TESTING THE FIREBALL/BLASTWAVE MODEL
BY MONITORING AFTERGLOWS FROM SOFT GAMMA REPEATERS

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Abstract The popular fireball/blastwave model of classical $\gamma$-ray bursts is applied to soft $\gamma$-ray bursts. It is found that X-ray afterglows from strong events may be above their quiescent levels for $40 - 400$ seconds. Optical afterglows may also be detectable. By monitoring the three repeaters, we will have an ideal way to check the fireball/blastwave model.

Keywords gamma rays: bursts, shock waves

Classification Index P142.6, P144.6

0 INTRODUCTION

The recent detection of afterglows from some $\gamma$-ray bursts (GRBs) located by BeppoSAX opens up a new era in the studies of GRBs.[1–3] Afterglows were detected in X-rays from GRB 970228, 970402, 970508, 970616, 970828, in optical band from GRB 970228, 970508, and even in radio from GRB 970508. The possible host galaxy of GRB 970228 and the determined redshift $0.835 < z < 2.1$ for GRB 970508 strongly indicate a cosmological origin for GRBs.

GRBs might be produced by highly relativistic fireballs,[4,5] After the main GRB, the collision between the GRB ejecta and the interstellar medium (ISM) provides a

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natural explanation for the power-law decay of the observed low energy afterglows.\cite{6-10} 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. Luckily enough, we do have such ideal objects at hand.

While the nature of the so called “classical $\gamma$-ray bursts” is still controversial, cases for a subtle class of GRBs, the soft $\gamma$-ray repeaters (SGRs), are much clearer. SGRs are characterized mainly by their soft spectrums and unpredictable recurrences.\cite{11} There are only three known SGRs (0526$-66$, 1806$-20$ and 1900$+14$), all have been tentatively associated with supernova remnants (SNRs). Recently a possible fourth SGR was reported, but need to be confirmed. A typical SGR burst lasts several hundred milliseconds, emitting $\sim 10^{40} - 10^{41}$ ergs in soft $\gamma$-rays. Due to the huge energy, the limited volume and the small timescale, a fireball seems inevitable before soft $\gamma$-rays are emitted, just as a cosmological GRB. This has led to our suggestion that we could check the fireball model by monitoring the SGR sources. Below the fireball/blastwave model is first briefly described and then applied to SGR bursts to predict their afterglows in X-ray and optical bands.

1 AFTERGLOWS FROM SGR BURSTS

1.1 the Adiabatic Expansion

A fireball with total initial energy $E_0$ and initial bulk Lorentz factor $\eta \equiv E_0/M_0c^2$, where $M_0$ is the initial baryon mass, is expected to radiate half of its energy in $\gamma$-rays during the GRB phase, either due to an internal-shock or an external-shock mechanism. The subsequent expansion generates an ultrarelativistic shock. The Lorentz factor of the shock ($\Gamma$) and the shocked ISM ($\gamma$) are related by $\Gamma^2 \approx 2\gamma^2$. In the shell’s comoving frame, number density ($n'$) and energy density ($e'$) of the shocked ISM are $n' \approx 4\gamma n$ and $e' \approx 4\gamma^2 nm_pc^2$, respectively, where $n$ is the number density of the unshocked ISM.\cite{12} In the case of adiabatic expansion, energy is conserved, then we get a useful expression for $\gamma$ and
\( R \) (shock radius),
\[
\gamma^2 R^3 \approx E_0/(8\pi n m_p c^2).
\] (1)

Photons observed within a time interval of \( dt \) are in fact emitted within an interval of \( dt_b = dt/(1 - v/c) \approx 2\gamma^2 dt \) in the burster’s fixed frame, where \( v \) is the observed velocity of the shocked ISM. Then \( R \) and \( t \) are related by
\[
\frac{dR}{dt} \approx 2\gamma^2 c.
\] (2)

Under the assumption that \( \gamma \gg 1 \), combining equation (1) and equation (2), we can derive a simple solution:
\[
R(t) \approx 8.93 \times 10^{15} E_{51}^{1/4} n_1^{-1/4} t^{1/4} \text{cm} = 5.02 \times 10^{13} E_{42}^{1/4} n_1^{-1/4} t^{1/4} \text{cm},
\] (3)

\[
\gamma(t) \approx 193 E_{51}^{1/8} n_1^{-1/8} t^{-3/8} = 14.5 E_{42}^{1/8} n_1^{-1/8} t^{-3/8},
\] (4)

where \( E_0 = 10^{51} E_{51} \) ergs = \( 10^{42} E_{42} \) ergs, \( n = n_1 \text{ cm}^{-3} \) and \( t \) is in unit of second. For a more accurate solution please see Huang et al.’s numerical evaluation.[10]

1.2 Synchrotron Radiation

Electrons in the shocked ISM are highly relativistic. Inverse Compton cooling of the electrons may not contribute to emission in X-ray and optical bands we are interested in. Only synchrotron radiation will be considered below. The electron distribution in the shocked ISM is assumed to be a power-law function of electron energy, as expected for shock acceleration,
\[
dn_e/d\gamma_e \propto \gamma_e^{-p}; \gamma_{e,\text{min}} \leq \gamma_e \leq \gamma_{e,\text{max}},
\] (5)

where \( \gamma_{e,\text{min}} \) and \( \gamma_{e,\text{max}} \) are the minimum and maximum Lorentz factors of electrons, and \( p \) is an index varying between 2 and 3. I suppose that the magnetic field energy density (in the comoving frame) is a fraction \( \xi_B^2 \) of the energy density, \( B^2/8\pi = \xi_B^2 \), and that the electron carries a fraction \( \xi_e \) of the energy, \( \gamma_{e,\text{min}} = (m_p/m_e)\xi_e \gamma + 1 \).

The spectral property of synchrotron radiation from such a collection of electrons is clear. In the comoving frame, the characteristic photon frequency is \( \nu_m = eB^2\gamma_{e,\text{min}}^2/(2\pi m_e c) \),
where $e$ is the electron charge. The spectral peaks at $\nu_{\text{max}} \approx 0.29 \nu_m$. For frequency $\nu \gg \nu_{\text{max}}$, and $\nu \ll \nu_{\text{max}}$, the flux density scales as $\nu^{-\alpha}$ and $\nu^{1/3}$ respectively, where $\alpha = (p - 1)/2$.

The specific intensity at frequency $\nu$ in the comoving frame ($I_{\nu,\text{co}}$) can be transformed into the observer’s frame by the following equations:

$$\nu_{\oplus} = (1 + v/c) \gamma \nu,$$

(6)

$$I_{\nu_{\oplus},\oplus} = (1 + v/c) \gamma^3 I_{\nu,\text{co}}.$$

(7)

Then the observed flux density is $S_{\nu_{\oplus},\oplus} = \pi (k \gamma ct)^2 I_{\nu_{\oplus},\oplus}/D^2$, where $k \approx 3$ is a coefficient introduced to correct for the effect on the observed emitting surface by the dynamical deceleration.$^{[10]}$ The flux observed by a detector is an integral of $S_{\nu_{\oplus},\oplus}$ over the range between lower and upper frequency limits of the detector.

1.3 Numerical Results

I have carried out detailed numerical evaluation to investigate the afterglows from SGR bursts, following Huang et al.’s simple model.$^{[10]}$ I chose $E_0$ between $10^{40}$ ergs and $10^{42}$ ergs, and $n = 1$ or $10$ cm$^{-3}$. In each case I set $p = 2.5$, $\xi_e = 0.1$ and $d = 10$ kpc. Since $M_0$ is a parameter having little influence on the afterglows, I chose $M_0$ so that $\eta \approx 280$ in all cases. X-ray flux ($F_X$) is integrated from 0.1 keV 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 Figures 1 and 2 respectively. We see that for a strong burst ($E_0 > 10^{41}$ ergs), $F_X$ can in general keep to be above $10^{-12}$ ergs·cm$^{-2}$·s$^{-1}$ for $40 - 200$ seconds and $S_R$ can keep to be above $10^{-29}$ ergs·cm$^{-2}$·s$^{-1}$·Hz$^{-1}$ (corresponding to $R \approx 24^m.0$) for $200 - 1000$ seconds. But if we take $E_0 = 10^{40}$ ergs, then $F_X$ can hardly be greater than $2 \times 10^{-12}$ ergs·cm$^{-2}$·s$^{-1}$.

To compare the afterglows from cosmological, Galactic Halo and SGR bursts more directly, we plot their X-ray and optical light curves in contrast in Figures 3 and 4. It is clearly shown that the predicted afterglows from cosmological GRBs last much longer than any kind of Galactic bursts. This is consistent with previous conclusion. Since X-ray afterglows are observed more than a week later and optical afterglow is observed even
more than six months later for GRB 970228, we suggest that the observed time scales of afterglows is another strong evidence favoring the cosmological origin.

2 COMPARISION BETWEEN PREDICTION AND OBSERVATION

The three known SGRs have been extensively looked after in X-ray, optical and radio bands. A pointlike X-ray source has been identified associating with each SGR, but only SGR 1806—20 has a detectable optical counterpart. Below is a brief review.\cite

SGR 0526—66 is associated with SNR N49, about 55 kpc from us. A permanent X-ray hot spot is found with an unabsorbed flux of $\sim 2.0 \times 10^{-12}$ ergs·cm$^{-2}$·s$^{-1}$ (0.1 – 2.4 keV). No optical counterpart has been identified. Dickel et al. placed 3$\sigma$ upper limits on the radio (less than 0.3 Jy at 12.6 cm), infrared (less than 39 $\mu$Jy and 58 $\mu$Jy at 2.16 and 1.64 $\mu$m respectively), and optical (less than 40 $\mu$Jy at 656.3 nm) emission from the X-ray source.

SGR 1806—20 is associated with the Galactic SNR G10.0—0.3, 10 to 15 kpc from the Earth. A steady pointlike X-ray source with an unabsorbed flux of $\sim 10 \times 10^{-12}$ ergs·cm$^{-2}$·s$^{-1}$ has been observed. Optical observations have revealed a luminous O/B type companion to this SGR. However, due to a giant molecular cloud located at this direction, interstellar extinction is serious ($A_V = 30^m$), and the optical source is heavily reddened.

The least active source SGR 1900+14 is associated with the Galactic SNR G42.8+0.6, 7 to 14 kpc from us. A quiescent, steady, point X-ray source is present at its position, with an unabsorbed flux of $3.0 \times 10^{-12}$ ergs·cm$^{-2}$·s$^{-1}$. No optical source is detected down to limiting magnitude of $m_V \approx 24^m.5$.

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

We notice that some researchers do have monitored the SGRs in optical and radio wavelengths. After monitoring SGR 1806–20 with the VLA in 10 epochs spreading over 5 months, Vasisht et al. reported that there was no radio variability above the 25% level on postburst timescales ranging from 2 days to 3 months. Radio afterglows are beyond our discussion here because strong self-absorption is involved. Pedersen et al. have reported three possible optical flashes from SGR 0526–66, but none of their light curves shows any sign of afterglows. We think it was either due to the limited aperture (50 cm) of their telescope or that maybe the flashes were spurious. The latter seems more possible since no soft $\gamma$-ray bursts were observed simultaneously.

Of special interest is the most prolific source SGR 1806–20. On 1993 October 9.952414 UT a soft $\gamma$-ray burst occurred. ASCA satellite happened to be observing the SGR at that moment and recorded a simultaneous X-ray burst. Sonobe et al. 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 day, but also on timescales of minutes.[14] This is not inconsistent with our predictions since it was a relatively weak burst, with $E_0$ about $10^{39}$ ergs. Afterglows from this burst are not expected to be detectable.

We have also calculated afterglows from such a unique burst as GRB 790305 from SGR 0526–66,[15] taking $E_0 = 10^{45}$ ergs and $d = 55$ kpc. The light curves are plotted in Figures 5 and 6. It is found that the X-ray afterglows should be detectable ($> 10^{-12}$ ergs-cm$^{-2}$-s$^{-1}$) for several hours, and $S_R$ will be above $100 \mu Jy \,(m_R \approx 19^m)$ for about one hour. Had the source been monitored on 1979 March 5, afterglows should have been observed.

3 DISCUSSION AND CONCLUSIONS
Gamma-ray bursts 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. 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 for the cosmological origin, but they are far from enough. Here we have stressed that the observed afterglow timescale (more than one week in X-rays and six months in optical band) is another strong proof, since afterglows from any kind of Galactic GRBs will be too weak to be viable on that timescale, as clearly shown in this paper.

Soft $\gamma$-ray bursts from SGRs might be good candidates to be used to test the fireball/blastwave model independently. The 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. According to our calculations, afterglows from a strong SGR burst will generally be detectable. It is thus suggested that the SGRs should be monitored during their active periods. Although such observations are imaginably difficult, the results will be valuable, not only in that the afterglows might be acquired and the fireball/blastwave model could be tested, but also that the simultaneous bursting behaviors in X-ray and optical wavelengths other than soft $\gamma$-rays are important to our understanding of the SGRs themselves.

We particularly noticed an X-ray burst from SGR 1806–20 detected by the ASCA satellite. It is a great pity that the corresponding soft $\gamma$-ray burst is rather weak so that no afterglow was observed. However, the negative detection of X-ray afterglows itself may be regarded as a proof supporting the fireball/blastwave model, although it is a relatively weak one.
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Fig. 1.— Predicted X-ray afterglows from SGR bursts. Flux (0.1 – 10 keV) is in unit of ergs·cm$^{-2}$·s$^{-1}$.

Fig. 2.— Predicted optical afterglows from SGR bursts. $S_R$ is in unit of ergs·cm$^{-2}$·s$^{-1}$·Hz$^{-1}$.
Fig. 3.— Theoretical X-ray afterglows from GRBs at different distances. The three lines correspond to cosmological ($E_0 = 10^{52}$ ergs, $d = 3$ Gpc, dotted line), the Galactic Halo ($10^{44}$ ergs, 300 kpc, dashed line), and SGR ($10^{41}$ ergs, 10 kpc, full line) bursts respectively.

Fig. 4.— Calculated optical afterglows from cosmological (dotted line), the Galactic Halo (dashed line), and SGR (full line) bursts.
Fig. 5.— Theoretical X-ray afterglows from GRB 790305

Fig. 6.— Calculated optical afterglows from GRB 790305