A relativistic particle outburst from the soft gamma-ray repeater 1900+14

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Abstract. Soft gamma-ray repeaters (SGR) are a class of high energy transients whose brief emissions are thought to arise from young¹ and highly magnetized neutron stars²,³,⁴,⁵,⁶. The exact cause for these outbursts and the nature of the energy loss remain unknown. Here we report the discovery of a fading radio source within the localization of the relatively under-studied SGR 1900+14. We argue that this radio source is a short-lived nebula powered by the particles ejected during the intense high energy activity in late August 1998, which included the spectacular gamma-ray burst⁷ of August 27. The radio observations allow us to constrain the energy released in the form of particles ejected during the burst, un-complicated by beaming effects. Furthermore, thanks to the astrometric precision of radio observations, we have finally localized this repeater to sub-arcsecond accuracy.

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Until recently SGR 1900+14 was routinely labeled as the least prolific of the SGRs with only three bursts in 1979 and another three in 1992. We investigated the relatively crude localization obtained from the 1979 activity and suggested that this SGR is associated with the supernova remnant (SNR) G 42.8+0.6 (see also ref. 11). Our Very Large Array (VLA) observations showed that G 42.8+0.6 was a typical shell-type object. Furthermore, we suggested that the X-ray source RX J190717+0919.3 located within the tighter 1994 localization was the quiescent counterpart of the SGR. Subsequent ROSAT High Resolution Imager (HRI) observations resulted in a tighter localization of the source.

We began a monitoring program of RX J190717+0919.3 at the VLA motivated by the notion that the high-energy bursts are most likely accompanied by bursts of energetic particles and these particles would power a synchrotron nebula, a mini-“plerion”. Our initial observations of the X-ray source showed no strong radio emission at or close to the position of RX J190717+0919.3. In Table 1 we list the results from our VLA monitoring study of RX J190717+0919.3.

Our first VLA observation after the bright burst of August 27 was made on September 3. As can be seen from Figure 1, a new source is apparent within the localization circle of RX J190717+0919.3. This radio source was not seen in earlier VLA images obtained from data obtained at the same frequency and similar resolution and sensitivity; see Figure 1. The probability of finding a steady background radio source by chance in this area is $10^{-3}$. The unusual time variability reduces the probability further still but by an unknown factor. The radio source is unresolved and we place an upper limit to the angular diameter of 0.8″. The precise position of the transient source (epoch J2000) is right ascension = 19h 07min 14.33s, declination = +09° 19′ 20.1″, with an uncertainty of 0.15″ in each coordinate.

Following the detection on September 3, the source underwent a rapid, monotonic decay and is no longer detectable; see Table 1. The decaying portion of the curve can be fitted to a power law ($\text{flux} \propto t^{\delta}$) with $\delta = -2.6 \pm 1.5$; here t is time since the burst of August 27; see Figure 2. On September 8 observations were also made at 1.43 GHz and 4.86 GHz, yielding a spectral index $\alpha = -0.74 \pm 0.15$ (where the flux at frequency $\nu$, $S_\nu \propto \nu^{\alpha}$); see Figure 2. No linear or circular polarization is detected but due to the faintness of the source, the limits are not restrictive; the percentage polarization is < 30%.

Radio sources which show such transient behavior on this timescale are quite rare in the sky. Furthermore, the source lies in the Ulysses–CGRO triangulation, which has a total area of 17 square arcminutes. We suggest that the transient radio source VLA J190714.3+091920 is powered by the heightened burst activity from SGR 1900+14 in late August, which included the intense burst of August 27. If we are correct, then we have localized SGR 1900+14 to sub-arcsecond accuracy. Hurley et al. report 5.17-s X-ray pulsations from the vicinity of RX J190717+0919.3. Such long period pulsations are also seen from the quiescent counterpart of SGR 1806-20 and in the bright burst from SGR 0526–66. Thus RX J190717+0919.3 is very likely the X-ray counterpart of SGR 1900+14.

SGR 1806–20 offers an excellent analog against which we now interpret our radio observations of SGR 1900+14. To start with, both SGRs are associated with SNRs: SGR 1806–20 is embedded in the plerionic SNR G10.0−0.3 (refs. 16,17,18) whereas SGR 1900+14 is found just outside G 42.8+0.6 (ref. 10). The intense bursts, the quiescent X-ray...
counterparts, the long-period pulsations and the associated supernova remnants have been interpreted in the framework of the magnetar model\textsuperscript{2,3}. Magnetars are highly magnetized neutron stars with dipole field strengths of $10^{14} - 10^{15}$ G, considerably larger than those of radio pulsars. The ultimate source of energy for the bursts and the quiescent emission comes from the decay of the magnetic field. The non-thermal quiescent X-ray emission and the highly suggestive radio images\textsuperscript{17,18} of SGR 1806–20 provide compelling evidence for a steady particle wind from the SGR. The “nested” appearance\textsuperscript{16} of G10.0–0.3 is best explained\textsuperscript{17} as being powered by an episodic injection of energy from the underlying SGR. Thus G10.0–0.3 is powered both by a steady and episodic power source.

VLA J190714.3+091920 shares characteristics similar to those of G10.0–0.3. Both have low brightness temperatures (a lower limit of 10 K is derived for SGR 1900+14 from the upper limit on the angular size of 0.8") and unusual (for a plerion) non-thermal radio spectra indices ($-0.6$ and $-0.74$). The main distinction is that G10.0–0.3 is bright and long-lived whereas VLA J190714.3+091920 is short-lived and fainter. We attribute these differences to (1) the low-pressure environment surrounding SGR 1900+14 and (2) the lower energy loss and activity of SGR 1900+14 as compared to that of SGR 1806–20. The radio nebula around SGR 1806–20 is bright because this prolific SGR (with implied large energy loss) is embedded in a high pressure environment, the supernova remnant G10.0–0.3. Thus the particle wind emanating from SGR 1806–20 is contained, thereby accounting for the high surface brightness. In contrast, SGR 1900+14 is not as prolific and lies outside G 42.8+0.6. Thus the particle wind from SGR 1900+14 is confined only by the ram pressure from the motion of SGR 1900+14 through interstellar medium. This weaker confinement does not allow for the buildup of a plerion, thereby resulting in a weaker plerion.

Accepting our reasoning that VLA J190714.3+091920 is a synchrotron emitting nebula we apply the synchrotron model\textsuperscript{19} to derive physical parameters. There are two major unknowns: the distance and angular size of the source. On general grounds, the distance to SGR 1900+14 is roughly 10 kpc, given that it is located in the inner Galaxy. However, if SGR 1900+14 is associated with G 42.8+0.6 then a distance of 5 kpc is probably reasonable\textsuperscript{10}. The minimum energy of the nebula (integrating the spectrum shown in Figure 2 from $10^7$ Hz to $10^{11}$ Hz) and the equipartition magnetic field strength is then $U_{\text{min}} = 3 \times 10^{42} d_5^{17/7} \theta_4^{9/7} \text{erg}$ and $B_{\text{min}} = 0.55 d_5^{2/7} \theta_4^{-6/7} \text{mG}$; here the distance is 5$d_5$ kpc and the angular radius of the nebula is $\theta = 0.4 \theta_4$ arcseconds.

Using the formulation of Scott & Readhead\textsuperscript{20} we can obtain a robust estimate of the angular size of the source, the so-called “equipartition radius”. $\theta_{\text{eq}} = 165 d_5^{-1/17} S_p^{8/17} \nu_p^{-1.07}$ $\mu$arcsecond where $\nu_p$ is the peak of the synchrotron spectrum (in GHz) and $S_p$ the corresponding flux (in mJy). The total energy of a source of size $\theta$ is $U = 1/2 U_{\text{eq}} \eta^{11}(1 + \eta^{-17})$ where $\eta = \theta/\theta_{\text{eq}}$ and $U_{\text{eq}}$ is the minimum energy of a source with an angular radius of $\theta_{\text{eq}}$. Small deviations from $\theta_{\text{eq}}$ result in steep energy demands and that is why most sources have angular sizes quite close to $\theta_{\text{eq}}$. Unfortunately, we do not have sufficient wavelength coverage to see the true synchrotron peak. Instead we use the lowest frequency data (1.43 GHz) on September 08 to obtain a true lower limit $\theta > \theta_a \sim 100 \mu$arcsecond. Using this angular radius results in $U_a \sim 7 \times 10^{37}$ erg and $B_a \sim 0.7$ G. The radiative decay timescale for the electrons responsible for the 8-GHz emission is then about 2 years.
Our incomplete knowledge of the true angular size of VLA J190714.3+091920 does not allow us to pinpoint the region from which the radio electrons originate and to infer the total particle energy and the magnetic field. We have two limits for $\theta$ and both limits are viable. The strength of the magnetic field of a $6 \times 10^{14}$ G magnetar rotating at 5.16 s (ref. 6) at the edge of the radio nebula of angular radius $\theta$ is $B_M \sim 0.13(\theta/\theta_a)^{-1}d_5^{-1}$ G, comparable to $B_a$ if $\theta \sim \theta_a$. In the other extreme, when $\theta = 0.4$ arcseconds, the magnetic field from the magnetar would be negligible but the inferred field strength can be easily explained as arising from compression of the ambient field by the bow shock. The mean expansion speed of the nebula is $3.5 \times 10^{10}d_5\theta_d^{-1}t_{10}^{-1}$ cm s$^{-1}$ where $t_{10}$ is the age of the nebula in units of 10 days. Thus in the limit of $\theta = 0.4$ arcseconds the nebula would have expanded relativistically. This is possible if previous outbursts have swept up the ambient gas. Interestingly enough, in this limit, $U_{\text{min}}$ is comparable with the isotropic burst energy of $3 \times 10^{42}d_5^2$ erg, as estimated from the fluence of the August 27 burst ($\sim 10^{-3}$ erg cm$^{-2}$, M. Feroci, pers. comm.). In either case, it is clear that nebular expansion accounts for the rapidly decaying radio emission. Thus the above energy estimates derived from observations 7–10 days after the burst need to be significantly revised upwards to obtain the initial release of energy.

In the future the availability of broad-band observations and/or direct measurement of the size of the nebula will enable us to directly estimate the energy of the burst in particles (without the uncertainties of beaming that bedevil estimates from gamma-ray data). Equally important are accurate measurements of the average particle luminosity, since particle-aided spindown can substantially modify estimates for the magnetic field and the characteristic age of a neutron star$^{21}$. These estimates, to our knowledge, are unobtainable in any other fashion. In those cases where the SGR is immersed in a high pressure region (e.g. SGR 1806–20) we are able to trace the entire history of energy loss from the magnetar. The sub-arcsecond localization presented in this paper will greatly help in identifying possible stellar counterparts of this SGR (as was done for SGR 1806–20; refs. 22,23).

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Figure 1. Images made at 8.46 GHz of the field around RX J190717+0919.3, a source proposed\textsuperscript{10} to be the X-ray counterpart of SGR 1900+14. Although ref. 13 does not discuss the size of the error circle, our assumed value of 10-arcsecond radius is an exceedingly conservative value. The “+” sign is the nominal location of RX J190717+0919.3. The June 25 image does not show any evidence for a radio source to a 2-$\sigma$ level of 92 $\mu$Jy. On September 3 there is an unresolved 300 $\mu$Jy radio source VLA J190714.3+091920 within the X-ray localization. This source faded to an undetectable level by October 1.
Figure 2. (left) The spectrum of the radio transient on 1998 September 8 between 1 and 10 GHz. A weighted least-squares fit to these data gives a spectral slope $\alpha = -0.74 \pm 0.15$. (right) The light curve at 8.46 GHz from 1998 September 3 to October 10. Since the exact time for the onset of the radio emission is unknown, the horizontal axis is drawn assuming that it originated at the same time as the gamma-ray burst of August 27.432 UT. A weighted least-squares fit to the declining portion of the light curves gives a power-law slope of $\delta = -2.6 \pm 1.5$.
Table 1. VLA Observations of RX J190717+0919.3

| Date   | Freq. (GHz) | Flux (µJy) | rms (µJy) |
|--------|-------------|------------|-----------|
| 1994 Oct. 05.00 | 1.43 |           | 110       |
| 1994 Oct. 05.01 | 8.41 |           | 30        |
| 1995 Dec. 14.80 | 8.41 |           | 33        |
| 1995 Dec. 21.96 | 8.41 |           | 55        |
| 1995 Dec. 26.81 | 1.43 |           | 125       |
| 1995 Dec. 26.82 | 4.59 |           | 44        |
| 1998 Jun. 25.25 | 8.46 | 285       | 38        |
| 1998 Sep. 03.12 | 8.46 | 315       | 52        |
| 1998 Sep. 06.26 | 8.46 | 745       | 110       |
| 1998 Sep. 08.07 | 4.86 | 300       | 33        |
| 1998 Sep. 08.08 | 1.43 | 206       | 26        |
| 1998 Sep. 08.09 | 8.46 | 70        | 43        |
| 1998 Oct. 01.06 | 8.46 |           | 25        |
| 1998 Oct. 11.12 | 1.43 |           | 70        |

(a) The entries (from left to right): the UT date of the observation, the observing frequency (in GHz), the flux density of the source if it was detected, and the rms noise in the image.

(b) All observations were made with a bandwidth of 100 MHz at each frequency. Antenna phase calibration was accomplished using extragalactic radio sources with well-known positions near SGR 1900+14. The absolute flux scale (accurate to better than ±2%) at each epoch was fixed by short observations of the radio sources 3C 48, 3C 147, or 3C 286.

(c) The angular resolution at 8.46 GHz was approximately 0.8–1.2 arcsecond, increasing linearly with decreasing frequency.