SOME CONSTRAINTS ON NEUTRON STAR PROPERTIES FROM GAMMA RAY BURSTER OBSERVATIONS

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ABSTRACT. The results of recent soft X-ray and optical searches for quiescent gamma ray burster counterparts are used to constrain the properties of the neutron stars responsible for bursters. Ages are restricted to the range 2×10^5 y and above based on temperature upper limits and theoretical cooling curves, or 10^7 y and above if bursters have evolved from pulsars. Velocities are greater than 20 km/s if the neutron stars are unmagnetized. Practically no main sequence star could have escaped detection in the optical/IR searches, so if the neutron stars are in binary systems, the companion is most likely a degenerate, low mass, low temperature object.

1. INTRODUCTION

It has become increasingly clear recently that the more than 400 observations of gamma ray bursts, carried out since their discovery in 1967, represent a significant fraction of the total number of galactic neutron stars observable to us. Other examples are the 437 pulsars now known (R. Manchester, this meeting), the ~150 galactic supernova remnants detected by their radio emission, not all of which show direct evidence for a neutron star (Helfand, 1985), the high mass X-ray binaries, which include about two dozen pulsating sources and as many X-ray burst sources (D. Lamb, 1985; F. Lamb, 1985; Trümper, 1985), the 93 binary X-ray sources and 22 X-ray supernova remnants in the HEAO A-1 catalog (Wood et al., 1984), and 2-4 high energy gamma ray sources in the COS-B data (Bignami, 1985). Qualitatively, it is still too early to determine exactly what the study of gamma ray bursts will teach us about the galactic neutron star population. One thing, however, is certain, namely that gamma bursters involve a quite different set of neutron stars from those observable in the radio, X-ray, or high energy gamma ray ranges. It is presently unknown whether they are related to those neutron stars, e.g. as earlier or later evolutionary phases, or not.

In this paper, some of the recent observations of bursters, particularly (but not exclusively) quiescent counterpart searches in

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the optical, infrared, and soft X-ray ranges, will be used to establish constraints on some of the properties of the neutron stars assumed to be related to gamma bursters: ages, velocities, distances, and possible membership in binary systems. Little of the observational data on bursters will actually be reviewed here (see, e.g., Hurley, 1985); likewise, nothing will be said about the possible mechanisms for energy generation and radiation which are, to a certain extent, independent of the topics considered here. The reader is referred instead to a comprehensive review edited by Liang and Petrosian (1986). Finally, another, new topic which will not be reviewed here for lack of space is the question of what can be learned about neutron star equations of state from burster observations: see Liang, 1985.

2. NEUTRON STAR AGES

Observations of burst time histories, and soft X-ray observations of bursters in the quiescent state, may be used to obtain lower limits to the ages of the neutron stars responsible for gamma bursts. The results of Einstein observations of 5 gamma-ray burst sources (Pizzichini et al., 1986) and EXOSAT observations of 2 sources (Atteia et al., 1986a) have recently appeared (Figure 1). With one possible exception, no point sources associated with bursters were detected. As explained in Pizzichini et al. (1986), these observations may be used to derive relatively model-independent upper limits to the temperatures of the neutron star surfaces. These limits may in turn be used to infer the minimum age of the neutron star if a cooling model is assumed. Using the Glen and Sutherland (1980) cooling curves for a 1.25M$_\odot$, 16 km radius neutron star for the cases B=0 Gauss and B=5x10^{12} Gauss gives the minimum ages in Figure 2. The temperature upper limit is a function of the (unknown) distance to the neutron star, and hence so is the minimum age. But in all cases the limits are reasonable ones, in the sense that both younger (e.g. SNR-associated) and older (e.g. pulsar) neutron stars are known.

The relation between age and time histories relies on the observations of periodicities. Two gamma ray burst time histories have been demonstrated convincingly to display periodicities (Barat et al., 1979; Wood et al., 1981), while a third has only marginally convincing evidence (Barat et al., 1984), and several more examples (as yet unpublished) exist in the Franco-Soviet SIGNE experiment data base. In all cases the periods fall in the range 4-10 s. The most natural explanation for these periodicities is the rotation of a magnetized neutron star. Some insight into the evolution of such an object can be obtained from the study of pulsars. Based on a study of 256 pulsars, Lyne, Manchester, and Taylor (1985) have shown that for a neutron star with a mean initial field of 0.75x10^{12} Gauss, the e-folding decay time for the field is 9.1x10^{6} years, and the average terminal period of the pulsar (i.e., the period for zero field) is 0.4 s. Using the fits to their data, a pulsar whose terminal period is 4 s must have started out with a minimum field of about 7.5x10^{12} Gauss, and is about 10^{7} years old. Mechanisms for pulsar spindown other than those considered in the study of Lyne et al. (1985) have also been proposed (e.g., Peng, Huang, and Huang, 1982) which may be efficient for long period pulsars. Thus if gamma bursters have evolved from lone pulsars, as some models predict (e.g. Shklovskii and Mitrofanov, 1985), their minimum ages should be around 10^7 years. Is it normal

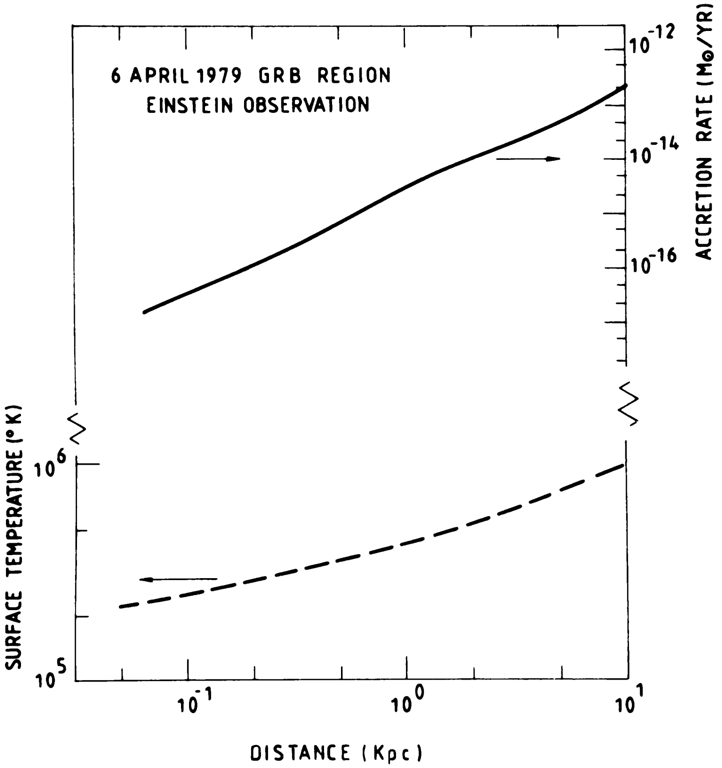

Figure 1. Typical result of an Einstein observation of a gamma ray burst source in the quiescent state (after Pizzichini et al., 1986). Dashed curve, left hand scale: upper limit to the blackbody temperature of the surface of the neutron star, as a function of the (unknown) distance. Solid curve, right hand scale: upper limit to the polar cap accretion rate as a function of distance. Note that the rates are at least 3 orders of magnitude below those proposed for X-ray bursters.

that such an object should not be detectable as an Einstein or EXOSAT soft X-ray source, either due to the residual blackbody radiation from its entire surface, or due to polar cap heating from accretion? The answer appears to be "yes" in both cases. The Glen and Sutherland (1980) cooling model predicts surface temperatures well below 10^5 °K, which are undetectable. Illarionov and Sunyaev (1975) have considered the fate of old pulsars, and have shown that the "propeller" mechanism prevents accretion onto a spinning, magnetized neutron star until the period is sufficiently long. Spindown by the propeller mechanism itself is not efficient enough to slow the star down on timescales shorter than the age of the galaxy.

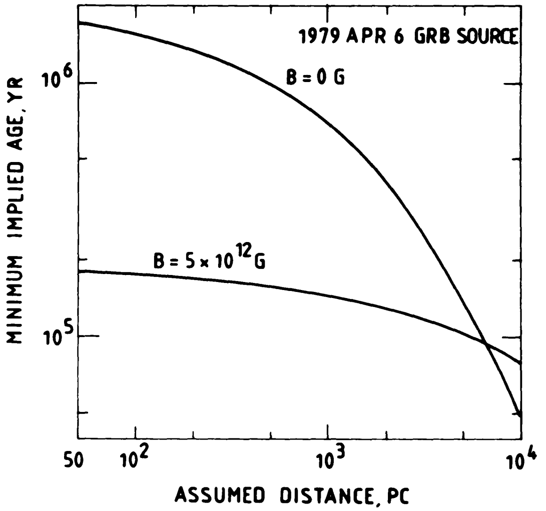

Figure 2. Minimum age of the 1979 Apr 6 burster, as a function of distance. The Einstein upper limits of Figure 1 have been used, as well as the cooling model of Glen and Sutherland (1980) for two values of the magnetic field.

The above discussion indicates that no fundamental inconsistency arises in the interpretation of soft X-ray and time history data if gamma bursters are assumed to be lone neutron stars, either magnetized or unmagnetized.

3. VELOCITIES

The soft X-ray observations of bursters in the quiescent state may also be used to estimate minimum neutron star velocities under some conditions. Here it is assumed that accretion is taking place over the entire surface of the neutron star, which results in heating and radiation in the soft X-ray region (Pizzichini et al., 1986). Higdon and Lingenfelter (1984) and Hameury (1984) have discussed the conditions under which accretion may take place onto the surface of a lone unmagnetized neutron star of mass M traveling through the interstellar medium at a velocity w and Hameury (1984) has shown that the rate is

$$dM/dt=5.8\times10^{-15}(10\ \mathrm{km\ s^{-1}}/w)^{3}(M/M_{\odot})^{2}n\ M_{\odot}/y$$

where n is the number density of the medium, and where w is never less than the sound speed (10 km/s). The result is shown in Figure 3, which gives the minimum allowed velocities for two densities n. As before, the accretion rate is a function of the (unknown) distance to the neutron star, and therefore so is the minimum allowed velocity. Here, as in Figure 2, the constraints are reasonable ones, since the minimum velocities are less than typical pulsar velocities.

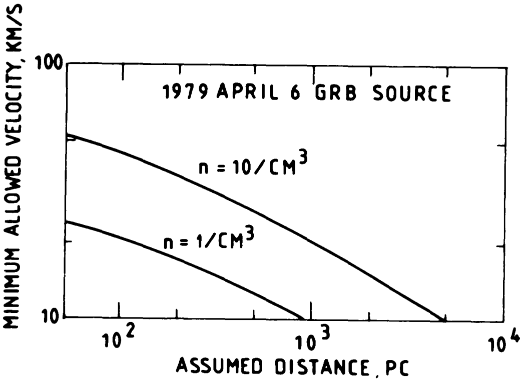

Figure 3. Lower limits to the velocities of lone, unmagnetized neutron stars in the interstellar medium (density n) as a function of distance. These curves are based on the Einstein upper limits.

4. DISTANCE AND MEMBERSHIP IN BINARY SYSTEMS

Some interesting constraints on burster distances and possible binary companions may be obtained from the results of deep optical searches for quiescent counterparts. Taking $m_V=24$ for the brightest possible counterpart, as obtained for two bursters (Chevalier et al., 1981; Pedersen et al., 1983; Schaefer, Seitzer, and Bradt, 1983; Motch et al., 1985), the absolute visual magnitude of a main sequence counterpart must be

$$M_V=29-5\log(d)-A$$

where d is the distance in pc and A the absorption in magnitudes. An unabsorbed main sequence star closer than 10^4 pc must thus have $M_V>9$. This excludes all classes except M (see, e.g., Allen 1976). The allowed distances of some M stars are shown in Figure 4.

A degenerate star is also possible as a binary companion. Again, using the statistics from Allen (1976), the minimum possible distances for two types of white dwarfs are shown in Figure 4. Finally, one can ask whether the deep optical searches could have detected a lone neutron star. Integrating the redshifted blackbody spectrum for a neutron star with $1.3M_\odot$, a true radius of 16 km, and a true temperature of 10^5 °K to obtain M_V gives the result shown in Figure 4: such an object can be detected out to about 27 pc. According to this calculation, higher temperature neutron stars could of course be detected optically out to larger distances (e.g. 94 pc for 10^6 °K), but here the soft X-ray constraints (Section 2) are more severe.

The extremely constraining value for M_V might prompt one to speculate that the optical counterparts are either cool or heavily absorbed, and that infrared observations might yield a detection or at least a more severe constraint. Apparao and Allen (1982) have reported infrared scans of two burster regions, which did not result in any likely detectection of a counterpart. One of their distance lower limits is shown as a dashed line in Figure 4. Schaefer et al. (1986) have recently reported their results of infrared observations of 7 burster regions, also with no probable detection of a counterpart.

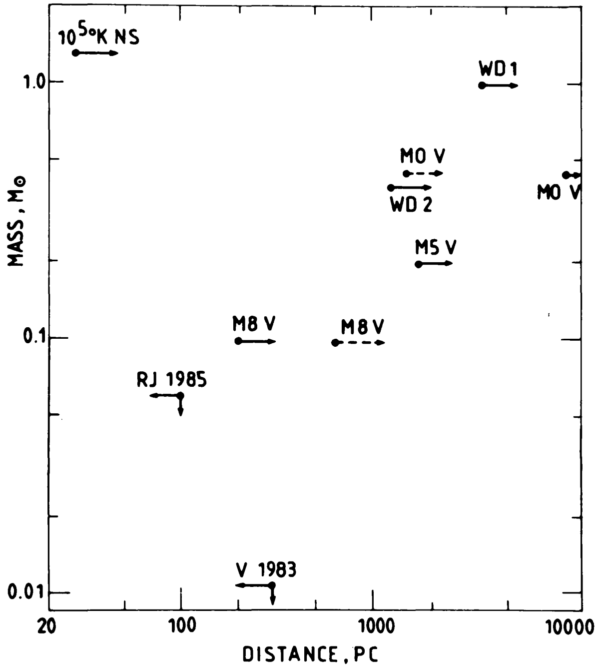

Figure 4. Where the bursters may lie, and what their masses are. The solid lines labelled M8 v, M5 v, M0 v, WD 1 and WD 2 are based on stellar statistics as tabulated by Allen (1976), and assume a maximum $m_V=24$ for burster counterparts. The dashed line labelled M0 v is from the infrared observations of Apparao and Allen (1982), and that for M8 v from Schaefer et al. (1986). The limit for the 10^5 °K neutron star is calculated as described in the text. The region labelled V 1983 is from the model of Ventura et al. (1983), and that labelled RJ 1985 is from the model of Rappaport and Joss (1985).

Several authors have considered the question of whether the presence of nearby bursters violates the Oort limit (e.g., Barat et al. 1979; Schaefer and Ricker, 1983; Epstein, 1985). Using Bahcall's (1984) estimate of 0.09 $M_\odot/pc^3$ for the invisible matter in the solar neighborhood, all the observed bursters could be placed in a sphere of radius

$$R=(2.65\ n\ t_{rec}\ M)^{1/3}\ pc$$

where n is the number of distinct (i.e. not coming from the same regions of the sky) bursts observed per year, t_{rec} is their recurrence period in years, and M is the mass of a burster in $M_\odot$. n may be estimated from Atteia et al. (1986b) to be 59 bursts/year, and to compare this limit to that set by the lone 10^5 °K neutron star in Figure 4, M may be taken to be 1.3$M_\odot$. However, for the purposes of this calculation, t_{rec} is not significantly constrained by observations. Schaefer and Cline (1985) and Atteia et al. (1986b) conclude that the best lower limit obtainable from the observations is of the order of 10 years. This leads to R=13 pc above, which is certainly not in conflict with the point in Figure 4. Note, though, that a quantity of greater interest here is just the distance to the nearest burster, and that this depends only on the value of the Oort limit and the assumed mass of the neutron star:

$$d_{min}=(M/0.09)^{1/3}\ pc=2.3\ pc$$

for the case considered here. Thus this can never give a more constraining lower limit to the distance than the optical observations, as interpreted in Figure 4.

Before membership in a binary system can be assumed, a consistency check should be carried out: should a magnetized neutron star in a binary system, rotating with a period of 4-10 s not be visible as a soft X-ray source? Neutron star spindown and accretion in a binary system have been studied by a number of authors (e.g., Illarionov and Sunyaev, 1975; Davies and Pringle, 1981). These models aim to explain the evolution of bright binary X-ray sources, which is obviously not the case of gamma bursters. However, as the critical parameters are the spin periods, which evolve through the periods of interest here to hundreds of seconds, the strength of the wind from the companion, of order 10^{-11} $M_\odot$/y, and the magnetic moment of the neutron star, of order 10^{30} G cm^3, some features of the models may be applicable. Of particular interest is the prediction that accretion cannot take place onto the compact object, even in the presence of a strong wind, until it has been spun down to rather long periods. This would therefore appear to be consistent with the properties of gamma bursters. On the other hand, these systems evolve into X-ray sources while the massive companion is still on the main sequence, which casts some doubt on the applicability to bursters.

As constraining as the optical limits are, it is still possible to imagine binary systems in which bursts may be produced. Ventura et al. (1983) and Rappaport and Joss (1985) have studied the evolution of very low mass binary systems for the specific purpose of explaining bursters. The system of Ventura et al. (1983), after passing through a phase as a bright X-ray source, ends up after 10^{10} y as a detached binary system whose X-ray and optical luminosities are undetectable at 300 pc. In the model of Rappaport and Joss (1985), after about 5 x 10^9 y the system is undetectable optically, although in principle it is undergoing mass transfer at a rate which would make it a bright X-ray source unless the transfer can be cut off somehow. But in any case, from the above discussion, it is clear that membership in a binary system, albeit a peculiar one, need not contradict the observational data.

5. MAGNETIC FIELDS

It is clear from the above discussion that the magnetic field strength is a crucial parameter in the interpretation of the observations. Two lines of observational evidence support the idea that a field should indeed exist. The first comes from the observations of periodicities. As pointed out in Section 2, however, relatively few events display them; even though this may just be an observational selection effect, its magnitude is difficult to estimate. In addition, the observation of periodicities does not provide an accurate estimate of the field strength. The second line of evidence is the observation of spectral features at energies around 50 keV (Mazets et al., 1981a), which have been interpreted as cyclotron absorption in a strong (several times 10^{12} G) magnetic field. Several questions concerning these observations must be considered. The first is, "Are the observations reliable?". Although one observation of such a spectral feature has been made, non-simultaneously, by an independent experiment (Hueter, 1984), simultaneous observations in another case failed to confirm a feature (Fenimore, Klebesadel, and Laros, 1983; Dennis et al, 1982). It has been demonstrated that in some cases such features could be artifacts (Fenimore, Klebesadel, and Laros, 1983). It appears, however, quite unlikely that all features can be explained in this way, and therefore that the reality of them should be accepted. The second is "Can they be interpreted as being due to effects other than cyclotron absorption?". Here too, the answer is yes. Two component spectra have been proposed (Fenimore et al., 1982; Lasota and Belli, 1983) which could mimic the observed features, and it has been pointed out that they could also be caused by photoelectric absorption of heavy atoms (Trümper, 1982; Bussard and Lamb, 1982). But in almost all of these cases, strong fields are still required. A final question concerns the observational statistics. Some 20 gamma bursts out of 143 (Mazets et al. 1981a) have been observed to display spectral features around 50 keV. What does this imply for the population of gamma bursters as a whole? A number of observational selection effects will tend to reduce the number of features detected. One might be the burst strength. Mazets et al. (1981a) report the observation of features only in bursts with fluences greater than 3 x 10^{-6} erg/cm^2, of which there are about 100 in the KONUS catalog (Mazets et al., 1981b). Thus *if* the detection were related to the fluence, the true ratio might be nearer to 20/100. Another is the energy at which the features appear in the spectra. The KONUS detectors had a lower energy threshold of 30 keV in general (but 17 keV in some cases), and many features appear in the second energy channel. Features with energies below about 27 keV (the lowest energy reported by Mazets et al., 1981a), if they existed, would go undetected. Finally, the geometry of the emission region itself may play a role. The detection of 20 features out of 143 does not seem unreasonable when compared to the statistics of pulsating X-ray sources, which are clearly associated with rotating magnetized neutron stars (e.g., Trümper, 1986). Here two sources out of about two dozen have been observed to display cyclotron features, Her X-1 at 40 keV and possibly 80 keV, and 4U0115+63 at 11.5 and 23 keV. It therefore does not seem unreasonable, based on the observations of bursts, to assume that all of them are produced on or near high magnetic field objects.

6. CONCLUSION

The deep optical and soft X-ray searches for burster counterparts reported over the last year have begun to impose significant constraints on the parameter space which GRB systems may occupy. There is still no general concensus on the question of whether bursts are generated in binary systems or by lone neutron stars, or even both, but it is now clear that any binary companion must be quite cool, have very low mass, be very distant, or a suitable combination of the above.

No mention has been made of the Mar 5 source, which remains as enigmatic as before. Recent optical studies by H. Pedersen, C. Motch and colleagues, as yet unpublished, have set limits of about $m_V > 17.7$ for an optical counterpart. At the distance of the LMC, this would imply $M_V > -1$, which would allow many stellar types as counterparts. However, the well known 8 s period of the source would still appear to conflict with the age of the N49 supernova remnant, 10^4 y. On the other hand, if the source is nearby, the Einstein observations make it difficult to understand the repeating bursts from the source in terms of an accretion-driven process (Pizzichini et al., 1986).

Further understanding of bursters may have to await the arrival of new instrumentation, particularly the Space Telescope and AXAF.

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DISCUSSION

C. Alcock: I would like to play devil's advocate for the fun of it. This comment applies to the VS^{2}Bs directly, and less directly to all GRB's. The 1979 March 5 burst is the brightest burst, so maybe it's the nearest. This is further suggested by it having the only optical identification. Why then are we assuming a galactic population?

K. Hurley: As long as we are only talking about soft bursts, I think that there is no hard observational evidence which constrains them to be local, at least not yet. But the gamma burster population as a whole is rather more constrained: we believe that the 400 keV features, for example, are not related to cosmological redshifts, but rather to gravitational redshifts at the neutron star surface. Very high energy emission (> 1 MeV) is also a reality, and is difficult to explain in distant sources. But these arguments don't apply to the soft bursts, where no emission is observed above a few hundred keV, or in the case of 5 Mar, ~1 MeV.

S. Woosley: Would you comment on the status of the various experiments that are presently searching for optical transients accompanying γ-ray bursts?

K. Hurley: George Ricker informs me that part of his Explosive Transient Camera has come on line at Kitt Peak, and has looked for optical transients from the Aries flasher. He will be presenting a review of his results at the COSPAR meeting in Toulouse in July. Holger Pedersen's telescope array is now starting to operate at ESO (La Silla) and he will also talk about his experiment at COSPAR.