PSR J1907+0918 — A YOUNG RADIO PULSAR NEAR SGR 1900+14 AND G42.8+0.6

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ABSTRACT
We have extensively searched for periodic signals from the soft-gamma repeater SGR 1900+14, at 430 and 1410 MHz with the Arecibo telescope. Our observations did not reveal the 5.16-s periodicity discovered at X-ray wavelengths by Hurley et al. (1998). We place pulsed flux-density upper limits of 150 and 30 \( \mu \)Jy at 430 and 1410 MHz respectively. In the course of the 1410-MHz search we discovered a 226-ms radio pulsar, PSR J1907+0918. Its period derivative implies that the age of J1907+0918 is only 38 kyr, making it one of the youngest members of the known pulsar population. Independent lines of evidence in support of this apparent youth are the unusually high degree of circular polarization and a relatively flat radio spectrum. The close proximity of this young radio pulsar to the supernova remnant G42.8+0.6 poses a problem for the proposed association between the G42.8+0.6 and SGR 1900+14.

Subject headings: stars — neutron — pulsars: individual (PSR J1907+0918) — stars: individual (SGR 1900+14) — supernova remnants: individual (G42.8+0.6)

1. INTRODUCTION
Since the discovery of the first soft-gamma repeater (SGR), the source of the famous “March 5” burst from the supernova remnant N49 in the Large Magellanic Cloud (Mazets et al. 1979; Cline et al. 1982), three other SGRs have been found close to the Galactic plane (1900+14: Mazets, Golenetskii & Gur’yan 1979; 1806–20: Laros et al. 1986; 1627–41: Kouveliotou et al. 1998b). Recently, Cline et al. (2000) report a possible fifth SGR, 1801–23. Several lines of evidence support the notion that SGRs are neutron stars: neutron — pulsars: individual (PSR J1907+0918) — stars: individual (SGR 1900+14) — supernova remnants: individual (G42.8+0.6)

2. SEARCH FOR RADIO PULSATIONS FROM SGR 1900+14
In early June 1998 we observed SGR 1900+14 using the Arecibo telescope seven days after the source became active following a long period of quiescence. Coordinated observations of the outburst by Ulysses and BATSE/CGRO resulted in an accurate localization of the source position \((\alpha_{2000} = 19^h07^m15s4; \delta_{2000} = +09^\circ9^\prime21^\prime\prime7)\) kindly provided to us in advance of publication by C. Kouveliotou. This allowed us to make deep search observations. The Arecibo search for radio pulsations was carried out with the Penn State Pulsar Machine (PSPM), a filterbank which records the total-power outputs of the receiver over \(128 \times 60\)-kHz frequency channels every 80 \( \mu \)s. We collected continuous PSPM data in search mode for 1380 s using the 430-MHz line feed (June 10) and the Gregorian L-narrow receiver at 1410 MHz (June 11). The error in the localized position (a 3 arcmin\(^2\) error ellipse) was sufficiently small to require only a single telescope pointing at each of the two frequencies (the 3-dB width of the Arecibo beam is 10 arcmin at 430 MHz and 3 arcmin at 1410 MHz).

These data were searched for the presence of periodic signals using software developed for a recent pulsar survey with the Effelsberg radio telescope (Lorimer et al. 2000). The search explores the three-dimensional parameter space defined by pulse period, pulse duty cycle and dispersion measure by de-dispersing and Fourier transforming the raw data before searching for statistically significant harmonic features in the amplitude spectra. The best candidates are folded in the time domain to produce diagnostic plots which are saved for later inspection.

To estimate the sensitivity of these searches, following Dewey et al. (1984), we calculate the minimum flux density...
$S_{\text{min}}$ required for a detection is given by:

$$S_{\text{min}} = \beta \sigma_{\text{min}} \left( \frac{T_{\text{rec}} + T_{\text{sky}}}{G} \right) \left( \frac{W}{P} \right) \sqrt{\frac{1}{\Delta \nu \tau_{\text{int}}}}.$$  \hspace{1cm} (1)

Here the factor $\beta \simeq 1.1$ reflects losses due to hardware limitations, $\sigma_{\text{min}} = 8$ is the threshold signal-to-noise ratio, $T_{\text{rec}}$ and $T_{\text{sky}}$ are the receiver and sky noise temperatures (K), $G$ is the effective antenna gain (K Jy$^{-1}$), $N_p = 2$ is the number of polarizations summed, $\Delta \nu = 128 \times 60$ kHz = 7.68 MHz is the total observing bandwidth, $\tau_{\text{int}} = 1380$ s is the integration time, $W$ is the detected pulse width and $P$ is the pulse period. For our 430-MHz search we can insert the above values along with $T_{\text{rec}} = 100$ K, $T_{\text{sky}} = 150$ K, $G = 10$ K Jy$^{-1}$ to find $S_{\text{min},430} \simeq 1.5(W/P)^{1/2}$ mJy. For the 1410-MHz search, $T_{\text{rec}} = 35$ K, $T_{\text{sky}} \simeq 7$ K, $G = 8$ K Jy$^{-1}$ so that $S_{\text{min},1410} \simeq 0.3(W/P)^{1/2}$ mJy. In both these cases, we have assumed that $W \ll P$. Note also that both the 430-MHz and 1410-MHz observations were carried out at necessarily high zenith angles ($> 10^\circ$) so that the quoted antenna gains are lower than those applicable to observations closer to the zenith (see [http://www.naic.edu/aomenu.htm](http://www.naic.edu/aomenu.htm) for up-to-date telescope information).

These search observations were carried out as part of a larger search for pulsars in supernova remnants at Arecibo. As part of this project, we undertook a number of calibration observations with the PSPM for pulsars with well-known flux densities and pulse widths. The signal-to-noise ratios predicted from equation (1) compare well with those obtained in practice and give us confidence in the above flux limits obtained from our blind search.

Our search was carried out before the announcement of the 5.16-s periodicity by Hurley et al. (1998). Following this discovery, and Shitov’s (1999) detection at 111 MHz, we de-dispersed and folded both sets of search data at the predicted topocentric period to look for evidence of a pulsed signal. We found no convincing evidence for pulsar-like profiles above a signal-to-noise threshold of 6. This effectively reduces the above limits from the blind periodicity searches by a factor of 6/8 to $S_{\text{min},430} \simeq 1.1(W/P)^{1/2}$ mJy and $S_{\text{min},1410} \simeq 0.2(W/P)^{1/2}$ mJy. Shitov, Pugachev & Kutuzov (2000) report a pulse width of 100 ms for the 5.16-s radio pulsations from SGR 1900+14 observed at 111 MHz. Based on the above sensitivity estimations, such a pulsed signal would be detectable down to a flux-density limit of 150 $\mu$Jy at 430 MHz and 30 $\mu$Jy at 1410 MHz. We note that these upper limits, together with Shitov et al.’s flux measurement of SGR 1900+14 as a 50-mJy radio pulsar at 111 MHz, constrain the power-law index of the radio spectrum to be steeper than $\sim 3$. Clearly, further radio observations at lower frequencies are required to confirm or refute the 111-MHz detection reported by Shitov et. al.

### 3. Discovery and Follow-up of PSR J1907+0918

During the analysis of our 1410-MHz search observations towards SGR 1900+14 we found a very promising 113-ms pulsar candidate. Subsequent 1410-MHz observations made in September 1998 confirmed the existence of the pulsar (J1907+0918) and identified its true period to be 226 ms (Xilouris et al. 1998). In order to accurately determine the spin and astrometric properties of PSR J1907+0918, we have been carrying out regular timing measurements using the PSPM since October 1998. A preliminary ephemeris, based on the discovery and confirmation observations, was used to predict the apparent pulse period initially. This period was sufficiently accurate to be used by the PSPM in timing mode to fold the incoming data from each of the 128 frequency channels for typically 90 s before saving the profiles to disk. The individual frequency channels were later de-dispersed to produce a time-tagged integrated pulse profile for each 90-s observation. For each of these scans, the mean pulse time of arrival (TOA) at the observatory was then determined by cross correlating the profile with a high signal-to-noise template (for further details, see Taylor 1992).

The TEMPO software package (which is freely available at [http://pulsar.princeton.edu/tempo](http://pulsar.princeton.edu/tempo)) and the DE200 planetary ephemeris were then used to correct these topocentric TOAs for the Earth’s motion around the Sun and transform them to the frame of the solar system barycenter before fitting them to a simple isolated pulsar spin-down model (see e.g. Manchester & Taylor 1977). Multiple passes of the TOAs through TEMPO were required in order to minimize the model minus observed timing residuals and resolve any pulse numbering ambiguities. The resulting ephemeris based on observations spanning a 15-month baseline between October 1998 and January 2000 yields a sub-arcsecond position and highly accurate spin-down parameters which are presented in Table [I]. The post-fit timing residuals for this ephemeris are free from systematic trends at the level of 108 $\mu$s rms.
polarized sources at radio frequencies above 1 GHz (von Hoenbroeck 1999).

In order to investigate the emission properties of PSR J1907+0918, in October and November 1998 we carried out a series of quasi-simultaneous multi-frequency observations at Arecibo using the 430-MHz line feed, along with the Gregorian receivers centered at 1410, 2380 and 5000 MHz. We used the Arecibo-Berkeley Pulsar Processor (ABPP) for these observations. The ABPP is a 32-channel coherent-dispersion-removal machine capable of high-precision timing and polarization (for details see Backer et al. 1997 and \[\text{http://www.naic.edu/~abpp}\]) which allowed us to carry out high-quality observations spanning a bandwidth of up to 35 MHz.

In Fig. 1 we present a high signal-to-noise polarization profile of PSR J1907+0918 based on ABPP observations carried out at 1410 MHz. The degree of circular polarization in this profile is 58%, making this the pulsar with the highest known degree of circular polarization at 1410 MHz. PSR J1907+0918 is ideally suited as a calibrator for future pulsar polarimetry observations. As can be seen from the scale in Fig. 1, the pulse duty cycle of J1907+0918 is extremely small, less than 2% at observing frequencies above 1 GHz. Fewer than 2% of all known pulsars have such a narrow pulse. At 430 MHz, however, the lowest frequency that we have data for, the profile appears to be broadened due to multi-path scattering. Fitting the profile to a truncated exponential function, we determine a scattering time-scale at 430-MHz of 17 ms. The flux density \(S_\nu\) at each frequency \(\nu\) are summarized in Table 1. Fitting these to a power law of the form \(S_\nu \propto \nu^{\alpha}\) yields a mean spectral index \(\alpha = -0.3 \pm 0.2\). Only two pulsars out of 260 listed by Lorimer et al. (1995) have flatter spectra. In summary, based on the timing and emission properties of PSR J1907+0918, we conclude that it is most likely a young radio pulsar.

4. DISCUSSION

Although our radio search for the 5.16-s pulsations from SGR 1900+14 was unsuccessful, the discovery of PSR J1907+0918 has important implications for the origins of SGR 1900+14 and its proposed association with the supernova remnant G42.8+0.6.

4.1. PSR J1907+0918 and SGR 1900+14

The angular separation between PSR J1907+0918 and SGR 1900+14 is \(\sim 2\) arcmin. Apart from globular cluster pulsars and double neutron star binaries, this is the closest pair of neutron stars on the plane of the sky. Either the two stars are physically close to each other (at the dispersion-measure distance of J1907+0918, 7.7 kpc, the projected separation is only 5 pc), or they are at different distances and only appear close when seen in projection.

To investigate the case of a simple geometric projection, we require an estimate of the expected number of pulsars per unit area that would be detectable in our deep search. Cordes & Chernoff (1997) provide a number of useful analytic expressions for these purposes. Starting from their equation (8) we find the mean search volume \(V\) to be proportional to \(S_{\text{min}}^{-3/2}\). Here for simplicity we have neglected any strong period dependence upon the sensitivity (reasonable for long-period pulsars) and weighted the mean over a pulsar luminosity function of the form \(d\log N/d\log L = -1\) (see e.g. Lorimer et al. 1993). Under the simplest assumption that the number density of pulsars is approximately constant, the expected number of pulsars \(N \propto \tau \propto S_{\text{min}}^{-3/2}\). To estimate the pulsar detection rate in our search we extrapolate the results of the current Parkes multibeam survey of the Galactic plane which is detecting about 1.5 pulsars deg\(^{-2}\) within \(|b| < 1^\circ\) around the location of PSR J1907+0918 on the Galactic plane (F. Camilo, private communication). Under the above assumptions, we would expect a deep Arecibo search of this part of the plane to detect around \(1.5 \times 2.5^{3/2} \approx 6\) pulsars deg\(^{-2}\). Since the width of the 1410-MHz beam is around 3.5 arcmin, this corresponds to about one pulsar detection every 60 telescope pointings. It is therefore not unreasonable to appeal to simple chance detection in this case where we have only made one pointing at 1410 MHz.

Aside from simple probability calculations, there is one other reason to believe that the apparent close angular proximity between PSR J1907+0918 and SGR 1900+14 is simply a projection effect. If we were to assume that the two neutron stars had a common binary origin, this would require a binary system in which both stars are sufficiently massive to undergo a supernova explosion. Although theoretical arguments can be made to explain the close proximity of PSR B1853+01 and PSR B1854+00 (Wolzczan Cordes & Dewey 1991) i.e. that both these neutron stars were formed from a massive binary system, the ages of the radio pulsars in this case differ by over 100 million years. The similar ages of SGR 1900+14 and PSR J1907+0918 (see below) would require the progenitor stars to have essentially identical main sequence lifetimes and hence masses. For example, to produce two neutron stars that differ in age by only \(10^4\) yr, we estimate from eq. 1.3.9 of Shapiro & Teukolsky (1983) that main sequence stars of the order of 6 \(M_{\odot}\) would differ in their absolute initial mass by only 0.05 \(M_{\odot}\), somewhat unlikely given the mass ratio distributions of binary stars (see e.g. Dewey & Cordes 1987 and references therein). Both on statistical and evolutionary grounds, we conclude that SGR 1900+14 and PSR J1907+0918 did not share a common origin.

4.2. Which neutron star is associated with G42.8+0.6?

As demonstrated in Fig. 3, J1907+0918 is clearly a young pulsar. Given that plausible cases for an association with a supernova remnant can be made for several young radio pulsars with similar characteristic ages to J1907+0918, it is appropriate to revisit the case for the association between SGR 1900+14 and the supernova remnant G42.8+0.6 following our discovery of PSR J1907+0918. There are three possibilities to be considered: (1) SGR 1900+14 is the neutron star produced in the supernova explosion that produced G42.8+0.6; (2) PSR J1907+0918 is associated with G42.8+0.6; (3) neither of these neutron stars are associated with G42.8+0.6.

In order to make a good case for any neutron star-supernova remnant association, the following criteria should be satisfied (see Kaspi 1996): (a) the distances to both objects should agree; (b) the ages of both objects should agree; (c) the implied transverse velocity, based on the neutron star offset from the remnant center and the age, should be reasonable. We now review the current ev-
idence for both SGR 1900+14 and PSR J1907+0918 in connection with what is known about G42.8+0.6.

(a) Distance estimates: PSR J1907+0918 is estimated to lie at 7.7 kpc based on its dispersion measure and assuming the Taylor & Cordes (1993) Galactic electron density model. The statistical uncertainty in this model is at least 25%. Hurley et al. (1999b) estimate the distance to SGR 1900+14 to be 5.7 kpc based on a spectral analysis of ASCA data, although no estimate of the uncertainty in this measurement is quoted. The distance to G42.8+0.6 is commonly taken in the literature to be 5 kpc (see e.g. Vasisht et al. 1994). Whilst this appears to be in agreement with SGR 1900+14, it should be stated that the latter distance was derived using the notoriously unreliable \( \Sigma-D \) relationship. A more recent \( \Sigma-D \) study places G42.8+0.6 at 10 \( \pm \) 3 kpc (Case & Bhattacharya 1998). Given the considerable uncertainties associated with this technique, it would obviously be premature to rule out an association between G42.8+0.6 and either of the two neutron stars in question. In this regard, we note that the recent discovery by Vrba et al. (2000) of a massive star cluster only 12 arcsec from SGR 1900+14 suggests that it may have been formed in this cluster rather than G42.8+0.6. Vrba et al. estimate the star cluster to lie at 14.5 kpc.

(b) Age estimates: The ages of any non-historical supernova remnants are strongly coupled with their distances since absolute remnant sizes, along with assumptions about the expansion velocities are required to constrain the ages. Hence the age of G42.8+0.6 is also subject to considerable uncertainty. Vasisht et al. (1994) quote an age of \( 10^4 \) yr but, given the above range of distance estimates, this could easily be uncertain by factors of a few. For SGR 1900+14, the traditional assumptions about dipolar spin-down are thought not to apply and the age is quite uncertain with current estimates of \( 10^4 \) yr (see e.g. Kouveliotou et al. 1999). For PSR J1907+0918, the 38-kyr characteristic age is probably indicative of its true age. This is somewhat model dependent since the age would be reduced if e.g. the birth spin period of PSR J1907+0918 was close to its current value or even increased if the neutron star braking is less than that expected from pure magnetic dipole braking (see e.g. Manchester & Taylor 1977). In summary, based on currently-available evidence we conclude that both neutron stars appear to be young enough to be considered as plausible candidates for an association with G42.8+0.6.

(c) Transverse speed estimates: Both neutron stars lie about 20 arcmin from the center of G42.8+0.6 which implies a transverse velocity of 4000 \( D_7/t_4 \) km s\(^{-1}\) to carry either of them to their present position. Here \( D_7 \) is the distance in units of 7 kpc and \( t_4 \) is the age in units of \( 10^4 \) yr. Although the exact values of \( D_7 \) and \( t_4 \) are highly uncertain, it is unlikely that they are such that the required velocity estimate is below 1000 km s\(^{-1}\). For either of the neutron stars, then, the implied transverse velocities would place them at the far extremes of the presently-observed distribution (Harrison, Lyne & Anderson 1993). To ultimately test for an association between PSR J1907+0918 and G42.8+0.6, and constrain the age of the pulsar, a proper motion measurement is required. The predicted pulsar proper motion is 120/\( t_4 \) mas yr\(^{-1}\). Future VLBI proper motion measurements of PSR J1907+0918, perhaps using Arecibo-Effelsberg-GBT are highly desirable.

To summarize, based on the currently-available information, we conclude that the proposed association between G42.8+0.6 and SGR 1900+14 is, contrary to frequent claims in the literature, far from secure since there is no reason against arguing equally strongly in favor of PSR J1907+0918 as being the neutron star produced in the supernova explosion rather than SGR 1900+14. Indeed, the additional possibility that neither of these young neutron stars is associated with G42.8+0.6 remains attractive at this stage! As noted by Gaensler (2000), large positional offsets between neutron stars and supernova remnants are more likely a result of random line-of-sight alignments rather than genuinely associated high-velocity neutron stars. This may well be the case here and further observations (e.g. deeper multi-wavelength maps of the region and proper-motion measurements) are clearly desirable to help resolve this most perplexing situation.

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Table 1

| Parameter                                      | Value          |
|------------------------------------------------|----------------|
| Right Ascension (J2000)                        | 19\(^{h}\) 07\(^{m}\) 22\(^{s}\) 441(4)  |
| Declination (J2000)                            | +09\(^{\circ}\) 18\(^{\prime}\) 30\(^{\prime\prime}\) 76(4)  |
| Barycentric Period (s)                         | 0.2261071098878(6) |
| Period derivative (10\(^{-15}\))               | 94.2955(4)      |
| Epoch (MJD)                                    | 51319          |
| Dispersion Measure (cm\(^{-3}\) pc)           | 357.9(1)       |
| Timing data span (MJD)                         | 51257–51540    |
| Flux density at 0.4 GHz (mJy)                  | 0.4(2)         |
| Flux density at 1.4 GHz (mJy)                  | 0.3(1)         |
| Flux density at 2.4 GHz (mJy)                  | 0.24(2)        |
| Flux density at 5.0 GHz (mJy)                  | 0.18(9)        |
| Mean spectral index                           | -0.3(2)        |
| Distance\(^{a}\) (kpc)                        | 7.7            |
| Dipole magnetic field strength\(^{b}\) B (10\(^{12}\) G) | 4.7            |
| Characteristic age\(^{b}\) \(\tau\) (kyr)     | 38             |
| Spin-down energy loss rate\(^{c}\) \(\dot{E}\) (10\(^{35}\) erg s\(^{-1}\)) | 3.2            |

Note.—Figures in parentheses represent 1\(\sigma\) uncertainties in least-significant digits quoted.

\(^{a}\)Calculated using the Taylor & Cordes (1993) Galactic electron density model.

\(^{b}\)Calculated using the standard magnetic dipole formulae viz: \(B = 3.2 \times 10^{18} \sqrt{PP}\) Gauss; \(\tau = P/2\dot{P}\) (Manchester & Taylor 1977).

\(^{c}\)Calculated assuming rigid-body rotation for a neutron star moment of inertia of 10\(^{45}\) gm cm\(^2\) (Manchester & Taylor 1977).