Fireball/Blastwave Model and Soft $\gamma$-ray Repeaters

HUANG Yong-feng, Dai Zi-gao, LU Tan
Department of Astronomy, Nanjing University, Nanjing 210093

Already published in:
Chinese Physics Letters, 1998, 15, 775

Soft $\gamma$-ray repeaters are at determined distances and their positions are known accurately. If observed, afterglows from their soft $\gamma$-ray bursts will provide important clues to the study of the so called “classical $\gamma$-ray bursts”. On applying the popular fireball/blastwave model of classical $\gamma$-ray bursts to soft $\gamma$-ray repeaters, it is found that their X-ray and optical afterglows are detectable. Monitoring of the three repeaters is solicited.

PACS: 98.70.Rz, 98.70.Qy, 97.60.Jd

Since their discovery nearly thirty years ago, $\gamma$-ray bursts (GRBs) have made one of the biggest mysteries in astrophysics, primarily because they have remained invisible at wavelengths other than $\gamma$-rays so that the distances are unknown.\(^1\) The recent detection of X-ray, optical and even radio afterglows from some GRBs located by the Italian-Dutch BeppoSAX satellite has opened up a new era.\(^2\),\(^3\) The possible host galaxy of GRB 970228 and the determined redshift $0.835 < z < 2.1$ for GRB 970508 strongly indicate a cosmological origin. Fireball model becomes the most popular and successful model for GRBs. After the main GRB, the blastwave generated between the GRB ejecta and the interstellar medium (ISM) provides a natural explanation for the power-law decay of the observed low energy afterglows.\(^2\)–\(^4\) We call such a GRB scenario as a fireball/blastwave model. However, so few GRBs have been located rapidly and accurately enough for us to search for their afterglows, that the cosmological origin of GRBs and the correctness of the fireball/blastwave model still need more tests. GRBs occurring at a definite distance and in a fixed direction would be ideal for checking the model. Here we suggest that soft $\gamma$-ray repeaters (SGRs), whose nature is much clearer, might be good candidates.

As a subtle class of GRBs, SGRs are characterized mainly by their soft spectra and unpredictable recurrences.\(^5\) There are only three known SGRs: 0526$-$66, 1806$-$20 and 1900$+$14, all of them have been tentatively associated with supernova remnants

\(^1\)Supported by the National Natural Science Foundation of China under grants 19573006 and 19773007, and the Foundation of the Ministry of Education of China.
(SNRs), indicating a neutron star origin. Recently, Hurley et al. (1997) seem to have observed a new (4th) soft γ-ray repeater.\(^7\) A typical SGR burst lasts several hundred milliseconds, emitting about \(10^{39} - 10^{41}\) erg in soft γ-rays. Due to the huge energies, the limited volume, and the small timescale, a fireball seems inevitable before soft γ-rays are emitted, just as for a cosmological GRB. This has led to our suggestion that we could check the fireball model by monitoring the SGR sources.

In fact, let us consider a fireball with a total radiation energy \(E_{41} \times 10^{41}\) erg and a radius \(r_6 \times 10^6\) cm in thermal equilibrium.\(^6\) The temperature will be \(T = 113 E_{41}^{1/4} r_6^{-3/4} \text{keV}\). The optical depth due to Compton scattering of photons from e\(^\pm\) pairs is \(\tau = 3.0 \times 10^{11} E_{41}^{3/8} r_6^{-1/8} \exp(-4.5 r_6^{3/4}/E_{41}^{1/4})\), obviously optically thick for a typical SGR burst. The same conclusion would be drawn even if the energy was supposed to be released steadily with a luminosity \(L > 10^{40}\) erg s\(^{-1}\). Below we will briefly describe the fireball/blastwave model and apply it to SGR bursts to predict their afterglows in X-ray and optical bands.

A fireball with total initial energy \(E_0\) and initial bulk Lorentz factor \(\eta \equiv E_0/M_0 c^2\), where \(M_0\) is the initial baryon mass and \(c\) the velocity of light, is expected to radiate half of its energy in γ-rays during the GRB phase, either due to an internal-shock or an external-shock mechanism. Subsequently the fireball will continue to expand as a thin shell into the ISM, generating an ultrarelativistic shock, which has already been studied analytically. A simple approximate solution for the shell radius, \(R(t)\), and the Lorentz factor of the shocked ISM, \(\gamma(t)\), is derived as:

\[
R(t) \approx 8.93 \times 10^{15} E_{51}^{1/4} n_1^{-1/4} t^{1/4} \text{cm} = 2.82 \times 10^{13} E_{41}^{1/4} n_1^{-1/4} t^{1/4} \text{cm},
\]

\[
\gamma(t) \approx 193 E_{51}^{1/8} n_1^{-1/8} t^{-3/8} = 10.9 E_{41}^{1/8} n_1^{-1/8} t^{-3/8},
\]

where \(E_0 = 10^{51} E_{51}\) erg = \(10^{41} E_{41}\) erg, \(n = n_1\) cm\(^{-3}\) is the number density of ISM and \(t\) is observer’s time in units of 1 s. These equations are good approaches only when \(\gamma \gg 1\) and \(t \gg t_G\) (duration of the main GRB). For a more accurate solution suitable even when \(t \approx t_G\) and/or \(\gamma \approx 1\), please see Huang et al.’s numerical evaluation.\(^4\)

Electrons in the shocked ISM are highly relativistic. Inverse Compton cooling may not contribute to emission in X-ray and optical bands that we are interested in. We will consider only synchrotron radiation below. In the comoving frame the electron number density \(n_e'\) distribution in the shocked ISM is assumed to be a power-law function of electron Lorentz factor \(\gamma_e\), as expected for shock acceleration, \(dn_e' / d\gamma_e \propto \gamma_e^{-p}\), \((\gamma_{min} \leq \gamma_e \leq \gamma_{max})\), where \(\gamma_{min}\) and \(\gamma_{max}\) are the minimum and maximum Lorentz factors, and \(p\) is the index varying between 2 and 3. We suppose that the magnetic
field energy density is a fraction \( \xi_B^2 \) of the energy density \( \varepsilon' \), 
\[ B'^2/8\pi = \xi_B^2 \varepsilon' \]
where \( B' \) is the magnetic field in the comoving frame, and the electron carries a fraction \( \xi_e \) of the energy, so that \( \gamma_{\text{min}} = \xi_e (m_p/m_e) \gamma (p - 2)/(p - 1) \), where \( m_p \) and \( m_e \) are proton and electron masses respectively, and \( \gamma_{\text{max}} = 10^8 B'^{1/2} \). Synchrotron radiation is then translated from the comoving frame into the observer’s frame. The derived flux densities at frequency \( \nu \) decay as a power-law, 
\[ S_\nu \propto t^{-\alpha} \]
where \( \alpha = 3(p-1)/4 \), in good agreement with recent observations.

Above is only a rough depict. We have carried out detailed numerical evaluation to investigate the afterglows from SGR bursts, following Huang et al.’s simple model.\(^4\) We chose \( E_0 \) between \( 10^{40} \) and \( 10^{42} \) erg, and \( n = 1 \) or \( 10 \) cm\(^{-3} \). In each case we set \( p = 2.5 \), \( \xi_e = 0.5, \xi_B = 0.1 \) and \( d = 10 \) kpc. Since \( M_0 \) is a parameter having little influence on the afterglows, we chose \( M_0 \) so that \( \eta \approx 280 \) in all cases. X-ray flux \( F_X \) is integrated from 0.1 to 10 keV, and optical flux densities for R band \( S_R \) are calculated. The evolution of \( F_X \) and \( S_R \) are illustrated in Figs. 1 and 2 respectively. We see that for a strong burst (\( E_0 > 10^{41} \) erg), \( F_X \) can in general keep to be above \( 10^{-12} \) erg\( \cdot \)cm\(^{-2} \)\( \cdot \)s\(^{-1} \) for 40 to more than 200 s and \( S_R \) can keep to be above \( 10^{-29} \) erg\( \cdot \)cm\(^{-2} \)\( \cdot \)Hz\(^{-1} \) (corresponding to magnitude \( R \approx 24.0 \) mag) for 200 to more than \( 10^3 \) s. But if we take \( E_0 = 10^{40} \) erg, then \( F_X \) can hardly be greater than \( 2 \times 10^{-12} \) erg\( \cdot \)cm\(^{-2} \)\( \cdot \)s\(^{-1} \).

Now we discuss the observability. The three known SGRs have been extensively looked after in X-ray, optical and radio bands. A pointlike X-ray source has been identified in each case, but only SGR 1806–20 has a detectable optical counterpart. SGR 0526–66 is associated with the Large Magnellanic Cloud SNR N49, about 55 kpc from us. A permanent X-ray hot spot is found with an unabsorbed flux of about \( 2 \times 10^{-12} \) erg\( \cdot \)cm\(^{-2} \)\( \cdot \)s\(^{-1} \) (0.1 – 2.4 keV).\(^8\) No optical counterpart brighter than magnitude \( m_\nu = 21 \) mag has been identified. SGR 1806–20 is associated with the Galactic SNR G10.0–0.3, about 10 to 15 kpc from the Earth. A steady pointlike X-ray source with an unabsorbed flux of about \( 10 \times 10^{-12} \) erg\( \cdot \)cm\(^{-2} \)\( \cdot \)s\(^{-1} \) has been observed.\(^9\) Optical observations have revealed a luminous companion (spectral type O9 – B2) to this SGR, but heavily reddened due to serious interstellar extinction (\( A_\nu \approx 30 \) mag). The least active source SGR 1900+14 is associated with the Galactic SNR G42.8+0.6, about 7 to 14 kpc from us. A quiescent, steady, point X-ray source is present at its position,\(^10\) with an unabsorbed flux of \( 3.0 \times 10^{-12} \) erg\( \cdot \)cm\(^{-2} \)\( \cdot \)s\(^{-1} \). No optical source is detected down to limiting magnitude of \( m_\nu \approx 24.5 \) mag.

In order to be detectable, the X-ray afterglow flux from an SGR burst should at least be comparable to that of the quiescent X-ray source. Taking \( 10^{-12} \) erg\( \cdot \)cm\(^{-2} \)\( \cdot \)s\(^{-1} \)
as a threshold, then the predicted afterglows will generally be above the value for about 40–200 s for intense events (Fig. 1). Since the peak flux can be as high as $10^{-8} - 10^{-7}$ erg cm$^{-2}$ s$^{-1}$, such an afterglow should be observable by those satellites now in operation, such as ROSAT, ASCA and Rossi. If detected afterglows from SGR bursts would be ideal to test the fireball/blastwave model, so we suggest that SGRs should be monitored during their active periods. Cases are similar for optical afterglows. If we took $S_R = 100 \mu$Jy ($R \approx 19$ mag) as the threshold, afterglow would last less than 100 s, but if we took $S_R = 1 \mu$Jy ($R \approx 24$ mag), then we would have more than $10^3$ s (Fig. 2).

We notice that some researchers do have monitored the SGRs in optical and radio wave bands. In 1995, Vasisht et al. reported a negative detection by the Very Large Array of any radio variability from SGR 1806–20 above the 25% level on postburst timescales ranging from 2 d to 3 month. Radio afterglows are beyond our discussion here because strong self-absorption is involved. In 1984, Pedersen et al. reported three possible optical flashes from SGR 0526–66, but none of their light curves shows any sign of afterglows. We think, they were either due to the limited aperture (50 cm) of their telescope or maybe simply spurious. The latter seems more possible since no soft $\gamma$-ray bursts were observed simultaneously with them.

Of special interest is the most prolific source SGR 1806–20. In 1993 October 9.952414 UT a soft $\gamma$-ray burst was recorded by the Compton Gamma-Ray Observatory. ASCA satellite happened to be observing the SGR at that moment and a coincident X-ray burst was recorded.\textsuperscript{9} Sonobe et al. particularly pointed out that there were no obvious mean intensity changes in X-rays prior to the burst nor following the burst, not only on a timescale of 1 d, but also on timescales of minutes.\textsuperscript{11} This is not inconsistent with our model since it was a relatively weak burst, with $E_0$ about $10^{39}$ erg. Afterglows from this burst are not expected to be detectable.

We have also calculated the afterglows from such a unique burst as GRB 790305 from SGR 0526–66,\textsuperscript{12} taking $E_0$ to be $1 \times 10^{45}$ erg and $d = 55$ kpc. We find that the X-ray afterglows should be detectable ($> 10^{-12}$ erg cm$^{-2}$ s$^{-1}$) for several hours, and $S_R$ will be above $100 \mu$Jy ($R \approx 19$ mag) for about one hour. Had the source been monitored on 1979 March 5, chances were good that afterglows should have been observed.

We end this letter by a brief comment on the importance of our suggestion. GRBs occurring at three different distance scales have been observed or suggested: classical GRBs at cosmological distances, classical GRBs in the Galactic Halo, and SGRs at about 10 kpc distances. Classical GRBs are intriguing puzzles because, if occurred
at cosmological distances, they would present stringent requirements on the energies and the initial baryon masses. The cosmological origin of classical GRBs and the fireball/blastwave model are two propositions. Although they are consistent with each other in that the observed power-law decays of afterglows from GRBs can be naturally explained, both of them are in urgent need of more observational tests, especially independent ones. The possible host galaxy of GRB 970228 and the red shift of GRB 970508 are two strong proofs, but far from enough. Here we have suggested that the three known SGRs, especially the most prolific one, SGR 1806–20, are good candidates to be used to test the fireball/blastwave model independently. Our arguments are obvious: the distances are much certain, their accurate positions are available, they burst out repeatedly, their origins are relatively clear so that we feel more confident about them. Although such monitoring observations are imaginably difficult, the results will be valuable, not only in that the afterglows might be acquired, but also that the simultaneous bursting behaviors in X-ray and optical wavelengths other than soft $\gamma$-rays are important to our understanding of these SGRs themselves.

REFERENCES

[1] G. J. Fishman and C. A. Meegan, Ann. Rev. Astron. Astrophys. 33 (1995) 415.
[2] E. Costa et al., Nature 387 (1997) 783.
[3] S. G. Djorgovski et al., Nature 387 (1997) 876.
[4] Y. F. Huang, Z. G. Dai, D. M. Wei and T. Lu, Mon. Not. R. Astron. Soc. (1998) in press.
[5] J. P. Norris, P. Hertz, K. S. Wood and C. Kouveliotou, Astrophys. J. 366 (1991) 240.
[6] T. Piran and A. Shemi, Astrophys. J. 403 (1993) L67.
[7] K. Hurley, C. Kouveliotou, T. Cline and E. Mazets, IAU Circular, No.6743 (1997).
[8] D. Marsden, R. E. Rothschild, R. E. Lingenfelter and R. C. Puetter, Astrophys. J. 470 (1996) 513.
[9] T. Murakami et al., Nature 368 (1994) 127.
[10] K. Hurley et al., Astrophys. J. 463 (1996) L13.
[11] T. Sonobe, T. Murakami, S. R. Kulkarni, T. Aoki and A. Yoshida, Astrophys. J. 436 (1994) L23.
[12] W. D. Evans et al., Astrophys. J. 237 (1980) L7.
Figure 1: Predicted X-ray afterglows from SGR bursts. Flux $F_X$ is integrated from 0.1 to 10 keV and is in unit of erg·cm$^{-2}$·s$^{-1}$. Time is measured from the end of the main $\gamma$-ray burst.

Figure 2: Predicted optical afterglows from SGR bursts. The R band flux density $S_R$ is in unit of erg·cm$^{-2}$·s$^{-1}$·Hz$^{-1}$.