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GAMMA RAY LINES
FROM THE
GALACTIC CENTER AND GAMMA RAY TRANSIENTS*

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ABSTRACT

The observations and interpretations of cosmic (nonsolar) gamma-ray lines are discussed. The most prominent of these lines is the e^+-e^- annihilation line which has been observed from the Galactic Center and from several gamma-ray transients. At the Galactic Center the e^+-e^- pairs are probably produced by an accreting massive black hole ($\sim 10^6 M_\odot$) and annihilate within the central light year to produce a line at almost exactly 0.511 MeV. In gamma-ray transients the annihilation line is redshifted by factors consistent with neutron star surface redshifts. Other observed transient gamma-ray lines appear to be due to cyclotron absorption in the strong magnetic fields of neutron stars, and nuclear deexcitations and neutron capture, which could also occur on or around these objects.

I INTRODUCTION

The first convincing detection[1] of an extra-solar gamma ray line was that of the positron annihilation line at 0.511 MeV from the direction of the Galactic Center. Exciting new observations[2,3] of this line on HEAO-3 suggest that the annihilations takes place in a region no larger than a light year and that the positrons are produced by a single object of a very high non-thermal luminosity ($\sim 10^{38}$ erg/sec). We discuss these observations and their implications in Section II.

Gamma ray lines have also been seen in gamma ray transients. Spectra of many gamma ray bursts show[4,5,6] both emission and absorption lines thought to be redshifted positron annihilation radiation and cyclotron absorption in teragauss (10^{12} gauss) magnetic fields. An additional line at 0.74 MeV, that could be redshifted ^{56}Fe nuclear deexcitation at 0.847 MeV, has been detected in one gamma ray burst, and several other gamma ray lines have been seen[7] in a transient of longer duration than the typical gamma ray bursts. The gravitationally redshifted e^+-e^- line was also observed[4] in the spectacular March 5, 1979 event whose source direction coincides (e.g. ref. 8) with a supernova remnant in the Large Magellanic Cloud (LMC). These line observations strongly suggest that many gamma ray burst sources are neutron stars. We discuss transient gamma ray lines in Section III.

II. ANNIHILATION RADIATION FROM THE GALACTIC CENTER

Intense positron annihilation radiation at 0.511 MeV has been observed from the direction of the Galactic Center for over a decade. This emission was first seen[9,10,11] in a series of balloon observations with low resolution NaI detectors, starting in 1970, but it was not until 1977 that the annihilation line energy of 0.511 MeV was clearly identified[1,12] with high resolution Ge detectors. The latter observations revealed that the line is very narrow (FWHM $\lesssim$ 3.2 keV) and that the continuum below 0.511 MeV could contain a significant contribution from positronium annihilation.

Recent Ge detector observations[2,3] on HEAO-3 have confirmed the existence of the line and its very narrow width, and have provided exciting new information on the spatial extent of the emission region and on the time variability of the line intensity. These measurements showed that the line emitting region is centered within a few degrees of the Galactic Center and that it is smaller than the angular resolution of the detector (35^oFWHM). The HEAO-3 observations also showed that the 0.511 MeV line is time variable, having decreased by a factor of three in six months from an intensity of $(1.84\pm.21)\times10^{-3}$ photons/cm^{2}sec, in the fall of 1979, to $(0.59\pm.23)\times10^{-3}$ photons/cm^{2}sec in the spring of 1980. Previous observations of the Galactic Center 0.511 MeV line also suggest intensity variations of as much as a factor of three between 1974 (ref. 11) and 1979 (ref. 12), although the statistical significance of this variation is much less than that of the HEAO-3 observations. We summarize in Figure 1 the data on the time dependence of the intensity of the 0.511 MeV line from the Galactic Center. These observations place strong constraints on both the properties of the annihilation region and the possible mechanism and objects that produce the positrons.

The Positron Annihilation Region.

The nature of the positron annihilation region is constrained by the line width and the intensity variations. The observed[1,3] line width of less than 3.2 keV requires[13] that the positrons annihilate in a gas that is at least partially ionized (i.e. $n_e>0.1n_H$). If the gas were neutral, the line width would be larger than observed because it would be Doppler broadened, not by the thermal motion of the gas, but by the velocity of energetic positrons forming positronium in flight by charge exchange with neutral H. In a partially ionized gas, however, positron energy losses to the plasma are high enough that the positrons thermalize before they annihilate or form positronium. The line width then reflects the temperature of the medium. A temperature $<10^5$K and a degree of ionization larger than 10% are consistent with the observations.

The observed intensity variations constrain the size of the annihilation region and the density of matter in it. The size of the region should obviously not exceed a light year and the density should be high enough to allow the positrons to annihilate on a time scale less than a year.

The total annihilation time, τ, shown in Figure 2, depends on the slowing down time of the positrons from the energies at which they are produced to energies below ~ 100 eV and on the positronium formation and direct annihilation times which occur predominantly at these low energies. This time is a function of the initial positron energy, E, and of the ionization, temperature and density of the medium, n_e/n, T and n, respectively. Because the variation of τ with inverse n is not exactly linear, the curves in Figure 2 are for $n = 10^5 cm^{-3}$.

The observed decrease of the 0.511 MeV line intensity between the fall of 1979 and the spring of 1980 requires that τ be less than about 10^7 sec. Since positrons are not expected to be produced with kinetic energies greatly exceeding mc^2 (see below), from Figure 2 it follows that regions of density $n \lesssim 10^5 cm^{-3}$ could annihilate the positrons on the required time scale. These regions could be[14] the compact clouds of ionized gas within Sgr. A West observed[15,16] in an infrared fine-structure line of NeII. These clouds are also sufficiently ionized ($n_e/n > 0.1$) and cool ($T < 10^5$ K) to account for the observed width of the gamma ray line.

The Positron Source

The mean observed 0.511 MeV line intensity of 10^{-3} photons/cm^{2}sec (see Figure 1) requires the annihilation of about $2 \times 10^{43} e^+$/sec at the Galactic Center. This value is based on a 0.511 MeV-photon to e^+ ratio of 0.65, resulting from 90% of the annihilations proceeding via positronium. That such a large fraction of the positrons annihilate as positronium follows from the apparent detection[1] of the 3-photon continuum in the Galactic Center data and from theoretical considerations[17,18] which indicate that if the ambient density is less than 10^{15}cm^{-3}, the bulk of the positronium atoms annihilate before they are broken up by collisions.

The large time variation of the 0.511 MeV line intensity observed[2,3] by the HEAO-3 detector implies that the positrons must be produced by not more than a few discrete objects in the central parsec. It is unlikely that these objects are pulsars, since the rate of positron production in pulsars is not expected[19] to exceed about 10^{41} e^+/sec. A single Type I supernova would be a potential candidate since it could produce sufficient positrons by explosive nucleosynthesis via the decay chain $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$. However, if a Type I supernova did occur during the last decade in the central parsec of the Galaxy, gamma ray line emission at 0.847 MeV from ^{56}Co decay should have been detected. All of the instruments that observed positron annihilation radiation from the Galactic Center during this time period were sensitive at 0.847 MeV, but none of them detected this line.

One object that might produce sufficient positrons at the Galactic Center and at the same time be variable on time scales $\lesssim$ 1 year is an accreting black hole. Positrons could be produced around black holes by nuclear reactions[20] in a two-temperature accretion disk, by thermally induced pair production[21] in a hot accretion disk, by pair production of gamma rays from the ergosphere[22], and by an e^+-e^- cascade resulting from dynamo action[23,24].

Energetic particle reactions are probably responsible for no more than a fraction of the positrons observed in the Galactic Center[25]. High energy gamma ray observations limit the contribution of nuclear interactions by relativistic particles producing π^+ mesons which decay into positrons. 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[26,27] (> 100 MeV) by SAS 2 and COS B during the last decade limit the contribution of relativistic particles to not more than about 2 percent of the observed 0.511 MeV line from the Galactic Center. Likewise, gamma ray observations in the MeV region can set limits on positron production by subrelativistic particles. Of particular importance is the 4.44 MeV line from ^{12}C deexcitation. A broad line at about this energy with an intensity of $\sim 10^{-3}$ photons/cm^2sec was reported [11] from the Galactic Center during a balloon flight in 1974, but an upper limit of only 3.3×10^{-4} photons/cm^2sec was set[28] for such a line in September 1977 by the HEAO-1 gamma ray detector. From calculations [20,30] of the e^+/4.44 MeV line yield, these observations can not rule out by nuclear reactions of subrelativistic particles as the source of the annihilating positrons. But the high observed annihilation radiation efficiency of the Galactic Center severely constrains such production models. This efficiency, defined as the ratio of the observed annihilation radiation luminosity of $\sim 3 \times 10^{37}$ erg/sec and the limiting bolometric luminosity[29] of the central few parsecs of $\lesssim 10^{41}$ erg/sec, is greater than 3×10^{-4}, a value which exceeds that expected for nuclear interactions[20,30] by at least an order of magnitude.

Electron-positron pair production[21,22] by photon-photon collisions in the hot disk models would require a relatively small black hole ($M \lesssim 10^3 M_\odot$) in order for the $\gamma\gamma \rightarrow e^+ + e^-$ opacity to be sufficiently high. We defer a discussion on these possibilities to a future paper. Here, we wish to briefly discuss positron production by a massive ($M \sim 10^6 M_\odot$) accreting, rapidly rotating Kerr black hole, since the existence of such an object is already suggested from infrared observations.

A $\sim 10^6 M_\odot$ black hole was suggested[15] from a study of the distribution of the velocities of the IR-emitting clouds within the central parsec. The accretion disk around such a hole is expected to emit in the ultraviolet and thus could also be responsible[15] for the ionization of the clouds. The Lyman continuum luminosity required for this ionization is $\sim 4 \times 10^{39}$ erg/sec. A rotating black hole accretion disk system may also emit nonthermally. If it has an ordered component of magnetic field, dynamo action[31,32] caused by rotation can produce a large electric field which could initiate a photon and e^+-e^- pair cascade[23,24]. 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 maximized if the bulk of them have kinetic energies $\lesssim mc^2$. The pair luminosity of $\sim 3 \times 10^{37}$ erg/sec, together with an equal luminosity in accompanying continuum photons (probably hard X-rays), yields a total nonthermal luminosity of $\sim 10^{38}$ erg/sec. This is no more than a few percent of the Lyman continuum luminosity, and is of the same order as the hard X-ray luminosity from the central region of the galaxy[12,33]. We note, however, that the soft X-ray ($\sim$ kev) luminosity[34] of the central parsec is quite low, $\sim 10^{35}$ erg/sec. This could be due to either the absorption of the X-rays, or a nonthermal pair production mechanism, which deposits most of the available energy around mc^2.

III. 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[35,36], 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[4,37,38,39], the March 5, 1979 event, appears to be extragalactic[8], since its positional error box lies within the supernova remnant N49 in the 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 ($<2\times10^{-4}$ 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[40] 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[8] 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 comes 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 absorption features are observed[6] at energies below about 100 keV in the spectra of 20 bursts. If these are due to cyclotron absorption, they require very strong magnetic fields, of the order 10^{12} gauss, such as those expected around neutron stars.

The most commonly observed emission line falls in the range from 0.4 to

0.46 MeV, as observed[6] by low resolution NaI detectors in seven gamma ray bursts. In the spectrum of one of these bursts, that of November 19, 1978, a small Ge detector has resolved[5] two lines, at ~0.42 MeV and ~0.74 MeV, which the NaI detectors have seen as one broad emission feature from 0.3 to 0.8 MeV. Line emission in the range 0.4 to 0.46 MeV is most likely due to gravitationally redshifted e^+-e^- annihilation radiation, while the line at 0.74 MeV could be collisionally excited and gravitationally redshifted 0.847 MeV emission from ^{56}Fe, an abundant constituent of the crusts of neutron stars. In all cases, the implied redshifts of 0.1 to 0.3, are consistent with those expected from neutron star surfaces. Thus, the magnetic fields, the redshifts and the surface composition indicate that the sources of the bursts with observed lines are probably neutron stars.

The widths of the 0.4 to 0.46 MeV lines contain important information on the temperature of the positron annihilation region. Since these widths do not exceed[5,6] about 0.2 MeV, the temperature should be less than about 3×10^8K. This temperature is surprisingly low in comparison with the energies of the particles that produce the observed continuum emission of the bursts. Since all gamma ray bursts with observed 0.4 to 0.46 MeV emission lines have continuum spectra which extend[5,6] to at least several hundred keV, the radiating particles must have energies of at least these values, i.e. higher by an order of magnitude or more than the kT of the annihilation region. Furthermore, conditions imposed by the pair production threshold, also require particles or photons of energies at least comparable to mc^2 to produce sufficient pairs. This could imply that the positrons annihilate in a spatially distinct region from that responsible for the continuum and the pair production, or that the annihilation region is nonthermal. In addition, a very narrow 0.511 MeV line could result[42] from stimulated e^+-e^- annihilation.

Although the observation[4] of ~0.43 MeV line emission from the March 5, 1979 event 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[4] that the burst direction just happened to coincide with that of N49. Several theorists[43,44,45,46,47] 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. On the other hand, taking the positional data at face value, it has been shown[48,49] 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 the proposed 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 3 (from ref. 49, using calculations of ref. 50) 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 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[7] 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 ~ 5.95 MeV. It has been suggested[20], however, 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^{10}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.

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 the Galactic Center and gamma ray transients. 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 HEAO-3 data indicates that the line intensity is time variable, a result whose consequence is that the positrons are produced by a discrete source, probably 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 bursts strongly suggest that neutron stars are the sources of many of these bursts. The most commonly observed emission line is in the range from 0.4 to 0.46 MeV 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.

Two of us have recently reviewed[14] the prospects for observing gamma ray lines from other astrophysical sites. There are good prospects for the detection of e^+ annihilation radiation from a variety of sites including the galactic plane and the lines of ^{26}Al, ^{56}Co and ^{44}Ti decay from various sites of nucleosynthesis.

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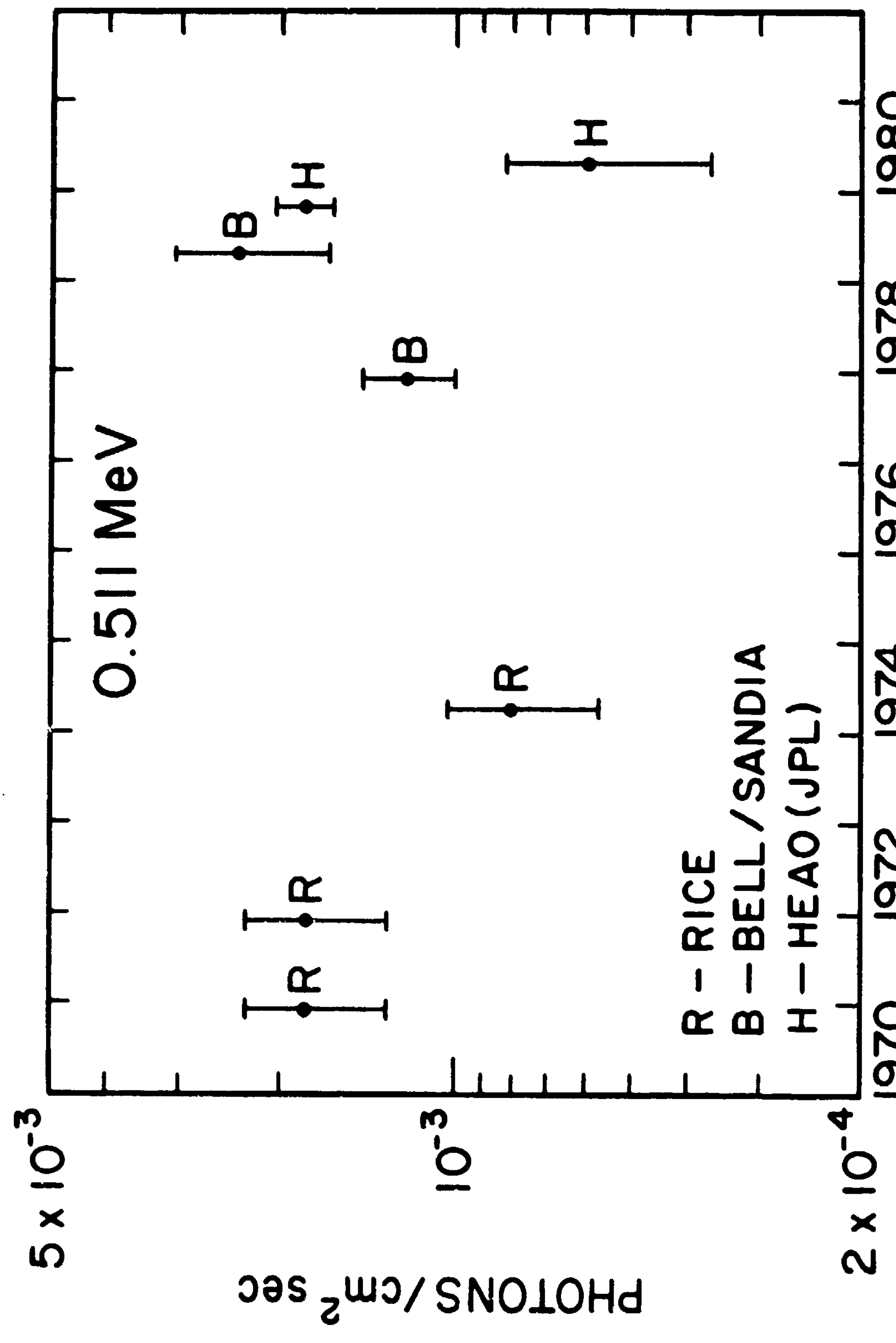
Figure Captions

1. Intensity of the 0.511 MeV line from the direction of the Galactic Center as a function of time. The Rice University measurements were made with low resolution NaI detectors which could not provide a good identification of the line energy. The Bell-Sandia Laboratories and HEAO-3 observations were carried out with high resolution Ge detectors and provided a precise determination of the energy of the line at 0.511 MeV. The time variation discussed in the text is based primarily on the two HEAO-3 observations in 1979 and 1980.
2. The slowing down and positronium formation times of positrons of initial energies E in a medium of ionization of $\eta = n_e/n$, temperature T and density $n = 10^5 cm^{-3}$ (J. McKinley private communication 1981).
3. 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 gamma-ray observations of the March 5 transient.



0.511 MeV
R
R
R
B
B
H
H
R - RICE
B - BELL/SANDIA
H - HEAO (JPL)
1970
1972
1974
1976
1978
1980
5 x 10⁻³
10⁻³
2 x 10⁻⁴
PHOTONS/cm² sec

Fig. 1

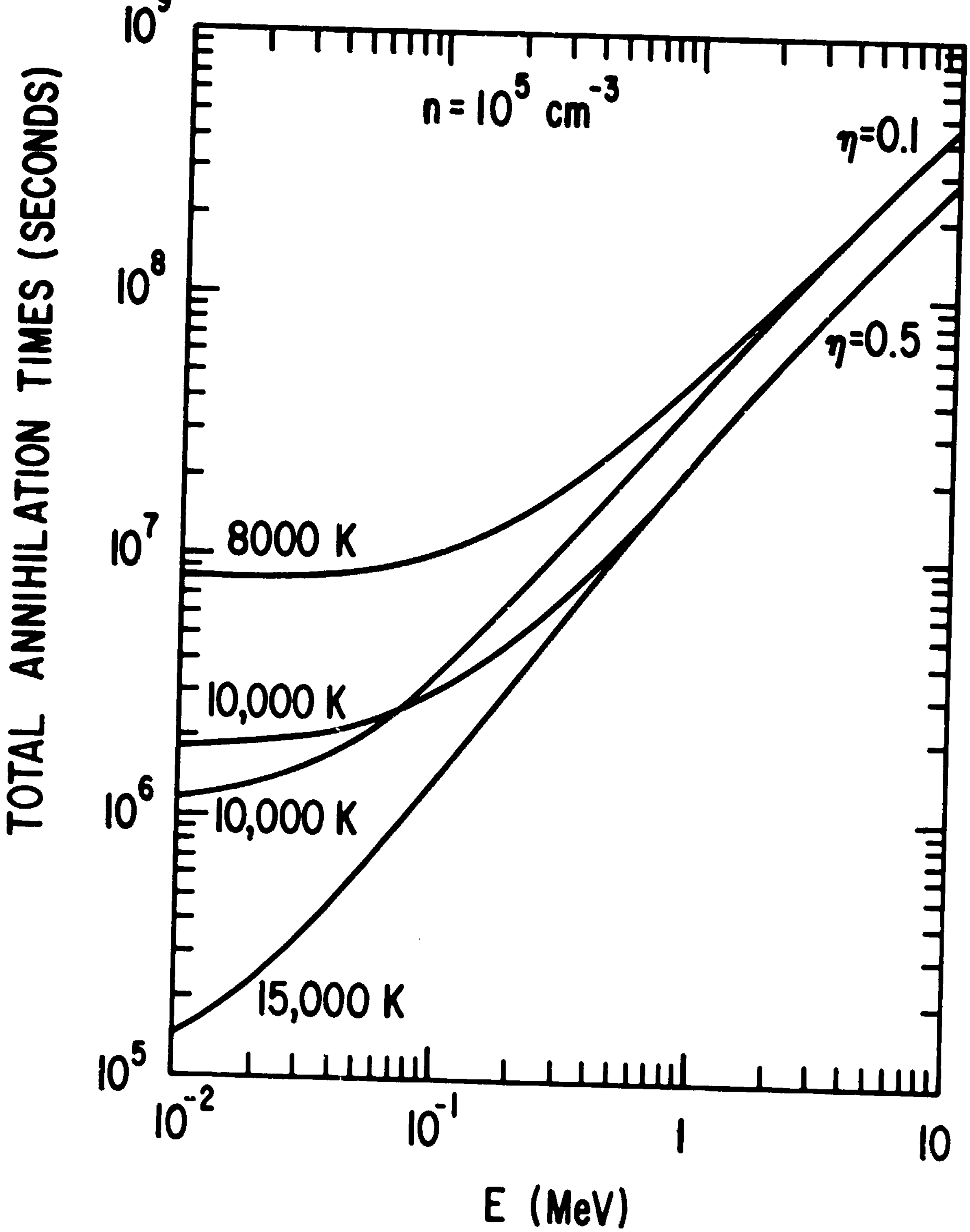

TOTAL ANNIHILATION TIMES (SECONDS)
10^9
10^8
10^7
10^6
10^5
$n = 10^5\ cm^{-3}$
η=0.1
η=0.5
8000 K
10,000 K
10,000 K
15,000 K
10^{-2}
10^{-1}
1
10
E (MeV)

Fig. 2

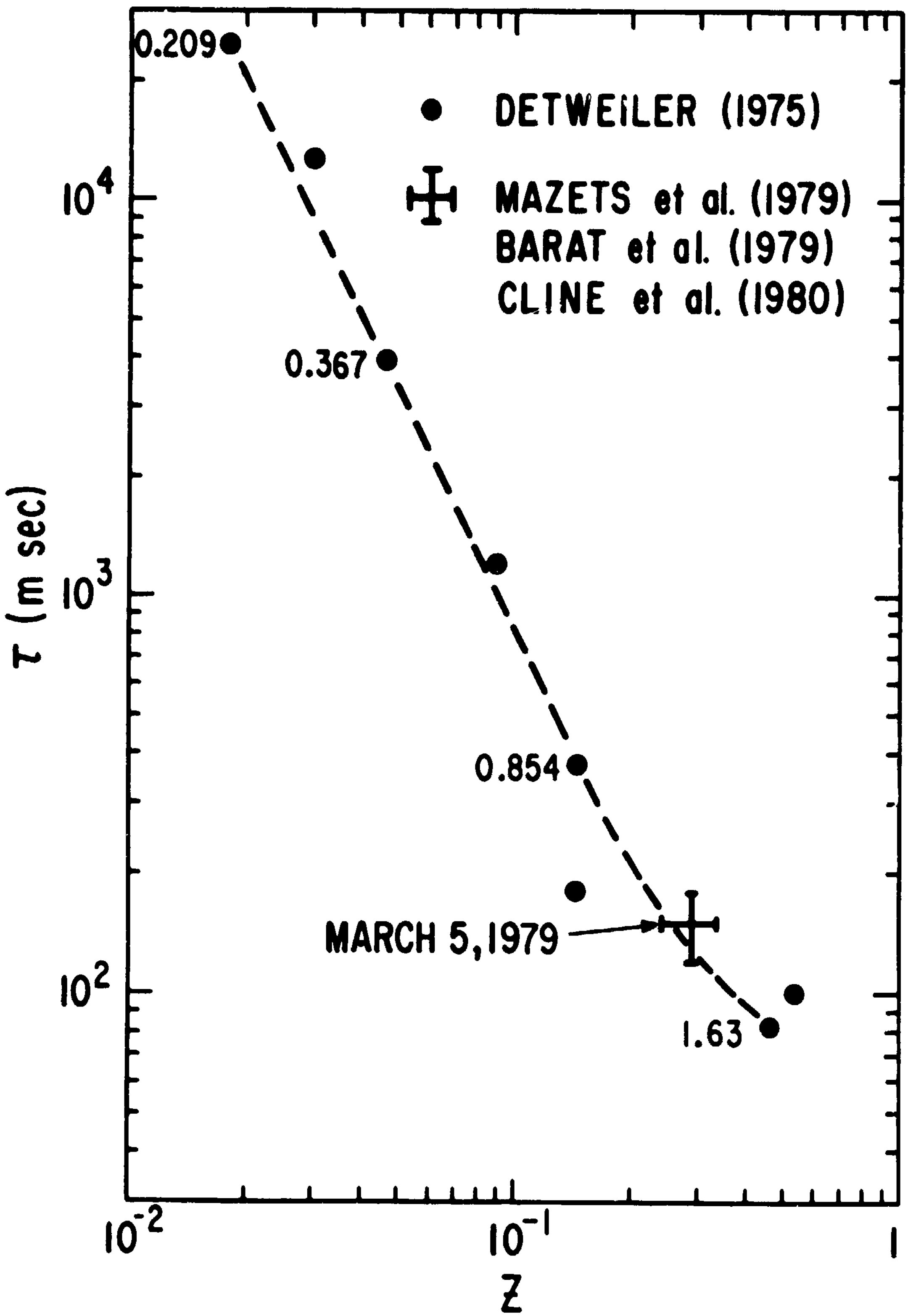

DETWEILER (1975)
MAZETS et al. (1979)
BARAT et al. (1979)
CLINE et al. (1980)
0.209
0.367
0.854
1.63
MARCH 5,1979
τ (m sec)
10^4
10^3
10^2
10^-2
10^-1
1
Z

Fig. 3