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HIGH ENERGY GAMMA RAY ASTRONOMY

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ABSTRACT

High energy gamma ray astronomy has evolved with the space age. Nonexistent twenty-five years ago, there is now a general sketch of the gamma ray sky which should develop into a detailed picture with the results expected to be forthcoming over the next decade. The galactic plane is the dominant feature of the gamma ray sky, the longitudinal and latitudinal distribution being generally correlated with galactic structural features including the spiral arms. Two molecular clouds have already been seen. Two of the three strongest gamma ray sources are pulsars. The Vela pulsar, PSR 0833-45, exhibits two pulses in the gamma ray region, as opposed to one in the radio region, neither of them in phase with the radio pulse. The other of the strongest gamma ray sources is that at L = 195, b = +5); it had no obvious counterpart at other wavelengths when it was found and correlation at other wavelengths is still uncertain. The highly variable X-ray source Cygnus X-3 was seen at one time, but not another in the 100 MeV region, and it has also been observed at very high energies ($>10^{11}$ eV). Beyond our galaxy, there is seen a diffuse radiation, whose origin remains uncertain, as well as at least one quasar, 3C 273. Looking to the future, the satellite opportunities for high energy gamma ray astronomy in the near term are the GAMMA-I planned to be launched in late 1987 and the Gamma Ray Observatory, scheduled for launch in 1990. The Gamma Ray Observatory will carry a total of four instruments covering the entire energy range from 3×10^4 eV to

3×10^{10} eV with over an order of magnitude increase in sensitivity relative to previous satellite instruments. On the ground, there is the possibility of much more sensitive measurements above 10^{11} eV than exist now. In the more distant future, the NASA Space Station should provide opportunities to fly quite large gamma ray instruments which might be refurbished or reconfigured in space.

1. INTRODUCTION

Gamma ray astronomy is truly a recent, space age addition to the field of astronomy. When Frank McDonald joined Goddard Space Flight Center in 1959, gamma ray astronomy consisted largely of theoretical papers describing its important scientific potential. Motivated in part by these articles, which were in some cases quantitatively rather optimistic about intensities, scientists began to develop instruments to detect celestial gamma rays first to be flown on high altitude balloons and later satellites. At the moment, the promised rich potential of gamma ray astronomy is beginning to be realized in the exploration of several aspects of astrophysics, and, if the missions planned for the next several years come into being, their results, in combination with those from other frequency ranges of astronomy, will almost certainly provide us with new concepts of the evolution and nature of the universe.

What the theorists realized approximately three decades ago was that, as the energies of the individual gamma ray photons suggest, gamma ray astronomy relates very directly to the most energetic processes in the universe ranging from the scale of individual particle acceleration and interaction through the formative processes in the galaxy and stellar explosions, to the largest ensembles imaginable. The nucleonic galactic cosmic rays reveal themselves through the high energy gamma rays emitted by the π° mesons which are formed in nuclear interactions between cosmic rays and interstellar matter throughout the galaxy. High energy cosmic ray electrons reveal themselves through interactions with matter and photons. The region around a black hole is predicted to emit characteristic gamma rays, and the death of a black hole should reveal itself with the emission of a very specific type of high energy gamma ray burst.

Matter-antimatter annihilation produces another characteristic type of gamma ray spectrum. Neutron star pulsars have already been seen in the gamma ray frequency, as has at least one quasar.

In addition to its value in relation to the physical processes of the universe to which it speaks, gamma ray astronomy has the very attractive feature that the universe is largely transparent to gamma rays. They can reach the solar system from the galactic center, distant parts of the universe, and dense regions near the centers of active galaxies—regions which cannot be viewed in the optical or low energy X-ray region, since, in contrast to optical photons which penetrate easily through the Earth's atmosphere, only the total amount of matter and not its form is relevant for gamma ray interactions. A specific illustration of the penetrating power of this radiation is the following. A high energy gamma ray passing through the diameter of the central plane of the galactic disk has about a one percent chance of interacting for a typical path. By contrast, an optical photon can only penetrate about one-tenth the distance from the galactic center to the Earth in the central plane of the disk. This remarkable window extends from a few times 10^7 eV, below which it begins to close slowly as the energy decreases so that as the X-ray region is reached the center of the galaxy is quite opaque, to 10^{15} eV, at which point there begins a one to two decade region in energy wherein gamma ray interactions with the blackbody radiation are important.

In spite of its importance, gamma ray astronomy is the last major wavelength range to yield its wealth of information. This relatively late development is the result of a combination of factors including the need to place gamma ray telescopes above the Earth's atmosphere, the requirement to develop rather complex instruments, and the relatively low intensity of gamma ray photons particularly in relation to the charged particle cosmic ray intensity. It is worth noting that even though the photon intensity is low, the energy emitted in the gamma ray range may be, and in several cases is, quite high because each photon carries a large energy, and the gamma ray frequency range is very broad.

The first certain detection of high energy celestial gamma rays was made with the gamma ray telescope flown on the third Orbiting Solar Observatory

(OSO-3) by Clark, Garmire, and Krqushaar [1968], who observed gamma rays with energies above 0.5×10^8 eV from the galactic disk, with a peak intensity toward the galactic center. The galactic center emission was confirmed, and its narrow width measured with a large balloon-borne gamma ray telescope flown in 1969 [Kniffen and Fichtel, 1970]. About this same time, there were several reports of a high energy pulsed flux from the Crab in phase with the radio pulsar [Browning, Ramsden, and Wright, 1971; Albats et al., 1972; Parlier et al., 1973; McBreen et al., 1973; Helmken and Hoffman, 1973; and Kinzer, Share, and Seeman, 1973], as well as the first hints of very high energy ($\sim 10^{12}$ eV) gamma rays [Grindlay, 1972; Fazio et al., 1972].

On November 15, 1972, a gamma ray telescope with approximately 12 times the sensitivity of the OSO-3 instrument and angular resolution of one to two degrees was launched on the second Small Astronomy Satellite (SAS-2). This instrument provided results which led to a much better picture of the high energy (E>35 MeV) gamma ray sky including fair detail on the galactic plane [e.g., Fichtel et al., 1975; Bignami et al., 1979] and energy spectral and isotropy measurements on the diffuse extragalactic high energy gamma radiation [Fichtel et al., 1977]. Another gamma ray instrument (E>50 MeV) with approximately equal sensitivity and angular resolution carried by the Cosmic Ray Satellite (COS-B), was launched on August 8, 1975, and provided information which further expanded our knowledge [e.g., Mayer-Hasselwander et al., 1980 and 1982], including the first detection of a quasar in gamma rays. These data were supplemented in the medium energy range by instruments carried on high altitude balloons [e.g., Agrinier et al., 1981; Graser and Schonfelder, 1982; and Bertsch and Kniffen, 1983].

These data showed the rich character of the galactic plane diffuse emission with its potential for the study of the forces of change in the galaxy, the study of the origin and expansion of the cosmic ray gas and the study of the galactic structure. When examined in detail the longitudinal and latitudinal distribution appear generally correlated with galactic structural features, including spiral arm segments. Two molecular clouds have already been seen. With the observations of discrete sources, some of which are associated with supernovae and pulsars and others apparently not correlated with radiation at other wavelengths, point-source gamma ray astronomy has also begun. The Crab nebula exhibits both continuum and double-pulsed radiation with both pulses

in phase with the radio pulsar, PSR 0531 + 21. The Vela pulsar, PSR 0833 − 45, on the other hand has two pulses in the gamma ray region, as opposed to one in the radio region, neither of them in phase with the radio pulse [Thompson et al., 1975 and 1977a; Bennett et al., 1977; and Kanbach et al., 1980]. One of the two strongest gamma ray sources (l = 195, b = + 5) yet observed [Thompson et al., 1977b; Swanenburg et al., 1981] had no obvious counterpart at other wavelengths at the time of its discovery by SAS-2. The highly variable X-ray source Cygnum X-3 was seen by SAS-2 [Lamb et al., 1977], but not COS-B.

In the very high energy ($> 10^{11}$ eV) region of the gamma ray spectrum, ground-based Cherenkov light reflector telescopes have evidence now of gamma ray emission not only from the Crab Pulsar PSR 0531 + 21, but also from the Vela Pulsar PSR 0833-45, Cygnus X-3, Centaurus-A, and possibly other sources. [For a summary, see, for example, Grindlay, 1982 or Weekes, 1983.] The implications with regard to the sources of these extremely energetic photons are obviously impressive.

In this paper, the current status of galactic extragalactic gamma ray astronomy will be summarized. Subjects of the lower end of the gamma ray spectrum which are covered elsewhere in this book, namely gamma ray spectroscopy and bursts, will not be emphasized. Finally, a short description of forthcoming gamma ray missions will be presented including the envisioned scientific significance of the data they should obtain.

2.   GALACTIC GAMMA RADIATION

As noted in the introduction, the gamma ray sky is dominated by radiation from the galactic plane, which is generally assumed to be the sum of diffuse radiation and unresolved point sources. The diffuse radiation was well anticipated. As early as 1952, Hayakawa [1952] noted the effect of meson-producing nuclear interactions between cosmic rays and interstellar gas. In the same year Hutchinson [1952] discussed the production of bremsstrahlung radiation by cosmic rays. Even earlier, Feenberg and Primakoff [1948] examined the astrophysics significance of the Compton effect in regard to cosmic ray electrons. The study of the diffuse radiation and its implications for our

galaxy is complicated by the fact that the point source contribution for the most part appears diffuse to the high energy gamma ray satellite instruments that have flown thus far because the angular resolution of these instruments for individual photons has been only one to a few degrees, or poorer, depending on energy. It is difficult to estimate the point source contribution since so little is known about them with only a few having been clearly identified. Several factors, however, suggest that point sources may not be a major contributor [e.g., Cesarsky, 1980]. These include the uniformity of the energy spectrum of the observed galactic radiation over the plane and its distribution being about what is expected from cosmic ray interactions. Even the earliest SAS-2 galactic gamma ray results [Kniffen et al., 1973] showed the general correlation of the gamma radiation with galactic structure, and subsequent work has shown it in greater detail, even quantitatively as will be shown in this section. This diffuse gamma radiation of cosmic ray origin will now be discussed followed by a summary of the current status of the knowledge of point sources.

A.   Cosmic Ray Interactions with Galactic Matter and Photons

Of the products formed in cosmic ray nucleon interactions with matter, the ones of most immediate interest to high energy gamma rays are the mesons, and among these are the most commonly produced ones, namely the π mesons. Many of the other mesons and hyperons also decay rapidly into π mesons. The charged π mesons decay into neutrinos and electrons adding to the cosmic ray electrons already present which also interact to produce gamma rays. The π° mesons, however, decay into two gamma rays which have equal energy in the rest frame. With a collection of π°'s of various energies, a gamma ray energy spectrum results with a maximum at approximately 68 MeV and a curve which is symmetric when plotted as a function of ln E_γ. The spectrum predicted for cosmic ray interactions with interstellar matter has nearly this shape being primarily slightly broader due to the minor components. For a further discussion of this interaction process and the ones about to be discussed, see Fichtel and Trombka [1981] and the references therein.

As the high energy cosmic ray electron primaries and secondaries interact with galactic matter, they produce gamma rays through bremsstrahlung. These gamma rays have a spectrum which reflects that of the electrons being approximately a power law.

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Cosmic ray electrons also interact with starlight photons, for which both the optical and infrared ranges are important, and with the blackbody radiation to produce Compton gamma rays. The source functions of these interactions are very much smaller in the galactic plane in the vicinity of the solar system. The total contribution to the galactic gamma radiation, however, is not completely negligible because the cosmic ray and stellar photon scale heights above the galactic plane are much greater than those of the matter and, of course, the blackbody photon density is uniform. Hence, the integral intensity along a line of sight is closer to that of the bremsstrahlung than the source functions would imply.

As an example of the spectrum which results from these three interaction processes, the calculated energy spectrum of the galactic gamma radiation for a region near the galactic center taken from the work of Fichtel and Kniffen [1984] is shown in Figure 1 and compared to data. The spectral shape elsewhere in the galactic plane is nearly the same with only minor variations resulting from small differences in the relative number of secondary electrons and the relative contribution of the Compton electrons. The agreement between theory and observation on the shape of the spectrum adds to the factors mentioned earlier for there at least being good reasons for believing that the majority of the measured apparently diffuse radiation is probably the result of cosmic ray interactions.

1.   Large Scale Diffuse Galactic Features

High energy gamma rays provide us the best known opportunity to determine the cosmic ray density distribution in the galaxy in general, in terms of spiral arms, and in association with molecular clouds. Thereby, they can ultimately contribute to our understanding of the dynamical effects in our galaxy in an important way. However, it is first necessary to have a good understanding of the galactic matter distribution, which at present is not as well-defined as one would like. It is, therefore, worth reviewing this subject to locate wherein the primary difficulty lies, since, as will be seen, it is an important factor in the current uncertainty in the large scale cosmic ray density distribution.
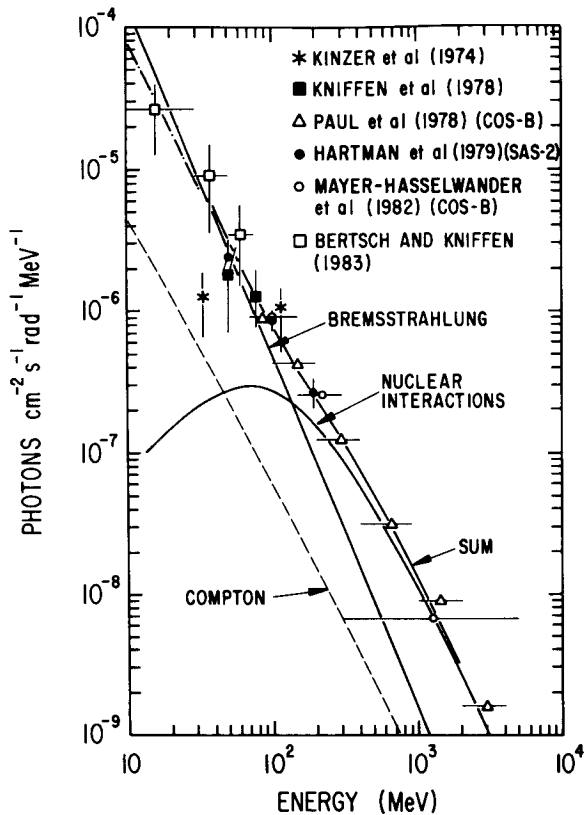
Figure 1. Energy spectrum of the galactic gamma radiation for a region near the galactic center. The calculated spectra are based on the work of Fichtel and Kniffen [1984]. The dot-dash curve includes an estimated correction for the increased energy loss by electrons in the inner galaxy. The 300-5000 MeV point of COS-B [Mayer-Hasselwander et al., 1982], which covers a large range in energy, is plotted at an energy where the differential energy spectrum of the equivalent power law spectrum is equal to the integral intensity divided by the energy interval width. The Compton component shown as a lightly dashed line is seen to be small and is somewhat uncertain. [This figure is from Fichtel and Kniffen, 1984.]

For the problem being considered here, the relevant concern is the galactic diffuse matter in the form of atoms, molecules, ions, and dust. The latter two are believed to be minor constituents and, hence, unimportant for gamma ray production through cosmic ray interactions. Hydrogen is the primary component of both the atomic and molecular matter. Helium and heavy nuclei add about 55% more to the gamma ray production. It is assumed these latter nuclei have a distribution in the galaxy similar to hydrogen, although little is known about them. Both atomic and molecular hydrogen are known to be confined to a narrow disk with the molecular hydrogen distribution generally having a smaller scale height [e.g., Gordon and Burton, 1976; Solomon and Sanders, 1980].

The neutral atomic hydrogen density distribution as revealed by the 21 cm emission is reasonably well-known; however, even it remains somewhat uncertain in the inner galactic regions because of uncertainty in the absorption correction. Recent work [e.g., Dickey et al., 1982; Thaddeus, 1982] suggests that the absorption had previously been somewhat underestimated and that the density in the region of 3-5 kpc from the galactic center is probably greater than previously estimated. The density distribution of molecular hydrogen is not as well-known because it is measured less directly. At present, the best estimate is obtained through the observation of the 2.6 mm spectral line of ^{12}CO, from which the distribution of cold interstellar matter is inferred. The nature of the interpretation of these measurements makes the derived molecular hydrogen density distribution less certain than that of the atomic hydrogen. In the long term, careful comparisons of gamma ray data with the atomic and molecular distributions should at least aid in the molecular hydrogen density normalization. The average galactic radial distributions of molecular and atomic hydrogen show clearly that the molecular hydrogen to atomic hydrogen ratio is larger in the inner galaxy than it is in the outer galaxy even if the absolute intensity of molecular hydrogen is still fairly uncertain. It is interesting to note that the great majority of the molecular hydrogen is in clouds. In most current analyses, the normalization of the molecular hydrogen density is treated as an adjustable parameter as long as it falls within the rather broad constraints set by other considerations.

If it were true that the cosmic ray density were constant throughout the galaxy, it would only be necessary to know the column density of the hydrogen in

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order to calculate the diffuse galactic gamma ray emission [see, for example, Fichtel and Kniffen, 1974]. However, if the cosmic ray density is variable, and this question will be addressed below, the product of the cosmic ray density and the matter density must be integrated over the line of sight in the galaxy, and hence, the matter distribution in the galaxy must be deduced. Although the translation of the observations into a galactic spatial distribution is difficult, on a broad scale the density profile is reasonably well accepted. Even though there is not complete agreement on details of arm structure, a general spiral pattern does appear to emerge. In addition to the 21 cm data, the distributions of continuum radiation [Landecker and Wielebinski, 1970; Price, 1974], gamma radiation [Bignami et al., 1975], H II regions [Georgelin and Georgelin, 1976], supernova remnants [Clark and Caswell, 1976], pulsars [Seiradakis, 1976], and infrared emission [Hayakawa et al., 1976] are all consistent with the existence of spiral structure in the galaxy. Until recently, it had not been clear whether molecular clouds were associated with spiral structure. However, now on the basis of a high sample survey and observations in both the first and second quadrants of the galactic plane, Cohen et al. [1980] have reported the existence of the molecular counterparts of the five classical 21 cm spiral arms segments in these quadrants, namely the Perseus arm, the Local arm, the Sagittarius arm, the Scutum arm, and the 4 kpc arm.

With regard to the cosmic ray density distribution in the plane and perpendicular to it, there is some relevant experimental evidence and several theoretical considerations. The radio continuum measurements of Cane [1977] used together with the assumption that the galactic magnetic fields energy density and the cosmic ray energy density have the same scale height give a scale height for the cosmic rays of about 0.6 kpc relative to the plane of the galaxy. The galactic magnetic fields and the cosmic rays tied to these fields can only be constrained to the galactic disk by the gravitational attraction of the matter [Biermann and Davis, 1960; Parker, 1966, 1969, and 1977]. The local energy density of the cosmic rays (~ 1 eV/cm^3) is about the same as the estimated energy density of the magnetic field and that of the kinetic motion of matter. Together, the total expansive pressure of these three effects is estimated to be approximately equal to the maximum that the gravitational attraction can hold in equilibrium. Further, the cosmic ray age determination suggests that this situation is the result of plentiful sources and leakage, not just chance accumulation to the maximum over time. Hence, excluding the possibility that

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the local conditions are anomalous, the most natural assumption is that the cosmic ray pressure is as great as it can be throughout the galaxy except possibly in the outer galaxy where sources or regions of further acceleration may be rare. The assumption that the cosmic ray density not only varies throughout the galaxy, but specifically on the scale of the arms, is based not only on the natural scale of the arms, but also on the scale height of cosmic ray electrons perpendicular to the plane, $\sim$ 600 pc, and the theoretically suggested mean diffusion length in the plane (a few to several tenths of a kiloparsec). Furthermore, support for this assumption is obtained from the recent work showing that the cosmic ray electron intensity within the spiral arms is about a factor of 2 higher than between the arms [Webber, 1983].

Before considering the general case of the whole galaxy, two simpler examples for diffuse gamma ray production by cosmic rays in the galaxy will be noted. For galactic latitudes where the local contribution may be expected to dominate, | b | greater than approximately 10°, the cosmic ray density as a function of position in the galactic plane presumably does not vary much. For this case, since the scale height of the cosmic rays is expected to be large compared to that of matter, a good approximation for the cosmic ray-matter interaction contribution to the gamma ray diffuse radiation is presumably obtained by using a constant cosmic ray density, which allows the direct use of atomic and molecular hydrogen column densities. If the point source contribution is small and if account is taken of the Compton contribution, it should be possible to obtain a good agreement using the matter column densities directly as shown by Strong et al. [1982] and Lebrun et al. [1982]. As an example, see Figure 2. It should also be possible to use this simplified approach successfully at intermediate longitudes, ($\sim$ 40° to $\sim$ 120° and $\sim$ 240° to $\sim$ 320°), where regions which are at galactic radii similar to the Earth are predominantly being viewed as shown, for example, by Arnaud et al. [1982] and Lebrun et al. [1983]. See Figure 3.

The more general case wherein the cosmic ray density is allowed to be variable and specifically proportional to matter on the scale of galactic arms is treated by Fichtel and Kniffen [1984]. They show that within uncertainties the present gamma ray results are in agreement with a coupling of the cosmic ray density in the plane with the broad spiral arm scale galactic features as predicted by theory. Their results are shown in Figures 4 and 5. Notice that the edges
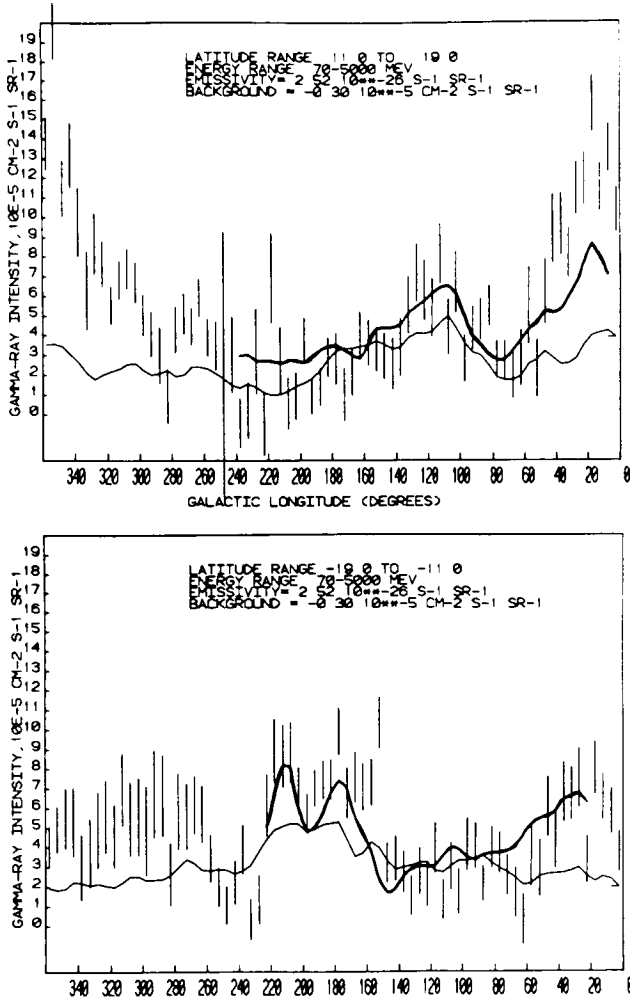
Figure 2. Comparison of measured and predicted gamma ray intensities. Bars: average measured intensity by COS-B with statistical errors based on counts in the bin. Thick line: predicted intensity based on estimated total column density (using galaxy counts). Thin line: predicted intensity for atomic hydrogen alone. [This figure is from Strong et al., 1982.]
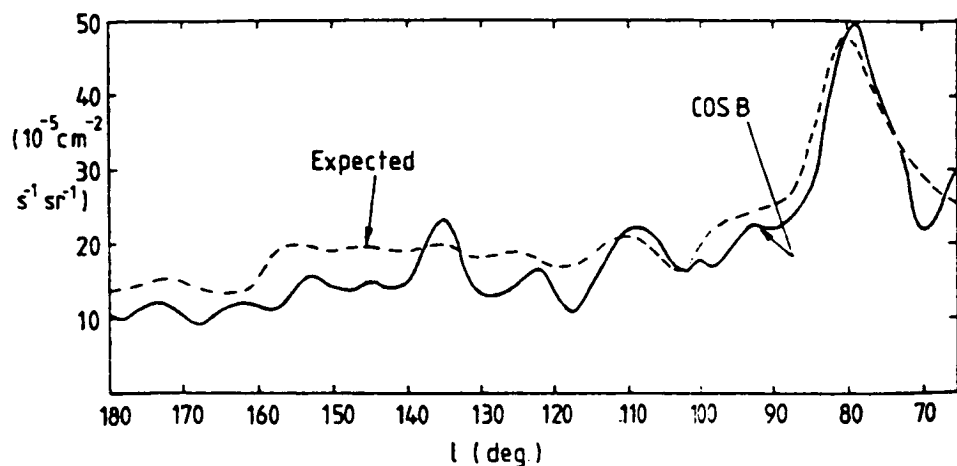
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Figure 3. A comparison of the gamma ray intensity ($E_\gamma > 100$ MeV) on a longitude along $b = 0°$ between that observed by COS-B [Mayer-Hasselwander et al. 1982] and that calculated by Arnaud et al. [1982] under the assumption of a constant cosmic ray density everywhere at the local galactic value. [This figure is from Arnaud et al., 1982.]

of the Sagittarius and Crux arms at about 55° and 310° respectively mark the beginning of the higher intensity associated with the central region of that galaxy, and that further steps near 35° and 330° mark the edges of the Scutum and Norma arms. There appear to be increases at 75° and 285° associated with the local arm and the Carina arm respectively. The expected increase at 265° for the local arm is masked by the large increase due to the Vela pulsar. The latitude distributions are also generally reasonable. Fichtel and Kniffen [1984] obtain a normalization for molecular hydrogen of 1.3×10^{20} mol cm^{-2} K^{-1} Km^{-1} s^{-1}, which is consistent with the rather broad range allowed by independent analyses of radio and other data by Blitz and Shu [1980] and Dame and Thaddeus [1985].

Other analyses which support at least a general galactic radial gradient of the cosmic ray density include those of Dodds, Strong, and Wolfendale [1975], Kniffen, Fichtel, and Thompson [1977], Issa et al. [1981], Hermsen and Bloemen [1982], Bloemen et al. [1984], and Harding and Stecker [1985]. The
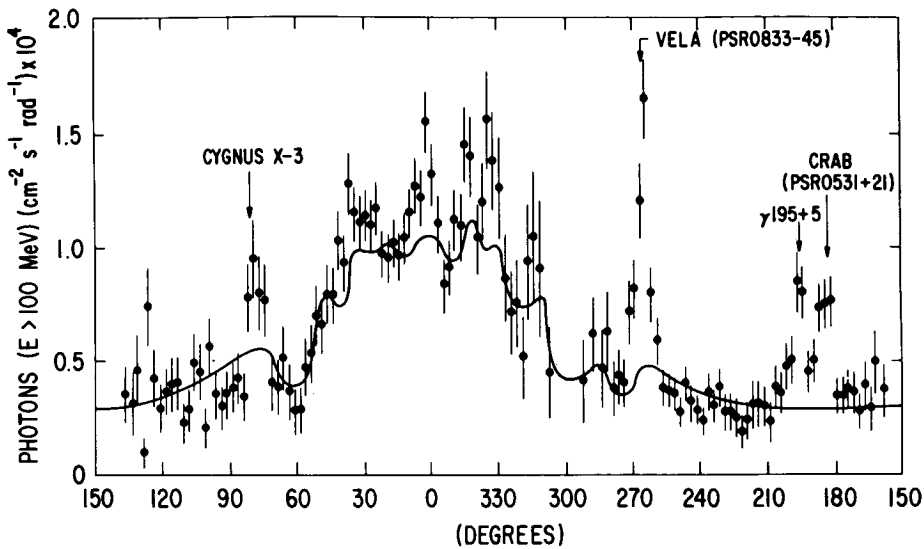
Figure 4. The high energy (E >100 MeV) gamma ray intensity as a function of longitude for − 10°<b<10° from the SAS-2 data [Hartman et al., 1979]. [This figure is from Fichtel and Kniffen, 1984.]

latter specifically deduce enhancements near the major inner galactic arm features. For example, an assumption of a constant cosmic ray density predicts too large a diffuse gamma ray intensity in the anticenter direction by a ratio of about 4:3 to 3:2, as noted several times before, e.g., Houston and Wolfendale [1982]. This result is expected, since as the matter density decreases in the outer galaxy, the cosmic ray density must also, since there is not then sufficient gravitational attraction to hold the local cosmic ray density.

It should be noted that Lebrun et al. [1983] showed that the gamma radiation above 300 MeV for (12° <l< 97°) and (− 5° <b< 10°) may be fit by a linear combination of column densities of HI and CO gas tracers and an isotropic background. However, as Pollack et al. [1985] note, to interpret this result as implying a constant cosmic ray density is an oversimplification. Fichtel and Kniffen [1984] point out several important factors. First, since the molecular hydrogen density is concentrated towards the galactic center, a large normalization value for molecular hydrogen is mathematically similar
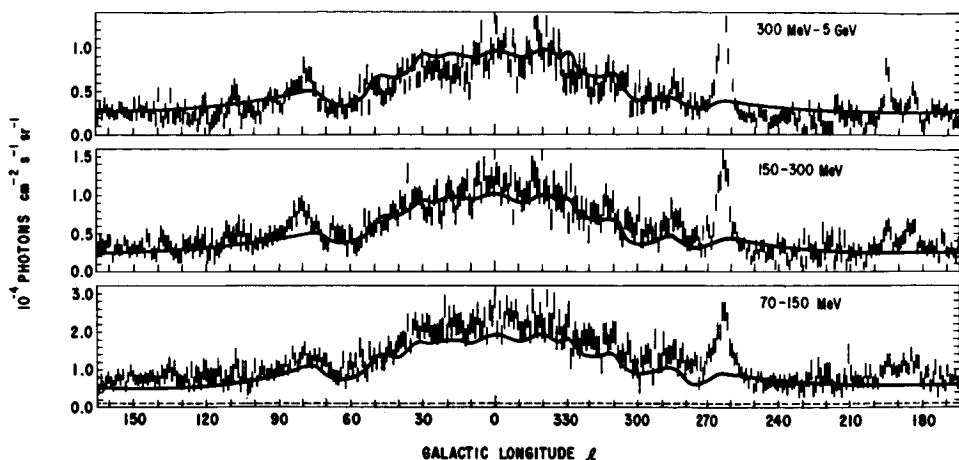
Figure 5. Gamma ray intensity as a function of longitude averaged over the latitude range − 10°<b<10° from 70 MeV to 150 MeV, 150 MeV to 300 MeV, and 300 MeV to 5000 MeV from the COS-B data [Mayer-Hasselwander et al., 1982] compared to the model discussed here shown by the solid line. The dashed line in the 70-150 MeV graph represents the new "0.0" line based on the revised background intensity for the COS-B data in this energy interval. [This figure is from Fichtel and Kniffen, 1984.]

to assuming a positive cosmic ray gradient towards the center in terms of the gamma rays produced. Lebrun et al. [1983] used 3.1×10^{20} molecules cm^{-2} $K^{-1} Km^{-1}$ s. Second, the variation in the observed gamma ray intensity between 50° and 10° in 1 is less for 300 MeV <E <5000 MeV than in the other two COS-B energy ranges, for reasons yet to be determined. Third and least, the Compton contribution, as a percentage of the total, probably decreases toward the galactic center.

In summary, most evidence at present seems to support, or be consistent with, the theoretically supported concept of the correlation of the cosmic ray density with matter density on the broad scale of galactic arms. The anticenter region seems to show a decrease in cosmic ray intensity, while the inner galaxy is consistent with a higher cosmic ray density in the region of the galactic arms.

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In addition to the galactic arms, the local galactic feature Gould's Belt has also been seen in gamma rays, having first been observed by Small Astronomy Satellite SAS-2 [Fichtel et al., 1975]. Also, there is the interesting feature of an apparent paucity of gamma rays coming from the galactic center itself (i.e., within a radius of 300 or 400pc of the center). Either the cosmic ray density must be very anomalously low relative to the matter density or the gas-to-dust ratio is exceptionally low. Based largely on circumstantial evidence, Blitz et al. [1985] favor a low H_2/CO abundance in the center region.

2. Molecular Clouds

Galactic molecular clouds contain much of the diffuse galactic matter and are generally believed to be the location for the formation of stars. There are, however, many unanswered questions about the nature of these regions and their formative processes. Gamma ray astronomy has the potential of making an important contribution through the determination of the cosmic ray distribution in these clouds. The limited sensitivity and angular resolution of the SAS-2 and COS-B instruments has restricted the gamma ray information on these objects; however, two positive identifications were made with the COS-B telescope, namely ρ Oph and the Orion cloud complex.

The Orion cloud complex has been observed as an extended gamma ray source [Caraveo et al., 1980] with the intensity distribution similar within uncertainties to the estimated matter distribution. See Figure 6. The centroids of the two excesses located approximately at α = 5h 4m, δ = 0°0'; (l = 205.4°, b = $-14.4°$) and at α = 5h 30m, δ = $-6°30'$ (l = 210.0°, b = $-20.6°$) are far enough from the galactic plane that source confusion is not likely. Detailed contours of the gamma ray emission, the CO line emission, the HI column densities, and the total gas column density are given separately by Bloemen et al. [1984], and then differences are taken to show a generally good correlation between the gamma radiation and the mass distribution.

The ρ Oph gamma ray excess [Swanenburg et al., 1981] is also clearly established, and its association with the cloud seems quite probable. There is a controversy over whether or not the gamma ray intensity is more than
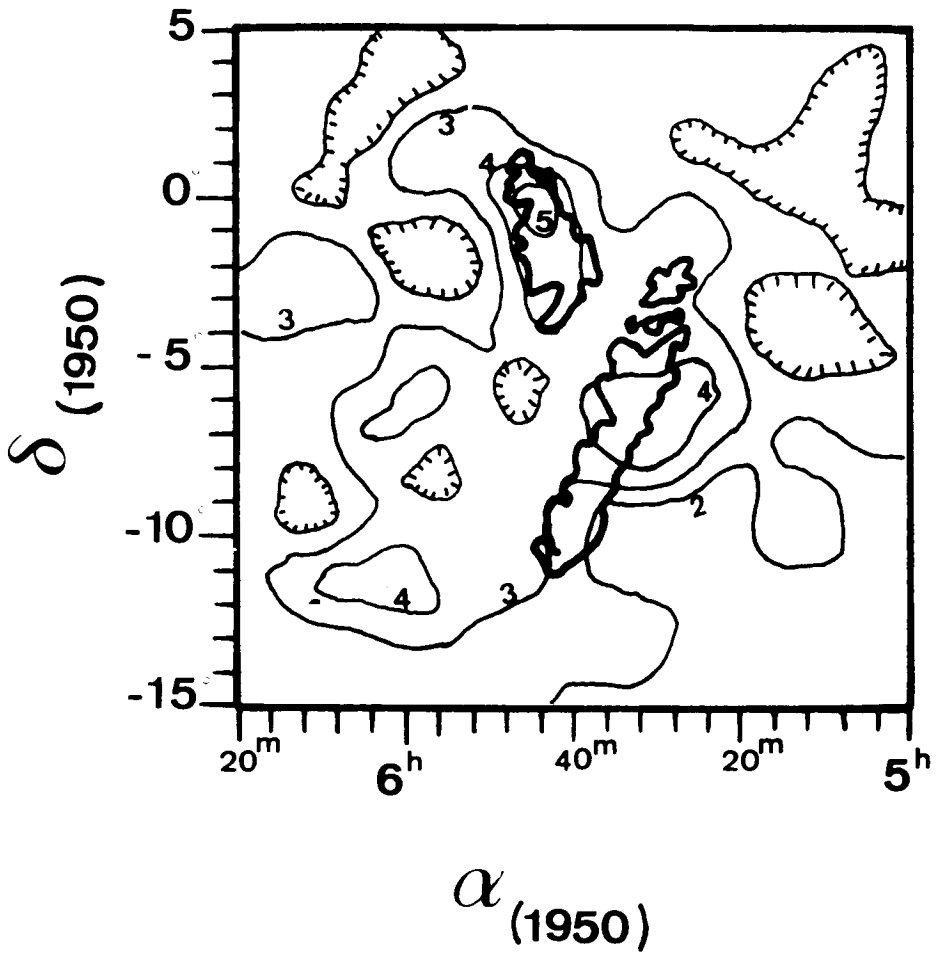
Figure 6. Gamma ray contour map of the Orion region. A smoothing has been applied to the data following Mayer-Hasselwander et al. [1980]. The contour unit is 2×10^{-3} "on axis counts" s^{-1} sr^{-1}. The thick line follows the boundaries of the L1641 and L1630 dark clouds. When considering the angular resolution of the COS-B satellite, the coincidence between the gamma ray excess and the cloud complex is further stressed. [This figure is from Caraveo et al., 1980.]

would be expected on the basis of cosmic rays at the local intensity level interacting with the matter in the cloud [For a summary, see Lebrun, 1984]. Although improved gamma ray data both in terms of angular resolution and statistics are desired, the greater uncertainty at present appears to lie in the estimate of the matter.

As noted, with future gamma ray observations of many clouds with greater sensitivity and better angular resolution, it is hoped that a better understanding can be achieved regarding the role of cosmic rays in internal cloud processes.

B. Compact Objects

The interest in the study of compact galactic objects in the gamma ray region, particularly neutron stars and black holes, is clearly quite high since these energetic photons are predicted to be able to provide answers on the fundamental nature of these objects. However, the angular resolution of the high energy gamma ray telescopes flown thus far, typically ½ ° to 1 °, has generally made association with specific objects impossible except for cases where time variation correlation could be used. Many of the approximately two dozen localized excesses listed in the COS-B catalog [Swanenburg et al., 1981] are likely to be associated with molecular clouds, but some are probably yet to be resolved compact objects. [For a further discussion of this subject, see Pollack et al., 1985.]

1. Neutron Stars and Pulsars

Almost immediately after their discovery, pulsars were proposed to be associated with neutron stars [Gold, 1968, 1969], and this relationship is now generally accepted. The large release of energy, the very fast period, and the remarkably small variation of the period seem to dictate that the pulsed radiation must be from a massive object of small size. The very short length of the individual pulses indicates that the size of the emitting region is associated with something substantially smaller than normal stellar dimensions. On the other hand, the periods in general are constant to one part in 10^8 or greater indicating a massive object rather than a plasma phenomenon. If the period

of the pulse is associated with a rotating body, then the object must be a neutron star rather than a normal stellar object because the surface cannot move faster than the speed of light. Further, the period is probably too short to be associated with an oscillating phenomenon.

No consensus yet exists with regard to the exact model for the pulsed radiation. Many theoretical models involve either synchrotron or curvature radiation in the high magnetic fields, often in association with the polar regions to give the beaming effect. There is still, however, a great variety of opinions regarding the details of the model, including the specific manner and location of the relativistic particle acceleration.

The highest intensity pulsar as observed at the Earth in the gamma ray region is the one in Vela, PSR 0833-45, for which $(1.2 \pm 0.2) \times 10^{-5}$ photons $E > 100$ MeV) cm^{-2} s^{-2} are seen [Thompson et al., 1975 and 1977b; Bennett et al., 1977; and Kanbach et al., 1980]. This pulsar as first seen by SAS-2 is shown in Figure 7. The two most striking features are the two gamma ray pulses as opposed to one in the radio region, and the fact that neither gamma ray pulse is in phase with the radio pulse. These features were confirmed by the data obtained later from the COS-B satellite gamma ray telescope [Buccheri et al., 1978]. They determined that the first gamma ray pulse followed the radio pulse [e.g., Komesaroff, Hamilton, and Ables, 1972] by 11.2 ± 0.4 ms. The period is 89 ms, and the time between the pulses is 38 ms. If this result were not enough to complicate attempts to find a satisfactory theoretical model, following the detection of PSR 0833-45 in gamma rays two peaks were found in the optical region by Wallace et al. [1977], neither one of which was in phase with either the gamma ray or the radio peaks as seen in Figure 8 wherein the COS-B gamma ray data are shown. In spite of many attempts to obtain a certain detection of pulsation in the X-ray wavelength range, none has yet been made.

The observational picture for the second strongest gamma ray pulsar PSR 0531 + 21 in the Crab nebula is much simpler to describe. This pulsar, which is faster than PSR 0833-45 and was the first gamma ray pulsar reported [Browning, Ramsden, and Wright, 1971], even though it is not the strongest, is seen with the double pulsed structure in the radio, optical, X-ray, and gamma ray
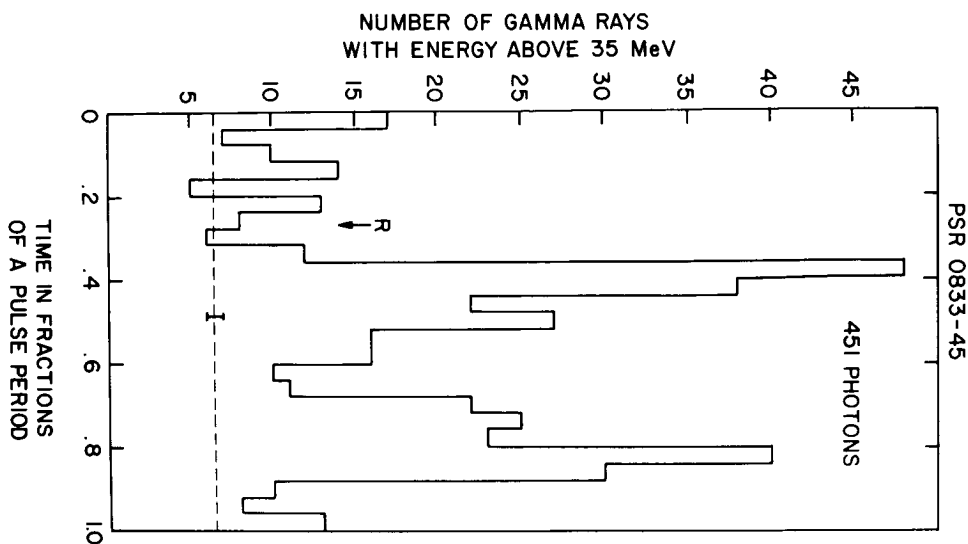
Figure 7. Distribution of gamma ray arrival times in fractions of a radio pulse period for gamma rays above 35 MeV from the direction of PSR 0833-45, as seen in the original data of the SAS-2 satellite. Arrow R marks the position of the radio pulse. The dashed line shows the gamma ray level expected from galactic and diffused radiation if no localized source were present [Thompson et al., 1977a]. Later data from PSR 0833-45 obtained with COS-B are shown in Figure 6. [This figure is from Thompson et al., 1977a.]

regions, and the pulses in each wavelength are in phase as shown in Figure 8. PSR 0531 + 21 has even been detected above 10^{11} eV by Helmken, Grindlay, and Weekes [1975] [see also, Grindlay, 1982; Cawley et al., 1985a; Kinov et al., 1985; and Tümer et al., 1985] using the ground-based 10 m reflector on Mt. Hopkins and others [e.g., Chadwick et al., 1985b; Cawley et al., 1985b]. The common in-phase double peak feature suggests the same mechanism for the radiation at all wavelengths for PSR 0531 + 21, which is perhaps to be expected for a pulsar which is only 10^3 years old. The older Vela pulsar, PSR 0833-45, apparently then has a dominant high energy component. In fact, whereas the pulsed luminosity ratio, L(PSR 0531 + 21)/L(PSR 0833-45), is about 5 above 100 MeV, it is almost 10^4 in the optical range. The
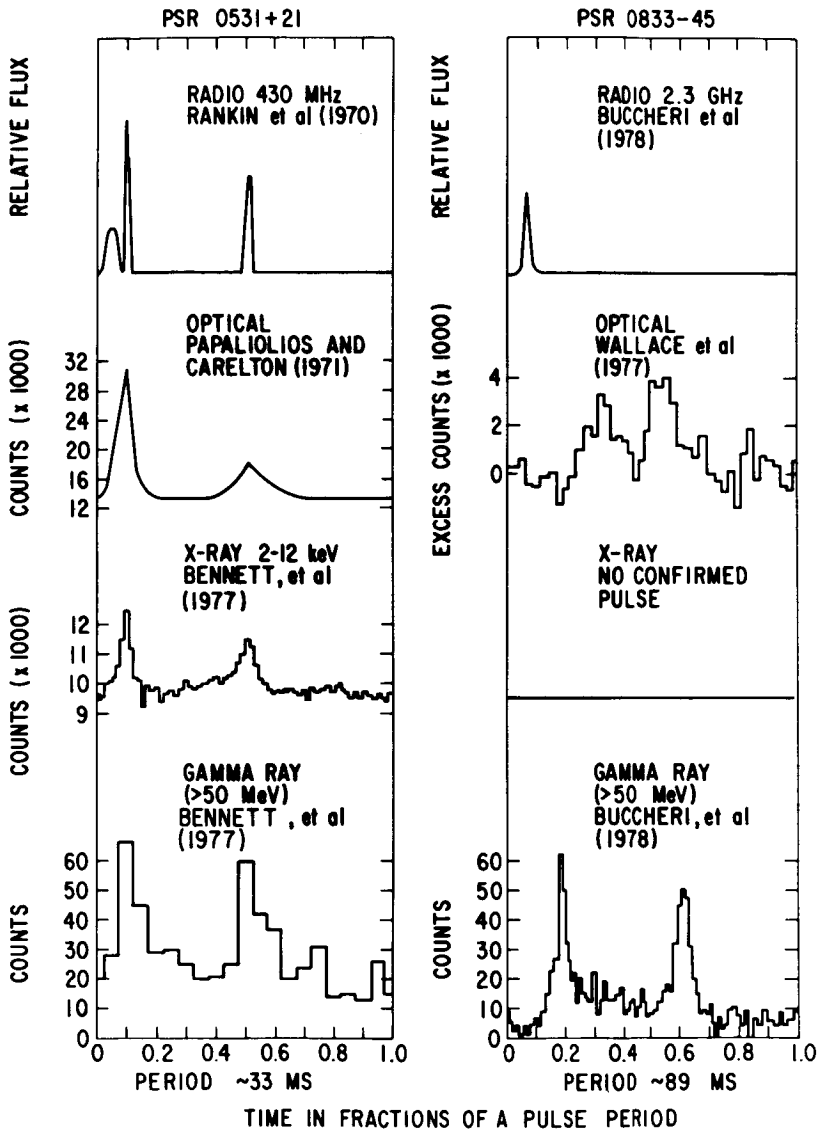
Figure 8. Comparison of the pulse structure and phase at radio, optical, X-ray, and gamma ray energies for PSR 0531+21 and PSR 0833-45, taken from Fichtel et al. [1980]. References to the work are given in the figure.

Crab nebula also has strong constant emission. The ratio of the pulsed to unpulsed emission appears to increase monotonically with energy until in the high energy gamma ray region the pulsed emission dominates.

The presence of 10^{12} eV gamma rays has been reported by Chadwick et al. [1985c] from the pulsar PSR 1953 + 29 with the characteristic 6.1 ms periodicity observed in the radio region. The 1.24s binary pulsar Her X-1 has also been seen at these very high energies [Dowthwaite et al., 1984; Cawley et al., 1985c].

Other radio pulsars have been reported to be possible gamma ray emitters both at 10^8 and 10^{12} eV, but confirmation is probably required because the statistical level of the observations is low. Most likely several of the radio pulsars will be revealed as gamma ray emitters. Semi-empirical analyses based on intensity as a function of age [Ogelman et al., 1976; Fichtel and Trombka, 1981] suggest that, with a factor of ten increase in sensitivity, many more pulsars will be seen in the gamma range.

2. Black Holes

Gamma rays are expected from black holes, although they are yet to be observed from a likely candidate. Maraschi and Treves [1977] have noted that, if the accretion flow onto the black hole is turbulent and dissipation maintains approximate equipartition among the different forms of energy, electrons can be accelerated by the induced electric fields. The resulting synchrotron energy spectrum is quite flat to about 20 MeV, above which it falls steeply. There would also be a Compton contribution. Under the right conditions, observable gamma ray fluxes would be generated. Collins [1979] has pointed out that matter falling onto a rotating black hole will be heated sufficiently that proton-proton collisions will produce mesons, including neutral pions which decay into two gamma rays. For massive ($> 10^3$ M_O) black holes, such as might exist in the galactic center, the resulting gamma ray luminosity may exceed 10^{36} ergs s^{-1}, which would give rise to over 3×10^{-6} gamma rays cm^{-2} s^{-1} at the Earth for a source at the galactic center. The energy spectrum would have a peak near 20 MeV. Emission from black holes through the Penrose process is another mechanism, but it is most appropriately discussed in relation to very large black holes which may exist at the centers of active galaxies.

One of the most intriguing predictions of gamma ray emission from black holes is that of bursts with a very unique signature from mini black holes left from the Big Bang [e.g., Page and Hawking, 1976; Hawking, 1977]. These mini holes, whose masses are only a very small fraction of that of the Sun, cannot be created in the universe as it exists today because the necessary compressional forces do not exist. As one of these primordial black holes continue to lose mass, its temperature rises, and it begins to emit particles of higher rest mass, until finally it ejects all its remaining rest mass in a very short time. The heavy hadrons emitted in this final release would decay very rapidly, giving about 10 to 30 percent of their energy ($\sim 10^{34}$ ergs) into a short burst (about 10^{-7}s) of hard gamma rays between 10^2 and 10^3 MeV, peaking around 250 MeV.

3. Other High Energy Gamma Ray Sources

Energetic (E > 35 MeV) gamma rays from Cygnus X-3 were observed with the SAS-2 gamma ray telescope by Lamb et al. [1977], as shown in Figure 9. They were modulated at the 4.8 hr period observed in the X-ray and infrared regions, and within the statistical error are in phase with this emission. The flux above 100 MeV had an average value of $(4.4 \pm 1.1) \times 10^{-6}$ photons $cm^{-2} s^{-1}$. Earlier, Galper et al. [1975] reported an excess above 40 MeV from Cygnus X-3 also with a 4.8 hr period at a higher intensity closer to the large 1972 radio burst, but with a lower statistical weight (3.6σ). If the distance to Cygnus X-3 is 10 kpc, the flux reported by SAS-2 implies a luminosity of more than 10^{37} ergs s^{-1} if the radiation is isotropic and about 10^{36} ergs s^{-1} if the radiation is restricted to a cone of one steradian, as it might be in a pulsar. At that luminosity level, during the time of the SAS-2 observation, Cygnus X-3 was the most luminous gamma ray source. However, since it is quite distant, the reported flux as observed at the Earth is just above the threshold for detection by SAS-2 or COS-B. When COS-B searched for radiation in later years (the SAS-2 observed it in 1973), no gamma radiation was detected [Bennett et al., 1977]. This result is not particularly surprising since the intensity as seen at other wavelengths such as X-rays was much lower then [e.g., Priedhorsky and Terrell, 1985]. The radio intensity is known to be quite variable.
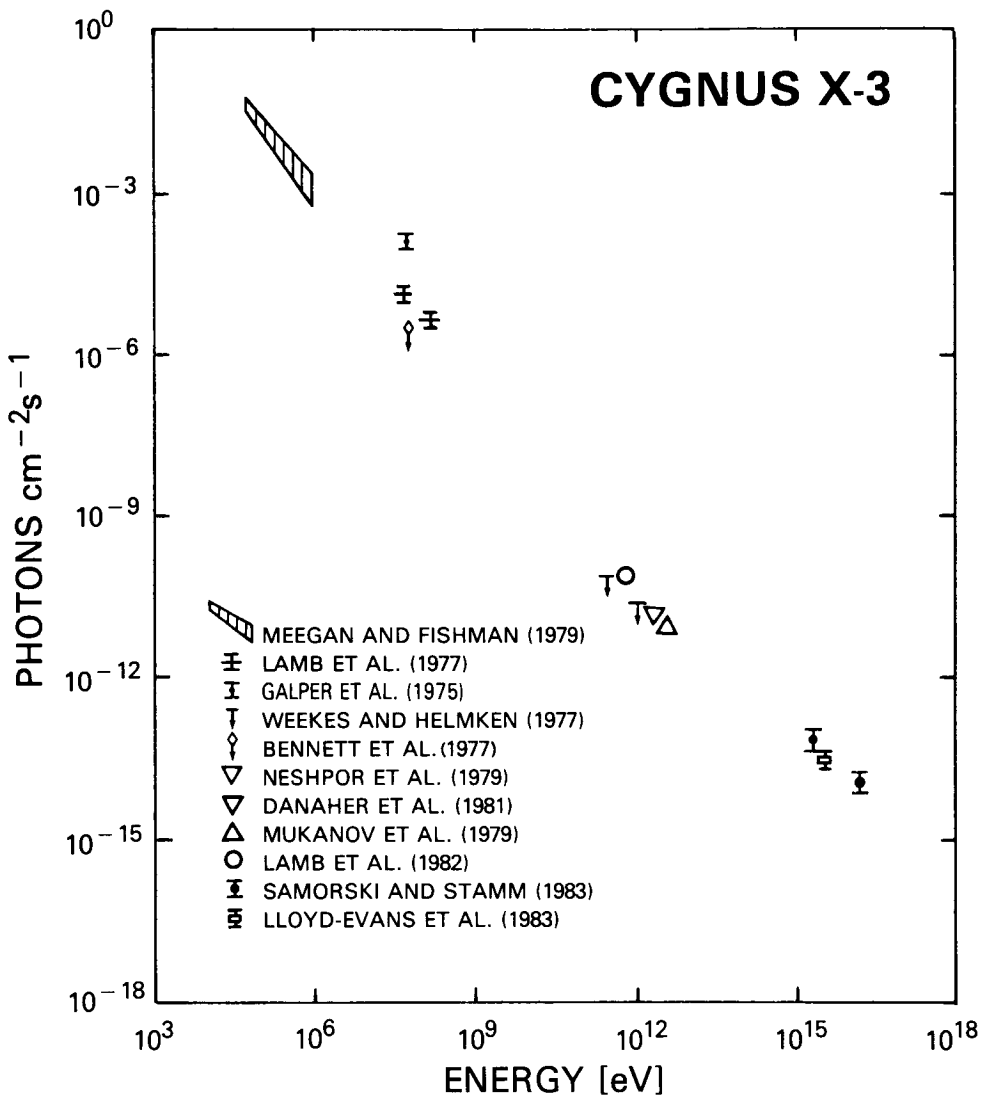
Figure 9. The photon energy spectrum observed for Cygnus X-3. References for the data points are shown in the figure. [This figure is a modification of one in Samorski and Stamm, 1983.]

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There are also several reports of gamma ray emission from Cygnus X-3 at higher energies (E > 10^{11} eV) [e.g., Vladimirsky, Stepanian, and Fomin, 1973; Stepanian et al., 1977; Danaher et al., 1981; Lamb et al., 1982; Dowthwaite et al., 1983; Cawley et al., 1985a; and Chadwick et al., 1985a], and even very high energies (E > 10^{15} eV) [Samorski and Stamm, 1983; Lloyd-Evans et al., 1983; Dowthwaite et al., 1983; Kifune et al., 1985; Bhat et al., 1985; and Alexeenko et al., 1985], making it one of the more interesting astronomical objects ever observed. In the very high energy region, it is clear that once again Cygnus X-3 is not a steady emitter [e.g., Cawley et al., 1985d]. There are several null results as well as the positive results. These variations in intensity in the gamma ray region are consistent with the nonstatic theories of high energy particle acceleration in an accreting binary wherein there would be frequent breakdowns in the conditions.

There are several reasons for believing that the Cygnus X-3 gamma rays are produced by nuclei rather than electrons. Being massive, they are able to carry off energy acquired by acceleration in the high field region near the pulsar (B > 10^5 G) and deposit it in a low field region from which gamma rays are able to escape (B < 10^3 G). Electrons cannot do this [Hillas, 1984]. The production of gamma rays begins with the decay of the π° mesons formed in the collisions of accelerated nuclei with nuclei in the atmosphere of the companion star or in the gaseous material known to enshroud the Cygnus X-3 system. Thus, the energy spectrum of the accelerated nuclei must extend to at least 10^8 GeV per nucleon. It has been shown by Hillas [1984] that a monoenergetic beam of 10^8 GeV protons impinging on a stellar atmosphere will generate a cascade whose escaping gamma rays have a spectrum similar to that from Cygnus X-3. The acceleration could be driven by the rotational energy of the compact object [Eichler and Vestrand, 1984] or the accretion disk [Chanmugan and Brecher, 1985]. Alternately, the acceleration may be due to shocks [Kazanas and Ellison, 1986]. Fichtel and Linsley [1986] have noted that, in several of these models, there is more than enough energy being generated per unit time in the form of cosmic rays to sustain the observed intensity of > 10^6 GeV cosmic rays in the galaxy.

Supernovae, the most spectacular of stellar events, were among the first objects considered by gamma ray theorists. A continuum emission from the Crab

supernova remnant has been observed ranging upward to at least the low energy gamma ray region suggesting synchrotron radiation from relativistic electrons. Other supernovae have not been seen to have this type of radiation, but it may be only a question of sensitivity. A further important test of whether cosmic rays are accelerated by supernovae would be the observation of a continuum gamma radiation resulting from cosmic ray-matter interactions. A straightforward calculation assuming 10^{49} ergs in the form of relativistic particles and a density the same as that locally gives an intensity of about 10^{-7} photons (E > 100 MeV) cm^{-2} s^{-1} for a supernova 1 kpc away. This level would be detectable with future experiments, but not those flown thus far. For the Vela supernova remnant, which is closer, but in a possibly less dense region, a larger number might be predicted, making it an interesting candidate for future study. Also, supernovae in high density regions would be logical objects to search for high energy gamma rays [Montmerle, 1979].

As noted in the introduction, one of the two strongest high energy ($\sim 10^2$ MeV) gamma ray sources is the one at (l = 195, b = + 5), which was first seen by SAS-2 [Lamb et al., 1977]. There is also a report of very high energy gamma rays from this source by Zyskin and Mukanov [1983 and 1985]. Radio, optical, and gamma ray searches have not revealed any object which stands out as being exceptional enough to have expected such strong gamma ray emission; however, there is now an X-ray source which seems to be a possible candidate [e.g., Bignami, Caraveo, and Lamb, 1983]. It is hoped that future gamma ray measurements may define the source location accurately enough to locate an object at lower wavelengths with more certainty.

3. EXTRAGALACTIC GAMMA RADIATION

A. Active Galaxies

Beyond our galaxy gamma ray emission has already been seen from four active galaxies, two Seyfert galaxies, one radio galaxy, and a quasar. For at least two of these, 3C 273 and NGC 4151, more energy is emitted in the gamma ray region (E > 0.1 MeV) than in the X-ray, optical, or radio regions. The photon intensities are relatively low, of course, because of the large energy per photon in the gamma ray region. No normal galaxy, other than our own, has been seen in gamma rays, but this result is not surprising on the basis

of the emission level of our own galaxy [See, for example, Fichtel and Trombka, 1981]. The gamma rays observed from the Seyfert galaxies NGC 4151 and MCG 8-11-11 are in the low energy gamma ray region [Auriemma et al., 1978; Coe et al., 1981; Gursky et al., 1971; Ives, Sanford, and Penston, 1976; Meegan and Haymes, 1979; Mushotsky, Holt, and Serlemitsos, 1978; Paciesas, Mushotsky, and Pelling, 1977; Perotti et al., 1979; Perotti et al., 1981; Schonfelder, Graml, and Penningsfeld, 1980; and White et al., 1980], and only upper limits to the high energy gamma radiation exist [Bignami et al., 1979]. The spectra are similar in that both show a very marked increase in the spectral slope in the energy region near 1 MeV. The several measurements in the gamma ray region for NGC 4151 were made at different times, and, assuming no significant errors in the data, clearly show a time variability. For five other Seyferts (and also several other emission-line galaxies) upper limits derived from the SAS-2 gamma ray data [Bignami et al., 1979] are substantially (more than an order of magnitude) below an extrapolation of the power law X-ray spectra [Mushotsky, Holt, and Serlemitsos, 1978], suggesting that a sharp spectral change in the low energy gamma ray region may be a general feature of these galaxies. Pollock et al. [1981] come to a similar conclusion in relation to the COS-B data.

Turning to quasars, 3C 273 is the brightest X-ray quasar and is the only quasar which has been clearly identified as a source of gamma rays [Swanenburg et al., 1978]. The differential energy spectrum of 3C 273 steepens sharply from the X-ray range to the gamma ray region, with the slope of the differential energy spectrum changing from 1.4 in the hard X-ray region to 2.7 in the high energy (E>50 MeV) gamma ray region as shown in Figure 10. The change in spectral shape between the hard X-ray and gamma ray region seen for 3C 273 is similar to that suggested for the Seyfert galaxies for which data exist. The COS-B instrument has observed 3C 273 in gamma rays in July 1976, June 1978, and June-July 1980, and no significant variation in the gamma ray fluxes among the observation was observed [Bignami et al., 1981b].

The closest known quasar is 2S 0241 + 622, but it is very close to the galactic plane (b $\simeq$ 2°). The error box of the COS-B gamma ray source CG 135 + 1 [Hermsen et al., 1977] contains the position of 2S 0241 + 622, and the possible association has been pointed out by Apparao et al. [1978]. Because of
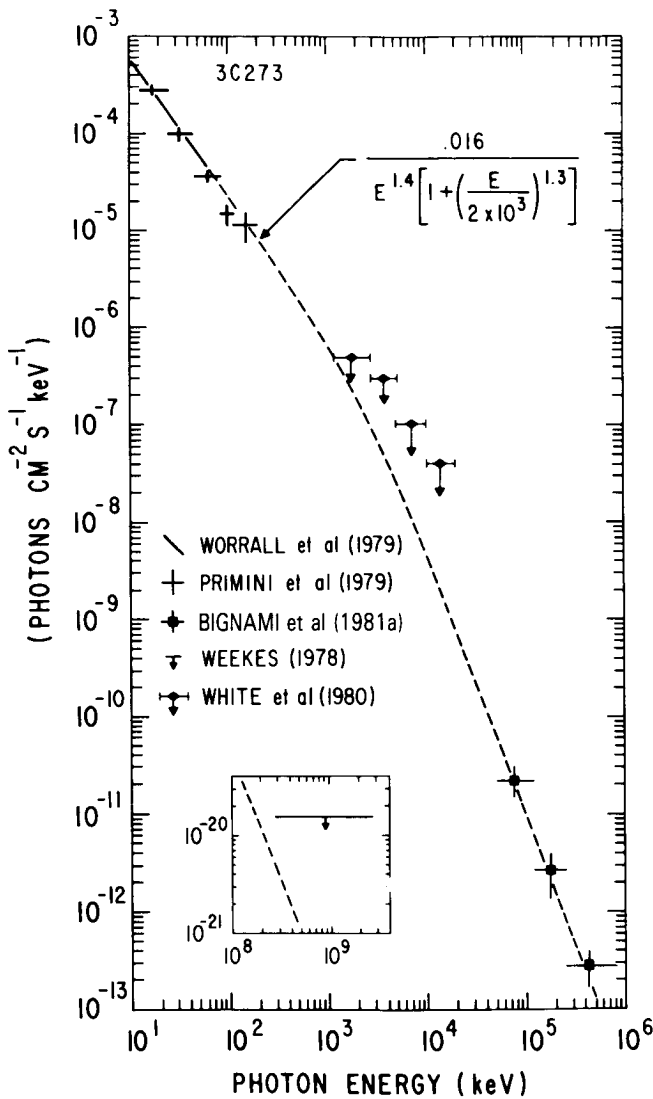
Figure 10. The differential high energy photon spectral results from several experiments as a function of energy for 3C 273. The dashed curve is given by the equation shown in the figure. [This figure is from Fichtel and Trombka, 1981.]

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the large area of the gamma ray source within the galaxy, this identification must be considered tentative.

The change in spectral shape between the hard X-ray and gamma ray region seen for 3C 273 is similar to that suggested for the Seyfert galaxies for which data existed. This spectrum, although as yet poorly defined, is consistent with several of the massive black hole models, including the synchrotron, self Compton type models [e.g., Grindlay, 1975; Shapiro and Saltpeter, 1975; Mushotzky, 1976; and Maraschi and Treves, 1977], possibly including some degree of subsequent photon-photon interactions [Jelley, 1966] and the Penrose pair production and Compton scattering processes [Leiter and Kafatos, 1978; Kafatos and Leiter, 1979], involving infalling protons and electrons.

Centaurus-A (NGC 5128), generally believed to be the closest radio galaxy, is the only radio galaxy that has been seen in gamma rays. It has now been observed in all frequency bands from radio through low energy gamma rays and, although gamma ray emission is not seen in the 30 to 10^3 MeV region [Bignami et al., 1979; Pollock et al., 1981], a strong indication of very high energy ($E > 3 \times 10^{11}$ eV) gamma ray emission has been found [Grindlay, 1975]. The observations of the radiation from CEN-A in the X-ray region through the very high energy gamma ray region again suggest a steepening of the spectral slope possibly similar to NGC 4151, MCG 8-11-11, and 3C 273.

B.   Diffuse Extragalactic Radiation

A diffuse celestial radiation, which is isotropic at least on a coarse scale, has been measured from the soft X-ray region to at least 150 MeV. The first indication that diffuse celestial radiation extended from the X-ray region into at least the low energy gamma ray (1 MeV) portion of the spectrum was reported by Arnold et al. [1962]. At energies above 10 MeV, the first measurements related to an extragalactic diffuse radiation were those of Kraushaar and Clark [1962], whose upper limits from Explorer 11 provided an experimental refutation of the steady-state theory of cosmology. The first suggestion of a diffuse high energy flux came from the Orbiting Solar Observatory OSO-3 satellite experiment [Kraushaar et al., 1972], and it was data from the SAS-2 high energy gamma ray experiment that clearly established

a high energy extension of the diffuse radiation with a steep energy spectrum above 35 MeV [Fichtel et al., 1977]. A recent reanalysis of the SAS-2 data which included galaxy counts as a tracer of the interstellar matter has been performed by Thompson and Fichtel [1982] and has added support to the concept of the spectrum being quite steep (having a power low index of about 2.4) in the energy region above 35 MeV. See Figure 11.

Although the diffuse spectral measurements are reasonably self-consistent, the degree of spatial isotropy is not well known. The X-ray spectrum through about 100 keV is known [cf., Schwartz and Gursky, 1973] to be isotropic to within about 5 percent. At high gamma ray energies (35 to 100 MeV), the center-to-anticenter ratio for radiation with $20° < |b| < 40°$ was measured to be 1.10 ± 0.19 and the perpendicular to the galactic plane intensity to that in the $20° < |b| < 40°$ region was measured to be 0.87 ± 0.09 each of these results is consistent with isotropy to within errors [Fichtel, Simpson, and Thompson, 1978]. Although much more precise measures of the isotropy are clearly desired, no evidence for a major anisotropy exists. In particular, the high energy gamma ray results just quoted eliminate a spherical galactic halo origin for the radiation in view of the Sun's great distance from the galactic center. For the future, trying to establish the level of isotropy or deviations therefrom on both a coarse scale and a fine scale will be quite important.

A large number of theories predicting a diffuse gamma ray background have appeared in the literature over the years. With the measurements of the spectrum and intensity which now exist, most of these seem not to be likely candidates for the majority of the diffuse radiations [see, for example, Fichtel and Trombka, 1981]. Two possibilities seem to remain at present. One of these involves a baryon-symmetric universe, containing superclusters of galaxies of matter and others of antimatter. The annihilation of nucleons and antinucleons at the boundaries [Stecker, Morgan, and Bredekamp, 1971] produces the gamma rays. The predicted energy spectrum is reasonable and the required normalization is within the rather wide currently accepted range. This theoretical model predicts a fairly smooth distribution over the sky; however, a test of this theory (in addition to a precise measure of the energy spectrum) would be the detection of fairly small enhancements in the gamma radiation in the direction of boundaries between close superclusters of galaxies. The
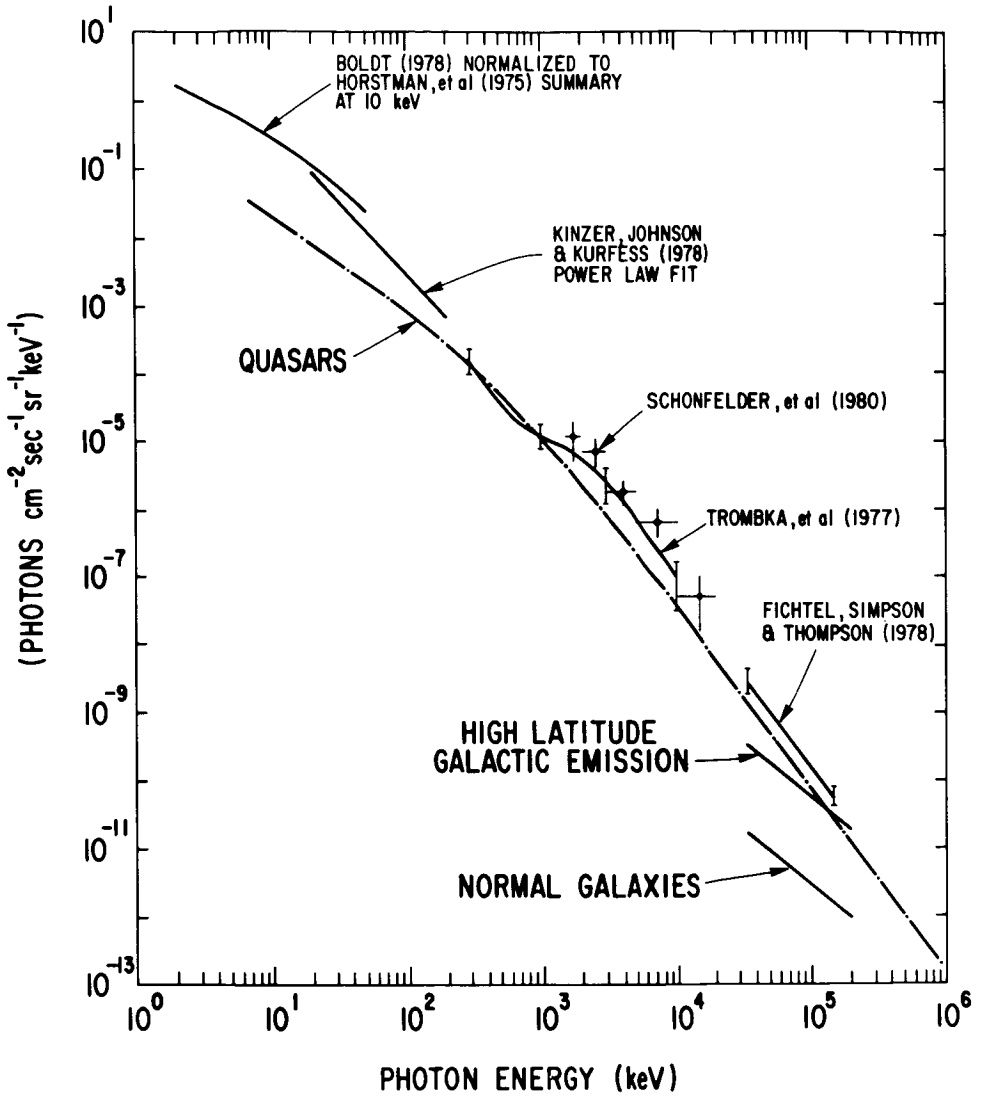
Figure 11. The diffuse gamma ray energy spectra estimated for quasars and normal galaxies under the assumptions described in the text, compared to some of the more recent experimental data. [This figure is from Fichtel and Trombka, 1981.]

diffuse gamma radiation associated with these particular boundaries would be at the higher energies.

The other possibility is the sum of the radiation from point sources, and particularly active galaxies, integrated over cosmological times [e.g., Strong and Worrall, 1976; Bignami, Lichti, and Paul, 1978; Schonfelder, 1978; and Grindlay, 1978]. Using the data on the few known objects, Bignami et al. [1979] and Fichtel and Trombka [1981] conclude that it is quite conceivable that Seyfert galaxies and quasars could account for the diffuse gamma radiation using conservative evolutionary models. The estimate of the quasar contribution by Fichtel and Trombka [1981], based on the existing, very limited knowledge is shown in Figure 11. Leiter and Boldt [1982] and Boldt and Leiter [1984] have proposed a model based on supermassive Schwarzschild black holes with accretion disks radiating near the Eddington luminosity limit. The authors believe that, if this theory is correct, there would be detectable variations in the diffuse radiation in small elements of the sky (10 deg^2) over several days in the ½ to 3 MeV region, giving a specific test for this theory.

4.   FUTURE PROSPECTS

The satellite opportunities for high energy gamma ray astronomy in the near future are the GAMMA I planned to be launched in late 1986 and the Gamma Ray Observatory, currently scheduled for launch in 1988. In the most distant future, the NASA Space Station should provide opportunities to fly quite large gamma ray instruments which might be refurbished or reconfigured in space.

A.   GAMMA I

The next gamma ray satellite expected to fly is GAMMA I. It is similar to SAS-2 and COS-B in the sense that its central element is a multilayer spark chamber system, triggered by a directional counter telescope, and surrounded on the upper end by an anticoincidence system. The upper spark chamber system is a twelve-level wide gap Vidicon system. The directionality of the electrons is determined by a time-of-flight system rather than a directional Cherenkov counter. The sensitive area is about 1600 cm^2 or about 2.7 times

that of SAS-2 or COS-B. The area solid angle factor is about the same, because the viewing angle is smaller. The gamma ray arrival direction measurements are expected to be an improvement over those of SAS-2 and COS-B.

B. The Gamma Ray Observatory (GRO)

Frank McDonald played a major role in bringing this observatory into being. Following his early work during the formative period, he was named the GRO Study Scientist for the initial formal phase of GRO's life. The Gamma Ray Observatory (GRO) is now an approved NASA mission with a launch tentatively planned for 1990, as mentioned above. An artist's concept of this spacecraft, which is to be launched by the shuttle, is shown in Figure 12. There are four instruments covering the energy range from 0.03 MeV to 3×10^4 MeV, with a major increase in sensitivity over previous satellite experiments. It is advantageous to combine the instruments into one mission not only because they place similar requirements on a spacecraft, but also because of the great scientific value of studying the entire gamma ray spectrum of any object at the same time to examine in detail the nature of time variations.

The four instruments to fly on GRO are:

1. Gamma Ray Observatory Scintillation Spectrometer Experiment (OSSE)

This experiment utilizes four large actively shielded and passively collimated sodium iodide (NaI) scintillation detectors, with a $5° \times 11°$ FWHM field of view. The large area detectors provide excellent sensitivity for both gamma ray line and continuum emissions. An offset pointing system modulates the celestial source contributions to allow background subtraction. It also permits observations of off-axis sources such as transient phenomena and solar flares without impacting the planned Observatory viewing program. The energy range is 0.1 to 10 MeV.

2. Imaging Compton Telescope (COMPTEL)

This instrument employs the signature of a two-step absorption of the gamma ray, i.e., a Compton collision in the first detector followed by total absorption in a second detector element. This method, in combination with effective charged particle shield detectors, results in a more efficient suppression

Figure 12. Artist's concept of the Gamma Ray Observatory taken from a color print prepared by TRW.

of the inherent instrumental background. Spatial resolution in the two detectors together with the well-defined geometry of the Compton interaction permits the reconstruction of the sky image over a wide field of view ($\sim$ 1 steradian) with a resolution of a few degrees. In addition, the instrument has the capability of searching for polarization of the radiation. The instrument has good capabilities for the search for weak sources, weak galactic features, and for the search for spectral and spatial features in the extragalactic diffuse radiation. The energy range is 1 to 30 MeV.

3. Energetic Gamma Ray Experiment Telescope (EGRET)

The High Energy Gamma Ray Telescope is designed to cover the energy range from 20 MeV to 30×10^3 MeV. The instrument uses a multithin-plate spark chamber system to detect and record gamma rays converted by the electron-positron pair process. A total energy counter using NaI (Tl) is placed beneath the instrument to provide good energy resolution over a wide dynamic range. The instrument is capped with a plastic scintillator anticoincidence dome to prevent readout on events not associated with gamma rays. The combination of high energies and good spatial resolution in this instrument provides the best source positions of any GRO instrument.

4. Burst and Transient Source Experiment (BATSE)

The Burst and Transient Source Experiment for the GRO is designed to continuously monitor a large fraction of the sky for a wide range of types of transient gamma ray events. The monitor consists of eight wide field detector modules. Four have the same viewing path as the other telescopes on GRO and four are on the bottom side of the instrument module viewing the opposite hemisphere. This arrangement provides maximum continuous exposure to the unobstructed sky. The capability provides for 0.1 msec time resolution, a burst location accuracy of about a degree, and a sensitivity of 6 $\times$ 10^{-8} erg/cm^2 for a 10 sec burst.

The combined complement of instruments to be incorporated into the Gamma Ray Observatory is expected to have the capability to carry out the following:

i. A survey of gamma ray sources and diffuse emission with sensitivities around 10^{-5} photon $cm^{-2} sec^{-1}$ and energy resolution around 10 percent at energies between 0.1 and 30 MeV.

ii. A survey of high energy gamma ray sources and diffuse emission with a point source sensitivity of 10^{-7} photons $cm^{-2} sec^{-1}$, angular resolution of about 0.1° for strong sources, and energy resolution around 15% at energies above 10^2 MeV.

iii. Detection and identification of nuclear gamma lines with an energy resolution of 4 percent and sensitivity of the order of 5×10^{-5} photon $cm^{-2} sec^{-1}$.

iv. Observations of gamma ray bursts, including studies of their spectral and temporal behavior.

The Gamma Ray Observatory will be a shuttle-launched, free-flyer satellite. The nominal circular orbit will be about 400 kilometers with an inclination of 28.5°. Celestial pointing to any point on the sky will be maintained to an accuracy of ± 0.5°. Knowledge of the pointing direction will be determined to an accuracy of 2 arc-minutes. Absolute time will be accurate to better than 0.1 milliseconds to allow precise comparisons of pulsars and other time varying sources with observations at other wavelengths from ground observations and other satellites. For further information on the instruments to be flown on GRO, see Kniffen et al. [1981].

C. Space Station

NASA is now considering a Space Station which would be a manned spacecraft permanently orbiting the Earth and capable of performing a variety of scientific missions. High energy gamma ray astronomy is certainly among the scientific disciplines which would be able to benefit very significantly from such an opportunity. With the gamma ray sky surveyed in some depth with the GRO, it would, for example, be possible to concentrate on the detailed features of discrete sources such as active galaxies to examine detailed characteristics including the temporal variability on time scales up to years and to study in depth limited regions such as clouds, galactic arms, and nearby galaxies.

D. Very High Energy Ground-Based Gamma Ray Telescopes

In the very high energy realm of gamma ray astronomy, there are plans for ground-based atmospheric Cherenkov experiments that would parallel the developments in sensitivity at gamma ray energies in the MeV-GeV region expected in the Space Station era. One of these [Weekes, 1985] consists of seven 10 to 15 m aperture optical reflectors in an array of spacing 7 m at a high mountain altitude (3.5 km). Each reflector would be equipped with a camera similar to that currently in use at the Whipple Observatory. The flux sensitivity will be a factor of ten better than that achievable with the current camera and will be competitive with the anticipated sensitivity of spaceborne calorimeters in the TeV energy range. The effective energy threshold could be as low as 10 GeV (10^{10} eV). A co-located particle detector array consisting of 61 scintillators of 1 m^2 area will give coverage in the even higher energy range from 10^{14} to 10^{17} eV, so that six magnitudes of the electromagnetic spectrum will be simultaneously monitored.

Should all these opportunities come into being, gamma ray astronomy should make a major contribution to the understanding of the universe.

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