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A REBRIGHTENING OF THE RADIO NEBULA ASSOCIATED WITH THE 2004 DECEMBER 27 GIANT FLARE FROM SGR 1806−20

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ABSTRACT

The 2004 December 27 giant γ-ray flare detected from the magnetar SGR 1806−20 created an expanding radio nebula that we have monitored with the Australia Telescope Compact Array and the Very Large Array. These data indicate that there was an increase in the observed flux ∼25 days after the initial flare that lasted for ∼8 days, which we believe is the result of ambient material swept up and shocked by this radio nebula. For a distance to SGR 1806−20 of 15 kpc, using the properties of this rebrightening, we infer that the initial blast wave was dominated by baryonic material of mass $M \gtrsim 10^{24.5}$ g. For an initial expansion velocity $v \sim 0.7c$ (as derived in an accompanying paper), we infer that this material had an initial kinetic energy $E \gtrsim 10^{44.5}$ ergs. If this material originated from the magnetar itself, it may have emitted a burst of ultra–high-energy ($E > 1$ TeV) neutrinos far brighter than that expected from other astrophysical sources.

Subject headings: pulsars: individual (SGR 1806−20) — neutrinos — radio continuum: stars — shock waves — stars: magnetic fields — stars: neutron

Online material: color figure, machine-readable table

1. INTRODUCTION

The soft gamma repeater SGR 1806−20 is believed to be a magnetar—a slowly spinning isolated neutron star with an extremely high magnetic field ($B \sim 10^{15}$ G; Duncan & Thompson 1992; Kouveliotou et al. 1998). On 2004 December 27, a giant flare of γ-rays was detected from this object (Borkowski et al. 2004), only the third such event. For a distance of 15 kpc (Corbel & Eikenberry 2004; McClure-Griffiths & Gaensler 2005; but see Cameron et al. 2005), the December 27 flare was roughly a hundred times more luminous than the previous two such events (Palmer et al. 2005; Hurley et al. 2005 and references therein). With the analysis of a Very Large Array (VLA) observation of SGR 1806−20 seven days after the flare, Cameron & Kulkarni (2005) and Gaensler et al. (2005a) discovered a bright, transient source, VLA J180839−202439, which is believed to have been created by the magnetar during the flare. This detection triggered a worldwide radio monitoring effort, whose initial results have been presented by Gaensler et al. (2005c) and by Cameron et al. (2005). In particular, it has been determined that the radio source was initially expanding with constant velocity $v \sim 0.7c$ (assuming a distance of 15 kpc and one-sided expansion) and that, after day 9, its

flux decayed as a steep power law (Gaensler et al. 2005c; Taylor et al. 2005).

Here we present observational evidence for a short-term rebrightening of this radio source that we model as the result of material shocked by ejecta from SGR 1806−20.[10] We then fit the observed fluxes to this model, deriving estimates for the mass and energy of the ejecta, and discuss this model's implications for the nature of the December 27 burst.

2. OBSERVATIONS AND RESULTS

As part of a long-term monitoring campaign of VLA J180839−202439, we have observed this source every few days with both the Australia Telescope Compact Array (ATCA) and the VLA. Here we focus on observations at 4.8 GHz from day 6 to day 63 after the outburst, as listed in Table 1. The ATCA observations used a bandwidth of 128 MHz, and SGR 1806−20 was observed for ∼20 minutes at this frequency in each observation. For each ATCA observation, we calibrated the flux density scale using an observation of PKS B1934−638 at the beginning of the run, and we calibrated the phase with a short observation of PMN J1811−2055 taken approximately every 3 minutes. To minimize background contamination, we only used data from baselines that included the fixed antenna located ∼3 km away from the other five antennae in the array. The VLA observations were reduced using the method described by Taylor et al. (2005) in which the final phase calibration was achieved by self-calibrating the SGR 1806−20 data. For both the VLA and the ATCA observations, the radio flux density of SGR 1806−20 was measured by fitting the visibility data to a source whose position was a free parameter, fitting the visibility data to a source whose position is fixed at the location of the SGR, and measuring the peak brightness in an image made from these visibilities. In general, these three methods yielded consistent results, and any differences are reflected in the errors provided in Table 1.

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[10] The dynamical properties of this model are described by Granot et al. (2005).

TABLE 1
RADIO OBSERVATIONS AT 4.8 GHz OF THE RADIO NEBULA
PRODUCED BY SGR 1806−20

Average Epoch (UT)	Days after Burst	Telescope	$S_{4.8\,\text{GHz}}$ (mJy)
2005 Jan 03.83	6.93	VLA	80 ± 1
2005 Jan 04.61	7.71	VLA	66 ± 3
2005 Jan 05.26	8.36	ATCA	60 ± 1

NOTE.—Flux densities before 2005 January 18.01 are also reported in the Supplementary section of Gaensler et al. (2005c). Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

The resultant light curve is shown in Figure 1. As reported in Gaensler et al. (2005c), at day 9 there was a break in the light curve after which the radio flux faded rapidly. Starting on day 15, the observed flux from SGR 1806−20 began to deviate significantly from a power-law decay, and on day 25 the flux began to increase for approximately 8 days. On day 33, the observed flux began to decay again, but at a slower rate than between days 9 and 15. In § 3, we model this behavior by that assuming it is a result of the source's transition from the coasting phase to the Sedov-Taylor phase of its evolution.

3. A SEMIANALYTIC MODEL

In this section, we present a semianalytic model for the evolution of the radio source created during the December 27 giant flare. We assume a quasi-spherical shell of filling factor f_b[11] and initial mass M expanding supersonically with an initial velocity v_0 into a medium of mass density ρ, driving a forward shock into the ambient material. Initially, the newly swept-up material is accumulated in a thin layer between the shell and the forward shock, and the equation of motion of this shell is

$$\frac{d}{dt}\left[\left(M + \frac{4\pi}{3}f_b R^3 \rho\right) v\right] = 4\pi f_b R^2 p, \quad (1)$$

where $R = R(t)$ is the radius of the shell, $v = v(t)$ is the expansion velocity of the shell, and $p = p(t)$ is the pressure inside the shell, which is found from energy conservation to be

$$E \equiv \frac{1}{2}Mv_0^2 = \frac{1}{2}\left(M + \frac{4\pi}{3}f_b R^3 \rho\right)v^2 + 2\pi f_b R^3 p. \quad (2)$$

This approximation also works well during the Sedov-Taylor phase (Zeldovich & Raizer 1966), because even at this stage most of the swept-up material is accumulated in a thin layer just downstream of the shock, whereas the rest of the volume is filled by a rarefied, hot gas at nearly constant pressure. By eliminating p and introducing dimensionless variables,

$$\tau \equiv \frac{t}{t_{\text{dec}}}; \quad r \equiv \frac{R}{v_0 t_{\text{dec}}}; \quad t_{\text{dec}} \equiv \left[\left(\frac{4\pi f_b}{3M}\rho\right)^{1/3} v_0\right]^{-1}, \quad (3)$$

[11] The results presented by Gaensler et al. (2005c) and Taylor et al. (2005) suggest that the radio source is elongated and moving along the elongation axis, implying a one-sided outflow and requiring a filling factor.
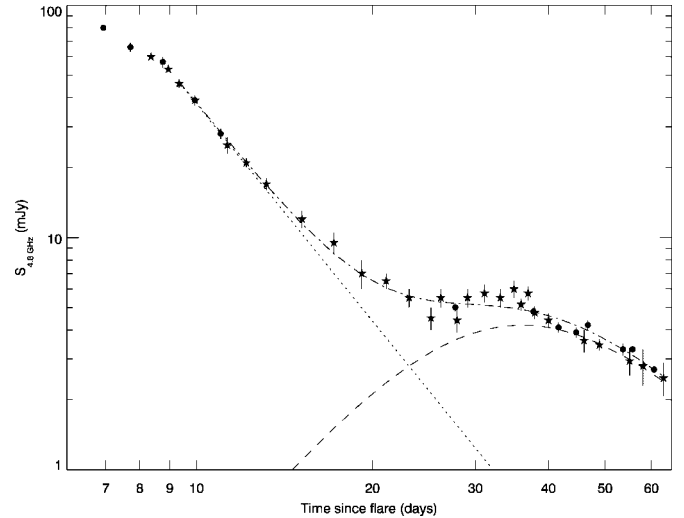

FIG. 1.—The 4.8 GHz light curve of the radio nebula associated with SGR 1806−20 up to day 62 (2005 February 28) after the giant flare. The circles represent data taken with the VLA, and stars data taken with the ATCA. The dot-dashed line in the light curve shows the result of fitting the data to the model described in § 3 whose parameters are given in the text. The dotted line shows the power-law component of the model fit, while the dashed line shows the additional component due to the swept-up, shocked, ambient material. The ends of the dot-dashed line correspond to the first and last data points included in the fit.

one finds

$$\frac{d}{d\tau}\left[(1 + r^3)\frac{dr}{d\tau}\right] = \frac{1}{r}\left[1 - (1 + r^3)\left(\frac{dr}{d\tau}\right)^2\right]. \quad (4)$$

At $\tau \ll 1$, the solution to equation (4) reduces to $v = v_0(1 - 0.8r^3)$. At $\tau \gg 1$, the solution to this equation asymptotically approaches $r = (2.5\tau^2)^{1/5}$, close to the Sedov-Taylor solution.

We assume that, at the forward shock, electrons are heated to an energy $\gamma_0 m_e c^2 = \epsilon m_p v^2$, where ϵ is proportional to the fraction of the energy density behind the shock in relativistic electrons.[12] Electrons with an Lorentz factor $\gamma > \gamma_0$ are assumed to have a power-law energy spectrum $N(\gamma) = K(\gamma/\gamma_0)^{-p}$ [we assume $\gamma_0 > 1$, which is fulfilled for $\epsilon > 5 \times 10^{-4}(c/v)^2$], where $N(\gamma)d\gamma$ is the number of electrons with energy between $\gamma m_e c^2$ and $(\gamma + d\gamma)m_e c^2$, $K = N(\gamma_0)$, and p is the particle distribution index—which observationally is $p \approx 2.5$ (Gaensler et al. 2005c), a typical value for shock-accelerated electrons. Additionally, we assume that the magnetic energy density just downstream of the shock front is $B^2/8\pi = (9/8)\epsilon_B \rho v^2$, where B is the magnetic field strength and ϵ_B is the ratio of magnetic to internal energy density behind the shock. If the number of emitting electrons is $\sim(4\pi/3)f_b R^3 \rho/m_p$, one can estimate the emission from the swept-up material as

$$S_\nu = aKf_b R^3 d^{-2}(\rho/m_p)\gamma_0^{p-1}B^{(1+p)/2}\nu^{(1-p)/2}, \quad (5)$$

where d is the distance to the source, S_ν is the flux density at a frequency ν, and $a = 4.7 \times 10^{-18}$ in cgs units. Substituting the above quantities into equation (5), one obtains

$$S_\nu(\tau) = 11\epsilon_{-1}^{1.5}(\epsilon_{B,-1}n_{-2})^{0.87}M_{24}v_{10}^{4.75}d_{15}^{-2}\nu_{\text{GHz}}^{-0.75}f(\tau) \text{ mJy}, \quad (6)$$

[12] In the literature, the electron spectrum is conventionally parameterized by the fraction of the accelerated electrons ξ_e, the fraction of the total energy transferred to these electrons ϵ_e, and the particle distribution index p. In order to avoid cumbersome expressions, we introduce $\epsilon = \epsilon_e(p - 2)/2\xi_e(p - 1)$.

where $d_{15} = d/(15 \text{ kpc})$, the ambient number density n is defined as $n \equiv \rho/m_p$ and $n_{-2} = n/(0.01 \text{ cm}^{-3})$, $v_{10} = v/(10^{10} \text{ cm s}^{-1})$, $\epsilon_{-1} = \epsilon/0.1$, $\epsilon_{B,-1} = \epsilon_B/0.1$, and the dimensionless function $f(\tau)$ may be found from the solution $r(\tau)$ to equation (4):

$$f(\tau) = r^3 \left(\frac{dr}{d\tau}\right)^{(5p-3)/2}. \tag{7}$$

Both $r(\tau)$ and $f(\tau)$ can be found from the numerical integration of equation (4) and are shown in Figure 2. During the coasting phase ($\tau \ll 1$), the luminosity grows as t^3 and reaches a maximum at $\tau = 0.78$, at which point the expansion velocity has only decreased by 22%. At $\tau \sim$ few, the luminosity decreases as t^{-2}; this is faster than the decrease during the Sedov-Taylor phase because the pressure within the cavity remains small for a long enough time and because the expansion velocity decreases faster than in the Sedov-Taylor solution where the expanding envelope is filled by the hot gas. During the Sedov phase ($\tau \gtrsim 10$), the luminosity decreases as $t^{-1.65}$. However, the rate of decline after the maximum depends strongly on the microphysics of the shock acceleration (Granot et al. 2005). We do not expect significant emission from a reverse shock in the ejecta since it was previously shocked by a collision with a preexisting shell (Gaensler et al. 2005c; Granot et al. 2005).

One can then estimate M and E as

$$M = 4.4 f_b n_{-2} t_{30}^3 v_{10}^3 \times 10^{24} \text{ g} \tag{8}$$

and

$$E = \frac{1}{2} M v_0^2 = 2.2 f_b n_{-2} t_{30}^3 v_{10}^5 \times 10^{44} \text{ ergs}, \tag{9}$$

assuming the emission peaked $30 t_{30}$ days after the explosion. This estimate for the energy is strongly dependent on v, whose uncertainty is dominated by errors in the distance, not on projection effects. If SGR 1806−20 was at a lower distance (Cameron et al. 2005), these estimates of E and M would decrease significantly, although recent results by McClure-Griffiths & Gaensler (2005) support $d \sim 15$ kpc. Additionally, v_{10} is related to f_b. The expansion velocity of $v \sim 0.7c$ quoted in the abstract assumes a one-sided expansion, requiring $f_b < 0.5$. Using the elongation observed by Taylor et al. (2005), we derive $f_b \sim 0.1$.

4. MODEL FITTING

To test the model in § 3 and to use it to independently estimate the initial mass and energy of the source, we fit the observed 4.8 GHz flux densities after day 8.8 to[13]

$$S_\nu(t) = S_0 \left(\frac{t}{9 \text{ days}}\right)^\delta + 11 A \nu_{\text{GHz}}^{-0.75} f(t/t_{\text{dec}}) \text{ mJy}, \tag{10}$$

where S_0 mJy is the flux density on day 9, δ is the index of the power-law decay, and

$$A = \epsilon_{-1}^{1.5} (\epsilon_{B,-1} n_{-2})^{0.87} M_{24} v_{10}^{4.75} d_{15}^{-2}, \tag{11}$$

as derived from equation (6). The fit, shown in Figure 1, was

[13] We only used data after day 8.8 in this fit because, as reported in Gaensler et al. (2005c), there is a break in the light curve at this epoch that cannot be explained by the model presented in § 3.
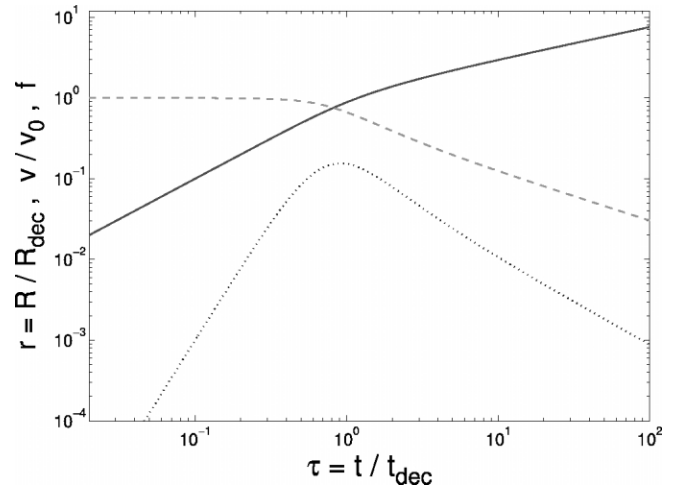

FIG. 2.—Evolution of the expanding shell. The solid line corresponds to the dimensionless radius r, the dashed line corresponds to the velocity v in units of the initial velocity, and the dotted line corresponds to the dimensionless synchrotron flux f. [*See the electronic edition of the Journal for a color version of this figure.*]

performed using a minimum χ^2 algorithm, and the best-fit parameters (reduced $\chi^2 = 1.23$) are $S_0 = 52.4 \pm 1.3$ mJy, $\delta = -3.12 \pm 0.11$, $A = 11.9 \pm 0.2$, and $t_{\text{dec}} = 46.5 \pm 1.7$ days. This model predicts that at $t \approx t_{\text{dec}}$, the source's expansion velocity should decrease, as indeed reported at this epoch by Taylor et al. (2005). The difference between the observed and the predicted shape of the rebrightening could be due to several factors—e.g., anisotropy in the outflow (Gaensler et al. 2005c; Taylor et al. 2005). However, the fit is good enough that we can use A and t_{dec} to express the ejected mass in terms of ϵ, $\epsilon_{B,-1}$, n_{-2}, v_{10}, and d_{15}. Rather than eliminate one of these variables, we adopt an expression for M that jointly minimizes the power-law dependences of all five parameters, finding

$$M = 6.6 f_b^{0.57} \epsilon_{-1}^{-0.64} \epsilon_{B,-1}^{-0.37} n_{-2}^{0.20} v_{10}^{-0.32} d_{15}^{0.86} \times 10^{24} \text{ g} \tag{12}$$

and

$$E = 3.3 f_b^{0.57} \epsilon_{-1}^{-0.64} \epsilon_{B,-1}^{-0.37} n_{-2}^{0.20} v_{10}^{1.68} d_{15}^{0.86} \times 10^{44} \text{ ergs}. \tag{13}$$

Here M and E are only weakly dependent on the ambient density, n (which is difficult to constrain from observations), but are more sensitive to the shock physics of the flow, ϵ and ϵ_B. The total energetics of equation (9) suggest that $n_{-2} < 10^3$. For $d_{15} \approx 1$, $n_{-2} \approx 10$, $f_b \approx 0.1$, and $v_{10} \approx 2.1$ (Taylor et al. 2005), the estimated initial mass is $M = 2.1 \epsilon_{-1}^{-0.64} \epsilon_{B,-1}^{-0.37} \times 10^{24}$ g. While ϵ and ϵ_B are unknown, we can estimate them from studies of gamma-ray bursts (GRBs) and supernova remnants. If the expanding nebula behaves like the relativistic jets produced in a GRB, then $\epsilon \sim 10^{-2.5}$ to $10^{-1.5}$, and $\epsilon_B \sim 10^{-5}$ to 10^{-1} (Panaitescu & Kumar 2002), implying that $M \sim 10^{25}$–10^{27} g. However, if the behavior of the expanding nebula is closer to that of a supernova blast wave, the magnetic field and relativistic electrons will be in energy equipartition, $\epsilon_B \approx \epsilon$ (Bamba et al. 2003), and $\epsilon \sim 10^{-2}$ to 10^{-3} (Ellison et al. 2000), implying $M \sim 10^{26}$–10^{27} g. Since it is extremely unlikely that ϵ or ϵ_B is larger than 0.1, we are rather confident that $M \gtrsim 2.1 \times 10^{24}$ g.

It is also possible that the ambient density is considerably different from $n \approx 0.1 \text{ cm}^{-3}$. Although the nebula initially expanded into a cavity $\sim 10^{16}$ cm in size (Gaensler et al. 2005c; Granot et al. 2005), by day 25 it had already expanded into the surrounding medium. If SGR 1806−20 is inside a stellar wind

bubble formed by its progenitor (e.g., Gaensler et al. 2005b) or nearby massive stars (Corbel & Eikenberry 2004), n is possibly $\sim 10^{-3}$ cm^{-3}, implying $M \sim 10^{24}$ g. However, SGR 1806−20 is embedded in a dust cloud, and n could be ~ 10 cm^{-3}, implying $M \sim 10^{25}$ g. In either case, the uncertainty in n does not change the order of magnitude of M and E, which are similar to those derived in equations (8) and (9) that depend on the time of the peak in the light curve (t_{30}) but are independent of the shock physics. As a result, we conclude that the December 27 flare created a nebula with an initial mass $\gtrsim 10^{24.5}$ g and an initial kinetic energy $\gtrsim 10^{44.5}$ ergs.

5. DISCUSSION

An inherent assumption in § 3 is that most of the energy of the radio source is in the form of modestly relativistic or sub-relativistic baryons, as argued in more detail by Granot et al. (2005). We postulate that the source of these baryons is the neutron star itself. The giant flare is caused by, and accompanied with, the violent restructuring of the magnetic field in which some magnetic field lines may, like a slingshot, throw away the matter from the surface layers of the star. Although the canonical picture (Thompson & Duncan 1995, 2001) assumes that the magnetic stresses excite predominantly horizontal motions of the crust, one can imagine that the stretching of magnetic field lines initially buried in the crust may break the force balance so that some magnetic field line tubes will rise, together with the beaded matter, into the magnetosphere. Note that the magnetic field of $\sim 10^{15}$ G easily overcomes the weight of the column of 10^{14} g cm^{-2} so that an upper layer of width ~ 100 m may be expelled from regions with an appropriate structure of the field. If the fraction ζ of the giant flare energy, $E = 10^{46}E_{46}$ ergs, is transferred to the ejected matter, a mass of $10^{26}\zeta E_{46}$ g may be ejected. As discussed in Granot et al. (2005), if all of the inferred ejecta were released from the surface of the neutron star during the initial "hard spike" ($\lesssim 0.5$ s) of the giant flare, the outflow would be opaque to γ-rays, and the December 27 flare would not have been observed. This can be avoided if there are regions on the magnetar surface from which radiation is expelled without matter, and other points from which matter is expelled.

One possible observational signature of this process is the detection of ultra–high-energy (UHE; $E_\nu > 1$ TeV) neutrinos from SGR 1806−20 coincident with the December 27 flare. In this nonrelativistic wind, internal shocks produced by significant variations in the outflow velocity within 0.5 lt-s of the star will accelerate some protons to energies high enough that they create pions through collisions with other protons. When these pions decay, they can produce TeV neutrinos. If the total energy in the neutrinos is $\epsilon_\nu E$, where E is the initial kinetic energy of the ejecta as estimated in equations (9) and (13), then the observed fluence of neutrinos, $\mathcal{F}_\nu$, is

$$\mathcal{F}_\nu \approx 1.2\epsilon_{\nu,-1}E_{44.5}d_{15}^{-2} \times 10^{-3} \text{ ergs cm}^{-2}, \qquad (14)$$

where $E_{44.5} = E/10^{44.5}$ ergs and $\epsilon_{\nu,-1} = \epsilon_\nu/0.1$ (e.g., Eichler & Schramm 1978). If $\epsilon_\nu \sim 0.1$, this is much higher than the 10^{-5} ergs cm^{-2} typically expected from bright GRBs (Eichler 1994). Depending on the exact values of ϵ_ν and E, these neutrinos could possibly have been detected with current arrays, and the December 27 event thus makes the best test case so far for testing the hypothesis of UHE neutrino emission from γ-ray outbursts. It is not expected than any UHE neutrinos will be produced in the forward shock generated by the outflow as it expands into the interstellar medium (Fan et al. 2005).

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