GAMMA-RAY BURSTS FROM NEUTRON STAR MERGERS AND EVOLUTION OF GALAXIES

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Abstract

Most of proposed models of cosmological gamma-ray bursts (GRBs) are associated to gravitational collapses of massive stars, and hence evolution of the GRB rate, which is crucially important in GRB intensity distribution analysis, is determined by the cosmic star formation history. Here we present complementary results of GRB log\(N\)-log\(P\) analysis, which were omitted in the previous paper (Totani 1997, ApJ, 486, L71). A unique feature of the binary neutron-star merger scenario, in contrast to other scenarios associated to single stellar collapses, is that a time delay during binary spiral-in phase emitting gravitational waves is not negligible and makes the rate evolution flatter than that of star formation rate. We show that the binary merger scenario is more favored than single stellar collapses. The estimated peak luminosity and total emitted energy in rest-frame 50-300 keV range is \(1-3 \times 10^{51}(\Omega/4\pi)\) erg/s and \(1-3 \times 10^{52}(\Omega/4\pi)\) erg, respectively, where \(\Omega\) is the opening angle of gamma-ray emission. Absolute rate comparison between GRBs and neutron-star mergers suggests that a beaming factor of \((\Omega/4\pi)^{-1} \sim \) a few hundreds is required. High-\(z\) SFR data \((z > 2)\) based on UV luminosity need to be corrected upwards by a factor of 5-10 for a good fit, and this is likely explained by the dust extinction effect.

1. Introduction

The observed log\(N\)-log\(P\) distribution of GRBs, where \(N\) is the observed number of GRBs with peak photon flux larger than \(P \; [cm^{-2}s^{-1}]\), has been known to agree with a cosmological distribution if the faintest bursts are located at redshift of \(z \sim 1\) and the comoving GRB rate density is constant with time. However, cosmological evolution of GRB occurrence rate is crucially important in the log\(N\)-log\(P\) analysis, and some artificial assumptions have been made so
Since most of GRB models are associated to massive stellar collapses and lifetime of massive stars is much shorter than the cosmological time scale, the GRB rate history is determined by the cosmic star formation history (Totani 1997, hereafter T97; Sahu et al. 1997; Wijers et al. 1998). GRB models associated to a single stellar core collapse [e.g., failed Ib supernova (Woosley 1993), hypernova (Paczyński 1997)] predict GRB rate evolution simply proportional to star formation rate (SFR). On the other hand, rate evolution of GRB models associated to binary systems [e.g., binary neutron-star (NS$^2$) mergers (Blinnikov et al. 1984), accretion-induced collapse of white dwarfs (Usov 1992)] is a little more complicated: a time delay between star formation and GRBs makes the rate evolution flatter than that of SFR (T97). In the NS$^2$ merger scenario, this time delay is dominated by the spiral-in phase before merger emitting gravitational waves. The duration of this phase is given as $0.0275 \left(\frac{a}{R_\odot}\right)^4$ [Gyrs], where $a$ is the initial binary separation between two neutron stars. This strong dependence of the delay on $a$ suggests that, a small dispersion in $a$ results in a quite wide distribution in the time delay. The time delay becomes larger than the age of the universe when $a \gtrsim 5R_\odot$. Considering the wide distribution of binary separation in main-sequence binaries, this time delay is clearly not negligible in calculation of GRB rate history.

In the previous paper (T97), we have reported the results of GRB rate calculation and comparison to the 3B BATSE data, taking account of the cosmic star formation history based on the recent observations and the time delay in the NS$^2$ merger scenario. Here we present some complementary results which were omitted in T97, including results for the case that GRB rate is simply proportional to SFR. For the details of analysis methods or procedures, see T97.

2. Results

The most important fitting parameter in log$N$-log$P$ analysis is the distance to GRBs, and here we take $z_0.4$: redshift of GRBs with $P = 0.4$ [cm$^{-2}$ sec$^{-1}$] (1024 msec). This peak flux is an analysis threshold of this work. Figure 1 shows the allowed region in $\alpha$-$z_{0.4}$ plane with 68 % C.L. (dotted line) and 95 % C.L. (solid line), for the case that GRB rate is simply proportional to SFR, where $\alpha$ is the photon spectral index of GRBs and shaded regions are feasible range of $\alpha$ expected from observed GRB spectra (Mallozzi, Pendleton, & Paciesas 1996). Therefore the allowed region should exist in the shaded region. This figure should be compared to Fig. 2 of T97, in which GRBs are assumed to be NS$^2$ mergers and hence the time delay is appropriately included. In the left three panels, observational star formation history is assumed, while a galaxy evolution model
Fig. 1. Allowed Regions for the case of GRB rate $\propto$ SFR.

is used in the right panels (see T97 for detail). The galaxy evolution model includes high-$z$ starbursts in elliptical galaxies which have not yet been detected. The used cosmological parameters are shown in the figure.

Compared to the NS$^2$ scenario (Fig. 2 of T97), the allowed region in Fig. 1 moves in the upper-right direction because of the steeper evolution of SFR. Note that the comoving SFR density evolves as $(1+z)^{3.9\pm0.75}$ (Lilly et al. 1996), while NS$^2$ merger rate evolves as $(1+z)^{2.5}$ in $z = 0$–1 (T97). The consequence is that the allowed region becomes more distant from the likely range of $\alpha$ (shaded regions). We cannot get any acceptable fit with $z_{0.4} \gtrsim 2.5$ for the observational SFR model, because of the turn over of SFR beyond $z \sim 2$–3. If we use the galaxy evolution model, high-$z$ starbursts may give an acceptable fit in the shaded region with $z_{0.4} \gtrsim 3$. (We show the allowed region only in $z_{0.4} < 3$, because it is difficult to perform a realistic comparison in $z_{0.4} \gtrsim 3$ without knowledge of the epoch of elliptical galaxy formation.) However, such high values of $z_{0.4}$ predict higher redshift for GRB970508. It should be noted that the estimated redshift of GRB970508 in the NS$^2$ merger scenario (T97) was already near the upper limit of $z = 2.3$ (Metzger et al. 1997). Even higher redshift in the single star scenario would be inconsistent with this constraint and in this case the intrinsic luminosity of this GRB should be significantly smaller than the average.

Cosmological time dilation analysis on GRBs gives another estimate of
GRB redshifts independent of the logN-logP statistics. A dilation test on the GRB duration suggested a dilation factor of \( \sim 2.25 \) and redshift of the dim bursts of \( \sim 2 \) (Norris et al. 1995), and this test using GRB durations is probably the best dilation test at present because the duration analysis is expected to be free from the energy-dependent pulse width effect (see, e.g., Fenimore & Bloom 1995). This requires the GRB rate evolution of \( \propto (1 + z)^{1.5-2} \) (Horack, Emslie, & Hartmann 1995; Horack, Mallozzi, & Koshut 1996; Mészáros & Mészáros 1996), which is well consistent with the NS\(^2\) scenario. In fact, 1024 msec peak flux of dim+dimmest bursts in Norris et al. (1995) is 0.46 cm\(^{-2}\)s\(^{-1}\) and our estimate of \( z_{0.46} \) is \( \sim 2-3 \) (see Fig. 3 of T97). The time dilation factor for the bright and dim+dimmest bursts is 2.0–2.3 in our analysis, again in nice agreement with the result of Norris et al. (1995). On the other hand, in the single stellar collapse scenario, the steeper evolution of SFR does not allow any acceptable fit with \( z_{0.4} \lesssim 3 \) and even larger \( z_{0.4} \) would make the dilation factor uncomfortably large. Norris (1995) revised the time dilation factor from 2.25 into 1.75, and if we believe this value, even the rate evolution in the NS\(^2\) scenario is steep. We conclude that the modest GRB rate evolution in the NS\(^2\) merger scenario gives more natural fit to the BATSE data than the single star scenario, although we cannot exclude the latter scenario completely because of some possible uncertainties, such as the energy-dependence of the GRB time profiles or the effect of the dispersion in the intrinsic GRB luminosity.

3. Discussion

We have concluded in T97 that the NS\(^2\) merger scenario gives an acceptable fit to the BATSE data, but it requires higher SFR in \( z \gtrsim 2 \), corresponding to high-\( z \) starbursts in elliptical galaxies. We have estimated the correction factor of high-\( z \) SFR required to explain the missing starbursts in elliptical galaxies, which is about a factor of 5–10. The upward correction of high-\( z \) UV flux of this degree is likely due to dust extinction. The extinction factor is difficult to estimate, but Pettini et al. (1997) suggest a correction factor of about 3, while Meurer et al. (1997) and Sawicki and Yee (1997) suggest a factor of more than 10.

Finally we estimate the peak luminosity and total emitted energy of GRBs for the case of the NS\(^2\) scenario. By using the estimated redshifts, peak luminosity is estimated as \( \sim 1-3 \times 10^{51}(\Omega/4\pi) \) erg/sec in the rest-frame 50–300 keV, where \( \Omega \) is the opening angle of gamma-ray emission. Average relation between peak flux and energy fluence of the BATSE data gives the total emitted energy of \( 1-3 \times 10^{52}(\Omega/4\pi) \) erg for long-duration bursts and 7 times smaller for short-duration bursts, in the same energy range. Absolute rate comparison between NS\(^2\) mergers
and the observed BATSE rate requires $(\Omega/4\pi)^{-1} \sim a$ few hundreds. It is very interesting that, from an energy-budget argument of the afterglow of GRB970508, Katz and Piran (1997) independently suggested a beaming factor of the same order. If this beaming factor is correct, energy required for the engine of a fireball is $\sim 10^{50}$ erg. This energy scale as well as the beaming factor will be useful constraints when one constructs a model of GRBs in the context of NS$^2$ mergers.

4. References

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