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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1981 **301**, 671-686
doi: 10.1098/rsta.1981.0151

Phil. Trans. R. Soc. Lond. A **301**, 671–686 (1981)
Printed in Great Britain

IV. GAMMA-RAY LINES AND FUTURE PROSPECTS

Interpretations and implications of γ-ray lines from solar flares, the galactic centre and γ-ray transients

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Observations and theories of astrophysical γ-ray line emission are reviewed and prospects for future observations by the spectroscopy experiments on the planned Gamma-Ray Observatory are discussed.

1. INTRODUCTION

For over two decades it has been recognized (Morrison 1958; Clayton *et al.* 1969; Lingenfelter & Ramaty 1978) that γ-ray spectroscopy could provide basic information on several important problems in astrophysics. But observational progress in the field has been slow, and positive observations of celestial γ-ray lines have been made only recently.

Gamma-ray line emission resulting from nuclear interactions of flare accelerated particles with solar atmosphere was first observed by Chupp *et al.* (1973). These, and more recent observations (Hudson *et al.* 1980; Prince *et al.* 1980; Chupp *et al.* 1981), can provide important information on particle acceleration in solar flares and on the flare process itself (Ramaty *et al.* 1975; Lin & Ramaty 1978; Ramaty *et al.* 1980*a*). We discuss the solar γ-ray spectroscopy results in §2.

The first convincing detection of an extra-solar γ-ray line was that of the positron annihilation line at 0.511 MeV (Leventhal *et al.* 1978) from the direction of the galactic centre. This line may have been observed earlier by Haymes *et al.* (1975) with a detector of much lower energy resolution. The most recent observations of the 0.511 MeV line on HEAO-3 (Riegler *et al.* 1980) have provided exciting new information on the spatial extent of the emission region and on its apparent time variability. The 0.511 MeV line emission is surprisingly intense and clearly suggests that there may be much new astrophysics to be learned from a full study of the sky just at this line energy alone. Indeed the role of this line in γ-ray astronomy may prove to be comparable with that of K-shell Fe line emission in X-ray astronomy and 21 cm line emission in radio astronomy. We discuss the galactic centre observations, including implications of the new HEAO-3 results, in §3.

Gamma-ray lines have also been seen in γ-ray transients. Spectra of several γ-ray bursts show (Mazets *et al.* 1979, 1981; Teegarden & Cline 1980) emission lines thought to be red-shifted positron annihilation and cyclotron absorption lines in hundreds of megatesla (10^8 T) magnetic fields. All of these observations strongly suggest that at least some of the γ-ray burst sources are neutron stars. Gamma-ray lines have also been seen in at least one transient of longer duration than the γ-ray bursts (Jacobson *et al.* 1978), and the identification of these lines as well requires a redshift characteristic of *ca.* $1 \times M_{\odot}$ neutron stars (Lingenfelter *et al.* 1978). Transient γ-ray spectroscopy is treated in §4.

There are in addition a variety of other astrophysical γ-ray lines, which, although below the sensitivity of detectors flown so far, should be observable with good statistical significance with future detectors. There are two spectroscopy experiments planned for the Gamma-Ray Observatory (GRO) that are particularly suitable to make these observations: the Gamma Ray Spectroscopy Experiment (G.R.S.E.), a high resolution Ge spectrometer with a broad field of view and good angular resolution achieved by a rotating modulator, and the Oriented Scintillation Spectroscopy Experiment (O.S.S.E.), a moderate-resolution NaI instrument of high sensitivity to astrophysically broadened lines. In §5 we compare the predicted intensities of the most promising γ-ray lines with the sensitivities of these detectors.

2. Solar γ-ray spectroscopy

Gamma-ray line emission from the Sun results from the nuclear interactions of energetic protons and nuclei with the solar atmosphere. These interactions produce γ-ray lines from neutron capture, positron annihilation and nuclear de-excitation. Observation of such γ-rays can provide unique information on high energy processes at the Sun. The first solar γ-ray lines, at 0.511, 2.22, 4.44, and 6.13 MeV, were observed (Chupp *et al.* 1973) by an NaI detector on the OSO-7 satellite during the 4 August 1972 flare. Most of these lines have been observed from several subsequent flares by detectors on the HEAO-1 (Hudson *et al.* 1980), HEAO-3 (Prince *et al.* 1980), and S.M.M. (Chupp *et al.* 1981) satellites. The measured relative intensities of these four lines were consistent with earlier predictions (Lingenfelter & Ramaty 1967).

In all of these flare observations the strongest line is that at 2.223 MeV, due to neutron capture on hydrogen, $^{1}H(n,\gamma)^{2}H$. The neutrons, initially produced at energies of about 1–100 MeV, are thermalized and captured in the photosphere. This leads to a delay of about 1–2 min between the emission of a 2.2 MeV photon and the production of its parent neutron in an energetic particle reaction. The delayed nature of the 2.2 MeV line has been unmistakably observed in several solar flares (4 August 1972 (Chupp *et al.* 1973); 11 July 1978 (Hudson *et al.* 1980); 9 November 1979 (Prince *et al.* 1980); 7 June 1980 (Chupp *et al.* 1981)). Neutron capture on ^{1}H in the photosphere must compete (Wang & Ramaty 1974) with capture on ^{3}He, even though ^{3}He is only a minor constituent of the photosphere, because the cross section for the reaction $^{3}He(n,p)^{3}H$ is about four orders of magnitude larger than that for the reaction $^{1}H(n,\gamma)^{2}H$. Observations of the intensity of the 2.223 MeV line compared with those of other lines can limit the photospheric $^{3}He/^{4}He$ ratio to the order of 10^{-4}; this limit is comparable with that measured in the chromosphere (Hall 1975) and solar wind (Geiss & Reeves 1972). The width of the 2.223 MeV line, determined by the photospheric temperature, is expected to be very narrow (*ca.* 100 eV), a result consistent with the high resolution HEAO-3 observations (Prince *et al.* 1980) which have set an upper limit of several kiloelectronvolts on the width of this line.

The second strongest solar flare line, at 0.511 MeV, is from the annihilation of positrons. There are many astrophysically important positron production mechanisms, as discussed in §3, but in solar flares the 0.511 MeV line results from energetic particle reactions which lead to short-lived radionuclei (e.g. ^{11}C, ^{13}N, ^{15}O, ^{17}F), π^{+} mesons and the first nuclear level of ^{16}O at

6.052 MeV which decays by electron positron emission. The initial energies of the positrons range from several hundred kiloelectronvolts to tens of megaelectronvolts, 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 (Wang & Ramaty 1975; Crannell *et al.* 1976). Positronium is formed by radiative combination with free electrons and by charge exchange with neutral hydrogen; 25% of the positronium atoms are in the singlet state and 75% in the triplet state. Singlet positronium annihilation and direct annihilation produce a line at 0.511 MeV. Triplet positronium annihilates into three photons which form a continuum below 0.511 MeV provided that the ambient density is less than about 10^{15} cm^{-3}; in this case positronium atoms can annihilate before they are broken up by collisions. It would, however, be difficult to observe this continuum in the presence of very intense hard X-ray emission from flares.

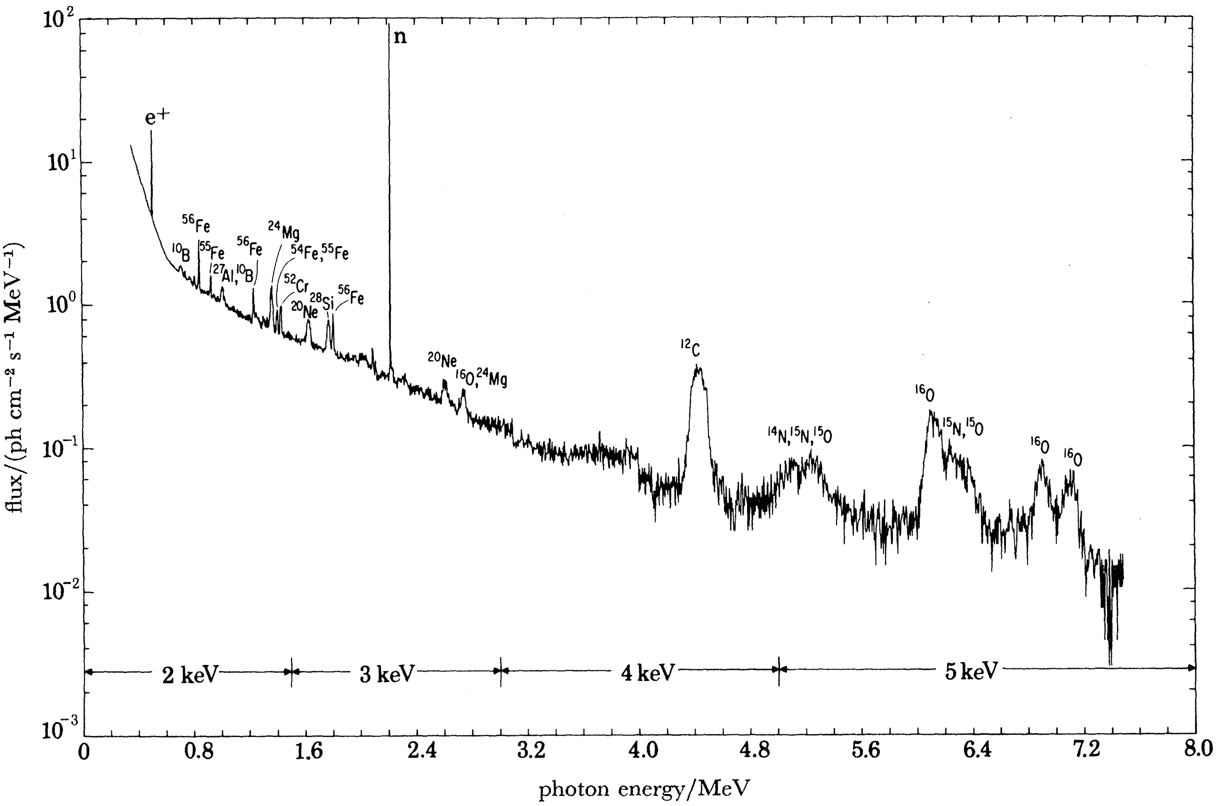

FIGURE 1. Calculated high resolution spectrum of the 4 August 1972 flare (see Lin & Ramaty 1978 for more details); $S = 2$, $E_c = 0$, (Mg, Si, Fe) = 2.5 × photospheric abundances.

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 kiloelectronvolts to tens of kiloelectronvolts, depending on whether the annihilation takes place predominantly in the cool photosphere or the hot flare plasma. Observations with high energy resolution could thus determine the positron annihilation site, but no such observations are yet available. The OSO-7 observations have only set an upper limit (*ca.* 40 keV) on the 0.511 MeV linewidth, and, while the γ-ray spectrometer on S.M.M. is much more sensitive than that on OSO-7, its energy resolution is about the same.

The Ge detector on HEAO-3, which observed the 2.223 MeV line from the 9 November 1979 flare, was not sensitive enough to solar γ-rays at lower energies to detect the line at 0.511 MeV. We hope that the necessary high-resolution observations will be made during the next solar maximum around 1990.

Energetic particle reactions also lead to many other lines, resulting from de-excitation of nuclear levels. The two strongest lines, at 4.44 and 6.13 MeV due to $^{12}C^*$ and $^{16}O^*$ de-excitation respectively, were observed (Chupp *et al.* 1973) from the solar flare of 4 August 1972. Future measurements of flare spectra by higher-resolution detectors should reveal many more lines, as can be seen from figure 1, which shows the theoretical spectrum for the 4 August flare. The de-excitation lines were obtained from a Monte Carlo calculation by using excitation functions for about 100 nuclear lines derived from either laboratory measurements or theoretical interpolations and evaluations (Ramaty *et al.* 1979). The shapes of the lines are calculated by taking into account nuclear kinematics and data on the differential cross sections of the reactions. The 2.223 and 0.511 MeV lines are based on separate calculations of neutron and positron production (Ramaty *et al.* 1975), and the bremsstrahlung, which contributes to the underlying continuum, is taken from the calculations of Bai (1977). The results of the calculation are binned into energy intervals ranging from 2 to 5 keV.

Currently, the most definite implications of these studies on solar energetic particles concern the timing of the acceleration, the confinement of the particles at the Sun, and the electron:proton ratio in the accelerated particles (Ramaty *et al.* 1975; Chupp 1975; Ramaty 1979; Ramaty *et al.* 1980*a*). It appears that the nuclei are accelerated during or very soon after the flash phase of the flare, that the γ-rays are produced by thick target interactions, i.e. by particles trapped at the Sun, and that the energy deposited by the nucleonic component in the solar atmosphere is at most only a small percentage of the total flare energy. From the analysis of the γ-ray line: continuum ratio, it follows that the acceleration mechanism imparts at least an order of magnitude more energy to the nucleonic component than to relativistic electrons. In this respect, this mechanism resembles galactic cosmic ray acceleration.

3. The galactic centre 0.511 MeV line

The richness of astronomy at 0.511 MeV is indicated by the great variety of astrophysical positron production mechanisms, and by the many astrophysical sites where such mechanisms could operate. These include cosmic ray interactions in the interstellar medium (Meneguzzi & Reeves 1975; Ramaty *et al.* 1979) radioactive decay in supernova remnants (Clayton *et al.* 1969; Ramaty & Lingenfelter 1979), e^+–e^- pair production in the strong magnetic fields of pulsars (Sturrock 1971; Sturrock & Baker 1979), electromagnetic processes (Blandford 1976; Lovelace 1976) and nuclear processes (Lingenfelter *et al.* 1978) in the vicinity of massive black holes in galactic nuclei, and the evaporation of primordial black holes (Okeke & Rees 1980). Because 0.511 MeV line emission has already been observed from the galactic centre (Leventhal *et al.* 1978, 1980), we devote this section to the discussion of the possible origins of this emission.

A potential source for the 0.511 MeV line from the galactic centre are energetic particle reactions. As we have seen, this mechanism can produce sufficient positrons to account for the observed 0.511 MeV line from solar flares, and, in the interstellar medium, cosmic ray interactions are known to produce the observed positrons in the galactic cosmic rays (see, for example,

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Ramaty 1974). But, for the galactic centre, energetic particles and cosmic rays appear to be responsible for only a small fraction of the observed 0.511 MeV line (Ramaty & Lingenfelter 1979), since positron production by energetic particles is accompanied by other emissions. In particular, subrelativistic particle interactions should lead to 4.4 MeV line emission from ^{12}C de-excitations and other nuclear lines in the 1–2 MeV range mainly from Mg, Si and Fe. The upper limits set on these emissions from the galactic centre by the γ-ray instrument on HEAO-1 (Matteson *et al.* 1979) imply that energetic particles up to energies of about 100 MeV per nucleon could produce not more than about 20 % of the observed 0.511 MeV line intensity. An even more stringent limit can be set on the contribution of higher-energy particles or cosmic rays which would produce positrons from π^+ decay. Since the production of π^+ mesons is accompanied by the production of π^0 mesons which decay into high-energy γ-rays, the γ-ray observations (above 100 MeV) of SAS-2 and COS-B limit the contribution of cosmic rays to not more than about 2 % of the observed 0.511 MeV line from the galactic centre.

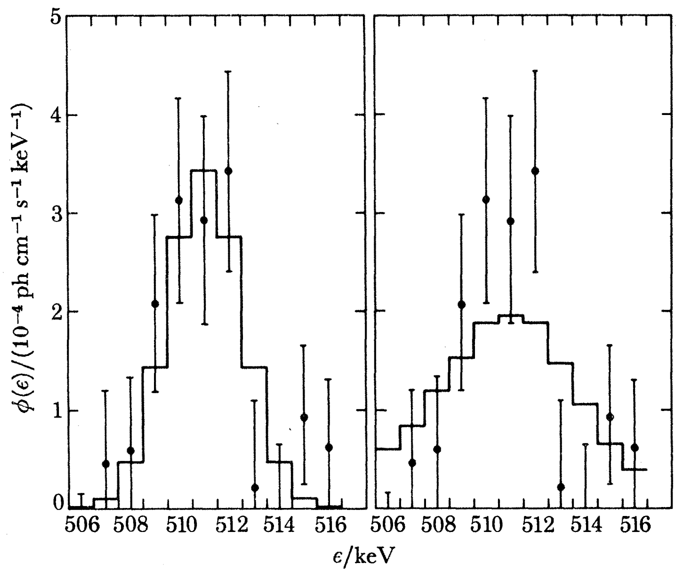

FIGURE 2. Calculated 0.511 MeV line spectra for e^+–e^- annihilation. The data points are from Leventhal *et al.* (1978). The histograms in the left and right panels show the line profiles in ionized and neutral H, respectively. The ionized case is for T = 8000 K and $n_e > n_H$. Both profiles have been broadened in accordance with the instrumental width of the Leventhal *et al.* detector (f.w.h.m. ≈ 3 keV), and their absolute intensities have been varied for a best fit to the data. The calculations have been made by R. W. Bussard using the theory of Bussard *et al.* (1979).

Currently, however, the strongest constraints on the origin of the 0.511 MeV line from the galactic centre come from recent observations with the Ge spectrometer on HEAO-3. These observations indicate that the source of the 0.511 MeV line is confined to an angular size smaller than the 30° f.w.h.m. of the detector (Mahoney *et al.* 1980), that the centroid of the source is within a few degrees of the galactic centre (G. Riegler, private communication 1980), and that the emission very likely varies with time (Riegler *et al.* 1980). More specifically, the 0.511 MeV line was observed by the HEAO-3 detector during a scan of the galactic plane in the autumn of 1979, but was not seen by this detector in a scan six months later. These observations suggest that the 0.511 MeV line is probably produced by a discrete object at the galactic centre, and that the size of the e^+ annihilation region does not exceed about one light year.

This conclusion is consistent with an earlier inference on the nature of the annihilation region (Bussard *et al.* 1979), based on the very narrow observed width of the 0.511 MeV line. These authors showed that the observed line shape suggests that the annihilation site of the positrons is a relatively low-density, partially ionized gas of temperature less than about 10^5 K. This argument is based on the fact that in a cold and neutral medium (e.g. dark interstellar clouds) the linewidth would be larger than observed. In such a medium, the line is Doppler broadened, not by the thermal motions of the medium, but by the velocities of the positrons forming positronium atoms in flight by charge exchange with neutral H. This leads to a width that exceeds the observed linewidth (see figure 2). In a partially ionized gas ($n_e \gtrsim 0.1 n_H$), on the other hand, the positron energy losses to the plasma are high enough to thermalize the positrons before they annihilate or form positronium. The linewidth does then reflect the temperature of the medium and leads to a narrower width consistent with the observations. This can be seen in figure 2 (Bussard *et al.* 1979; R. W. Bussard, private communication 1979).

Such an annihilation region can be found in the central light year of the Galaxy, in the warm clouds of ionized gas within Sgr A West. These clouds, observed in an infrared fine-structure line of Ne II (Lacy *et al.* 1979, 1980), orbit the galactic centre at distances of the order of a light year, and have temperatures, ionization states, and densities of the right magnitude to account for the observed width of the γ-ray line and for the observed continuum from triplet positronium annihilation (Leventhal *et al.* 1978). According to a recent calculation (Ramaty *et al.* 1981), e^+–e^- pairs, emitted from a central object, could stop and annihilate in these i.r. clouds, to produce the observed 0.511 MeV line. The source size would then be of the order of a light year, consistent with the time variability data, and it would appear point-like to all currently used or planned γ-ray detectors.

The observed 0.511 MeV line intensity from the galactic centre requires the production of *ca.* 2×10^{43} e^+ s^{-1} (see, for example, Ramaty & Lingenfelter 1979), and the apparent time variability implies a single source. It is unlikely that this object is a pulsar, since the rate of positron production in pulsars is not expected to exceed about 10^{41} e^+ s^{-1} (Sturrock & Baker 1979). A single type I supernova (see §5) would be a better candidate since it could produce sufficient positrons by explosive nucleosynthesis via the decay chain $^{56}Ni \longrightarrow {}^{56}Co \longrightarrow {}^{56}Fe$. But is is difficult to see how a supernova would produce a variable positron output as suggested by the observations.

One object that might produce such variability is (Ramaty *et al.* 1981) a massive, rapidly rotating Kerr black hole (Thorne 1974). Based on the distributions of the velocities of the i.r.-emitting clouds within the central parsec, Lacy *et al.* (1979, 1980) suggest the existence of a black hole of several million solar masses at the galactic centre. Accretion of matter onto this hole should form a disc around it. Powered by the gravitational energy of in-falling matter, this accretion disc is expected to radiate in the ultraviolet to produce the *ca.* 2×10^{50} ph s^{-1} required for the ionization of the clouds. The lower limit on the bolometric luminosity of the accretion disc is thus *ca.* 4×10^{39} erg s^{-1}† (Lacy *et al.* 1980).

The disc can also emit non-thermally. If it has an ordered component of magnetic field, then dynamo action (Blandford 1976; Lovelace 1976) caused by rotation can produce a large electric field which could initiate a photon and e^+–e^- pair cascade (Lovelace *et al.* 1979; Blandford 1979). Depending on the optical depth of the cascade region, the pairs that ultimately escape can have a range of kinetic energies. For a given total cascade energy, the number of escaping

† 1 erg s^{-1} = 10^{-7} W.

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pairs is close to a maximum if the bulk of them have kinetic energies close to mc^2. In this case, to produce *ca.* 2×10^{43} e$^+$–e$^-$ pair s^{-1}, as required by the 0.511 MeV observations, the pair luminosity has to be *ca.* 6×10^{37} erg s^{-1}. If an equal luminosity is contained in continuum photons that accompany the pairs (probably hard X-rays), the total non-thermal luminosity should be *ca.* 10^{38} erg s^{-1}. This is no more than a small percentage of the bolometric luminosity, and is of the same order as the hard X-ray luminosity of *ca.* 10^{38} erg s^{-1} from the central region of the Galaxy (Leventhal *et al.* 1980; Dennis *et al.* 1980).

A massive black hole at the galactic centre could thus be consistent with infrared, hard X-ray and 0.511 MeV observations. It is necessary, however, to establish more precisely the nature of the 0.511 MeV line variability and its correlation with other emissions, in particular the hard X-rays that may be produced by the same source. Observations with GRO, in particular with G.R.S.E. which has good sensitivity down to *ca.* 20 keV, should help confirm this very exciting possibility for the origin of the 0.511 MeV line from the galactic centre.

4. Lines from γ-ray transients

Despite more than a decade of observations, the origin of γ-ray bursts and other γ-ray transients remains unsolved. The observed distribution of the number of bursts as a function of apparent luminosity ($\lg N$ against $\lg S$) favours a galactic origin for the bulk of the bursts (Fishman *et al.* 1978; Jennings & White 1980), but it is not clear what population or populations of galactic objects are responsible for them. Moreover, the first burst whose source position has been well determined, the 5 March 1979 event (Barat *et al.* 1979; Cline *et al.* 1980; Evans *et al.* 1980; Mazets *et al.* 1979), appears to be extragalactic (Cline 1980) since its positional error box lies within the supernova remnant N49 in the Large Magellanic Cloud (L.M.C.). This burst, however, is exceptional and could belong to a different class of γ-ray transients than the more commonly observed galactic γ-ray bursts. This follows from the unique characteristics of the March 5 event which include the extremely rapid rise time (less than 2×10^{-4} s) of the impulsive emission, the relatively short duration (*ca.* 0.15 s) and high luminosity of this emission spike, the 8 s pulsed emission following the impulsive spike, and the subsequent outbursts (Mazets & Golenetskii 1981) of lower intensity from apparently the same source direction on 6 March, 4 April, and 24 April 1979. No other γ-ray burst shows all these characteristics (Cline 1980), and no other burst position coincides with likely candidate objects. Thus, while the 5 March 1979 event has generated much excitement, it has not given the origin of the γ-ray bursts.

More general information on the nature of γ-ray burst sources has come from observations of lines in the burst spectra. Emission lines and absorption features have been seen in the spectra of many γ-ray bursts and transients. The most commonly observed emission line falls in the range from 400 to 460 keV, as observed by Mazets *et al.* (1981) in seven γ-ray bursts. In the spectrum of one of these bursts, that of 19 November 1978, Teegarden & Cline (1980) have resolved two lines, at *ca.* 420 keV and 740 keV, which Mazets *et al.* (1981) have seen as one broad emission feature from 300 to 800 keV.

Line emission around 400 keV is most likely due to gravitationally redshifted e$^+$–e$^-$ annihilation radiation. Since the necessary redshifts of 0.1–0.3 are consistent with neutron star surface redshifts, these objects are very promising candidates for γ-ray burst sources. In determining the redshift of e$^+$–e$^-$ annihilation, however, it is necessary to consider the temperature of the annihilating pairs, since the emitted photon energy in the rest frame of an e^+–e^- pair is equal to the electron rest mass plus half of the kinetic energy of the pair in that frame. Thus, as the temperature increases, the annihilation line is not only broadened but also blueshifted (Zdziarski 1980). This is illustrated in figure 3 (Ramaty & Mészáros 1981), where annihilation spectra from an optically thin e^+–e^- plasma are shown for plasma temperatures of 10^8, 10^9, and 10^{10} K.

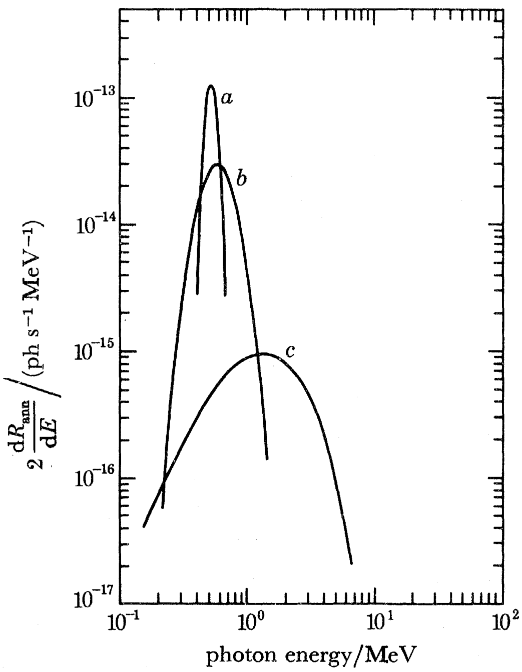

FIGURE 3. Calculated e^+–e^- optically thin annihilation spectra in a hot pair plasma (Ramaty & Mészáros 1981). *a*, $T = 10^8$ K; $R_{ann} = 7.3 \times 10^{-15}$ s^{-1}; f.w.h.m. = 0.11 MeV. *b*, $T = 10^9$ K; $R_{ann} = 6.4 \times 10^{-15}$ s^{-1}; f.w.h.m. = 0.41 MeV. *c*, $T = 10^{10}$ K; $R_{ann} = 1.2 \times 10^{-15}$ s^{-1}; f.w.h.m. = 1.4 MeV. R_{ann} is the rate of annihilation, i.e. one half the integral under the curves; $n_+ = n_- = 1$ cm^{-3}.

As can be seen, when kT becomes comparable with or larger than mc^2, the peak of the line is shifted to energies significantly greater than 0.511 MeV, and the line is substantially broadened. Therefore, to observe annihilation features above the continuum, the temperature in the region of annihilation must not be too high ($kT \ll mc^2$). On the other hand, conditions imposed by the pair production threshold require that the temperature be high enough ($kT \gtrsim mc^2$) to produce sufficient pairs. Thus, to observe e^+–e^- annihilation radiation from γ-ray bursts, a mechanism is needed to cool the pairs before they annihilate. Such a mechanism has been proposed by Ramaty *et al.* (1981), who showed that synchrotron cooling and subsequent annihilation of e^+–e^- pairs in the skin layer of a hot radiation-dominated pair atmosphere can account for the observed spectrum of the impulsive spike of the 5 March 1979 event. The necessary magnetic field, $B \gtrsim 10$ MT, is typical of neutron stars. Variants of this mechanism could be applicable to models for the observed spectral features at *ca.* 400 keV for other γ-ray bursts. The cyclotron features observed between 30 and 70 keV from several of these bursts (Mazets *et al.* 1981) also require large magnetic fields and thus suggest, as well, that neutron stars are the sources of at least some of the γ-ray bursts.

The line at 740 keV observed by Teegarden & Cline (1980) in the spectrum of the 19 November 1978 γ-ray burst may also indicate a neutron star source, since this could be gravitationally redshifted 847 keV emission from ^{56}Fe, an abundant constituent of neutron star surfaces. On timescales typical of γ-ray bursts, this line can only be produced by energetic particle reactions with neutron star surface material (Ramaty *et al.* 1973). Such reactions produce other γ-ray lines (see, for example, figure 1) whose detection would provide further information on the temperature and composition of the neutron star surface material.

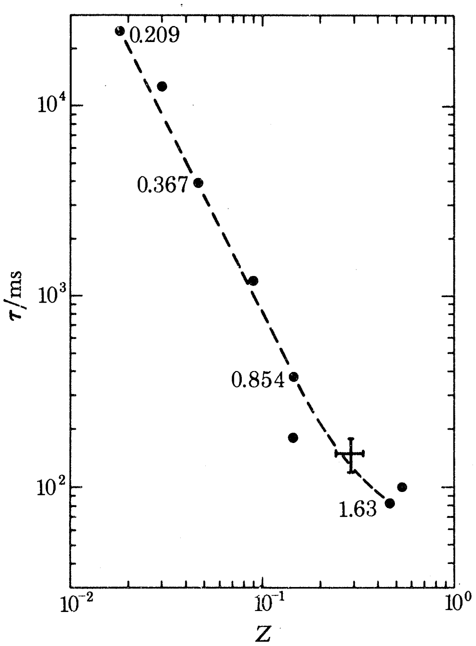

FIGURE 4. The calculated (Detweiler 1975) (●) quadrupole gravitational radiation damping time against gravitational redshift for neutron stars. The dashed curve connects cases having the same equation of state, and the numerical values are neutron star masses in multiples of $M_{\odot}$. The datum point (ɨ┼ɨ) is from γ-ray observations of the 5 March transient (Mazets *et al.* 1979; Barat *et al.* 1979; Cline *et al.* 1980).

Although observations of 400 keV line emission from the 5 March 1979 event (Mazets *et al.* 1979) suggest that the source of this transient was also a neutron star, the origin of this spectacular event remains unresolved. The central question is whether the burst did indeed originate in the L.M.C., or whether its source was much closer. In the latter case, it has been suggested (Mazets *et al.* 1979) that the burst direction just happened to coincide with that of N49. Several theorists (Aharonian & Ozernoy 1979; Mitrofanov 1981; Bisnovatyi-Kogan & Chechetkin 1980; Colgate & Petchek 1980) have also opted for this possibility, since it obviously relieves the quite severe energy and luminosity requirements implied by the large distance to a source in the L.M.C. This approach, however, ignores potentially most interesting data, namely the remarkably precise source direction which coincides with that of an interesting astronomical object. Ramaty *et al.* (1980) and Ramaty *et al.* (1981) have taken the positional data at face value and have argued that there is no intrinsic theoretical difficulty in observing a burst of the 5 March kind from a neutron star at the L.M.C. distance. In their model, the γ-ray emission is produced by the conversion of the mechanical energy of the magnetized crust of a vibrating neutron star into electromagnetic emission, including e^+–e^- pairs. Because the energy that can be stored in the atmosphere of the star is much smaller than the total emitted energy, the object radiates only as long at it continues to vibrate. The damping of the vibrations, therefore, determines the duration of the burst. Indeed, an interesting aspect of this theory is that the neutron star mass: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. This can be seen in figure 4 (from Ramaty *et al.* 1980, with the use of calculations of Detweiler 1975) which shows the damping time of quadrupole and higher mode neutron star vibrations as a function of surface redshift, the dashed curve connecting points obtained from the same equation of state. The numerical values next to these points are the corresponding neutron star masses in multiples of $M_{\odot}$. The 5 March 1979 data point shows the observed duration of the impulsive phase (120–180 ms) against the approximate redshift. The implied neutron star mass is about $1–1.3 \times M_{\odot}$, its radius about 10 km, and its quadrupole vibrational frequency about 0.4 ms. Gamma-ray spectroscopy, by suggesting a neutron star origin for the 5 March transient and by pointing toward a gravitational origin of the redshift, has played a key role in the development of these ideas.

There is apparently another class of γ-ray transients in which essentially all the observed radiation is in the form of lines. Such a γ-ray line transient was discovered (Jacobson *et al.* 1978) with a high resolution Ge detector on 10 June 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. There are no simple schemes that can account for all four observed lines, primarily because there is no obvious candidate for the line at *ca.* 5.95 MeV. Lingenfelter *et al.* (1978), however, have suggested that the observed lines could result from episodic accretion onto a neutron star from a binary companion, thus producing both redshifted and non-redshifted lines. The observations could then be understood in terms of neutron capture and positron annihilation, which are also the strongest line-producing mechanisms in solar flares. Specifically, such accretion onto a neutron star from a close binary companion could lead to the formation of a high temperature (above 10^{10} K for ions) accretion disc in which nuclear interactions could occur producing neutrons and positrons. Positron annihilation and neutron capture on hydrogen and iron at and near the surface of the neutron star with a surface redshift of *ca.* 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 essentially 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 observed because of the large atmospheric and detector background at this energy, while the line emission from neutron capture on iron should be significant only in the redshifted emission from the iron-rich surface of the neutron star but not in the non-shifted emission.

5. Prospects for γ-ray line detections

As mentioned in the Introduction, in addition to the 0.511 MeV line from the galactic centre and the lines from γ-ray bursts, there are other astrophysical γ-ray lines which, although below the sensitivity of detectors flown so far, should be detectable with good statistical significance with future detectors, particularly those on GRO. These lines are produced by processes of nucleosynthesis in supernovae and novae, and by low-energy cosmic ray interactions in the

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interstellar medium. In addition, the 0.511 MeV line should be observed from a variety of sites other than the galactic centre, for example the interstellar medium, supernovae, pulsars, and possibly active galaxies. Concerning the galactic centre, high sensitivity and high angular and energy resolution measurements will give further information on the time variability, line shape and spatial location of the 0.511 MeV source, and thus test the ideas discussed in §3. Finally, the spectroscopy of γ-ray transients, along with precise source locations for a larger number of events than available so far, will reveal more about the origins of these phenomena. It may turn out that γ-ray spectroscopy will do for neutron stars what optical spectroscopy has done for ordinary stars.

(a) *Gamma-ray lines from processes of nucleosynthesis*

The origin of the elements is one of the major problems in astrophysics, and it is recognized (see, for example, Clayton *et al.* 1969) that the detection of γ-ray lines from radioactive nuclides produced by explosive nucleosynthesis in supernovae would be a major contribution to its understanding. The detection of such lines would provide clear evidence that elements are produced continually throughout the lifetimes of galaxies, and provide much information on supernova explosions. The lines most likely to be detected are at 1.809 MeV from ^{26}Al decay, at 0.847 and 1.238 MeV from ^{56}Co decay, and at 1.156, 0.078 and 0.068 MeV from ^{44}Ti decay. In addition, the 0.511 MeV line from the annihilation of positrons accompanying these decays is also very likely detectable.

Explosive nucleosynthesis could produce masses of ^{56}Ni of the order of $10^{-1} \times M_{\odot}$ per supernova. This isotope decays with a half-life of 6 days into excited states of ^{56}Co, but the resultant γ-ray lines are probably not visible because the supernova shell is not expected to become transparent in such a short time interval. On the other hand, γ-ray lines from ^{56}Co decay (half-life 77 days) should be seen, but only from young type I supernova remnants because the larger ejected masses of type II supernovae would remain opaque to line emission for times much longer than the half-life of ^{56}Co. The best prospects for detecting these lines are from extragalactic supernovae, since it is unlikely that a galactic supernova would occur shortly before or during the flight of a γ-ray spectroscopy experiment such as the two-year mission of GRO.

According to earlier estimates (Clayton 1973; Lingenfelter & Ramaty 1978) and more recent detailed calculations (Woosley *et al.* 1981), the intensities of the 0.847 and 1.238 MeV lines from a supernova at 10 Mpc should be about 10^{-4} and 7×10^{-5} ph cm^{-2} s^{-1} respectively. These lines are expected to be significantly Doppler broadened by the *ca.* 10^4 km s^{-1} expansion velocity of the supernova. The f.w.h.m. of the 0.847 MeV line should be about 60 keV. The NaI instrument, O.S.S.E., on GRO has a sensitivity of about 10^{-5} ph cm^{-2} s^{-1} to such broadened lines, and should be able, therefore, to detect the ^{56}Co lines from a supernova in the Virgo cluster. About one supernova per year is detected optically from this cluster (Tammann 1974), but the actual rate could be larger if some of them are obscured by dust. Thus, there is a good chance for observing the ^{56}Co lines from a type I supernova in the Virgo cluster during the lifetime of GRO.

Galactic ^{56}Co decay could be observed in the 0.511 MeV line from the annihilation of the positrons that accompany this decay (0.2 positron per ^{56}Co disintegration). As discussed in §3, the 0.511 MeV line from the galactic centre appears to come from a single point source which is probably not a young supernova. However, the positrons that escape the supernova shells and later annihilate primarily in the warm and cold phases of the interstellar medium, would produce an essentially steady 0.511 MeV emission, since the annihilation time is much longer (*ca.* 10^5 years) than the interval between galactic supernova explosions. As discussed in §3, the annihilation linewidth in the cold interstellar medium is *ca.* 5 keV; in the warm medium, which is partially ionized, the width is less than 3 keV.

If $M/M_\odot$ solar masses of ^{56}Ni are produced per supernova, and if a fraction, f_{esc}, of the positrons from the resultant ^{56}Co decay escape the supernova shell, then, for a type I supernova rate of 0.02 $year^{-1}$ in the Galaxy, the total rate of galactic 0.511 MeV line luminosity is *ca.* $2 \times 10^{45}(M/M_\odot)\, f_{esc}$ ph s^{-1}. If we compare this luminosity with that of 100 MeV photons (*ca.* 5×10^{41} ph s^{-1}, Higdon & Lingenfelter 1976), we can use the observed (Fichtel *et al.* 1975) γ-ray intensity above 100 MeV from the general direction of the galactic centre, *ca.* 10^{-4} ph $cm^{-2}\,s^{-1}\,rad^{-1}$, to estimate a diffuse galactic plane 0.511 MeV line intensity of approximately $0.4(M/M_\odot)\,f_{esc}$ ph $cm^{-2}\,s^{-1}\,rad^{-1}$. Since $M/M_\odot$ could be about 0.5 (Axelrod 1980), the Ge instrument on GRO, G.R.S.E., with a sensitivity of *ca.* 10^{-5} ph $cm^{-2}\,s^{-1}\,rad^{-1}$, could test models with f_{esc} as low as 5×10^{-5}. A previous estimate (Colgate 1970) suggested that $f_{esc} \approx 0.1$.

Another set of important lines are those from ^{44}Ti decay. Explosive nucleosynthesis could produce about $2 \times 10^{-4}\,M_\odot$ of ^{44}Ti per supernova. This isotope decays with a half-life of 47 years into an excited state of ^{44}Sc, which cascades to its ground state, emitting lines at 0.078 and 0.068 MeV. ^{44}Sc subsequently decays into the 1.156 MeV state of ^{44}Ca, but, since the half-life of this decay is very short (3.9 h), the relevant lifetime for all three ^{44}Ti-generated lines is 47 years. Within such a time interval, the shells of both type I and type II supernovae should become transparent, but the type I have the larger ^{44}Ti yield (Woosley *et al.* 1981). At any given time, there should be several young galactic remnants of such supernovae that could be visible in ^{44}Ti lines, since the half-life is comparable with the typical time between galactic supernova explosions. Most importantly, the half-life is short enough to allow the detection of hitherto unknown individual remnants which are too young to have begun producing detectable radio emission. With the above yield of ^{44}Ti, a 50-year-old remnant at 10 kpc, for example, would produce 1.156, 0.078 and 0.068 MeV line intensities of *ca.* 1.5×10^{-4} $cm^{-2}\,s^{-1}$. Because of Doppler broadening due to the expansion of the supernova shell, the 1.156 MeV line will be best detected by O.S.S.E.; the 0.078 and 0.068 MeV lines can be better seen by G.R.S.E., since O.S.S.E. is not sensitive below about 0.1 MeV.

Processes of nucleosynthesis in type II supernovae can be best observed in γ-ray lines from radionuclides with long lifetimes. The line with the best prospects for detection (Ramaty & Lingenfelter 1977; Arnett 1977) is at 1.809 MeV from ^{26}Al decay (half-life *ca.* 7×10^5 years). That ^{26}Al is indeed produced in supernovae is strongly supported by cosmochemical data (Lee *et al.* 1977) as well as by recent detailed theoretical nuclear network and stellar evolution calculations (Weaver & Woosley 1980). We also note that nucleosynthesis in novae (Wallace & Woosley 1981) and red giants (Norgaard 1981) may contribute to ^{26}Al production. Because of its long lifetime, ^{26}Al decays and produces γ-rays after it has been mixed into the interstellar medium. The 1.809 MeV line, therefore, is expected to be spatially diffuse, reflecting the distribution of type II supernovae in the galactic plane, and spectrally very narrow, since it is broadened only by motions of the interstellar medium. The predicted intensity of the line is about 5×10^{-5} ph $cm^{-2}\,s^{-1}\,rad^{-1}$ and its f.w.h.m. about 3 keV determined principally by galactic rotation (Ramaty & Lingenfelter 1977). G.R.S.E. should have sufficient sensitivity, energy and angular resolution to resolve the line and thus possibly provide information on the distribution of ^{26}Al along lines of sight.

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Other γ-ray lines from processes of nucleosynthesis resulting from the decay of long-lived radioactivity are at 1.332 MeV and 1.173 MeV from ^{60}Co decay (Clayton 1973). The theoretical predictions about these lines are less certain than those for ^{26}Al, but their intensities could be of the same order as that of the 1.809 MeV line.

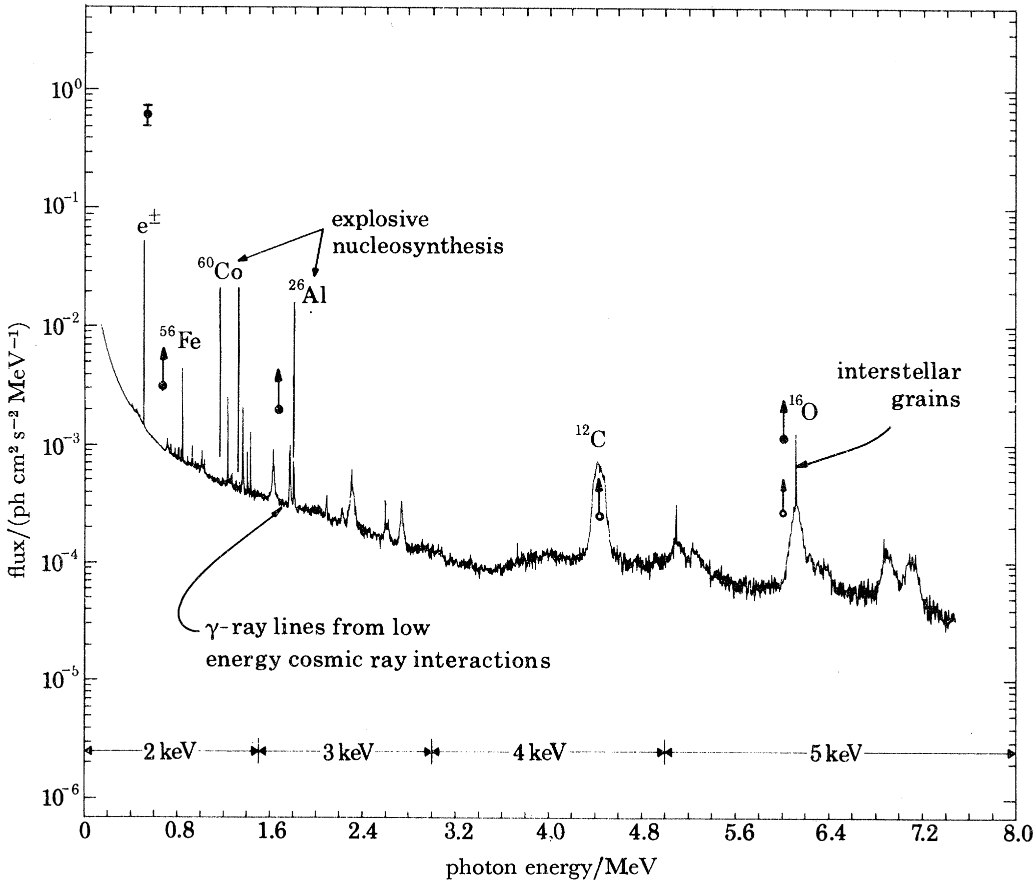

FIGURE 5. Diffuse γ-ray line emission from the interstellar medium. Lines of low-energy cosmic ray interactions are from Ramaty *et al.* (1979), and of explosive nucleosynthesis as explained in the text. The GRO-G.R.S.E. sensitivities for very narrow lines (●↑) and narrow lines (○↑) are from J. Matteson (1980 private communication ⧳, Leventhal *et al.* (1978).

(*b*) *Lines from low-energy cosmic ray interactions*

Calculations of diffuse line emission from cosmic ray interactions in the interstellar medium have been made most recently by Ramaty *et al.* (1979). This line emission results principally from the interactions of protons and nuclei in the energy range from about 1–100 MeV per nucleon with interstellar gas and dust. These interactions are quite similar to those producing the observed γ-ray lines from solar flares. There are, however, several important differences: In the interstellar medium, but not in the solar atmosphere, a large fraction of the heavy nuclei are in grains, and for sufficiently large grain sizes γ-ray line emission has a very narrow component (Lingenfelter & Ramaty 1977) resulting from de-excitations of nuclei embedded in grains. The most conspicuous grain line is the very narrow component of the 6.129 MeV line in ^{16}O (figure 5) which has no counterpart in the solar spectrum (figure 1). On the other hand,

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the strongest solar flare line, at 2.223 MeV from neutron capture, should not be present in the interstellar spectrum, since the hydrogen density is not high enough (above 10^{16} cm^{-3}) to capture the neutrons before they decay.

A calculated interstellar γ-ray line spectrum is shown in figure 5 (Ramaty *et al.* 1979). This spectrum results primarily from cosmic ray interactions in the interstellar medium based on a local low-energy cosmic ray density of 1 eV cm^{-3}, and a gradient in both this density and the relative abundances of interstellar heavy nuclei towards the galactic centre. There are, of course, large uncertainties in these parameters, but detection of such line emission could provide direct information about them.

The 1.809, 1.332 and 1.173 MeV lines also shown in figure 5 are from explosive nucleosynthesis. As discussed in §5(*a*) above, the intensity of each of these lines is *ca.* 5×10^{-5} ph cm^{-2} s^{-1} rad^{-1}; they are shown in figure 5 with f.w.h.m. of 3 keV for the ^{26}Al line and 2 keV for the ^{60}Co lines.

The 0.511 MeV line, shown with a f.w.h.m. of 2 keV, is from positrons produced solely by low-energy cosmic ray interactions. The intensity is *ca.* 10^{-4} ph cm^{-2} s^{-1} rad^{-1}, which is larger than that given by Ramaty *et al.* (1979) because of the additional positron-producing reactions that we have recently taken into account (B. Kozlovsky, private communication, 1980). This intensity is comparable with that expected from ^{56}Co decay positrons escaping from supernova shells (see estimate in §5(*a*)) if $(M/M_{\odot}) f_{esc} \approx 3 \times 10^{-4}$.

Also shown in figure 5 are the sensitivities of the G.R.S.E. experiment on GRO to diffuse lines from the galactic plane based on three combined exposures of 30 days each (J. Matteson, private communication, 1980). The closed circles show the sensitivity to very narrow lines, i.e. lines of width comparable with or less than the instrumental resolution, while the open circles are the sensitivities to the narrow 4.44 and 6.13 MeV lines. As can be seen, G.R.S.E. could have sufficient sensitivity to detect the strongest lines from cosmic ray interactions at 0.847, 4.44 and 6.129 MeV, providing information on the low-energy cosmic ray intensity and interstellar grains. In addition, this experiment has a good chance of seeing the 1.809 MeV line of ^{26}Al and thereby measuring the current rate of galactic nucleosynthesis. Finally, G.R.S.E. should certainly observe both diffuse and discrete sources of 0.511 MeV emission from the galactic plane with high statistical significance and high spatial and energy resolution, allowing a variety of studies, including the determination of the relative contributions of the various galactic positron-producing mechanisms.

6. Summary

We have discussed in this paper the interpretations and implications of astrophysical γ-ray line observations. Such lines have so far been seen from solar flares, the galactic centre and γ-ray transients. In flares, γ-ray lines are an excellent probe of energetic protons and nuclei. The continuing observations with the γ-ray spectrometer on S.M.M. during the current maximum of solar activity should lead to much new insight into particle acceleration mechanisms and the flare process itself.

The 0.511 MeV line from the galactic centre, first observed by balloon-borne detectors, has been confirmed by the HEAO-3 γ-ray spectrometer. The preliminary HEAO-3 data indicate that the line is time-variable, a result whose implication is that the positrons are produced by a discrete source, possibly a massive black hole, within an annihilation region no larger than a light year at the galactic centre.

Gamma-ray lines seen in the spectra of γ-ray bursts strongly suggest that neutron stars are

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the sources of at least some of these bursts. The most commonly observed emission line is in the range from 400 to 450 keV, where it is likely to be gravitationally redshifted positron–electron annihilation radiation. The short duration of the 5 March 1979 burst may reflect the damping of neutron star vibrations by gravitational radiation.

No γ-ray lines have yet been seen from processes of nucleosynthesis, but good prospects exist for detecting the lines produced by the decay of ^{26}Al, ^{56}Co and ^{44}Ti.

The research was supported by NSF Grant AST 79–11987 and NASA Grant NSG–7541.

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