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# On the Origin of the March 5, 1979, Gamma Ray Transient:
# A Vibrating Neutron Star in the Large Magellanic Cloud*

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## Abstract

We propose that a vibrating neutron star in the LMC is the source of the March 5 transient. Neutron star vibrations transport energy rapidly to the surface, heat the atmosphere by wave dissipation, and decay by gravitational radiation reaction. The electromagnetic emission arises from $e^+$-$e^-$ pairs which cool and annihilate in the strong magnetic field of the neutron star. The field also confines the pairs, and this allows the production of the redshifted annihilation feature observed in the data. The redshift implies a gravitational radiation damping time which agrees with the 0.15 second duration of the impulsive phase of the event. Thus, the March 5 transient may be both the first detection of a vibrating neutron star and indirect evidence for gravitational radiation.

An unusual gamma ray transient was observed on March 5, 1979, with 12 different instruments on 9 different spacecraft.[1,2,3,4] Most of these instruments are incorporated into an interplanetary gamma ray burst network. The source position of the March 5 transient, determined by this network to an accuracy of about 1 by 2 arc minutes,[4] is consistent with the direction of the supernova remnant N49 in the Large Magellanic Cloud (LMC). Subsequent analysis[5] of the data, by narrowing the source error box to an area of about 6 by 30 arc seconds inside the supernova remnant, considerably strengthens this identification. This is the only identification of a gamma ray transient with a known astronomical object.

In addition to its identification, the March 5 transient has several unique characteristics that set it apart[3,6] from the general class of gamma ray bursts: The peak flux of $\sim 10^{-3}$ erg/cm$^2$ sec in the impulsive phase of the event is an order of magnitude greater than that of any other gamma ray burst. At the distance of the LMC (55 kpc) this implies a luminosity of $\sim 3\times 10^{44}$ erg/sec. The duration of the impulsive phase, $\sim .15$ sec, is also shorter than that of most gamma ray bursts which last for several seconds. The March 5 impulsive energy release, $\sim 5\times 10^{43}$ ergs, would thus be larger by more than 5 orders of magnitude than typical gamma ray burst energies, whose probable galactic origin[7] requires energy releases of only $\sim 10^{38}$ ergs.

The exceedingly short rise time of this impulsive phase, $\sim 2\times 10^{-4}$ sec, suggests that the size of the emission region does not exceed $\sim 60$ km, the light travel distance for this time. That the source may in fact be a neutron star is implied by the energy spectrum[1] of the impulsive phase (Figure 1) which shows a broad feature centered at about 0.4 to 0.43 MeV probably due to the gravitational redshift of 0.511 MeV electron-positron annihilation radiation. This radiation should be produced close to the surface of a neutron star with $Z \approx (1-2GM/Rc^2)^{-1/2}-1 \approx 0.19$ to 0.28 where M and R are the mass and radius of the star. Similar redshifts have been reported for at least one other gamma ray burst [8,9] and longer duration gamma ray transients.[10,11]

A neutron star origin for the March 5 event is also suggested by the observed[1,2,3] pulsations which follow the impulsive phase for at least 3 minutes.[3] The pulse period is 8.0±0.05 sec, and the average pulsed flux, $\sim 10^{-5}$ erg/cm$^2$ sec, decreases exponentially with a characteristic time of $\sim$50 sec. These pulsations could be due to rotation, although the period appears to be too long for a young ($\lesssim 10^4$ years) neutron star in N49. Such pulsations have not been seen from any other gamma ray burst. The March 5 transient was also followed by three other outbursts,[9] apparently from the same source direction, on March 6, April 4 and April 24. The peak intensities of these outbursts, however, were much lower than that of the March 5 event, and decreased with each burst.

The energy spectrum of the March 5 event is much softer than that of typical[12] gamma ray bursts. In fact, the bulk of the emission of the March 5 event is in the lower energy ($\lesssim$0.2 MeV) part of the spectrum which is significantly steeper than that of other gamma ray bursts[13,14] in this energy range.

Despite the fact that the burst source position strongly suggests association with N49, there are several apparent problems, if the source is a neutron star in the LMC. These concern the origin and rapid release of the observed energy, and the very high efficiency of the radiation mechanism. The required mechanism would appear to violate the black-body limit in that it must provide a very large luminosity at relatively low photon energies from a small emitting area. Indeed, several authors, using arguments based on the Eddington limit for accretion models,[1] on the opacity of gamma rays to Compton scattering and pair production,[15,16] and on the slow diffusion of photons to the neutron star surface,[17] have concluded that the source of the March 5 transient should be closer than a few hundred parsec.

In the present paper we do take the point of view that the source of the March 5 transient is in the LMC, based on the rather convincing positional identification with N49. The arguments against an LMC origin based on radiation mechanisms are removed by the $e^+$-$e^-$ synchrotron cooling and annihilation model presented in a previous paper[18] and briefly discussed here as well. Regarding the energy source, its very large magnitude requires that it be interior to the star, most likely of gravitational origin. The transport of this energy cannot be by photon diffusion. We propose instead that neutron star vibrations could, in a coherent and rapid fashion, communicate the internal energy to the upper crust and atmosphere. Decay of these vibrations by gravitational radiation[19] would then account for the duration of the impulsive phase, $\sim$0.15 sec. An LMC origin for the March 5 transient is not in conflict[6,20] with a galactic origin for the more common gamma ray bursts, since these probably belong to a different class of transients than does the March 5 event.

The basic source of energy in the March 5 transient is not clear, but it could be gravitational energy released by a phase transition[21] in the interior. Such a mechanism could release much more energy than observed in gamma rays, but the bulk of this energy is not expected to be emitted as electromagnetic radiation. A large fraction of the released energy could in fact be in vibrations,[22] $E_{vib} \sim 10^{53}$ erg $(\delta R/R)^2$, where $\delta R$ is the vibrational amplitude. For example if $\delta R/R \sim 10^{-3}$, $E_{vib} \sim 10^{47}$ ergs, in which case conversion of only a small fraction $(10^{-3})$ of this energy into gamma rays would be sufficient to account for the observations.

The strong magnetic fields that are tied to the neutron star play an important role in this conversion. Since these fields oscillate together with the surface, they should produce wave motions which would accelerate particles in the atmosphere. In particular, the bulk motions may be converted into magnetoacoustic waves, the high frequency portions of which dissipate in the atmosphere and heat it. Because of the relatively small number of ambient atmospheric particles, this heating would rapidly raise the temperature to a value $(\gtrsim 10^9 K)$ at which $e^+$-$e^-$ pair production sets in. Further heating increases the radiation density, and the atmosphere becomes radiation dominated. In this case the density of pairs which coexist with the radiation greatly exceeds that of the ambient matter. As this hot pair plasma attempts to escape from the neutron star, it pushes the magnetic field outward. But the field, being tied to the star, is compressed, and in the resulting strong field regions the pairs are rapidly cooled by synchrotron radiation.

The $e^+$-$e^-$ synchrotron cooling and annihilation model,[18] which we now briefly describe, can account (see curve in Figure 1) for the observed impulsive spectrum. The essential feature of this model is the radiation dominated $e^+$-$e^-$ pair plasma. Even though its annihilation time is very short ($\sim 10^{-12}$ sec for the parameters[18] of the March 5 transient), this plasma can maintain itself because the annihilation photons have enough energy to produce new pairs. The energy spectrum of the coexisting radiation, however, is much harder than the observed spectrum. But in regions of strong magnetic field, the pairs can lose their kinetic energies before they annihilate and this converts the hot ($\sim$MeV) photon-pair plasma into cooler radiation ($\sim$tens of keV) that is devoid of pairs. This conversion takes place in a layer whose thickness does not exceed the photon-photon pair production mean free path. This outer skin layer is also the effective radiating volume of the star. The magnetic field, the pair density and the thickness of the layer are $\gtrsim 10^{11}$ gauss, $\sim 2 \times 10^{26}$ cm$^{-3}$, and 0.1 mm, respectively.[18] The curve in Figure 1 is the calculated[18] spectrum produced in the layer: the low energy part ($\gtrsim$0.2 MeV) is the synchrotron radiation of the pairs, while the high energy part is their annihilation radiation.

The stability and confinement of the radiating layer is an essential requirement of the model, since its absence would lead to relativistic outward expansion that would result in blueshifted radiation rather than the redshifted emission needed to account for the observations. We believe that the magnetic field does play a major role in the confinement, since the energy density in the field is at least as large as that of the $e^+ - e^-$ plasma. In particular, confinement may be achieved in the highly compressed magnetic field ahead of the pair plasma. The positive (outward) gradient of the field should exert an inward confining force on the plasma. Possible instabilities, such as the exchange instability, and a radiation-pressure driven Rayleigh-Taylor instability, may be stabilized by the continuous transformation of particles into photons and vice versa, as well as by the strongly sheared field.

The conversion of the neutron star vibrational energy into gamma rays should go on as long as the star continues to vibrate. The principal damping mechanism of the vibrations should be gravitational radiation.[19] Neutrino emission[23] is an important damping mechanism only for very young hot neutron stars, while viscous effects (the Urca process and a process[24] involving $\Sigma^-$ hyperons) are slower[22] than gravitational radiation damping. Escaping shock waves can also damp the vibrations,[22] but the loss rate due to shocks should not exceed the observed electromagnetic emission which in our model constitutes only a small fraction of the vibrational energy.

Gravitational radiation is expected to damp the quadrupole and higher mode vibrations on time scales ranging from about 0.1 to 10 sec, depending on the properties of the neutron star.[25,26] Using the calculations of Detweiler,[26] we plot in Figure 2 the damping time $\tau$ as a function of redshift Z, 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[1,2,3] duration of the impulsive phase (120 to 180 msec) vs. the approximate redshift.[1] 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. The sensitivities of the present gravitational wave detectors were insufficient to observe the expected gravitational radiation (J. A. Tyson, private communication, 1980), and the time resolution of the gamma ray instruments were insufficient to resolve the expected vibrational period in the impulsive emission.

Although gravitational radiation is very effective in damping the quadrupole and higher mode vibrations, it will damp the radial oscillations more slowly.[19,22] The $\Sigma^-$ process,[24] however, could damp the radial vibrations on a time scale of $\sim$50 sec, the characteristic decay time of the pulsed phase of the March 5 transient. Thus, the energy source for this phase as well could be neutron star vibrations. The observations would, therefore, imply that the gamma ray luminosity produced by the radial oscillations is smaller than that of the higher modes. This could result from asymmetric excitation of the vibrations which would put more energy into nonradial vibrations. Also, due to its small scale height, the atmosphere is expected to couple better with the higher modes than with radial oscillations. The 8 sec period of the pulsed emission, however, is not likely to be a vibrational period. It may be caused by the rotation of the neutron star, although neutron star precession is an alternative explanation (K. Brecher, private communication, 1980). The subsequent weaker bursts which appear to come from the same source on March 6, April 4 and 24, may be aftershocks of the March 5 burst if it indeed results from a major quake in the neutron star interior.

There are of course several unresolved aspects of the model that clearly need further study These include the more precise description of the source of energy of the burst, the nature and efficiency of vibrational heating, the stability of the thin emission region, and the origin of the 8 second pulsed emission These and other aspects should be addressed in future papers. We have given here a general outline of a model for the March 5 burst which can account for both the enormous luminosity and the complex temporal and spectral features of the burst by emission from a neutron star in the LMC.

## References

1. Mazets, E.P., Golenetskii, S.V., Il'inskii, V.N., Aptekar', R.L. Guryan, Yu. A., Nature 282, 587-489 (1979).
2. Barat, S., et al., Astron. and Astrophys. 79, L24-L25 (1979).
3. Cline, T.L., et al., Astrophys. J. Lett. 237, L1-L6 (1980).
4. Evans, W.D., et al., Astrophys. J. Lett. 237, L7-L10 (1980).
5. Cline, T.L., et al., Bull. Amer. Phys. Soc. 25, 527-527 (1980).
6. Cline, T.L., Comments on Astrophys., in press (1980).
7. Fishman, G.J., Meegan, C.A., Watts, J.W., Jr., and Derrickson, J.H., Astrophys. J. Lett. 223, L13-L15 (1978).
8. Teegarden, B.J., and Cline, T.L., Astrophys. J. Lett. 236, L67- (1980).
9. Mazets, E.P. and Golenetskii, S.V., Proc. Symp. on Cosmic Gamma Ray Bursts, in press in Astrophys. and Space Sci. (1980).
10. Jacobson, A.S., Ling, J.C., Mahoney, W.A., and Willett, J.B., Gamma Ray Spectroscopy in Astrophysics (ed. Cline, T.L., and Ramaty, R.), 228-251 (NASA TM79619, 1978).
11. Leventhal, M., MacCallum, J.C., and Watts, A.C., Astrophys. J. 216, 491-502 (1977).
12. Cline, T.L., and Desai, U.D., Astrophys. J. Lett. 196, L43-L46 (1975).
13. Wheaton, W.A., et al., Astrophys. J. Lett. 185, L57-L61 (1973).
14. Metzger, A.E., Parker, R.H., Gilman, D., Peterson, L.E., and Trombka, J.I., Astrophys. J. Lett. 194, L19-L25 (1974).
15. Helfand, D.S., and Long, K.S., Nature 282, 589-591 (1979).
16. Aharonian, F.A., and Ozernoy, L.M., Astronomicheskii Tsirkulyar, No. 1072 (Sept. 17), 1-4 (1979).

17. Petschek, A.G., and Colvin, J.D., preprint (1979).

18. Ramaty, R., Lingenfelter, R.E., and Bussard, R.W., *Proc. Symp. on Cosmic Gamma Ray Burst*, in press in *Astrophys. and Space Science* (1980).

19. Wheeler, J.A., Ann. Rev. Astron. Astrophys. *4*, 393-432 (1966).

20. Cline, T.L., Desai, U.D. and Teegarden, B.J., *Proc. Symp. on Cosmic Ray Bursts*, in press in *Astrophys. and Space Sci.* (1980).

21. Hartle, J.B., Sawyer, R.F., and Scalapino, D.J., Astrophys. J. *199*, 471-481 (1975).

22. Zeldovich, Ya. B., and Novikov, I.D., *Relativistic Astrophysics, Vol. 1, Stars and Relativity* (Univ. of Chicago Press, 1971).

23. Kazanas, D., and Schramm, D.N., Astrophys. J. *214*, 819-825 (1977).

24. Langer, W.D. and Cameron, A.G.W., Astrophys. and Space Sci. *5*, 213-253 (1969).

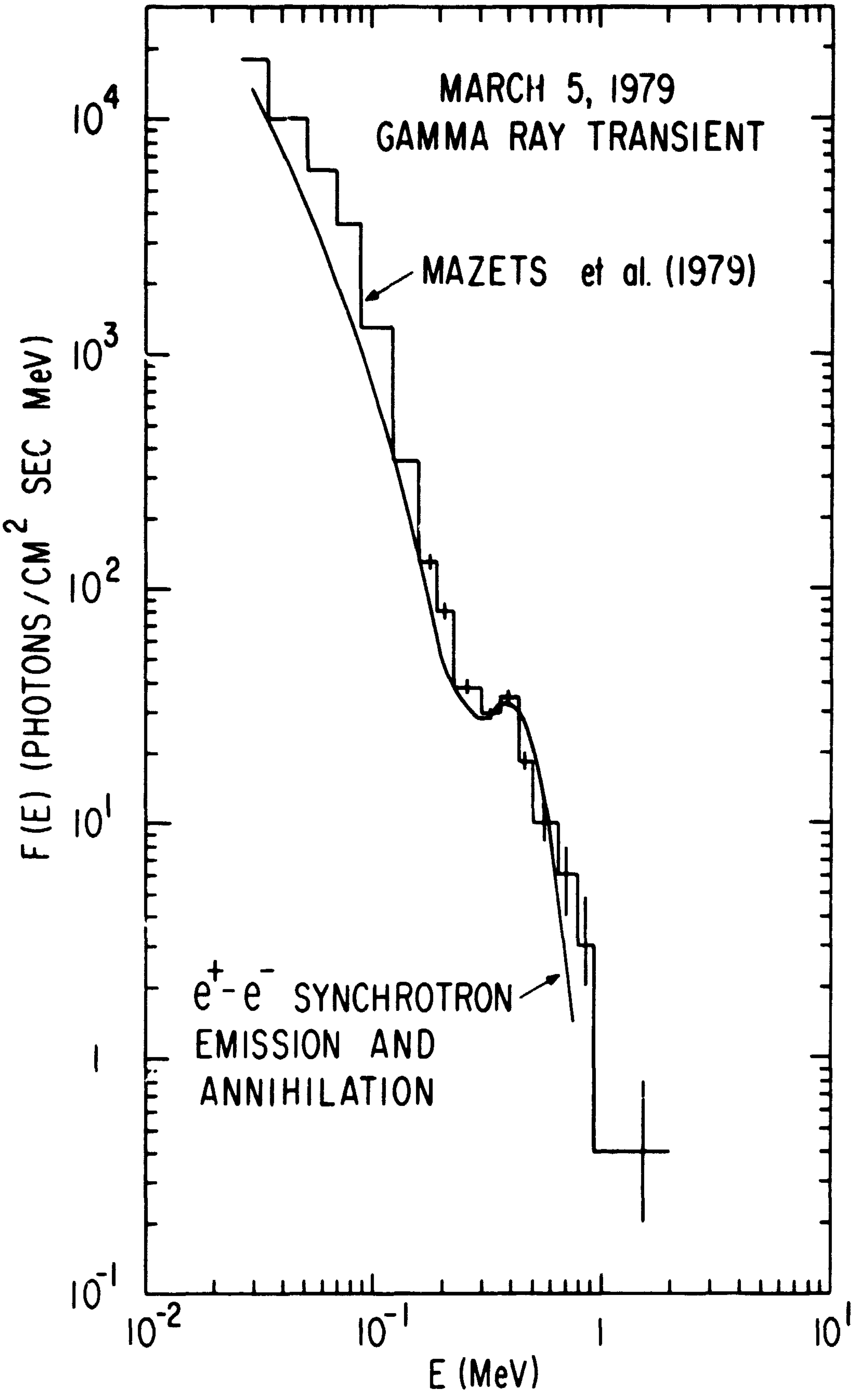
25. Thorne, K.S., Astrophys. J. *158*, 1-16 (1969).

26. Detweiler, S.L., Astrophys. J. *197*, 203-217 (1975).

## Figure Captions

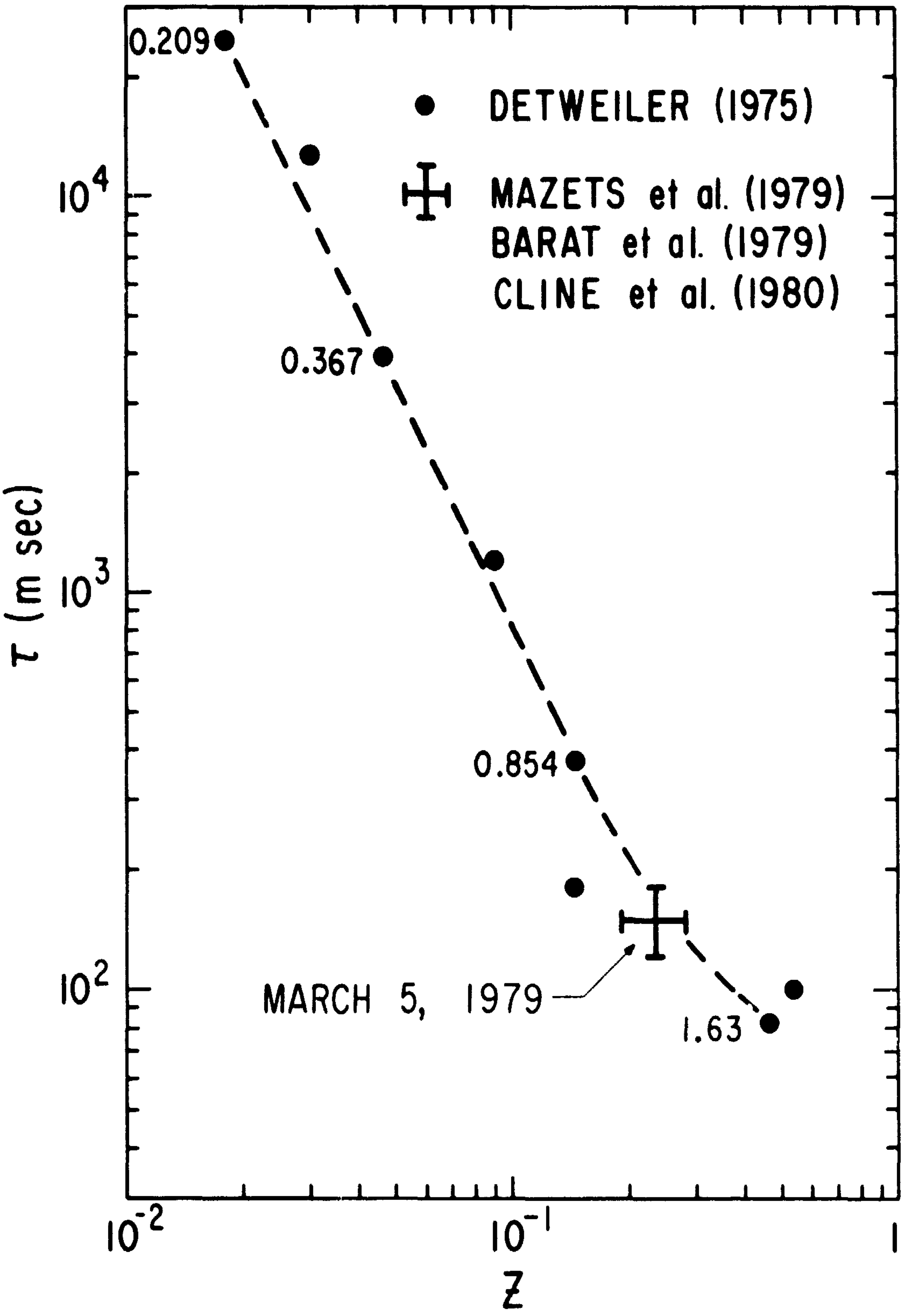
1. Energy spectrum[1] of the impulsive phase of the March 5 transient. The curve is the calculated[18] spectrum in the $e^+$-$e^-$ synchrotron cooling and annihilation model.

2. The calculated[26] (shown by dots) quadrupole gravitational radiation damping time vs. 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 data point is from gamma ray observations of the March 5 transient.



MARCH 5, 1979
GAMMA RAY TRANSIENT
MAZETS et al. (1979)
$e^+-e^-$ SYNCHROTRON EMISSION AND ANNIHILATION
F(E) (PHOTONS/CM$^2$ SEC MeV)
$10^4$
$10^3$
$10^2$
$10^1$
1
$10^{-1}$
$10^{-2}$
$10^{-1}$
1
$10^1$
E (MeV)

Fig. 1



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

Fig. 2