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Advances in Gamma-Ray Line Astronomy

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ADVANCES IN GAMMA-RAY LINE ASTRONOMY*

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ABSTRACT

Recent gamma-ray line observations and their interpretations are reviewed and prospects for future line detections are discussed.

INTRODUCTION

Very important advances have taken place in gamma-ray line astronomy since our previous review for COSPAR [1]. These include new results on solar flares, gamma-ray bursts and the Galactic Center. Solar gamma-ray lines, observed [2] from many flares by the spectrometer on SMM, imply nuclear interactions in thick targets by protons and nuclei confined to closed loops with little escape into interplanetary space. The timing of the gamma-ray line fluxes indicate that the acceleration of the particles is very impulsive.

Lines have been seen from gamma-ray bursts [3]. Electron-positron pair production and annihilation are probably responsible for the emission line seen just below 0.5 MeV from several bursts. The shift in energy is due to either a gravitational redshift or grasar action [4].

The 0.511 MeV line from the Galactic Center has been shown to be time variable [5]. The theoretical analysis of this observation, together with observations at other wavelengths, strongly suggests [6] that the positrons are produced by photon-photon collisions in the vicinity of a massive black hole.

We discuss these topics below. We also review the prospects for future observations of other gamma-ray lines, especially lines from processes of nucleosynthesis.

SOLAR FLARES

The interactions of solar flare accelerated particles with the ambient solar atmosphere are a source of gamma rays, both lines and continuum. The first detailed calculation [7] of the expected energetic particle interaction rates in flares predicted observable gamma-ray line fluxes at Earth.

Gamma-ray lines from solar flares were first observed [8] with a NaI spectrometer flown on board the OSO-7 satellite. The lines were observed at 0.511 MeV from positron annihilation, at 2.223 MeV from neutron capture on ^{1}H, and at 4.438 and 6.129 MeV from deexcitations of nuclear levels in ^{12}C and ^{16}O, respectively. These lines, as well as other nuclear deexcitation lines, have been seen from a number of subsequent flares by detectors on the HEAO-1 [9], HEAO-3 [10] and SMM [2, 11, 12] satellites.

Gamma-ray continuum from solar flares below an MeV is electron bremsstrahlung. But above an MeV, 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 [13, 14]. Continuum emission at higher energies is only rarely observed [12]. This emission could be a combination of electron bremsstrahlung and π^0 meson decay [7, 15].

The strongest predicted and observed line from solar flares is at 2.223 MeV from neutron capture on hydrogen, ^{1}H(n,γ)^{2}H. Studies of neutron production in flares [16, 17] 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,nπ^+)^{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 [18] of neutron slowing down and capture in the solar atmosphere show that the principal capture reactions are ^{1}H(n,γ)^{2}H and ^{3}He(n,p)^{3}H.

Comparisons of the observed [11] time dependence of the intensity of prompt nuclear deexcitation lines to that of the 2.223 MeV line show delays of ~ 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 ~ 10^2 sec implies [18] that the mean density of the gas where the neutrons are captured is ~ 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 [2] of the neutron capture line fluence to that of nuclear deexcitation lines show that the capture line, while essentially unattenuated for disk flares, is attenuated by at least a factor of 10 for limb flares. This attenuation results from Compton scattering in the photosphere [18]. 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 [10] which have set an upper limit of several keV on the width of this line.

A significant fraction of the fastest (> 100 MeV) neutrons can travel as far as the Earth before they decay, resulting [16] in detectable neutron fluxes at the Earth following large flares. High energy solar neutrons were observed from a large flare in 1980 [12].

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 [17] 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 [e.g. 19].

Positronium in astrophysical sites is formed by radiative combination with free electrons and by charge exchange with neutral hydrogen [19]; 25% of the positronium atoms decay from the singlet state and 75% from 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 > 10^{15}H/cm^3, as may be the case for solar flare positrons, then much of the positronium is broken up by collisions before it can decay [19]. 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,pα)^{16}O$^{*6.13}$), nonthermal fusion reactions (e.g. $^4He(\alpha, p)^7Li^{*0.478}$) 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. 20] of the excitation functions of a great number of such reactions, calculations have been made [21] of gamma-ray spectra produced by the interaction of energetic particles in cooler ambient matter.

In the solar atmosphere these gamma-ray spectra have two components: a narrow-line component resulting from the deexcitation of ambient nuclei excited by interactions with energetic protons and α particles, and a broad-line 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 ^7Li and 0.431 MeV from ^7Be, which result from the reactions $^4He(\alpha,p)^7Li^*$ and $^4He(\alpha,n)^7Be^*$. 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 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 [22, 23, 24] that as much as a few percent of the total flare energy resides in protons and nuclei which are 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 [25] and modifications in the line widths [26].

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 gamma-ray bursts are the most common class of these transients. 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. The observations of emission lines and absorption features in the energy spectra of gamma-ray bursts has added a new dimension to the study of these transients [see 27 for review]. The absorption features, observed [3, 28] 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.

The most commonly observed emission line falls in the energy range from 0.40 to 0.46 MeV, as seen [3] 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 [29] 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 [4] 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 [30], or gravitationally redshifted single photon e^+-e^- annihilation [31, 32] radiation at 1.022 MeV in a very strong (> 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 [33] from the March 5, 1979 burst suggesting that the source of this burst was also a neutron star. But other characteristics of this burst seem to place it in a different class from that of the typical galactic bursts [34, 35].

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. 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 [36, 37]. 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 [38, 39]. 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 [40, 41]. 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 ~ 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 (~ 10^{53} erg), appear to be adequate for the March 5 burst [39]. But no detailed calculations on these possibilities have yet been published.

Electron-positron pairs probably play an important role in producing radiation from gamma-ray bursts. As already mentioned, pair annihilation is 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. This confinement could be achieved by the strong magnetic field (~ 10^{12} gauss) of a neutron star [39]. 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 [41] 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. 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 [42], Comptonization [43, 44, 45] and synchrotron radiation [46, 47]. In the March 5 burst the continuum below about 300 keV could be synchrotron emission from electron-positron pairs [46], while the continuum at higher energies could be due to Compton scattering of the synchrotron photons by the same e^+-e^- pairs that produce the synchrotron radiation [43].

An important property of gamma-ray burst spectra is that they appear to be optically thin [42], especially at the higher energies (> 100 keV). An optically thin emission region is also required [46] to produce the ~ 0.43 MeV emission line, except in the case where grasar action is important [4]. 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 ref. [46] the observed radiation comes from a magnetically confined thin layer (~ 0.1 mm) of dense (~ 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 [39].

In addition to the gamma-ray bursts, 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 [48, 49] 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 [50], however, failed to observe such transients and therefore imply that their frequency is less than 30 per year.

It has been suggested [51] that the June 10, 1974 gamma-ray line transient 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 and that the lines are due to 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 (FWHM < 4.9 keV) emission line, which may vary slightly in energy from 73 to 77 keV was first observed [52] from the Crab nebula. The line was subsequently shown [53] 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 ($\sim 8 \times 10^{12}$ gauss) magnetic field at the polar cap of a neutron star. In addition, a very narrow 0.4 MeV line was observed [54] from a broad field of view that included both the Crab nebula and the source direction of the June 10, 1974 transient.

GALACTIC GAMMA-RAY LINE EMISSIONS

Intense positron annihilation radiation at 0.511 MeV has been observed from the Galactic Center, and gamma-ray line emission at this and other energies is expected from a variety of discrete and diffuse sites in the Galaxy.

Annihilation radiation from the Galactic Center was first seen in a series of balloon observations with low-resolution NaI detectors, starting in 1970 [55, 56, 57]. But it was not until 1977 that the annihilation line energy of 0.511 MeV was clearly identified with high-resolution Ge detectors [58]. 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 $\sim 90\%$ 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.

Recent Ge detector observations [5] on HEAO-3 confirmed the narrowness (FWHM < 2.5 keV) of the line and 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 $\pm 4^0$ 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 [59] 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 $< 5\times10^4$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 $< 1.5 \times 10^7$ sec requires a density of $> 10^5$ H/cm^3. Such regions appear to exist in both the peculiar warm clouds [60] and the compact non-thermal source [61] 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 [62], supernovae [63], or primordial black holes [64], previously proposed. Instead, it essentially requires [6] 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 been reviewed recently [6]. It has been found that the observational [65, 66] upper limits on accompanying continuum emission at energies $> m_e c^2$ appear to set the strongest constraints on the positron production process, requiring high efficiency such that more than 30% of the total radiated energy $> m_e c^2$ 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 ($< 5 \times 10^8$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 [6], such as 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.

Turning now to the other sources of galactic line emission, thermonuclear burning in supernovae and novae [e.g. 67, 68] and nuclear interactions of low-energy cosmic rays with interstellar gas [21] are all expected [69] to produce throughout the Galaxy a variety of nuclear deexcitation lines, as well as additional positron-annihilation line emission. Observations [70] of galactic 0.511 MeV emission with wide (~ 100°) 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. Only upper limits have been set [71] on the intensities of other lines from processes of nucleosynthesis, but these already significantly constrain some of the theoretical models [68].

The most abundant radionuclide expected from explosive nucleosynthesis in supernovae is ^{56}Ni [72] 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. 67]. The bulk of the gamma rays [73] and positrons [74]) 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 [73] and optical lines from both ^{56}Co and the resulting ^{56}Fe have recently been detected [75] 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 [63, 69]. 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 ~ 3×10^5 yrs) and ^{26}Al (half life ~ 7.2×10^5 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 [76, 77] 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 [78].

Another important radionuclide from explosive nucleosynthesis in supernovae is ^{44}Ti [72]. 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 [79] and ^{26}Al [80]. 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 [81]. 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.

EXTRAGALACTIC GAMMA-RAY LINE EMISSION

Extragalactic gamma-ray line emission has so far been reported [82] only from the radiogalaxy Centaurus A. The observed lines at 4.4 and 1.6 MeV could be produced [51] in nuclear reactions in the vicinity of a massive black hole, but the statistical significance of these observations is quite low.

As in the nucleus of our Galaxy, electron-positron pair production could play an important role in active galaxies as well. Gamma rays have been observed from some of the brightest active galaxies, from the radio galaxy Centaurus A [82, 83, 84], from the Seyfert galaxy NGC 4151 [85, 86] and the quasar 3C273 [87, 88]. The comparison of these observations with observations at lower energies shows [e.g. 89] that the luminosities of active galaxies 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. The fact that these energies are close to the electron or positron rest mass energy may be due to the onset of pair production which prevents the sources from emitting a large fraction of their luminosities at higher energies. The resultant pairs could produce an annihilation feature. But unlike the nucleus of our Galaxy where e^+-e^- pairs annihilate in relatively cool regions, in an active galaxy the annihilation region could be much hotter in which case the line would be both broadened and blueshifted [90, 91]. This would explain, for example, the absence of a narrow 0.511 MeV line from the spectrum of Centaurus A [82, 84].

Observable extragalactic gamma-ray lines could also result from nucleosynthesis in supernovae. In particular, the gamma-ray lines from ^{56}Co decay, at 0.847 and 1.238 MeV, could be detected from Type I supernovae at distance as large as that of the Virgo cluster [e.g. 69]. About one supernova per year is detected optically from this cluster [92], but the actual rate could be larger if some of them are obscured by dust.

SUMMARY AND CONCLUSIONS

We have discussed in this paper the interpretations and implications of new astrophysical gamma-ray line observations. Such lines have been seen from solar flares, gamma-ray transients and the Galactic Center. Gamma-ray lines from solar flares are excellent probes of acceleration mechanisms and interaction models of energetic protons and nuclei in the solar atmosphere. The continuing observations with the gamma-ray spectrometer on SMM during the current maximum of solar activity are providing much new insight into these aspects of solar physics.

Gamma-ray lines seen in the spectra of gamma-ray bursts suggest that neutron stars are the sources of many of these bursts. The most commonly observed emission line is in the range from 400 to 460 keV, where it is likely to be positron-electron annihilation radiation, either redshifted by the gravitational field of a neutron star or produced at energies < 0.511 MeV by grasar action. Precise measurements of the energy and width of this line as well as the detection of other lines are very important objectives of future observations.

The 0.511 MeV line from the Galactic Center, first observed by balloon-borne detectors, has been confirmed by the HEAO-3 gamma-ray spectrometer. Moreover the HEAO-3 and subsequent balloon observations [93] have shown that the line is time-variable. This result, together with gamma-ray continuum observations implies that the positrons are produced by photon-photon collisions, probably close to a massive black hole, and that they annihilate in a region no larger than a light year. Important objectives for future Galactic Center observations are the better determination of the position of this source, continued monitoring of the temporal variability of the 0.511 MeV line intensity, and the determination of whether this variability is correlated with other observations, especially X-rays.

No gamma-ray lines have yet been seen from processes of nucleosynthesis. Good prospects, however, exist for detecting a diffuse galactic 0.511 MeV line from ^{56}Co decay and deexcitation lines from ^{26}Al and ^{44}Ti, produced by galactic nucleosynthesis, and for seeing the lines of ^{56}Co from an extragalactic supernova.

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