

UPPER LIMITS ON PERIODIC, PULSED RADIO EMISSION FROM THE X-RAY POINT SOURCE IN CASSIOPEIA A

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ABSTRACT

The *Chandra X-Ray Observatory* recently discovered an X-ray point source near the center of Cassiopeia A, the youngest known Galactic supernova remnant. We have conducted a sensitive search for radio pulsations from this source with the Very Large Array, taking advantage of the high angular resolution of the array to resolve out the emission from the remnant itself. No convincing signatures of a dispersed, periodic source or of isolated dispersed pulses were found, whether for an isolated or a binary source. We derive upper limits of 30 and 1.3 mJy at 327 and 1435 MHz for its phase-averaged pulsed flux density. The corresponding luminosity limits are lower than those for any known radio pulsar with an age less than 10^4 yr. Our search sensitivities to single pulses were 25 and 1.0 Jy at 327 and 1435 MHz. For comparison, the Crab pulsar emits roughly 80 pulses per minute with flux densities greater than 100 Jy at 327 MHz and eight pulses per minute with flux densities greater than 50 Jy at 1435 MHz. These limits suggest that Cas A belongs to the growing population of young neutron stars that are radio-quiet.

Subject headings: pulsars: individual (Cassiopeia A) — supernova remnants

1. INTRODUCTION

Cassiopeia A, with an age of only 320 yr, is the youngest known Galactic supernova remnant (SNR). The supernova that gave rise to this remnant was probably discovered in 1680, when Flamsteed (1725) observed a sixth magnitude star within 13' of Cas A's location (Ashworth 1980). Because its abundances of heavy elements are consistent with those expected from the explosion of a massive star (Hughes et al. 2000), Cas A is thought to be the remnant of a Type II supernova. Given the stellar initial mass function, a large fraction of Type II supernovae are expected to leave behind neutron stars. While many searches at various wavelengths for the compact remnant in Cas A have been undertaken, only upper limits had been established until the recent *Chandra* discovery of an X-ray point source (XPS) near the center of the remnant (Tananbaum 1999). This XPS was later confirmed in archival *ROSAT* (Aschenbach 1999) and *Einstein* (Pavlov & Zavlin 1999) images. The XPS is within 5" of the expansion center of the remnant (van den Bergh & Kamper 1983). For a remnant distance of $3.4^{+0.3}_{-0.1}$ kpc, calculated through radial velocity, proper motion, and age data (Reed et al. 1995), this offset corresponds to a maximum transverse velocity of roughly 200 km s^{-1} , a typical velocity for young pulsars (Cordes & Chernoff 1998).

Pavlov et al. (2000) find that the X-ray spectrum of the XPS is fit well by a power law with index 2.6–4.1, with luminosity $(2\text{--}60) \times 10^{34} \text{ ergs s}^{-1}$. Similarly, Chakrabarty et al. (2001) estimate a power-law index of 2.8–3.6 and luminosity of $(2\text{--}16) \times 10^{34} \text{ ergs s}^{-1}$. These indices are much steeper than the X-ray spectra of active galactic nuclei (AGNs). Further-

more, given the measured surface density of AGNs, the probability of finding an AGN that close to the center of the SNR is negligible. For these reasons, Pavlov et al. (2000) conclude that the XPS is almost certainly associated with the Cas A remnant. The fitted power-law indices for the XPS are also much steeper than those measured for the six young X-ray pulsars having ages less than 10^4 yr, whose spectral indices range from 1.1 to 1.7 (Chakrabarty et al. 2001). In addition, the estimated XPS luminosities are only marginally consistent with measured young pulsar X-ray luminosities, which range from 3×10^{35} to $4 \times 10^{36} \text{ ergs s}^{-1}$. It is also significant that, unlike five of the six young pulsars with ages less than 10^4 yr, Cas A shows no evidence for a synchrotron nebula surrounding the point source.

While there is much evidence for and against the neutron star nature of the XPS, the definitive proof would be the detection of pulsations. No X-ray pulsations have been found in data taken with the *Chandra* high-resolution camera. However, a time-tagging problem caused the timing accuracy to be degraded from $16 \mu\text{s}$ to $\approx 4 \text{ ms}$, allowing searches for only broad pulses with periods greater than 20 ms (Chakrabarty et al. 2001). The detection of radio pulsations, however, would be just as conclusive. For this reason, we have conducted a search for radio pulsations from the XPS using the Very Large Array (VLA) at frequencies of 327 and 1435 MHz. There have been several previous searches for a radio pulsar in Cas A (Davies & Large 1970; Seiradakis & Graham 1980; Woan & Duffett-Smith 1993; Lorimer, Lyne, & Camilo 1998). Our VLA search is many times more sensitive, as having an accurate position for the XPS allows us to resolve out the strong emission from the remnant, which with 327 and 1435 MHz flux densities of 6400 and 2000 Jy is one of the strongest radio sources known.

2. DATA

We observed the XPS on 3 days (1999 October 23, October 31, and November 28) with the phased-array VLA in the B configuration, where the maximum baseline is 11.4 km. The J2000 coordinates of the XPS are R.A. = $23^{\text{h}}23^{\text{m}}27^{\text{s}}.94$, decl. = $+58^{\circ}48'42''$, with positional uncertainty of 1" (Tananbaum 1999). As the 327 and 1435 MHz synthesized beam-

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widths are approximately 20" and 4", respectively, one beam at each frequency was sufficient for this search. During each session, the XPS was observed at center frequencies of 327 and 1435 MHz, resulting in three pointings of length 20, 40, and 50 minutes at 327 MHz and four pointings of length 40, 40, 45, and 50 minutes at 1435 MHz. During each observing session, we observed the known pulsar PSR B0355+54, which has a period of 154 ms and a dispersion measure (DM) of 57 pc cm^{-3} . A blank-sky pointing and the flux and phase calibrator J2350+646 (with flux densities of 27 and 5 Jy at 327 and 1435 MHz) were also observed.

We used the VLA's High Time Resolution Processor (Moffett 1997) to record dual circular polarization data at a sampling frequency of 9.22 kHz. Each scan was started on a 10 s tick, tied to the VLA's hydrogen maser, compared to Universal Time through the Global Positioning System. At 327 MHz, 14×0.125 MHz frequency channels covered a total bandwidth of 1.75 MHz. These channels were spaced noncontiguously to avoid known interference frequencies and covered a total bandwidth range of 3 MHz. At 1435 MHz, 14×4 MHz channels covered a total contiguous bandwidth of 48 MHz. (As only 50 MHz of bandwidth is available, some channels were duplicated.) The gain in each of the 28 channels (two polarizations and 14 frequencies) was calculated from observations of the calibrator source.

3. ANALYSIS

For each of the seven XPS data sets, we first summed right- and left-circular polarizations and then dedispersed the data over a range of trial DMs. The Taylor & Cordes (1993) model predicts a maximum DM of approximately 75 pc cm^{-3} in the direction of the XPS. We dedispersed the data with 60 trial DMs from 0 to 300 pc cm^{-3} to allow for an underestimate or a contribution from Cas A. These 60 DMs were spaced non-uniformly, with greater spacing at higher DMs, where the temporal smearing due to dispersion across an individual frequency channel is larger. Each dedispersed time series was Fourier transformed with 32 Mpoint and/or 16 Mpoint fast Fourier transforms (FFTs), depending on the length of the data set. Shorter FFTs of 8 and 4 Mpoints were done to increase our sensitivity to some binary pulsars. The resulting power spectra were harmonically summed (up to a maximum of 16 harmonics) to increase our sensitivity to narrow pulses (Lyne & Smith 1998). All features in the resulting power spectra with signal-to-noise ratio above a threshold of 7 were saved as pulsar candidates. For each candidate, the corresponding dedispersed time series was folded at the period corresponding to the fundamental harmonic. These profiles were inspected, and candidate lists from different days and at different frequencies were compared. While many periodic signals were detected, they were predominantly at low DM, had noiselike pulse profiles, and did not appear on multiple epochs or at multiple frequencies, and were therefore attributed to radio frequency interference (RFI). Figure 1 shows the folded pulse profiles resulting from applying the search algorithm to PSR B0355+54.

An independent Fourier analysis of the same data, carried out at the New Mexico Institute of Mining and Technology, was also unsuccessful. This analysis was sensitive to periods ≥ 10 ms and covered a smaller DM range but with a finer DM spacing. Three filter-bank channels with high levels of RFI were rejected, decreasing the number of spurious candidates significantly with only a 12% sensitivity loss. Power spectra were

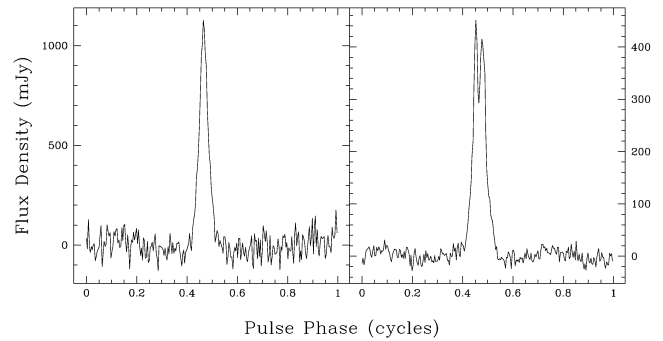


FIG. 1.—Folded pulse profiles for PSR B0355+54, which has a period of 156 ms and DM of 57 pc cm^{-3} at 327 MHz (left) and 1435 MHz (right). Note that these profiles are for 5 and 2 minutes of data at 327 and 1435 MHz, whereas our longest XPS search scans were 50 minutes at these same frequencies.

harmonically summed up to a maximum of 32 harmonics. Final pulsar candidates were evaluated by comparing average profiles from two halves of the bandpass and two halves of profiles folded over a two-period span. These were compared with the corresponding profiles for nondispersed data.

The Crab pulsar, currently the youngest known radio pulsar, was initially detected through its “giant” pulses, not through its time-averaged pulsed emission (Staelin & Reifenstein 1968). Giant pulses are individual pulses with amplitudes much greater than the mean pulse amplitude (Lundgren et al. 1995). As we might expect other young pulsars to behave similarly to the Crab, we also searched for aperiodic, dispersed pulses from the XPS. We recorded all pulses with amplitudes above a signal-to-noise ratio threshold of 4 for each dedispersed time series, enhancing our sensitivity to broadened pulses by repeating this thresholding with different levels of time series smoothing. Given our 4σ threshold, we were sensitive to all single pulses with flux densities greater than $25/(w_{\text{ms}})^{1/2}$ Jy, where w_{ms} is the pulse width in milliseconds, at 327 MHz and $1.0/(w_{\text{ms}})^{1/2}$ Jy at 1435 MHz. Our smoothing algorithm optimized the search for pulse widths up to 15 ms. (For comparison, the widths of the Crab pulsar’s giant pulses range from roughly 0.2 to 0.4 ms.) We found no evidence for isolated pulses from the XPS. The result of this analysis, along with the result for PSR B0355+54, is shown in Figure 2. For comparison, the Crab pulsar emits roughly 80 pulses per minute with flux densities greater than 100 Jy at 327 MHz and eight pulses per minute with flux densities greater than 50 Jy at 1435 MHz.

4. RESULTS

To calculate an upper limit for pulsed radio emission from the XPS, we must account for the excess system temperature due to the emission from Cas A itself. The Cas A remnant is 5' in size (D. A. Green 2000⁸). Hence, the ratios of our beam area to the remnant area are 0.003 and 0.0002 at 327 and 1435 MHz. Given Cas A’s measured flux density and spectral index (see footnote 8), we calculate remnant flux densities of 6432 and 2060 Jy at 327 and 1435 MHz, contributing to an increase in system temperature of a modest 40 K at 327 MHz and a mere 1 K at 1435 MHz for the phased array. However, while the

⁸ A Catalogue of Galactic Supernova Remnants (2000 August version; Cambridge: Mullard Radio Astronomy Observatory, Cavendish Laboratory); available at <http://www.mrao.cam.ac.uk/surveys/snrs>.

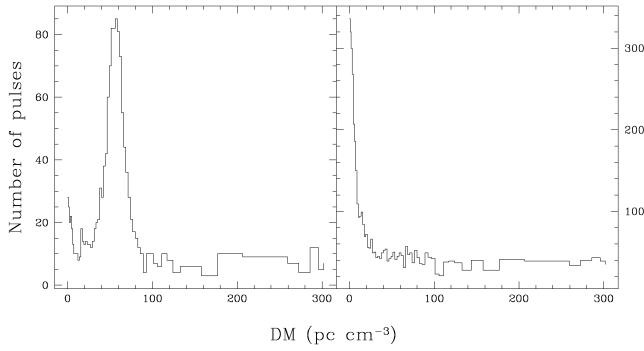


FIG. 2.—Number of isolated, dispersed pulses at 327 MHz above a 4σ threshold vs. DM for a 5 minute observation of PSR B0355+54 (*left*) and a 50 minute observation of the XPS (*right*). While a peak at the 57 pc cm^{-3} DM of PSR B0355+54 is obvious, there is no evidence for such an excess from the XPS. The peak at low DM in the right plot is consistent with interference and is similar to the number of counts observed in the consecutive blank-sky pointing. In the absence of RFI and/or a pulsar, we would expect a flat distribution.

phased array resolves out emission from the nebula, each single dish will see the whole remnant, leading to an increase in system temperature of 475 K at 327 MHz and 230 K at 1435 MHz. By comparison, a single dish with the same collecting area as the VLA would suffer increases of system temperature of 13,000 and 6200 K at 327 and 1435 MHz.

We calculate the minimum detectable flux density of our search using the expression (Cordes & Chernoff 1997)

$$S_{\min} = \frac{\eta T_{\text{sys}}}{G \sqrt{N_{\text{pol}}} \Delta\nu \Delta t N_{\text{FFT}}} \frac{\sqrt{N_h}}{\sum_{l=1}^{N_h} R_l}, \quad (1)$$

where η is the signal-to-noise ratio threshold used, T_{sys} is the system temperature, G is the telescope gain, N_{pol} is the number of polarization channels, $\Delta\nu$ is the total bandwidth, Δt is the sample interval, N_{FFT} is the number of points in the FFT, N_h is the optimal number of harmonics with which a pulsar can be detected, and $R_l \leq 1$ is the ratio of the l th harmonic to the fundamental. The value of N_h will depend on the pulsar's duty cycle, or ratio of pulse width to period, with narrower pulses producing more harmonics. For this calculation, we take the intrinsic duty cycle to be the minimum of 0.3 and $0.03(P_{\text{ms}}/1000.)^{-0.5}$, where P_{ms} is the pulse period in milliseconds (Biggs 1990). Pulses may then be additionally broadened by propagation effects, including scattering and dispersion. The Taylor & Cordes (1993) model predicts 1.7 ms and $3\ \mu\text{s}$ of pulse broadening due to scattering in the direction of the XPS and for a distance of 3.4 kpc at 327 and 1435 MHz, respectively.

Figure 3 shows the dependence of our search sensitivity on DM and period at the two observing frequencies, accounting for the effects of scattering and dispersion on the intrinsic duty cycle of the pulsar. Assuming values for period and DM of 30 ms and 75 pc cm^{-3} , we calculate 7σ upper limits of 30 and 1.3 mJy at 327 and 1435 MHz. As shown in Figure 3, these limits will decrease for longer period, smaller duty cycle, and lower DM. There are no hardware limitations to our maximum detectable period, determined solely by the length of the FFT.

While there is no infrared or optical evidence for a binary companion (van den Bergh & Pritchett 1986), acceleration ef-

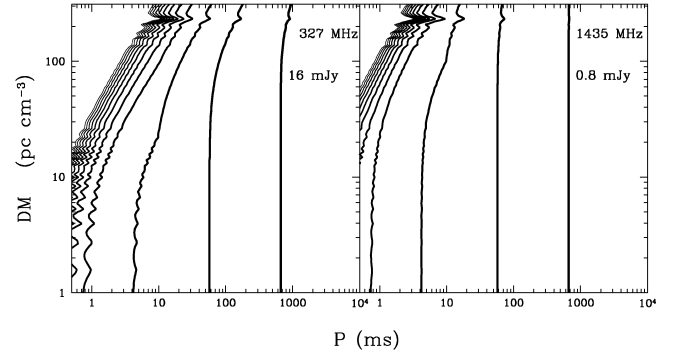


FIG. 3.—Contours of pulsed search 7σ sensitivity vs. period and DM for searches at both 327 and 1435 MHz. The thickest (rightmost) line corresponds to a sensitivity of 16 mJy at 327 MHz and of 0.8 mJy at 1435 MHz. Minimum detectable flux densities increase by a factor of 2 with each subsequently thinner line. The contours are not smooth because of the finite spacing of our trial DMs.

fects from such a companion would cause pulse smearing, decreasing our sensitivity. We estimate the signal-to-noise ratio degradation introduced for various orbital systems by taking a Gaussian pulse and applying orbital smearing by iteratively calculating emission times across the orbit. Smearing times due to time constant, DM, and scattering are calculated and applied to the orbital-smearred pulse. We calculate the best harmonic sum for the resultant waveform and compare this to the best harmonic sum for a waveform with no orbital smearing to calculate the loss in signal-to-noise ratio. For a 30 ms period and duty cycle of 0.2, a 1 solar mass companion in an 8 hr circular orbit with an inclination angle (i.e., angle between the orbital plane and our line of sight) of 30° , our sensitivity decreases by roughly a factor of 2, averaging over all orbital phases, for a 16 Mpoint FFT. In the case of our 8 and 4 Mpoint FFTs, these same binary parameters would decrease our search sensitivity by factors of 2.4 and 2.8 over the original 16 Mpoint sensitivity to an unaccelerated pulsar. Although the nominal sensitivities are less for these shorter FFT lengths, the shorter FFTs would allow us to detect pulsars in fast binaries where the binary smearing during a longer FFT is comparable to or greater than the pulse period. The sensitivity would be further decreased for smaller spin periods, faster orbits, and more massive companions. If the orbit was eccentric, the net smearing, averaged over all orbital phases, would be less, and the resultant sensitivity would be higher. Accretion from a binary companion could completely quench the radio emission.

Interstellar scintillation modulations of the flux of the XPS are mostly negligible during our observations. The predicted scintillation bandwidth and timescale (see Cordes & Rickett 1998), assuming a uniform medium and a velocity of 50 km s^{-1} , are approximately 0.1 kHz and 30 s at 327 MHz and 0.6 MHz and 150 s at 1435 MHz, in both cases too small to significantly affect our quoted upper limits. If this velocity is higher than 50 km s^{-1} , as a young pulsar's velocity is likely to be (Cordes & Chernoff 1998), the predicted scintillation timescale will be smaller and will therefore be even less of a factor in our analysis.

We have also used VLA images of Cas A to search for a radio continuum point source at the position of the XPS. At 1.3 and 4.4 GHz, we find 5σ upper limits on the flux density from the XPS of 40 and 6 mJy, respectively. While not as constraining as those derived from our VLA and Arecibo pulsed searches described above, these continuum upper limits are

completely independent of the period, dispersion, and scattering of any radio pulsations from this source.

5. CONCLUSIONS

We have calculated upper limits of 30 and 1.3 mJy at 327 and 1435 MHz for the phase-averaged pulsed flux density from the XPS in Cas A. We did not detect any single, dispersed pulses above our sensitivity of 25 and 1.0 Jy (assuming a pulse width of 1 ms) at 327 and 1435 MHz. We now compare our upper limit to those from previous Cas A searches. Davies & Large (1970) carried out an unsuccessful 408 MHz search for single pulses from Cas A. Seiradakis & Graham (1980) quoted a 1420 MHz upper limit of 1.6 mJy for pulsed emission from Cas A. However, their limit does not account for the additional system temperature contributed by the nebula, significant for their beamwidth of 9'. More recently, Woan & Duffett-Smith (1993) published an upper limit of 80 mJy at 408 MHz, and Lorimer et al. (1998) published an upper limit of 46 mJy at 606 MHz. For a typical pulsar spectrum, our 1435 MHz upper limit is an order of magnitude better than these previously published limits due to the known position of the XPS and the power of the VLA to resolve out the excess emission from the nebula.

Our upper limit of 1.3 mJy at 1435 MHz translates to a luminosity of 15 mJy kpc² for a neutron star at a distance of 3.4 kpc. This is lower than the mean 1400 MHz luminosity of 30 mJy kpc² estimated for young pulsars (Frail & Moffett 1993) and is lower than the luminosity of any known radio pulsar with characteristic age less than 10⁴ yr (see Figs. 1 and 2 of Brazier & Johnston 1999). This suggests that the XPS in Cas A is either not a pulsar, is a radio-quiet pulsar, or is a radio pulsar beamed away from us. While evidence suggests that pulsar beams are wider at short periods (see, e.g., Biggs 1990) and that they are therefore likely to intersect the Earth's line of sight, individual pulsars show mixed properties. For instance, the Crab pulsar shows narrow radio components that may be part of a large beam, but the profile of another young pulsar in the Large Magellanic Cloud, PSR B0540–69, is very broad (Manchester et al. 1993). Furthermore, it is difficult to disentangle true beam width from viewing angle for these pulsars. It is certainly possible that, like the Geminga pulsar, the XPS shows no radio pulses but is an X-ray, and perhaps gamma-

ray, pulsar. Although there is no EGRET point source near the position of the XPS, gamma-ray searches with future, more sensitive instruments, could be successful. Further measurements of the spectrum and time variability of the XPS will also help determine which of the above scenarios is the case.

This search adds to the growing body of evidence that there are manifestations of young neutron stars other than the standard Crab-like radio pulsar. Although it is widely accepted that radio pulsars are born in supernovae, fewer than 10% of searches targeted at SNRs have found young (age < 25 kyr) pulsars (Kaspi et al. 1996; Gorham et al. 1996; Lorimer et al. 1998). Some of this may be due to scattering at low frequencies in the Galactic plane and the decreased sensitivity due to the bright remnants, but it also hints at the unrecognized diversity of the neutron star population. While some neutron stars are detected as radio pulsars, others may be born as anomalous X-ray pulsars, soft gamma-ray repeaters, quiescent neutron stars, or other classes of objects not yet discovered (Kaspi 2000; Gotthelf & Vasisht 2000). The pathways to and percentages of these different classes of objects are not yet clear. However, future *Chandra* detections of compact X-ray sources and large-scale radio pulsar surveys, like the Parkes Multibeam Survey (Lyne et al. 2000), will help to answer these questions.

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