

THE BRIGHT GAMMA-RAY BURST 991208: TIGHT CONSTRAINTS ON AFTERGLOW MODELS FROM OBSERVATIONS OF THE EARLY-TIME RADIO EVOLUTION

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ABSTRACT

The millimeter wavelength emission from GRB 991208 is the second brightest ever detected, yielding a unique data set. We present here well-sampled spectra and light curves over more than two decades in frequency for a 2 week period. This data set has allowed us for the first time to trace the evolution of the characteristic synchrotron self-absorption frequency ν_a , peak frequency ν_m , and the peak flux density F_m ; we obtain $\nu_a \propto t^{-0.15 \pm 0.23}$, $\nu_m \propto t^{-1.7 \pm 0.7}$, and $F_m \propto t^{-0.47 \pm 0.20}$. From the radio data we find that models of homogeneous or wind-generated ambient media with a spherically symmetric outflow can be ruled out. A model in which the relativistic outflow is collimated (a jet) can account for the observed evolution of the synchrotron parameters, the rapid decay at optical wavelengths, and the observed radio-to-optical spectral flux distributions that we present here, provided that the jet transition has not been fully completed in the first 2 weeks after the event. These observations provide additional evidence that rapidly decaying optical/X-ray afterglows are due to jets and that such transitions either develop very slowly or perhaps never reach the predicted asymptotic decay $F(t) \propto t^{-p}$.

Subject headings: cosmology: observations — gamma rays: bursts — radio continuum: general

1. INTRODUCTION

GRB 991208 was detected with the Interplanetary Network (IPN) by the *Ulysses*, *Wind*, and *Near* spacecraft on 1999 December 8 at 04:36:52 UT. The gamma-ray properties, the localization, and the subsequent discovery of the radio counterpart to GRB 991208 are presented by Hurley et al. (2000).

The IPN can typically localize events within 1 or 2 days. Therefore, important spectral transitions such as the passage of the synchrotron peak and cooling frequencies (Ramaprakash et al. 1998; Galama et al. 1998) that occur at optical and infrared wavelengths a few hours after the event are missed by optical and infrared follow-up observations on IPN bursts. Fortunately, the radio range allows similar studies on timescales from days to weeks.

Here we present an extensive set of radio observations monitoring GRB 991208 between 1.4 and 250 GHz during the first 2 weeks after the event. It is the second brightest afterglow detected at millimeter wavelengths to date (Shepherd et al. 1999). The brightness of the afterglow allows us to trace the evolution of the characteristic synchrotron peak frequency, the self-absorption frequency, and the peak flux density. The ob-

servations and results are presented in § 2 and compared with appropriate models in § 3.

2. OBSERVATIONS AND RESULTS

Observations were made from 1.43 to 250 GHz at a number of facilities: the Max-Planck Millimeter Bolometer (MAMBO; Kreysa et al. 1998) at the IRAM 30 m telescope on Pico Veleta (Spain; Baars et al. 1987), the IRAM Plateau de Bure Interferometer (PdBI) in the French Alps (Guilloteau et al. 1992), the Owens Valley Radio Observatory (OVRO) millimeter-wave array, the OVRO 40 m telescope, the Ryle Telescope at Cambridge (UK), and the NRAO Very Large Array (VLA).¹¹ We have detailed our observing and calibration strategy in Kulkarni et al. (1999b), Galama et al. (1999), Frail et al. (2000), and Berger et al. (2000). A log of the observations is provided in Table 1.

The millimeter emission from GRB 991208 is one of the brightest ever detected (Bremer et al. 1998; Smith et al. 1999; Shepherd et al. 1998), enabling us to obtain a unique data set. Rather than single-epoch snapshot spectra (Galama et al. 1998), we have well-sampled spectra and light curves over more than two decades in frequency for a 2 week period. GRB 991208 is therefore well suited to a study of the broadband evolution of the radio afterglow in the first 2 weeks after the burst. We display light curves for a subset of these data in Figure 1. The data from Table 1 at 22, 30, and 86 GHz are too sparse to plot in this form.

Several trends are apparent. At the highest frequencies (250, 100, and 15 GHz) the flux densities are either declining or constant during the first week but thereafter fade below detectability. At frequencies below 10 GHz we see erratic flux density variations due to interstellar scintillation (ISS; see, e.g., Goodman 1997; details on the ISS properties of GRB 991208 can be found in T. J. Galama et al. 2000, in preparation). Therefore, below 10 GHz it is harder to discern a pattern. The overall

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TABLE 1
RADIO OBSERVATIONS OF GRB 991208

Date (1999 December) (UT)	Frequency (GHz)	Flux (μ Jy)	Remarks ^a
11.77	250	2600 \pm 800	MAMBO, $\tau_{\text{atm}} = 0.16$
12.38	250	2000 \pm 500	MAMBO, $\tau_{\text{atm}} = 0.22$
14.35	250	2000 \pm 700	MAMBO, $\tau_{\text{atm}} = 0.54\text{--}0.77$
21.38	250	100 \pm 600	MAMBO, $\tau_{\text{atm}} = 0.16$
11.63	100	3600 \pm 800	OVRO MA
13.84	100	3500 \pm 800	OVRO MA
15.72	100	1900 \pm 800	OVRO MA
16.89	100	1700 \pm 800	OVRO MA
15.62	86.24	2500 \pm 500	PdBI
13.63	30.0	2700 \pm 1300	OVRO 40 m
14.62	30.0	1700 \pm 1000	OVRO 40 m
14.84	30.0	3600 \pm 1200	OVRO 40 m
11.51	15.0	2100 \pm 300	Ryle
12.44	15.0	2100 \pm 400	Ryle
13.55	15.0	3100 \pm 600	Ryle
15.61	15.0	2300 \pm 400	Ryle
20.68	15.0	300 \pm 600	Ryle
23.60	15.0	500 \pm 500	Ryle
21.96	22.49	1100 \pm 300	VLA
21.96	14.97	1650 \pm 250	VLA
10.92	8.46	707 \pm 39	VLA
12.04	8.46	1630 \pm 51	VLA
13.81	8.46	1900 \pm 66	VLA
15.91	8.46	1990 \pm 33	VLA
17.81	8.46	999 \pm 50	VLA
18.81	8.46	1182 \pm 52	VLA
19.92	8.46	1930 \pm 53	VLA
20.92	8.46	1173 \pm 49	VLA
21.96	8.46	1146 \pm 66	VLA
10.92	4.86	327 \pm 45	VLA
12.04	4.86	622 \pm 66	VLA
21.96	4.86	820 \pm 52	VLA
15.90	1.43	250 \pm 60	VLA
16.80	1.43	250 \pm 70	VLA
21.96	1.43	18 \pm 56	VLA

^a Abbreviations: MAMBO is the Max-Planck Millimeter Bolometer; OVRO MA is the Owens Valley Radio Observatory Millimeter Array; PdBI is the IRAM Plateau de Bure Interferometer; OVRO 40 m is the Owens Valley Radio Observatory 40 m telescope; Ryle is the Ryle Telescope; VLA is the Very Large Array; and τ_{atm} is the sky opacity toward the source.

trend in Figure 1 is for the peak flux density to decline with decreasing frequency, while the time to maximum increases.

An alternate way to view the data in Table 1 is to construct instantaneous spectral flux distributions at several epochs, which were chosen to obtain a maximum number of observations sufficiently close in time. All values were brought to the same epoch by applying a correction that was determined by fitting cubic splines to each of the light curves in Figure 1. We have added in quadrature an additional error of 25% of the synchrotron spectral model flux (see § 2.1) to the fluxes below 10 GHz to reflect the uncertainty due to ISS (T. J. Galama et al. 2000, in preparation). The resulting spectral flux distributions are presented in Figure 2. The spectra for all four epochs show the same overall morphology—flat from 10 to 250 GHz and dropping precipitously below 10 GHz.

In addition, we reconstruct the radio-to-optical spectral flux distribution at the epoch of December 15.5 UT by including K -, R -, and I -band detections (Bloom et al. 1999; Masetti et al. 1999; Sagar et al. 2000). All values were brought to the same epoch by applying a correction using the slope of the fitted optical light curve (Sagar et al. 2000). We corrected for Galactic foreground reddening ($A_R = 0.043$, $A_I = 0.031$, and

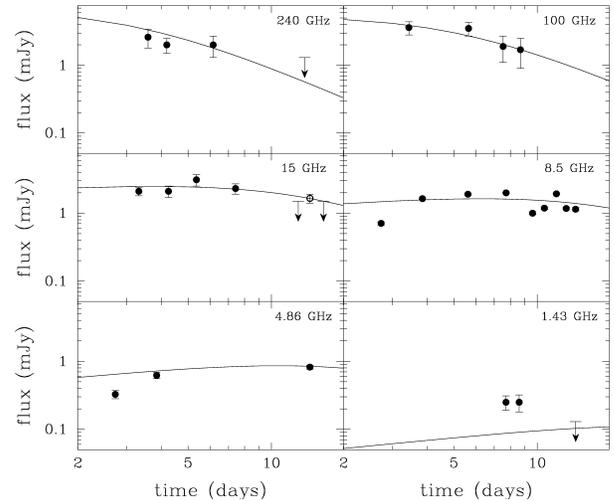


FIG. 1.—Radio, millimeter, and submillimeter light curves of GRB 991208 from 1.4 to 250 GHz. These data are compiled in Table 1 and are taken at various telescopes, which include the IRAM 30 m (250 GHz), the OVRO millimeter array (100 GHz), the Ryle Telescope (15 GHz), and the VLA (8.5, 4.9, and 1.4 GHz). At 15 GHz there is one additional point on the plot (*open circle*) that was taken with the VLA. All upper limits are plotted as the peak flux density at the location of the afterglow plus 2 times the rms noise in the image. Frequencies below 10 GHz show erratic flux density variations due to ISS. Shown are the light curves that result from assuming an evolution of ν_a , ν_m , and F_m as derived in § 2, i.e., $\nu_a \propto t^{-0.15 \pm 0.12}$, $\nu_m \propto t^{-1.7 \pm 0.4}$, and $F_m \propto t^{-0.47 \pm 0.11}$, and using the Granot et al. (1999a, 1999b) formulation.

$A_K = 0.006$ as inferred from the dust maps of Schlegel, Finkbeiner, & Davis 1998¹²). The result is presented in Figure 3.

2.1. Spectral Fits

The centimeter/millimeter/optical-to-X-ray afterglow emission is believed to arise from the forward shock of a relativistic blast wave that propagates into the circumburst medium (see Piran 1999 and van Paradijs, Kouveliotou, & Wijers 2000 for reviews).

The synchrotron afterglow spectrum has four distinct

¹² See <http://astro.berkeley.edu/davis/dust/index.html>.

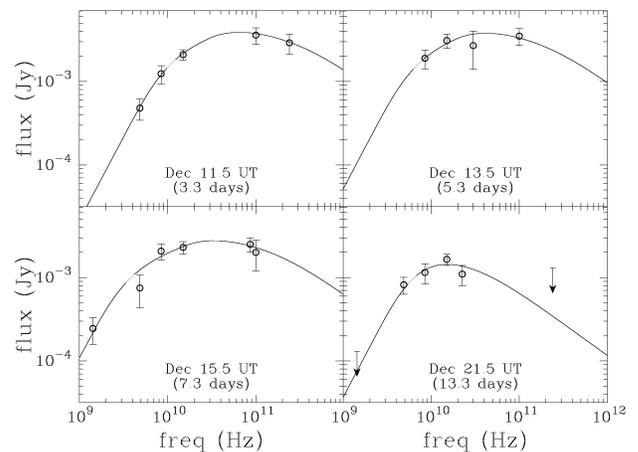


FIG. 2.—Radio spectral flux distribution of GRB 991208 from 1.4 to 250 GHz at several epochs. Shown are fits of the synchrotron spectra to the radio data from a relativistic blast wave as specified by Granot et al. (1999a, 1999b) for $p = 2.52$.

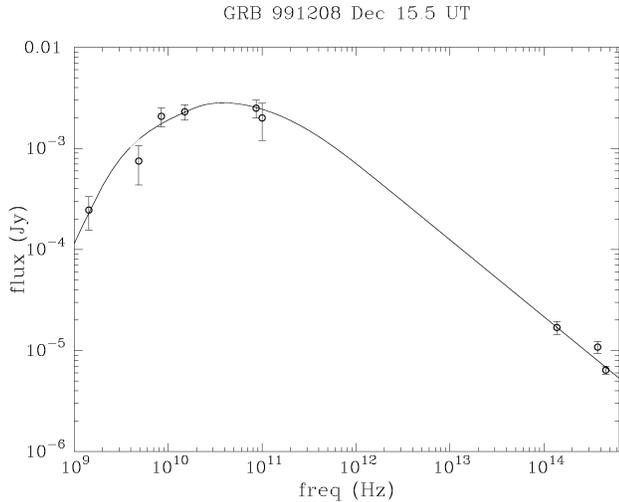


Fig. 3.—Radio-to-optical spectral flux distribution of GRB 991208 at December 15.5 UT (7.3 days after the event). Shown is a fit of the synchrotron spectrum to the radio and infrared/optical data from a relativistic blast wave as specified by Granot et al. (1999a, 1999b) for $p = 2.52$.

regions: $F_\nu \propto \nu^2$ below the synchrotron self-absorption frequency ν_a ($\nu < \nu_a$); $F_\nu \propto \nu^{1/3}$ up to the synchrotron peak at ν_m ($\nu_a < \nu < \nu_m$); $F_\nu \propto \nu^{-(p-1)/2}$ above the peak up to the cooling frequency ν_c ($\nu_m < \nu < \nu_c$); and $F_\nu \propto \nu^{-p/2}$ above cooling ($\nu > \nu_c$: see, e.g., Sari, Piran, & Narayan 1998; we have assumed slow cooling, i.e., $\nu_m < \nu_c$). Here p is the power-law index of the electron energy distribution.

The spectral flux distribution of December 15.5 UT (Fig. 3) peaks at $\nu_m \sim 40$ GHz. A fit to the radio data is provided by a synchrotron spectrum from a relativistic blast wave as specified by Granot, Piran, & Sari (1999a; see their Fig. 10 for the equipartition field model). We scale their dimensionless functional form by peak frequency ν_m and peak flux density F_m to derive a function $g(\nu)$ with asymptotic behavior of $\nu^{1/3}$ ($\nu \ll \nu_m$) and $\nu^{-(p-1)/2}$ ($\nu \gg \nu_m$). We account for synchrotron self-absorption at ν_a by multiplying $g(\nu)$ by $F_\nu = [1 - \exp(-\tau)]/\tau$, where $\tau = (\nu/\nu_a)^{-5/3}$ (Granot, Piran, & Sari 1999b).

First we fit the radio-to-optical spectral flux distribution of December 15.5 UT and find $p = 2.52 \pm 0.13$, $\nu_a = 3.6_{-1.6}^{+2.2}$ GHz, $\nu_m = 35 \pm 8$ GHz, and $F_m = 2.85 \pm 0.30$ mJy ($\chi_r^2 = 1.6$; 6 degrees of freedom [dof]). The spectrum is well described by synchrotron emission from a power-law electron distribution with index $p = 2.52$, self-absorbed at low frequencies; the fit is shown in Figure 3.

Next we fix $p = 2.52$ and fit all the epochs of the radio spectral flux distributions (the fits are shown in Fig. 2); the derived values of ν_a , ν_m , and F_m and their uncertainties are given in Table 2. These are plotted in Figure 4, where a clear temporal evolution of ν_m and F_m is apparent. We note that assuming $p = 2.2$ (see § 3) does not change the results of the fits (i.e., when no optical data is included the fits are rather insensitive to the assumed value of p). To characterize this evolution, we made power-law least-squares fits to the data. The results are given in Table 3.

3. DISCUSSION

The brightness of the radio counterpart to GRB 991208 has allowed for the first time the tracing of the evolution of the characteristic synchrotron parameters ν_a , ν_m , and F_m . We may

TABLE 2
RESULTS OF SPECTRAL FITTING FOR GRB 991208

Date (1999 December) ^a (UT)	ν_a^b (GHz)	ν_m^c (GHz)	F_m^d (mJy)	χ_r^2	Degrees of Freedom
11.50	$11.0_{-3.0}^{+3.0}$	55_{-28}^{+56}	3.9 ± 0.8	0.0	2
13.50	7_{-7}^{+8}	35_{-24}^{+44}	3.9 ± 1.0	0.8	1
15.50	$3.8_{-0.8}^{+2.4}$	30_{-16}^{+24}	2.8 ± 0.6	1.0	3
21.50	$8.8_{-3.2}^{+2.0}$	$4.8_{-2.8}^{+4.4}$	2.1 ± 0.5	1.2	3

NOTE.—In the spectral fitting we have included the nondetections at 1.4 and 250 GHz on 1999 December 21.5 UT as the peak flux density at the location of the afterglow. For December 21.5 UT, we have also fitted using $\tau = 13/6$ (see § 2.1) to account for the fact that the peak frequency ν_m is below the self-absorption frequency ν_a at this epoch and so $F_\nu \propto \nu^{5/2}$. The result of the fit was the same within the error bars.

^a Epoch of the spectral flux distribution.

^b Synchrotron self-absorption frequency.

^c Peak frequency.

^d Peak flux density.

now compare this result directly with expectations from relativistic blast-wave models.

Currently popular scenarios for the origin of GRBs are a compact object merger (the neutron star–neutron star [Eichler et al. 1989] and neutron star–black hole [Lattimer & Schramm 1974; Narayan, Paczyński, & Piran 1992] merger models) and the core collapse of a very massive star (“failed” supernova or hypernova; Woosley 1993; Paczyński 1998). In principle, afterglow observations can distinguish a compact object merger, which is expected to occur in a constant density interstellar medium (constant density ISM model; see Sari et al. 1998 and Wijers & Galama 1999 for details) from a hypernova, where the circumburst environment will have been influenced by the strong wind of the massive progenitor star (wind model; see Chevalier & Li 1999, 2000). Below we compare each of the afterglow models separately with the observations. The expected scalings (we assume adiabatic expansion of the remnant) for each of the models, including the case where the outflow

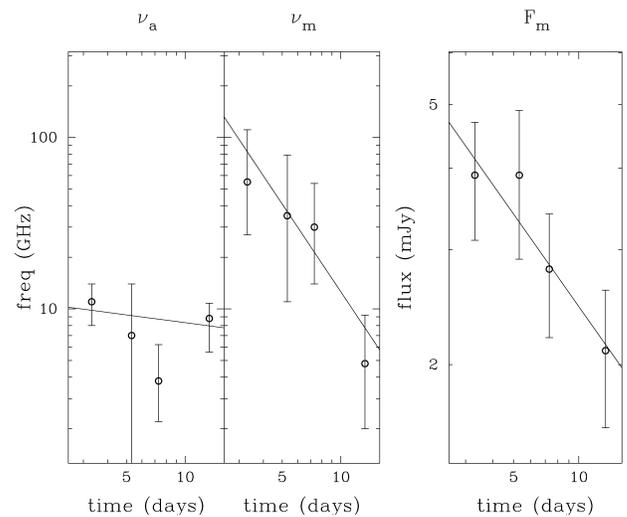


Fig. 4.—Evolution of the synchrotron self-absorption frequency ν_a , the synchrotron peak frequency ν_m , and the peak flux density F_m as derived from broadband radio (from 1.4 to 250 GHz) spectral fits of GRB 991208 at several epochs. Shown are power-law fits to the data: $\nu_a \propto t^{-0.15 \pm 0.23}$, $\nu_m \propto t^{-1.7 \pm 0.7}$, and $F_m \propto t^{-0.47 \pm 0.20}$. The fitted spectra are shown in Fig. 2, and the respective fit parameters can be found in Table 2.

TABLE 3
INFERRED EVOLUTION OF SYNCHROTRON PARAMETERS FOR GRB 991208
AND PREDICTED SCALINGS FROM MODELS

Parameter	ν_a	ν_m	F_m
Observed	$12_{-4}^{+7} \times 10^9 t_{\text{obs}}^{-0.15 \pm 0.23}$ Hz	$6_{-5}^{+18} \times 10^{11} t_{\text{obs}}^{-1.7 \pm 0.7}$ Hz	$7.2_{-2.3}^{+3.4} t_{\text{obs}}^{-0.47 \pm 0.20}$ mJy
χ_r^2 ; degrees of freedom	3.5; 2	1.1; 2	0.6; 2
Constant density ISM model	$\propto t_{\text{obs}}^0$	$\propto t_{\text{obs}}^{-3/2}$	$\propto t_{\text{obs}}^0$
Wind model	$\propto t_{\text{obs}}^{-3/5}$	$\propto t_{\text{obs}}^{-3/2}$	$\propto t_{\text{obs}}^{-1/2}$
Jet model	$\propto t_{\text{obs}}^{-1/5}$	$\propto t_{\text{obs}}^{-2}$	$\propto t_{\text{obs}}^{-1}$

NOTE.— t_{obs} is the observer time in units of days after the event. The scalings for the jet model are valid if the evolution is dominated by the sideways expansion of the jet (i.e., at late times).

is collimated in a jet, are also provided in Table 3 for comparison with the evolution derived from the spectral fits.

The observed decay of the peak flux density F_m is inconsistent with the constant density ISM model (see Table 3), which predicts a constant peak flux. Also, the optical afterglow of GRB 991208 (R band) displays a rapid decay: $\alpha = -2.2 \pm 0.1$, $F_\nu \propto t^\alpha$ (Sagar et al. 2000; see also Castro-Tirado et al. 2000). A constant density ISM model would require $p \geq 3.6$ in order to account for the rapid decay observed at optical wavelengths. For $p \geq 3.6$ the synchrotron spectrum above the peak should be much steeper than observed ($F_\nu \propto \nu^{-(p-1)/2}$). We note that optical extinction local to the host would cause the observed spectrum to be even shallower. The constant density ISM model can thus be ruled out on the basis of the spectral flux distribution on 1999 December 15.5 UT, which shows a flat spectrum corresponding to $p = 2.52$ (see Fig. 3).

Comparing GRB 991208 with the wind model (see Table 3) we find that the evolution of the peak flux density F_m and the peak frequency ν_m are as expected, but we find no evidence for a decrease with time of the self-absorption frequency ν_a . And, similar to the case of the constant density ISM model, a wind model would require $p \geq 3.3$ in order to account for the rapid decay observed at optical wavelengths. We therefore also reject the wind model.

Finally, the outflow may be collimated into jets (jet model; for details see Rhoads 1999; Sari, Piran, & Halpern 1999; Panaitescu & Mészáros 1999). Once sideways expansion of the jet dominates the dynamics of the relativistic blast wave, a jet plus constant ambient density medium (ISM + jet) or a jet plus wind stratified ambient medium (wind + jet) will have very similar properties. In this stage, the morphology of the ambient medium will be difficult to constrain.

The observed evolution of ν_a and ν_m are as expected in the jet model, but the drop in peak flux density F_m is not as rapid as predicted (see Table 3). To obtain the predicted decay rate $F_m \propto t^{-1}$ we have to raise χ^2 by 7.2 (corresponding to >99% confidence); the observed decay is thus significantly different from the predicted decay. And, in the case of a jet, at late times, when the evolution is dominated by the spreading of the jet, the model predicts $\alpha = -p$ and the R -band measurement thus corresponds to $p = 2.2 \pm 0.1$. For $p = 2.2$ the synchrotron spectrum above the peak should be shallower than observed. But, we find that $p = 2.52$ gives a satisfactory description of the December 15.5 UT data (Fig. 3). For example, assuming $p = 2.2$ provides a worse fit ($\chi_r^2 = 3.4$ as opposed to 1.6 for $p = 2.52$; December 15.5 UT radio-to-optical spectral flux distribution; Fig. 3).

A $p = 2.2$ jet model could be saved only if one assumes a cooling break between the millimeter and optical passbands around $\nu_c = 5 \times 10^{13}$ Hz (the optical decay would still satisfy

$\alpha = -p$, i.e., $p = 2.2 \pm 0.1$). However, in that case the optical/infrared synchrotron spectrum $F_\nu \propto \nu^{-p/2} = \nu^{-1.1}$, i.e., significantly steeper than observed ($\beta = -0.75 \pm 0.03$, $F_\nu \propto \nu^\beta$; Sagar et al. 2000). We therefore reject the possibility that $p = 2.2$.

In the jet model, the shallow decay of the peak flux density F_m and the apparent discrepancy in the value of p derived from the spectrum and from the light curve can be understood if during the first 2 weeks the GRB remnant was still undergoing the transition from a quasi-spherical (either constant density ISM or a wind), i.e., $F(t) \propto t^{-(3p-3)/4} \sim t^{-1.1}$ (constant density ISM) or $F(t) \propto t^{-(3p-1)/4} \sim t^{-1.6}$ (wind), to a jet evolution, $F(t) \propto t^{-p} \sim t^{-2.5}$. As discussed by Kumar & Panaitescu (2000), this transition takes place over at least an order of magnitude, but more likely several orders of magnitudes, in observer time. Since typically we expect the jet transition to take place around 1 to several days (Sari et al. 1999), it is natural to expect that the transition was still ongoing; the evolution of the synchrotron parameters will then be somewhere between fully spherical at early times (either constant density ISM or a wind) and be fully dominated by a jet later. This is consistent with the data, would explain the shallow decay of the peak flux density, and would also explain why the optical decay rate exponent $\alpha = -2.2$ (Sagar et al. 2000) is not as steep as for a fully developed jet transition $\alpha = -p = -2.52$. Determination of p from light curves requires observations after the transition has been completed, and from the optical data we cannot establish whether this is the case. Also, the light curve is not necessarily expected to approach the asymptotic limit $\alpha = -p$. The value of p derived from the optical light curve is thus rather uncertain, and the value of $p = 2.52$ that we have inferred from the spectral flux distribution is the more robust number, since p so derived is independent of the hydrodynamical evolution of the blast wave.

A similarly slowly developing jet transition was observed for GRB 990123 (Kulkarni et al. 1999a; Fruchter et al. 1999; Castro-Tirado et al. 1999), where after the jet break (at $t_j \sim 2$ days) the optical decay rate exponent $\alpha \sim -1.8$, whereas a steep $\alpha = -p = -2.4$ would have been expected for a fully developed jet transition. Also for GRB 991216 a slow transition is seen, but as a result of host contamination, the late-time decay rate exponent can only be constrained to lie between -2.1 and -1.5 (Halpern et al. 2000). On the other hand, GRB 990510 and GRB 000301C appear to be examples of relatively fast and fully developed jet transitions (Harrison et al. 1999; Berger et al. 2000; but see Kumar & Panaitescu 2000).

In conclusion, the jet model can account for the observed evolution of the synchrotron parameters of GRB 991208, the rapid decay at optical wavelengths, and the observed radio-to-optical spectral flux distributions, provided that the jet transition

has not been fully completed in the first 2 weeks after the event. These observations provide additional evidence that rapidly decaying afterglows are due to jets (Sari et al. 1999) and that at least in some afterglows these transitions are not fully developed.

Around 10 days after the event, ν_m passed ν_a ($\nu_m < \nu < \nu_a$; see Fig. 4) at ~ 8 GHz; from then on ν_a is expected to evolve differently: $\nu_a \propto t^{-2(1+p)/(4+p)} = t^{-14/13}$ (for $p = 2.5$); we have assumed a jet model evolution. Also after ν_m has passed 8.46 GHz (~ 12 days) and 4.86 GHz (~ 17 days), the flux densities at these frequencies should decay rapidly, $F_\nu \propto t^{-2.2-2.5}$. Con-

tinued monitoring with the VLA (T. J. Galama et al. 2000, in preparation) will allow tests of these expectations.

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