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SUPERNOVA REMNANT CANDIDATES FOR THE SOFT γ-RAY REPEATER 1900+14

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ABSTRACT

Motivated by the association of two soft γ-ray repeaters (SGRs) with supernova remnants (SNR) we have carried out radio, optical and X-ray studies of two cataloged SNRs in the large KONUS error box ($11° \times 8'$) of SGR 1900+14. Our VLA observations of SNR G43.9+1.6 do not reveal any obvious plerionic component. A radio flat-spectrum source, close to, but outside the error box was found. We suggest this to be a distant H II region foreground to the SNR. A sensitive VLA image at meter wavelengths show that the other SNR, G42.8+0.6, is an ordinary typical SNR with a shell morphology with no peculiarities such as a plerionic component. No *ROSAT* source with an apparent flux $\gtrsim 10^{-13}$ ergs cm^{-2} s^{-1} is found within the two SNRs. Recently, Hurley et al. have reported a new very small error box close to G42.8+0.6. There is no radio feature within or close to the error box. However, a *ROSAT* source is found just outside this localization. We speculate that this is the quiescent X-ray counterpart of SGR 1900+14. We suggest that SGR 1900+14 is a neutron star that was born with high speed which has now overtaken the expanding shell of SNR G42.8+0.6. Owing to the low confining pressure, there has been no development of a synchrotron bubble which explains the absence of the radio plerion. In our picture, SGR 1900+14 is the oldest known SGR.

Subject headings: gamma rays: bursts — ISM: individual (G43.9+1.6, G42.8−0.6) — supernova remnants

1. INTRODUCTION

Soft γ-ray repeaters (SGRs) are a subset of the high-energy transients and have distinctive spectral and temporal properties compared to the γ-ray bursters (GRBs; see Cline 1990 for a review). Unlike the GRBs, SGRs repeat, whence the name. There are three known SGRs: 0526−66, 1806−20 and 1900+14. SGR 0526−66 apparently lies in the SNR N49 (Cline et al. 1982) and SGR 1806−20 has been associated with the SNR G10.0−0.3 (Kulkarni & Frail 1993; Murakami et al. 1994; Kulkarni et al. 1994). A steady X-ray counterpart coinciding with the peak of central radio emission has been detected by *ROSAT* (Cooke 1993) and ASCA (Murakami et al. 1994).

SNR G10.0−0.3 is a radio "plerion," a nonthermal nebula with emission from the center. In contrast, a majority of SNRs have edge brightened emission or a shell morphology. Plerions are powered by a central source of relativistic wind (particles and magnetic fields) usually from the spindown of a pulsar. Mathewson et al. (1983) detected excess emission in N49 close to the error box of SGR 0526−66 but its possible relation to the SGR appears not to have been appreciated. The newer *ROSAT* data (Rothschild, Kulkarni, & Lingenfelter 1994) shows clearly the excess emission to be a point source which has been interpreted as synchrotron nebula powered by a young pulsar (i.e., SGR 0526−66). Logically, the next step is to investigate whether SGR 1900+14 (Mazets et al. 1979) is also associated with a SNR. Such an investigation is very timely since this repeater is now active again after more than a decade of quiescence (Kouveliotou et al. 1993).

Discovery of such plerions is very important for further understanding of the nature of SGRs. The plerion acts as a convenient calorimeter and allows us to observationally infer the time integrated and instantaneous energetics of the SGR. The plerion constrains the age of the SGR and the spatial offset of the SGR from the centroid of the plerion yields an upper limit on the velocity of the SGR. Driven by the unique and fundamental diagnostics offered by plerions, we investigated the KONUS error box (Mazets et al. 1979). We have found two cataloged SNRs, G43.9+1.6 and G42.8+0.6. This coincidence was independently noted by Kouveliotou et al. (1994) and in the companion paper by Hurley et al. (1994). Here we present detailed investigations at radio, optical and X-ray wavelengths.

2. THE ERROR BOX OF SGR 1900+14

The 2 σ error box for SGR 1900+14 (Fig. 1 [Pl. L3]) was generated with the help of position errors for the three 1979 March events for this source, from detectors aboard the *Venera* space probes, kindly provided to us by E. P. Mazets. Two cataloged SNRs, G43.9+1.6 and G42.8+0.6, fall within this error box, the details of which can be found in Green (1991). We investigated the confines of this error box using the 21 cm (Reich, Reich, & Fürst 1990b), 11 cm (Reich et al. 1990a), and 11 cm linear polarization (Junkes, Fürst, & Reich 1987) maps obtained at the 100 m Effelsberg telescope. Using the Effelsberg maps, we independently searched for SNR candidates and failed to find any more SNRs other than the two discovered by Reich and coworkers. We also note that search of the Princeton pulsar data base showed that there is no known pulsar within the KONUS localization.

2.1. G43.9+1.6

G43.9+1.6 is a large ($35' \times 50'$), poorly defined, faint source which Green (1991) has classified as "F?" i.e., a possibly

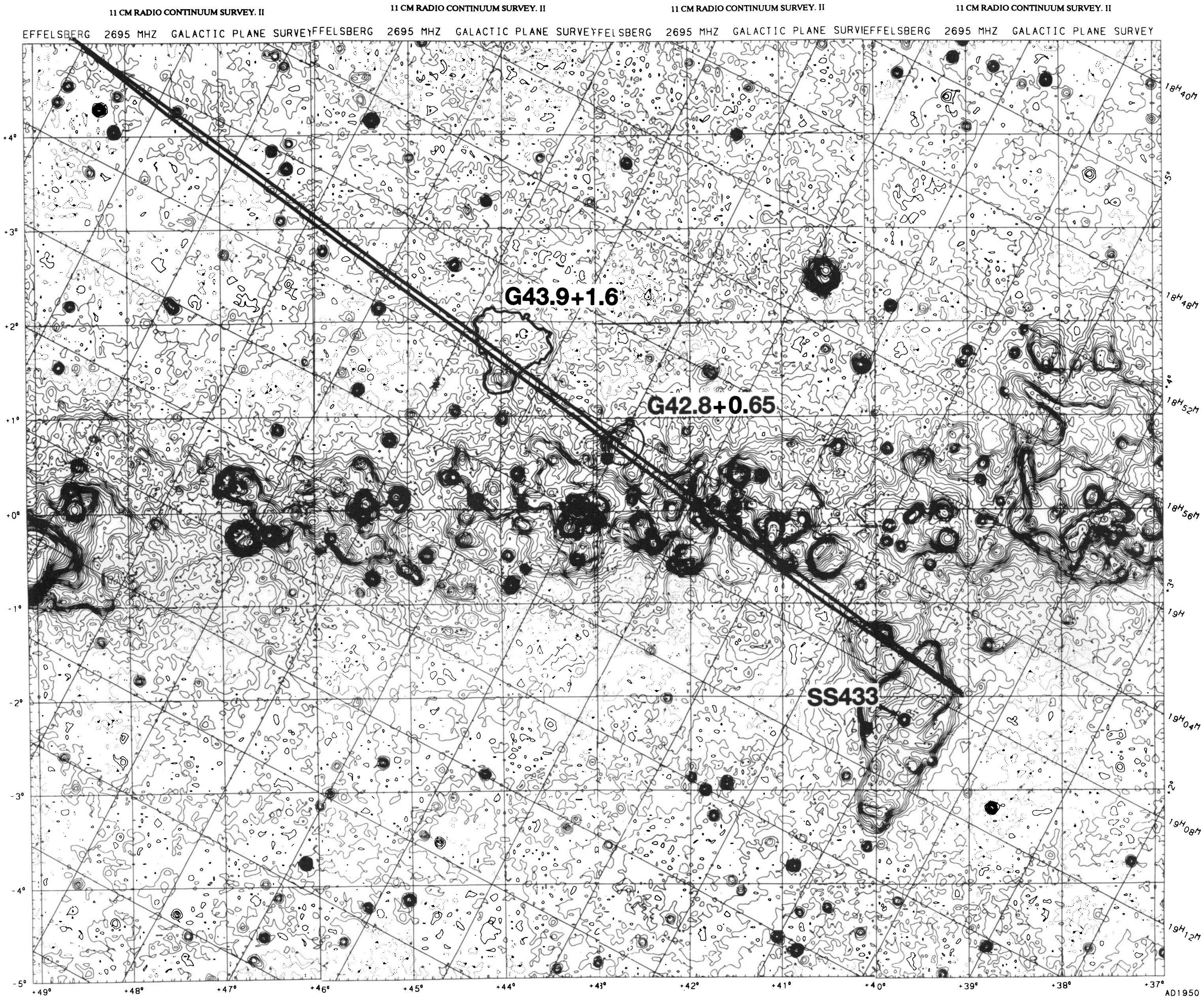

FIG. 1.—11 cm map of the Galactic plane in the area of the SGR 1900+14 error box. The map was made from a survey made of the plane from the Effelsberg 100 m telescope (Reich et al. 1990a). The error box and the intersecting SNR are clearly marked. Vertices of the KONUS error trapezium are $(\alpha, \delta)_{1950}$ (284°885, 16°147), (285°178, 14°698), (286°635, 6°120), (286°808, 4°442).

VASISHT et al. (see 431, L35)

center-filled morphology. The plerion classification is exciting for the diagnostic reasons listed above. Additionally, since only 10% of the SNRs are plerions, the coincidence becomes statistically more meaningful. We estimate the 21 and 11 cm fluxes from the survey contour maps (Reich et al. 1990b; Reich et al. 1990a) to be 10 and 9 Jy, respectively. From our estimated measurement error of $\sim$20% we obtain a spectral index α of 0.16 ± 0.5, where $S_\nu = S_0 \nu^{-\alpha}$. The spectrum seems to be flat like that of plerion. However, this is inconclusive due to the large error in α.

VLA observations towards G43.9+1.6 were conducted on 1993 November 18 and 26 at a central frequency of 327 MHz. We obtained 50 minutes of useful data of a total of 1.5 hours of observations. The mode of observations and data reduction procedure were identical to that described in Frail, Kassim, & Weiler (1994). Due to the incomplete sampling of the *u-v* plane (spatial frequency plane), much of the extended flux that is apparent in the Effelsberg survey maps is missing (see Fig. 2). The poor *uv* coverage and the presence of bright radio sources in the primary beam, prevented us from cleaning the map to below 12 mJy beam^{-1}, which is 4 times worse than the expected theoretical value. Much of the emission we see in this image is the western limb of the SNR. We see some features in the intersection between the KONUS error box and the SNR limb. Most likely these are associated with the SNR limb. It is fair to say that we see no source similar to G10.0−0.03 in this portion of the error box.

The most interesting radio object closest to the 2 σ error box, but perhaps within the 3 σ error box, is a bright compact radio source protruding to the east. This source has an estimated flux of $\sim$1 Jy at 90 cm (VLA data), 21 cm (Reich et al. 1990b), and 11 cm (Reich et al. 1990a). However, it is unpolarized (Junkes et al. 1987), leading us to believe that it may be a foreground H II region. Nonetheless it is intriguing to note that high-resolution ("HIRES") maps of the region in all the four *IRAS* bands do not show any infrared counterpart. We observed this source at the Palomar 60 inch telescope with a reimaging camera (field of view, 8 square arcmin) and a CCD detector with narrow Hα (20 Å) and [S II] (20 Å) filters and suitable wide-band off-line filters for a total integration time of 1 hour each. We derive an upper limit of 24 mag arcsec^{-2} at the location of this source, in each band. Thus if this source is an H II region it must be suffering from extinction. Parenthetically we note that there is a point source at α = 19:02:45 and δ = 10:30 (equinox 1950) which lies outside the SGR 1900+14 error box but close to the center of the SNR.

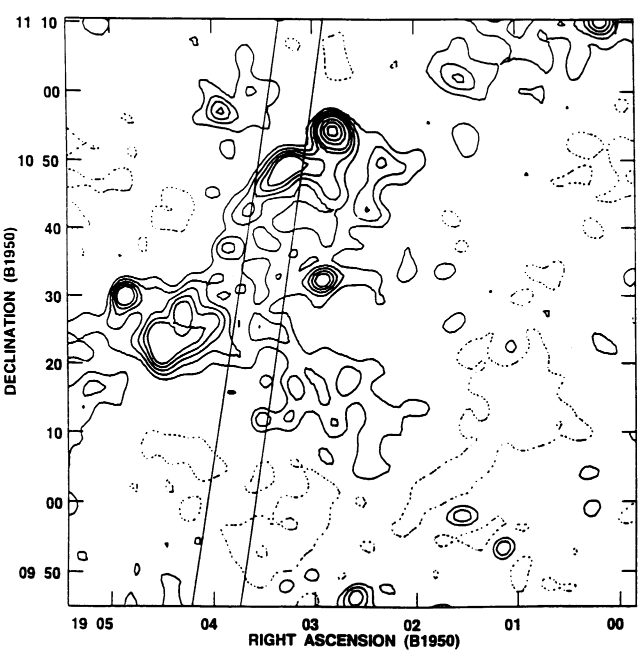

FIG. 2.—*P*-band (327 MHz) image of the remnant G43.9+1.6 from observations at the Very Large Array in D configuration. The integration time on the source is 16 minutes. The synthesized beam size is 202 × 193 arcsec^2. Noise level is at 12 mJy/beam^{-1} with contours at −3, 2, 4, 6, 8, 10, 15, 20, 25 times the noise level. The position of the KONUS error box is superposed, as lying between the vertically running parallel lines. All coordinates are B1950.

Crucial to further discussion is the distance to the SNR and to the SGR. The Σ-D relation (radio surface brightness-diameter; Milne 1979) puts G43.9+1.6 at 4 kpc. However, in our opinion, these estimates are unreliable because the basis of this relation, homogeneity in SNe explosions and properties of the ambient media, are clearly not satisfied. Assuming that the luminosity of primary bursts is the same for all repeaters, and that SGR 0526−66 is located in the LMC, Norris et al. (1991) argue $d_{10} \sim 1$ for SGR 1900+14. However, there is no compelling reason to believe that SGR bursts are standard candles.

The radio luminosity of G43.9+1.6 is $L_R \sim 10^{35} d_{10}^2$ ergs s^{-1}, where d_{10} is the distance to the remnant in units of 10 kpc; here we assume a high-frequency cutoff at 100 GHz. A minimum energy calculation (Pacholcyzk 1970, chap. 7) shows that the energy in particles and magnetic field is $E_{\rm min} = 4 \times 10^{50} d_{10}^{17/7}$ ergs. We stress this point because if SGR 1900+14 and G43.9+1.6 are associated then the system must be much closer, probably at a distance of $\lesssim 5$ kpc; otherwise the energetics and linear size are unprecedented and the transverse velocity implied by the spatial offset of SGR 1900+14 from the center is an impressive $\gtrsim 2.5 \times 10^3 d_{10} t_4^{-1}$ km s^{-1}. Here the age of the remnant is $10^4 t_4$ yr.

2.2. G42.8+0.6 *and the New Network Localization*

The second remanant in the error box is G42.8+0.6, a faint SNR shell (Fürst et al. 1987). Its spectral index α of 0.5 seems to confirm its classification as a shell SNR but its high linear polarization of 22% (at 4750 MHz) is more commonly seen for plerions (Reynolds 1988). Interest in this otherwise ordinary SNR is heightened by the fact that the recent interplanetary network (IPN) localization, reported by Hurley et al. in a companion paper is less than 15 arcmin from this SNR. Observations were conducted at *P*-band (327 MHz) with the VLA in the D-array and spectral line mode on 1994 February 7. The total integration time was 2 hours spread over 4 hours which enable reasonable spatial frequency coverage. The data reduction procedure was similar to that employed for G43.9+1.6.

G42.8+0.6 is seen as a typical shell in the new VLA image. There is no indication of any sort of plerionic component close to the eastern limb where the Konus error box intersects nor is there evidence for a radio plerion at the IPN position (Fig. 3). Parenthetically we note that there is a flat-spectrum, polarized point source at the edge of the remnant (at α = 19:07:42, δ = 09:06, equinox J2000; see also Fürst et al. 1987) that could be related in some way to the remnant. However it does not lie within the error box of SGR 1900+14.

The Σ-D distance to G42.8+0.6 is $\sim$5 kpc. As above, if the SNR is associated with SGR 1900+14 then its distance can be

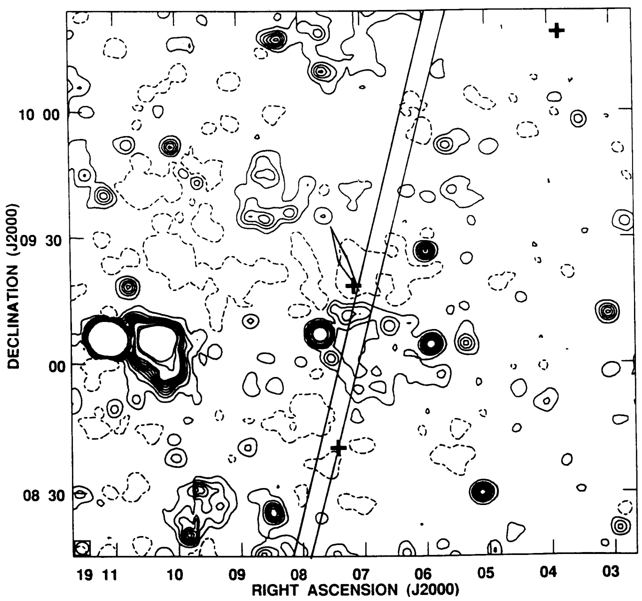

FIG. 3.—*P*-band (327 MHz) VLA image of G42.8+0.6 and its vicinity. See caption for Fig. 2 for approximate beam size. Noise level in the image is at 7 mJy beam^{-1} with contours at −3, 3, 8, 13, 18, 23, 28, 33, 38, 43, 75, 100 times the noise. The parallel lines enclose the KONUS localization box. The diamond to the north of G42.8+0.6 is the IPN localization of Hurley et al. (1994). *ROSAT* sky survey sources in the field are indicated by crosses with RX J190717+0919.3 marked close to the IPN and KONUS error boxes. We speculate this is the quiescent X-ray counterpart of SGR 1900+14. RX J190724+0843.4 which lies close to the KONUS localization is identified as possible coronal emission from the star HD 178215 (see Table 1). All coordinates are J2000.

as large as 10 kpc and much of the above discussion, i.e., the energetics and the size are also applicable to this SNR. It is interesting to note that the KONUS error box does not pass through the center of the SNR and the velocity of SGR (assuming an association) is 10^3 km s^{-1} for an assumed remnant age of 10^4 yr.

3. *ROSAT* SKY SURVEY OBSERVATIONS

The identification of a quiescent counterpart to SGR 1806−20 (Murakami et al. 1994) and SGR 0526−66 (Rothschild et al. 1994) prompted us to look for a similar quiescent source in the general vicinity of the two SNRs in the *ROSAT* All Sky Survey (Trümper 1983). This survey scanned the sky in the range between 0.1–2.4 keV. The area of SGR 1900+14 was scanned by *ROSAT* between 1990 September 22 and October 9 for a mean total observing time per location of about 500–630 s.

We find no hint of X-ray emission from these SNRs and the mean point source 3 σ upper limit is 0.006 counts s^{-1}. A number of sources in the general vicinity of the SNR were found (Table 1), some of which we identify with coronal emission of bright stars. Our upper limit is a factor of 4 higher than the detection counting rate of RX J180840−2024.5, the quiescent *ROSAT* source of SGR 1806−20 (Cooke 1993). However, if the SGR is located at a distance between 5 to 10 kpc then the quiescent X-ray source would be heavily absorbed (cf. the counterpart of SGR 1806−20; Murakami et al. 1994) and our upper limits are not inconsistent with the possible presence of a source similar to the counterparts of SGR 1806−20 and SGR 0526−66.

4. DISCUSSION

We have investigated the two cataloged SNRs G43.9+1.6 and G42.8+0.6 that lie in the KONUS error box. To this end we conducted observations at the VLA and Palomar 60 inch telescope and analyzed the *ROSAT* sky survey in this region of the sky. We come to the following conclusions:

1. Although G43.9+1.6 has been classified to be a possibly center-filled SNR (Green 1991) we find the motivating evidence, neither the center-filled morphology nor the apparent flat spectral index, not compelling. G43.9+1.6 appears to be an ordinary evolved shell. A flat spectrum component has been found close to but outside the intersection region. We believe that this is a distant H II region.

2. Our new high quality images of G42.8+0.6 and its vicinity (which includes the new IPN position of Hurley et al. 1994) show that this SNR is an ordinary shell with no plerionic component either at the center or intersecting the KONUS error box.

3. No radio plerion similar G10.0−0.3 is seen at the new IPN diamond.

4. No *ROSAT* source is seen within the intersection of the error box with either of the two SNRs to a limiting apparent flux sensitivity in the *ROSAT* band of $\sim 6 \times 10^{-14}$ erg cm^{-2} s^{-1}; the unabsorbed flux, assuming a Crab-like spectrum and $N_H \sim 10^{22}$ cm^{-2} is a factor of 10 higher. However, one of the X-ray sources from Table 1, RX J190717+0919.3, is located only 1.5 arcmin from the IPN diamond (Fig. 3). A check of the X-ray position on the Palomar Observatory Sky Survey plate reveals no optical object brighter than 17th mag. Thus, the lower limit of the ratio of the X-ray to the optical luminosity of RX J190717+0919.3 excludes stellar coronal emission of late-

TABLE 1

ROSAT X-RAY SOURCES NEAR THE TWO SNRs[a]

Name	Count Rate (counts s^{-1})	Tentative Identification	Brightness Magnitude	Optical Position (2000.0)
RX J190333+1043.9..........	0.072	GSC	10.1	19ʰ03ᵐ33ˢ.7 + 10°44′00″
RX J190350+1039.1..........	0.013	GSC	11.1	19 03 48.5 + 10 39 36
RX J190448+1025.8..........	0.008	...	...	
RX J190354+1018.1..........	0.010	...	...	
RX J190724+0843.4..........	0.015	HD 178215	10.1	19 07 23.4 + 08 43 32
RX J190935+0845.2..........	0.009	...	...	
RX J190717+0919.3..........	0.011	...	...	

[a] X-ray position error is 30 arcsec in each coordinate.

type stars, WDs, CVs, etc., but not LMXBs, AGNs, or SNRs (though there are no hints for the X-ray source to be extended).

RX J190717+0919.3 is tantalizingly close to the IPN diamond. It is possible this is the quiescent X-ray source of SGR 1900+14. We propose that SGR 1900+14 is a highly evolved version of SGR 0526−66. As with SGR 0526−66, we propose that the neutron star SGR 1900+14 was born with a large velocity, $\sim 10^3$ km s^{-1} but in the latter case, it eventually overtook the rapidly slowing down SNR blast wave and is now outside its parent SNR. Indeed, this phenomenon is quite commonly seen in many SNRs associated with pulsars (Kulkarni et al. 1988; Shull, Fesen, & Saken 1989). Owing to the low confining pressure, the SGR 1900+14 does not develop any substantial radio plerion.

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REFERENCES

Cline, T. L. 1990, in Proc. 21st Int. Cosmic-Ray Conf. 12, 19
Cline, T. L., et al. 1982, ApJ, 255, L45
Cooke, B. A. 1993, Nature, 366, 413
Frail, D. A., Kassim, N. E., & Weiler, K. W. 1994, AJ, 107(3), 1120
Fürst, E., Handa, T., Reich, W., & Reich, P. 1987, A&ASS, 69, 403
Green, D. A. 1991, PASJ, 103, 209
Hurley, K., Sommer, M., Kouveliotou, C., Fishman, G., Meegan, C., Cline, T., Boer, M., & Niel, M. 1994, ApJ, in press
Junkes, N., Fürst, F., & Reich, W. 1987, A&ASS, 69, 451
Kouveliotou, C., et al. 1993, Nature, 362, 728
———. 1994, Nature, 368, 125
Kulkarni, S. R., et al. 1988, Nature, 331, 50
Kulkarni, S. R., & Frail, D. A. 1993, Nature, 365, 33
Kulkarni, S. R., Frail, D. A., Kassim, N. E., Murakami, T., & Vasisht, G. 1994, Nature, 368, 129
Mathewson, D. S., et al. 1983, ApJS, 51, 345
Mazets, E. P., et al. 1979, Soviet Astron. Lett., 5(6), 343
Milne, D. K. 1979, Australian J. Phys., 32, 83
Murakami, T., Tanaka, Y., Kulkarni, S. R., Ogasaka, Y., Sonobe, T., Ogawara, Y., Aoki, T., & Yoshida, A. 1994, Nature, 368, 127
Norris, J. P., Hertz, P., Wood, K. S., & Kouveliotou, C. 1991, ApJ, 366, 240
Pacholczyk, A. G. 1970, Radio Astrophysics (San Francisco: Freeman)
Reich, W., Fürst, E., Reich, P., & Reif, K. 1990a, A&AS, 85, 633
Reich, W., Reich, P., & Fürst, E. 1990b, A&AS, 83, 539
Reynolds, S. P. 1988, ApJ, 327, 853
Rothschild, R. E., Kulkarni, S. R., & Lingenfelter, R. E. 1994, Nature, 368, 432
Shull, J. M., Fesen, R. A., & Saken, J. M. 1989, ApJ, 346, 860
Trümper, J. 1983, Adv. Space Res., 2, 241