NASA

Technical Memorandum 83905

Gamma-Ray Astronomy

(NASA-TM-83905) GAMMA-RAY ASTRONOMY (NASA) N82-22104
60 p HC A04/MF A01 CSCL 03A

Unclas
G3/83 17916

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MARCH 1982

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Space Administration

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GAMMA RAY ASTRONOMY

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Invited Paper for the Annual Review of Nuclear and Particle Science
Vol 32, 1982

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6. SUMMARY

1. INTRODUCTION

The gamma-ray region is one of the last energy bands of the electromagnetic spectrum to be opened to astronomical observations. While early attempts to detect gamma rays were often frustrated by difficulties of distinguishing fluxes of cosmic origin from those produced in the atmosphere and the detectors, more recent observations on balloons, satellites and space probes have detected gamma rays from many astronomical objects, including the Sun, the Moon, neutron stars, interstellar clouds, the center of our Galaxy and the nuclei of active galaxies.

Cosmic gamma rays are produced in a variety of physical processes: nuclear deexcitation, neutron capture and positron annihilation produce the lines first observed from solar flares by Chupp et al. (1973) and from the lunar surface by Metzger et al. (1974); π^0 meson decay and bremsstrahlung can lead to observed (Clark, Kraushaar and Garmire 1968) gamma-ray emission from the interstellar medium; bremsstrahlung, Compton scattering and gyrosynchrotron radiation in multibillion degree and trillion gauss plasmas are probably responsible for the continuum emission seen (Klebesadal, Strong and Olson 1973) from gamma-ray bursts; electron-positron pair production by photon-photon collisions, expected in similar plasmas, could be the source of the annihilation radiation detected (Leventhal, MacCallum and Stang 1978) from the Galactic Center as well as from gamma-ray bursts (Mazets et al. 1981); radiation produced by particles accelerated along curved magnetic field lines at neutron star polar caps may be responsible for gamma-ray emission observed (Kniffen et al. 1974) from pulsars; nonthermal synchrotron and Compton emissions from relativistic electrons could produce the broad spectrum of gamma rays seen (e. g. Grindlay et al. 1975, Swanenburg et al. 1978) from active galaxies; and the superposition of emission from similar objects at cosmological distances, together with possible matter-antimatter annihilation radiation, could lead to the observed (e. g. Fichtel, Kniffen and Hartman 1973) diffuse gamma-ray background.

Gamma-ray observations have provided important information on a variety of astronomical objects and sites. In solar flares, gamma-ray line observations provide information on particle acceleration mechanisms by giving a measure of the flare energy that resides in energetic nucleons and of the acceleration time of these nucleons; in the interstellar medium, gamma-ray continuum observations map the product of the densities of cosmic rays and interstellar gas and provide a demonstration that the cosmic rays are of galactic origin; for gamma-ray bursts, line observations, by showing evidence for redshifts in strong gravitational fields and absorptions in intense magnetic fields, suggest that neutron stars are the sources of these bursts; for active galactic nuclei, hard X-ray and gamma-ray continuum observations, by indicating that a major fraction of the observed luminosity is in the gamma-ray band, suggest that powerful nonthermal sources, perhaps massive black holes, power these objects; for the nucleus of our Galaxy, the observed electron-positron annihilation line, also seems to require such a hole.

These achievements notwithstanding, several of the promises of gamma-ray astronomy have not yet been fulfilled. Chief among these is the observation of gamma-ray lines from processes of nucleosynthesis in supernovae and novae.

Balloon-borne detectors have provided pioneering observations in gamma-ray astronomy, but much of the recent progress has been the result of space missions which carried instruments above the atmosphere. The space vehicles that have contributed most significantly to gamma-ray astronomy have been two Orbiting Solar Observatories (OSO-3 and OSO-7), the second Small Astronomical Satellite (SAS-2), the European satellite COS-B, two High Energy Astrophysical Observatories (HEAO-1 and HEAO-3), the Solar Maximum Mission (SMM), and a variety of space probes with gamma-ray burst experiments on board. Future progress in gamma-ray astronomy, however, will only be possible if additional flight opportunities are made available to instruments that are both more sensitive and have more resolving power than those flown so far.

In the present article we describe gamma-ray observations from the solar system, from rapid nonsolar transients, from quasi-steady galactic sources and from extragalactic sites. We consider the most reliable and statistically significant observations; gamma-ray observations, in some cases, are still limited by counting statistics which can lead to questionable results. We particularly emphasize the physical processes responsible for astrophysical gamma-ray production. These involve processes of atomic physics (positronium formation and annihilation), of low energy nuclear physics (deexcitation lines), of medium energy particle physics (π^0 meson production), of electromagnetism and magnetohydrodynamics (electron-positron pair production, confinement and annihilation), as well as the more exotic processes in and around neutron stars, close to black holes and even in the early universe.

2. SOLAR SYSTEM GAMMA RAYS

Gamma rays have been observed from both the Sun and the Moon. Solar gamma-ray emission is produced by particles accelerated in flares, while lunar gamma rays result from galactic cosmic-ray interactions with the lunar surface and the decay of long-lived natural radioisotopes.

2.1 Solar Flares

The interactions of solar flare accelerated particles with the ambient solar atmosphere are a source of gamma rays, both lines and continuum. Line emission results from the interactions of protons and nuclei, while the continuum is from relativistic electron bremsstrahlung. The first detailed calculation of the expected energetic particle interaction rates in flares, carried out by Lingenfelter and Ramaty (1967), predicted observable gamma-ray line fluxes at the Earth.

Gamma-ray lines from solar flares were first observed by Chupp et al. (1973) with a NaI spectrometer flown on board the OSO-7 satellite. The lines were observed at 0.51 MeV from positron annihilation, at 2.22 MeV from neutron capture on ^{1}H, and at 4.44 and 6.13 MeV from deexcitations of nuclear levels in ^{12}C and ^{16}O, respectively. These lines, as well as other nuclear deexcitation lines, have been observed from a number of subsequent flares by detectors on the HEAO-1 (Hudson et al. 1980), HEAO-3 (Prince et al. 1982) and SMM (Chupp et al. 1981, Chupp and Forrest 1981, Chupp 1982) satellites.

Gamma-ray continuum from solar flares was first observed by Peterson and Winckler (1959) with a balloon-borne detector. This continuum below an MeV is electron bremsstrahlung, now routinely observed from many solar flares (e.g. Kane et al. 1980). But at higher energies Doppler broadened, unresolved nuclear lines make a significant contribution to the continuum and in the energy range from 4 to 7 MeV nuclear radiation from C, N and O constitutes the dominant radiation mechanism (Ramaty, Kozlovsky and Suri 1977, Ibragimov and Kocharov 1977). Continuum emission at higher energies is only rarely observed (Chupp and Forrest 1981). This emission could be a combination of electron bremsstrahlung and π^0 meson decay (Lingenfelter and Ramaty 1967, Crannell, Crannell and Ramaty 1979).

The strongest predicted and observed line from solar flares is that at 2.223 MeV from neutron capture on hydrogen, ^{1}H(n,γ)^{2}H. Studies of neutron production in flares (Lingenfelter et al. 1965, Ramaty, Kozlovsky and Lingenfelter 1975) indicate that the bulk of the neutrons responsible for this line result from the breakup of helium by protons at energies greater than about 20 MeV/nucleon, $^{4}He(p,pn)^{3}He$ and $^{4}He(p,2pn)^{2}H$, with lesser contributions from spallation of heavier nuclei and from π^{+} production, $^{1}H(p,n\pi^{+})^{1}H$. The neutron production may take place above the photosphere, but the 2.223 MeV line emission comes from captures in the photosphere where the density is high enough ($> 10^{16} H/cm^{3}$) for the bulk of neutrons to be slowed down and captured before they decay. Calculations (Wang and Ramaty 1974) of neutron slowing down and capture in the solar atmosphere show that the principal capture reactions are $^{1}H(n,\gamma)^{2}H$ and $^{3}He(n,p)^{3}H$. Even though ^{3}He is only a minor constituent of the solar atmosphere, $^{3}He/^{1}H \sim 5\times10^{-5}$ (Geiss and Reeves 1972, Hall 1975), its thermal capture cross section is 1.6×10^{4} times that of hydrogen.

Comparisons of the observed (Chupp et al. 1981, Chupp 1982, Prince et al. 1982) time dependence of the intensity of prompt nuclear deexcitation lines to that of the 2.223 MeV line show delays of $\sim 10^{2}$ sec which are due to the mean thermal neutron capture time. The time required for the neutrons to slow down is much less than that required for their capture. A capture time of $\sim 10^{2}$ sec implies (Wang and Ramaty 1974) that the mean density of the gas where the neutrons are captured is $\sim 10^{17}$ H/cm^{3}, a density corresponding to a depth of ~ 300 km into the photosphere. Independent evidence for neutron capture in the photosphere comes from the relative attenuation, or limb darkening, of the neutron capture line from solar flares occurring close to the visible limb of Sun. Comparisons (Chupp 1982) of the neutron capture line fluence to that of nuclear deexcitation lines show that the capture line is attenuated by a factor of 10 or more for limb flares than for disk flares. This attenuation results from Compton scattering in the photosphere (Wang and Ramaty 1974) and implies (Ramaty, Lingenfelter and Kozlovsky 1982) a column density of

$\sim 10^{25}$H/cm^2 for the limb flares, consistent with a density of $\sim 10^{17}$ H/cm^3. The width of the 2.223 MeV line, determined by the photospheric temperature, is expected to be very narrow (~ 100 eV), a result consistent with the high resolution HEAO-3 observations (Prince et al. 1982) which have set an upper limit of several keV on the width of this line.

A significant fraction of the fastest ($\gtrsim$ 100 MeV) neutrons can travel as far as the Earth before they decay, resulting (Lingenfelter et al.1965) in detectable neutron fluxes at the Earth following large flares. High energy solar neutrons were observed from a large flare in 1980 (Chupp and Forrest 1982).

The next most intense solar flare line is that at 0.511 MeV from the annihilation of positrons. There are many astrophysically important positron production mechanisms, but in solar flares the 0.511 MeV line results (Ramaty, Kozlovsky and Lingenfelter 1975) from nuclear interactions producing short-lived radionuclei (e.g. ^{11}C, ^{13}N, ^{15}O, ^{17}F) and π^+ mesons which decay by positron emission, as well as excited ^{16}O in the 6.052 MeV level which decays by electron-positron pair emission. The initial energies of the positrons range from several hundred keV to tens of MeV, but only a few annihilate at these high energies. The bulk of the positrons slow down to energies comparable with those of the ambient electrons, where annihilation takes place either directly or via positronium (Stecker 1969). For a recent review of the physics of positronium see Berko and Pendleton (1980).

Positronium in astrophysical sites is formed by radiative combination with free electrons and by charge exchange with neutral hydrogen (Ramaty and Lingenfelter 1973, Crannell et al. 1976); 25% of the positronium atoms decay from the singlet state and 75% in the triplet state. Singlet positronium annihilation and direct annihilation produce a line at 0.511 MeV, while triplet positronium annihilates into three photons which form a continuum below 0.511 MeV. But if the ambient density is $\gtrsim 10^{15}$H/cm^3, as may be the case for solar flare positrons, then the positronium will be broken up by collisions before it can decay (Crannell et al. 1976). The width of the 0.511 MeV line from solar flares depends on the temperature of the annihilation region, and could range from a few keV to tens of keV, depending on whether the annihilation takes place predominantly in the cool photosphere or the hot flare plasma. Measurements of the positronium continuum and the width of the 0.511 MeV line could thus provide important information on the positron annihilation site, but such observations are not yet available.

A variety of gamma-ray lines are produced by the deexcitation of nuclear levels. In solar flares these levels are populated by inelastic collisions (e.g. $^{12}C(p,p')\ ^{12}C^{*4.44}$), spallation reactions (e.g. $^{20}Ne(p,p\alpha)^{16}O^{*6.13}$), fusion reactions (e.g. $^{4}He(\alpha,\ p)^{7}Li^{*0.478}$) and the decay of radionuclei produced by spallation reactions (e.g. $^{16}O(p,p2n)^{14}O(e^{+})^{14}N^{*2.31}$. Using laboratory measurements (e.g. Dyer et al. 1981) of the excitation functions of a great number of such reactions, Ramaty, Kozlovsky and Lingenfelter (1979) calculated theoretical gamma-ray spectra produced by the interaction of energetic particles in cooler ambient matter, assuming a variety of energetic particle spectra.

In the solar atmosphere two line components are produced: a narrow component resulting from the deexcitation of ambient nuclei excited by interactions with energetic protons and α particles, and a broad component from the deexcitation of energetic heavy nuclei excited by interactions with ambient hydrogen and helium. The relative widths of the narrow lines, broadened by the recoil velocities of the heavy target nuclei, are on the order 1% to 2%, while those of the broad lines, reflecting the velocities of the projectiles themselves, are about an order of magnitude larger. If the elemental and isotopic compositions of both the energetic particles and the ambient medium resemble that of the solar photosphere, the strongest narrow lines are at 6.129 MeV from ^{16}O, 4.438 MeV from ^{12}C, 2.313 MeV from ^{14}N, 1.779 MeV from ^{28}Si, 1.634 MeV from ^{20}Ne, 1.369 MeV from ^{24}Mg, 1.238 MeV and 0.847 MeV from ^{56}Fe, all produced primarily by direct excitation of these nuclei, and at two lines, 0.478 MeV from ^{7}Li and 0.431 MeV from ^{7}Be, which result from fusion reactions, $^{4}He(\alpha,p)^{7}Li^{*}$ and $^{4}He(\alpha,n)^{7}Be^{*}$. The role of these fusion reactions for producing gamma-ray lines in astrophysics was first pointed out by Kozlovsky and Ramaty (1974). As already mentioned, the broad lines, together with many unresolved narrow lines, contribute significantly to the gamma-ray continuum, in particular in the 4 to 7 MeV range.

The most important implications of the gamma-ray observations of solar flares concern the timing of the acceleration, the confinement of particles at the Sun, the fraction of the total flare energy that resides in energetic nucleons, chemical and isotopic abundances and the possible beaming of the energetic particles. In particular the gamma-ray observations show (Von Rosenvinge, Ramaty and Reames 1981, Chupp 1982, Ramaty, Lingenfelter and Kozlovsky 1982) that as much as a few percent of the total flare energy resides in protons and nuclei, accelerated to tens of MeV per nucleon on time scales of a few seconds in closed magnetic loops with little escape into the interplanetary medium. Further analysis of data should provide important and potentially unique information on abundances and on geometric effects such as beaming. The latter would follow from shifts in the peak line energies (Ramaty and Crannell 1976) and modifications in the line widths (Kozlovsky and Ramaty 1977).

2.2 Lunar and Planetary Surfaces

The most intense gamma-ray line and continuum emission from the Moon results from interactions of galactic cosmic rays with the lunar surface material. The strongest lines are from excitations and captures of secondary neutrons generated by relativistic primary cosmic-ray particles in nuclear cascades of spallation interactions. The secondary electrons and positrons of these cascades produce the bulk of the continuum emission by bremsstrahlung. Decay of the natural radionuclei ^{40}K, ^{232}Th and ^{238}U, remnants of nucleosynthesis prior to the formation of the solar system, also produce several intense gamma-ray lines.

Detailed studies (Reedy, Arnold and Trombka 1973, Reedy 1978) of cosmic-ray secondary particle interactions showed that the two most intense lines from the lunar surface are at 1.779 and 6.129 MeV from deexcitation of the two most abundant nuclei, ^{28}Si and ^{16}O, excited by inelastic neutron scattering. But these calculations also predicted a large number of other detectable lines from less abundant elements, the nuclear deexcitation lines at 0.847, 1.369 and 2.210 MeV from inelastic excitation of ^{56}Fe, ^{24}Mg and ^{27}Al and the neutron capture lines on ^{48}Ti at 6.762 MeV and on ^{56}Fe at 7.631 and 7.646 MeV. These studies also predicted line intensities from the decay of natural radionuclei comparable to those produced by cosmic-ray interactions. The three strongest lines are those at 1.461 MeV from decay of ^{40}K (half life $\sim 1.28 \times 10^9$ yr), at 2.615 MeV from decay of ^{208}Tl in the decay chain of ^{232}Th (half life $\sim 1.41 \times 10^{10}$ yr) and at 0.609 MeV from the decay of ^{214}Bi in the ^{238}U (half life $\sim 4.47 \times 10^9$ yr) decay chain.

All of these lines have been observed (Metzger et al. 1974, Bielefeld et al. 1976) with NaI gamma-ray spectrometers on the lunar-orbiting Apollo 15 and

16 spacecraft. These detectors mapped a sizeable portion of the lunar surface and the relative line strengths revealed significant regional variations. The lunar mare regions showed enrichments of a factor of three or more in Fe, Ti, K, Th and U, and depletions of as much as 50% in Al and Ca abundances with respect to the lunar highland regions. These observations provide important constaints on the differentiation and thermal evolution of the Moon.

Reedy (1978) has pointed out that similar observations by orbiting gamma-ray spectrometers could also provide maps of the surface compositions of Mercury and Mars, which have atmospheres thin enough for the surface gamma-ray emission to be observed.

3. RAPID GAMMA-RAY TRANSIENTS

Temporal variability is a common property of a large fraction of the astronomical sources of high-energy radiation. In fact, many gamma-ray sources have so far been observed only by their intense transient emission. The most common class of these transients, known as gamma-ray bursts, appear suddenly and persist for times ranging from a fraction of a second to a few minutes. We first consider these bursts, including the possibly unique March 5, 1979 burst. We then briefly review the properties of two very unusual transients that last for tens of minutes and have only been seen in line emission.

3.1 Gamma Ray Bursts

Gamma-ray bursts were discovered accidentally in 1967 (Klebesadel, Strong and Olson 1973) by detectors on board the Vela satellites whose primary purpose was to monitor artificial nuclear detonations in space. Detailed reviews of the observational properties of gamma-ray bursts can be found in Hurley (1980), Vedrenne (1981) and Cline (1981) and a catalogue of recent bursts in given by Mazets et al. (1981a). The early theories of gamma-ray bursts were reviewed by Ruderman (1975), while more recent outlooks on the presently accepted theoretical ideas were given by Woosley (1982), Lamb (1982) and Ramaty, Lingenfelter and Kozlovsky (1982). A variety of other recent observational and theoretical papers can be found in Lingenfelter, Hudson and Worrall (1982). Here we give a relatively brief discussion of both the observations and theories.

Gamma-ray bursts are generally observed in the photon energy range from a few tens of keV to several MeV with typical event durations ranging from about 0.1 to 30 sec. The observed burst energy fluences (> 30 keV) range from about 10^{-7} to 10^{-3} erg/cm^2, and the frequency of occurrence of bursts range from a few per year with fluences > 10^{-4} erg/cm^2 to a few thousand per year with fluences > 10^{-7} erg/cm^2. At fluences less than 10^{-5} erg/cm^2, the frequency of bursts falls below that expected from an unbounded, isotropic and homogeneous distribution of sources. Therefore, the observed frequency distribution requires a source distribution of finite extent, implying a galactic origin (Fishman et al. 1978). The average distances of the observed sources, however, are still uncertain. Therefore, galactic source distributions have been constructed, which can reproduce the observed sizes and frequencies with typical burst energies of 10^{37} ergs (Higdon 1982) to 10^{40} ergs (Jennings 1982).

Because the bursts originate from unpredictable celestial directions at unpredictable times, they have generally been observed with detectors of large fields of view. Such instruments, however, have poor angular resolution and can determine source positions to an accuracy of only a few degrees (Mazets and Golenetskii 1981). But much more accurate burst positions can be determined from arrival-time differences using a network of instruments placed on widely separated interplanetary space probes (e.g. Cline 1981). The presence of sharp temporal features in the burst time profiles allows the measurement of differences in arrival times of wavefronts of the order of a few milliseconds over baselines separated by hundreds of light seconds. For the strongest and most rapidly varying bursts, such measurements yield angular resolutions on the order of arc seconds.

The most precise source position determined by arrival-time differences is that of the March 5, 1979 burst (Evans et al. 1980). This burst, the most intense observed so far, has been detected by instruments on nine different spacecraft (see Cline 1980, 1982, for review). The resultant positional error box, of size 0.1 arc min^2, lies within the supernova remnant N49 in the Large Magellanic Cloud (LMC), a neighboring galaxy at a distance of 55 kpc. If the burst source is at this distance, the total radiated energy is $\sim 10^{44}$ ergs which is at least four orders of magnitude larger than that of a typical galactic gamma-ray burst. But since the March 5 burst exhibited a number of remarkable and possibly unique observational properties which we discuss in more detail below, it appears (Cline 1980, Klebesandel et al. 1982) to belong to a separate class of less frequent but more energetic transients than do the typical galactic bursts.

Small positional error boxes have also been determined for a few other gamma-ray bursts (Cline et al. 1981, Laros et al. 1981). But searches at longer wavelengths (e.g. Hjellming and Ewald 1981) have not produced unambiguous associations of the burst sources with identifiable astronomical objects. Nevertheless, an exciting development has ocurred recently with the discovery (Schaefer 1981) of an optical flash in one of these error boxes, that of the November 19, 1978 burst (Cline et al. 1981). This flash was found on an archival plate of the Harvard College Observatory exposed on November 17, 1928. Since good arguments exist (Schaefer 1981) that the 1928 flash and

1978 burst were from the same source, this discovery provides the strongest evidence to-date for repetitions of galactic gamma-ray bursts and demonstrates that the bursts can also be monitored optically.

A new dimension in the study of gamma-ray bursts has been added by the discovery of emission lines and absorption features in their energy spectra (see Teegarden 1982, for review). The absorption features, observed (Mazets et al. 1981b, Dennis et al. 1982) at energies below about 100 keV, are probably due to cyclotron absorption in intense magnetic fields of the order 10^{12} gauss which are expected around neutron stars (Baym and Pethick 1975).

The most commonly observed emission line falls in the energy range from 0.40 to 0.46 MeV, as seen (Mazets et al. 1981b) by low resolution NaI detectors in the spectra of a third of the most intense gamma-ray bursts. In the spectrum of the November 19, 1978 burst, a Ge detector has resolved (Teegarden and Cline 1980) two emission lines at ~ 0.42 MeV and ~ 0.74 MeV, which the NaI detectors saw as one broad feature from 0.3 to 0.8 MeV. Line emission in the range of 0.4 to 0.46 MeV is probably optically thin e^+-e^- annihilation radiation redshifted by the strong gravitational field of a neutron star. In an optically thick region, however, stimulated annihilation radiation (Ramaty, McKinley and Jones 1982) could produce a line at ~ 0.43 MeV without a gravitational redshift. The line at 0.74 MeV could be either collisionally excited and gravitationally redshifted 0.847 MeV emission from ^{56}Fe (Teegarden and Cline 1981), or gravitationally redshifted single photon e^+-e^- annihilation (Daugherty and Bussard 1980, Katz 1982) radiation at 1.022 MeV in a very strong ($\gtrsim 10^{13}$ gauss) magnetic field. In all cases, the implied redshifts of 0.1 to 0.3 are consistent with those expected from neutron stars.

The ~ 0.43 MeV e^+-e^- annihilation line was also seen (Mazets et al. 1979) from the March 5, 1979 burst suggesting that the source of this burst was also a neutron star. But as mentioned above, other characteristics of this burst seem to place it in a different class from that of the typical galactic bursts. These characteristics include (Cline 1980, 1982) the extremely rapid rise time ($< 2x10^{-4}$ sec) of the impulsive emission spike, the relatively short duration ($\sim$ 0.15 sec) and high luminosity of this spike, the 8-sec pulsed emission following the impulsive spike, the subsequent outbursts of lower intensity from apparently the same source direction on March 6, April 4 and April 24, 1979, and, as already mentioned, the coincidence of the positional error box with a extragalactic supernova remnant.

Current theoretical ideas on gamma-ray bursts generally involve strongly magnetized neutron stars. These ideas have developed, in part, as a result of the detailed March 5 observations, even though it is quite likely that the underlying energy source of this burst is not typical of all gamma-ray bursts.

The most probable energy source of gamma-ray bursts is either gravitational or nuclear. Magnetic field annihilation, responsible for energy generation in solar flares (e.g. Sturrock 1980), can be shown on the basis of total energetics to be inadequate for gamma-ray burst production. The absence of evidence for bulk antimatter in our Galaxy or in neighboring galaxies (Steigman 1976) also makes matter-antimatter annihilation an unlikely processes for energy generation in gamma-ray burst sources.

Gravitational energy can be released impulsively from a neutron star when a large amount of solid matter such as an asteroid or comet is accreted onto its surface (Harwitt and Salpeter 1973, Colgate and Petschek 1981). Such accretion releases about 100 MeV/nucleon, the potential energy at the neutron star surface. Gravitational energy could also be released in a corequake of a neutron star (Tsygan 1975, Ramaty et al. 1980). Such quakes can set up neutron star vibrations which dissipate mainly by gravitational radiation. A fraction of the vibrational energy, however, can be converted into magnetoacoustic waves which dissipate by accelerating particles in the magnetosphere. Radiation from these particles is then responsible for the observed gamma-ray emission.

Alternatively, impulsive energy release from neutron stars could result from a nuclear detonation of degenerate matter accumulated over a relatively long period of time by accretion of gas (Woosley and Taam 1976, Woosley 1982). Such detonations release several MeV per nucleon from the burning of helium to the iron peak nuclei.

All three of these processes, solid body accretion, a corequake, or a nuclear detonation, appear to be quite capable of providing the 10^{37} to 10^{40} ergs required for typical galactic gamma-ray bursts. But to account for the $\sim 10^{44}$ ergs of the March 5, 1979 burst, very large amounts of accreted matter must be involved and this probably rules out solid body accretion and nuclear detonation for this burst. Corequakes, however, which could in principle release energies up to a fraction of the gravitational binding energy of a neutron star ($\sim 10^{53}$ erg, Borner and Cohen 1973), appear to be adequate for the March 5 burst (Ramaty et al. 1980). But no detailed calculations on these possibilities have yet been published.

An issue comparable in importance to the energy source is the radiation mechanism and the nature of the emitting region. Electron-positron annihilation, as already mentioned, is probably responsible for the observed emission line between 0.40 and 0.46 MeV. Since these lines have relatively narrow widths requiring a narrow and well defined range of gravitational redshift, the emitting material must be confined to a thin region close to the neutron star surface. It was first proposed by Ramaty et al. (1980) that this confinement is achieved by the strong magnetic field ($\sim 10^{12}$ gauss) of a neutron star. Magnetic confinement is necessary especially for the March 5 burst where the inferred radiation pressure greatly exceeds the gravitational pull of the neutron star. Magnetic fields similarly play an important role in nuclear detonation models of galactic bursts (Woosley 1982) where magnetic confinement of the nuclear burning products, or lack of it, may constitute the difference between a gamma-ray burst and an X-ray burster. For a recent review of the properties of X-ray bursters see Lewin and Joss (1981). Lastly, if the absorption features, observed below 100 keV in gamma-ray bursts, are due to cyclotron absorption, then they provide direct observational evidence for $\gtrsim 10^{12}$ gauss magnetic fields in the burst sources.

The principal continuum emission processes suggested for gamma-ray burst sources are bremsstrahlung (Gilman et al. 1980), Comptonization (Liang 1981, Bussard and Lamb 1982, Fenimore et al. 1982) and gyrosynchrotron radiation (Ramaty, Lingenfelter and Bussard 1981). To account for the observed gamma-ray burst spectra, bremsstrahlung requires a hot plasma with $T \gtrsim 10^9$K, Comptonization requires similar temperature electrons and a copious supply of cooler photons which gain energy from the electrons in Compton collisions, and gyrosynchrotron radiation is produced in strong magnetic fields (10^{11} to 10^{12} gauss) by MeV electrons. In certain cases these mechanisms can operate simultaneously as in the model of Liang (1981) where MeV electrons produce gyrosynchrotron photons of energies $\lesssim$ 100 keV and subsequently Compton scatter them up to energies up to an MeV. Figure 1, from Liang (1981), shows the observed (Mazets and Golenetskii 1981) spectrum of the March 5 event and theoretical calculations that involve annihilation, synchrotron radiation and Comptonization of the synchrotron photons.

An important property of gamma-ray burst spectra is that they appear to be optically thin (Gilman et al. 1980), especially at the higher energies

($\gtrsim$ 100 keV). An optically thin emission region is also required to produce the $\sim$ 0.43 MeV emission line, except in the case where grasar action is important (Ramaty, McKinley and Jones 1982). An optically thin source requires a sufficiently small ratio of source depth to source area, so that the small opacity can be consistent with the high observed luminosity. The gamma-ray emission should therefore be produced in a thin layer containing a high density of radiating matter. The most extreme conditions are found in the March 5 event, where in the model of Ramaty, Lingenfelter and Bussard (1981) the observed radiation comes from a magnetically confined thin layer ($\sim$ 0.1 mm) of dense ($\sim 10^{26}$cm^{-3}) e^+-e^- pairs covering the surface of a neutron star. The instantaneous energy content of this layer is orders of magnitude smaller than the total energy of the burst, so that energy must be supplied continuously to the layer. This is achieved by the neutron star vibrations discussed above. An attractive consequence of the continuous energization by vibrations is that the duration of the burst is determined by the damping time of the vibrations. Indeed, the neutron star mass-to-radius ratio, deduced from the observed gravitational redshift, implies a vibrational damping time which is almost exactly the same as the duration of the main emission spike of the burst (Ramaty et al. 1980).

3.2 Gamma-Ray Line Transients

There are apparently two other types of gamma-ray transients in which all of the radiation observed so far is in emission lines. One such gamma ray line transient was discovered (Jacobson et al. 1978, Ling et al. 1982) with a high resolution Ge detector on June 10, 1974 from an unknown source. This event, lasting about twenty minutes, was characterized by strong emission in four relatively narrow energy bands at 0.40-0.42 MeV, 1.74-1.86 MeV, 2.18-2.26 MeV, and 5.94-5.96 MeV with no detectable continuum. Subsequent searches for similar line transients (Heslin et al. 1981), however, failed to observe such transients and therefore imply that their frequency is less than 30 per year.

Lingenfelter, Higdon, and Ramaty (1978), suggested that the gamma-ray line transient observed by Jacobson et al. (1978) could result from episodic accretion onto a neutron star from a binary companion leading to redshifted lines from the neutron star surface and unshifted lines from the atmosphere of the companion star. The observations could then be understood in terms of neutron capture and positron annihilation. Specifically, positron annihilation and neutron capture on hydrogen and iron at and near the surface of the neutron star with a surface redshift of ~ 0.28 would produce the observed redshifted line emission at about 0.41, 1.79, and 5.95 MeV, respectively. The same processes in the atmosphere of the companion star would produce unshifted lines, of which only the 2.223 MeV line from neutron capture on hydrogen was observed. The unshifted 0.511 MeV positron annihilation line could not have been seen because of the large atmospheric and detector background at this energy, while the line emission from neutron capture on iron should be significant only from the iron rich surface of the neutron star but not from the companion star.

The other type of transient line emission is observed in the pulsed spectrum of the Crab pulsar. This very narrow (FWMM < 4.9 keV) emission line, which may vary slightly in energy from 73 to 77 keV was first observed by Ling et al. (1979) from the Crab nebula. The line was subsequently shown (Strickman, Kurfess and Johnson 1982) to be pulsed with the Crab pulsar period of 0.033 sec and to persist only for about 20 minutes and then turn off. The most likely source of this line is cyclotron emission in an intense (~ 8 x 10^{12}gauss) magnetic field at the polar cap of a neutron star. In addition, a very narrow 0.4 MeV line was observed (Leventhal, MacCallum and Watts 1977) from a broad field of view that included both the Crab nebula and the source direction of the June 10, 1974 transient.

4. GALACTIC GAMMA RAYS

In addition to the transients, there are a rich variety of other more steady sources of galactic gamma-ray emission. These include an intense source of electron-positron annihilation radiation at the Galactic Center, the Crab and Vela pulsars, the binary source Cygnus X-3, a number of unidentified discrete sources, and diffuse emission resulting from cosmic-ray interactions in the interstellar medium.

We shall discuss first the gamma-ray line emission from the Galactic Center and other potential sources, then turn to the continuum emission from both diffuse regions localized sources.

4.1 Galactic Center

Intense positron annihilation radiation at 0.511 MeV has been observed from the direction of the Galactic Center for over a decade. This emission was first seen in a series of balloon observations with low-resolution NaI detectors, starting in 1970 (Johnson, Harnden and Haymes 1972, Johnson and Haymes 1973, Haymes et al. 1975). But it was not until 1977 that the annihilation line energy of 0.511 MeV was clearly identified with high-resolution Ge detectors flown by Leventhal, MacCallum and Stang (1978). The latter observation also revealed that the line is very narrow (FWHM $\lesssim$ 3.2 keV) and that it shows evidence for three-photon positronium continuum emission below 0.511 MeV, implying that ~ 90% of the positrons annihilate via positronium. Thus, the observed intensity of $\sim 2 \times 10^{-3}$ photons/cm^2 sec implies an annihilation rate of $\sim 4 \times 10^{43}$ positrons/sec or an annihilation radiation luminosity of $\sim 6 \times 10^{37}$ ergs/sec at the 10 kpc distance of the Galactic Center. The gamma-ray line at 511 keV and the continuum at lower energies are shown in Figure 2 (from Leventhal, MacCallum and Stang 1978).

Recent Ge detector observations (Riegler et al. 1981) on HEAO-3 have confirmed the narrowness (FWHM < 2.5 keV) of the line and have provided more precise information on the location of the source and strong constraints on the size of the emission region. These measurements showed that the direction of the source is coincident with that of the Galactic Center (within the $\pm 4^o$ observational uncertainty) and that the line intensity varies with time, decreasing by a factor of three in six months from the fall of 1979 to the spring of 1980. This six month variability implies that the sizes of both the annihilation region and the positron source are less than the light- travel distance of 10^{18}cm.

The nature of the positron annihilation region is further constrained by the observed line width and intensity variations. The line width (FWHM < 2.5 keV) requires (Bussard, Ramaty and Drachman 1979) a gas temperature in the annihilation region less than 5×10^4K and an ionization fraction greater than 10%. If the gas were neutral, the line width would be larger than observed, because it would be Doppler broadened, not by the thermal motion of the gas, but by the velocity of energetic positrons forming positronium in flight by charge exchange with neutral hydrogen. In a partially ionized gas, however, the positrons lose energy to the plasma fast enough that they thermalize before they annihilate or form positronium. The line width thus reflects the temperature of the medium, requiring it to be $\lesssim 5 \times 10^4$K. The intensity variation not only constrains the size of the annihilation region to be < 10^{18}cm, but it requires that the density of gas in it be high enough that the positrons can slow down and annihilate in less than half a year. If the positrons are produced with kinetic energies on the order of their rest mass, then the time it takes for them to slow down by Coulomb collisions is longer than the time it takes for them to form positronium in such a gas once they have slowed down. Both times are inversely proportional to the gas density. A slowing down time of $\lesssim 1.5\times10^{7}$sec requires a density of $\gtrsim 10^{5}$H/cm^{3}. Such regions appear to exist in both the peculiar warm clouds (Lacy et al. 1979) and the compact non-thermal source (Kellermann et al. 1977) within the central parsec of the Galaxy.

The nature of the positron source is also strongly constrained by the observed variation of the 0.511 MeV intensity and by observations at other wavelengths. The decrease of a factor of three in the line intensity in six months clearly excludes any of the multiple, extended sources, such as cosmic rays, pulsars (Sturrock and Baker 1979), supernovae (Ramaty and Lingenfelter 1979), or primordial black holes (Okeke and Rees 1980), previously proposed. Instead, it essentially requires a single, compact ($<10^{18}$cm) source which is apparently located either at or close to the Galactic Center and which is inherently variable on time scales of six months or less. With a luminosity of at least 6×10^{37} ergs/sec, this source is the most luminous gamma-ray source in the Galaxy.

The various possible positron production processes and the observational constraints on them have recently been reviewed by Lingenfelter and Ramaty (1982). They find that the observational (Matteson et al. 1979) upper limits on accompanying continuum emission at energies $> m_ec^2$ appear to set the strongest constraints on the positron production process, requiring high efficiency such that more than 10% of the total radiated energy $>m_ec^2$ goes into electron-positron pairs. Under the conditions of positron production on time scales comparable to that of the observed variation and in an optically thin, isotropically emiting region, only photon-photon pair production among ~ MeV photons can provide the required high efficiency. Moreover, the absolute luminosity of the annihilation line requires that the photon-photon collisions take place in a very compact source ($d < 5\times10^8$cm). Pair production in an intense radiation field around an accreting black hole of $<10^3 M_\odot$ appears to be a possible source. Other mechanisms (Lingenfelter and Ramaty 1982), such as β^+- decay of radionuclei produced by thermonuclear burning or pair production in an electromagnetic cascade in a strong electric field of an accreting and rotating black hole, would be possible if the above constraints are relaxed.

4.2 Other Sources of Line Emission

Thermonuclear burning in supernovae and novae (e.g. Woosley, Axelrod and Weaver 1981, Clayton 1982) and nuclear interactions of low-energy cosmic rays with interstellar gas (Ramaty, Kozlovsky and Lingenfelter 1979) are all expected (Ramaty and Lingenfelter 1981) to produce throughout the Galaxy a variety of nuclear deexcitation lines, as well as additional positron-annihilation line emission. Observations (Albernhe et al. 1981, Gardner et al. 1982) of galactic 0.511 MeV emission with wide ($\gtrsim 50^\circ$) field-of-view detectors have found considerably higher line intensities than would be expected from the Galactic Center source alone, suggesting that there may be a spatially diffuse source of 0.511 MeV line emission in the Galaxy. However, apart from these tentative observations and the well-established annihilation line from the Galactic Center, no statistically significant steady galactic line emission has yet been observed.

The most abundant radionuclide expected from explosive nucleosynthesis in supernovae is ^{56}Ni (Clayton, Colgate and Fishman 1969) which decays with a 6.1 day half-life to ^{56}Co, which, in turn, decays with a half-life of 78.8 days to ^{56}Fe; 20% of the ^{56}Co decays are via positron emission. Nucleosynthesis of ^{56}Ni in supernovae is thought to be the primary source of galactic ^{56}Fe (e. g. Woosley, Axelrod and Weaver 1981). The bulk of the gamma rays (Colgate and

McKee 1969) and positrons (Arnett 1979) from the ^{56}Ni decay chain, however, are absorbed in the expanding nebula and their energy emerges only as lower energy radiation. The characteristic light curves of Type I supernovae, in fact, appear to follow the ^{56}Ni and ^{56}Co decay (Colgate and McKee 1969) and optical lines from both ^{56}Co and the resulting ^{56}Fe have recently been detected (Axelrod 1980) in the spectrum of an extragalactic supernova, SN 1972e. Any direct gamma-ray line emission from the decay which could escape from the nebula would be detectable for only a few years after the supernova explosion. But a fraction of the positrons from ^{56}Co decay could escape into the interstellar medium. Since in the tenuous interstellar gas the positron lifetime against annihilation is quite long (10^5 yrs in a density of 1 cm^{-3}), positrons should accumulate from several thousand supernovae, assuming that galactic supernovae occur about once every 30 years. Their annihilation should thus produce diffuse galactic gamma-ray line emission at 511 keV (Ramaty and Lingenfelter 1979). Conclusive measurements of such diffuse line emission can put constraints on the fraction of positrons that escape from supernovae and on the average rate of galactic nucleosynthesis during the last 10^5 years.

Similarly, the long-lived radionuclei ^{60}Fe (half life ~ $3\text{x}10^5$ yrs) and ^{26}Al (half life ~ $7.2\text{x}10^5$ yrs), which are also expected from explosive nucleosynthesis, should accumulate from ~ 10^4 or more supernovae and be well distributed through the interstellar medium before they decay. Diffuse galactic line emission is thus expected at 1.809 MeV from ^{26}Al decay to ^{26}Mg (Ramaty and Lingenfelter 1977, Arnett 1977) and at 1.332 MeV, 1.173 MeV and 0.059 MeV from ^{60}Fe decay to ^{60}Co and its subsequent decay to ^{60}Ni (Clayton 1971).

Another important radionuclide from explosive nucleosynthesis in supernovae is ^{44}Ti (Clayton, Colgate and Fishman 1969). This isotope decays with a half-life of 47 years into ^{44}Sc, producing lines at 0.078 and 0.068 MeV. ^{44}Sc subsequently decays into ^{44}Ca with line emission at 1.156 MeV. The ^{44}Ti half life is comparable to the average time between galactic supernova explosions and therefore gamma-ray lines from this decay chain could be observed from the few youngest galactic supernova remnants.

Explosive nucleosynthesis in novae is expected to produce ^{22}Na (Clayton and Hoyle 1974) and ^{26}Al (Woosley and Weaver 1980). Since about 40 novae occur in the Galaxy every year, the 1.275 MeV line emission from ^{22}Na with a 2.6 yr half life should be observable from $> 10^2$ novae at any particular time. Thus, both ^{22}Na and ^{26}Al from novae can also provide diffuse galactic line emission, and observational limits on their intensity can constrain nuclesynthetic models of novae.

The most intense deexcitation lines resulting from low-energy (< 100 MeV/nucleon) cosmic ray interactions are expected at 6.129 MeV from $^{16}O^*$, at 4.438 MeV from $^{12}C^*$ and at 0.847 MeV from $^{56}Fe^*$. Of special interest are the very narrow lines (FWHM ~ 5 keV), such as that at 6.129 MeV from ^{16}O, resulting from deexcitation of nuclei in interstellar grains (Lingenfelter and Ramaty 1977). The line broadening, which in gases is caused by the recoil velocities of the excited nuclei, is greatly reduced in solids where these nuclei or their radioactive progenitors can come to rest before deexcitation. The detection of gamma-ray lines from low-energy cosmic-ray interactions in the interstellar medium would measure the unknown interstellar density of these cosmic rays, and provide information on the distribution, motion, composition and size of interstellar dust grains.

4.3 Diffuse Continuum Emission

Diffuse gamma-ray continuum emission from the Galaxy was first observed by (Clark, Garmire and Kraushaar 1968) with a high-energy (>50 MeV) detector on OSO-3. These observations showed (Kraushaar et al. 1972) a clearly defined band (±15^0 latitude) of enhanced intensity lying along the galactic equator, resulting from emission from the galactic disk. The observations also showed a strong longitudinal dependence of the intensity with a broad peak extending from -30^0 to +30^0 longitude around the Galactic Center, resulting from enhanced emission from the region within about 5 kpc of the Galactic Center. The intensity in this direction was (1.3±0.3) x 10^{-4} photons/cm^2 sec rad of longitude, approximately three times that from other directions in the disk.

Subsequent surveys in this energy range with spark chambers on SAS-2 (Fichtel et al. 1975, Hartman et al. 1979) and COS-B (Mayer-Hasselwander et al. 1982) have mapped the sky with an angular resolution of a few degrees. They have resolved a number of particularly intense discrete sources, including the Crab and Vela pulsars (Kniffen et al. 1974, Thompson et al. 1975). Calculations by Higdon and Lingenfelter (1976) suggested that as much as half of the observed galactic gamma-ray continuum emission may come from young (<10^4 yr), distant (> 1 kpc) and as yet undiscovered pulsars. More recent studies give both lower (Harding 1981a) and higher (Salvati and Massaro 1982) values of the pulsar contributions. Surveys with much higher sensitivity and angular resolution are needed to determine what fraction of the galactic continuum emission comes from such sources and what fraction is truly diffuse emission from the interstellar medium.

Several possible sources of gamma-ray continuum emission, resulting from cosmic-ray interactions in the interstellar medium, have been suggested: Compton scattering of starlight (Feenberg and Primakoff 1948) and cosmic blackbody (Gould 1965) photons by cosmic-ray electrons; bremsstrahlung from cosmic-ray electron interactions with interstellar gas (Hutchinson 1952); and decay of π^0 mesons produced by cosmic-ray nucleon interactions with interstellar gas (Hayakawa 1952). Whatever the emission process maybe, diffuse gamma-ray continuum observations should give new information on the galactic distribution of cosmic-rays.

The unique energy spectrum of gamma-rays expected from the decay of π^0 mesons, resulting from cosmic-ray interactions, can be calculated (Stecker 1970, 1971; Cavallo and Gould 1971; Higdon 1974; Badhwar and Stephens 1977) with reasonable accuracy since the cosmic-ray nucleon spectrum above the effective pion production threshold is fairly well known. But even though the other emission processes are well understood (e.g. Blumenthal and Gould 1970) their relative contributions as a function of gamma-ray energy are harder to determine because the spectrum and intensity of both the low-energy (< 500 MeV) cosmic-ray electrons, responsible for the bremsstrahlung, and the ambient interstellar photons, responsible for the Compton scattering are only poorly known.

Comparative calculations (Fichtel et al. 1976, Stecker 1977, Cesarsky, Paul and Shukla 1978, Higdon 1979), however, all suggest that π^0 decay is the principal source above 100 MeV, while at lower energies bremsstrahlung is the dominant mechanism, except at high galactic latitudes (Kniffen and Fichtel 1981) where Compton scattering is more important. These conclusions are also consistent with the spectrum of the galactic continuum measured from 50 MeV to 3 GeV on SAS-2 (Hartman et al. 1979) and COS-B (Paul et al. 1978), as well as with the lower energy emission (0.06 to 5 MeV) observed (Gilman et al. 1979) from the galactic disk by a detector on Apollo 16. The differential gamma-ray production rates at the solar position in the Galaxy, including the contribution of pulsars, are shown in Figure 3, together with the observed spectrum above 50 MeV (from Harding and Stecker 1981).

Finally, since the absolute intensity of diffuse gamma-rays above 100 MeV depends primarily on the product of the cosmic-ray and ambient gas densities along the line of sight, the variation of that product as a function of galactocentric distance can be deduced from the variation of the diffuse intensity as a function of galactic longitude. Assuming interstellar gas density distributions, based on either spiral arm structure or large scale density gradients in molecular hydrogen, and further assuming that the observed intensity is entirely of diffuse origin, calculations have been made (Stecker et al. 1975, Fichtel et al. 1976, Hartman et al. 1979, Higdon 1979) of the implied cosmic-ray distribution. These calculations imply a cosmic-ray gradient in the Galaxy with higher densities in the inner part of the Galaxy and lower densities in the outer part, which is consistent with current ideas of a galactic origin for the cosmic rays.

4.4 Discrete Galactic Sources

A number of discrete galactic sources of gamma-ray continuum have been discovered by balloon- and satellite-borne detectors at energies of an MeV to several GeV and by ground based detectors at very high energies (> 100 GeV). These sources appear to encompass a variety of objects: dense interstellar clouds, pulsars, accreting neutron stars and several, as yet unidentified objects. The proposed gamma-ray emission processes are equally diverse, including not only π^0 meson decay, electron bremsstrahlung, Compton scattering and synchroton emission, but also curvature radiation of electrons in intense ($\sim 10^{12}$ gauss) magnetic fields. The observations and models of these sources have recently been reviewed by Salvati (1980), Pinkau (1980), Sreekantan (1981) and Bignami and Hermsen (1982).

Gamma-ray emission from the relatively close interstellar cloud near the star ρOph was first reported from balloon observations at > 100 MeV by Frye et al. (1972) and Dahlbacka, Freier, and Waddington (1973). Subsequent observations on COS-B confirmed (Mayer-Hasselwander et al. 1980) these measurements and also showed (Caraveo et al. 1980) high-energy gamma-ray emission from the Orion cloud complex. Black and Fazio (1973) first suggested that the gamma rays from the ρOph cloud were produced by cosmic-ray interactions with the dense gas in the cloud. Subsequent studies (see Bignami and Hermsen 1982, for review) indicate that cosmic-ray electron bremsstrahlung and decay of π^0 mesons produced by cosmic-ray nucleons can indeed account for the observed emission for both the ρOph and Orion clouds.

Pulsed gamma-ray emission has been observed only from the Crab and Vela pulsars and their spectra and light curves differ significantly from each other.

Observations of the Crab pulsar emission from 15 keV to 10 MeV were made from HEAO-1 (Knight 1981) and from 30 MeV to several GeV from SAS-2 (Kniffen et al. 1974) and Cos-B (Lichti et al. 1980). Conflicting reports of very high (> 500 GeV) energy emission are reviewed by Sreekantan (1981). The light curves of the Crab pulsed emission are remarkably similar at all wavelengths, radio, optical, X-ray and gamma-ray, showing two peaks ~ 0.4 phase apart. The relative intensity of the peaks, however, varies with wavelength and also with time (Wills et al. 1981) at gamma-ray energies > 50 MeV. The overall spectrum of the Crab pulsar indicates that its peak luminosity occurs at several MeV (Knight 1981).

Gamma-ray emission from the Vela pulsar has been confirmed only in the energy range from 50 MeV to several GeV by detectors on SAS-2 (Thompson et al. 1975) and COS-B (Lichti et al. 1980). No pulsed emission was detected at 15 keV to 10 MeV by HEAO-1 (Knight 1981) and there are conflicting reports of emission at > 500 GeV (see Sreekantan 1981). Unlike the Crab, the Vela light curves in the radio, optical and gamma-ray bands differ greatly from one another and the resultant spectrum is more strongly peaked in the gamma-ray range with a peak luminosity at $\gtrsim$ 1 GeV.

The emission process responsible for the pulsed gamma rays is still uncertain, but the most likely, and certainly the best studied, process is curvature radiation. This emission is produced by charged particles moving along intense (~ 10^{12} gauss), curved magnetic field lines near the polar caps of the neutron star. The particles are accelerated by electric fields induced by the star's rotation. This source of pulsar gamma-ray emission was first suggested by Sturrock (1971) and more detailed models have since been developed (e.g. Ayasli 1981, Harding 1981b) that give good fits to the observed spectra from about 50 MeV to several GeV.

Alternative emission processes for the pulsed gamma rays have been suggested. These include synchrotron emission (Hardee 1979) and Compton scattering (Schlickeiser 1980, Kundt and Krotscheck 1980) of synchrotron photons by ultrarelativistic electrons. These particles could be accelerated (Hardee 1979) in electric fields associated with the breakdown of corotation in the magnetosphere at the light circle where the corotation velocity approaches the speed of light. Details of the geometry responsible for the light curves and their energy and time variation remain a problem in all of the models.

The peculiar source Cygnus X-3 has been studied in radio, infrared, X-rays and gamma-rays (see Stepanian 1981, for review). The emission shows a 4.8 hour modulation, attributed to eclipsing of the source, or to rotation or precession of an emission beam. Gamma-ray emission at > 40 MeV with this modulation period has been detected (Galper et al. 1977, Lamb et al. 1977) from the source for about six months following a giant radio outburst in

September, 1972, but not subsequently (Bennett et al. 1977). At much higher energies (>10^3 GeV), however, gamma-ray emission modulated with the 4.8 hour period has been steadily observed (e.g. Neshpor et al. 1981) since 1972.

There is no generally accepted model of Cygnus X-3 (see Stepanian 1981, and Bignami and Hermsen 1982, for review), but most involve a rapidly rotating neutron star with a close binary companion from which gas may be accreted. The proposed gamma-ray emission processes include those suggested for pulsars as well as decay of π^0 mesons produced by accelerated accreting matter.

In addition to these known objects, several other localized sources of gamma-ray emission have been reported (Swanenburg et al. 1981) which have not yet been identified with any known astronomical object. The most intense of these unidentified sources, CG195+4 first observed by SAS-2 (Hartman et al. 1976), is in fact the second brightest source in the sky at energies > 10 MeV. Some if not all of these could be unidentified pulsars or dense clouds.

5. EXTRAGALACTIC GAMMA RAYS

Gamma rays have been observed from a few extragalactic objects (see Dean and Ramsden 1981, for review). In addition, there also is a diffuse background which on a coarse scale appears to be isotropic (Trombka et al. 1977, Fichtel, Simpson and Thompson 1978). The discrete extragalactic sources are nearby active galaxies of various types, and the diffuse background could be, at least in part, unresolved emission from similar galaxies at cosmological distances. We first discuss the observations of discrete sources and their implications.

5.1 Discrete Extragalactic Sources

There are a variety of very luminous extragalactic objects which are generally referred to as active galaxies (e.g. Hazard and Mitton 1979). This class of objects contains radio galaxies, Seyfert galaxies, BL Lacertae objects and quasars. Gamma rays have been observed from some of the brightest of these objects: the radio galaxy Centaurus A (Grindlay et al. 1975, Hall et al. 1976, Baity et al. 1981), the Seyfert galaxy NGC 4151 (Perotti et al. 1979, 1981) and the quasar 3C273 (Swanenburg et al. 1978, Bignami et al. 1981).

Active galaxies have been extensively observed in the radio, infrared, optical, ultraviolet and X-ray bands. In Figure 4 we have combined such observations with the gamma-ray observations for the three active galaxies from which gamma rays were seen. For Centaurus A, the radio measurements are from Kellermann (1974), Price and Stull (1975) and Beall et al. (1978); the infrared data are from Grasdalen and Joyce (1976); the optical measurements are from Kunkel and Bradt (1971); the X- and gamma-ray results up to a few MeV are from the HEAO-1 observations of Baity et al. (1981); the gamma-ray upper limits around 100 MeV are from the SAS-2 observations of Bignami et al. (1979); and the gamma-ray measurement above a few hundred GeV is from the atmospheric Cerenkov light observations of Grindlay et al. (1975). For NGC 4151 the radio observations are from Haynes (1975), the infrared and visible data are from Rieke and Lebofsky (1979); the X- and gamma-ray data and limits up to several MeV are from the summary of White et al. (1980); and the gamma-ray limits at ~ 100 MeV and ~ 100 GeV are, respectively, from Bignami et al. (1979) and Porter and Weekes (1979). For 3C273, the radio data are from Kellermann and Pauliny-Toth (1969); the infrared and visible measurements are from Rieke and Lebofsky (1979); the ultraviolet observations are from Boggess et al. (1979); the X-ray data are from Worrall et al. (1979) and Bradt et al. (1979); the ~ 100 MeV gamma-ray observations are from Bignami et al. (1981); and the high energy gamma-ray upper limits are from Porter and Weekes (1978).

The spectra are plotted as dL/dlnE in Figure 4 in order that the relative luminosity at various photon energies can be easily compared. As can be seen, the luminosities in the radio galaxy Centaurus A, the Seyfert galaxy NGC4151 and the quasar 3C273 all peak at gamma-ray energies somewhat above 0.1 MeV suggesting that observations in these energy regions can directly probe the central source of power of these objects. Moreover, this result is apparently not limited to just these three objects. A sample (Boldt 1981) of nearly 20 active galaxies observed in the 3 to 50 keV range all show differential luminosities, dL/dlnE, that increase with increasing photon energy demonstrating that the luminosities of these active galaxies also peak at energies at least as high as 50 keV.

A likely source of energy in active galaxies is accretion onto a massive black hole (Lynden-Bell 1969). The luminosity that can be extracted from such accreting matter is not expected to significantly exceed the Eddington limit, $L_E = 4\pi GMm_pc/\sigma_T \simeq 1.2\text{x}10^{38}\ M/M_\odot$ erg/sec, where G is the gravitational constant, m_p is the proton mass, σ_T is the Thompson cross section and $M_\odot$ is the mass of the Sun. If the isotropic luminosity of an accreting object were to substantially exceed L_E, the radiation pressure due to the emergent radiation would be larger than the gravitational attraction on the infalling gas and accretion would stop. The luminosities of 10^{46}, 10^{43} and 10^{42} erg/sec for 3C273, NGC4151 and Centaurus A, respectively, would thus imply accreting black holes with masses in excess of 10^8, 10^5 and 10^4 $M_\odot$.

Upper limits on the sizes of the X-ray emitting regions in active galaxies can be obtained from observed time variations (Marshall, Warwick and Pounds 1981, Tennant 1981). The source sizes should be less than $c\Delta t$, where Δt is the time scale of the variability. Using such arguments, Bassani and Dean (1981) have set upper limits on the sizes of the X-ray sources in a number of active galaxies, including 3C273 and NGC415. For both these objects they find $c\Delta t \lesssim 10^{15}$cm. These limits are consistent with the minimal size of the emitting region which clearly is the Schwarzschild radius of the hole, $r_s = 2GM/c^2 \approx 3\times10^5(M/M_\odot)$ cm. Using the lower limits set on M by the Eddington limit, we see that at least for 3C273 the size of the X-ray source is not much larger than the minimal Schwarzschild radius, i.e. $c\Delta t < 30r_s$. This is also consistent with the large observed luminosities of active galaxies which require the very efficient release of energy from accreted matter. Such energy release is possible in the deep potential well of the black hole close to its Schwarzschild radius.

Similar constraints could be set on the size of the gamma-ray emitting region, but the time variability of gamma-ray emission from active galaxies is only very poorly known. The fact that finite gamma-ray fluxes up to an MeV were reported from NGC4151 on two occasions (Perotti et al. 1979, 1981), but only lower upper limits were reported at essentially the same energies on another occasion (White et al. 1980), can be interpreted as a time variation. On the other hand, 3C273 was observed twice with the instrument on COS B (Swanenburg et al. 1978, Bignami et al. 1981), and both observations yielded essentially the same gamma-ray flux at ~ 100 MeV.

Independent information on the nature of the gamma-ray sources, however, can be obtained from considerations of opacity due to photon-photon pair production. The optical depth to gamma rays of the X-ray source region can be estimated from the observed X-ray luminosity and the upper limits on the source size obtained from the observed variability. Thus, Bassani and Dean (1981) find that for isotropic X-ray emission, 3C273, as well as several other quasars, should be opaque to essentially all gamma-rays of energies greater than the pair-production threshold (0.511 MeV). But since ~ 100 MeV gamma rays have been observed from 3C273 (Swanenburg et al 1978, Bignami et al.

1981), either the X-ray emission is beamed or the gamma-ray source is much larger than the X-ray source (>> 10^{15} cm). A large gamma-ray source region in 3C273 would be consistent with the apparent lack of variability of the ~ 100 MeV gamma-ray luminosity inferred from the two Cos B observations of 3C273 (Swanenburg et al. 1978, Bignami et al. 1978). On the other hand, Bassani and Dean (1981) find that the X-ray sources in Seyfert galaxies are transparent to all gamma rays up to a GeV, so that for these objects the X-ray and gamma-ray sources could be of the same size. Clearly more data are required on the time variability of the gamma-ray emission from active galaxies.

Several radiation mechanisms could be responsible for gamma-ray productions in active galaxies. At least some of the gamma rays could be produced by the same mechanisms that produce the X-rays (e.g. Fabian 1979): bremsstrahlung from a hot (~ 10^9K) gas, Comptonization of cool photons and the synchrotron self-Compton model.

In addition, there are mechanisms which operate only in the gamma-ray region. As we have already seen, e^+-e^- pair production in photon-photon collisions could be important in active galactic nuclei. If the resultant pairs annihilate in an optically thin region, the annihilation radiation should be observable. In the nucleus of our Galaxy, e^+-e^- pairs annihilate in a relatively cool region thereby producing a sharp line at 0.511 MeV (Section 4.1). In an active galaxy, however, the annihilation region could be much hotter in which case the line would be both broadened and blueshifted (Ramaty and Mészáros 1981) and thus could produce a photon excess around an MeV. This effect would explain the absence of a narrow 0.511 MeV line from the spectrum of Centaurus A (Hall et al. 1976, Baity et al. 1981) and possibly account (D. Leiter, private communication 1981, Bassani and Dean 1982) for the reported (Perotti et al. 1981) photon excess around 1 MeV in NGC 4151.

Gamma rays in the MeV region could also be due to Penrose Compton scattering (Piran and Shaham 1977, Leiter and Kafatos 1978, Leiter 1980). Here the scattering takes place in the ergosphere (Penrose 1969) of a rapidly rotating black hole where blueshifted X-ray photons from an accretion disk could interact with transient matter. If a Compton scattered electron is knocked into the hole's event horizon, the photon picks up rotational energy from the hole and can emerge into free space as a gamma ray. Both e^+-e^- pair annihilation and Penrose Compton scattering predict a break in the photon energy spectrum above a few MeV, consistent with observations (Bignami et al. 1979).

The ~ 100 MeV gamma rays in 3C273 could result from π^0 meson decay. However, the observed photon energy spectrum of 3C273 (Bignami et al. 1981) is much steeper than that predicted from π^0 meson decay produced by galactic cosmic-ray interactions. This difference could indicate a different energetic particle spectrum in active galactic nuclei from that in our Galaxy, or could be caused by photon-photon absorption in the more compact source region of an active galaxy.

5.2 Diffuse Extragalactic Emission

The diffuse gamma-ray background was first observed in the energy range from about 0.1 to 2 MeV by detectors on the lunar probes, Rangers 3 and 5, (Arnold et al. 1962, Metzger et al. 1964) and at ~ 100 MeV by a detector on the OSO-3 spacecraft (Clark, Garmire and Kraushaar 1968, Kraushaar et al. 1972). Subsequent observations have been carried out by a number of observers (see Horstman, Cavallo and Moretti-Horstman 1975, for review). In particular, the background has been studied in the 0.3 to 10 MeV range with detectors on several Apollo missions (Trombka et al. 1977) and from about 30 to 150 MeV by the instrument on the SAS-2 spacecraft (Fichtel, Simpson and Thompson 1978).

The spectrum of the diffuse background from a few keV to about 100 MeV is shown in Figure 5 (Trombka et al. 1977, Fichtel, Simpson and Thompson 1978, Marshall et al. 1980, Rothschild 1982). As can be seen, there is considerable structure to this spectrum. The X-ray background below ~ 50 keV can be well fitted by a thermal bremsstrahlung spectrum with kT ≃ 40 keV (Boldt 1981), but at higher energies much more radiation exists than would be predicted by this spectrum.

Estimates (Marshall et al. 1980) of the contribution of Seyfert galaxies to the background up to ~ 50 keV indicate that these galaxies cannot account for the X-ray background. But if the spectra of the Seyfert galaxies extend into the MeV region, as indicated by the observations of Perotti et al. (1979, 1981), then the combined contribution of such galaxies could account (Strong, Wolfendale, Worrall 1976, Bignami et al. 1979) for the bulk of the gamma-ray background at least up to a few MeV. Furthermore, if at earlier stages in their evolution Seyfert galaxies were more luminous than at the present epoch and if their spectra were thermal (kT ~ 200 keV), then these objects could also account for the X-ray background (Leiter and Boldt 1982). Active galaxies could account for the background at the high energies as well, since the steepening of the background spectrum above a few MeV (see Figure 5) is qualitatively similar to the steepening of the energy spectra of individual active galaxies (Bignami et al. 1979), and the background spectrum at ~ 100 MeV has essentially the same spectral index (2.7±0.4, Fichtel, Simpson and Thompson 1978) as that of 3C273 (2.5±0.6, Bignami et al. 1981).

Several other explanations have been put forth for the origin of the diffuse gamma-ray background (e.g. Silk 1970, Horstman, Cavallo and Moretti-Horstman 1975). We mention here, in particular, the possibility of producing the background from matter-antimatter annihilation at the boundaries of superclusters in a baryon-symmetric cosmology (Stecker, Morgan and Bredekamp 1971, Stecker 1978). Here the characteristic peak of the π^0 decay spectrum at 67 MeV is redshifted by the expansion of the universe to about an MeV.

The principal difficulty of a baryon-symmetric cosmology concerns the present photon-to-baryon ratio in the universe (Steigman 1976). In a well-mixed symmetric universe, the bulk of the matter and antimatter is expected to annihilate at a very early stage, leading to a present photon-to-baryon ratio of $\sim 10^{18}$. This is in contrast to the observed ratio of $\sim 10^9$ (e.g. Steigman 1976). Brown and Stecker (1979), however, point out that symmetry breaking in Grand Unified Field theories could produce domains of predominantly matter or antimatter, which, while conserving the overall symmetry of the universe would greatly reduce the early cosmological annihilation rate and thereby lead to a present photon-to-baryon ratio consistent with observations. The problems of the production and growth of these domains in the early universe was discussed recently by Sato (1981) and by Kuzmin, Shaposhnikov and Tkachev (1981).

6. SUMMARY

We have reviewed observations of cosmic gamma rays, the physical processes responsible for their production and the astrophysical sites from which they were seen or are expected to be observed in future observations. The bulk of the observed gamma-ray emission is in the photon energy range from about 0.1 MeV to 1 GeV, where observations are carried out above the atmosphere by instruments on balloons and spacecraft. There are also, however, gamma-ray observations at higher energies ($\gtrsim$ 100 GeV) obtained by detecting the Cerenkov light produced by the high-energy photons in the atmosphere.

Gamma-ray emission has been observed from sources as close as the Sun and the Moon and as distant as the quasar 3C273, as well as from various other galactic and extragalactic sites. The radiation processes also range from the well understood, e.g. energetic particle interactions with matter, to the still incompletely researched, such as radiation transfer in optically thick electron-positron plasmas in intense neutron star magnetic fields. It is hoped that future studies of the gamma-ray sky will reveal much new information on both the properties of astronomical objects and the high-energy processes that take place in them.

ACKNOWLEDGMENTS

We wish to acknowledge financial support from NASA Grant NSG 7541 and The Solar Terrestrial Theory Program. We also acknowledge discussions with E. A. Boldt, E. L. Chupp, A. K. Harding, C. E. Fichtel, J. C. Higdon, D. A. Kniffen, D. Leiter, R. E. Rothschild and F. W. Stecker.

FIGURE CAPTIONS

1. The observed and calculated energy spectrum of the March 5, 1974 gamma-ray burst (from Liang 1981). The observations are from Mazets et al. (1979), the solid curve is the synchrotron and annihilation spectrum of an e^+-e^- plasma (from Ramaty et al. 1980) and the dashed curve is the spectrum resulting from the Compton scattering of the synchrotron photons by the energetic e^+-e^- pairs.

2. The energy spectrum of the Galactic Center region observed by Leventhal, MacCallum and Stang (1978). The solid curve is the continuum produced by triplet positronium annihilation in addition to a power-law X-ray continuum as indicated by the dashed curve.

3. Diffuse gamma-ray production rates by galactic cosmic rays in the vicinity of the solar system and the contribution of pulsars (from Harding and Stecker 1981).

4. The energy spectra of three active galaxies. The origin of the data is given in the text.

5. The diffuse X-ray and gamma-ray background spectrum. The origin of the date is given in the text.

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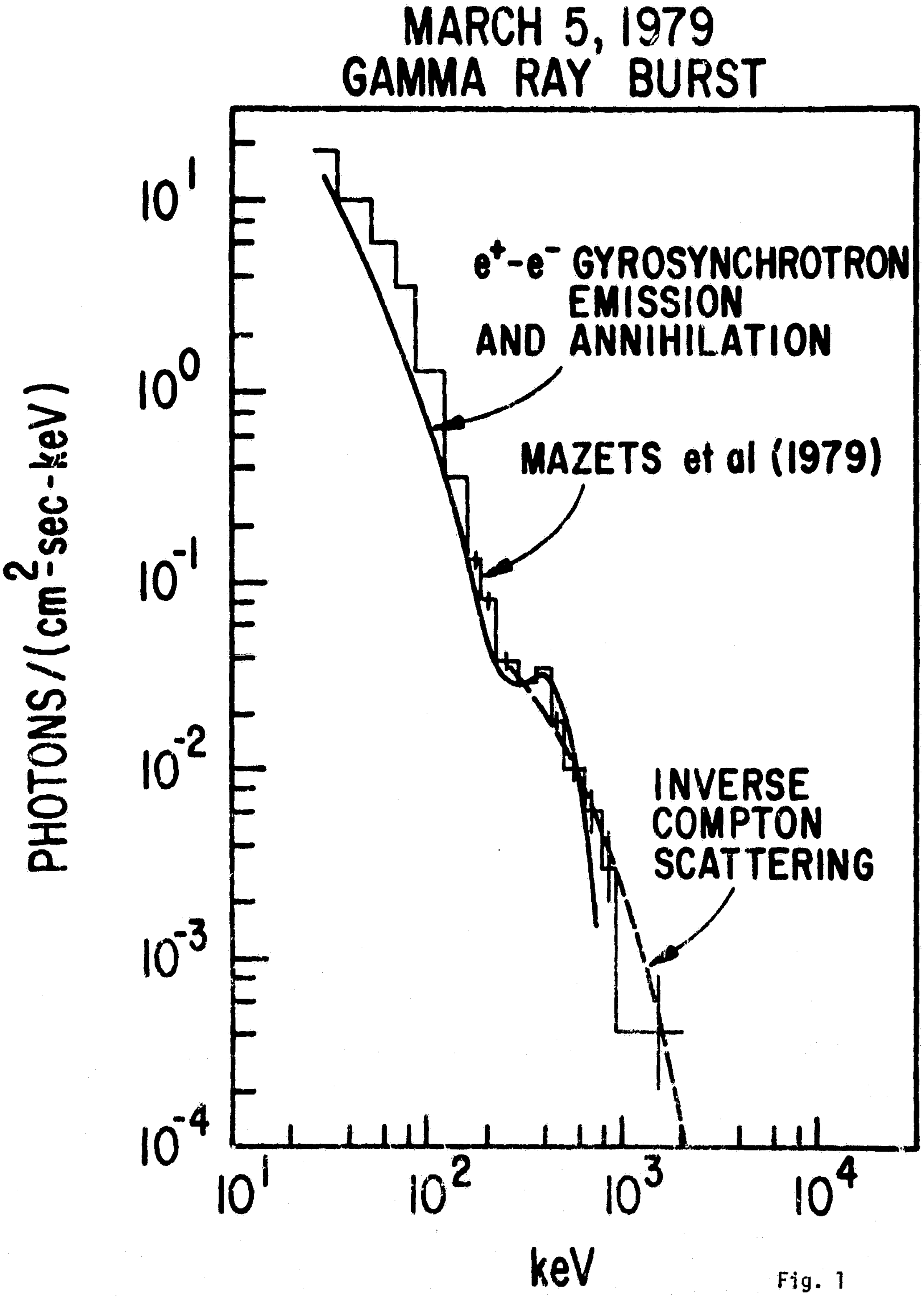

MARCH 5, 1979
GAMMA RAY BURST
PHOTONS/(cm^2-sec-keV)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
10^4
keV
e^+-e^- GYROSYNCHROTRON EMISSION AND ANNIHILATION
MAZETS et al (1979)
INVERSE COMPTON SCATTERING

Fig. 1

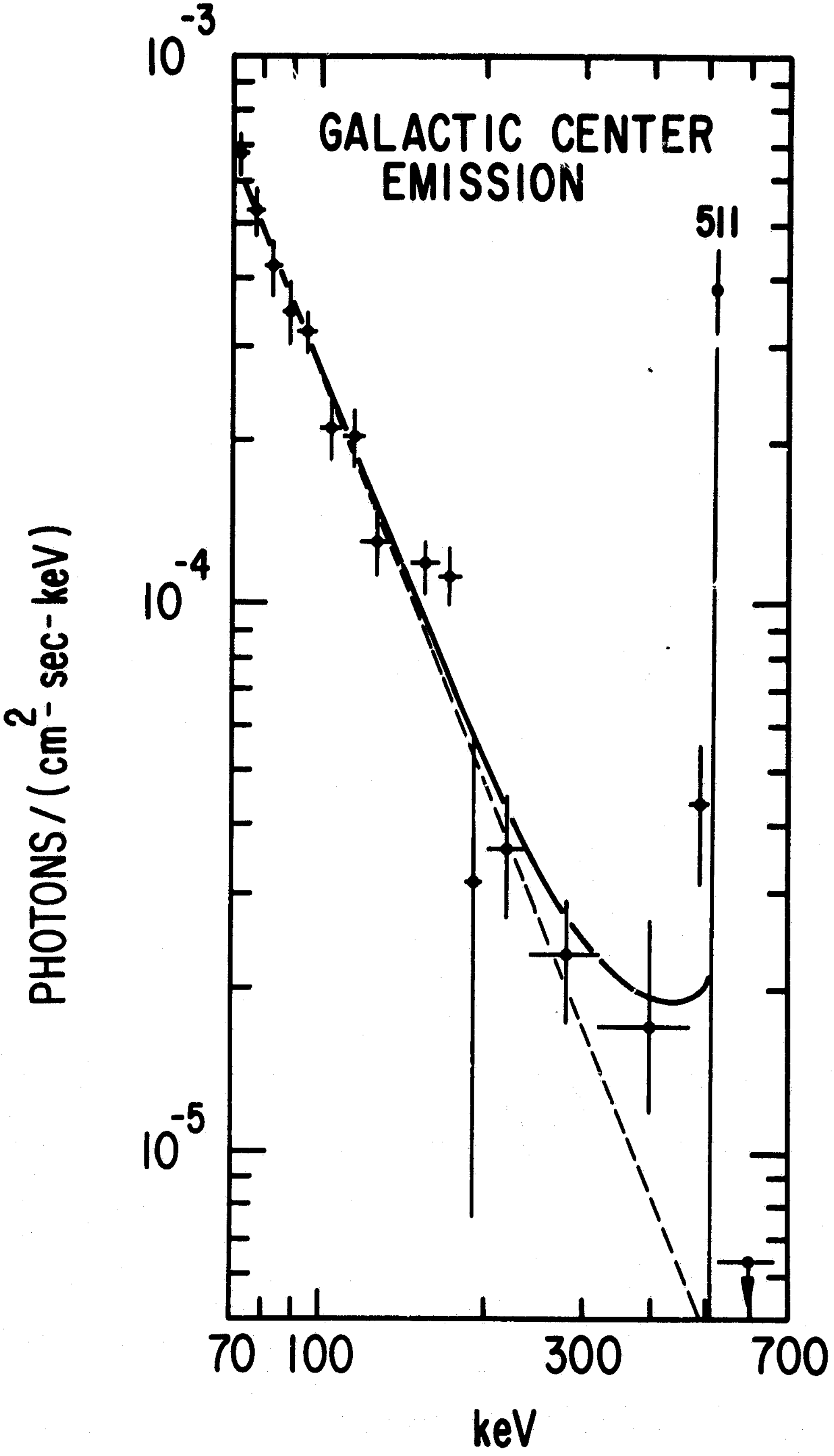

GALACTIC CENTER EMISSION
511
10^{-3}
10^{-4}
10^{-5}
PHOTONS/(cm^2-sec-keV)
70
100
300
700
keV

Fig. 2

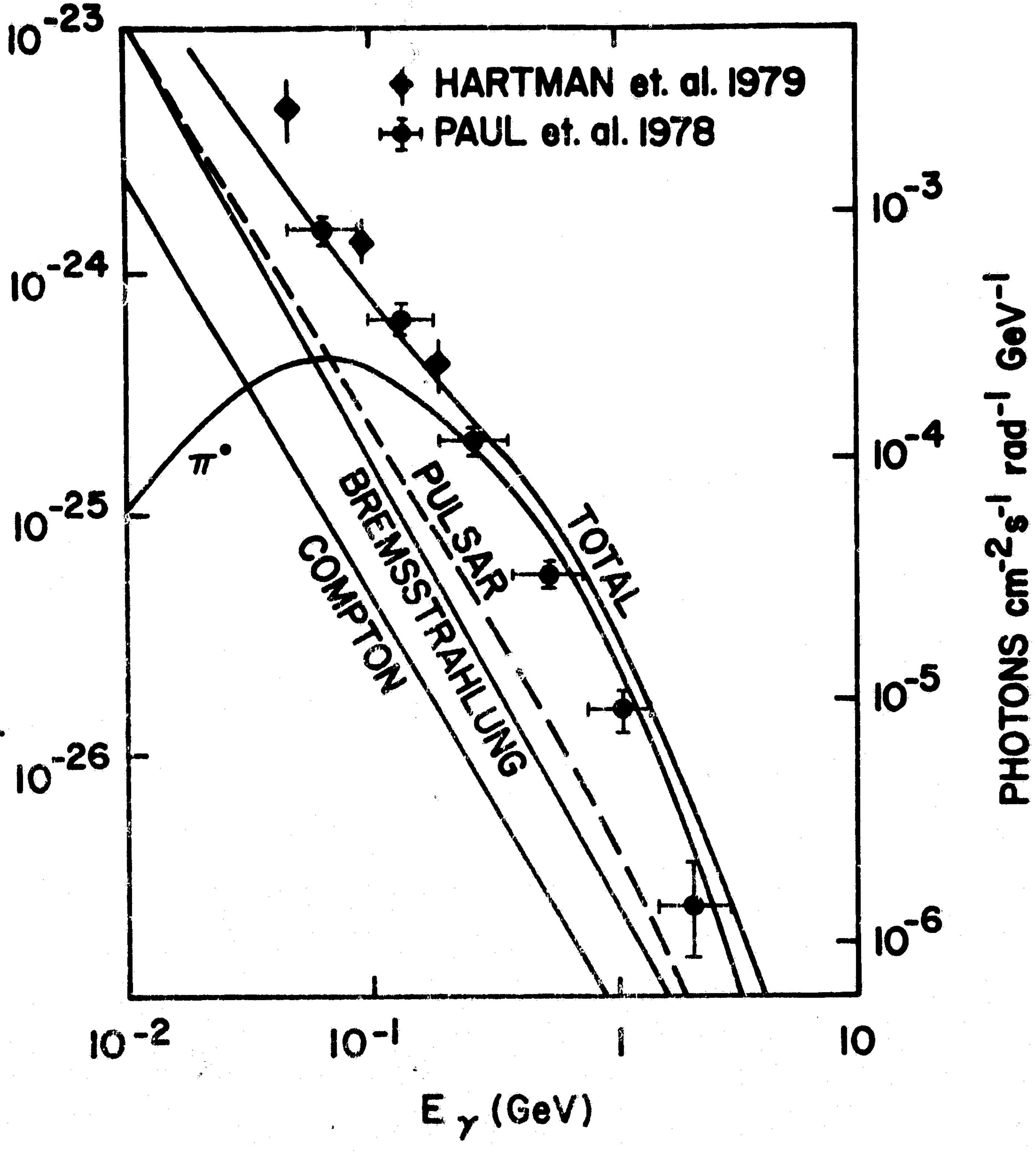
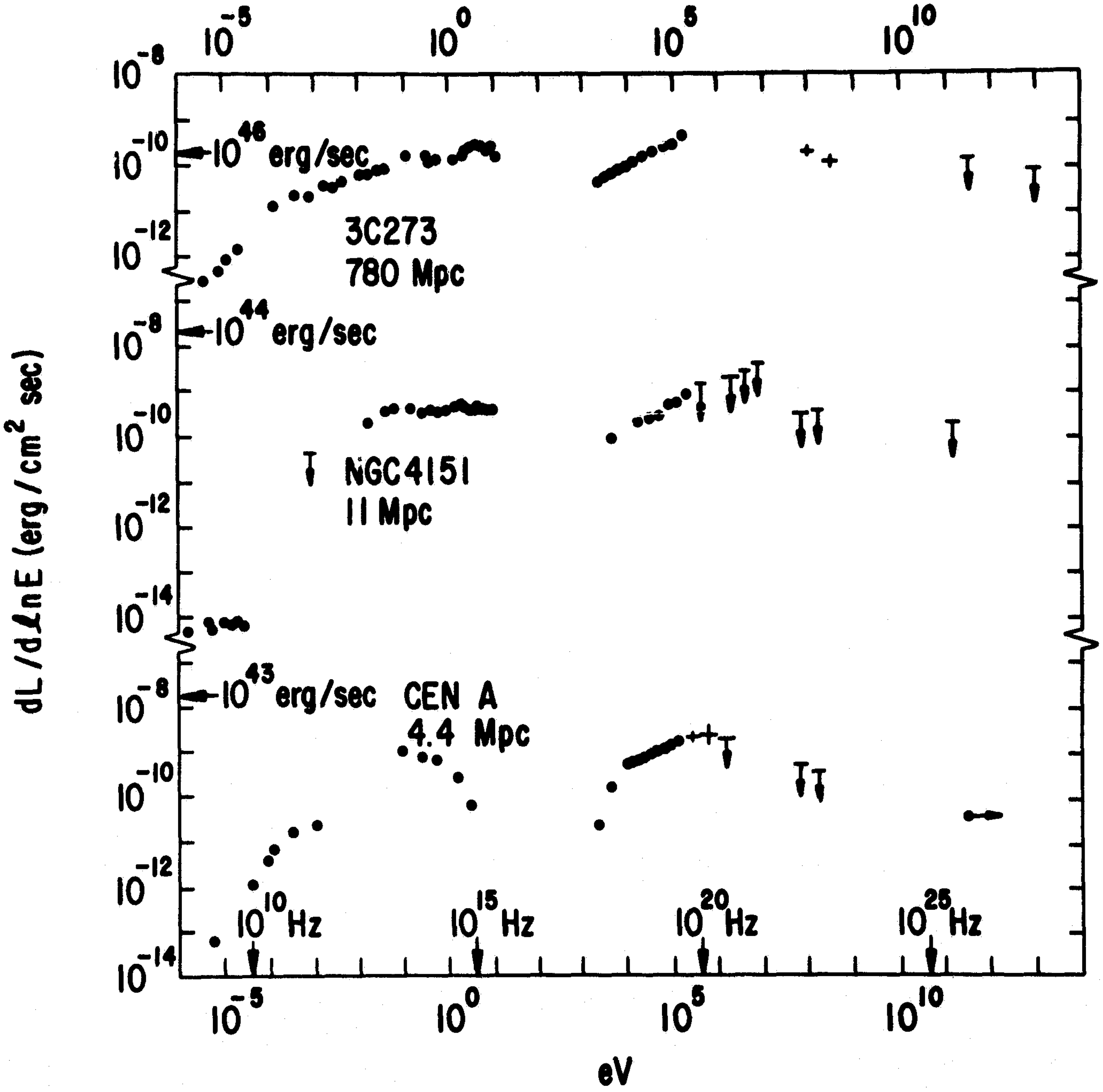

HARTMAN et. al. 1979
PAUL et. al. 1978
10^{-23}
10^{-24}
10^{-25}
10^{-26}
$Q(E_\gamma)$ (PHOTONS cm^{-3}s^{-1} GeV^{-1})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
PHOTONS cm^{-2}s^{-1} rad^{-1} GeV^{-1}
π°
TOTAL
PULSAR
BREMSSTRAHLUNG
COMPTON
10^{-2}
10^{-1}
1
10
E_γ (GeV)

Fig. 3



10^{-5}
10^{0}
10^{5}
10^{10}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{46} erg/sec
3C273
780 Mpc
10^{44} erg/sec
NGC4151
11 Mpc
10^{43} erg/sec
CEN A
4.4 Mpc
10^{10} Hz
10^{15} Hz
10^{20} Hz
10^{25} Hz
dL/dℓnE (erg/cm^2 sec)
eV

Fig. 4

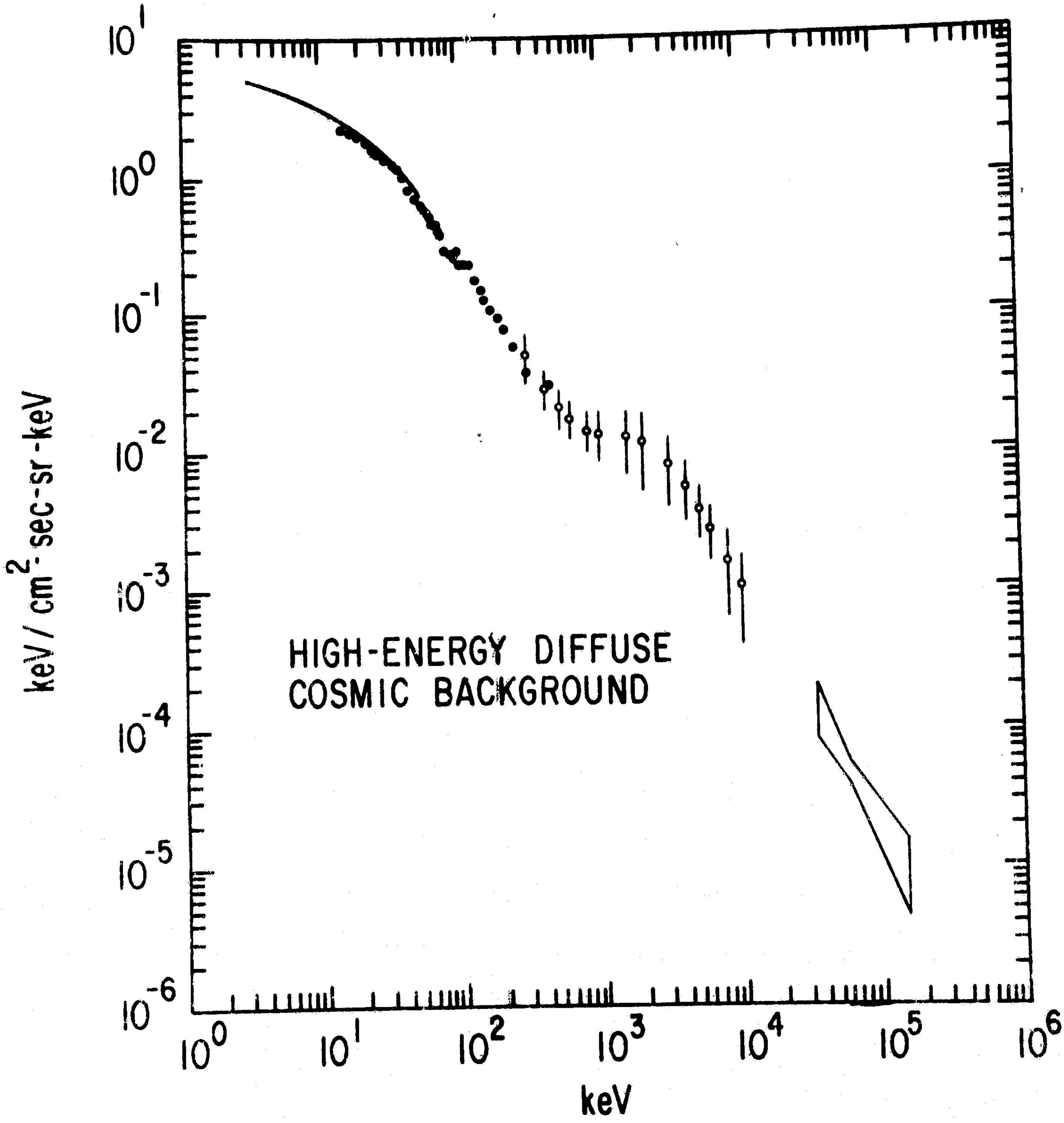

keV/cm^2-sec-sr-keV
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
HIGH-ENERGY DIFFUSE
COSMIC BACKGROUND
10^0
10^1
10^2
10^3
10^4
10^5
10^6
keV

Fig. 5