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GAMMA-RAY BURSTS FROM NEUTRON STAR MERGERS

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ABSTRACT

Binary neutron stars merger (NS^2M) at cosmological distances is probably the only γ-ray bursts model based on an independently observed phenomenon which is known to be taking place at a comparable rate. We describe this model, its predictions and some open questions.

Cosmological γ-Ray Bursts and Fireballs

Compton-GRO has demonstrated, quite convincingly, that γ-ray bursts (grbs) originate from cosmological sources[1,2]. Evidence for the predicted[3,4] correlations between the duration, the strength and the hardness of the bursts begins to emerge[5,6]. Preliminary analysis suggests that the weakest bursts originate from $z \approx 1$, in agreement with a cosmological C/C_{min} distribution[4], corresponding to a local rate of $\approx 10^{-6}$/year/galaxy (depending on the cosmological model and on other factors). The energy released in each burst depends also on the cosmological model $10^{50} \gtrsim E \lesssim 10^{51}$ergs if the energy emission is isotropic.

The intense energy released in a small volume (evident by the rapid rise time of some of the pulses) implies that any cosmological grb source is initially optically thick[7] to $\gamma\gamma \rightarrow e^+e^-$. The large initial optical depth prevent us from observing directly the photons released by the source regardless of the specific nature or the source. The sources produce an optically thick radiation-electron-positrons plasma "fireball", which behaves like a fluid, expands and reaches relativistic velocities[8,9]. The observed radiation emerges only after the fireball has expanded significantly and became optically thin.

One should divide, therefore, the discussion of cosmological grbs to a discussion of the nature of the energy source (for which we present a model here) and a discussion of the fireball phase (which we address elsewhere in this volume). For the paper it is sufficient to recall that the fireball must reach ultra-relativistic velocities with a Lorentz factor $\gamma \gtrsim 10^2$ to produce a grb. Since $\gamma \approx E/Mc^2$ (where E is the total energy of the fireball and M is the mass of the baryons in the fireball) the condition $\gamma > 10^2$ sets a strong upper limit on the amount of baryons: $M < E/\gamma c^2 \approx .510^{-5} M_\odot (E/10^{51} ergs)(\gamma/10^2)^{-1}$. This condition poses a strong constraint on grb models.

NS^2M and GRBs - Agreement at a Glance

Neutron star binaries, such as the one observed in the famous binary pulsar PSR 1916+13, end their life in a catastrophic merge event (denoted here NS^2M). Using the three observed binary pulsars we can estimate the expected rate of NS^2M events[10,11] as $\approx 10^{-5.5\pm.5}$/year/galaxy. An energy comparable to a neutron star binding energy ($\gtrsim 5 \times 10^{53}$ ergs) is released in NS^2Ms mostly as neutrinos and gravitational radiation. The neutrino signal is comparable in its signature to supernova neutrino signals which are thousand times more frequent. It is unlikely that it will ever be detected. The gravitational radiation pulses, have however, a unique signature and Two gravitational radiation detectors, LIGO and VIRGO are currently constructed to detect them.

Several years ago Eichler, Livio Piran and Schramm[13], (see also [14,15,16,17]) suggested that grbs originate at NS^2Ms. Between 10^{-2} to 10^{-3} of the total energy released in NS^2Ms is sufficient to power a grb at a cosmological distance. The required energy could be converted to electromagnetic energy either via13, 15 $\nu\bar{\nu} \rightarrow e^+e^-$ or via magnetic processes in an accretion disk that forms in the merger[18]. The rates of NS^2Ms estimated from binary pulsars and the observed rate of grbs measured by BATSE and estimated from cosmological fits are within half an order of magnitude from each other. A remarkable agreements in view of the large uncertainties involved in both estimate.

Numerical Simulations of NS^2M - Some Answers to Further Questions

It worthwhile, therefore, to explore whether the mergers can produce clean enough fireballs (i.e. fireballs with sufficiently low baryonic load) as required from the fireball analysis and to ask whether enough energy can be converted to electromagnetic energy in this events. To address these iissues we[19] developed a numerical code that follows neutron star binary mergers and calculates the thermodynamic conditions of the coalesced binary. The process of coalescence, from initial contact to the formation of an axially symmetric object, takes only a few orbital periods. Some of the material from the two neutron stars is shed, forming a thick disk around the central, coalesced object. The mass of this disk depends on the initial neutron star spins; higher spin rates resulting in greater mass loss, and thus more massive disks. For spin rates that are most likely to be applicable to real systems, the central coalesced object has a mass of $2.4 M_\odot$, which is tantalizingly close to the maximum mass allowed by any neutron star equation of state for an object that is supported in part by rotation. Using a realistic nuclear equation of state we estimate the temperatures after the coalescence: the central object is at a temperature of ~ 10MeV, whilst the disk is heated by shocks to a temperature of 2-4MeV.

A typical density cut perpendicular to the equatorial plan is shown in Fig. 1. The disk is thick, almost toroidal; the material having expanded on heating through shocks. This disk surrounds a central object that is somewhat flattened due to its rapid rotation. An almost empty centrifugal funnel forms around the rotating axis and there is practically no material above the polar caps. This funnel provides a region in which a baryon free radiation-electron-position plasma could form[20]. Neutrinos and antineutrinos from the disk and form the polar caps would collide and annihilate preferentially in the funnel (the energy in the c.m. frame is larger when the colliding ν and $\bar{\nu}$ approach at obtuse angle, a condition that easily holds in the funnel). The numerical computations do not show any baryons in the funnels. The resolution of our computation is insufficient, howeer, to show that the baryonic load in the funnel is as low as needed. The neutrinos radiation pressure on polar cap baryons can generate a baryonic wind that will load the flow. Estimates of this effect[21,22] show that it is negligible if the temperature on the polar caps is sufficiently low. The estimated temperature from our computations is ≈ 2MeV, which is marginal. Our temperature estimate is, however, least certain in low temperature regions like this.

If the core does not collapse directly to a black hole it will emit its thermal energy as neutrinos. The neutrino flux is sufficiently large that $\approx 10^{-2}$ to 10^{-3} of it could be converted to electron-positron pairs via $\nu\bar{\nu} \rightarrow e^+e^-$ and produce a grb. The time scale for the neutrino burst is short enough to accommodate even the shortest rise times observed. An additional energy source that could power a grb is the accretion of the disk surrounding the central object. This energy source can operate on a longer time scale and it takes place regardless of the question of whether the central object collapse directly to a black hole or not.

Open Questions and Predictions

The numerical calculations support earlier suggestions[17] that the energy release in anisotropic and that an empty funnel forms around the rotating axis of the binary system. The fireball is highly non spherical and it expands along the polar axis and forms a jet. This poses an immediate constraint on the model. If the width of the jet is θ than we observe grbs only from a fraction $2\theta^{-2}$ of NS^2Ms. The rates of grbs and NS^2Ms agree only if $\theta \gtrsim 0.2$ (unless the rate of NS^2Ms is much higher than the current estimates). A condition which at first glance is satisfied by the funnel seen in Fig. 1.

The duration and spectra of grbs vary greatly from one burst to another. Both are determined by the fireball phase but the source might contribute in producing fireballs with different Lorentz factors and different initial durations. Within the funnel the baryonic load will vary as a function of the angular position leading to varying final Lorentz factors which, in turn, produce bursts with different durations and spectra. Another source of variability could arise from the interplay between the two energy sources in NS^2Ms: Neutrino annihilation and accretion energy of the disk. These mechanisms would operate on different time scale and produce different looking bursts. An additional source of diversity[19] is the distinction between systems that collapse directly to a black hole and those that undergo a longer rotating core phase. Finally, black hole-neutron star binaries are predicted to be as common as neutron star binaries[10]. A black hole neutron star merger[14] would produces grbs with different characteristics than NS^2M.

NS^2M events can take place in a variety of host systems including dwarf galaxies, or even in the intergalactic space if the neutron star binary is ejected from the host galaxy when it forms[18]. Hence, unlike other cosmological models it is not essential that an optical counter part will be observed in the location of grbs[23]. A unique prediction of the NS^2M model is that grbs should be accompanied by gravitational radiation signals from the final stages of the merger and vice versa (the latter is true only up to the anisotropic emission factor discussed earlier). This coincidence could prove or disprove this model. It could also serve to increase the sensitivity of the gravitational radiation detectors[12]. Hopefully, this coincidence will be detected and the model will be confirmed when gravitational radiation detectors will become operational at the turn of the century.

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Figure Captions

Fig. 1 Logarithmic density contour lines at the end of the computation of the merger. The contours are logarithmic, at intervals of 0.25 dex (from [19]).

Figure 1