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<th>The radio afterglow from the giant flare of SGR 1900+14: The same mechanism as afterglows from classic gamma-ray bursts?</th>
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1. INTRODUCTION

Soft gamma repeaters (SGRs) are generally characterized by sporadic and short (~0.1 s) bursts of hard X-rays with luminosities as high as $10^6$ Eddington luminosity. They are also well known for two giant flares: the first on 1979 March 5 from SGR 0526–66 (Mazets et al. 1979) and the second on 1998 August 27 from SGR 1900+14 (Hurley et al. 1999). Frail, Kulkarni, & Bloom (1999) reported, following the giant 1998 August flare from SGR 1900+14, the detection of a transient radio source. Their observations covered the time from about one week to one month after the flare. The spectrum between 1 and 10 GHz is well fitted by a power law with $F_{\nu} \propto \nu^{-0.74 \pm 0.17}$. The source appears to have peaked at about a week after the burst and subsequently undergone a power-law decay with an exponent of $\alpha = -2.6 \pm 1.5$.

The initial hard spike of the August 27 flare has a duration of ~0.5 s and luminosity greater than $2 \times 10^{46}$ ergs s$^{-1}$ (>15 keV) if the source distance is $d \approx 7$ kpc (Vasisht et al. 1994). The short duration, high luminosity, and hard spectrum indicate that a relativistically expanding fireball was driven from the star. The fireball should be relatively clean, and the Lorentz factor $\Gamma \approx 10$ was inferred from the luminosity and the temporal structure (Thompson & Duncan 2001). With the experience of GRB afterglows, one may naturally ask whether this power-law fading radio afterglow is due to the blast wave emission driven by the fireball. Huang, Dai, & Lu (1998) and Eichler (2003) had made some discussions on the possible afterglow emission from SGRs. In this Letter, we try to explain the radio afterglow from this flare. We study the afterglow emission from the giant flare in § 2. We find that shock emission from an ultrarelativistic outflow fails to explain this radio afterglow. However, we propose that a mildly or subrelativistic outflow expanding into the interstellar medium could fit the observations. Finally, we discuss the possible origin for this kind of outflow in § 3.

2. RADIO AFTERGLOW FROM SGR GIANT FLARES

We consider that an outflow with “isotropic” kinetic energy $E_{\nu}$ and Lorentz factor $\Gamma_{\nu}$ ejected from the SGR expands into the ambient medium with a constant number density $n$. The interaction between the outflow and the surrounding medium is analogous to GRB external shock (Rees & Mészáros 1992; Mészáros & Rees 1997), but with quite different $E_{\nu}$ and $\Gamma_{\nu}$. The Sedov time at which the shock enters the nonrelativistic phase is roughly given by $t_{\text{sd}} = (3c\rho_{\text{ISM}}^{-1}/4\pi n_{\text{ISM}}^{-1})^{1/3} \approx 1 \text{ day} \times (E_{\nu,44}/n_{\text{ISM}}^{1/3})^{1/3}$, where $m_p$ is the proton mass and we used the usual notation $a \equiv 10^{-4}a_{w}$. As the shock must have entered the nonrelativistic phase during the observation time of the radio afterglow from the giant flare, we develop a model that holds for both the relativistic and nonrelativistic phases. From the view of the energy conservation, the dynamic equation can be approximately simplified as (e.g., Huang, Dai, & Lu 1999; Wang, Dai, & Lu 2003)

$$\Gamma - 1) M_0 c^2 + (\Gamma^2 - 1)m_{sw} c^2 = E_0,$$

where $\Gamma$ is the Lorentz factors of the outflow, $m_{sw} = (4/3)\pi R^3 m_p n$ is the mass of the swept-up interstellar medium (ISM) ($R$ is the shock radius), and $M_0$ is the mass of the original outflow.

The kinematic equation of the ejecta is

$$dR/dt = \beta c/\Gamma(1 - \beta),$$

where $\nu = \beta c$ is the bulk velocity of the outflow with $\beta(\Gamma) = (1 - \Gamma^{-1})^{1/2}$ and $t$ is the observer time. If the outflow is beamed and sideways expansion with sound speed takes place, the expression of $m_{sw}$ and the half-opening angle of the beamed outflow $\theta$ are, respectively, given by

$$\frac{dm_{sw}}{dt} = 2\pi R^2 (1 - \cos \theta) \frac{nm_p \beta c}{1 - \beta},$$

$$\frac{d\theta}{dt} = \frac{c(\gamma + \sqrt{\gamma^2 - 1})}{R},$$
where \( c_s \) is the sound speed and we use the approximate expression derived by Huang, Dai, & Lu (2000), which holds for both the ultrarelativistic and nonrelativistic limits.

Assuming that the distribution of the shock-accelerated electrons takes a power-law form with the number density given by

\[
\eta(N) dN_r = K_\gamma N_r^{-\gamma_m} \rho_s d\rho_s \quad \text{for} \quad \gamma_m < \gamma < \gamma_s,
\]

the volume emissivity at the frequency \( \nu' \) in the comoving frame of the shocked gas is (Rybicki & Lightman 1979)

\[
j_{\nu'} = \frac{3q^3}{2m_c^2c^3} \left( \frac{4\pi m_c e^2}{3q} \right)^{1/2} B_p^{(p+1)/2} K_\psi(p', \nu'_e, \nu'_m),
\]

where \( q \) and \( m_c \) are, respectively, the charge and mass of the electron, \( B_p \) is the strength of the component of magnetic field perpendicular to the electron velocity, \( \nu'_e \) and \( \nu'_m \) are the characteristic frequencies for electrons with \( \gamma_s \) and \( \gamma_m \), respectively, and

\[
F_p(p', \nu'_e, \nu'_m) = \int_{\nu'_e}^{\nu'_m} F(x) x^{(p-3)/2} dx,
\]

with \( F(x) = \frac{1}{\Gamma} K_{\gamma/3}(\Gamma x) x^\Gamma dx \) [\( K_{\gamma/3}(\Gamma x) \) is the Bessel function]. The physical quantities in the preshock and postshock ISM are connected by the jump conditions (Blandford & McKee 1976): \( \gamma_s = (\gamma + 1)/\gamma \), \( \gamma = (\gamma + 1)/(\gamma - 1) \), \( \nu_s = (\gamma + 1)/\gamma \), where \( \nu_s \) and \( \nu_s' \) are the energy and number densities of the shocked gas in its comoving frame and \( \gamma_s \) is the adiabatic index, a simple interpolation of which between ultrarelativistic and nonrelativistic limits, \( \gamma_s = (4\Gamma + 1)/3\Gamma \), gives a valid approximation for trans-relativistic shocks.

Assuming that shocked electrons and the magnetic field acquire constant fractions (\( \epsilon_s \) and \( \epsilon_B \)) of the total shock energy, we get \( \gamma_s = \epsilon_s [(p - 2)/(p - 1)] (m_e/m_p) (\Gamma - 1) \), \( B_s = \epsilon_B (8\pi e \epsilon_s)^{p/2} \), and \( \gamma_s = (p - 1)\gamma_m^{-1} \) for \( p > 2 \). From the spectrum \( F_p \propto \nu^{-0.34+0.14} \) of the radio afterglow, we infer that \( p = 2.5 \). It is reasonable to believe that \( \nu_s' \), in comparison with the radio frequencies, is very large throughout the observations. The observer frequency \( \nu_o \) relates to the frequency \( \nu_s' \) in the comoving frame by \( \nu_s' = \nu_s D/c \), where \( D = 1/\Gamma (1 - \beta \cos \theta) \) is the Doppler factor. The observed flux density at \( \nu_s' \) is given by

\[
F_s = V_{\nu_s} D^2 j_{\nu_s}/4\pi d^2,
\]

where \( V_{\nu_s} \) is the effective volume of the postshock ISM from which the radiation is received by the observer and should be \( V = m_{sw} n m_p \Gamma^2 \) for the isotropic case.

2.1. Ultrarelativistic Outflow

In terms of equations (1)–(3), we can obtain the dynamic evolution of the outflow, i.e., we get \( \Gamma(t) \), \( R(t) \), \( m_{sw}(t) \), and \( \theta(t) \). Then using equation (4) and the expressions for \( B_s, K \), and \( \gamma_s \), we can get the evolution of the observed flux with time. The radio afterglow of the 1998 August flare peaks at about one week after the burst. In the relativistic shock model, it is required that the peak frequency \( \nu_s \) cross the observation band at the peak time for optically thin synchrotron radiation. However, this can hardly be satisfied for a ultrarelativistic outflow with \( \Gamma_0 \sim 10 \), for reasonable values of the shock parameters and the medium density \( n \). Instead, the model light curves generally peak at \( t < 0.1 \) day. This can be clearly seen in Figure 1, in which we plot the model light curves with different values of \( n \) and \( \epsilon_B \) for both the isotropic and beamed outflow cases and compare them with the observation data. Moreover, the peak flux \( F_s \) is generally much larger than the observed peak flux. The reason can be easily understood from the following analytic estimate.

At the peak time \( t \sim 10 \) days of the radio afterglow, the shock had entered the nonrelativistic phase, so the radius of the shock is roughly \( R = (5/2) \beta c t \). From the condition of energy conservation \( 4/3 \pi R^3 (\beta^2/2 \eta) n c^2 = E \), one can get \( \beta = (12E/125 \pi (\pi/12) n m_e)^{1/5} = 0.16 \rho_4^{1/5} \nu_3^{0.8} \eta_4^{0.8} \). The magnetic field is \( B = (8\pi e \epsilon_s)^{p/2} = 1.4 \times 10^{-3} G \epsilon_k^{-1} \nu_4^{0.8} \eta_4^{0.8} \), and the peak frequency and the peak flux are, respectively, given by

\[
\nu_s = 3 \times 10^3 \text{ Hz} \left( \frac{\epsilon_B}{0.3} \right)^{1/2} E_{44}^{3/5} \nu_{0.7}^{0.16} \eta_{0.8}^{-0.4} \epsilon_{0.3}^{0.4},
\]

\[
F_s = \frac{N_e \rho_{45}^2}{4\pi d^2} = 4.4 \times 10^7 \text{ \mu Jy} E_{44}^{2/5} \nu_{0.7}^{0.16} \eta_{0.8}^{-0.4} \epsilon_{0.3}^{0.4}.
\]

where \( N_e \) is the total number of the swept-up electrons and \( E_{45} \) is the peak spectral power (Sari, Piran, & Narayan 1998). It is clearly seen that \( \nu_s \) can hardly be as large as \( \nu_{obs} = 8.46 \text{ GHz} \) for reasonable shock parameters of \( \epsilon_s \) and \( \epsilon_B \) (e.g., Granot, Piran, & Sari 1999; Wijers & Galama 1999; Panaitescu & Kumar 2002), and, furthermore, the peak flux is much larger than detected from the giant flare. Though this analytic estimate is for an isotropic outflow case, the beamed outflow has also this problem as shown in Figure 1.

Although the ultrarelativistic shock associated with the initial hard spike of the giant flare could not be responsible for the observed radio afterglow, we know from Figure 1 that its radio afterglow emission should be easily detected at the early time even for the beamed case. The optical afterglow emission from the ultrarelativistic shock is also calculated and shown in Figure 2. Clearly, early optical afterglow emission can be as bright as \( 100 \text{ \mu Jy} (R\text{-band magnitude} m_e = 19) \) at \( t \lesssim 0.1 \) day for
Below we show that a mildly or subrelativistic outflow from the SGR giant flare could provide a plausible explanation for this radio afterglow.

3. DISCUSSIONS AND CONCLUSIONS

We have shown that a mildly or subrelativistic outflow from the SGR could be consistent with this radio afterglow. This outflow is expected to originate from the neutron star crust, accompanying the giant flare. SGRs are now believed to be "magnetars," neutron stars with surface field of order $10^{14}$–$10^{15}$ G or more (Duncan & Thompson 1992; Thompson & Duncan 1995). A magnetic field with $B > (4\pi \phi_{\text{max}} \mu)^{1/2} \approx 2 \times 10^{14} \phi_{\text{max}}^{1/2} G$ can fracture the crust, where $\phi_{\text{max}} \approx 10^{31} (\rho_{\text{max}}^{1/2} \text{ergs cm}^{-3})^{-1/2}$ is the shear modulus of the crust and $\rho_{\text{max}}$ is the nuclear density and $\phi_{\text{max}}$ is the yield strain of the crust. However, such a patch of crust is too heavy to be able to overcome the binding energy of the neutron star. We expect that only a tiny fraction of the fracturing crust matter can overcome the gravitational binding energy and is able to be accelerated to a mildly relativistic velocity $\Gamma_{\text{iso}} \sim 1 \sim 0.1$ by the released magnetic field energy. Note that the kinetic energy of the energy to initial energy $E_{\text{iso}}$ and the sideways expansion may take place, so it is expected that the flux may decay more steeply than the isotropic case (e.g., Rhoads 1999; Sari, Piran, & Halpern 1999).

The fits with model light curves for mildly or subrelativistic, beamed outflows are presented in Figure 3, where the isotropic energy is chosen to be $E_{\text{iso, max}} = 10^{45}$ ergs. We also present the model light curve for the same outflow but without sideways expansion, denoted by the dashed line. Clearly, the case without sideways expansion decays too slowly to fit the observations. In all these fits, we used fixed values for $E$, $p$, $\theta_{\text{iso}}$, $e$, and with only two free parameters: the initial Lorentz factor $\Gamma_{\text{iso}}$ and $\epsilon_{\text{p}}$. We can also obtain a nice fit to the observations for the case of a larger isotropic energy $E_{\text{iso}}$, $\theta_{\text{iso}}/2 = 10^{45}$ ergs. In this case, the fitted parameters are $(n = 1 \text{ cm}^{-3}, \Gamma_{\text{iso}} = 1.13, e = 0.3, \epsilon_{\text{p}} = 3 \times 10^{-5})$ and $(n = 0.01 \text{ cm}^{-3}, \Gamma_{\text{iso}} = 1.4, e = 0.3, \epsilon_{\text{p}} = 1.5 \times 10^{-5})$ for different $n$. So the beamed outflow model can provide nice fits of the observations for a wide range of shock parameters such as $n$ and $E_{\text{iso}}$. We therefore conclude that the mildly or subrelativistic outflow from the SGR giant flare could provide a plausible explanation for this radio afterglow.

By using the formulae in Wang et al. (2000), we estimate that the synchrotron self-absorption frequency is below $10^{17}$ Hz at this time.
mildly relativistic matter per unit of mass \((\Gamma_o - 1)c^2\) is comparable to the binding energy \(GM_{\text{NS}}/R\), where \(M_{\text{NS}}\) and \(R\) are the mass and radius of the neutron star, respectively. Let us denote the amount of matter as \(\Delta m\), the isotropic kinetic energy \(E_o\) and the real energy of the beamed outflow \(E_\psi = E_o\theta^2/2\), where \(\theta\) is the beaming angle of this outflow. For \(\Gamma_o - 1 \lesssim 0.1\), \(\Delta m = 5 \times 10^{-10}E_{\text{opt}}\), \(g = 5 \times 10^{-11}E_{\text{opt}}\), \(g\). Let the size of this patch of matter be \(\Delta r\). Because of the insensitivity of \(\Delta r\) on \(\Delta m\) for the outermost crust of neutron star, we estimate \(\Delta r = 0.1 - 0.3\) km for \(E_\psi = 10^{32} - 10^{34}\) ergs.

Once we know \(\Delta r\), we can estimate the beaming angle \(\theta_o\) of the outflow when it breaks away from the confinement of the magnetic field. This amount of matter will be vaporized and become plasma near the neutron star surface, which moves out along the open field lines of the magnetar. The initial kinetic energy density of this outflow is \(E_o = \frac{\epsilon_o}{(A_o\beta_o c)} = 1.6 \times 10^{-10}\) ergs cm\(^{-3}\) \(\dot{E}_{\text{opt}}(\Delta r/2\text{ km})^{-2} (\beta_o/0.4)^{-1}\), where \(\dot{E}\) is the real kinetic energy luminosity of this outflow, \(\beta_o c\) is the initial velocity of this outflow, and \(A_o\) is the initial sectional area. As the plasma moves out to radial radius \(r\), the sectional area \(A = \pi r^2 \sin \theta\), where \(\theta\) is the angle relative to the magnetic axis. Because the magnetic field lines satisfy \(r \propto \sin^2 \theta, A \propto r^3\) for small \(\theta\) and \(\epsilon_o \propto r^{-3}\). On the other hand, the magnetic field energy scales with \(r\) as \(E_o = (B^2/8\pi r^3(r/R)^{-6})\), where \(B_o\) is the surface magnetic field of the neutron star. When the magnetic field energy decreases to be comparable to the kinetic energy density, the outflow plasma breaks from the confinement of the magnetic field. This corresponds to a radius \(r_o/R = (B^2/8\pi \epsilon_o)^{1/3} \approx 30B_{15}^{2/3}E_{\text{opt}}^{-1/3} (\beta_o/0.4)^{1/3} (\Delta r/0.2\text{ km})^{2/3}\) and \(\dot{\theta}_o/\theta_o = (r_o/R)^{1/2} = 5.5B_{15}^{1/3}E_{\text{opt}}^{-1/6}(\beta_o/0.4)^{1/6}(\Delta r/0.2\text{ km})^{-1/3}\). Note that \(\dot{\theta}_o\), which is roughly equal to the beaming angle \(\theta_o\), is very insensitive to the value of \(\dot{E}\). As the initial opening angle near the neutron star surface \(\theta_0 = (\Delta r/R) = 0.02(\Delta r/0.2\text{ km})\), we estimate the beaming angle of the outflow is \(\theta_o = 0.1 - 0.2\) for typical parameters.

What powers the ejection of this patch of matter? We think that the reconnection of the magnetic field within a region of size \(\Delta r\) during the period of the giant flare will release energy of \((B^2/8\pi)(\Delta r)^2 V_{\psi} \Delta r \sim (B^2/8\pi)(\Delta r)^2 R\), which should be equal to \(\Delta m(T_o - 1)c^2\), where \(B\) is the crust magnetic field, \(V_{\psi}\) is the internal Alfvén velocity, and \(\Delta r\) is the growth time of the instability causing the giant flare, viz., the duration of the giant flare spike of the August 27 giant flare (Thompson & Duncan 1995, 2001). The size is therefore estimated to be \(\Delta r \sim 0.2\) km, and the mass is \(\Delta m \sim 10^{23}B_{15}\) g, which are in reasonable agreement with the above estimates according to the light curve fits if \(E_o \sim 10^{45}\) ergs or equally \(E_{\psi} \sim 10^{45}\) ergs.

Note that continuing acceleration of electrons at the surface of the neutron star is also a possible mechanism for the radio afterglow, and needs further careful investigation in future.

In summary, we studied the afterglow emission from the possible ultrarelativistic outflow and mildly or subrelativistic outflow accompanying the SGR giant flares. The radio afterglow emission from the August 27 giant flare of SGR 1900+14 is consistent with a mildly or subrelativistic outflow but could not be produced by the forward shock emission from an ultrarelativistic outflow. However, we predict that this ultrarelativistic outflow, suggested to be associated with the hard spike of the giant flare, if it exists, should produce bright radio to optical afterglows at the early phase \((t \lesssim 0.1\text{ days})\), which can be tested by future observations.

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