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# NONDETECTION OF A PULSAR-POWERED NEBULA IN PUPPIS A AND THE IMPLICATIONS FOR THE NATURE OF THE RADIO-QUIET NEUTRON STAR RX J0822−4300

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## ABSTRACT

We report on a deep radio search for a pulsar wind nebula associated with the radio-quiet neutron star RX J0822−4300 in the supernova remnant Puppis A. The well-determined properties of Puppis A allow us to constrain the size of any nebula to less than 30″; however, we find no evidence for such a source on any spatial scale up to 30′. These nondetections result in an upper limit on the radio luminosity of any pulsar-powered nebula that is 3 orders of magnitude below what would be expected if RX J0822−4300 was an energetic young radio pulsar beaming away from us, and they cast doubt on a recent claim of X-ray pulsations from this source. The lack of a radio nebula leads us to conclude that RX J0822−4300 has properties very different from most young radio pulsars and that it represents a distinct population that may be as numerous, or even more so, than radio pulsars.

*Subject headings:* ISM: individual (Puppis A) — pulsars: general — radio continuum: ISM — stars: individual (RX J0822−4300) — stars: neutron — supernova remnants

## 1. INTRODUCTION

While the vast majority of neutron stars so far discovered are seen as radio pulsars, there are also a small but increasing number of neutron stars that have very different observational properties. Approximately half these sources are soft $\gamma$-ray repeaters (SGRs) or anomalous X-ray pulsars (AXPs), both of which show pulsed X-rays at long periods ($P \sim 10$ s; e.g., Mereghetti 1999). The remaining sources are grouped together as “radio-quiet neutron stars” (RQNSs; Caraveo, Bignami, & Trümper 1996; Brazier & Johnston 1999), most of which are characterized by unpulsed thermal X-ray emission at a temperature of a few million degrees, a complete lack of radio emission, and very high X-ray–to–optical ratios. Many of these sources have been associated with supernova remnants (SNRs) and are thus probably quite young ($\lesssim$20 kyr) objects.

The AXPs and SGRs are quite distinct from radio pulsars in their properties and are believed to be either “magnetars” (neutron stars with magnetic fields $B \gtrsim 10^{14}$ G; Thompson & Duncan 1996) or exotic accreting systems (e.g., van Paradijs, Taam, & van den Heuvel 1995); however, an interpretation for the RQNSs is less clear. Brazier & Johnston (1999) argue that RQNSs are energetic young radio pulsars like the Crab pulsar, but whose beams do not cross our line of sight. However, Vasisht et al. (1997) and Frail (1998) propose that RQNSs are neutron stars with large initial periods ($P_0 \gtrsim 0.5$ s) and/or high magnetic fields ($B \gtrsim 10^{14}$ G) and are thus possibly related to the SGRs and AXPs, while Geppert, Page, & Zannias (1999) suggest that they may rather be fast-spinning but weakly magnetized sources.

One way to distinguish between all these possibilities would be to detect pulsations from a RQNS. The period and period derivative of the source could then be used to infer a surface magnetic field (Manchester & Taylor 1977), while if the RQNS can also be associated with an SNR, an independent age determination for the latter can be used to estimate an initial period for the neutron star (e.g., Reynolds 1985).

The RQNS RX J0822−4300 (Petre, Becker, & Winkler 1996) is near the center of and is almost certainly associated with the young (<5000 yr; Winkler et al. 1988; Arendt, Dwek, & Petre 1991) and nearby (2.2 kpc; Reynoso et al. 1995) supernova remnant Puppis A (G260.4−3.3). Recently, Pavlov, Zavlin, & Trümper (1999, hereafter PZT99) and Zavlin, Trümper, & Pavlov (1999, hereafter ZTP99) have analyzed two archival *ROSAT* data sets on RX J0822−4300, separated by 4.6 yr. In each data set, they find evidence for weak pulsations, the periods of which are slightly different as would be expected for pulsar spin-down. The resulting period, $P = 75.5$ ms, and period derivative, $\dot{P} = 1.49 \times 10^{-13}$ s s$^{-1}$, when combined with the age of the SNR, imply a dipole magnetic field $B = 3.4 \times 10^{12}$ G, a spin-down luminosity $\dot{E} = 1.4 \times 10^{37}$ ergs s$^{-1}$, and an initial period $P_0 \approx 55$ ms, all of which (despite the radio-quiet nature of the source) are properties typical of a young energetic radio pulsar associated with an SNR.

However, energetic young pulsars in SNRs have some unmistakable signatures. *Every* young ($\lesssim$20 kyr) pulsar located within the confines of an SNR powers an observable pulsar wind nebula (PWN)—a filled-center synchrotron source resulting from the confinement of the relativistic pulsar wind by external pressure. Thus, a simple test to determine if RX J0822−4300 is indeed an energetic young pulsar, as argued by Brazier & Johnston (1999) and as implied by the detection of pulsations by PZT99 and ZTP99, is to see if it has an associated PWN. At radio wavelengths, existing data (e.g., Arendt et al. 1990; Dubner et al. 1991) let us put no useful constraints on the presence or absence of a PWN associated with RX J0822−4300. This is because these observations were carried out at relatively low frequencies (where Puppis A is brightest) and low spatial resolution, resulting in a great deal of confusing emission at the position of RX J0822−4300 both from the SNR shell and from diffuse internal emission. We have therefore carried out new observations toward RX J0822−4300, at higher frequency and spatial resolution than previous measurements, aimed at searching for a radio PWN associated with RX J0822−4300 and thus determining whether its properties are consistent with it being a young pulsar. Our observations are described in § 2, while in

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§ 3 we demonstrate the absence of any radio PWN at the position of RX J0822−4300 and quantify the consequent upper limits. In § 4 we argue that this nondetection implies that RX J0822−4300 must have properties very different from the young energetic pulsars that do power observable PWNs.

## 2. OBSERVATIONS

Radio observations toward RX J0822−4300 were made with the Australia Telescope Compact Array (ATCA; Frater, Brooks, & Whiteoak 1992) in its 0.750D configuration on 1999 July 24/25. In this configuration, the array contains 10 baselines in the range of 31– 719 m and another five baselines in the range of 3750–4469 m. Since these two sets of baselines cannot be easily combined in a single image, this effectively results in two sets of data: one appropriate for imaging extended structure on a wide range of scales (a "large-scale" image) and another sensitive only to a narrow range of spatial scales, but at much higher spatial resolution (a "small-scale" image).

Two separate observations were made, each with a duration of 12 hr. In the first, data were collected at frequencies of 1.4 and 2.5 GHz, while in the second, a single observation was made centered at 4.8 GHz. At 1.4 and 2.5 GHz, the bandwidth was 128 MHz, while at 4.8 GHz, the bandwidth was 256 MHz, in all cases divided into 4 MHz channels.

Observations at 1.4/2.5 GHz consisted of a two-point mosaic with mean position centered on RX J0822−4300; at 4.8 GHz, observations consisted of a single pointing, offset 2′.5 to the west of RX J0822−4300 so as to avoid sidelobe contamination from the nearby bright source PMN J0820−4259. Amplitudes were calibrated by observations of PKS B1934−638, assuming flux densities of 14.9, 11.1, and 5.7 Jy at 1.4, 2.5, and 4.8 GHz, respectively. Instrumental gains and polarization were determined using regular observations of PKS B0823−500.

## 3. ANALYSIS AND RESULTS

After standard editing and calibration using the MIRIAD package, total intensity images were formed at each frequency, using a multifrequency synthesis approach to both improve the $u$-$v$ coverage and minimize the effects of bandwidth smearing (Sault & Wieringa 1994). At 1.4 and 2.5 GHz, mosaic images were formed using maximum entropy deconvolution, both pointings being deconvolved simultaneously (Sault, Staveley-Smith, & Brouw 1996). The 4.8 GHz image was deconvolved using the CLEAN algorithm. At each frequency, both large-scale and small-scale images were formed. At 2.5 GHz, the two shortest baselines sample emission from the SNR that fills the entire field of view of the large-scale image and prevents it from being successfully deconvolved; therefore, at this frequency, these two baselines were not used when forming the large-scale image.

In all cases, deconvolution was constrained to act only on specific regions of the image, namely the shell component of the SNR (defined using the 0.8 GHz MOST image of Bock, Turtle, & Green 1998) and background point sources outside the SNR. The resulting model was subtracted from the $u$-$v$ data to produce a data set that contained visibilities corresponding only to emission from the interior of the SNR. This data set was then imaged, deconvolved, smoothed with a Gaussian restoring beam, and corrected for the mean primary-beam response of the ATCA antennas.

In all six images (1.4, 2.5, and 4.8 GHz; small scale and large scale), no radio emission could be seen at or around the position of RX J0822−4300; one such image is shown in Figure 1. To quantify these nondetections, we performed a series of simulations, in each of which we modeled the appearance of a PWN by using a circular disk of a given surface brightness and radius, centered on RX J0822−4300. This simple morphology is a reasonable approximation to observed PWNs, most of which are centered on their associated pulsar with approximately constant surface brightness across their extent. In each simulation, the Fourier transform of this disk was added to the $u$-$v$ data from which the shell emission had been subtracted, and the imaging and deconvolution process was then repeated.[5] For a given diameter, we increased the brightness of the simulated disk until it could clearly be distinguished from the underlying noise (this criterion corresponds to an $\sim 5\ \sigma$ detection for small diameters but is closer to $3\ \sigma$ for larger sources). We were thus able to quantify the sensitivity of the data to a PWN as a function of its size, incorporating effects due to non-Gaussian noise in the image, unrelated background sources, and the limited range of spatial scales sampled by the interferometer.

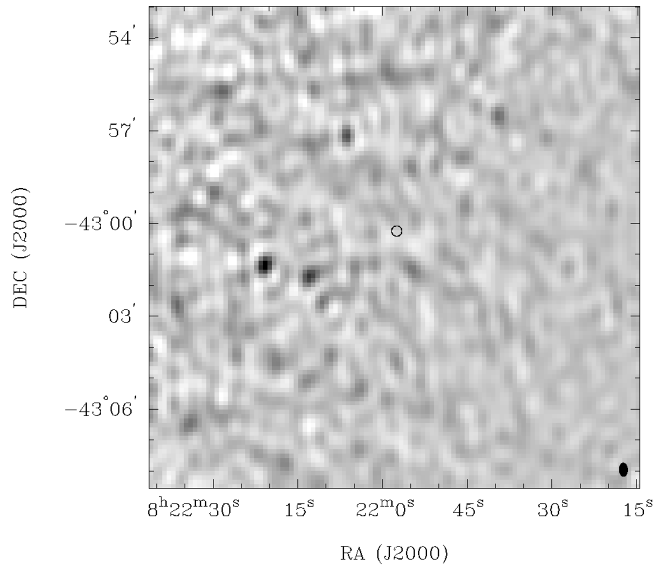


FIG. 1.—Large-scale ATCA image of the region surrounding RX J0822−4300 at a frequency of 2.5 GHz. The emission from the shell of Puppis A and from bright point sources exterior to the SNR has been subtracted. The circle marks the position of RX J0822−4300 (Petre et al. 1996)—the positional uncertainty is half the radius of the circle. The gray scale ranges from 0.0 to 2.4 mJy beam$^{-1}$ at a resolution of $27'' \times 17''$ (indicated at the lower right); the rms noise is 0.2 mJy beam$^{-1}$.

The results of these simulations are shown in Figure 2. At each frequency, the sensitivity curve consists of four regimes. At the smallest scales, each curve is essentially flat, corresponding to the sensitivity of the small-scale image to an unresolved source. The curve then increases approximately as $S_{\rm min} \propto D^2$, as expected for an extended source (see Fig. 2 of Gaensler et al. 2000); slight deviations from this relation are due to the effects of noise fluctuations in the data. At a certain scale, the sensitivity of the large-scale image to an unresolved source becomes better than that of the small- scale image to a resolved source, and the curve becomes flat once more. Finally, at scales that are resolved by the large-scale image, the curve once again increases proportional to $D^2$. The curve at each frequency terminates at the largest scale detectable by the in-

[5] The increase in antenna temperature resulting from the flux of the disk is negligible in all cases.

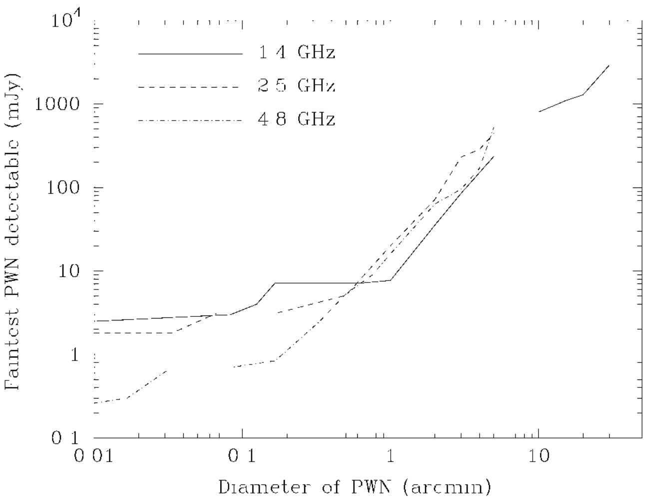


FIG. 2.—Minimum detectable flux density of a PWN at the position of RX J0822−4300 at 1.4, 2.5, and 4.8 GHz as a function of size.

terferometer; note that the 2.4 GHz curve ends prematurely because the two shortest baselines were not used, as discussed above.

## 4. DISCUSSION AND CONCLUSIONS

To determine whether the limits derived in Figure 2 are constraining, we need to determine the expected size and flux density for a PWN associated with RX J0822−4300. A PWN will expand until the pulsar wind comes into pressure equilibrium with the external pressure. As discussed by Gaensler et al. (2000), there are two possible sources for this pressure: either the external gas pressure, $p_{\rm gas} = nkT$, or the ram pressure produced by the pulsar's motion, $p_{\rm ram} = \rho V^2$, where $n$ and $\rho$ are the number and mass density, respectively, of the ambient medium, $V$ is the velocity of the pulsar, and $T$ is the temperature of ambient gas.

By modeling the infrared emission from Puppis A, Arendt et al. (1991) derive parameters for the gas interior to the SNR (into which the PWN is expanding) of $n = 1.3$ cm$^{-3}$ and $T = (3–6) \times 10^6$ K; similar values are derived from X-ray spectroscopy (e.g., Winkler et al. 1981; Berthiaume et al. 1994). This corresponds to a pressure $p_{\rm gas} = 0.05–0.11$ nPa that, if equated with the pressure $\dot{E}/4\pi r^2 c$ from the pulsar wind (where $r$ is the radius of the PWN and $\dot{E} = 1.4 \times 10^{37}$ ergs s$^{-1}$), results in a PWN of diameter 11″–16″ at a distance 2.2 kpc.

For the same number density as used above, and assuming the ambient gas to be composed only of atomic hydrogen, we find that $p_{\rm ram} = 2.2V_3^2$ nPa, where $V = 10^3 V_3$ km s$^{-1}$. Balancing this pressure with that from the pulsar wind (e.g., Gaensler et al. 2000) results in a PWN of angular diameter $\sim 4V_3^{-1}$ arcsec.

Since the mean velocity of the pulsar population is $V_3 \approx 0.38$ (Cordes & Chernoff 1998), and in fact, in this particular instance, the offset of RX J0822−4300 from the dynamical center of the SNR argues that $V_3 > 1$ (Petre et al. 1996), it is likely that $p_{\rm ram} > p_{\rm gas}$ and that the smaller of the two sizes we have just estimated, corresponding to a bow-shock morphology, should apply. We note that in such a case, it is still reasonable to model the PWN as a circular disk since, in observed bow-shock nebulae, most of the emission is concentrated close to the head of the nebula. In any case, regardless of the dominant source of confining pressure, the expected extent of a PWN powered by RX J0822−4300 is small. Although we believe the sizes derived above to be robust, we conservatively adopt a maximum angular size for any PWN of 30″ in order to take into account possible uncertainties in $V$, $n$, $T$, or the distance to the source. From Figure 2, it can be seen that at all three frequencies, the upper limit on the flux density for such a source is ∼7 mJy.

Assuming a typical PWN spectral index of $\alpha = -0.3$ ($S_\nu \propto \nu^\alpha$), an upper limit of 7 mJy at 1.4 GHz corresponds to a broadband radio luminosity (integrated between 10 MHz and 100 GHz) of $L_R = 2 \times 10^{30}$ ergs s$^{-1}$. Defining $\epsilon \equiv L_R/\dot{E}$ to be the ratio between a PWN's broadband radio luminosity and its spin-down luminosity, we find that for $\dot{E} = 1.4 \times 10^{37}$ ergs s$^{-1}$ as reported by PZT99 and ZTP99, we can derive an upper limit $\epsilon < 10^{-7}$. This is a more stringent limit on $\epsilon$ than has been derived for almost any other pulsar (see Frail & Scharringhausen 1997; Gaensler et al. 2000). In particular, this upper limit is sharply at odds with the values of $\epsilon$ seen for other young ($\lesssim$20 kyr) pulsars, almost all of which produce radio PWNs or have upper limits consistent with $\epsilon \geq 10^{-4}$ (Frail & Scharringhausen 1997; Gaensler et al. 2000). The glaring exception to this is PSR B1509−58 in the SNR G320.4−1.2 (MSH 15−52), which powers an X-ray PWN for which no radio PWN has yet been detected (Gaensler et al. 1999). However, this can be understood in terms of the low ambient density ($n < 0.01$ cm$^{-3}$), which results in severe adiabatic losses and a consequently underluminous radio PWN (Bhattacharya 1990). This condition is not satisfied for RX J0822−4300 and therefore cannot be considered as a possible explanation for the nondetection of a PWN.[6] We thus find that any PWN in Puppis A has a radio luminosity 3 orders of magnitude fainter than expected for the spin parameters derived by PZT99 and ZTP99.

Nevertheless, if we assume, as Brazier & Johnston (1999) have argued, that RX J0822−4300 is a rotation-powered pulsar, what spin parameters can we infer for it? If we require that $\epsilon \geq 10^{-4}$ as seen for other young pulsars, the maximum value of $\dot{E} \equiv 4\pi^2 I\dot{P}/P^3$ that is consistent with our nondetection of a radio PWN is $\sim 10^{33}$ ergs s$^{-1}$. Meanwhile, it is unlikely that the characteristic age, $\tau \equiv P/2\dot{P}$, of the pulsar is more than 50 kyr, ∼10 times the true age of the system. These upper limits on $\dot{E}$ and $\tau$ correspond to lower limits of $P > 3.5$ s, $\dot{P} > 1.1 \times 10^{-12}$ s s$^{-1}$, and $B > 6.4 \times 10^{13}$ G, parameters which are very similar to those seen for the SGRs/AXPs (Kaspi, Chakrabarty, & Steinberger 1999) and for the young radio pulsar PSR J1814−1744 (Pivovaroff, Kaspi, & Camilo 2000; Camilo et al. 2000) but quite different than those of other young pulsars in SNRs for which typically $P < 0.2$ s, $\dot{E} > 10^{36}$ ergs s$^{-1}$, and $B \approx 10^{12}$ G.

Whether RX J0822−4300 indeed has a long initial period and high magnetic field or whether it has some other properties such that it does not produce a detectable radio nebula or radio pulsations, the lack of a PWN around this source (and around other RQNSs such as 1E 1207.4−5209 in the SNR G296.5+10.0; Mereghetti, Bignami, & Caraveo 1996; Giacani et al. 2000) argues that at least some RQNSs have drastically different properties from young radio pulsars.

Brazier & Johnston (1999) list six RQNSs that are younger than 20 kyr and nearer than 3.5 kpc. Excluding two RQNSs from their list that do power PWNs and thus may well be radio pulsars beaming away from us but including the recently dis-

[6] Furthermore, PSR B1509−58 powers a bright X-ray PWN (e.g., Seward et al. 1984; Brazier & Becker 1997), while no X-ray nebula is seen around RX J0822−4300 (G. G. Pavlov, D. Sanwal, & V. E. Zavlin 2000, in preparation).

covered RQNS in the young and nearby SNR Cassiopeia A (Tananbaum 1999; Pavlov et al. 2000; Chakrabarty et al. 2000), this implies a Galactic birthrate for such sources of at least once every ∼200 yr, comparable to or even in excess of the birthrate for radio pulsars (e.g., Lyne et al. 1998). Radio-quiet neutron stars thus point to the possibility that pulsars like the Crab are not the most common manifestation of a neutron star.

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