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Gamma-Ray Astrophysics: A New Look at the Universe

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Summary. Progress in γ-ray astronomy has been very encouraging in recent years. These observations provide the most direct means of studying the largest transfer of energy occurring in astrophysical processes: the dynamic effects of the energetic charged cosmic-ray particles, element synthesis, and particle acceleration. Gamma-ray astronomical observations also find important application in studies of the development of the planets from the primitive solar nebula and of the nature of high-energy processes in the sun's atmosphere and their relation to the basic problems of solar activity.

A new window on the universe is being opened at the high-energy end of the electromagnetic spectrum. Gamma-ray astronomy, which may be defined to include the spectral region from above 100 keV to about 1000 GeV, 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: the dynamic effects of the energetic charged cosmic-ray particles, element synthesis, and particle acceleration. Further, γ-rays suffer negligible absorption or scattering 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. These include 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 even certain aspects of cosmology and the origin of the universe.

Progress in this field of astronomy has, however, been slower than in some other fields such as x-ray astrophysics. Because of the smaller production cross sections and correspondingly lower fluxes of γ-rays, relatively large and sophisticated instruments are required. In the lower-energy portion of the γ-ray spectrum, nuclear activation with subsequent γ-ray decay further complicates 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 of γ-rays from solar, planetary, and galactic sources has already been obtained, largely from satellite experiments. Extragalactic radiation, possibly of cosmological origin, may also have been detected. 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 of the galactic structure, the origin and distribution of cosmic rays in the galaxy, and γ-ray emission. Point sources of cosmic γ-rays with energies from more than 100 MeV up to 1000 GeV have been detected, and one of the great surprises has been the identification of several γ-ray pulsars with radio counterparts.

Emission from a galaxy other than our own, Centaurus A, has been detected at very low (~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 γ-ray line emission from the moon has also been observed and used to infer the elemental composition over about 20 percent 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 around 1 MeV. The observed bursts generally have complex temporal behavior and often contain what appear to be multiple emission peaks. None of these bursts have been associated with any known celestial objects.

The results obtained so far are important not only because of their astrophysical significance, but also because of the effect they have had on development of the next generation of instrumentation, for which the technology now exists. The detectors carried on future missions will have greatly improved sensitivity. In this article we describe some of the results already obtained by γ-ray astronomy from observations of our own solar system, of other γ-ray sources in our galaxy, and of objects beyond our galaxy.

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Gamma-Ray Observation of Our Solar System

In the last two decades, observational data have been obtained from both space flight programs and meteorite studies that allow 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 the chronology and the present-day dynamics of the sun and solar system can be examined critically with γ-ray astronomical observations. First we consider the study of the sun, which, in addition 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 either from 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 their propagation in the solar atmosphere, and on the density and temperature of the ambient medium in which they decelerate. Next, γ-ray line emission is evidence that a particular nuclear species with a corresponding nuclear level has been excited by particles with energies above the excitation threshold. The 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- and 4.4-MeV γ-ray lines 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- and 6.1-MeV γ-ray lines of ^{12}C are ^{16}O, respectively. Since γ-rays are emitted in a time that is 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 Orbiting Solar Observatory satellite OSO-7 (*3, 4*). There was evidence of significant enhancement of the 0.51- and 2.2-MeV spectral regions. Line features at 4.4 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 astronomical observations also find important application in studying the development of the planets out of the primitive solar nebula. For planets whose atmospheres and trapped radiation environments 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.

For an understanding of the geology of a planetary body, knowledge of the total chemical composition and of the variation of the surface composition of the body is of fundamental importance. The overall composition is related to the mechanism of accretion and accumulation leading to planetary formation, and the distribution of elements is related to geological processes that were operative during planetary evolution.

Such information has been obtained from a number of missions to the moon and Mars—for example, Apollo 15 and Apollo 16 in the American space program and a number of lunar missions, Mars 4 and Mars 5, and the Venera mission in the Russian program. The distribution of Th, U, and K measured by the γ-ray spectrometer during the Apollo 15 and Apollo 16 missions is shown in Fig. 1, where concentration increases are indicated by darkening in the orbital path. The data from the Apollo 15 and Apollo 16 x-ray and γ-ray spectrometers have been thoroughly analyzed (*5-9*). These

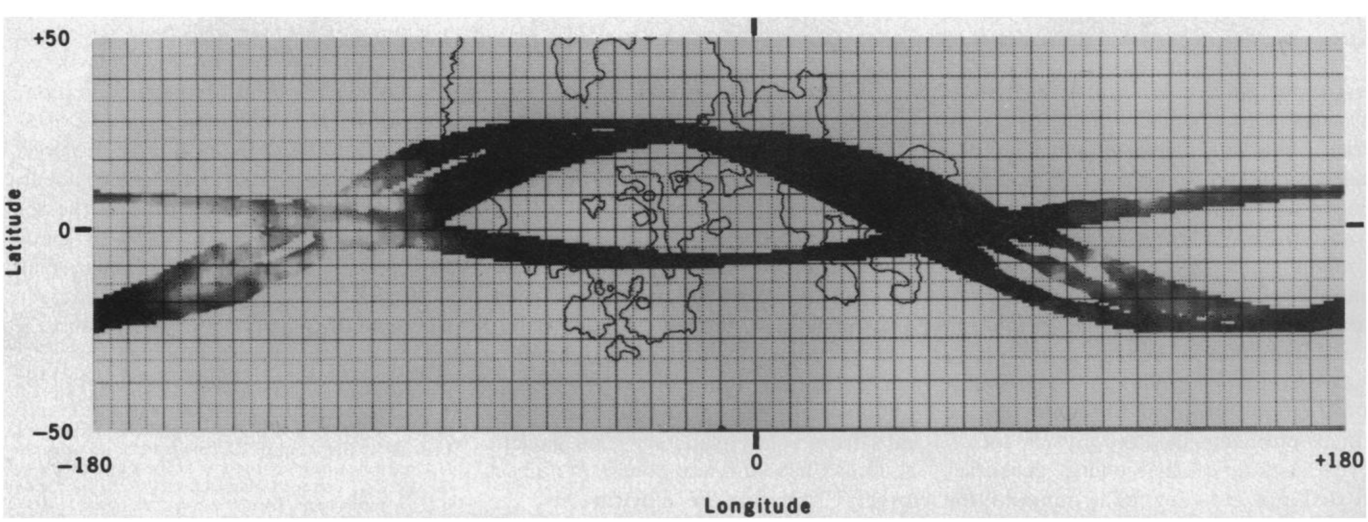

Fig. 1. Distribution of lunar activity in the energy range 0.55 to 2.75 MeV over the Apollo 15 and Apollo 16 ground tracks. The intensity of emission is proportional to the darkness of the gray scale. [Map provided by E. Eliason, U.S. Geological Survey, Flagstaff, Arizona]

measurements indicate that the moon has a global aluminum 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 U, Th, and K, the γ-ray information suggests that large basin-forming events were capable of creating the geochemical provinces by ejection from depths of 10 or more kilometers. The depletion of volatile materials relative to refractory materials in the lunar surface was found to hold true on a global basis, since the K/Th ratio determined from the lunar γ-ray measurements was significantly lower over most of the moon than it is on the earth. Measurements of U, Th, and K 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 that occur in stellar objects, and should therefore be valuable 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. Less than a decade ago the discovery of radio pulsars provided the first observational evidence for the existence of collapsed stellar objects. These pulsars are now generally considered to be 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 10^{33} to 10^{35} ergs per second 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 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*). For the Crab pulsar, however, 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 Fig. 2, two pulses of nearly equal size separated by about half a period were observed in the γ-ray region with the Small Astronomy Satellite SAS-2 γ-ray telescope and subsequently by the European Space Agency's COS-B satellite, whereas only a single pulse was seen in the radio region for this same source.

The most luminous galactic γ-ray source that has been observed so far is Cygnus X-3 (*22*); the flux of more than 30 MeV observed by SAS-2 implies a luminosity of more than 10^{37} erg/sec if the radiation is confined to a cone of 1 steradian. The γ-ray emission is observed to have the same 4.8-hour 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.

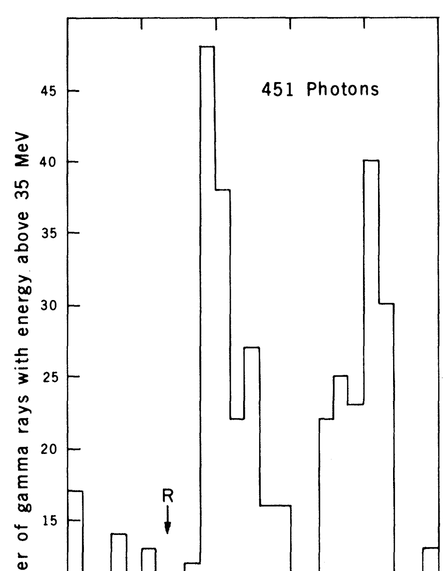

Fig. 2. Distribution of arrival times, in fractions of a radio pulse period, for γ-rays with energies above 35 MeV from the direction of PSR 0833-45 as observed by SAS-2. The arrow labeled *R* marks the position of the radio pulse. The dashed line shows the γ-ray level expected from galactic and diffuse radiation if no localized source were present. [Reprinted from Thompson *et al.* (*21*)]

Gamma-ray sources have also been observed by SAS-2 and COS-B that have no apparent counterpart at other wavelengths (*22-25*), which suggests that there may be a whole class of stellar objects that were previously unknown. Further, it is expected that γ-rays will prove to be a valuable probe of black holes, since the intense gravitational field near a black hole subjects infalling matter to extreme conditions. Recent theory has predicted the existence of relatively small primordial black holes that may signal the evaporation of their last $\sim 10^{14}$ grams by emitting ~ 10 percent of this rest mass energy in a short (2×10^{-7} second) burst of high-energy γ-rays with energies around 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 (*27-31*). These bursts have been detected several times a year with photons whose energies appear to be concentrated below a few million electron volts. They generally last a few seconds to 1/2 minute, and some, such as the one shown in Fig. 3, are observed to have substantial fine structure (*30, 31*). The sources of these bursts have not yet been precisely located on the celestial sphere, but it is anticipated that some accurate source locations will be forthcoming over the next 2 years. Recent results 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 these particles are accelerated in objects such as pulsars or supernovae, they will reveal their presence by interacting with the surrounding matter. Supernovae are expected to be among the more likely γ-ray emitters, and indeed the Crab Nebula was the first individual γ-ray source seen.

Nucleosynthesis has long been postulated to occur in the outer envelopes of supernovae, and this theory would be supported by the detection of γ-rays from the decay of the more abundant unstable nuclei produced, such as ^{56}Ni, ^{56}Co, ^{48}V, and ^{44}Sc (*33*). Identification of more than one nucleus would provide a quantitative test of the theory that 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 are planned for the Space Test Program satellite STP78-1 and the High Energy Astronomical Observatory satellite HEAO-C (*35*).

Diffuse Gamma-Ray Emission from Our Galaxy

When one considers the interstellar medium of our galaxy, the tenuous gas consisting largely of atomic and molecular hydrogen and interstellar dust often comes to mind first. However, two other constituents 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 an important role in the galaxy. Gamma-ray astronomy can provide information on the density distribution of the galactic cosmic-ray nuclei, which contain the great bulk of the energy, and independently on the density distribution of the cosmic-ray electrons. The latter results, combined with continuum radio measurements, would give a much more quantitative picture of the galactic magnetic fields than we currently have.

The most complete picture of the large-scale structure of the γ-ray sky that we have 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 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 to an extended region of 21-centimeter radio emission. When examined in detail, the longitude and latitude distributions appear to be generally correlated with galactic structural features as shown in Fig. 4. In particular, the γ-ray emission appears to be associated with segments of the spiral arms of the galaxy and with the enhancement of matter near 5 kiloparsecs from the galactic center; however, the sensitivity of the γ-ray instruments used does not yet permit a discussion of fine detail. Because of the correlation between the cosmic rays and matter on the scale of the galactic arms, a very high contrast picture of the galaxy should ultimately be forthcoming from γ-ray studies. In addition, γ-ray experiments with improved sensitivity and angular resolution should be able to answer the question of whether cosmic rays play a major role in cloud formation, since the relative γ-ray intensity expected from clouds compared to the intercloud region can be predicted for different models of the interrelationship between cosmic rays and clouds.

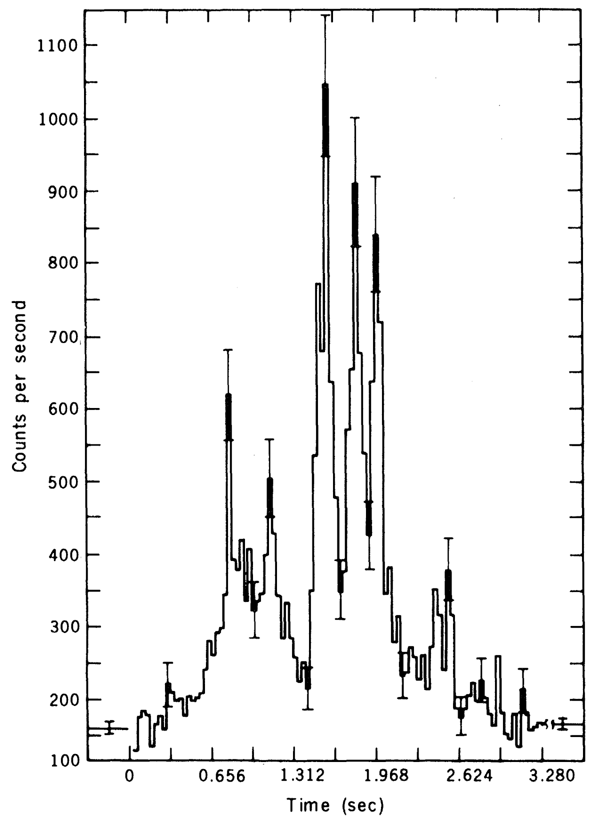

Fig. 3. Measured time profile of intensity of γ-ray burst observed during the Apollo 16 trans-Earth mission, 27 April 1972. [Reprinted from Metzger *et al.* (*30*)]

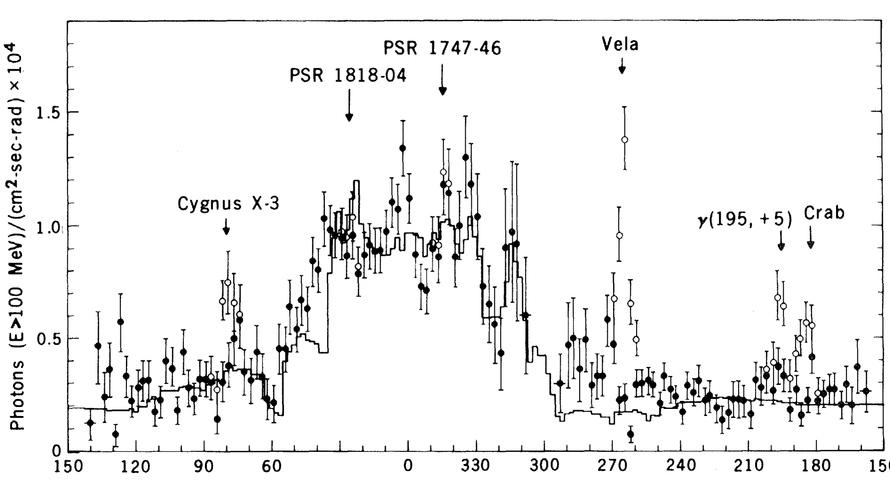

Fig. 4. Comparison of the calculated longitude distribution (solid line) of γ-rays with energies above 100 MeV with the SAS-2 results (*37*), summed between −10° and +10°. A correlation between the cosmic rays and matter on the scale of galactic arms was assumed, and the hydrogen density deduced by Gordon and Burton (*42*) and the matter model of Simonson (*43*) were used. Open circles represent the contributions of the point sources noted above them.

Other Galaxies and Cosmology

So far, only the closest active galaxy, Centaurus A, has been detected in γ-rays (*38*). With instruments of sufficient sensitivity it will be possible to study other galaxies in high-energy γ-rays and to determine whether they have cosmic-ray densities similar to that of our own galaxy. 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 in quasars, which are now thought to be distant galaxies. The intimate relationship between γ-rays and dynamic high-energy processes makes the extraordinary galaxies, such as Seyfert galaxies, radio galaxies, and quasars, prime candidates for γ-ray studies. For example, spectral observations of Centaurus A in high-energy x-rays through low-energy γ-rays, combined with Compton scattering models for the very high energy (~300 GeV) γ-rays, have established the magnetic field and cosmic-ray spectrum of this peculiar object.

The study of cosmology through γ-ray astronomy consists largely of the study of the diffuse γ-ray background—the part of the observed radiation that cannot be associated with known galactic or extragalactic sources. The measured intensity, energy spectrum, and degree of isotropy of this γ-ray background have already put significant constraints on cosmological models. For example, the intensity observed at energies above 150 MeV 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 (*39*).

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 that would be many orders of magnitude larger than the observed flux. The baryon-symmetric big-bang model could avoid an overabundance of photons compared to nucleons, but only by postulating the separation of matter from antimatter at a very early stage in the universe. This type of model could produce the observed γ-ray energy spectrum (*40, 41*) shown in Fig. 5. Other measurements could be made to further test this possibility—for example, precise measurements of flux isotropy and more careful measurements of the spectral shape of the radiation spectrum. Another cosmological model, in which cosmic rays and matter at a large redshift 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 areas of research in modern astrophysics. Perhaps the most dramatic and 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 identified has increased from one (the Crab Nebula and pulsar) to at least ten, and more may be found in data that have not yet been fully analyzed. Several of these new sources are identified with radio pulsars but many are unidentified. The rate of discovery of γ-ray sources is now roughly parallel to that of cosmic x-ray sources in the first few years of rocket-borne x-ray astronomy. However, whereas the first cosmic x-ray sources were bright enough to be seen on short-duration flights of sounding rockets, 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)

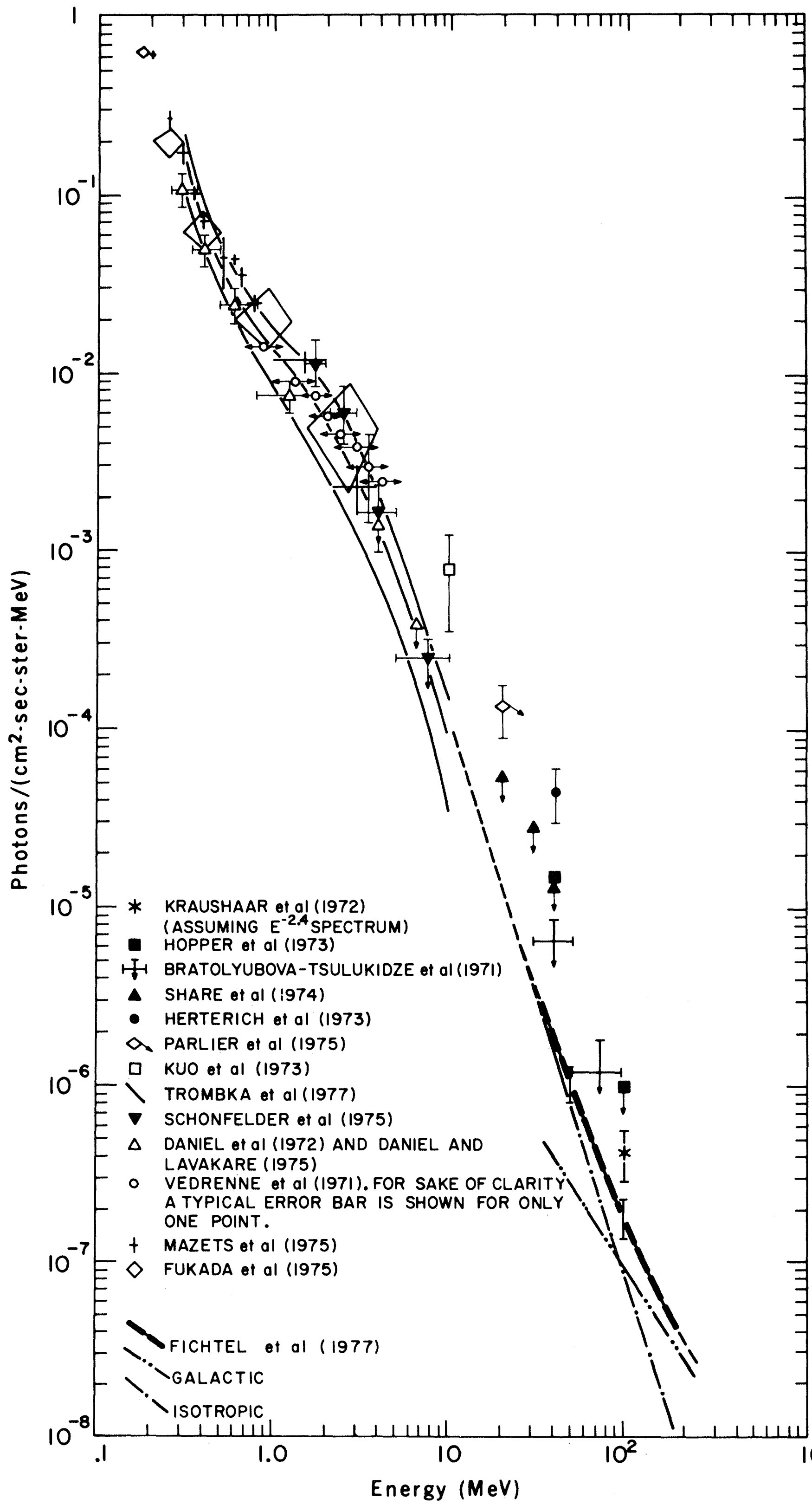

Fig. 5. Energy spectrum of the diffuse radiation (*41, 44–58*).

and exposure times of several weeks have been required in most cases. A particularly exciting possibility is that new classes of astronomical sources will be found, such as γ-rays and cosmic rays produced in the ergospheres of rotating black holes or γ-rays from very high temperature accretion on massive black holes.

The results obtained with the instruments aboard the γ-ray observatories now contemplated will yield a much clearer view of the galactic structure of gas, magnetic fields, and cosmic rays. 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-ray nucleon distributions in the galaxy as well as maps of the 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 be applicable to problems of cloud formation, the confinement of galactic cosmic rays, the galactic halo, and the diffuse cosmic γ-ray background and its relation to cosmological models.

With the development of high-resolution γ-ray energy spectrometers, the prospects for developing nuclear γ-ray astronomy are promising. Observations of discrete γ-ray lines emitted during electromagnetic deexcitation of nuclei would prove that excited states of nuclei are being produced and could be used to determine nuclear abundances. The specific nuclear species and their rates of excitation could be determined from the magnitude of the fluxes and the spectral distribution. Because extreme physical circumstances are required for the production of excited nuclei at sufficiently low densities that they can be observed, unique information about the source regions will be obtainable. Observations of γ-ray line emission from supernova ejecta and the accumulated background of the universe may make it possible to prove that supernovae eject new nuclei, measure the supernova yield, determine the supernova structure from the profiles of the lines and their Compton tails, discover galactic supernova remnants, determine the average rate of nucleosynthesis, learn more about the average density of the universe, and further evaluate the evolving and steady-state cosmologies.

With a new generation of satellite experiments, sources much fainter than the Crab could be detected in our galaxy by long exposures. The greatly improved statistics would make it possible to determine the positions of point sources within ~10 arc minutes. The greatly increased sensitivities and improved angular resolution of such detector systems would, 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 in magnetic fields. Measurement of the spatial and spectral distributions as well as the temporal variations from compact sources may provide the crucial data for a new understanding of these objects.

The exact direction in which the investigations we have discussed will lead cannot be predicted, but it is clear that γ-ray astronomy is a spectral frontier that will provide new insights needed for the understanding of astrophysical phenomena.

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