NASA-CR-195176

FINAL

11 CIT.

IN-93-CR

206751
6P

NEUTRON STAR MERGERS AND GAMMA-RAY BURSTS

Final Technical Report

Period Ending December 31, 1993

Ramesh Narayan, Principal Investigator
Harvard College Observatory
60 Garden Street, MS-51
Cambridge, MA 02138

NAG5-1904

(NASA-CR-195176) NEUTRON STAR
MERGERS AND GAMMA-RAY BURSTS Final
Technical Report, period ending 31
Dec. 1993 (Harvard Coll.
Observatory) 6 p

N94-25091

Unclas

G3/93 0206751

Report on Research carried out under Grant NAG 5-1904

Ramesh Narayan and Tsvi Piran

February 24, 1994

Under the support of grant NAG 5-1904, we have carried out research on several topics related to gamma-ray bursts (GRBs). In our proposal we stated that we would study three topics: (i) Fireball evolution, (ii) Neutron star mergers, and (iii) Statistics of bursts. We have completed a significant amount of work in each of these areas, resulting in the following papers (copies are attached):

Fireball Evolution

1) Piran, T., Shemi, A., and Narayan, R., "Hydrodynamics of Relativistic Fireballs," *MNRAS*, **263**, 861 (1993).

2) Piran, T., and Shemi, A., "Fireballs in the Galactic Halo and γ-ray Bursts," *ApJL*, **403**, L67 (1993).

3) Piran, T., "Fireballs," to appear in the *Proceedings of the 1993 Huntsville Gamma-Ray Burst Workshop*, October 1993.

Neutron Star Mergers

4) Narayan, R., Paczyński, B., and Piran, T., "Gamma-Ray Bursts as the Death Throes of Massive Binary Stars," *APJL*, **395**, L83, (1992).

5) Piran, T. 1993, "Gamma-ray Bursts and Neutron Star Mergers - Possibly the Strongest Explosions in the Universe," in the *Proceedings of the XXVI International Conference on High Energy Physics*, Dallas, TX, 1992, James R. Sanford, ed., 1626-1633, AIP, 1993.

6) Kochanek C., and Piran T., 1993 "Gravitational Waves and γ-Ray Bursts" *APJL*, **417**, L17 (1993).

7) Davies, M. B., Benz, W., Piran T., and Thielemann F. "Merging Neutron Stars I: Initial Results for Coalescence of Non-Corotating Systems", in press.

8) Piran, T., "γ-ray Bursts from Neutron Star Mergers," to appear in the *Proceedings of the 1993 Huntsville Gamma-Ray Burst Workshop*, Oct. 1993.

Statistics of Bursts Data

9) Mao, S., Narayan, R., and Piran, T., "On the Bimodal Distribution of Gamma-Ray Bursts", *ApJ*, **420**, 171 (1993).

10) Narayan R., and Piran, T., "Do Gamma-Ray Burst Sources Repeat?", *MNRAS*, **265**, L65 (1993).

11) Narayan, R., and Piran, T., "Do Gamma-Ray Burst Sources Repeat?", to appear in the *Proceedings of the 1993 Huntsville Gamma-Ray Burst Workshop*, June 1993.

The following sections describe the research in greater detail.

1. Relativistic Fireball Evolution

If GRBs originate at cosmological distances then they must involve the release of a huge amount of energy in a very small volume. The optical depth of this radiation to $\gamma\gamma \rightarrow e^+e^-$ will be very large and the radiation will behave like a relativistic fluid (Goodman 1986; Paczynski 1986; Shemi and Piran 1986; Piran, Narayan and Shemi 1992). The resulting object is referred to as a relativistic fireball. Because of the large optical depth the radiation in a fireball cannot initially escape. Instead the fluid is accelerated readily to relativistic velocities. The fireball thus expands and cools until eventually it becomes optically thin and the radiation escapes. Because of the large relativistic motion, an observer at infinity sees the radiation blue shifted and so, even though the fireball may be cool in the rest frame, the observed radiation corresponds roughly to the initial temperature, leading to a gamma-ray burst. Any baryonic matter that is present in the fireball will be accelerated along with the radiation. In fact, if there is enough matter all the initial energy is converted to kinetic energy and very little radiation escapes when the fireball becomes optically thin. This is however not a serious problem because the kinetic energy of the relativistic baryons can be converted back to radiation when the baryons interact with external matter, e.g. in the interstellar medium. Therefore one will still observe a gamma-ray burst even if there is modest barayonic contamination (Meszaros and Rees 1992; see also Narayan Paczyński and Piran 1992, and Shemi and Piran 1989).

As described above much of the evolution of a fireball takes place in a hydrodynamic phase in which the radiation behaves like a fluid. We have developed a spherical relativistic hydrodynamics code to investigate this phase. Using this we have studied numerically the evolution of a relativistic fireball and compared the results with analytical scaling laws (Piran, Shemi and Narayan 1992). We find that, after an early rearrangement phase, most of the matter and energy in the fireball is concentrated within a narrow shell. The shell propagates at nearly the speed of light, with a frozen radial profile and according to a simple set of scaling laws. The spectrum of the escaping radiation is harder at early times and softer later on. These findings confirm the basic picture that emerged from the earlier homogeneous models of Goodman (1986) and Shemi and Piran (1990). The analytical scaling laws that we have found provide us with a powerful tool for determining the evolution of fireballs under a variety of circumstances. They enable us to determine quickly what the outcome of a given initial configuration will be, i.e. whether the energy will be released as γ-rays or as relativistic particles, and what the spread of the observed γ-ray pulse will be.

In another study (Piran and Shemi 1993), we showed that if gamma ray burst sources are in the galactic halo they will inevitably involve the creation of an opaque pair plasma fireball, just as in cosmological sources. We find that the typical physical conditions in a galactic halo fireball are: optical depth $\approx 10^8$, thermal energy $\approx 100keV$, maximal relativistic expansion $\gamma \approx 300$, and maximal baryonic load $\approx 10^{-15}M_\odot$. These results do not rule out galactic halo models but they do pose additional severe constraints on all such sources. Specifically, we can rule out optically thin models. Thus, models that were originally proposed for galactic disk sources cannot be simply transferred to the galactic halo.

2. The Neutron Star Merger Scenario

Among the various cosmological models that have been proposed for gamma-ray bursts, the idea of neutron star mergers is unique in that it is the only proposal that makes use of objects that have been observed independently and are therefore certain to be found in distant galaxies. The total energy released in these events, $\approx 5 \times 10^{53}$ergs, is more than the $\approx 10^{51}$ergs needed for GRBs at cosmological distances. Prior to this grant, and before the announcement of the BATSE results, we had calculated the event rate of neutron star mergers based on the statistics of binary pulsars in the Galaxy (Narayan, Piran and Shemi 1991; see also Phinney 1991). Our estimate agrees very well with the rate required to explain the observed rate of GRBs if they originate at cosmological distances (Piran 1992). This is therefore an additional reason for favoring this model.

Although the total energy released in a merger is much more than the energy required in gamma-rays, nevertheless a major puzzle in the merger model is the mechanism by which a fraction of the energy is converted into gamma-rays. Several years ago Eichler, Livio, Piran and Schramm (1989) (see also Goodman, Dar and Nussinov 1987) suggested that neutrino annihilation $\nu_e \bar{\nu}_e \rightarrow e^+ e^-$ may convert enough energy to power GRBs. Under the present grant we have explored another energy conversion mechanism that appears to be quite promising (Narayan, Paczyński and Piran 1992). We suggest that magnetic fields may build up in an accretion disk that forms in the merger event and that reconnection of this field when it builds up to equipartition may directly convert the rotational energy into high energy electromagnetic radiation. In the same paper we also discuss various common objections to the cosmological scenario in general and to the neutron star merger scenario in particular, and we show how most of the objections can be avoided.

In another investigation (Davies, Benz, Piran and Thielemann 1993) we developed a SPH computer code to simulate neutron star mergers. The code follows the spiraling in phase of a neutron star binary, all the way to the collision between the two neutron stars and coalescence. Unlike previous attempts to study neutron star mergers we focus in this code on the collision itself and its thermodynamics rather than on the gravitational radiation signals. We employ a realistic (Lattimer and Swensy) equation of state. Using it we are able to find the resulting temperature structure of the system after the merger. We find that the colliding neutron stars form a dense rapidly rotating object that contains 90% of the mass of the system and a thick disk surrounding it. There are two potential energy sources to power a gamma ray burst from such a collision. The central object is very hot and if it does not collapse and form a black hole its cooling through neutrinos will provide the energy needed for the burst. Alternatively, the energy could be obtained from the disk when it accretes on the central object.

If the γ-ray burst sources detected by GRO are coalescing binaries at cosmological distances they should produce coincident gravitational radiation signals. Using the rate of GRBs, we predict (Kochanek and Piran 1993) the rate at which gravitational radiation signals should be detected as a function of the gravitational wave strain on the earth. From this calculation we find that the bright γ-ray bursts ought to be detected by LIGO. In fact, by using the bursts as triggers, the sensitivity of LIGO could be improved by 50% and the detection rate increased by a factor of three. If LIGO reaches a strain sensitivity of

$10^{-20.7}h_0$ it should detect one burst per decade, and if LIGO fails to find coincidences at a rate of one per year with a strain sensitivity of $10^{-21.5}h_0$, then we will be in a position to rule out the binary hypothesis of GRBs. On the other hand, if GRBs are detected as gravitational wave sources with the right signal, then it would be a beautiful confirmation of the merger model. Moreover, the time delay between the γ-rays and the gravitational waves may provide some information on the burst mechanism, and the polarization of the gravitational waves will help to determine the burst geometry.

One of us (Piran) gave invited review talks on GRBs and the neutron star merger scenario at the XXVI Conference on High Energy Physics in Dallas, Texas in June 1993 and at the Huntsville Gamma-Ray Burst Worskhop in October 1993. These review talks will be published in the proceedings of the meetings.

3. STATISTICS OF BATSE DATA

Kouveliotou et al. (1993) recently confirmed that gamma-ray bursts are bimodal in duration. We (Mao, Narayan and Piran 1993) have computed the statistical properties of the short (≤ 2 s) and long (> 2 s) bursts using a method of analysis that makes no assumption regarding the location of the bursts, whether in the Galaxy or at a cosmological distance. We find the 64 ms channel on BATSE to be more sensitive to short bursts and the 1024 ms channel to be more sensitive to long bursts. We show that all the currently available data are consistent with the simple hypothesis that both short and long bursts have the same spatial distribution and that within each population the sources are standard candles. The rate of short bursts per unit volume is ~ 0.4 of the rate of long bursts. Although the durations of short and long gamma-ray bursts span several orders of magnitude and the total energy of a typical short burst is smaller than that of a typical long burst by a factor of ~ 20, surprisingly the peak luminosities of the two kinds of bursts are equal to within a factor of ~ 2.

Recently, Quashnock and Lamb (1993) found that there is an excess of pairs of bursts with small angular separations ($< 4^o$). They argue that this means that some of the bursts repeat on a time scale of month. This, of course, has significant implication for models of GRBs, since it is unlikely that the huge amount of energy needed to power cosmological bursts can be produced multiple times in the same source within such a short time scale. We have reanalyzed the data (Narayan and Piran 1993) and find that in addition to the excess of close pairs of bursts, there is also an excess of antipodal pairs of bursts, i.e. pairs separated by $\sim 180°$ on the sky. Since it is very unlikely that any physical model can give rise to an excess of antipodal pairs we argue that both the nearest neighbor and antipodal pairs are caused by some unknown selection effect (see e.g. Maoz, 1993). We conclude that there is no evidence for repeaters in the current data.

References (* indicates the work was supported by this grant)

* Davies, M. B., Benz, W., Piran T., and Thielemann F.,1993, in press.

Eichler, D., Livio, M., Piran, T., and Schramm, D. N. 1989, Nature, **340**, 126.

Goodman, J., 1986, ApJL. **308** L47.

Goodman, J., Dar, A. and Nussinov, S. 1987, ApJL, **314**, L7.

* Kochanek C. and Piran T., 1993, ApJL, **417**, L17.

Lamb, D. Q., & Graziani, C. 1993, ApJL, in press.

* Mao, S., Narayan, R., and Piran, T., 1993 ApJ, **420**, 171.

Maoz, E., 1993, ApJL, submitted.

* Narayan, R., Paczyński, B., and Piran, T., 1992, ApJL, **395**, L83.

Narayan, R., Piran,. T. and Shemi, A., 1991, ApJL, **379**, L17.

* Narayan R., and Piran, T., 1993, MNRAS, **265**, L65.

Méśzaros, P. and Rees, M.J., 1992, ApJ, in press.

Phinney, E. S., 1991, ApJL, **380**, L17.

Piran, T., Narayan, R. & Shemi, A., 1992, in Paciesas W. S. and Fishman, G. J., eds. *Gamma-Ray Bursts, Huntsville, 1991*, AIP press.

Piran, T., 1992, APJL, **389**, L45.

* Piran, T. Shemi, A., and Narayan, R., 1992 MNRAS, **263**, 861.

* Piran, T. and Shemi, A., 1993, ApJL, **403**, L67.

* Piran, T. 1993, to appear in the *Proceedings of the XXVI International Conference on High Energy Physics*, Dallas, TX, 1992, 1626-1633, AIP, 1993.

Quashnock J., and Lamb, D., 1993, MNRAS, **265**, L45.

Shemi, A. and Piran, T., 1990, ApJL, **65**, L55.