NASA

Technical Memorandum 82066

Interpretations and Implications of Gamma Ray Lines from Solar Flares, the Galactic Center in Gamma Ray Transients

R. Ramady and R. E. Lingenfelter

NOVEMBER 1980

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

INTERPRETATIONS AND IMPLICATIONS OF GAMMA RAY LINES FROM SOLAR FLARES, THE GALACTIC CENTER AND GAMMA RAY TRANSIENTS*

R. Ramaty
Laboratory for High Energy Astrophysics
Goddard Space Flight Center
Greenbelt, MD, USA

R. E. Lingenfelter**
Center for Astrophysics and Space Research
University of California, San Diego
La Jolla, CA, USA

Abstract

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

---

* Invited paper presented at the Royal Society Meeting on Gamma Ray Astronomy, November 27-28, 1980. To be published in the Philosophical Transactions of the Royal Society

** Research supported by NSF Grant AST 79-11987 and NASA Grant NSG-7541

I. INTRODUCTION

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

Gamma ray line emission resulting from nuclear interactions of flare accelerated particles with the 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, Kozlovsky, and Lingenfelter 1975, Lin and Ramaty 1978, Ramaty et al. 1980). We discuss the solar gamma-ray spectroscopy results in Section II.

The first convincing detection of an extra-solar gamma ray line was that of the positron annihilation line at 0.511 MeV (Leventhal, MacCallum, and Stang 1978) from the direction of the galactic center. 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 (Mahoney, Long, and Jacobson 1980, 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 gamma ray astronomy may prove to be comparable to that of K-shell Fe line emission in X-ray astronomy and 21-cm line emission in radio astronomy. We discuss the galactic center observations, including implications of the new HEAO-3 results in Section III.

Gamma ray lines have also been seen in gamma ray transients. Spectra of several gamma ray bursts show (Mazets et al. 1979, 1980; Teegarden and Cline 1980) emission lines thought to be redshifted positron annihilation and cyclotron absorption lines in teragauss (10^{12} gauss) magnetic fields. All of these observations strongly suggest that at least some of the gamma ray burst sources are neutron stars. Gamma ray lines have also been seen in at least one transient of longer duration than the gamma ray bursts (Jacobson et al. 1978), and the identification of these lines as well, requires a redshift characteristic of $\sim 1 M_{\odot}$ neutron stars (Lingenfelter, Higdon, and Ramaty 1978). Transient gamma ray spectroscopy is treated in Section IV.

There are in addition a variety of other astrophysical gamma 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) which are particularly suitable to make these observations: the Gamma Ray Spectroscopy Experiment (GRSE), a high resolution Ge spectrometer with a broad field of view and good angular resolution achieved by a rotating modulator, and the Oriented Scintilation Spectroscopy Experiment (OSSE), a moderate resolution NaI instrument of high sensitivity to astrophysically broadened lines. In Section V we compare the predicted intensities of the most promising gamma ray lines with the sensitivities of these detectors.

II. SOLAR GAMMA 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 gamma ray lines from neutron capture, positron annihilation and nuclear deexcitation. Observation of such gamma rays can provide unique information on high energy processes at the Sun. The first solar gamma ray lines, at 0.511, 2.22, 4.44, and 6.13 MeV, were observed (Chupp et al. 1973) by a NaI detector on the OSO-7 satellite during the August 4, 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 SMM (Chupp et al. 1981) satellites. The measured relative intensities of these four lines were consistent with earlier predictions (Lingenfelter and Ramaty 1967).

In all of these flare observations the strongest line is that at 2.223 MeV, due to neutron capture on hydrogen, $^1H(n,\gamma)^2H$. The neutrons, initially produced at energies of about 1 to 100 MeV, are thermalized and captured in the photosphere. This leads to a delay of about 1 to 2 minutes 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 (August 4, 1972, Chupp et al. 1973; July 11, 1978, Hudson et al. 1980; November 9, 1979, Prince et al. 1980; June 7, 1980, Chupp et al. 1981). Neutron capture on ^1H in the photosphere must compete (Wang and Ramaty 1974) with capture on ^3He, even though ^3He is only a minor constituent of the photosphere, because the cross section for the reaction $^3He\ (n,p)^3H$ is about four orders of magnitude larger than that for the reaction $^1H\ (n,\gamma)^2H$. Observations of the intensity of the 2.223 MeV line compared to that of other lines can limit the photospheric $^3He/^4He$ ratio

ORIGINAL PAGE IS
OF POOR QUALITY

to several times 10^{-4}; this limit is comparable to that measured in the chromosphere (Hall 1975) and solar wind (Geiss and Reeves 1972). The width of the 2.223 MeV line, determined by the photospheric temperature, is expected to be very narrow (~ 100 eV), a result consistent with the high resolution HEAO-3 observations (Prince et al. 1980) which have set an upper limit of several keV on the width of this line.

The second strongest solar flares line, at 0.511 MeV, is from the annihilation of positrons. There are many astrophysically important positron production mechanisms, as discussed in Section III, but in solar flares the 0.511 MeV line results from energetic particle reactions which lead to a variety of 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 keV to tens of MeV, but only a small fraction annihilate at these high energies. The bulk of the positrons slow down to energies comparable to those of the ambient electrons, where annihilation takes place either directly or via positronium (Wang and Ramaty 1975, Crannell et al. 1976). Positronium is formed by radiative combination with free electrons and by charge exchange with neutral hydrogen; 25 percent of the positronium atoms are in the singlet state and 75 percent 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 ~ 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.

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 several tens of keV, 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 (~ 40 keV) on the 0.511 MeV line width, and while the gamma ray spectrometer on SMM 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 November 9, 1979 flare, was not sensitive enough to solar gamma rays at lower energies to detect the line at 0.511 MeV. We hope that the necessary high resolution observations will be carried out during the next solar maximum around 1990.

Energetic particle reactions also lead to many other lines, resulting from deexcitation of nuclear levels. The two strongest lines, at 4.44 and 6.13 MeV due to $^{12}C^*$ and $^{16}O^*$ deexcitation respectively, were observed (Chupp et al. 1973) from the solar flare of August 4, 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 August 4 flare. The deexcitation lines were obtained from a Monte Carlo calculation using excitation functions for ~ 100 nuclear lines derived from either laboratory measurements or theoretical interpolations and evaluations (Ramaty, Kozlovsky, and Lingenfelter 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.

At the present, 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-to-proton ratio in the accelerated particles (Ramaty, Kozlovsky, and Lingenfelter 1975, Chupp 1975, Ramaty 1979, Ramaty et al. 1980). It appears that the nuclei are accelerated during or very soon after the flash phase of the flare, that the gamma 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 several percent of the total flare energy. From the analysis of the gamma ray line to 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.

III. THE GALACTIC CENTER 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 and Reeves 1975, Ramaty, Kozlovsky, and Lingenfelter 1979), radioactive decay in supernova remnants (Clayton et al. 1969, Ramaty and Lingenfelter 1979), $e^+ - e^-$ pair production in the strong magnetic fields of pulsars (Sturrock 1971, Sturrock and 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 and Rees 1980). Because 0.511 MeV line emission has already been observed from the galactic center (Leventhal et al. 1978, 1980; Mahoney et al. 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 center is 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 (e.g., Ramaty 1974). But for the galactic center, energetic particles and cosmic rays appear to be responsible for only a small fraction of the observed 0.511 MeV line (Ramaty and Lingenfelter 1979), since positron production by energetic particles is accompanied by a variety of other emissions. In particular, subrelativistic particle interactions should lead to 4.4 MeV line emission from ^{12}C deexcitations and other nuclear lines in the 1 to

2 MeV range mainly from Mg, Si, and Fe. The upper limits set on these emissions from the galactic center by the gamma ray instrument on HEAO 1 (Matteson, Nolan, and Peterson 1979) imply that energetic particles up to energies of about 100 MeV/nucleon could produce not more than about 20 percent 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 gamma rays, the gamma ray observations (> 100 MeV) of SAS II and CosB limit the contribution of cosmic rays to not more than about 2 percent of the observed 0.511 MeV line from the galactic center.

The strongest constraints on the origin of the 0.511 MeV line from the galactic center at the present, however, 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° FWHM of the detector (Mahoney et al. 1980), that the centroid of the source is within a few degrees of the galactic center (G. Riegler, private communication 1980), and that the emission is very likely time variable (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 fall of 1979, but was not seen by this detector in a subsequent scan 6 months later. These observations suggest that the 0.511 MeV line is probably produced by a discrete object at the galactic center, and that the size of the e+ annihilation region does not exceed about 1 light year.

This conclusion is consistent with an earlier inference on the nature of the annihilation region (Bussard, Ramaty, and Drachman 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 $\sim 10^5$K. This argument is based on the fact that in a cold and neutral medium (e.g., dark interstellar clouds) the line width 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 line width (See Figure 2). In a partially ionized gas ($n_e \geqslant 0.1\ n_H$), on the other hand, the positron energy losses to the plasma are high enough to thermalize the positrons before they annihilate or form positronium. In this case, the line width does 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).

An annihilation region of such nature 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 center 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 gamma ray line and for the observed continuum from triplet positronium annihilation (Leventhal et al. 1978). According to a recent calculation (Ramaty, Leiter and Lingenfelter 1981), e^+- e^- pairs emitted from a central object, could stop and annihilate in these

IR 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 presently employed or planned gamma ray detectors.

The observed 0.511 MeV line intensity from the galactic center requires the production of ~ 2 x 10^{43} e^+/sec (e.g., Ramaty and 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^+/sec (Sturrock and Baker 1979). A single Type I supernova (see Section V) would be a better candidate since it could produce sufficient positrons by explosive nucleosynthesis via the decay chain $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$. But it 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, Leiter and Lingenfelter 1981) a massive, rapidly rotating Kerr black hole (Thorne 1974). Based on the distributions of the velocities of the IR-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 center. Accretion of matter onto this hole should form a disk around it. Powered by the gravitational energy of infalling matter, this accretion disk is expected to radiate in the ultraviolet to produce the ~ 2 x 10^{50} photons/sec required for the ionization of the clouds. The lower limit on the bolometric luminosity of the accretion disk is thus ~ 4 x 10^{39} erg/sec (Lacy et al. 1980).

The disk can also emit nonthermally. If it has an ordered component of magnetic field, 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, MacAuslan, and Burns 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 pairs is close to maximum if the bulk of them have kinetic energies close to mc^2. In this case, to produce $\sim 2 \times 10^{43}$ $e^+ - e^-$ pairs/sec, as required by the 0.511 MeV observations, the pair luminosity has to be $\sim 6 \times 10^{37}$ erg/sec. If an equal luminosity is contained in continuum photons that accompany the pairs (probably hard X-rays), the total nonthermal luminosity should be $\sim 10^{38}$ erg/sec. This is no more than a few percent of the bolometric luminosity, and is of the same order as the hard X-ray luminosity of $\sim 10^{38}$ erg/sec from the central region of the galaxy (Leventhal et al. 1980, Dennis et al. 1980).

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

IV. LINES FROM GAMMA RAY TRANSIENTS

Despite more than a decade of observations, the origin of gamma ray bursts and other gamma ray transients remains unsolved. The observed distribution of the number of bursts as a function of apparent luminosity (log N versus log S) favors a galactic origin for the bulk of the bursts (Fishman et al. 1978, Jennings and 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 March 5, 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 (LMC). This burst, however, is exceptional and could belong to a different class of gamma ray transients than the more commonly observed galactic gamma ray bursts. This follows from the unique characteristics of the March 5 event which include the extremely rapid rise time ($< 2 \times 10^{-4}$ sec) of the impulsive emission, the relatively short duration (~ 0.15 sec) and high luminosity of this emission spike, the 8-sec pulsed emission following the impulsive spike, and the subsequent outbursts (Mazets and Golenetskii 1981) of lower intensity from apparently the same source direction on March 6, April 4, and April 24, 1979. No other gamma ray burst shows all these characteristics (Cline 1980), and no other burst position coincides with likely candidate objects. Thus, while the March 5, 1979 event has generated much excitement, it has not solved the origin of the gamma ray bursts.

More general information on the nature of gamma 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 gamma 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. (1980) in seven gamma ray bursts. In the spectrum of one of these bursts, that of November 19, 1978, Teegarden and Cline (1980) have resolved two lines, at ~ 420 keV and 740 keV, which Mazets et al. (1980) 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 to 0.3 are consistent with neutron star surface redshifts, these objects are very promising candidates for gamma 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 (Mészáros and Ramaty 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. As can be seen, when kT becomes comparable to 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 excessively 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 gamma ray bursts, a mechanism is needed to cool the pairs before they annihilate. Such a mechanism has been proposed by Ramaty, Lingenfelter, and Bussard (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 March 5, 1979 event. The necessary magnetic field, $B \gtrsim 10^{11}$ gauss, is typical of neutron stars. Variants of this mechanism could be applicable to models for the observed $\sim$ 400 keV spectral features for other gamma ray bursts. The cyclotron features observed between 30 and 70 keV from several of these bursts (Mazets et al. 1980) also require large magnetic fields and thus suggest, as well, that neutron stars are the sources of at least some of the gamma ray bursts.

The line at 740 keV observed by Teegarden and Cline (1980) in the spectrum of the November 19, 1978 gamma ray burst may also indicate a neutron star source, since it could be gravitationally redshifted 847 keV emission from ^{56}Fe, an abundant constituent of neutron star surfaces. On time scales typical of gamma ray bursts, this line can only be produced by energetic particle reactions with neutron star surface material (Ramaty, Borner, and Cohen 1973). Such reactions produce a variety of other gamma ray lines (e.g. Figure 1) whose detection would provide further information on the temperature and composition of the neutron star surface material.

Although observations of 400 keV line emission from the March 5, 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 LMC, 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 and Ozernoy 1979, Petchek and Colvin 1979, Mitrofanov 1981, Bisnovatyi-Kogan and Chechetkin 1980, Colgate and 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 LMC. This approach, however, ignores a potentially most interesting piece of data, namely the remarkably precise source direction which coincides with that of an interesting astronomical object. Ramaty et al. (1980) and Ramaty, Lingenfelter, and Bussard (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 March 5 kind from a neutron star at the LMC distance. In their model, the gamma 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 as 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-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. This can be seen in Figure 4 (from Ramaty et al.

1980, using calculations of Detweiler 1975) which shows the damping time of quadrupole and higher mode neutron star vibrations as a function of surface redshift, where the dashed curve connects points obtained from the same equation of state. The numerical values next to these points are the corresponding neutron star masses in units of $M_\odot$. The March 5, 1979 data point shows the observed duration of the impulsive phase (120 to 180 msec) versus the approximate redshift. The implied neutron star mass is about 1 to 1.3 $M_\odot$, its radius about 10 km, and its quadrupole vibrational frequency about 0.4 msec. Gamma ray spectroscopy, by suggesting a neutron star origin for the March 5 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 gamma ray transients in which essentially all the observed radiation is in the form of lines. Such a gamma ray line transient was discovered (Jacobson et al. 1978) 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. There are no simple schemes that can account for all four observed lines, primarily because there is no obvious candidate for the line at $\sim$ 5.95 MeV.
Lingenfelter, Higdon, and Ramaty (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 nonredshifted 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 ($> 10^{1}$ °K

for ions) accretion disk in which nuclear interactions could take place 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 ~ 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 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 in the redshifted emission from the iron rich surface of the neutron star but not in the unshifted emission.

V. PROSPECTS FOR FUTURE GAMMA RAY LINE DETECTIONS

As mentioned in the Introduction, in addition to the 0.511 MeV line from the galactic center and the lines from gamma ray bursts, there are a variety of other astrophysical gamma 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 the GRO. These lines are produced by processes of nucleosynthesis in supernovae and novae, and by low energy cosmic ray interactions in the interstellar medium. In addition, the 0.511 MeV line should be observed from a variety of sites other than the galactic center, for example the interstellar medium, supernovae, pulsars, and possibly active galaxies. Concerning the galactic center, 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 Section III. Finally, the spectroscopy of gamma 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 gamma 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 has been recognized for quite some time (e.g., Clayton, Colgate, and Fishman 1969) that the detection of gamma ray lines from radioactive nuclides produced by explosive nucleosynthesis in supernovae would be a major contribution to the understanding of this problem. The detection of such lines would provide clear evidence that elements are produced continually throughout the lifetimes of galaxies, and provide a great deal of 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 several tenths of $M_\odot$ of ^{56}Ni per supernova. This isotope decays with a halflife of 6 days into excited states of ^{56}Co, but the resultant gamma 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, gamma 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 halflife 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 gamma ray spectroscopy experiment such as the 2-year mission of GRO.

According to earlier estimates (Clayton 1973, Lingenfelter and Ramaty 1978) and more recent detailed calculations (Woosley, Axelrod and Weaver 1980), 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} photons/cm^2 sec, respectively. These lines are expected to be significantly Doppler broadened by the $\sim 10^4$ km/sec expansion velocity of the supernova. The FWHM of the 0.847 MeV line should be about 60 keV. The NaI instrument, OSSE, on the GRO has a sensitivity of about 10^{-5} photons/cm^2 sec 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 the 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 Section III, the 0.511 MeV line from the galactic center 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 ($\sim 10^5$ years) than the interval between galactic supernova explosions. As discussed in Section III, the annihilation line width in the cold interstellar medium is ~ 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 per year in the galaxy, the total rate of galactic 0.511 MeV line luminosity is $\sim 2 \times 10^{45}$ $(M/M_\odot)$ f_{esc} photons/sec. If we compare this luminosity with that of 100 MeV photons ($\sim 5 \times 10^{41}$ photons/sec, Higdon and Lingenfelter 1976), we can use the observed (Fichtel et al. 1975) > 100 MeV gamma ray intensity from the general direction of the galactic center, $\sim 10^{-4}$ photons/cm^2 sec rad, to estimate a diffuse galactic plane 0.511 MeV line intensity of approximately 0.4 $(M/M_\odot)$ f_{esc} photons/cm^2 sec rad. Since $M/M_\odot$ could be about 0.5 (Axelrod 1980), the Ge instrument on GRO, GRSE, with a sensitivity of $\sim 10^{-5}$ photons/cm^2 sec rad, could test models with f_{esc} as low as 5×10^{-6}. A previous estimate (Colgate 1970) suggested that $f_{esc} \sim 0.1$.

Another set of important lines are those from ^{44}Ti decay. Explosive nucleosynthesis could produce about 2×10^{-4} solar masses of ^{44}Ti per supernova. This isotope decays with a halflife 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 hours), 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's have the larger ^{44}Ti yield (Woosley, Axelrod and Weaver 1980). At any given time, there should be a few young galactic remnants of such supernovae that could be visible in ^{44}Ti lines, since the half life is comparable to typical time between galactic supernova explosions. Most importantly, the halflife 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 ~ 1.5 x 10^{-4} photons/cm^2 sec. Because of Doppler broadening due to the expansion of the supernova shell, the 1.156 MeV line will be best detected by OSSE; the 0.078 and 0.068 MeV lines can be better seen by GRSE, since OSSE is not sensitive below ~ 0.1 MeV.

Processes of nucleosynthesis in Type II supernovae can be best observed in gamma ray lines from radionuclides with relatively long lifetimes. The line with the best prospects for detection (Ramaty and Lingenfelter 1977, Arnett 1977) is at 1.809 MeV from ^{26}Al decay (halflife ~ 7 x 10^5 years). That ^{26}Al is indeed produced in supernovae is strongly supported by cosmochemical data (Lee, Papanastassiou, and Wasserburg 1977) as well as by recent detailed theoretical nuclear network and stellar evolution calculations (Weaver and Woosley 1980). We also note that nucleosynthesis in novae (Wallace and Woosley 1981) and red giants Norgaard (1981) may contribute to ^{26}Al production. Because of its long lifetime, ^{26}Al decays and produces gamma 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 x 10^{-5} photons/ cm^2 sec rad and its FWHM about 3 keV determined principally by galactic rotation (Ramaty and Lingenfelter 1977). GRSE should have sufficient sensitivity, energy and angular resolution to actually resolve the line and thus possibly provide information on the distribution of ^{26}Al along lines of sight.

Other gamma ray lines from processes of nucleosynthesis resulting from the decay of longlived radioactivity are at 1.332 MeV and 1.173 MeV from ^{60}Co decay (Clayton 1973). The theoretical predictions regarding 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.

b. Lines from Low Energy Cosmic Ray Interactions

Calculations of diffuse line emission from cosmic ray interactions in the interstellar medium have been carried out most recently by Ramaty, Kozlovsky and Lingenfelter (1979). This line emission results principally from the interactions of protons and nuclei in the energy range from about 1 to 100 MeV/nucleon with interstellar gas and dust. These interactions are quite similar to those producing the observed gamma 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 gamma ray line emission has a very narrow component (Lingenfelter and Ramaty 1977) resulting from deexcitations 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, 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 ($> 10^{16}$ cm^{-3}) to capture the neutrons before they decay.

A calculated interstellar gamma ray line spectrum is shown in Figure 5 (Ramaty, Kozlovsky and Lingenfelter 1979). This spectrum results primarily from cosmic ray interactions in the interstellar medium based on a local low energy cosmic ray density of 1eV/cm^3, and a gradient in both this density and the relative abundances of interstellar heavy nuclei towards the galactic center. There are, of course, large uncertainties in these parameters, but detection of such line emission could provide direct information on them.

The 1.809, 1.332 and 1.173 MeV lines also shown in Figure 5 are from explosive nucleosynthesis. As discussed in (Va) above, the intensity of each of these lines is $\sim 5 \times 10^{-5}$ photons/cm^2 sec rad; they are shown in Figure 5 with FWHM's of 3 keV for the ^{26}Al line and 2 keV for the ^{60}Co lines.

The 0.511 MeV line, shown with a FWHM of 2 keV, is from positrons produced solely by low energy cosmic ray interactions. The intensity is $\sim 10^{-4}$ photons/cm^2 sec rad, which is somewhat larger than that given by Ramaty, Kozlovsky and Lingenfelter (1979) because of the additional positron producing reactions that we have recently taken into account (B. Kozlovsky, private communication 1980). This intensity is comparable to that expected from ^{56}Co decay positrons escaping from supernova shells (see estimate in Va) if $(M/M_\odot)\ f_{esc} \simeq 3 \times 10^{-4}$.

Also shown in Figure 5 are the sensitivities of the GRSE experiment on GRO to diffuse lines from the galactic plane based on 3 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 to 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, GRSE 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 present rate of galactic nucleosynthesis. Finally, GRSE 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.

VI. SUMMARY

We have discussed in this paper the interpretations and implications of astrophysical gamma ray line observations. Such lines have so far been seen from solar flares, the galactic center and gamma ray transients. In flares, gamma ray lines are an excellent probe of energetic protons and nuclei. The continuing observations with the gamma ray spectrometer on SMM during the present 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 center, first observed by balloon-borne detectors, has been confirmed by the HEAO-3 gamma ray spectrometer. The preliminary HEAO-3 data indicates that the line is time variable, a result whose consequence 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 center.

Gamma ray lines seen in the spectra of gamma ray burst strongly suggest that neutron stars are 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 March 5, 1979 burst may reflect the damping of neutron star vibrations by gravitational radiation.

No gamma 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.

REFERENCES

Aharonian, F. A. and Ozernoy, L. M. 1979, *Astronomicheskii Tsirkulyar*, No. 1072 (September 17), p. 1.

Arnett, W. D. 1977, *Ann. N.Y. Acad. Sci*. *302*, 90.

Axelrod, T. A. 1980, Upublished Ph.D. Thesis UC Santa Cruz.

Bai, T. 1977, Unpublished Ph.D. Thesis University of Maryland

Barat, S. et. 1979, *Astron. and Astrophys*. *79*, L24.

Bisnovatyi-Kogan, G. S. and Chechetkin, B. M. 1980, Acad. of Sci USSR, Space Res. Institute, Preprint 561.

Blandford, R. D. 1976, *Mon. Not. Roy. Astron. Soc*., *176*, 465.

Blandford, R. D. 1979, *Active Galactic Nuclei*, eds. C. Hazard and S. Mitton (Cambridge), P. 241.

Bussard, R. W., Ramaty, R. and Drachman, R. J., 1979, *Ap. J*., *228*, 928.

Chupp, E. L. et al. 1973, *Nature* *241*, 333.

Chupp, E. L. et al. 1981, *Ap. J. Lett*. (in press).

Clayton, D. D., 1973 *Gamma Ray Astrophysics* eds. F. W. Stecker and J. Trombka (NASA SP-339), p. 263.

Clayton, D. D., Colgate, S. A. and Fishman, D. J., 1969, *Ap. J*., *155*, 75.

Cline, T. L. 1980, *Comments on Astrophysics* (in press).

Cline, T. L. et al. 1980, *Ap. J. Lett*. 237, L1.

Colgate, S. A. and Petchek, A. G. 1980, Paper presented at the Conference on Cosmic Ray Astrophysics and Low Energy Gamma Ray Astronomy, University of Minnesota, September 1980.

Crannell, C. J., Joyce, G., Ramaty, R. and Werntz, C., 1976, *Ap. J*. *210*, 582.

Dennis, B. R. et al., 1980, *Ap. J. Lett*. *236*, L49.

Detweiler, S. L., 1975, *Ap. J*., *197*, 203.

REFERENCES (Cont'd.)

Evans, W. D. et al., 1980, Ap. J. Lett. 237, L7.

Fishman, G. J., Meegan, D. A., Watts, J. W. and Derrickson, J. H., 1978, Ap. J. Lett. 223, L13.

Geiss, J. and Reeves, H., 1972, Astron. Astrophys. 18, 126.

Hall, D. N. B., 1975, Ap. J., 197, 509.

Hall, R. C. et al. 1976, Ap. J., 210, 631.

Haymes, R. C. et al. 1975, Ap. J. 201, 593.

Higdon, J. C. and Lingenfelter, R. E., 1976, Ap. J. Lett. 208, L107.

Hudson, H. S. et al., 1980, Ap. J. Lett. 236, L91.

Jacobson, A. S., Ling, J. C., Mahoney, W. A. and Willet, J. B., 1978, Gamma Ray Spectroscopy in Astrophysics, eds. T. L. Cline and R. Ramaty (NASA TM 79619) p. 228.

Jennings, M. C. and White, R. S., 1980, Ap. J. 238, 110.

Lacy, J. H., Baas, F., Townes, C. H. and Geballe, T. R., 1979, Ap. J. Lett. 227, L17.

Lacy, J. H., Townes, C. H., Geballe, T. R., Hollenback, D. J., 1980, Ap. J. (in press).

Lee, T., Papanastassiou, D. A. and Wasserburg, G. J. 1977, Ap. J. Lett. 211, L10

Leventhal, M., MacCallum, D. J. and Stang, P. D. 1978, Ap. J. Lett. 225, L11.

Leventhal, M., MacCallum, C. J., Huters, A. F. and Stang, P. D., 1980, Ap. J., 240, 338.

Lin, R. P. and Ramaty, R., 1978, Gamma Ray Spectroscopy in Astrophysics eds. T. L. Cline and R. Ramaty (NASA TM 79619) p. 76.

Lingenfelter, R. E. and Ramaty, R. 1967, High Energy Nuclear Reactions in Astrophysics ed. B. S. P. Shen (Benjamin) p. 99.

REFERENCES (Cont'd.)

Lingenfelter, R. E., Higdon, J. C. and Ramaty, R., 1978, Gamma Ray Spectroscopy in Astrophysics eds. T. L. Cline and R. Ramaty (NASA TM 79619) p. 252.

Lingenfelter, R. E. and Ramaty, R., 1977, Ap. J. Lett. 211, L19.

Lingenfelter, R. E. and Ramaty, R., 1978, Phys. Today 31:3, 40.

Lovelace, R. V. E., 1976, Nature 262, 649.

Lovelace, R. V. E., MacAuslan, J. and Burns, M., 1979, Particle Acceleration Mechanisms in Astrophysics eds. J. Arons, C. Max and C. McKee (AIP) p. 399.

Mahoney, W. A., Ling, J. C. and Jacobson, A. S., 1980, Paper presented at the Conference on Cosmic Ray Astrophysics and Low Energy Gamma Ray Astronomy, University of Minnesota, September 1980.

Matteson, J. L., Nolan, P. L. and Peterson, L. E., 1979, X-Ray Astronomy, eds. W. A. Baity and L. E. Peterson (Pergamon Press) p. 543.

Mészáros, P. and Ramaty, R., 1981, in preparation.

Mazets, E. P., Golenetskii, S. V., Il'inskii, V. N., Aptekar', R. L., Guryan, Yu. A., 1979, Nature, 282, 587.

Mazets, E. P., Golenetskii, S. V., Aptekar', R. L., Guryan, Yu. A., and Il'inskii, V. N., 1980, Acad. of Sci. of the USSR preprint, Leningrad 1980, Ioffe Physico-Tech. Inst. Preprint 687.

Mazets, E. P. and Golenetskii, S. V., 1981, Astrophys. and Space Sci. (in press).

Meneguzzi, M. and Reeves, H. 1975, Astr. Ap. 40, 91.

Mitrofanov, I. G., 1981, Symp. on Theor. Problems on High Energy Astrophys. ed. H. S. Hudson (Pergamon Press) in print.

Morrison, P. 1958, Nuovo Cimento 7, 858.

Norgaard, H. 1981, Ap. J. (in press).

Okeke, P. N. and Rees, M. J. 1980, to be published.

REFERENCES (Cont'd.)

Petchek, A. G. and Colvin, J. D., 1980, preprint.

Prince, T., Ling, J. C., Mahoney, W. A., Riegler, G. R. and Jacobson, A. S., 1980, Paper presented at the Conference on Cosmic Ray Astrophysics and Low Energy Gamma Ray Astronomy, University of Minnesota, September 1980.

Ramaty, R., 1974, High Energy Particles and Quanta in Astrophysics, eds. F. B. McDonald and C. E. Fichtel (MIT Press) p. 122.

Ramaty, R., 1979, Particle Acceleration Mechanisms in Astrophysics, eds. J. Arons, C. Max and C. McKee (AIP), p. 135.

Ramaty, R., Bonazzola, S., Cline, T. L., Kazanas, D., Mészáros, P., and Lingenfelter, R. E., 1980, Nature, 287, 122.

Ramaty, R., Borner, G. and Cohen, J. M., 1973, Ap. J., 181, 891.

Ramaty, R., Kozlovsky, B. and Lingenfelter, R. E., 1975, Space Sci. Rev. 18, 341.

Ramaty, R., Kozlovsky, B. and Lingenfelter, R. E., 1979, Ap. J. Suppl. 40, 487.

Ramaty, R., Leiter, D. and Lingenfelter, R. E., 1981, in preparation.

Ramaty, R. and Lingenfelter, R. E., 1977, Ap. J. Lett. 213, L5.

Ramaty, R. and Lingenfelter, R. E., 1979, Nature, 278, 127.

Ramaty, R., Lingenfelter, R. E. and Bussard, R. W., 1980, Astrophys. and Space Sci. (in press).

Ramaty, R. et al. 1980, Solar Flares, ed. P. A. Sturrock (Colo. Univ. Press) p. 117.

Riegler, G. R., Mahoney, W. A., Ling, J. C., Prince, T. and Jacobson, A. S. 1980, Paper presented at the Conference on Cosmic Ray Astrophysics and Low Energy Gamma Ray Astronomy, University of Minnesota, September 1980.

Sturrock, P. A., 1971, Ap. J., 164, 529.

Sturrock, P. A. and Baker, K. B., 1979, Ap. J., 234, 612.

Tammann, G. A. 1974, Supernova and Supernova Remnants, ed. C. B. Cosmovici (D. Reidel) p. 155.

REFERENCES (Cont'd.)

Teegarden, B. J. and Cline, T. L., 1980, Ap. J. Lett. 236, L67.

Thorne, K. 1974, Ap. J., 191, 507.

Wallace, R. K. and Woosley, S. E., 1981, Ap. J. Suppl. (in press).

Wang, H. T. and Ramaty, R. 1974, Solar Phys. 36, 129.

Wang, H. T. and Ramaty, R. 1975, Ap. J. 202, 532.

Weaver, T. A. and Woosley, S. E., 1980, Ann. N.Y. Academy of Science, 336. 335.

Woosley, S. E., Axelrod, T. A. and Weaver, T. A., 1980, Comments on Nuclear and Particle Physics (in press).

Zdziarski, A. A. 1980, Acta Astronomica (in press).

FIGURE CAPTIONS

1. Calculated high resolution spectrum of the August 4, 1972, flare (see Lin and Ramaty 1978 for more details).
2. Calculated 0.511 MeV line spectra for $e^+ - e^-$ annihilation. The data points are from Leventhal, MacCallum and Stang (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 = 8000K and $n_e > n_H$. Both profiles have been broadened in accordance with the instrumental width of the Leventhal et al. detector (FWHM $\simeq$ 3 keV), and their absolute intensities have been varied for a best fit to the data. The calculations have been performed by R. W. Bussard using the theory of Bussard, Ramaty and Drachman (1979).
3. Calculated $e^+ - e^-$ optically thin annihilation spectra in a hot pair plasma (Mészáros and Ramaty 1981). R_{ann} is the rate of annihilation, i.e., one half the integral under the curves.
4. The calculated (Detweiler 1975)(●) quadrupole gravitational radiation damping time versus 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 units of $M_\odot$. The datum point is from γ-ray observations of the 5 March transient.
5. Diffuse gamma ray line emission from the interstellar medium. Lines of low energy cosmic ray interactions are from Ramaty, Kozlovsky and Lingenfelter (1979) and of explosive nucleosynthesis as explained in the text. The GRO-GRSE sensitivity is from J. Matteson (private communication 1980).

FIGURE 1

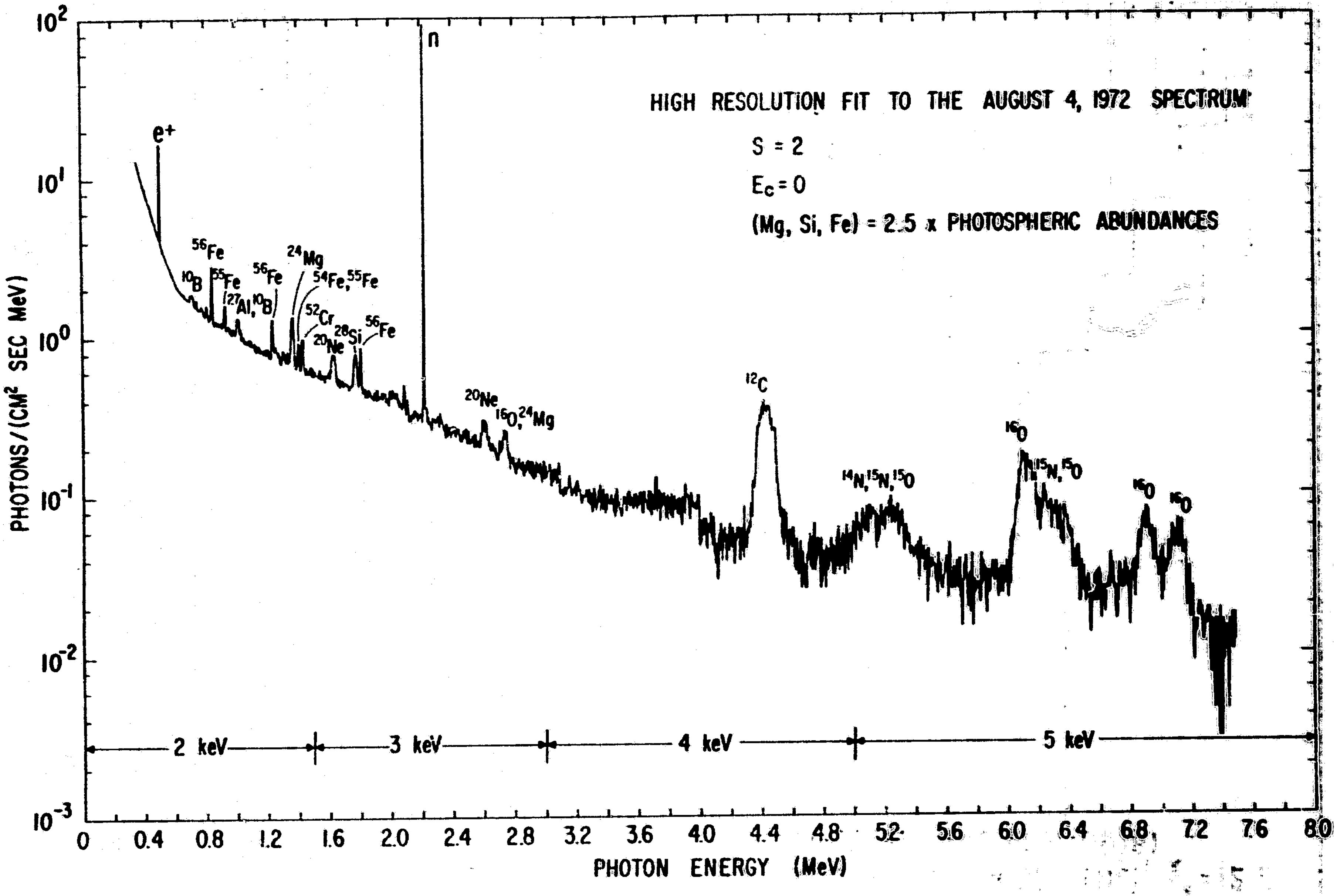
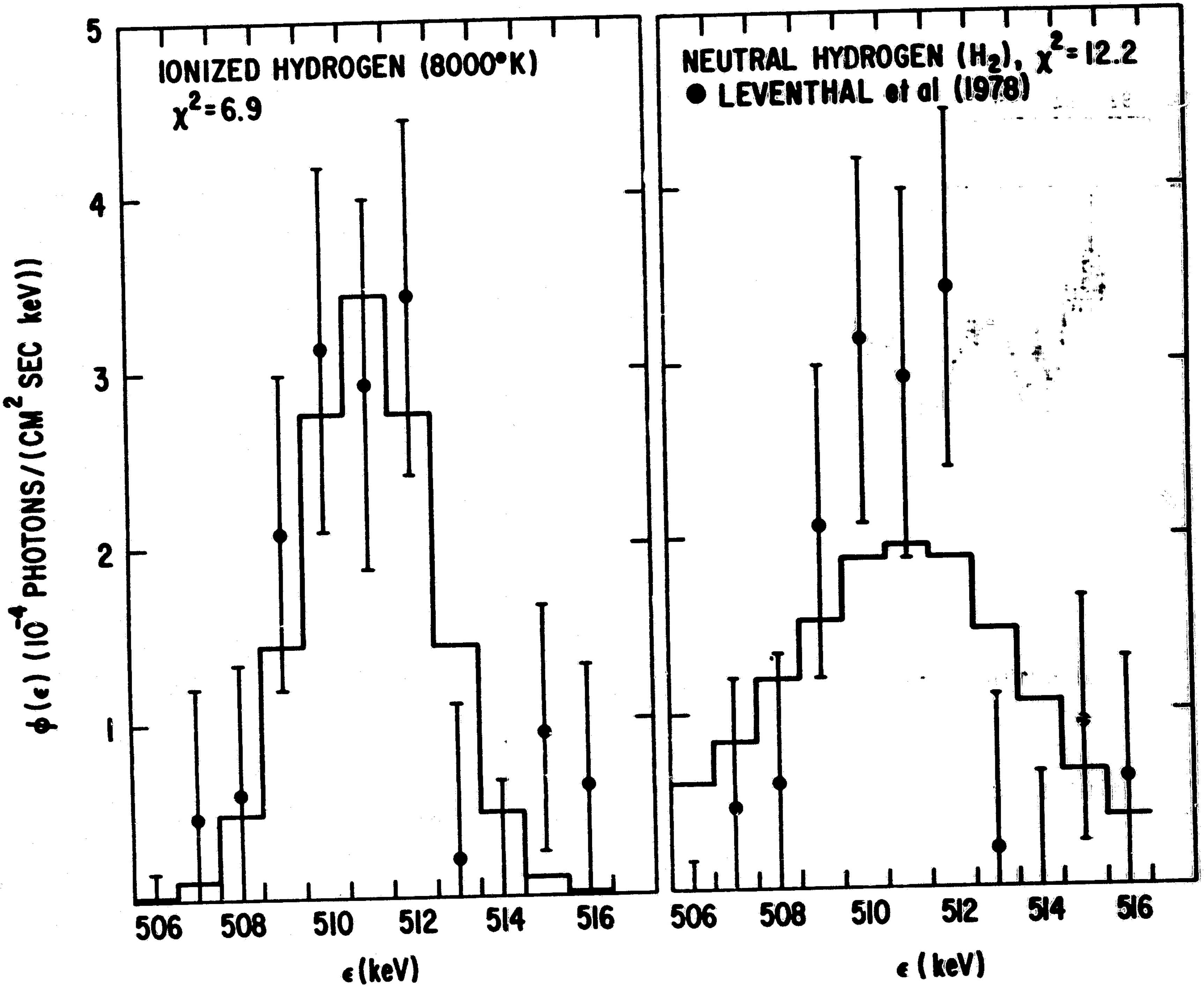

HIGH RESOLUTION FIT TO THE AUGUST 4, 1972 SPECTRUM
S = 2
$E_c = 0$
(Mg, Si, Fe) = 2.5 x PHOTOSPHERIC ABUNDANCES
PHOTONS/(CM² SEC MeV)
PHOTON ENERGY (MeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
7.2
7.6
8.0
e+
n
^{10}B
^{56}Fe
^{55}Fe
^{27}Al, ^{10}B
^{56}Fe
^{24}Mg
^{54}Fe, ^{55}Fe
^{52}Cr
^{20}Ne
^{28}Si
^{56}Fe
^{20}Ne
^{16}O, ^{24}Mg
^{12}C
^{14}N, ^{15}N, ^{15}O
^{16}O
^{15}N, ^{15}O
^{16}O
^{16}O
2 keV
3 keV
4 keV
5 keV

FIGURE 2


IONIZED HYDROGEN (8000°K)
$\chi^2 = 6.9$
NEUTRAL HYDROGEN (H_2), $\chi^2 = 12.2$
● LEVENTHAL et al (1978)
$\phi(\epsilon)$ (10^{-4} PHOTONS/(CM^2 SEC keV))
5
4
3
2
1
506
508
510
512
514
516
ϵ (keV)
506
508
510
512
514
516
ϵ (keV)

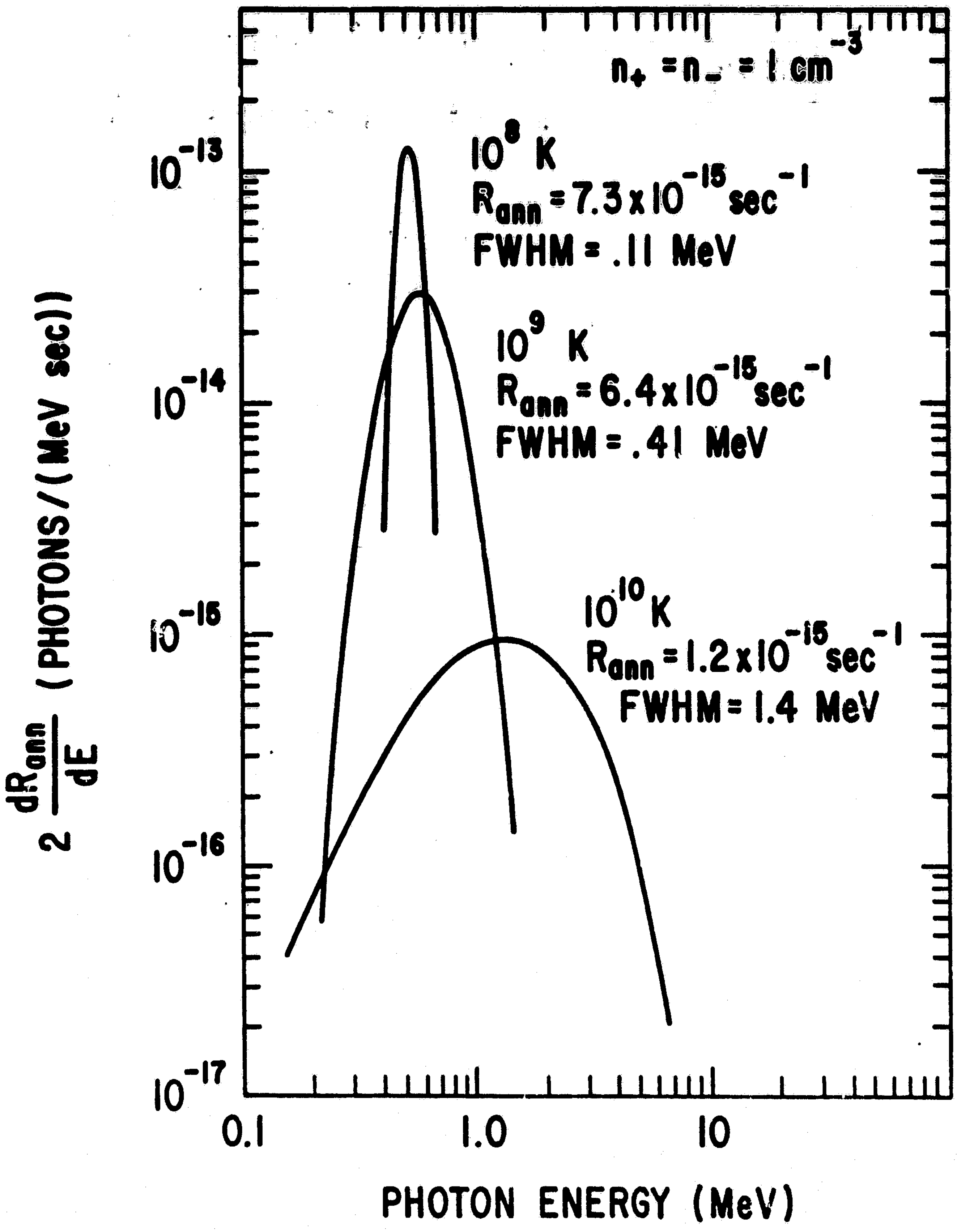

$n_+ = n_- = 1\ \mathrm{cm}^{-3}$
10^8 K
$R_{ann} = 7.3 \times 10^{-15}\ \mathrm{sec}^{-1}$
FWHM = .11 MeV
10^9 K
$R_{ann} = 6.4 \times 10^{-15}\ \mathrm{sec}^{-1}$
FWHM = .41 MeV
10^{10} K
$R_{ann} = 1.2 \times 10^{-15}\ \mathrm{sec}^{-1}$
FWHM = 1.4 MeV
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
0.1
1.0
10
PHOTON ENERGY (MeV)
$2\frac{dR_{ann}}{dE}$ (PHOTONS/(MeV sec))

FIGURE 3

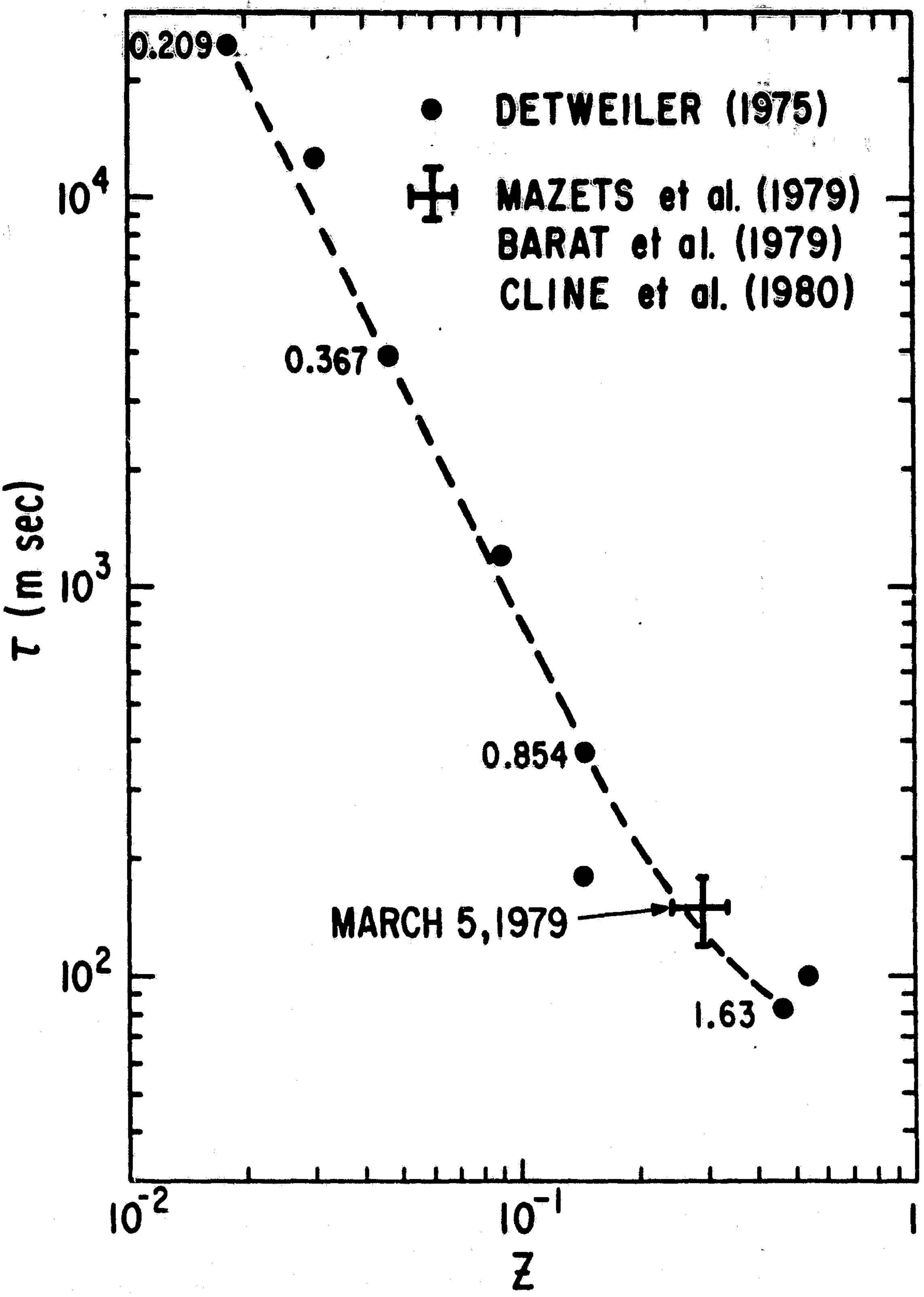

● DETWEILER (1975)
MAZETS et al. (1979)
BARAT et al. (1979)
CLINE et al. (1980)
0.209
0.367
0.854
1.63
MARCH 5,1979
τ (m sec)
10^4
10^3
10^2
10^{-2}
10^{-1}
1
Z

FIGURE 4

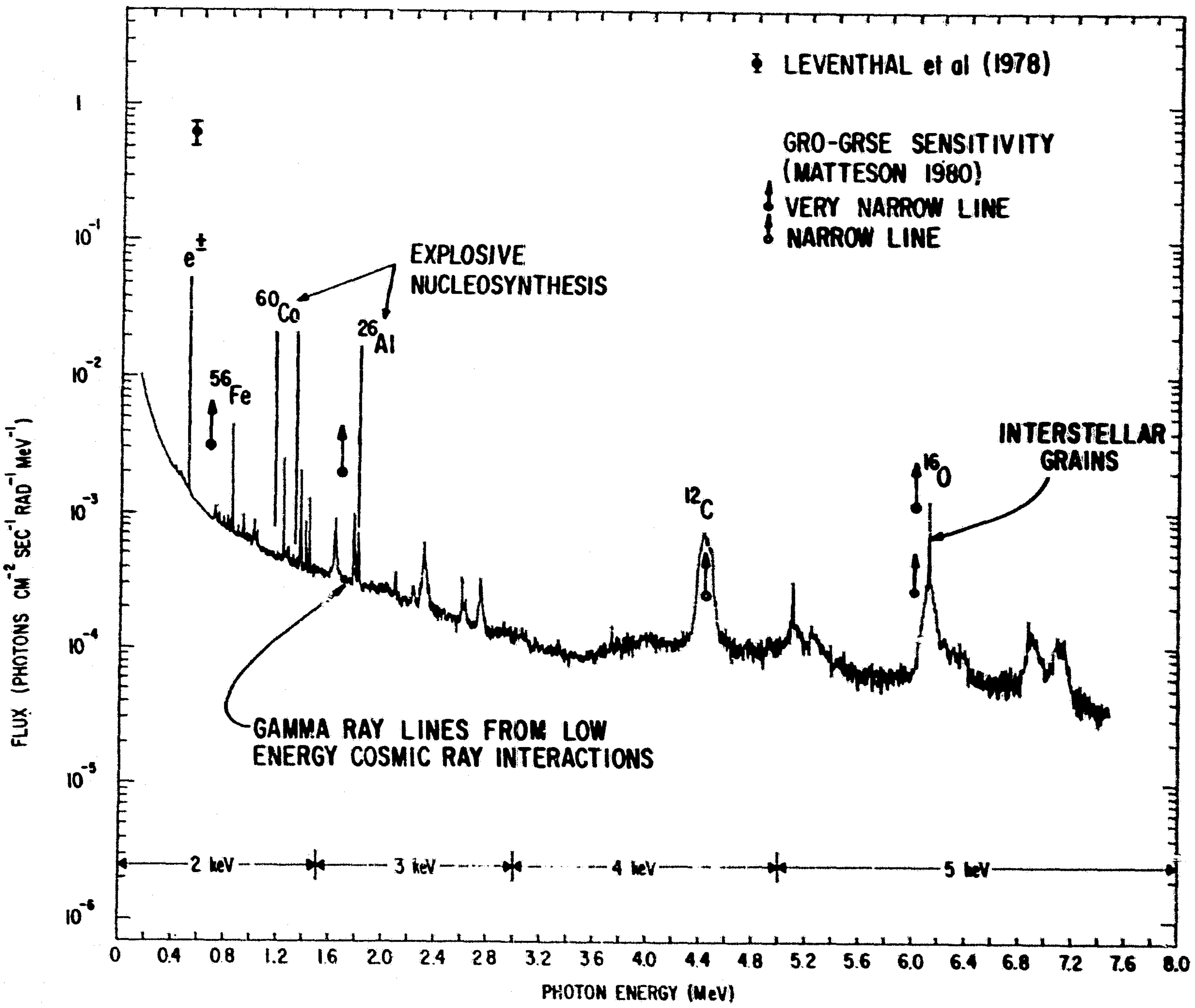

LEVENTHAL et al (1978)
GRO-GRSE SENSITIVITY
(MATTESON 1980)
VERY NARROW LINE
NARROW LINE
$e^{\pm}$
EXPLOSIVE
NUCLEOSYNTHESIS
^{60}Co
^{26}Al
^{56}Fe
^{12}C
^{16}O
INTERSTELLAR
GRAINS
GAMMA RAY LINES FROM LOW
ENERGY COSMIC RAY INTERACTIONS
2 keV
3 keV
4 keV
5 keV
FLUX (PHOTONS CM^{-2} SEC^{-1} RAD^{-1} MeV^{-1})
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
6.8
7.2
7.6
8.0
PHOTON ENERGY (MeV)

FIGURE 5