GAMMA-RAY LINE ASTROPHYSICS

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ABSTRACT

We review recent observations of gamma-ray line emission from solar flares, gamma-ray bursts, the galactic center, the interstellar medium and the jets of SS433, and we discuss the implications of these observations on high energy processes in these sources.

INTRODUCTION

Gamma-ray line astrophysics has developed rapidly in recent years with exciting new observations by gamma-ray spectrometers on balloons and on the HEAO, Venera, Hinotori and SMM satellites and space probes. These observations are providing unique new insights into a wide range of problems in high energy astrophysics and cosmic rays.

The relationship between gamma-ray and cosmic ray studies, of course, goes back to the very earliest observations. When Victor Hess[1] discovered the extraterrestrial origin of atmospheric ionization in 1912 he suggested that it was caused by high energy gamma rays from outside the solar system and hence named them "cosmic rays." But in 1927 on a voyage from Java to Genoa, Clay[2] discovered that the intensity of cosmic rays varied with geomagnetic latitude and thus they were charged particles not gamma rays. Extraterrestrial gamma rays were finally discovered over thirty years later when Peterson and Winckler[3] observed gamma-ray emission from a solar flare with a balloon-borne detector in 1959. Three years later Arnold et al.[4] discovered the diffuse extragalactic gamma-ray emission with a detector on the Ranger probe.

Gamma-ray astronomy has grown rapidly since then and at this conference fully one-fifth of the contributed paper sessions are devoted to gamma-ray observations and theory.

Recent developments in gamma-ray spectroscopy have revealed a diversity of gamma-ray lines in the spectra of astrophysical sources. The wide range of these observed lines, processes and sources can be seen in Table 1.

Although we reviewed[5] all of gamma-ray astronomy just three years ago, there have been a number of important new observations since then that need to be discussed here. In particular, gamma-ray spectra from solar flares have been observed[6] in much greater detail by the spectrometer on the Solar Maximum Mission (SMM), providing new information on both the flare accelerated particles and on chemical abundances in the solar atmosphere. A gamma-ray line from radioactive ^{26}Al was seen[7] from the interstellar medium by a high-resolution spectrometer on the Third High Energy Astronomical Observatory (HEAO-3), providing new information on processes of explosive nucleosynthesis in the Galaxy. Gamma-ray lines have been reported[8] also by HEAO-3 from the compact galactic object SS433, possibly providing clues to the understanding of the acceleration of the jets that are revealed by optical and radio observations. We will review all of these and other important sources of gamma-ray line emission.

Table 1
OBSERVED ASTROPHYSICAL GAMMA RAY LINES

Observed Lines	**Processes**	**Sources**
Cyclotron emission & absorption ~50 keV	Emission & absorption by electrons in $\gtrsim 10^{12}$ gauss magnetic fields	Gamma-ray bursters X-ray pulsars Crab pulsar(?) (magnetic neutron stars)
$e^{\pm}$ pair annihilation radiation 0.511 MeV	$e^+e^- \rightarrow 2\gamma$ by e^+ from: $\gamma\gamma \rightarrow e^+e^-$ $\gamma e^- \rightarrow e^-e^+e^-$ $\gamma B_\perp \rightarrow B_\perp e^+e^-$ β^+ decay $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay	Solar flares (accel. particle interactions) Galactic center (accreting black hole) Gamma-ray bursters (magnetic neutron stars)
Nuclear deexcitation 6.129 MeV 4.438 1.779 1.634 1.369 0.847	Inelastic excitation $^{16}O(p,p')^{16}O^*$ ^{12}C . . . ^{28}Si . . . ^{20}Ne . . . ^{24}Mg . . . ^{56}Fe . . .	Solar flares (accel. particle interactions) SS433 jets (jet nuclei interactions)
1.809 MeV	Radioactive decay $^{26}Al(\beta^+)^{26}Mg^*$	Interstellar gas (explosive nucleosynthesis)
Radiative capture 2.223 MeV 7.632 7.646	Neutron capture $^{1}H(n,\gamma)^{2}H$ $^{56}Fe(n,\gamma)^{57}Fe$	Solar flares (accel. particle interactions) Jacobson transient (accreting neutron star?)

SOLAR FLARES

Recent observational and theoretical studies of gamma rays and neutrons from solar flares have provided new insights into the problem of particle acceleration and have given new information on the composition of the solar atmosphere. These results have been discussed in a number of recent papers (e.g. Refs. 6, 9-12). The gamma-ray lines and neutrons result from nuclear interactions of accelerated protons and heavier nuclei, while the continuum is due to relativistic electron bremsstrahlung and the superposition of Doppler-broadened gamma-ray lines.

Theoretical studies predicted[13] that the principal gamma-ray lines should be those at 2.223 MeV from neutron capture on ^{1}H, at 0.511 MeV from positron annihilation, and at 4.438 and 6.129 MeV from deexcitation of nuclear levels in ^{12}C and ^{16}0, respectively. These predictions were confirmed when gamma rays were first observed[14] with a detector on OSO-7 from the solar flare of 4 August 1972. These and other weaker lines have since been observed from more than 30 flares by detectors on HEAO-1[15] HEAO-3[16], Hinotori[17] and most extensively SMM[6,10,18]. Neutrons from solar flares have also been observed, confirming earlier predictions (e.g. Ref. 19). The neutron observations consist of direct spacecraft[20,21] and ground based[22,23] detections, as well as of the measurement[24] of the protons resulting from the decay of the neutrons in interplanetary space.

Energetic particles from solar flares have been observed in interplanetary space on numerous occasions, but there is clear evidence that the nuclear interactions that produce the gamma rays and neutrons are caused by accelerated particles that remain trapped in the magnetic fields of the flare region and interact as they slow down in the solar atmosphere. This is most clearly seen (e.g. Ref. 25) by the fact that, if the escaping particles were responsible for the observed gamma-ray emission, they should also show great enrichments in spallation products, such as ^2H, ^3H, Li, Be and B, which are not observed[26].

Further evidence for this trapping comes from the comparison of the number of particles required to produce the observed gamma rays and neutrons with the number of escaping particles, and from the comparison of the number of positrons produced at the Sun with the observed flux in the 0.511 MeV line.

The number of gamma-ray producing particles can be derived from measurements of the neutron-capture line at 2.2 MeV and the photon flux in the 4 to 7 MeV band, which is dominated[27,28] by C and O deexcitation lines. Since the effective threshold for neutron production is significantly higher than that for C and O excitations, the 2.2 MeV line and the 4 to 7 MeV band sample different portions of the accelerated particle spectrum. The ratio of the fluxes in the 2.2 MeV line and in the 4 to 7 MeV band therefore constrains the particle spectrum, while the 4 to 7 MeV flux determines the particle number. Results for several flares from which gamma rays were observed are summarized in Table 2. The spectral indexes and total proton numbers at the Sun are given for two possible forms for the accelerated particle energy spectra, a power law in kinetic energy and a Bessel function. For the former, the number of accelerated particles per unit kinetic energy is proportional E^{-S}, where E is particle kinetic energy. For the latter, this number is proportional to $K_2(12p/m_pc\alpha T)^{1/2}$, where p is particle momentum per nucleon and αT an index characterizing the hardness of the spectrum. A power law in kinetic energy is the nonrelativistic approximation of a power law in momentum, which is the spectral form expected (e.g. Ref. 29) from first order shock acceleration at a planar and infinite shock. The Bessel-function spectrum is the nonrelativistic approximation to the spectrum expected from stochastic acceleration[30]. Nonrelativistic approximations are adequate for calculations involving protons and nuclei, since the bulk of the nuclear reactions in flares occur at energies much lower than m_pc^2.

Table 2
ENERGETIC PARTICLE PARAMETERS IN SOLAR FLARES[11]

	In Solar Atmosphere				**Interplanetary**	
	Bessel Function		Power Law			
FLARE	αT	N_p (>30 MeV)	S	N_p (>30 MeV)	Spectral Index	N_p (>30 MeV)
	Determined from Gamma-Ray Line Measurements					
4 Aug. 1972	0.029±0.004	1.0×10^{33}	3.3±0.2	7.2×10^{32}	–	4.3×10^{34}
11 Jul. 1978	~0.032	1.6×10^{33}	~3.1	1.3×10^{33}	–	–
9 Nov. 1979	0.018±0.003	3.6×10^{32}	3.7±0.2	2.6×10^{32}	–	–
7 Jun. 1980	0.021±0.003	9.3×10^{31}	3.5±0.2	6.6×10^{31}	$\alpha T \simeq 0.015$	8×10^{29}
1 Jul. 1980	0.025±0.006	2.8×10^{31}	3.4±0.2	1.9×10^{31}	–	$< 4 \times 10^{28}$
6 Nov. 1980	0.025±0.003	1.3×10^{32}	3.3±0.2	1.0×10^{32}	–	3×10^{29}
10 Apr. 1981	0.019±0.003	1.4×10^{32}	3.6±0.2	1.0×10^{32}	–	–
	Determined from Neutron and Gamma-Ray Line Measurements					
21 Jun. 1980	0.025±0.005	7.2×10^{32}	INCONSISTENT		$\alpha T \simeq 0.025$	1.5×10^{31}
3 Jun. 1982	0.034±0.005	2.9×10^{33}	INCONSISTENT		$s \simeq 1.7$	3.6×10^{32}

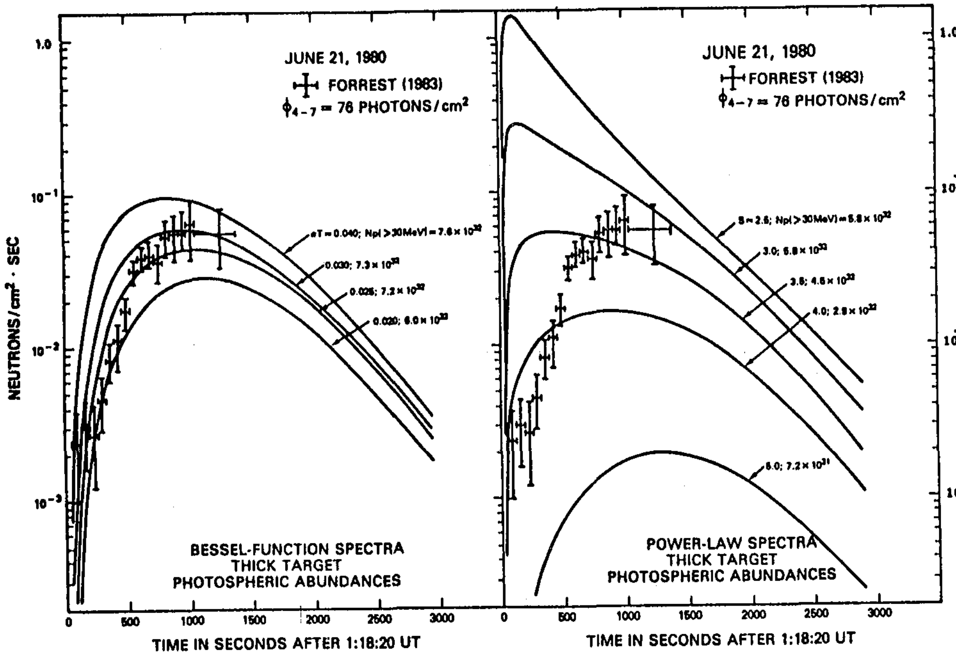

Fig. 1. Determination[11] of the number and spectrum of flare accelerated protons at the Sun from observations[6] of the time dependent neutron flux and the gamma-ray line emission in the 4-7 MeV range.

The number of neutron-producing particles and their energy spectrum can be derived from observations of the time-dependent neutron flux at Earth. For consistency, this number and spectrum must be the same as those derived from the gamma-ray observations. Observations of a time-dependent neutron flux for the flare of 21 June 1980 are shown in Figure 1 together with calculated fluxes. These fluxes are normalized such that the calculated 4 to 7 MeV flux agrees with the observed[6] flux in this energy band, ~76 photons/cm^2. It is evident that the combined neutron and gamma-ray emission cannot result from particles with a power-law spectrum. For, as we see from Figure 1, none of the combinations of power-law spectra and total particle numbers that could produce the observed 4-7 MeV flux can also produce a neutron flux consistent with that which was measured. As can also be seen in Figure 1, however, both observations are quite consistent with accelerated particles having a Bessel-function spectrum with $\alpha T \sim 0.025$ and a total number of 7×10^{32} protons >30 MeV. Qualitatively, the difference between this Bessel-function spectrum and a power-law in kinetic energy is the gradual steepening of the former as the energy increases. Shock acceleration can also produce[29] such a steepening, or high-energy cutoff, if the shock is of finite size and the acceleration is of finite duration. Thus, while these results cannot definitively determine the acceleration mechanism, they demonstrate that a consistent interaction model can be set up involving either one of them.

Comparing these results with those inferred from the direct particle observations (Table 2), we see that independent of the spectral form, the number of particles that produce the observed gamma rays and neutrons are generally much higher than the number of interplanetary particles from flares which produce detectable gamma rays. This implies that the gamma rays and neutrons are produced predominantly in closed magnetic configurations from which very few charged particles escape. As mentioned above, the absence of spallation products in the escaping particles indicates that this latter population is not involved in significant gamma-ray and neutron production. We discuss separately the implications of the exceptional

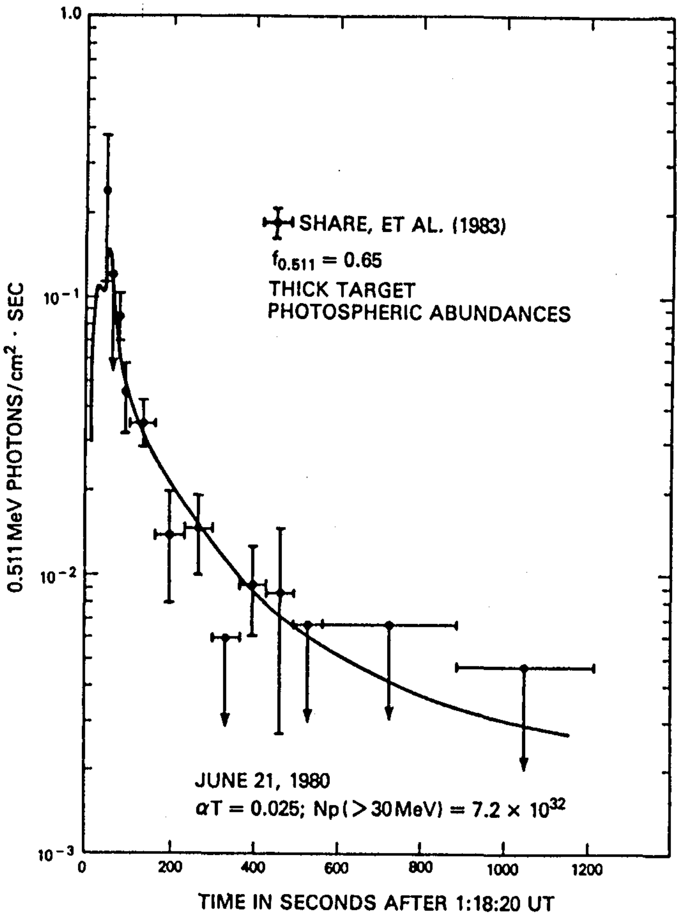

Fig. 2. Observed[31] 0.511 MeV line flux from the 21 June 1980 flare compared with that expected[11] from the number and spectrum of accelerated particles determined in Figure 1.

case of the 4 August 1972 flare for which the number of particles observed in interplanetary space was much larger than the number of trapped particles (Table 2).

Further evidence that the gamma rays are generally produced in closed magnetic configurations comes from the analysis of the time-dependent flux of the 0.511 MeV line from positron annihilation. This is shown in Figure 2 where observations[31] of the 21 June 1980 flare are compared with the calculated[11] 0.511 MeV flux. In these calculations the radioactive β^+ emitters and π^+ mesons were produced by accelerated particles with the same spectrum and total number as determined from the neutron and 4-7 MeV observations, and it was assumed that the positrons remain trapped at the Sun and annihilate essentially instantaneously. The agreement with the observations shown in Figure 2 strongly supports these assumptions. The trapping of the positrons is further evidence for the trapping of all the gamma-ray producing charged particles, while their short annihilation time implies a sufficiently high ambient density which suggests that the annihilation site, and hence also the interaction site, is in the chromosphere below the transition layer.

In addition to the 4 August 1972 flare, for which the number of interplanetary particles was much larger than that involved in gamma-ray production, there are many other flares[32]

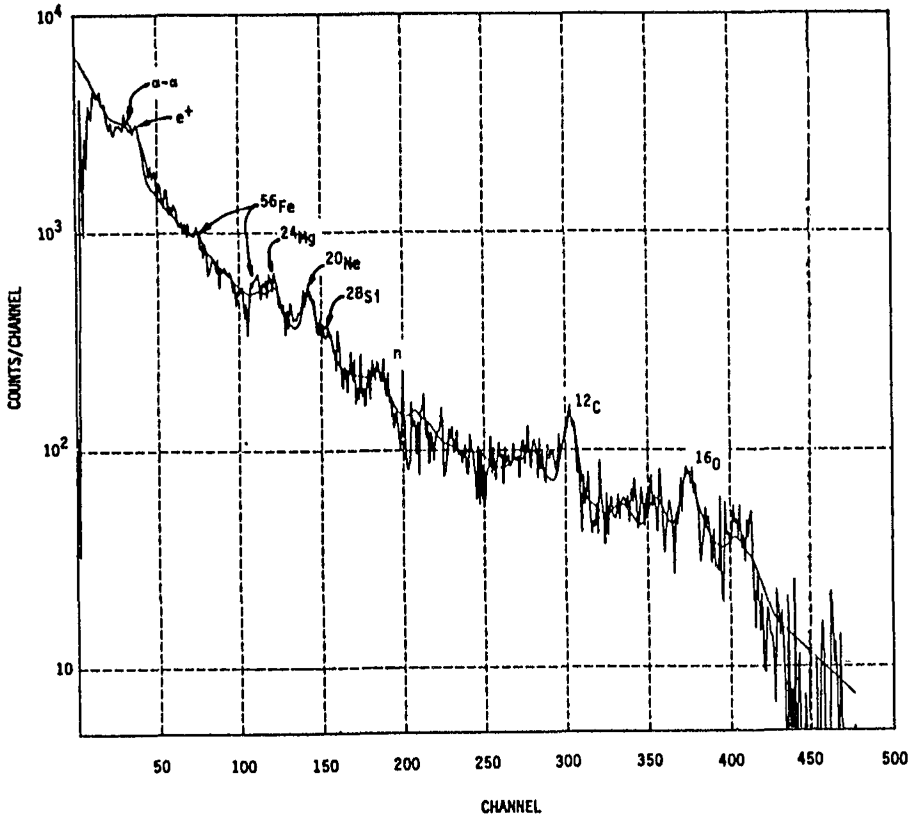

Fig. 3. Observed[6,10] and calculated[33] spectra of the 27 April 1981 flare.

which produce large fluxes of interplanetary particles without producing detectable gamma rays. These particles, always devoid of spallation products, are most likely accelerated at sites with ready access to interplanetary space.

We turn now to the determination of the relative composition of the solar atmosphere in the flare region from comparisons of the various deexcitation line intensities. A sample spectrum shown in Figure 3 was observed[6,10] from the 27 April 1981 flare by the gamma-ray spectrometer on the SMM. Nuclear reactions of accelerated protons and alpha particles with heavier nuclei in the ambient gas produce narrow lines, such as those shown at 6.129 MeV from deexcitation of $^{16}O^*$, 4.438 MeV from ^{12}C, 1.779 MeV from $^{28}Si^*$, 1.634 MeV from $^{20}Ne^*$, 1.369 MeV from $^{24}Mg^*$ and 0.847 MeV from ^{56}Fe. The inverse reactions, between accelerated heavy nuclei and ambient H and He, produce broad lines which effectively merge into a continuum. Also evident are the lines at 2.223 and 0.511 MeV. The feature just below the positron annihilation line results from reactions between accelerated alpha particles and ambient He nuclei leading to $^7Li^{*0.478MeV}$ and $^7Be^{*0.431MeV}$ line emission. The continuum, upon which the narrow lines are superimposed, is due to both relativistic electron bremsstrahlung and the Doppler broadened deexcitation lines of the accelerated heavy nuclei.

The relative intensities of the narrow nuclear deexcitation lines depend on several factors, such as the energy spectrum of the accelerated particles, but they are obviously most sensitive to the elemental abundances of the ambient gas in the interaction region. Even though the location of this region cannot be determined by direct gamma-ray imaging, a variety of indirect arguments, such as the time dependence of the 0.511 MeV line discussed above, indicate that most of the nuclear reactions take place in the chromosphere. The observed gamma-ray spectrum, therefore, can be used to infer chromospheric abundances. The most direct evaluation[12] consists of theoretical calculations of the spectrum with variations of the abundances until the best fit to the data is achieved. The resultant best-fitting spectrum[33] is shown by the smooth curve in Figure 3.

With the normalization given by the best-fit, the principal difference between the gamma-ray and local galactic[34] abundances is the underabundance of C and O in the gamma-ray deduced abundances. The Fe, Si, Mg and Ne abundances are in good agreement, while the statistical errors for Ca, S, Al and N and the systematic errors for H and He are too large to permit any quantitative conclusion (see Ref. 12). A similar suppression of C and O in the coronal abundances relative to local galactic abundances has been pointed out in Ref. 34 where it was suggested that the suppression may be caused by charge-dependent mass transport from the photosphere to the corona. Since the photosphere is collisionally ionized at a relatively low temperature, the transport could depend on the first ionization potentials of the elements. Mass transport to the chromosphere could be influenced by similar fractionation effects. However, if the Ne abundance in the photosphere (where it has not yet been measured) is the same as in the local galactic set, then the mechanism which produces differences between the gamma-ray and photospheric abundances must include additional effects, because correlation with first ionization potential alone would predict a Ne abundance at least as low as the O abundance, contrary to that implied by the gamma-ray observation.

Independent of the mechanism responsible for the fractionation, significant abundance differences exist between various sites in the solar atmosphere. It seems inevitable that similar fractionation phenomena could affect the abundance determinations of objects other than the Sun.

GAMMA RAY BURSTS

Gamma-ray bursts were discovered[35] accidentally in 1967 by detectors on board the Vela satellites whose primary purpose was to monitor artificial nuclear detonations in space. The observational properties of the bursts and current theoretical ideas about their origin have been extensively reviewed in recent workshop proceedings[36,37].

Gamma-ray bursts are generally observed in the photon energy range from a few tens of keV to several MeV with event durations ranging from about 0.1 to 100 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 detector bursts range from about ten per year with fluences $>10^{-4}$ erg/cm^2 to several 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 which might be expected from an unbounded, isotropic and homogeneous distribution of sources[38,39]. Although it has been suggested that this results from the finite galactic distribution of sources and is thus evidence for a galactic origin, recent studies[40,41] have shown that this deviation can be explained entirely by temporal and spectral selection biases in the detectors.

The distribution of gamma-ray burst source directions on the sky is essentially isotropic, which suggests that if they are galactic the sources typically lie within a scale height of the disk ($\leqslant 1$ kpc) and release energies of $\leqslant 10^{39}$ ergs.

The determination[42] of several very precise source positions, however, has not lead to the identification of any burst sources with known objects, except for one case. That exception is the source of the 5 March 1979 burst, GBS 0526-66, whose positional error box[43] of size 0.1 arc min^2, lies within the supernova remnant N49 in the Large Magellanic Cloud which is 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 about five orders of magnitude larger than that inferred for a typical galactic gamma-ray burst. But the 5 March burst exhibited a number of remarkable and possibly unique observational characteristics, including[44,45] the extremely rapid rise time ($< 2\text{x}10^{-4}$ sec) of the impulsive emission spike, the relatively short duration (~ 0.15 sec) and high luminosity of this spike, the 8-sec pulsed emission following the impulsive spike, and 15 subsequent[46], apparently nonrandom[47], outbursts of lower intensity from the same source direction over the last several years. Thus it appears[44,48] to belong to a separate class of less frequent but more energetic transients than do the typical galactic bursts.

Although searches (e.g. Ref. 49) of other positional error boxes have not produced any likely source objects, a search[50,51] of archival optical plates has revealed evidence of possible optical flashes from a couple of the burst sources in the past. Very recently optical flashes have also been detected[52] from the direction of the repeating, 5 March 1979 source direction. This appears to open a new window for monitoring such bursts, but simultaneous optical and gamma-ray observations are still needed before it can be established that gamma-ray bursts are in fact accompanied by the detectable optical flashes.

The best insight into the nature of gamma-ray burst sources has come from the discovery[53] of absorption and emission features in the energy spectra of the bursts.

The absorption features have been observed[53,54] in a number of spectra, generally in the energy range from about 30 to 60 keV, as can be seen in the spectra of the 25 March 1978 burst[54] shown in Figure 4. These features, like those in the spectra of X-ray binaries, appear to be the result of cyclotron absorption in intense magnetic fields of a few times 10^{12} gauss, which strongly suggests that magnetic neutron stars are the source of many, if not all, gamma-ray bursts. Moreover the narrowness of the observed absorption features, implying a small range of effective magnetic field strengths, further suggest that the soft burst emission (<0.1 MeV) comes from a relatively small region close to the polar cap of a neutron star and is observed at a large angle to the axis of the field. The soft continuum spectra are in fact quite consistent[55] with gyrosynchrotron emission in such fields.

As can be seen in the spectrum of the 25 March 1978, however, this soft component accounts for only a fraction ($\sim$20%) of the observed burst emission. Most of the emission in this burst is seen in a spectrally distinct hard component between $\sim$0.25 and 6 MeV. Similar hard components, with energies extending as high as 20 MeV, have been observed[56] in many other bursts. The photon-photon $e^{\pm}$ pair production opacity of these hard photons imposes a strong constraint[57,58] on the minimum size of the emission region. This size greatly exceeds that of a neutron star polar cap, unless the star is uncomfortably close or the emission is highly beamed.

To reconcile these features it has been suggested[57,58] that the bulk of the observed burst energy was initially ejected from the polar cap of a neutron star in a highly collimated jet of $e^{\pm}$ pairs which disrupted and isotropized far above the star to form a fireball[59] that expanded until it became transparent to photon-photon pair production and the observed photons escaped. In such a model the emission time-scale is determined by the size at which the fireball becomes transparent. Thus the observed duration can give a measure of the total energy, and hence the distance, of the burst[58].

There is also evidence for possible redshifted $e^{\pm}$ annihilation line emission in the spectra of some gamma-ray bursts. The most commonly observed emission line in burst spectra falls in the energy range from 0.40 to 0.46 MeV, as seen[53] by low resolution NaI detectors in the spectra of a third of the most intense gamma-ray bursts. Such line emission may be optically thin $e^{\pm}$ annihilation radiation redshifted by the strong gravitational field of a neutron star. But in an optically thick region, stimulated annihilation radiation[60] could also produce a line at about 0.43 MeV without a gravitational redshift. A well resolved line at $\sim$0.43 MeV (Figure 5) was also seen[61,62] in the spectrum of the 5 March, 1979 burst, suggesting that the source of this burst was also a neutron star.

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 observations and modelling[63,64] of the 5 March 1979 burst even though it is quite likely that the underlying energy source of this burst in 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 rapid energy generation in solar flares, is insufficient energetically.

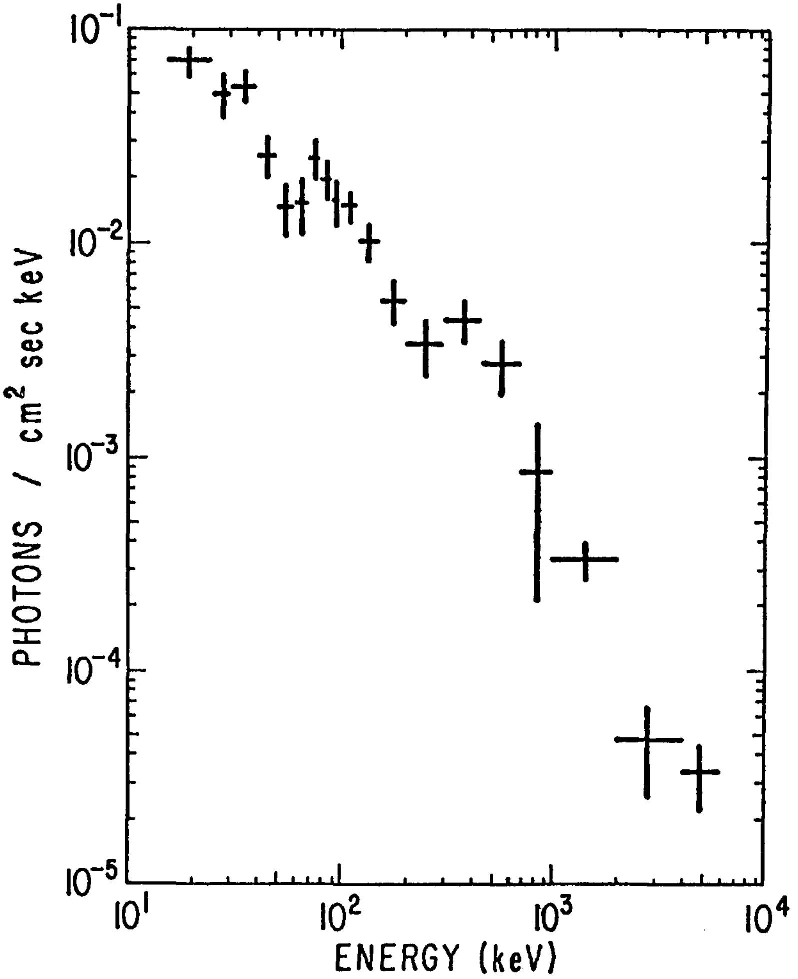

Fig. 4. Observed[54] gamma-ray spectrum of the 25 March, 1978 burst.

Gravitational energy can be released in a burst from a neutron star when a large amount of matter is impulsively accreted onto its surface, in an asteroid or comet impact[65,66] or sporadic dumping of an accretion disk by magnetospheric instabilities[67]. 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[63,68]. Such quakes could result[69] from a collapse following a phase transition from ordinary nuclear matter to a new state containing a Bose-Einstein condensate of pions[70]. Pion condensates are believed to exist above a critical density, about twice the nuclear density, and to have lower energies per baryon and a significantly softer equation of state than ordinary nuclear matter. As a result of accretion or reduced centrifugal forces due to a slowing rate of rotation, the core density of a neutron star may increase beyond the critical density resulting in a supercompressed metastable state which could eventually collapse to the pion condensed state. Such a collapse could release[71] about 10^{48} erg in a time no longer than the free fall time (10^{-4} sec). As much as 10% of this energy could go into neutron star vibrations if the oscillation amplitude is on the order of the radius change (~10m). Neutron star quakes can set up neutron star vibrations which dissipate mainly by gravitational radiation (e.g. Ref. 72). A fraction of the vibrational energy, however, can be

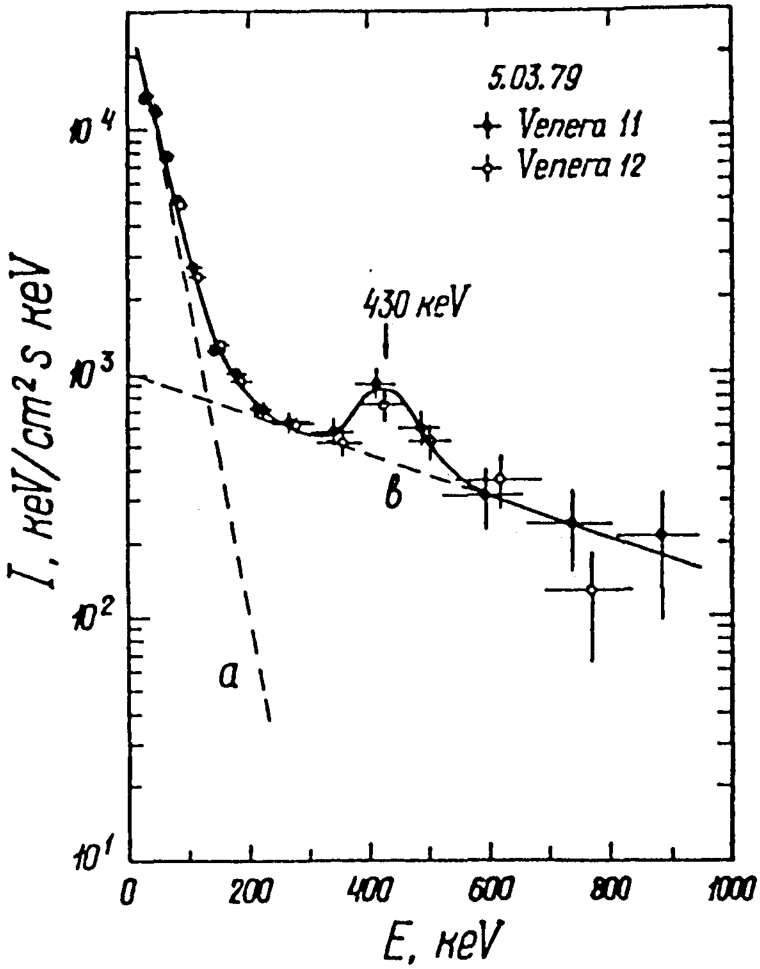

Fig. 5. The spectrum[62] of the impulsive emission spike of the 5 March, 1979 gamma-ray burst.

converted[63,69] into magnetoacoustic waves which dissipate by accelerating particles in the magnetosphere. Radiation from these particles would then be 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 slow accretion of gas[73,74]. Such detonations release several MeV per nucleon from the burning of helium to the iron peak nuclei. All three of these processes, impulsive accretion, corequakes, or nuclear detonations, 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 5 March 1979 burst, such large amounts of accreted matter are required that accretion and nuclear detonation appear to be ruled out, so that only corequakes appear to be capable of providing the energy needed for this burst.

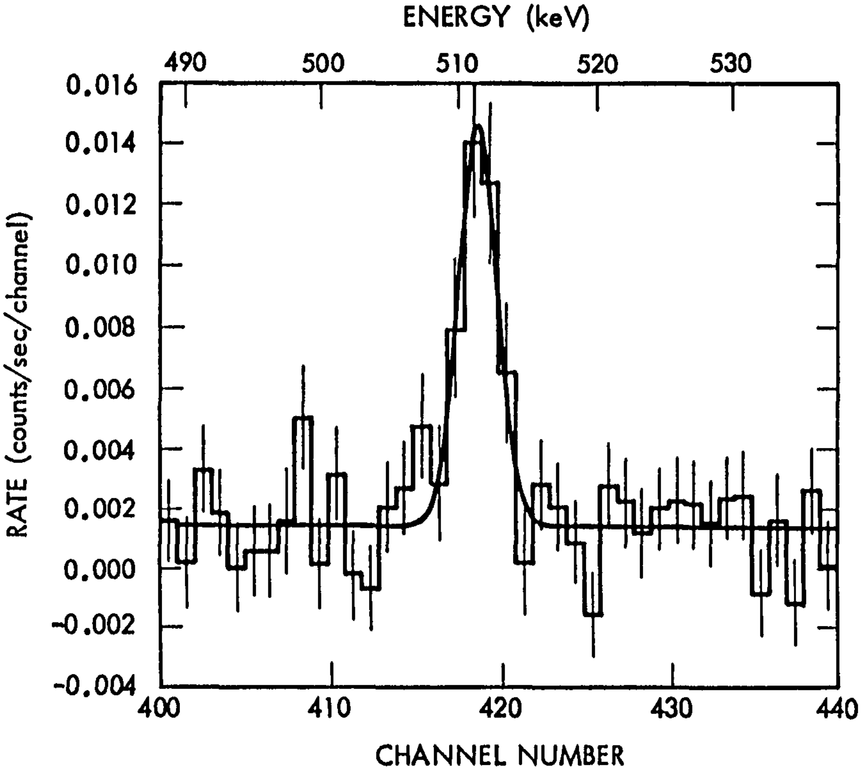

Fig. 6. Gamma-ray spectrum near 0.511 MeV observed[79] from the direction of the Galactic Center.

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 reported in a series of balloon observations with low-resolution NaI detectors, starting in 1970[75-77]. But it was not until 1977 that the annihilation line energy of 0.511 MeV was clearly identified with high-resolution Ge detectors[78]. The latter observation also revealed that the line is very narrow (FWHM <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 $\sim 10^{-3}$ photons/cm^2 sec implies an annihilation rate of $\sim 2\text{x}10^{43}$ positrons/sec or an annihilation radiation luminosity of $\sim 3\text{x}10^{37}$ ergs/sec at the 10 kpc distance of the Galactic Center.

Subsequent Ge detector observations[79-80] on HEAO-3 have confirmed the narrowness (FWHM <2.5 keV) of the line and have provided more precise information on the line center energy (510.90±0.25 keV, see Figure 6). These measurements also showed that the direction of the source is coincident with that of the Galactic Center (within the ±4° observational uncertainty). Most important, the HEAO-3 observations revealed that the line intensity varies with time, decreasing by a factor of three in six months from $(1.85\pm0.21)\text{x}10^{-3}$ photons/cm^2 sec in the fall of 1979 to $(0.65\pm0.27)\text{x}10^{-3}$ photons/cm^2 sec in the spring of 1980. This decrease, confirmed by later observations[81-83] 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 reported annihilation line fluxes from the Galactic Center as a function of time during the last 15 years are shown in Figure 7.

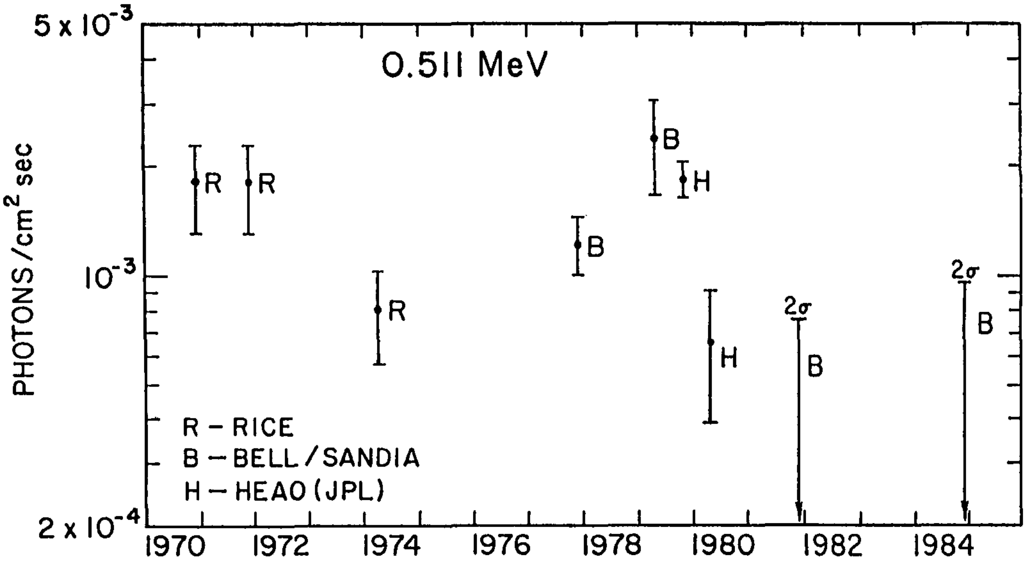

Fig. 7. Observed 0.511 MeV fluxes and upper limits from the direction of the Galactic Center.

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[84] a gas temperature in the annihilation region less than $5\text{x}10^4$ K and the intensity variation requires that the density of gas at this site be high enough ($>10^5$ cm^{-3}) that the positrons can slow down and annihilate in less than half a year. Such regions appear to exist in both the peculiar warm clouds[85] and the compact non-thermal source[86] within the central parsec of the Galaxy. While previous theoretical studies[84] suggested that the line width also constrains the ionization fraction of the ambient gas to values greater than ~10%, it has recently been pointed out[87] that, when the results of new laboratory measurements[88] of positron annihilation in neutral H are taken into account, this constraint is no longer valid.

The nature of the positron source is strongly constrained[89] 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[90], supernovae[91] or primordial black holes[92] previously proposed. Instead, it essentially requires[93] 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. However, because the observed line-center energy shows no evidence for any gravitational redshift, the annihilation site must be removed by at least 10^3 Schwartzschild radii from this compact object.

The strongest constraints on the positron production processes are set[89] by observations[80,94] of the accompanying continuum emission at energies $>m_ec^2$. These require a high positron production 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 emitting 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 $<5\text{x}10^8$ cm). Pair production in an intense radiation field around an accreting black hole of $\lesssim 10^3 M_\odot$ appears to be a possible source[89,95]. However, if the gamma-ray continuum is beamed, the observed continuum cannot be used to determine the photon density at the source. In this case, a photon density high enough to produce pairs at the observed rate may be present in a much larger source region than that estimated for isotropic gamma-ray emission. Such pair sources may be associated with jets in massive, million-solar mass black holes[89,93,96–99]. But the total gamma-ray luminosity in these models is much higher ($\sim 10^{40}$ erg/sec) than that of the isotropic model ($\sim 10^{38}$ erg/sec). Another important difference between the $\sim 10^3 M_\odot$ and the $\sim 10^6 M_\odot$ black hole models is that while dynamical considerations imply that the more massive hole should reside at the nucleus of the Galaxy, the currently determined positional uncertainty of the line source (±4°) would allow a variety of locations for the less massive object. Future imaging experiments with much better angular resolution could therefore differentiate between the models.

GALACTIC NUCLEOSYNTHESIS

The search for gamma-ray lines from nucleosynthetic radionuclei in our galaxy has been carried on for over a decade to test current theories of the explosive nucleosynthetic origin of most nuclei heavier than helium. This search has at last resulted in the first observation[7,100] of such a line from ^{26}Al, made with the high resolution Ge spectrometer on HEAO-3. That this line should be detectable was pointed out earlier [101,102], but the observed intensity is nearly an order of magnitude greater than was predicted.

A rich variety of explosive nucleosynthetic lines have been proposed from both supernovae and novae. The most abundant radionucleus expected[103] from explosive nucleosynthesis in supernovae is ^{56}Ni, which decays with a 8.8 day mean-life to ^{56}Co, which, in turn, decays with a mean-life of 114 days to ^{56}Fe; 20% of the ^{56}Co decays are via positron emission. Nucleosynthesis of ^{56}Ni in supernovae is thought[104] to be the primary source of galactic ^{56}Fe.

The bulk of the gamma rays[105] and positrons[106] 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 and optical lines from both ^{56}Co and the resulting ^{56}Fe have recently been detected[107] in the spectrum of an extragalactic supernova, SN 1972e. Any such direct gamma-ray line emission escaping from the nebula would be detectable for only a few years after the supernova explosion.

Gamma-ray lines from other longer-lived radionuclei, such as 1.1 yr ^{57}Co, 3.8 yr ^{22}Na and 68 yr ^{44}Ti from supernovae, have also been suggested[103,108,109]. But these too could only be detectable for at most about 100 years after the explosion.

There are, however, three much longer lived ($>10^5$ yr) sources of nucleosynthetic gamma-ray lines, namely β^+ decay positrons, ^{26}Al and ^{60}Fe, which could give a direct measure of the overall galactic average rate of explosive nucleosynthesis. Since a fraction of the positrons from ^{56}Co decay are expected[105,106] to escape into the interstellar medium and since in the tenuous interstellar gas the positron lifetime against annihilation is quite long ($\sim 10^5$ yr in a density of 1H cm^3), positrons should accumulate from several thousand supernovae, assuming that galactic supernovae occur about once every 30 years. Their annihilation should thus produce[91,110] diffuse galactic gamma-ray line emission at 0.511 MeV. Furthermore, estimates (e.g. Ref. 93) of the rate of positron production by other types of sources suggest that the principal source of galactic positrons should in fact be those escaping from ^{56}Co decay produced in Type I supernovae.

Recent observations[111,112] of galactic 0.511 MeV emission with wide (>50°) field-of-view detectors reveal considerably higher line intensities than would be expected from the Galactic Center source alone, which suggests that there may be a spatially diffuse source of 0.511 MeV line emission in the Galaxy. Conclusive measurements of such diffuse line emission can thus provide information on the average rate of galactic nucleosynthesis of ^{56}Fe during the last 10^5 years.

Similarly, the long-lived radionuclei ^{60}Fe (mean-life $\sim 4 \times 10^5$ yr) and ^{26}Al (mean-life $\sim 1 \times 10^6$ yr), which are also expected from explosive nucleosynthesis, should accumulate from $\sim 10^4$ or more supernovae and be well distributed through the interstellar medium before they

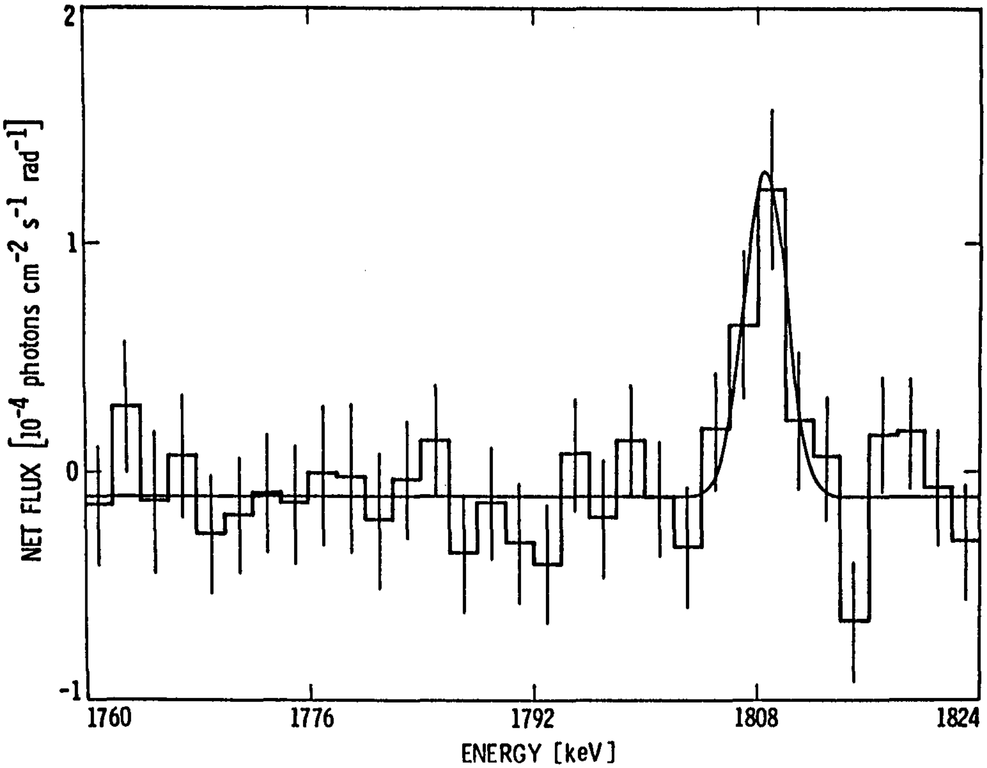

Fig. 8. Observed[100] gamma-ray spectrum near 1.809 MeV from the galactic plane in the direction of the Galactic Center.

decay. Diffuse galactic line emission is thus expected at 1.809 MeV from ^{26}Al decay to ^{26}Mg (Refs. 101,102) 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 (Ref. 113).

Diffuse galactic line emission at 1.809 MeV from ^{26}Al has now been measured[7,100] and confirmed[114]. The measured line, shown in Figure 8, has a width (FWHM) $\leqslant 3.0$ keV which is quite consistent with that expected solely from galactic rotation. The intensity varies with galactic longitude from $(4.8 \pm 1.0) \times 10^{-4}$ photons/cm^2 sec rad in the direction of the galactic center[100] to less than 40% of that in the direction of the anti-center[114]. This intensity is roughly an order of magnitude greater than that predicted[101,102] from supernova production.

The observed flux corresponds to a total mass of about $3M_{\odot}$ of ^{26}Al in the interstellar medium. Assuming steady state, this implies a present galactic production of $\sim 3 \times 10^{-6} M_{\odot}$/yr of ^{26}Al. By comparison the estimated present production rate of ^{27}Al is of the order of $10^{-4} M_{\odot}$/yr which thus requires that the production ratio of ^{26}Al/^{27}Al in the ^{26}Al source must be $> 3 \times 10^{-2}$. Otherwise too much ^{27}Al would be produced. The calculated[115] yields of Type II supernovae, however, give a ^{26}Al/^{27}Al ratio of only (1 to 2)$\times 10^{-3}$ which, like the predicted intensity, is an order of magnitude too low.

There are however other possible sources of ^{26}Al: Novae[116,117], red giants[118] and 0 and Wolf-Rayet stars[119]. For novae the calculated[116,117] production ratio of ^{26}Al/^{27}Al is of the order of unity which is more than sufficient. Moreover estimates[7,100,120] of the current galactic rate of ^{26}Al production by novae come quite close to the required rate inferred from the observations. Calculations of the ^{26}Al/^{27}Al ratio from pulsating red giants[118] is also of the order of unity and that in the winds of 0 and Wolf-Rayet stars is about 4×10^{-2} which would be just sufficient. But the estimated total galactic production rate from these sources appears to be less than that of novae. Thus it seems at the present that the bulk of the ^{26}Al in the interstellar medium is most likely produced by novae while the bulk of the ^{27}Al may come from Type II supernovae with only about 10% of it coming from novae. The recent discovery[121] of a new low lying resonance for ^{26}Al production in the ^{25}Mg (p, γ) reaction suggest, however, that new theoretical calculations of the yields for the various sources are needed.

SS433

Intense, time-variable and very narrow gamma-ray line emission has recently been observed[8,122] from SS433 with the high resolution Ge spectrometer flown on HEAO-3. This instrument is particularly sensitive to very narrow lines (widths less than a few keV). The line with the strongest intensity and highest statistical significance was seen[8] at 1.497 MeV (see Figure 9). In addition, spectral features at $\sim$1.2 MeV[8] and $\sim$6.695 MeV[122] were also reported. All of these lines have very narrow widths (FWHM < 10 keV). Searches for these very narrow lines were carried out also with a Ge spectrometer flown on a balloon[123] and the NaI spectrometer on SMM[124] whose energy resolution is much lower than that of the Ge spectrometers. Although no lines were detected in either of these searches, this negative result could be due to the time variability of the SS433 gamma-ray source.

Two different identifications of the 1.497 MeV line have been proposed, both of which assume that this line is blueshifted emission from the approaching jet. The first suggestion[8] identifies the line with the 1.369 MeV line from ^{24}Mg* excited by inelastic collisions, while the other[125] associates it with a line at 1.380 MeV from the fusion reaction $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}^*$ in a very narrow resonance at a proton energy of 0.278 keV. The optically determined[126] Doppler shifts of the approaching jet of SS433 at the epoch of the gamma-ray observations are consistent with both of these identifications, as is the possible association of the 1.2 MeV feature with the redshifted counterpart of the 1.497 MeV line from the receding jet. Moreover, the inelastic excitations and fusion models, based on these identifications, each predict another line at either 6.129 MeV from ^{16}O* deexcitations[127] or 6.175 MeV from ^{15}O* deexcitations[125]. The observed feature at $\sim$6.695 MeV could be identified with either of these lines. The two models also predict other lines which have not yet been observed.

If the observed 1.497 MeV line is due to ^{24}Mg deexcitations, then the fact that the gamma-ray and optical Doppler shifts are similar implies that the Mg nuclei are moving essentially at the flow speed (0.26c) of the jets. This corresponds to a kinetic energy of $\sim$33 MeV/nucleon. At this energy, the 1.369 MeV line can be produced in nuclear reactions with either ambient protons or moving protons, provided that the proton velocity in the Mg rest frame exceeds $\sim$0.07c, corresponding to the effective threshold energy ($\sim$2 MeV) for exciting the 1.369 MeV level. But unless the relative proton velocity is less than $\sim$0.09c, corresponding to a rest frame energy less than $\sim$4 MeV, the recoil of the excited Mg nuclei in a gas would broaden the line to a width which is larger than that observed[8]. Therefore, for inelastic excitations in a gas[128], the velocity differential between the protons and the Mg nuclei must lie in a very narrow range, so that the protons have sufficient energy to excite the line, but not too much energy to broaden it excessively. Moreover, if the 6.695 MeV line is confirmed with a very narrow width, excitations in a gas can be ruled out because at proton velocities < 0.09c required by the line width ^{16}O cannot be excited.

These constraints, however, can be eliminated[127] by a line-narrowing effect[129,130] involving deexcitations of nuclei embedded in dust grains. The grains also offer a simple explanation[127] to the fact that the strongest very narrow line is at 1.369 MeV from ^{24}Mg. For local galactic abundances and deexcitations in a gas, the strongest lines are generally at other energies, depending on the proton energy in the Mg rest frame. Since at $\sim$4 MeV the strongest line is at 1.634 MeV from ^{20}Ne deexcitations, a very strong depletion of Ne relative to Mg is required if the 1.497 MeV line is due to Mg deexcitations in a gas. In grains, on the other hand, Ne and other volatiles are naturally depleted.

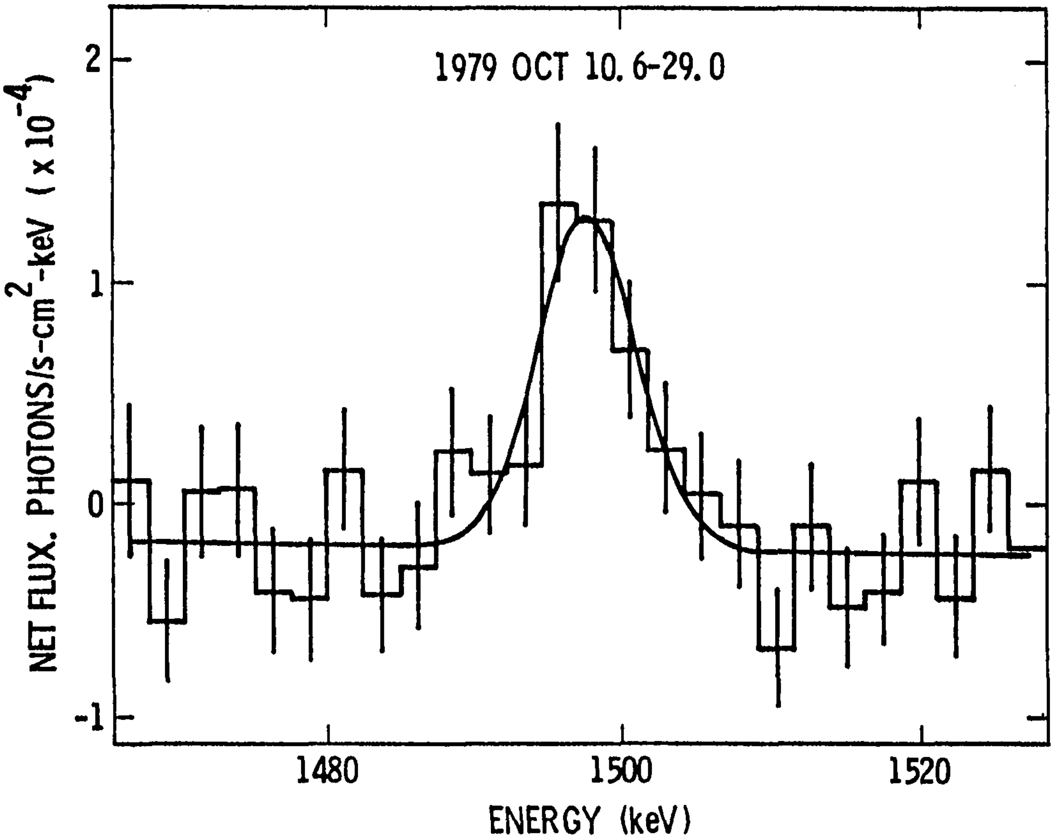

Fig. 9. Observed[8] gamma-ray spectrum within ± 30 keV of the 1.5 MeV line from the direction of SS433.

Very narrow gamma-ray lines can be produced from the deexcitation of nuclei embedded in dust grains if the sizes of the grains are large enough ($\geqslant 10^{-4}$ cm) and the lifetimes of the nuclear levels are long enough ($\geqslant 10^{-12}$ sec). If these two conditions are met, an excited nucleus produced in a grain loses its recoil energy by Coulomb collisions and stops in the grain before it deexcites. Thus, the line is not broadened by the recoil following deexcitation. A variety of very narrow grain lines are expected[129,130] with relative intensities depending on the elemental abundances in the grains, as well on the details of the interaction model.

In the jet-grain interaction model[127] refractory grains were assumed in which the abundances of Mg, Si and Fe were the same as the local galactic abundances[34], while the more volatile elements were depleted, such that the C, N and O abundances were reduced relative to the local galactic abundances by a factor f and the H, He, Ne and S abundances were set to zero. It was also assumed that the grains, moving with the jet velocity, interact with a stationary ambient medium. This corresponds to a thin-target interaction model in which the bombarding proton energy in the grain rest frame has the fixed value of 33 MeV. Alternatively, the gamma-ray lines may be produced while the grains, moving at the speed of the jet flow, sweep up the ambient protons. This would occur if the bulk of the heavy elements were in the grains and the radiation pressure which accelerates the jets couples primarily to these elements and not to the hydrogen. This corresponds to thick-target interactions where the bombarding protons in the jet rest frame have initially 33 MeV, but produce the gamma rays as they slow down and eventually stop in this frame.

The relative intensities of very narrow lines for these abundances in the thin- and thick-target cases are shown in Table 3. The line at 4.438 MeV from ^{12}C is not shown because even in grains this line is broad owing to the very short (0.06 psec) lifetime of the 4.439 MeV level. Also shown are relative intensities for MgO, a very refractory compound with a very high melting temperature, a feature that is important for the survival of the grains[127].

Table 3
RELATIVE VERY NARROW LINE INTENSITIES FROM GRAINS

Photon Energy (MeV)	Excitation Process	(O:Mg:Si:Fe) (22f:1:1.1:1)		(O:Mg:Si:Fe) (1:1:0:0)
		Thin Target (Ref. 127)	Thick Target	Thick Target
0.847	$^{56}Fe(p,p')^{56}Fe^*$	0.5	0.7	0.0
0.931	$^{56}Fe(p,pn)^{55}Fe^*$	0.6	0.4	0.0
1.317	$^{56}Fe(p,pn)^{55}Fe^*$	0.5	0.3	0.0
1.369	$^{24}Mg(p,p')^{24}Mg^*$ $^{28}Si(p,x)^{24}Mg^*$	1.0	1.0	1.0
1.634	$^{24}Mg(p,x)^{20}Ne^*$	0.5	0.3	0.3
1.779	$^{28}Si(p,p')^{28}Si^*$	0.4	0.6	0.0
6.129	$^{16}O\ (p,p')\ ^{16}O^*$	4.0f	4.4f	0.2

As can be seen, in all cases the strongest very narrow line is at 1.369 MeV, provided that the depletion factor f is small enough. As already pointed out, the 6.129 MeV line can be associated with the reported feature at ~6.7 MeV. The confirmation of this feature and the measurement of its relative intensity would determine the depletion factor. An upper limit on the 1.634 MeV line, reported[131] at this conference, appears to be in conflict with the thin-target ratio given in Table 3, but not with the thick-target ratios. The thin-target ratio for this line in Table 3 is lower than that suggested[132] previously, where the contribution of Si spallation to the 1.369 MeV line was ignored. There is as yet no data on the other lines shown in Table 3. As can be seen, such data would provide important information on the composition of the grains.

In the absence of grains, the 1.497 MeV line could still be identified[128] with the 1.369 MeV line from inelastically excited ^{24}Mg, provided that the excitations were due to protons with velocities relative to the ^{24}Mg nuclei less than 0.09c. At higher relative velocities, the line width would be larger than observed. But the composition of the gas in which these interactions take place must be quite different from the local galactic composition[34]. For such a composition, the intensity of the 1.634 MeV line produced by protons of a few MeV is larger by about an order of magnitude than that of the 1.369 MeV line in conflict with the fact that the upper limit on the ^{20}Ne line intensity is considerably lower than the observed intensity of the 1.369 MeV line.

In the fusion model[125] for gamma-ray production in SS433, the line at 1.380 MeV results from the deexcitation of the 7.556 MeV level of ^{15}O to the ground state via a state at 6.176 MeV. The 7.556 MeV level is populated by p-^{14}N reactions through a narrow resonance at a proton energy of 0.278 MeV[133,134]. The low energy and narrow width of this resonance lead to a very narrow width for the 1.380 MeV line, provided that the temperature of the ^{14}N nuclei in the jets is sufficiently low ($< 10^8$K). This implies that the protons and the ^{14}N nuclei must have different temperatures or that the particle distributions are nonthermal. This has profound implications on the energetics of the system, as discussed below. The deexcitation of the 7.556 MeV level produces additional lines at 6.176, 0.764, 6.793, 2.374 and 5.183 MeV with intensities relative to that the 1.380 MeV line of 1, 0.40, 0.40, 0.28 and 0.28, respectively. Although as mentioned above, the 6.176 MeV line could be identified with the 6.695 MeV line, the fact that this line is observed[122] to be much weaker than the 1.497 MeV line, argues strongly against the fusion model. Searches for the other predicted lines have not yet been carried out.

Gamma-ray line production by inelastic excitations is accompanied by energy loss to Coulomb collisions. If the gamma-ray lines were due to fusion, the line production would also be accompanied by Coulomb losses, because of the nonthermal nature of the particle distributions implied by the observed line widths. But the rate of Coulomb energy loss for a given rate of gamma-ray line production is much larger for fusion than for inelastic excitation because the line production cross section for fusion in the resonance ($\sim$0.1 mb) is much smaller than that for inelastic excitation ($\sim$200 mb). The observed gamma-ray line luminosity of SS433 of $\sim 10^{37}$ erg/sec implies a Coulomb energy loss $>10^{47}$ erg/sec for the fusion model. The Coulomb energy loss in the inelastic excitation models can be as low as $\sim 4\times10^{40}$ erg/sec, in the thick-target jet-grain model. Since even this value is highly super-Eddingtonian for a stellar size object, the bulk of the Coulomb energy loss should go into mass motion in the jets. This Coulomb energy loss will also heat the grains, but the estimated temperature, $<$3000K, is below the melting point of MgO. The survival of grains in the environment of the jets of SS433 has not yet been studied in detail. However, it has been suggested[135] that the presence of clumps of dense matter (e.g. grains) may be a prerequisite for the acceleration of the jets by line locking. Crucial tests of the proposed models for gamma-ray line production in SS433 will come from the confirmation of the already reported lines and from further observations of the relative intensities and widths of the predicted lines.

SUMMARY

We have highlighted some of the important recent advances in gamma-ray line astrophysics. The solar flare observations, including a remarkably detailed gamma-ray line spectrum, provide insights into problems of particle acceleration and confinement and allow the determination of elemental abundances by a powerful new technique. Recent gamma-ray bursts studies have provided much new insight into the nature of their sources, with magnetized neutron stars emerging as the best candidates. Continuing observations of the Galactic Center provided only upper limits on the 0.511 MeV line flux, but a variety of theoretical and laboratory studies have elaborated considerably the physical processes that govern the production of pairs and the annihilation of the positrons. The gamma-ray line from recently synthesized ^{26}Al has been observed and confirmed by independent observations, providing evidence for ongoing nucleosynthesis in the galaxy, and requiring some modification of current ideas. Gamma-ray lines have been observed from the compact galactic object SS433, which have very exciting theoretical implications. Further progress in these and other areas is expected from future observations with the Gamma Ray Observatory, to be launched in 1988.

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