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THE RADIO–TO–X-RAY SPECTRUM OF GRB 970508 ON 1997 MAY 21.0 UT


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ABSTRACT

We have reconstructed the spectrum of the afterglow of GRB 970508 on 1997 May 21.0 UT (12.1 days after the gamma-ray burst) on the basis of observations spanning the X-ray–to–radio range. The low-frequency power-law index of the spectrum, $\alpha = 0.44 \pm 0.07$ ($F \propto \nu^\alpha$), is in agreement with the expected value $\alpha = 1/3$ for optically thin synchrotron radiation. The 1.4 GHz emission is self-absorbed. We infer constraints on the break frequencies $\nu_b$ and $\nu_{\alpha}$ on 1997 May 21.0 UT from a spectral transition from $F_{\nu} \sim \nu^{-0.6}$ to $F_{\nu} \sim \nu^{-1.1}$ in the optical passband around 1.4 days. A model of an adiabatically expanding blast wave emitting synchrotron radiation, in which a significant fraction of the electrons cool rapidly, provides a successful and consistent description of the afterglow observations over nine decades in frequency, ranging in time from trigger until several months later.

Subject headings: gamma rays: bursts — gamma rays: observations

1. INTRODUCTION

GRB 970508 was a moderately bright gamma-ray burst (Costa et al. 1997; Kouveliotou et al. 1997). It was detected on 1997 May 8.904 UT with the Gamma-Ray Burst Monitor (Frontera et al. 1995) on board the Italian-Dutch X-ray observatory BeppoSAX (Piro, Scarsi, & Butler 1995). Optical observations of the wide field camera error box (Heise et al. 1997) made on May 9 and 10 revealed a variable object at R.A. = 06\(^{h}\)53\(^{m}\)49\(^{s}\).2, decl. = +79°16′19″ (J2000), which showed an increase by ∼1 mag in the V band (Bond 1997) and whose spectrum indicated that the distance to the gamma-ray burst (GRB) source corresponds to a redshift of at least 0.83 (Metzger et al. 1997). The BeppoSAX narrow field instruments revealed an X-ray transient (Piro et al. 1997a) whose position is consistent with that of the optical variable, and Frail et al. (1997a, 1997b) found the first GRB radio afterglow for GRB 970508; the radio source position coincides with that of the optical source (Bond 1997).

The global properties of the X-ray, optical, and radio afterglows of GRBs have been successfully described by relativistic blast-wave models (e.g., Wijers, Rees, & Mészáros 1997). In this Letter, we show that the detailed properties of the spectrum of the afterglow of GRB 970508 and its evolution are well described by a blast-wave model in which significant cooling of the electrons plays an important role (Sari, Piran, & Narayan 1995). This model predicts the occurrence of an extra break at $\nu_b$ in the spectrum, which corresponds to the Lorentz factor $\gamma_e$ above which the electron cooling time is shorter than the expansion time of the blast wave.

2. THE X-RAY–TO–RADIO SPECTRUM ON 1997 MAY 21.0 UT

In the second week after the GRB 970508 event, many observations of its afterglow were made by ground-based and orbiting instruments, which allows us to derive the X-ray–to–radio afterglow spectrum on 1997 May 21.0 UT (12.1 days after the event) with only a few assumptions.

During the first month, the 4.86 and 8.46 GHz observations by Frail et al. (1997a) show strong fluctuations attributed to interstellar scintillation (ISS) (see, e.g., Goodman 1997). At 8.46 GHz, the interval of 8–14 days after the event corresponds to a flare. It would therefore appear that the “true” underlying 4.86 and 8.46 GHz flux densities are better represented by long-term average values. To discern, apart from an average flux, a possible trend in the 8.46 and 4.86 GHz data of Frail et al. (1997a), we have fitted a power law (in time $t$, measured in days since the burst) to the data for $t < 30$ days. We find $F_{4.86\text{GHz}} = (101 \pm 17) \times t^{0.61 \pm 0.06}$ mJy (3σ = 254/10), and $F_{8.46\text{GHz}} = (321 \pm 18) \times t^{0.274 \pm 0.020}$ mJy (3σ = 521/25), and we have used these expressions to derive a flux estimate for May 21.0 UT at these frequencies. At lower frequencies, the afterglow was not (or was barely) detected during this week.

The average Westerbork Synthesis Radio Telescope 1.4 GHz flux density (May 9.7–July 16.44 UT) is less than 80 mJy (2 σ; Galama et al. 1998b; we note, however, that Frail et al. 1997a report a flux density of ∼100 mJy).

Pooley & Green (1997) observed GRB 970508 on six consecutive days (May 17–22) with the Ryle Telescope at 15 GHz. The source was detected on May 16.52 UT at 1.57 ± 0.25 mJy, but an individually significant detection was not made on any of the other days. However, averaging all observations obtained in the interval May 17–22 (8–13 days after the event), the source was detected at 660 ± 110 mJy. Again, since ISS can modulate the flux densities strongly below ∼20 GHz at this Galactic latitude, we assume that the detection on May 16.52 UT was boosted by this effect and that the source-intrinsic 15 GHz flux on May 21.0 is better represented by the 5 day average stated above.

Bremer et al. (1998) detected GRB 970508 with the IRAM Plateau de Bure Interferometer (PdBI) at 86 GHz but not at 232 GHz. No significant variation is observed between the three 86 GHz PdBI detections (May 19.07–May 22.99; center epoch May 21.0 UT) and, combining them, we obtain an average $F_{86\text{GHz}} = 1.71 \pm 0.26$ mJy. For the 232 GHz upper limit, we...
use the May 21.15 (day 12.2) upper limit of $F_{323 \text{GHz}} < 4.22 \text{ mJy}$ (2 $\sigma$; Bremer et al. 1998).

In an observation with the Infrared Space Observatory (ISO) on May 21, the source was not detected (Hanlon et al. 1998); the preliminary upper limit was $F_{12 \mu m} < 120 \mu$mJy.

We have fitted a power law, $F_{\nu} = 120^{+75}_{-45} \times \nu^{-0.89^{+0.27}_{-0.27}} \mu$mJy ($\chi^2_{\nu=3} = 0.23/1$), to the three $K$ band (2.2 $\mu$m) detections of Chary et al. (1998) and find $F_{\nu} = 13^{+26}_{-15} \mu$mJy for May 21.0 UT.

For an estimate of the optical flux density, we used the fit by Galama et al. (1998a) to the power-law decay of the differential Cousins $R$ ($R_c = 6400$ Å) light curve, i.e., $F_{\nu} = (82.7 \pm 2.3) \times \nu^{1.14^{+0.014}_{-0.014}} \mu$mJy; using an absolute calibration uncertainty of 0.1 mag, we find $4.8 \pm 0.5 \mu$mJy.

X-ray fluxes (2–10 keV) of the afterglow obtained with BeppoSAX have been reported by Piro et al. (1997b). These observations were made during the burst and between 6 hr and 6 days afterward. We have inferred the X-ray flux $F_X = (7.3 \pm 4) \times 10^{-5} \mu$mJy for May 21.0 UT by extrapolating the power-law fit ($F_{\nu} \propto \nu^{-1.1^{+0.1}_{-0.1}}$) of Piro et al. (1997b).

### 3. DISCUSSION

#### 3.1. The Radio-to–X-Ray Spectrum

The radio–X-ray spectrum on May 21.0 UT is shown in Figure 1. We have divided the spectrum into four parts, corresponding to the lowest frequencies (region I; less than $2.5 \times 10^5$ Hz), the low frequencies (region II; $2.5 \times 10^5$–$10^{11}$ Hz), the intermediate frequencies (region III; $10^{11}$–$10^{14}$ Hz), and the high frequencies (region IV; greater than $10^{14}$ Hz).

Region I has a much steeper spectral slope ($\alpha_{1.4-4.86 \text{GHz}} > 1.1$) than region II ($\alpha_{1.4-46.86 \text{GHz}} = 0.44 \pm 0.07$ [$\chi^2_{\nu=1} = 1.4/2$]). The 1.4 GHz flux density (region I) is consistent with the expectation for self-absorbed emission ($F_{\nu} \propto \nu^{-2}$; Katz, Piran & Sari 1997), i.e., the self-absorption break $\nu_B \approx 2.5 \text{ GHz}$. The low-frequency region (II) is in agreement with the expected low-frequency tail of synchrotron radiation ($F_{\nu} \propto \nu^{-0.5}$; Rybicki & Lightman 1979). The high-frequency X-ray–to–optical slope ($\alpha = -1.12 \pm 0.07$) is consistent (Galama et al. 1998b, hereafter Paper I) with synchrotron radiation from electrons, of which a significant fraction cools rapidly, with a power-law distribution of Lorentz factors, $N(\gamma_e) \propto \gamma_e^{-\alpha}$ (Sari et al. 1998). Optical multicolor photometry which was obtained in the first 5 days after the event showed that the optical spectrum was well represented by a power law and approached $\alpha = -1.11 \pm 0.06$ (2.1–5.0 days after the GRB; $\chi^2_{\nu=3} = 3.0/4$) after reaching maximum optical light (Galama et al. 1998a; we used $t > 2.1$ days), i.e., consistent with the X-ray to optical slope on May 21.0 UT, which suggests that the slope remained constant over this period. We note that the extrapolation of the X-ray flux is uncertain, but none of the further discussion depends on the validity of the extrapolation, since both of the spectral breaks that we infer lie below the optical. In the spectrum, the local optical spectral slope derived from Galama et al. (1998a) is also indicated.

For region III, only upper limits are available. Extrapolating from the adjacent regions and assuming one single spectral break, we find a peak flux of $4.5 \text{ mJy}$ at $10^{12}$ Hz. However, the temporal development of GRB 970508 indicates that a second break frequency exists.

#### 3.2. Evidence for a Second Spectral Break

As noted before by Katz, Piran, & Sari (1998), during the first day the optical–to–X-ray spectral slope of GRB 970508 is $\alpha \approx -0.5$, which these authors attribute to rapid electron cooling. This is consistent with the UV excess reported by Castro-Tirado et al. (1998) and with the reddening of the optical spectrum during the first 5 days (Galama et al. 1998a). From the data of Galama et al. (1998b), we determine (using $A_V < 0.01$, based on the IRAS 100 $\mu$m cirrus flux instead of the value $A_V = 0.08$ used by Galama et al. 1998b) $\alpha = -0.54 \pm 0.14$ for $t$ between 0 and 1.5 days and $\alpha = -1.12 \pm 0.04$ for $t$ between 1.5 and 5 days. This suggests that a spectral break moved through the optical passband between 1.0 and 1.8 days after the burst, separating a range with slope $\alpha \approx -0.5$ from one with slope $\alpha \approx -1.1$ (see Fig. 2, top). By May 21 we expect this break to have moved downward in frequency to $\sim 10^{14}$ Hz (see Fig. 1 and § 3.4). Additional observational evidence for rapid cooling of a significant fraction of the electrons is given in Paper I.

#### 3.3. Rapid Electron Cooling

Sari et al. (1998) argued that the most energetic electrons may lose a significant fraction of their energy to radiation. Their model predicts the occurrence of an extra break at $\nu_B$ (corresponding to the critical Lorentz factor $\gamma_e$ above which cooling by synchrotron radiation is significant), in addition to the regular break frequency $\nu_m$ (the frequency that corresponds to the lowest energy injected electrons; Lorentz factor $\gamma_m$). The evolution in time of the GRB afterglow is determined by the evolution of the two break frequencies: $F_{\nu} \propto \nu^{-0.5/2}$ and $F_{\nu} \propto \nu^{-1/2}$ (Sari et al. 1998). We assume adiabatic evolution of the GRB remnant (see § 3.6). Since $\nu_m$ is initially greater than $\nu_B$ (Sari et al. 1998) but decays more rapidly, there is a time $t_m$ at which the two are equal. For late times $t > t_m$, we have $\nu_m < \nu_B$, and the spectrum varies as $F_{\nu} \propto \nu^{-0.5/2}$ from $\nu_m$ up to $\nu_B$; above $\nu_B$ it follows $F_{\nu} \propto \nu^{-2}$, and below $\nu_m$ it follows the low-frequency tail, $F_{\nu} \propto \nu^{-0.5}$ (Sari et al. 1998).

#### 3.4. Constraints on the Break Frequencies $\nu_B$ and $\nu_m$ for May 21.0 UT

The 86 GHz PdBI observations do not detect the source before 10 days, followed by three detections and subsequently...
only nondetections, i.e., at 86 GHz the emission peaked between ~10 and ~14 days (Bremmer et al. 1998). This implies that the peak flux $F_{\nu, \text{max}} \sim 1700 \mu$Jy at 86 GHz. The decay after the maximum is quite rapid: for $F_{\nu} \propto t^{-\alpha}$, we find $\delta < -1.1$ using the $3\sigma$ upper limit on May 28.41 (Bremmer et al. 1998). If this maximum would correspond to the break frequency $\nu_0$ passing 86 GHz, then we would expect the decay to be much slower: $F_{\nu} \propto t^{-0.9}$ (Sari et al. 1998). If it reflects the passage of $\nu_{\text{m}}$, the subsequent decay would go as $F_{\nu} \propto t^{1-0.4} = t^{-0.6}$ (Sari et al. 1998). The observed decay rate is in marginal agreement with the passage of the break frequency $\nu_0$ but definitely excludes that $\nu_0$ was passing 86 GHz. We therefore identify the maximum at 86 GHz with the passage of $\nu_0$ at $t_{\nu, 86\,\text{GHz}} \sim 12$ days, i.e., at the time of the derived spectrum (May 21.0 UT).

There is no evidence for a break at $\nu < 86$ GHz (the 86 GHz detection is consistent with the low-frequency tail; see Fig. 1). This implies that $\nu > \nu_0$, and so for $\nu > \nu_0$ the spectrum is predicted to follow $F_{\nu} \propto \nu^{-(1-\alpha/2)} = \nu^{-0.6}$ (we will use $\nu = 2.2$; Paper I). Note also that, therefore, $t > t_0$ at 12.1 days. The intersection of the high-frequency extrapolation with $F_{\nu} \propto \nu^{-0.6}$ for \nu > \nu_0 gives an estimate for $\nu_0$ (see Fig. 1); we find $\nu_0 = 1.6 \times 10^{14}$ Hz at 12.1 days (May 21.0 UT). Independently, we identify the observed optical spectral transition between 1.0 and 1.8 days from $\alpha = -0.54 \pm 0.14$ to $\alpha = -1.12 \pm 0.04$ (§ 3.2 and Fig. 2) with the break frequency $\nu_0$ passing the $R_c$ band at $t_{\nu, R_c}$. For $t < t_{\nu, R_c}$ we expect $F_{\nu} \propto \nu^{0.6}$, while for $t > t_{\nu, R_c}$ we expect $F_{\nu} \propto \nu^{1/2} = \nu^{0.5}$ in the optical passband, which is in excellent agreement with the observed transition. Using $t_{\nu, R_c} = 1.4$ days ($\nu_0 \propto t^{-1/2}$), we find $\nu_0 = 1.6 \times 10^{14}$ Hz at $t = 12.1$ days (May 21.0 UT). This is in remarkable agreement with the value derived above from the intersection of $F_{\nu} \propto \nu^{-0.6}$ for $\nu > \nu_0$ in region III with the high-frequency extrapolation. We therefore identify the transition observed in the optical passband with the passage of the break frequency $\nu_0$ at $t_{\nu, R_c} \sim 1.4$ days. The frequencies $\nu_{\text{opt}}$, $\nu_{\text{m}}$, and $\nu_0$ are shown in Figure 1; they determine the division of the spectrum into the four regions. We note that the upper limit given for the ISO nondetection (Hanlon et al. 1998) is a conservative number, and further analysis may provide a stronger constraint on the shape of the spectrum.

### 3.5. The Near-Infrared Range

At 2.2 $\mu$m ($K$ band), we expect $\nu_0$ to pass at $t_{\nu, K} \sim 16.5$ days ($\nu_0 \propto t^{-1/2}$). Before that, the $K$-band flux density should decay as $F_{\nu} \propto \nu^{-0.9}$ (see above). The decay $F_{\nu} \propto \nu^{-0.9} \pm 0.27$ (§ 3.1), fitted to the data of Chary et al. (1998), is in good agreement with this. The $K$- to $R$-band spectrum should show a gradual transition between 1.4 days (when $\nu_0$ passes $R_c$) and 16.5 days from $F_{\nu} \propto \nu^{-0.6}$ to $F_{\nu} \propto \nu^{-1.5}$. Spectral indices $\alpha$ derived from the $K$-band data of Chary et al. (1998) and the optical $R_c$ light curve of Galama et al. (1998a), are in good agreement with this: $\alpha_{K-R_c} = -0.61 \pm 0.12$ ($t = 4.3$), $\alpha_{K-R_c} = -0.69 \pm 0.12$ ($t = 7.3$), and $\alpha_{K-R_c} = -0.91 \pm 0.27 (t = 11.3$; see Fig. 2, bottom). $H$-band ($1.6 \mu$m) Hubble Space Telescope observations (Pian et al. 1998) detect the optical transient at $H = 20.6 \pm 0.3$ ($F_H = 6.2 \pm 1.5$ $\mu$Jy, $t = 24.7$), and comparison with Galama et al. (1998a) gives $\alpha_{H-R_c} = -1.18 \pm 0.29$ (Fig. 2, bottom). This is consistent with the expectation that $\nu_0$ had by then already passed the $H$ band.

### 3.6. Adiabatic Dynamical Evolution of the Blast Wave and the Value of $t_0$

The observed transitions $t_{\nu, 86\,\text{GHz}} \sim 12$ days and $t_{\nu, R_c} \sim 1.4$ days imply that $t_0 \sim 0.006$ days (500 s). For $t > t_0$, the dynamical evolution of the remnant is almost certainly adiabatic, while before that time it could possibly be radiative (Sari et al. 1998; but see Mészáros, Rees, & Wijers 1998). This means that one would expect nearly all of the remnant’s observed dynamical evolution to be adiabatic.

However, the maximum flux at 8.46 GHz is $F_{\nu, \text{max}} \sim 700$ $\mu$Jy at $t_{\nu, 8.46\,\text{GHz}} \sim 55$ days (Frail et al. 1997a); this value of $t_{\nu, 8.46\,\text{GHz}}$ is as expected from the 86 GHz observations for $\nu_0 \propto t^{-0.6}$. This is less than the peak of 1700 $\mu$Jy at 86 GHz and would argue for some radiative losses, since in the perfectly adiabatic case the maximum flux should be constant with time, while the peak moves to lower frequencies. Also, the rather gradual early evolution of the radio light curves of GRB 970508 and the observed transition from optically thick to thin emission at 1.4 GHz around $t \sim 45$ days suggest the possibility of radiative evolution (Paper I). However, the absence of a break in the smooth power-law decay of the optical light curve from 2–60 days after the burst (Pedersen et al. 1998; Castro-Tirado et al. 1998; Sokolov et al. 1998; Galama et al. 1998a) shows that there is no important transition in that period. Also, the optical spectra and the optical temporal slope indicate adiabatic remnant dynamics with $\nu > \nu_0$ during this period (Paper I). Taken together, these results indicate that some additional ingredient is needed to fully explain the radio and millimeter behavior; for example, Waxman, Kulkarni, & Frail (1998) have argued that the transition from ultrarelativistic to mildly relativistic expansion of the blast wave may explain these anomalies.

### 4. Conclusion

We have found that on May 1997 21.0 UT, the afterglow spectrum of GRB 970508 contains all of the characteristic parts of a synchrotron spectrum. We infer that the dynamical evolution of the remnant is adiabatic (in agreement with Waxman...
et al. 1998) but that a significant fraction of the electrons have synchrotron cooling times that are shorter than the remnant’s expansion time. In accordance with the theory outlined by Sari et al. (1998), this produces an additional break in the spectrum. The break frequencies \( \nu_m \) and \( \nu_s \), which correspond to the minimum electron energy and the energy above which electrons cool rapidly, respectively, are equal at a time \( t_0 \) which we find to be 500 s. This synchrotron spectrum and adiabatic dynamics can explain most of the afterglow behavior over nine decades in frequency spanning the X-rays to radio waves, from the first optical to the late radio data. Some aspects of the afterglow are not explained by this model: (1) the flux at \( \nu_m \) should be constant but is seen to decrease from 12 days when it lies at millimeter wavelengths to 55 days when it lies in the radio; (2) the self-absorption frequency \( \nu_s \) is predicted to be time-independent but is seen to decrease with time, and the early rise of the radio fluxes is slower than expected (see Paper I); and (3) the decay after maximum at millimeter wavelengths is perhaps somewhat faster than expected (see Paper I for a discussion on the radio light curves).

In summary, we find that an adiabatically expanding blast wave emitting synchrotron radiation with a significant fraction of rapidly cooling electrons describes most of the afterglow data on GRB 970508 very well.

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