rays is, however, of extreme interest in determining if other normal galaxies have cosmic-ray densities similar to our own. Ultimately the relationship of the nucleonic cosmic-ray distribution in an external galaxy may be compared with its optical and radio features. The closest galaxies to our own are expected to be emitting γ rays at a level such that their fluxes as measured at the Earth would be easily detectable with the next generation of γ-ray telescopes.

One of the outstanding problems in astrophysics today is the nature of the compact central sources that appear to power the energetic phenomena observed in the nuclei of active galaxies and quasars. The intimate relationship between γ rays and dynamic high-energy processes makes the extraordinary galaxies, such as Seyfert galaxies, radio galaxies, and QSO's, prime candidates for γ-ray studies. For example, considering Compton scattering models for the very high energy ($\sim$300 GeV) γ rays and combining these results with the hard x-ray through low energy γ-ray spectral observations obtained on CEN-A, the magnetic field and cosmic-ray spectrum in this peculiar object has been established and limits set.

The study of cosmology through γ-ray astronomy consists largely of the study of the diffuse γ-ray background. This background is that part of the observed radiation which cannot be associated with known galactic or extragalactic sources. The intensity, energy spectrum, and degree of isotropy of this γ-ray background as measured to date have already put significant constraints on cosmological models. The intensity observed at energies above 150 MeV, for example, rules out the possibility of having the combination of a closed universe and a universal cosmic-ray intensity at the level seen at the Earth (41).

In terms of specific cosmological models, the present results argue strongly against the steady state matter-antimatter model which predicts a γ-ray flux due to annihilation which would be many orders of magnitude larger than that which is observed. The baryon-symmetric big-bang model could avoid an overabundance of photons compared to nucleons, but only by postulating a separation of the matter from the antimatter at a very early stage in the universe. This type of model could produce the observed γ-ray energy spectrum (42, 43) shown in Figure 5. Clearly, there are other measurements which could be made to further test this possibility. A precise measurement of flux isotrophy is an example of such a measurement. In addition, more careful measurements of the spectral shape of the radiation spectrum would be of great value. Another cosmological model in which cosmic rays and matter at a large red shift are responsible for the diffuse spectrum would produce a similar spectrum at low energies, but a markedly different one at high energies.

Future Prospects

Gamma-ray astronomy has now emerged as one of the most promising and significant areas of research in modern astrophysics. Perhaps the most dramatic and most immediate discoveries will be made in galactic γ-ray astronomy — particularly the discovery of many new point sources. In the past few years the number of point sources has increased from one (the Crab nebula and pulsar) to at least ten, with the promise of more to come in data not yet fully analyzed. Several of these new sources are identified with radio pulsars, but many are unidentified. The number of sources is now roughly parallel to the first few years of rocket-borne x-ray astronomy in terms of rate of discovery. However, whereas these first cosmic x-ray sources were bright enough to be seen on short duration sounding rocket flights, satellite experiments have been required to detect the first γ-ray sources at ~100 Mev. The actual detector areas used have been small (less than 10^3 cm^2) and most of the newly discovered sources have required exposures of several weeks.

Particularly exciting is the possibility that new classes of astronomical sources will be found such as γ-ray and cosmic-ray production in the ergospheres of rotating black holes or gamma rays from very high temperature accretion on massive black holes.

With the expected discoveries of many new sources and measurements of their spectra by instruments aboard the γ-ray observatories now contemplated, a much clearer view of the galactic structure of gas, magnetic fields, and cosmic rays will be forthcoming. The angular resolution will be improved so that the true extended emission can be separated clearly from the effects of multiple point sources. A much more complete picture of the cosmic-rays, nucleon distribution in the galaxy as well as a map of magnetic fields and gas density will then emerge. Measurements of the spatial distribution of the diffuse γ-ray sky at high galactic latitudes with higher spatial and spectral resolution will address problems of cloud formation, confinement of galactic cosmic rays, the galactic halo, and the studies of the diffuse cosmic γ-ray background and its relationship to cosmological models.

With the development of high resolution γ-ray energy spectrometers the prospects for developing nuclear γ-ray astronomy are most promising. If discrete γ-ray lines emitted during electromagnetic deexcitation of nuclei can be detected, their observations will confirm that excited states of nuclei are being produced and determine nuclear abundances. The magnitude of the fluxes and spectral distribution will allow the identification of the specific nuclear species and determination of their rate of excitation. Because extreme physical circumstances are required for the production of excited nuclei at low densities where they can be seen, unique information about the source regions will be obtainable. Observation of γ-ray line emission from supernova ejecta and in the accumulated background of the universe may make it possible to: prove supernovae eject new nuclei and measure the supernova yield, measure the supernova structure by the profiles of the lines and their Compton tails, discover galactic supernova remnants, determine the average rate of nucleosynthesis and its possible present day occurrence, learn more about the average density of the universe and help further evaluate evolving versus steady-state cosmologies.

This rich promise of γ-ray astronomy can be realized by a new generation of satellite experiments. Long exposures would permit detection of sources much fainter than the Crab anywhere in our Galaxy, and greatly improved statistics would enable point source positions to be determined to within $\sim$10 arcmin. The greatly increased sensitivities and improved angular resolution of such detector systems would also, of course, allow the beginning of extragalactic high-energy astronomy. The incredible cosmic ray accelerators that must exist in giant radio galaxies and quasars may also produce spectacular γ-ray fluxes since particles are probably not accelerated without interactions with matter on magnetic fields. It is entirely possible that the detection and measurement of the spatial and spectral distributions as well as the temporal variations from compact sources will provide the crucial data for a new understanding of these objects.

The exact direction that the investigations discussed in this paper may lead cannot be predicted but it is clear that γ-ray astronomy is an open-ended spectral frontier that will provide new insights needed in the understanding of astrophysical phenomena.

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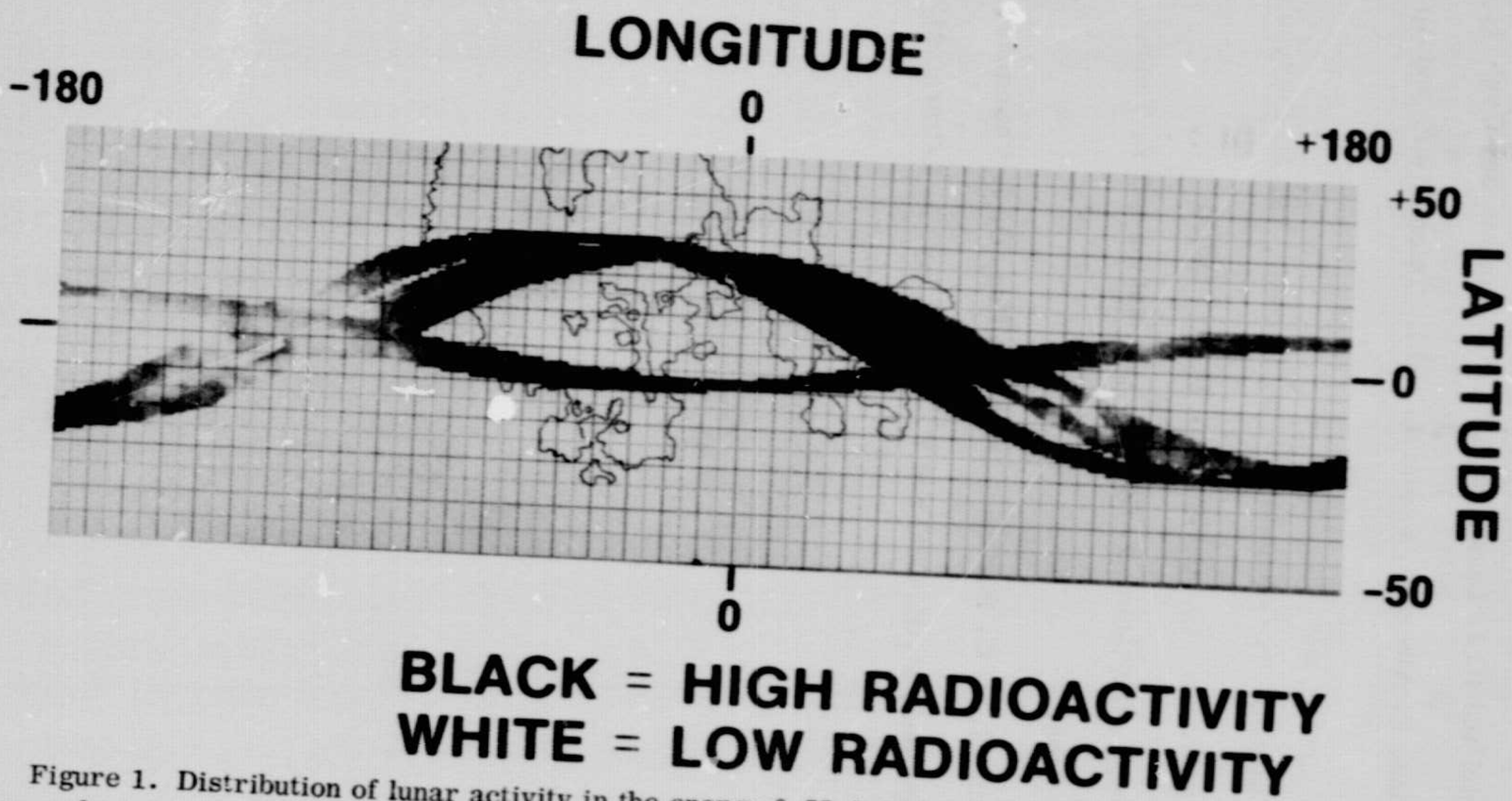

Figure 1. Distribution of lunar activity in the energy 0.55–2.75 MeV over the Apollo-15 and Apollo-16 ground tracks. The intensity of emission is proportional to the darkness of the gray scale. The map was provided by E. Eliason, U.S. Geological Survey, Flagstaff, Arizona.

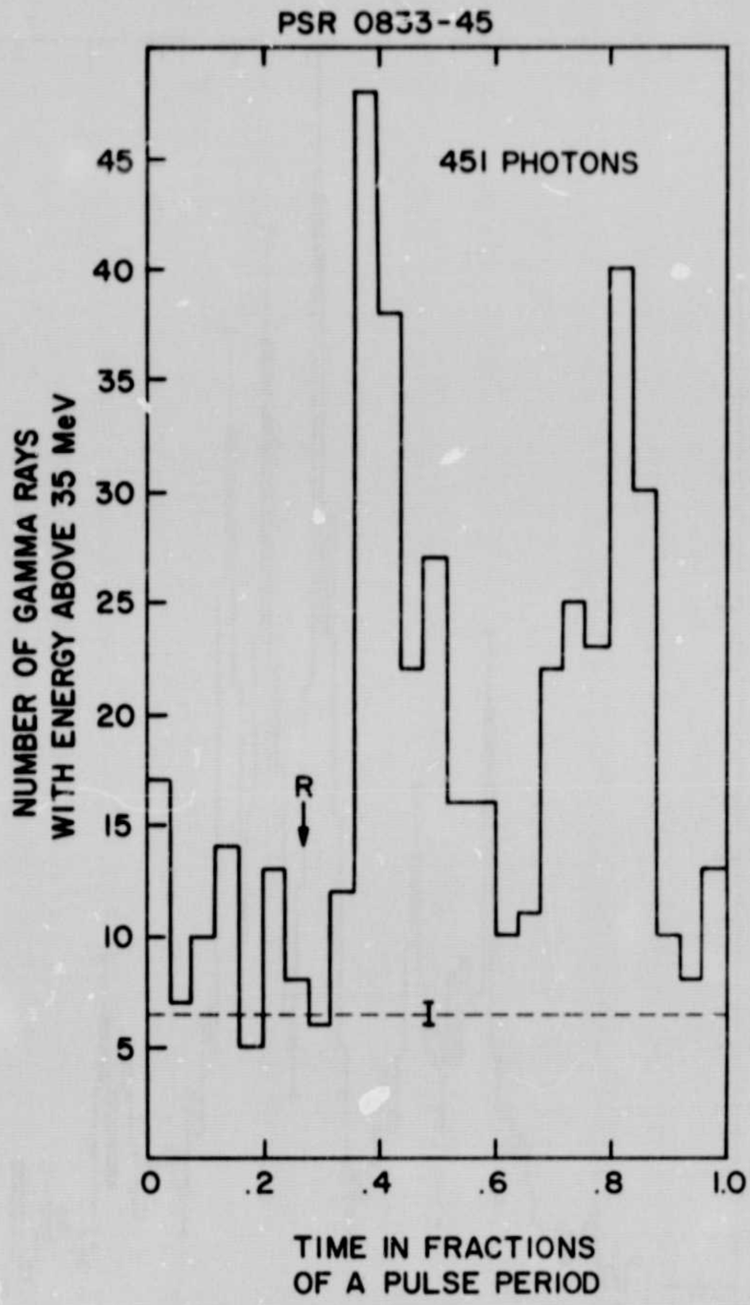

Figure 2. Distribution of γ-ray arrival times in fractions of a radio pulse period for γ-rays above 35 MeV from the direction of PSR 0833-45 as observed by SAS-2. Arrow R marks the position of the radio pulse. The dashed line shows the γ-ray level expected from galactic and diffuse radiation if no localized source were present. (reprinted from Ap. J., ref. 21)

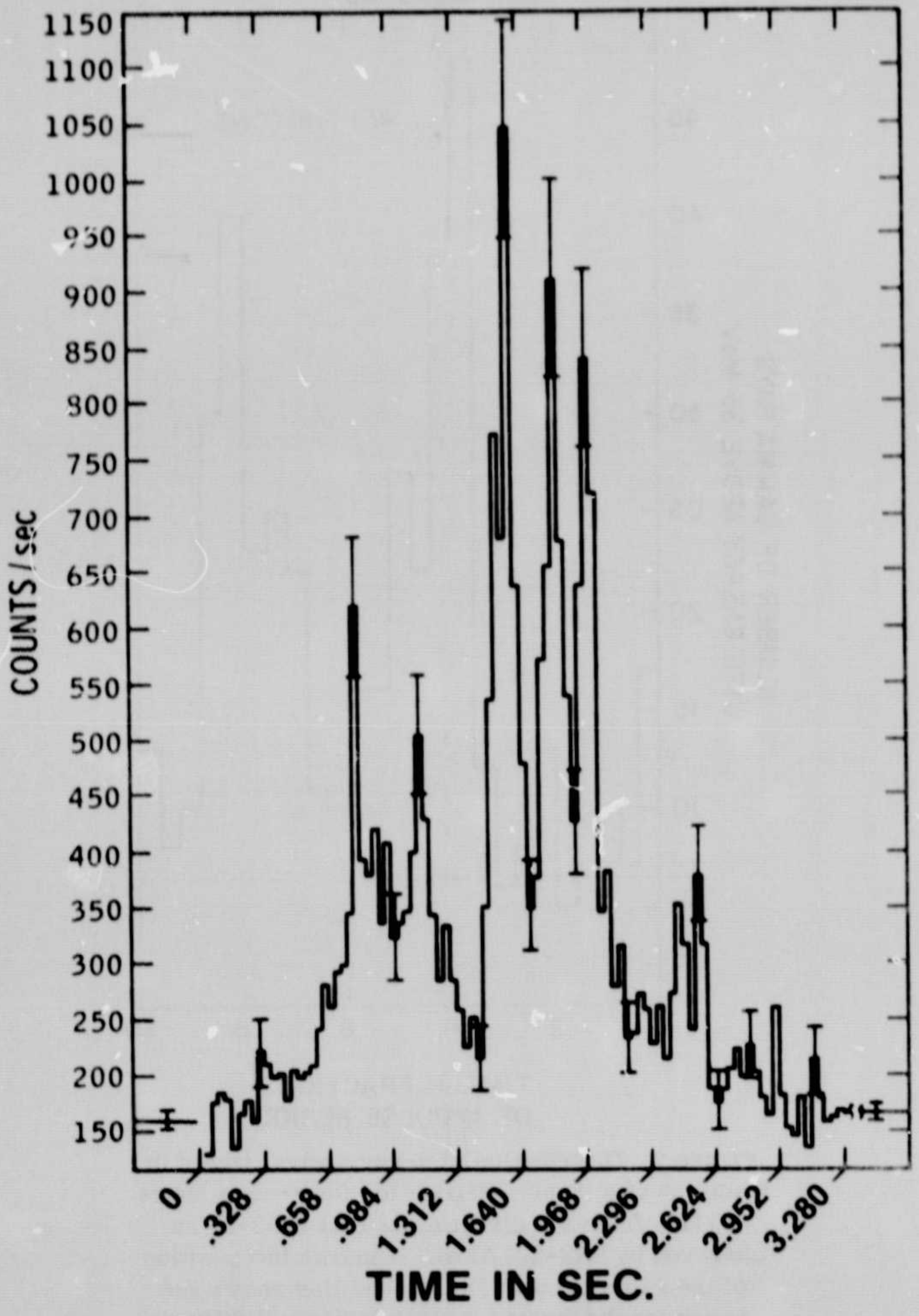

Figure 3. Measured time profile of intensity of gamma ray burst observed during Apollo 16 trans-earth mission April 27, 1972. (reprinted from Ap. J., ref. 30)

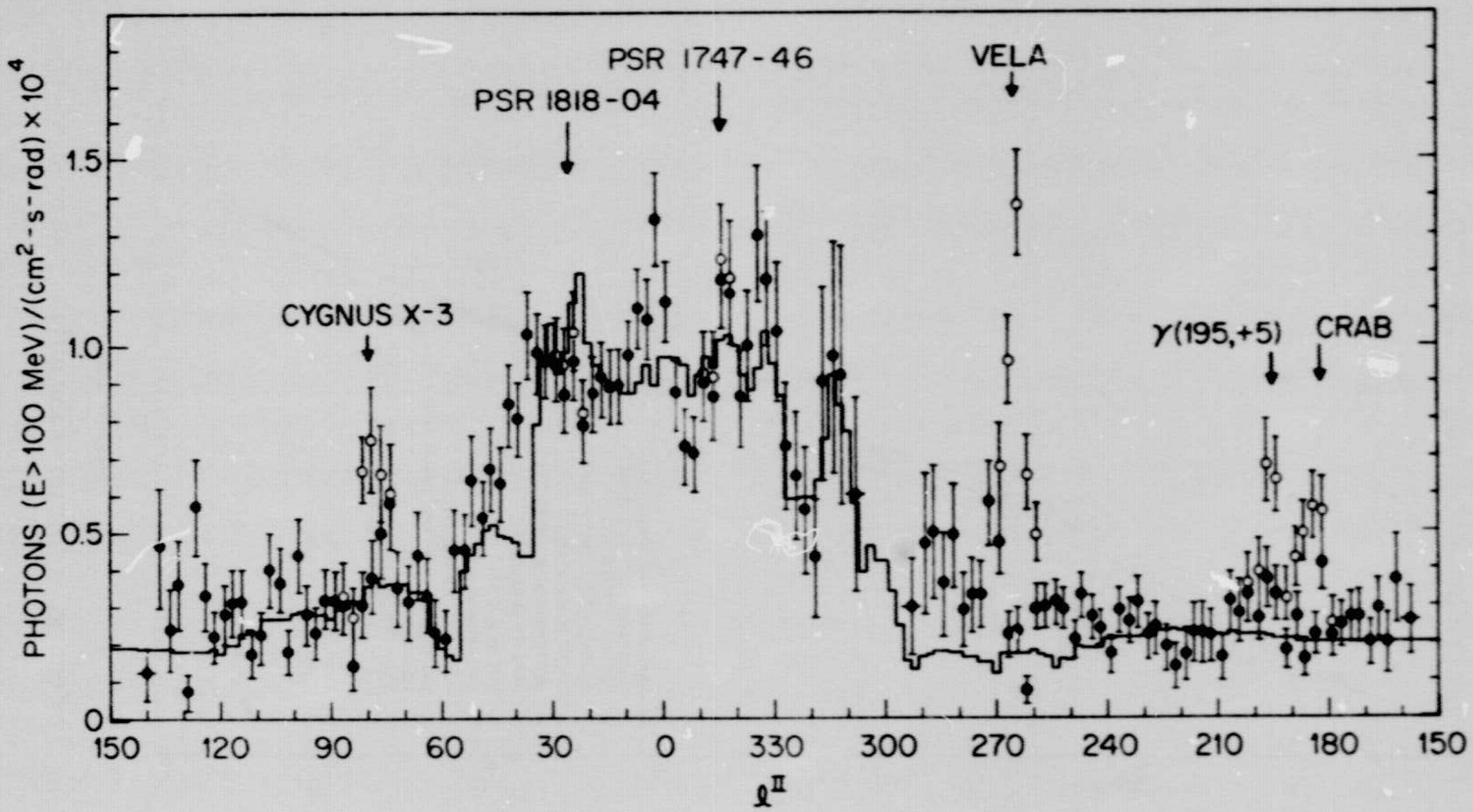

Figure 4. Comparison of the calculated longitude distribution of γ-rays with energy above 100 MeV with the SAS-2 results (37), summed between -10° and +10°. The calculation assumes a correlation between the cosmic rays and matter on the scale of galactic arms and uses the hydrogen density deduced by Gordon and Burton (38) and the matter model of Simonson (39).

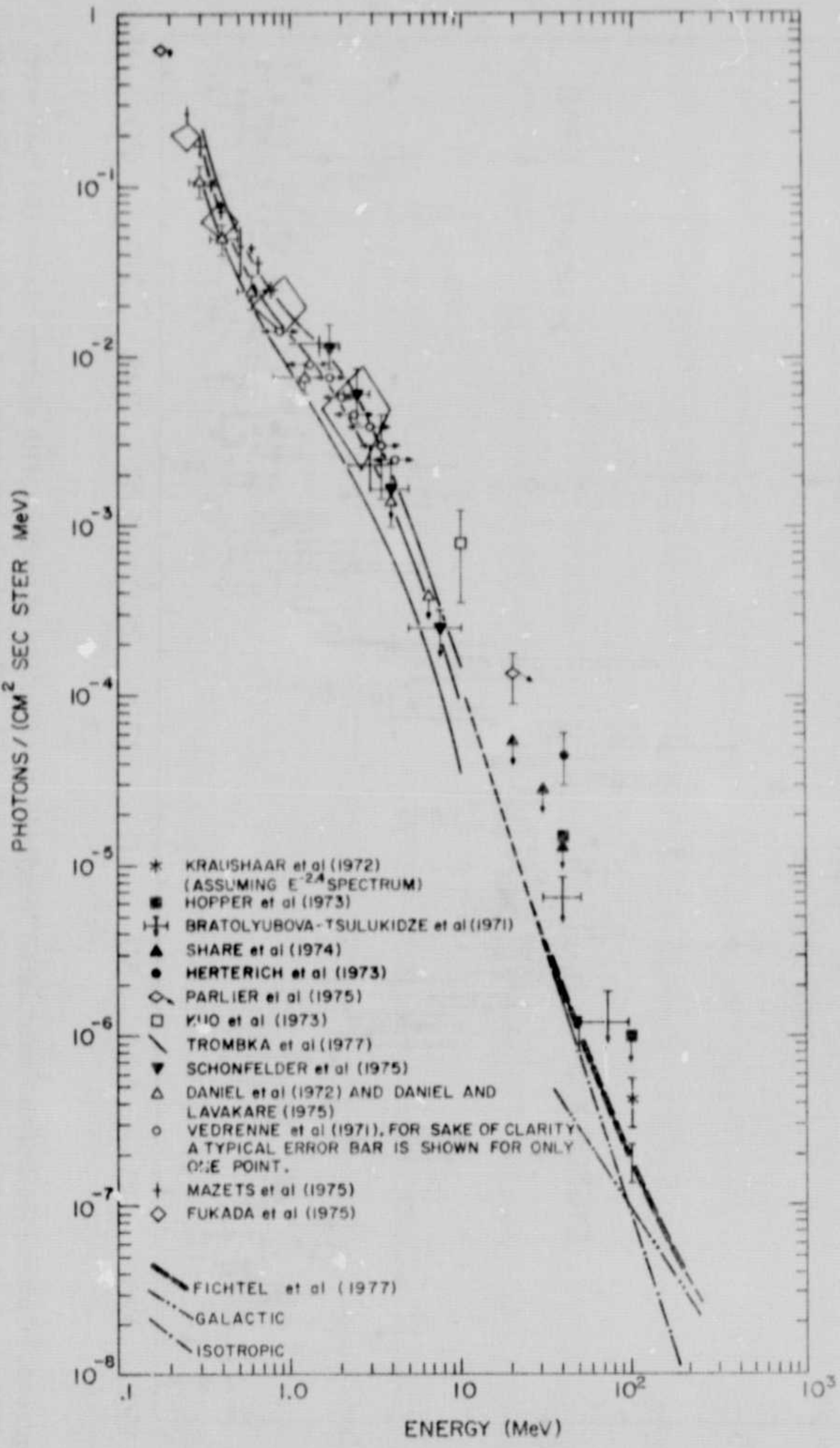

Figure 5. The energy spectrum of the diffuse radiation (44-58).

FIGURE CAPTIONS

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