High-energy gamma-ray astronomy

The highest-energy particles and processes in the Universe provide clear and often unique information on the structure and history both of our Galaxy and of the regions beyond.

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All the natural electromagnetic radiation reaching the Earth, whether from nearby or remote parts of the universe, brings with it information on the contents or structure of the region in which it originated. This is true of each part of the spectrum, from radio waves through the visible, ultraviolet and x-ray regions, to the realm of high-energy gamma rays which is our subject here. We will be concentrating on celestial gamma rays, with energies above about 10 MeV, which provide clear and in some respects unique information on the high-energy particles and processes in the universe, both currently and in the remote past.

Gamma rays relate directly both to the very high energy electrons as they interact with photons, matter and magnetic fields, and to the energetic nuclei as they interact with matter. Of all the electromagnetic spectrum, high-energy gamma-ray astronomy measures most directly the presence and effects of the energetic charged particles—cosmic rays. Moreover, not only our own galaxy but also the universe is extremely transparent to gamma rays; therefore, these photons retain the detailed imprint of spectral, directional and temporal features imposed at their birth, even if they were born deep in regions opaque to visible light and x rays.

After more than a decade of searching for the rare celestial gamma radiation, the region of the spectrum above 35 MeV has now reached the exploratory phase with recent observations. These latest observations are confirming the utility of gamma-ray astronomy as a very important tool in the study of galactic structure and dynamics, as well as the contents and evolutionary history of the universe. The study of localized source regions at these very short wavelengths provides important new information with which to determine the emission mechanisms of objects such as pulsars, supernova remnants, external galaxies and possible black holes, and perhaps objects that emit radiation only in the gamma-ray portion of the spectrum—gamma-ray stars.

The radiation reaching us from the greatest distance takes us back in time. The radiation now arriving from the farthest bounds of the universe had a much higher energy at its creation than the one seen by local gamma-ray telescopes because of the cosmological red shift, and this radiation images a universe in a more compressed and earlier state of evolution. For these reasons—and because of the present transparency of the universe at gamma-ray energies—the radiation from such remote regions is probably not too weak to detect. In fact, such radiation may account for most of the diffuse gamma-ray background seen at high galactic latitudes.

Early observations

Although it had long been realized that high-energy gamma-ray astronomy held these potentially great rewards, its development has been slow and difficult, primarily because of the low intensity of celestial gamma rays both in absolute terms and relative to the cosmic rays. Early experimental attempts to detect gamma rays with relatively simple instruments flown on balloons in the 1940's and 1950's were unsuccessful. New theoretical work in the late 1950's reemphasizing the importance of gamma-ray astronomy stimulated experimenters to develop more sophisticated detectors in spite of the failure of the early experiments to achieve positive results.

The first certain detection of celestial high-energy gamma rays came from a satellite experiment flown on the third Orbiting Solar Observatory (OSO-3). With this detector, William Kraushaar, George Clark, Gordon Garmire and their colleagues[1] observed the emission from the galactic disk of gamma rays with energies above 50 MeV as well as a possible diffuse flux. The limited spectral and spatial resolution of this excellent pioneering experiment left many questions unanswered, however. A gamma-ray spark-chamber telescope with substantially greater sensitivity and angular resolution (a few degrees) flown on the Second Small Astronomy Satellite (SAS-2), has now provided a better picture of the gamma-ray sky, especially when combined with the data on low-energy gamma rays that are becoming available from several other satellite and balloon experiments.

Instruments

The small wavelengths involved in gamma-ray studies preclude the use of conventional optical techniques for the direct detection of the primary photons; however the high energy contained in the quanta permits their detection by such varied particle counters as scintillators, spark chambers, proportional counters, Cerenkov detectors and solid-state counters. Because of the low intensities of the celestial gamma rays and the high background of charged particles to which these devices are also

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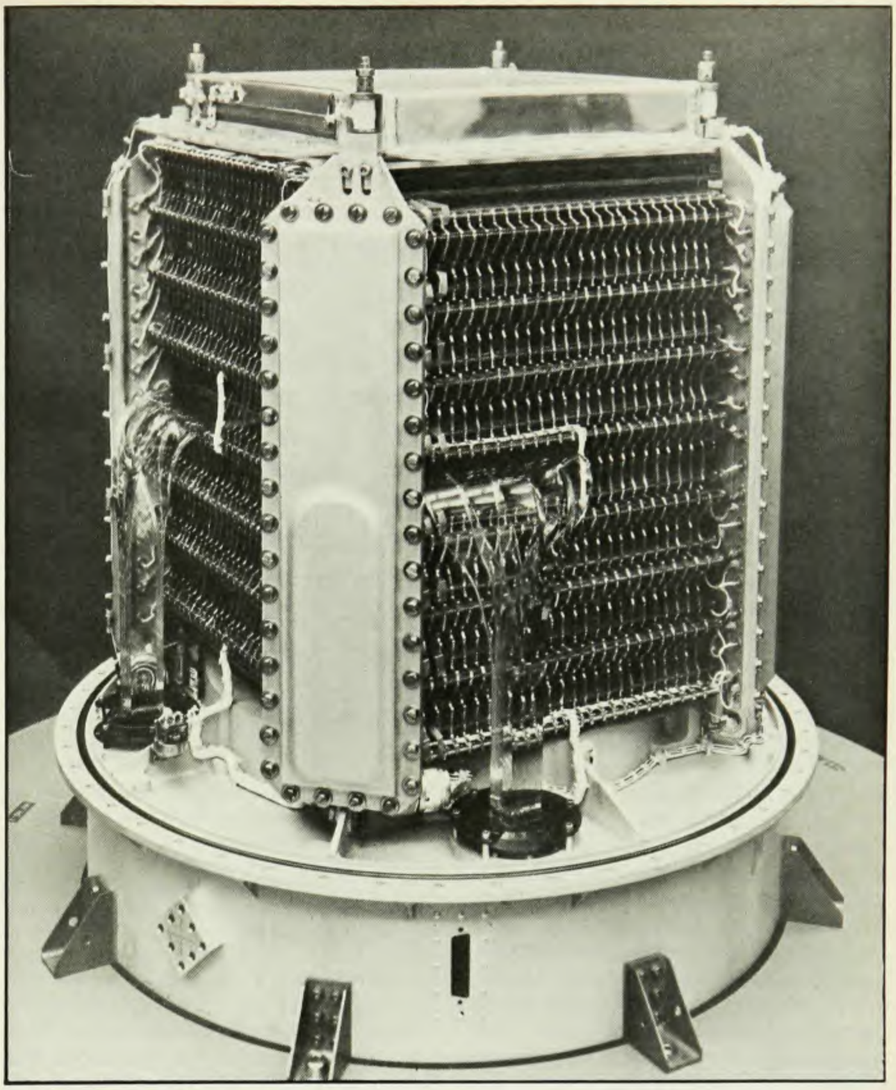
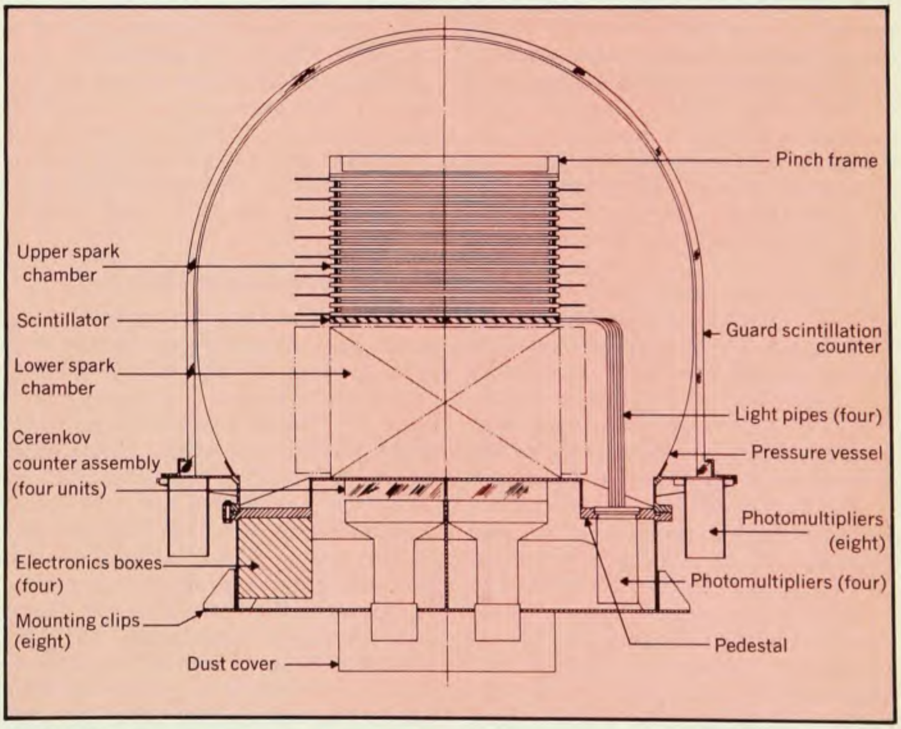
sensitive, one must use counter configurations that provide efficient detection combined with a reliable identification of the gamma rays and virtually total rejection of primary charged particles.

The basic property of the gamma ray that distinguishes it from the bulk of the cosmic rays is its chargeless state; hence the observing telescope generally includes an active anticoincidence counter as its outermost element. Upon passing through the anticoincidence system the high-energy gamma ray is converted into an electron pair whose presence is detected by a system of particle counters. Accurate angular measurements are difficult, both because the high frequency precludes optical and low-energy x-ray techniques, and because the low absorption cross section makes collimating techniques impractical. As a result, angular information on the arriving gamma ray must be obtained from measurements on the electron pair. This leads to some uncertainty owing to Coulomb scattering, especially at low energies and for thick converters.

In the 1960's the pictorial type detectors were developed and used for the energy range above about 10 MeV to provide an unambiguous identification of the gamma ray by observing the unique pair-production process and to give relatively good angular resolution over a large acceptance angle. The pictorial detector is an extension of the earlier counter-telescope technique with the addition of imaging devices to provide a "picture" of the electron and positron trajectories, allowing the positive identification of the ambient gamma ray as well as a better determination of its arrival direction and energy.

Figure 1 shows a photograph of the



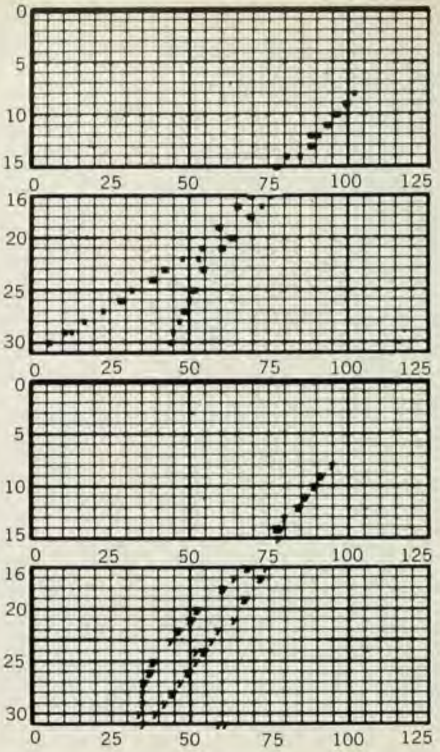


The SAS-2 gamma-ray experiment. The photograph shows the gamma-ray spark-chamber telescope with the thermal cover, anticoincidence dome and pressure-vessel removed; these components are shown, however, in the schematic cross-sectional diagram. Figure 1

SAS-2 experiment and a schematic drawing of its components.[2] This detector contains the anticoincidence counter and the two-element charged-particle coincidence telescope characteristic of the counter telescopes, but introduces in addition two spark-chamber assemblies, each consisting of 16-wire grid spark-chamber modules. The converter consists of thin plates of high-Z material interleaving the 16 upper-chamber modules. This configuration optimizes the information that can be obtained on the secondary electrons; the high-Z material minimizes the energy loss of the electrons for a given gamma-ray conversion probability. Similar plates in the lower assembly allow a clear identification of the gamma ray and a better estimate of the energies of the electrons from a study of their multiple Coulomb scattering, and hence the energy of the parent gamma ray. The determination of the position at which the electrons pass through each module level of the spark chamber stack provides a three-dimensional "picture" of the charged-particle trajectory. Figure 2 presents a computer-generated reproduction of such a gamma-ray produced electron-pair event seen by the SAS-2 gamma-ray telescope.

In the energy range above a few hundred MeV, observations have been made with a gas Cerenkov counter telescope developed by Kenneth Greisen and his group at Cornell,[3] depicted in figure 3. Again, a very efficient anticoincidence system is employed to discriminate against charged particles. This instrument is a modification of the counter gamma-ray telescope in which the Cerenkov counter contains a gas radiator rather than a solid one as in the earlier devices. With its inherent small acceptance angle this instrument is not suited for a sky survey, but it has the advantage of good directionality and the potential for very large collection areas at relatively low cost and complexity.

At extremely high energies (above 10^{11} eV), ground-based gamma-ray observations can be attempted by detecting the Cerenkov emission produced by the cascade shower induced in the atmosphere by a single impinging high energy gamma ray. Because the radius of the Cerenkov light pool at the ground is about 100 meters, the Cerenkov shower techniques provide a large sensitive area (10^4–10^5 m^2) and hence rather high counting rates even for primaries of quite high energy. Unless special care is taken the background in this experimental approach is quite high, being the sum of that produced by high-energy charged-particle cosmic rays, starlight, and other light that appears in the night sky. One can reduce this background problem by using a small



A gamma-ray pair-production event seen by the SAS-2 gamma-ray telescope. In these two orthogonal views the x's and y's denote cores set by the passage of charged particles in the x and y view, respectively. The vertical axis is compressed by a factor 2.7 relative to the horizontal axis. Figure 2

acceptance angle, a very short resolving time, and a large (about 10 meters) reflector system, which focuses the light onto a photoelectric device,[5] or by using more complex techniques with more than one reflector system.[6]

Many instruments have been developed by other groups who use variations of the gamma-ray detection techniques described here. More extensive discussions of gamma-ray detectors appear in a number of reviews on this specific topic.[7–11]

Galactic gamma-ray emission

The most striking feature of the celestial sphere when viewed in the frequency range of high-energy gamma rays is the emission from the galactic plane,[1,12,13] which is particularly intense in the galactic longitudinal region from about 300° to 50°. When examined in detail the longitudinal and latitudinal distribution appears generally correlated with galactic structural features, and particularly with spiral-arm segments. For example, the peaks shown in figure 4 are seen in the experimental distribution at 310–315°, 330–335° and 340–345°, corresponding to galactic features known as the "Scutum arm," the "Norma arm" and the 4-kpc arm, respectively.[4] Whereas any one peak may not be considered statistically significant, the fact that all three peaks are observed *is* significant. On the other side of the galactic center, the arms are not as clearly separated; however, the observations show an excess between 20° to 40° that may be related to the tangents to the 4-kpc and Scutum arms. The sharp decrease between $l^{II} = 50°$ and 55° is consistent with the tangent to the Sagittarius arm as shown in figure 5 from the work of Christopher Simonson.[14] The valley from 50° to 70° reflects a lack of features in that direction, and the increase in Cygnus from 70° to 80° is in the direction of the Orion arm. There also appears to be a contribution from the galactic center itself, or other sources in that direction.

On the basis of its amplitude, spectrum and angular distribution, and on the lack of quantitatively successful alternatives, the diffuse high-energy gamma radiation from the galactic plane appears to be explained best as resulting primarily from cosmic-ray interactions with interstellar matter—principally atomic and molecular hydrogen.

The nuclear component of cosmic rays, because of the relatively large mass of the individual nuclei compared with electrons, does not respond strongly to the electromagnetic fields; but it does interact strongly with nuclei. Hence, the nuclear cosmic rays selectively induce responses from any matter that is distributed in space—such as interstellar gas, atoms, ions, molecules and dust. The characteristic nuclear reactions lead to the prolific creation of pions, and the neutral pions decay into gamma rays. The spectrum of these gamma rays carries a unique signature of their mode of origin: namely, the spectrum has a broad peak at

$$\frac{M_{\pi^0} c^2}{2} = 68 \text{ MeV}$$

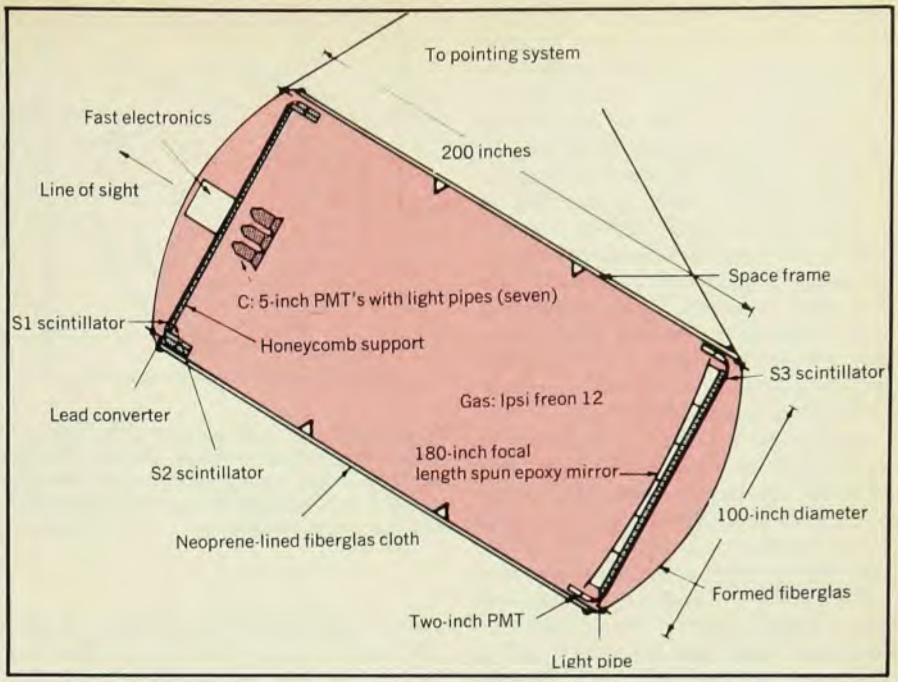
and above a GeV parallels the high-energy (>10 GeV) cosmic-ray spectrum.

The amplitude of the spectrum from any direction is proportional to the line integral of the product of the cosmic-ray flux and the matter density. Absorption of the radiation is normally unimportant, because the mean free path of the high-energy gamma radiation is more than a hundred times the distance through the longest path in our galaxy, and at least 10^3 times the average thickness of the universe. Thus by variations seen in the amplitude of the gamma-ray distribution, we can identify the arm structure of our galaxy, estimate the product of the cosmic-ray density and the gas density near the center of the galaxy, and measure (eventually) the large gas clouds.' Also the excess cosmic-ray flux surrounding a supernova appears to have been observed.[15,16]

The high-energy electrons and positrons in cosmic rays, which are much less numerous than protons of the same energy, produce gamma rays by interacting with matter via bremsstrahlung, with lower-energy photons through Compton scattering, and with magnetic fields via synchrotron radiation. Bremsstrahlung appears likely to be the most important of these three for the gamma rays below about 30 MeV in the general diffuse galactic radiation. The other two mechanisms probably are not important for the galactic nor the extragalactic diffuse radiations, with the possible exception of Compton radiation in the galactic center; but they could be quite important for compact objects, which we will discuss later.

The general galactic radiation may ultimately prove to be of great value in studies of the galactic structure. We have already noted the high penetrating power of gamma rays, which allows them to reach the solar system easily from almost anywhere in the galaxy. Further, the structure contrast as revealed by gamma rays (at least on the scale of galactic arm segments) may be very high, as seen from the following considerations: If it is assumed that the cosmic rays and magnetic fields are galactic and not universal, then, as Peter Bierman and Leverett Davis,[17] and Eugene Parker[18] showed in more detail, the magnetic fields and cosmic rays can only be contained by the weight of the gas through which the magnetic fields penetrate; hence, they are tied to the matter. The local energy density of the cosmic rays is about the same as the estimated energy density of the average magnetic fields and the kinetic motion of matter. Together the total pressure due to the cosmic-ray gas, the magnetic fields and the kinetic motion of the matter is estimated to be approximately equal to the maximum that the gravitational attraction can hold in equilibrium. This estimate suggests that the cosmic-ray density may generally be as large as would be expected under quasi-equilibrium conditions. Lending some theoretical support to this concept is the calculated slow diffusion rate of cosmic rays[19–21] in the magnetic fields of the galaxy, based on the cosmic-ray lifetime and the small cosmic-ray anisotropy, and also the likely high production rate of cosmic rays. These two facts together suggest that in general the cosmic rays should be plentiful in a dense region and will not move quickly to less dense regions.

Therefore, it appears reasonable to assume[22] that the energy density of the cosmic rays is larger where the matter density is larger. If, for example, the cosmic rays are assumed to be proportional to the average matter density on the scale of galactic arms reasonable agreement with the experimental data is achieved,[23] as shown in figure 4. On the other hand, with a constant cosmic-ray density (as an extragalactic theory of cosmic rays would require) this degree of agreement is not possible.

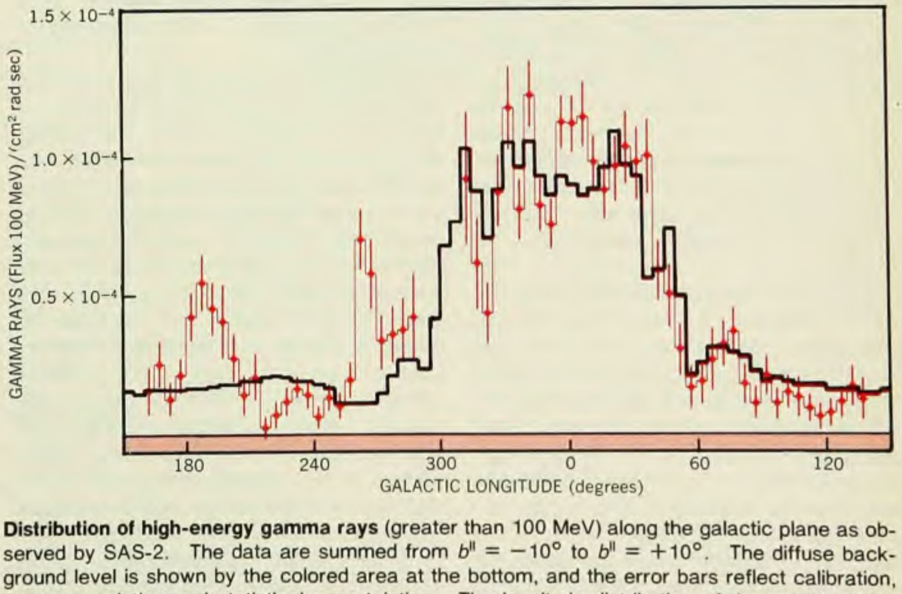


The gas Cerenkov gamma-ray detector developed by the Cornell group. The gamma "signature" (coincidence and anticoincidence signals recorded by the passage of a gamma ray) is: $\overline{S1}(t)$, S2(t), S3(t +17ns), C(t +32ns). Figure 3

The molecular-hydrogen distribution, which was assumed to be proportional to the atomic hydrogen in the above, remains one of the greater uncertainties in these calculations. Floyd Stecker and his colleagues[24] have used a model for the molecular-hydrogen distribution based on the work of Nicholas Scoville and Philip Solomon,[25] which suggests that, although the cosmic rays must still be preferentially associated with the matter to obtain agreement with the observations, the correlation is not nearly as strong as the first power of the matter density. The degree to which the cosmic-ray density is related to the matter density in any specific region will only be established when more detailed gamma-ray measurements and better estimates of the total matter density become available.

Diffuse celestial radiation

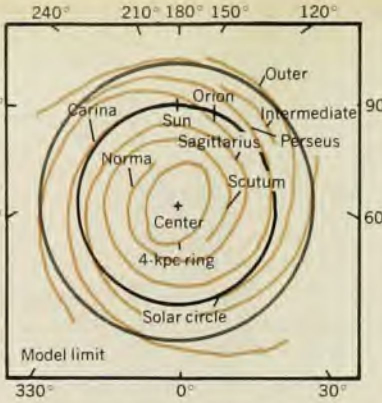
Regions away from the galactic plane show an apparently diffuse intensity of



Distribution of high-energy gamma rays (greater than 100 MeV) along the galactic plane as observed by SAS-2. The data are summed from $b^{II} = -10°$ to $b^{II} = +10°$. The diffuse background level is shown by the colored area at the bottom, and the error bars reflect calibration, energy resolution and statistical uncertainties. The longitude distribution of the galactic high-energy gamma-ray emission deduced from the spiral-arm model is shown by the colored line. The increase around longitude 265° is due to the Vela supernova remnant, and the increase from 180° to 205° is due to the Crab nebula and possibly other sources. Figure 4 gamma rays that has been observed by several experiments and now appears clearly established. In view of the limited angular resolution of the experiments (from a few degrees to over 10 deg) and the limited region of the sky surveyed by most of the experiments, caution must be used in interpreting the radiation as truly diffuse, as opposed to the sum of many point sources. The energy spectrum determined for this radiation has the rather interesting shape shown in figure 6.[26] The line labeled "B" in this figure is a plot of the function $dJ/dE = 0.11E^{-2.3}$ in units of photons/(cm^{2}sec-sr-MeV), with E expressed in MeV. This line, chosen to pass through both the SAS-2 data[13] and the 1-MeV gamma-ray data, is also consistent with the high-energy x-ray data within stated uncertainties.[28,29] However, the majority of the data from 1 to 10 MeV seem to lie above this line and have a flatter spectral shape than this power law would indicate, implying first a decrease and then an increase in spectral slope. The intensity in the 5 to 40 MeV energy range is quite uncertain at present.

The list of candidate models to explain the diffuse radiation is lengthy. The shape of the spectrum is at present consistent with a red-shifted gamma-ray spectrum, integrated over the time of the universe, with an additional steep component at low energies. These characteristics have led to several cosmological origin theories including: the particle–antiparticle annihilation in the baryon-symmetric big-bang model; the cosmic-ray–intergalactic-matter interaction model, and the cosmic-ray–blackbody interaction model. To these we could add numerous multiple discrete source models, including one in which matter falls toward a black hole, producing neutral pions in interactions outside the Schwarzschild radius. The mesons decay into gamma rays, which are red shifted as they leave the gravitational field. In the future we may be able to distinguish between these theories by measuring the degree of small-scale uniformity of the diffuse radiation and making improved determinations of the energy spectrum at all energies.

Before we leave the discussion of the diffuse radiation, we should mention an interesting conclusion that can be drawn from the relatively low intensity of gamma rays above 100 MeV in the diffuse radiation. This intensity level places a constraint on the distance to which cosmic rays at the density observed in the vicinity of Earth may extend in a closed universe. Because the limit is sufficiently close to Earth to avoid any major cosmological effects, the calculation is straightforward. The observed gamma-ray intensities imply a limiting radius of about 50 megaparsecs



Spiral arms and other features of the galaxy, shown in a smoothed spatial diagram of the locations of the maxima of the matter density deduced from 21-cm HI line measurements and the density wave theory. Figure 5

for the local cosmic-ray density, if the gas density outside the galaxy is that required for a closed universe—namely about 10^{-5}/cm^3. Thus, a cosmic-ray density equal to that near Earth cannot pervade the universe if it is closed; however, the possibility that cosmic rays exist at the local density throughout our local super-cluster of galaxies cannot be eliminated under these conditions. If the universe is not closed, the matter density may be much lower. For an open universe we must consider specific cosmological models, because the large distances that then apply lead to substantial red shifts in the observed gamma radiation.

Discrete sources

Gamma-ray astronomy has been limited in its search for localized sources by the low intensity of the sources, the limited angular resolution of the detectors and (in the case of observations from balloon platforms) by the atmospheric background.

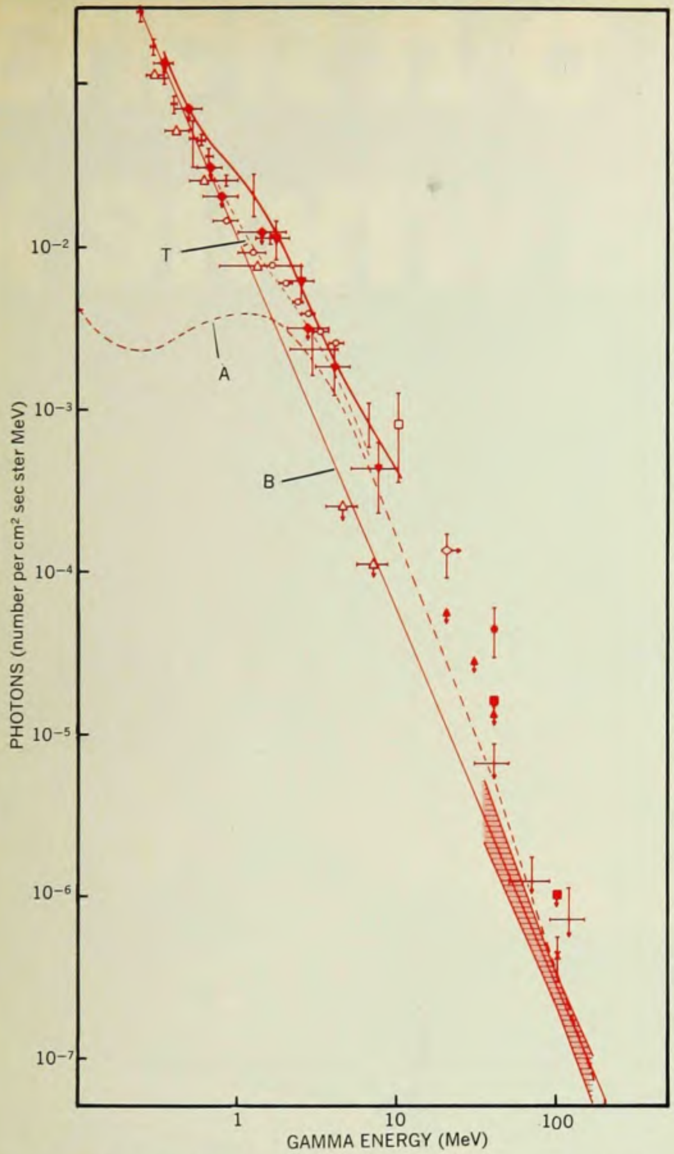
The first confirmed discrete source of high-energy gamma radiation is NP0532 in the Crab nebula, the fastest (that is, shortest-period) pulsar known. In this case the observation of pulsed emission at the same period as, and in phase with, the radio pulsar adds confidence to the identification of the source. The observations of this source[30] are summarized in figure 7 where it can be seen that the observations extend to at least a GeV. Observations in the 15–100-MeV range have yielded rather uncertain results, with reported upper limits and fluxes in apparent or near disagreement. Because the reported intensities in these balloon observations were just marginally detectable above atmospheric background, this uncertainty is understandable.

The most striking feature of the spectral distribution for the Crab pulsar in the 10^4 to 10^9 eV range is the transition from a predominantly unpulsed flux at lower energies to a predominantly pulsed flux at higher energies. The data are still too uncertain to allow definitive interpretation; however, we may draw a few conclusions. The pulsed and unpulsed emission mechanisms clearly have a different energy dependence, which is understood, qualitatively at least, by a model in which the pulsed emission comes from synchrotron radiation at the speed-of-light cylinder while the unpulsed component comes from regions of lesser magnetic field strength, probably by a combination of scattering of electrons by the unpulsed synchrotron radiation and interaction of high-energy protons and the ambient gas. The unpulsed synchrotron radiation is known to extend at least to x-ray energies; so the upper limits that can be set on the Compton-synchrotron emission lead to a lower limit of 10^{-4} gauss on the magnetic field strength in the nebula.[31] Meanwhile the absence of significant circular polarization in the radio spectrum sets an upper limit of about 10^{-3} gauss in the emitting regions, bracketing the field in the nebula rather closely.

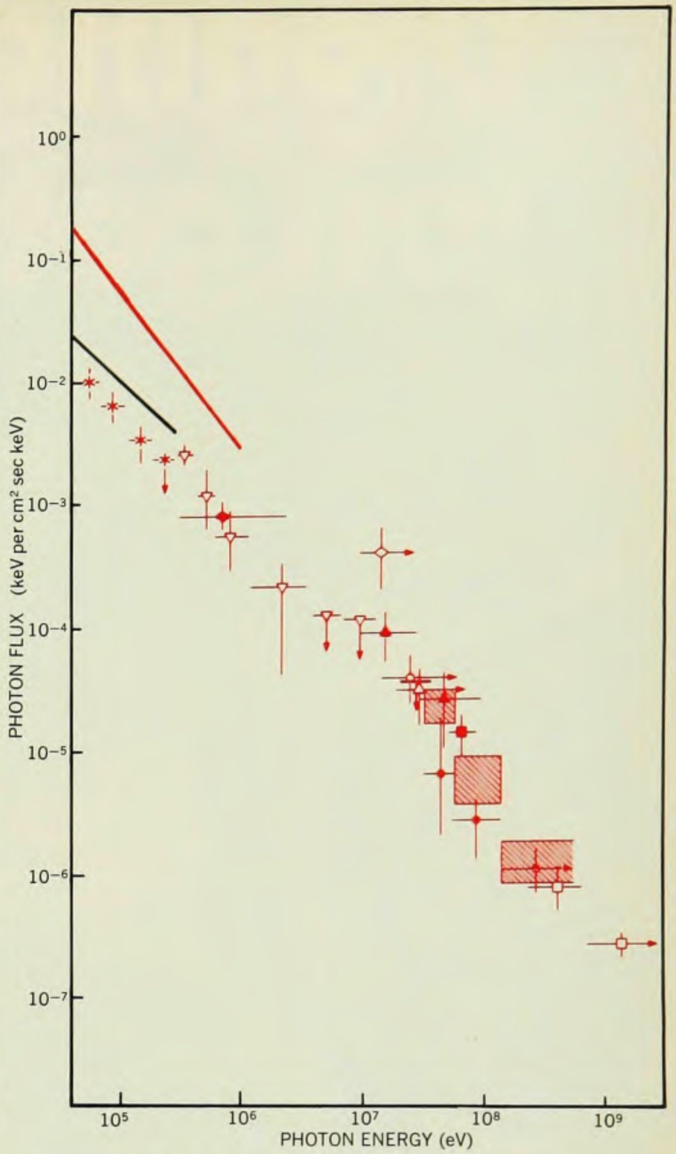
Recently the intensity of the pulsed radiation at high energies (greater than 0.8 GeV) has been reported to have changed significantly (by at least a factor of five)[32] between October 1971 and July 1973, in marked contrast to the lack of any significant (30% or more) variation in the total emission in the 1- to 10-keV range over the same period as observed by UHURU. This significant result is difficult to understand without additional observations.

The third fastest radio pulsar known at present is PSR 0833-45 in the Vela region. It is four times closer than the Crab pulsar and also within the envelope of a supernova remnant. The total gamma-ray flux seem from Vela[15,16,33] is about the same as that from the Crab. A temporal analysis shows that there is a very significant luminosity of pulsed emission at the radio pulsar period, as well as a constant component. The pulsed emission consists of two peaks, one following the radio peak by about 13 msec, the other 0.4 of a period later. The pulsed emission above 100 MeV from Vela is 0.1 that of the pulsar NP0532 in the Crab nebula, whereas the pulsed emission from Vela at optical wavelengths is less than 2×10^{-4} that from the Crab.[34,35]

The flux observed at Earth from the total Vela emission above 100 MeV is $(6.3 \pm 1.1) \times 10^{-6}$ photons/(cm^{2}sec). Even if it is assumed that only a fourth of this emission is associated with cosmic rays from the Vela supernova remnant interacting with local matter, 10^{50} ergs of cosmic rays from the supernova are contained within the remnant, a



Diffuse celestial radiation observed by several experiments (see ref. 26). The line B is the function 0.011 $E^{-2.3}$ photons/(cm^2 sec ster MeV), as discussed in the text. Colored lines A and T represent calculations by Floyd Stecker and his colleagues (ref. 27) based on the matter–antimatter annihilation of the baryon-symmetric cosmology (A) and the annihilation curve plus a low-energy power-law component (T). (Normalized to reflect recent measurements.) Figure 6



Spectrum distribution of fluxes observed from the region of the Crab nebula (ref. 30). The colored line and the colored boxes refer to the total flux and the remaining lines, points and upper limits refer to the pulsed flux. The most striking feature here in the 10^4 to 10^9-eV range is the transition from a predominantly unpulsed flux at lower energies to a predominantly pulsed flux at higher energies, with a different energy dependence in the two cases. Figure 7

value well above the minimum required if supernovae are to supply the galaxy with cosmic rays at the level observed in the vicinity of the solar system. It should be possible to confirm this hypothesis, at least as a mechanism of gamma-ray emission, by observation of the angular diameter of the source, for both Vela and the Crab. This result emphasizes the need for more refined observations (especially with improved sensitivity and angular resolution) to examine in more detail other young supernova remnants. A very likely possibility is the Cygnus region, for instance, which shows a gamma-ray enhancement in a direction that contains nine supernova remnants. However, the angular resolution of the present observations is insufficient to determine if excess emission is associated with some or all of these supernova remnants, or is just a generally enhanced galactic emission.

Another region of localized enhancement is that associated with Gould's Belt (a local galactic feature), and there are several other reports of localized sources beyond those already mentioned.

In the future . . .

The association of the high-energy gamma rays with cosmic-ray–interstellar-matter interactions suggests that, in the future, gamma-ray astronomy together with astronomy at other wavelengths holds great promise for the study of the galaxy—both in terms of the matter distribution and the cosmic-ray pressure distribution. Gamma-ray instruments of the future will have the sensitivity and the angular resolution to study the cosmic-ray–matter distribution not only on the broad scale of arms, but on the finer scale of variations within arms. Then the question of cosmic-ray expansion from sources and their propagation and distribution can also be studied in detail to see the effects of the cosmic-ray gas pressure and to study galactic structure in finer detail.

With improved angular resolution, possible contributions from discrete objects would be distinguished more clearly from more extended features of the interstellar medium, which might show enhanced gamma-ray emission—such as HI and HII regions, molecular clouds, globular clusters, dark clouds, supernova remnants and the hot regions

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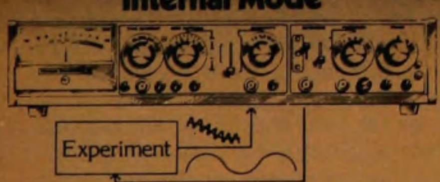
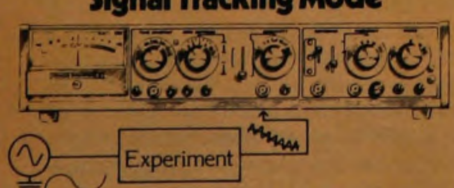


Internal oscillator modulates experiment.

External Mode

External reference from signal source.

Signal Tracking Mode



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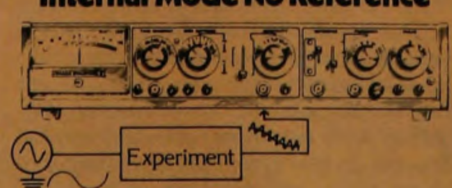
Internal Mode No Reference



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thought possibly to be the source of 0.25-keV x rays. As well as the study of the matter distribution and the cosmic-ray nucleons within these regions through observations of high-energy gamma rays, the study of the energy spectra in the medium-energy range (about 8 to 40 MeV) is important for investigating the electromagnetic processes in galactic gamma-ray production. The study of emission from supernova remnants should provide the most direct available evidence indicating whether supernovas are the long-sought sources of cosmic rays; if they are, details of the emitted radiation will provide a means of studying the question of cosmic-ray expansion from sources, and their propagation and distribution can be studied in detail.

With the addition of improved energy measurements and angular resolution, the energy spectrum and uniformity of the diffuse radiation could be studied with the hope of testing the currently proposed explanations of this radiation, including models that place its origin in the cosmological past, models that account for the gamma rays as an extension of the diffuse x-ray spectrum, and models that attribute the gamma rays to distinct high-energy processes in the contemporary universe. These three theories predict significantly different energy spectra for the gamma radiation. Also, as greater sensitivity permits studies at high galactic latitudes in more detail, emission from other galaxies can be studied, thereby providing a new dimension to galactic studies.

From these considerations, we see that the motivation for continued research in gamma-ray astronomy is clearly high. Much of what can be learned is predictable, but, from the previous experience in astronomy when large steps in sensitivity of the observing instruments have occurred, we know that many discoveries will be made that cannot be foreseen.

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