

PSR J2021+3651: A YOUNG RADIO PULSAR COINCIDENT WITH AN UNIDENTIFIED EGRET γ -RAY SOURCE

MALLORY S. E. ROBERTS,¹ JASON W. T. HESSELS, SCOTT M. RANSOM,¹ AND VICTORIA M. KASPI¹

Department of Physics, McGill University, Rutherford Physics Building, 3600 University Street, Montreal, QC H3A 2T8, Canada; roberts@physics.mcgill.ca

PAULO C. C. FREIRE

National Astronomy and Ionosphere Center, Arecibo Observatory, HC-03, Box 53995, Arecibo, PR 00612

FRONEFIELD CRAWFORD

Department of Physics and Astronomy, Haverford College, Haverford, PA 19041

AND

DUNCAN R. LORIMER

University of Manchester, Jodrell Bank Observatory, Lower Withington,
Macclesfield, Cheshire SK11 9DL, UK

Received 2002 June 10; accepted 2002 August 8; published 2002 August 19

ABSTRACT

We report on a deep search for radio pulsations toward five unidentified *ASCA* X-ray sources coincident with EGRET γ -ray sources. This search has led to the discovery of a young and energetic pulsar using data obtained with the new Wideband Arecibo Pulsar Processor. PSR J2021+3651 is likely associated with the X-ray source AX J2021.1+3651, which in turn is likely associated with the *COS B* high-energy γ -ray source 2CG 075+00, also known as GeV J2020+3658 or 3EG J2021+3716. PSR J2021+3651 has a rotation period of $P \sim 104$ ms and $\dot{P} \sim 9.6 \times 10^{-14}$, implying a characteristic age of $\tau_c \sim 17$ kyr and a spin-down luminosity of $\dot{E} \sim 3.4 \times 10^{36}$ ergs s⁻¹. The dispersion measure $DM \sim 371$ pc cm⁻³ is by far the highest of any observed pulsar in the Galactic longitude range $55^\circ < l < 80^\circ$. This DM suggests a distance $d \gtrsim 10$ kpc and a high γ -ray efficiency of $\sim 15\%$, but the true distance may be closer if there is a significant contribution to the DM from excess gas in the Cygnus region. The implied luminosity of the associated X-ray source suggests the X-ray emission is dominated by a pulsar wind nebula unresolved by *ASCA*.

Subject headings: gamma rays: observations — pulsars: general — pulsars: individual (PSR J2021+3651) — stars: neutron — X-rays: individual (AX J2021.1+3651)

1. INTRODUCTION

The majority of high-energy γ -ray sources observed by EGRET and other telescopes have long escaped identification with lower energy counterparts (Hartman et al. 1999). Young pulsars remain the only Galactic source class (other than the Sun) unambiguously shown to emit radiation in the 100 MeV–10 GeV range (Thompson 2001). It is likely that many of the unidentified γ -ray sources at low Galactic latitudes are young pulsars as well. Many of these sources have characteristics similar to those of the known γ -ray pulsars but have no known pulsars within their error boxes. This fact, along with modeling of the multiwavelength pulse profiles and the still singular example of Geminga (Halpern & Holt 1992; Helfand 1994), has led to the suggestion that a large fraction of the radio beams from γ -ray sources will miss the Earth and appear radio quiet (Romani 1996).

Recently, a number of young pulsars coincident with known γ -ray sources have been discovered (D’Amico et al. 2001; Camilo et al. 2001). These new discoveries are largely a result of greater sensitivity to pulsars with high dispersion measures (DMs) obtainable with newer pulsar back ends, such as the Parkes multibeam system (Manchester et al. 2001). The recent detection of a young radio pulsar in the supernova remnant 3C 58 with a 1400 MHz flux density of only ~ 50 μ Jy (Camilo et al. 2002) suggests that many more faint radio pulsars await discovery in deep, targeted, searches.

A major stumbling block in the identification of the EGRET sources is their large positional uncertainty, which can be greater

than 1° across. We approach this problem by targeting potential hard X-ray counterparts, whose size and positional uncertainty are much smaller than the typical single-dish radio beam. Using as our guide the *ASCA* catalog of potential X-ray counterparts of GeV sources (based on the Lamb & Macomb 1997 catalog of sources with significant flux above 1 GeV) by Roberts, Romani, & Kawai (2001, hereafter RRR), we have searched five X-ray sources for radio pulsations using the 305 m Arecibo Telescope and the 64 m Parkes Telescope (see Table 1). Previous searches of these targets were limited. In particular, two of the three sources observed at Parkes (AX J1418.7–6058 and AX J1809.8–2332) were not previously the subject of any directed search and were observed only as a matter of course during the Parkes multibeam Galactic plane survey (Manchester et al. 2001). A survey of EGRET sources by Nice & Sayer (1997) looked at two of the sources searched here (AX J1826.1–1300 and AX J2021.1+3651) with a limiting flux density for slow pulsars of 0.5–1.0 mJy at frequencies of 370 and 1390 MHz but found no new pulsars. Our search has led to the discovery of one young and energetic pulsar, PSR J2021+3651. We argue that it is a likely counterpart to AX J2021.1+3651 and GeV J2020+3658/2CG 075+00.

2. OBSERVATIONS AND ANALYSIS

On 2002 January 30 and 31, we observed the only two unidentified sources in the RRR catalog visible from the Arecibo radio telescope, AX J1907.4+0549 and AX J2021.1+3651, using the Wideband Arecibo Pulsar Processor (WAPP). The WAPP is a fast-dump digital correlator with adjustable bandwidth (50 or 100 MHz) and variable numbers of lags and sample times (for details see Dowd, Sisk, & Hagen 2000). Our

¹ Center for Space Research, Massachusetts Institute of Technology, 70 Vassar Street, Building 37, Cambridge, MA 02139.

TABLE 1
OBSERVATIONAL PARAMETERS

Source Name	Right Ascension (J2000.0)	Declination (J2000.0)	Epoch (MJD)	Telescope	ν_c^a (MHz)	$\Delta\nu^b$ (MHz)	N_{ch}^c	t_{sam}^d (μs)	T_{int}^e (s)	S_{min}^f (mJy)
AX J1418.7–6058/GeV J1417–6100	14 18 41.5	–60 58 11	51,951.63	Parkes	1390	256	512	250	16900	0.08
			51,953.67	Parkes	1373	288	96	250	16900	0.08
AX J1809.8–2332/GeV J1809–2327	18 09 50.2	–23 32 23	51,951.83	Parkes	1390	256	512	250	16900	0.08
			51,954.77	Parkes	1373	288	96	250	16900	0.08
AX J1826.1–1300/GeV J1825–1310	18 26 04.9	–12 59 48	51,952.83	Parkes	1390	256	512	250	13234	0.09
			51,955.83	Parkes	1373	288	96	250	14832	0.09
AX J1907.4+0549/GeV J1907+0557	19 07 21.3	+05 49 14	52,305.58	Arecibo	1425	100	512	200	6480	0.02
AX J2021.1+3651/GeV J2020+3658	20 21 07.8	+36 51 19	52,304.67	Arecibo	1425	100	512	200	1627	0.04
			52,305.66	Arecibo	1425	100	256	200	3000	0.03

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Central observing frequency.

^b Total bandwidth of the observation.

^c Number of frequency channels.

^d Sampling time.

^e Length of the observation.

^f Flux density sensitivity limit.

observations were made at 1.4 GHz with 100 MHz of bandwidth and summed polarizations. The observational parameters are summarized in Table 1. The 16 bit samples were written to a disk array and then transferred to magnetic tape for later analysis.

On 2001 February 11–15, the three extended hard X-ray sources listed by RRK as potential pulsar wind nebulae, AX J1418.7–6058 (the Rabbit), AX J1809.8–2333, and AX J1826.1–1300, were searched for radio pulsations with the Multibeam receiver on the Parkes radio telescope. Each source was observed once at a central observing frequency of 1390 MHz with a 512 channel filter-bank spectrometer covering 256 MHz of bandwidth and once at a central observing frequency of 1373 MHz with 96 channels and 288 MHz of bandwidth (see Table 1). During each observation, signals from each channel were square-law detected and added in polarization pairs before

undergoing high-pass filtering. The signals were one-bit digitized every 0.25 ms and recorded onto magnetic tape for later analysis.

Analysis of Arecibo observations was done using the PRESTO software suite (Ransom 2001)² by first removing obvious narrowband and/or short-duration interference in both the time and frequency domains. We then dedispersed the data at 500 trial DMs between 10 and 510 pc cm^{−3} for AX J2021.1+3651 and 540 trial DMs between 0 and 2695 pc cm^{−3} for AX J1907.4+0549. Employing harmonic summing, the fast-Fourier transforms of each time series were searched, and interesting candidates were folded over a fine grid in DM, period, and period derivative space to optimize the signal-to-noise ratio.

The Parkes observations were analyzed using FVLSA/I (available from the Australia Telescope National Facility) and a similar procedure by searching the 96 channel data at 279 trial DMs ranging from 0 to 1477 pc cm^{−3} and the 512 channel data at 501 trial DMs ranging from 0 to 670 pc cm^{−3}. We tested the system by observing a known bright pulsar (PSR B1124–60) for 300 s, which was clearly detected in the processing. Re-analysis of the data using PRESTO has not revealed any new candidates.

3. RESULTS

A new highly dispersed 104 ms pulsar was detected in the Arecibo observations made of AX J2021.1+3651; it is clearly visible in both of the original search observations and represents an $\sim 40\sigma$ detection in the longest observation. The pulse profile is shown in Figure 1.

A subsequent series of seven observations performed between MJD 52,405 and 52,416 allowed us to determine a phase-connected solution for some of the pulsar parameters. Integrated pulse profiles from these observations were convolved with a template profile to extract 12 topocentric times of arrival (TOAs). Using TEMPO³ and adopting the ROSAT position for the pulsar (§ 4.1), the topocentric TOAs were converted to TOAs at the solar system barycenter at infinite frequency and fitted simultaneously for pulsar period, period derivative, and DM, with a residual rms of 91 μs . The measured and derived parameters for this pulsar are listed in Table 2. If the X-ray

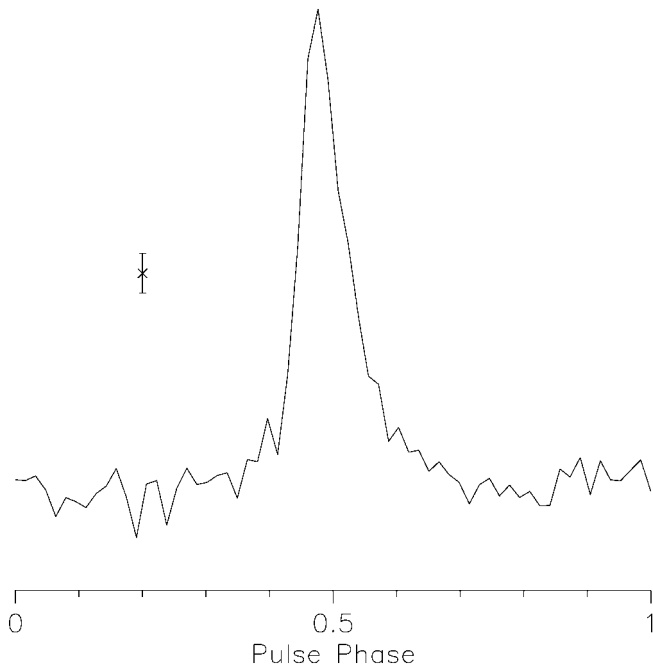


FIG. 1.—The 1.4 GHz pulse profile for PSR J2021+3651 from the MJD 52,305 observation. Error bar represents 1 σ uncertainty.

² See http://www.physics.mcgill.ca/~ransom_thesis_2001.pdf.

³ See <http://pulsar.princeton.edu/tempo>.

TABLE 2
MEASURED AND DERIVED PARAMETERS FOR PSR J2021+3651

Parameter	Value
Right ascension (J2000.0) ^a	20 21 04.5
Declination (J2000.0) ^a	+36 51 27.0
Galactic longitude l (deg)	75.23
Galactic latitude b (deg)	+0.11
Pulse period P (s)	0.10372222480(17)
Period derivative \dot{P}	$9.563(48) \times 10^{-14}$
Pulse frequency ν (s ⁻¹)	9.641135271(16)
Frequency derivative $\dot{\nu}$ (s ⁻²)	$-8.889(45) \times 10^{-12}$
Epoch (MJD)	52,407.389
DM (pc cm ⁻³)	371.2(3.2)
Pulse width at 50% of peak w_{50} (ms)	9.9
Pulse width at 10% of peak w_{10} (ms)	18
Flux density at 1425 MHz (mJy)	~0.1
Spin-down luminosity \dot{E}^b (ergs s ⁻¹)	3.4×10^{36}
Surface dipole magnetic field B^c (G)	3.2×10^{12}
Characteristic age $\tau_c \equiv (1/2) P/\dot{P}$ (kyr)	17

^a Coordinates of the *ROSAT* X-ray source 1RXS J202104.5+365127 with estimated positional error of 24". Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^b $\dot{E} = 4\pi^2 I \dot{P} / P^3$, with $I = 10^{45}$ g cm²

^c Assuming standard magnetic dipole spin-down $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G (Manchester & Taylor 1977)

source is not related to the pulsar, an error in position of up to half the Arecibo beam width of 3' will cause an inaccurate \dot{P} with an error of approximately the same magnitude as the TEMPO errors reported in Table 2. If the positional error is much smaller (i.e., the error of the *ROSAT* position, assuming it is the X-ray counterpart), the \dot{P} error is dominated by statistical effects and the quoted TEMPO errors should apply.

No convincing pulsar candidates were detected in any of the search observations conducted at Parkes. We estimate upper limits of $S \cong 0.08$ mJy at 1.4 GHz for pulse periods $P \geq 10$ ms for most of the 512 channel observations. A comparable sensitivity was obtained for long periods in the 96 channel observations. For DMs larger than about 100 pc cm⁻³, the sensitivity to fast pulsars ($P \leq 50$ ms) is significantly degraded in the 96 channel system. These sensitivity limits were estimated using a sensitivity modeling technique described in detail elsewhere (e.g., Manchester et al. 2001). Likewise, extensive searching of AX J1907.4+0549 yielded no convincing pulsar candidates. We estimate an upper limit of $S \cong 0.02$ mJy at 1.4 GHz for a long-period pulsar assuming a 10% duty cycle.

4. DISCUSSION

4.1. PSR J2021+3651

Our search targeted AX J2021.1+3651, which was identified as a potential high-energy counterpart to GeV J2020+3658 by RRK. The X-ray source is near the *ASCA* field edge, and so the positional uncertainty from *ASCA* is $\geq 1'$ (Gotthelf et al. 2000). A subsequent search of the *ROSAT* All Sky Survey Faint Source Catalog (Voges et al. 2000) revealed the source 1RXS J202104.5+365127 with a smaller positional error of 24". Given the rarity of such young, energetic pulsars and the small size of the Arecibo beam (3' at FWHM), an association with the X-ray source is highly probable.

The DM of PSR J2021+3651 is by far the highest known in the Galactic longitude range $55^\circ < l < 80^\circ$, which is mainly an interspiral arm direction. Using the recent Cordes & Lazio (2002) update to the Taylor & Cordes (1993) DM model gives a distance of ~ 12.4 kpc, at the outer edge of the last spiral arm

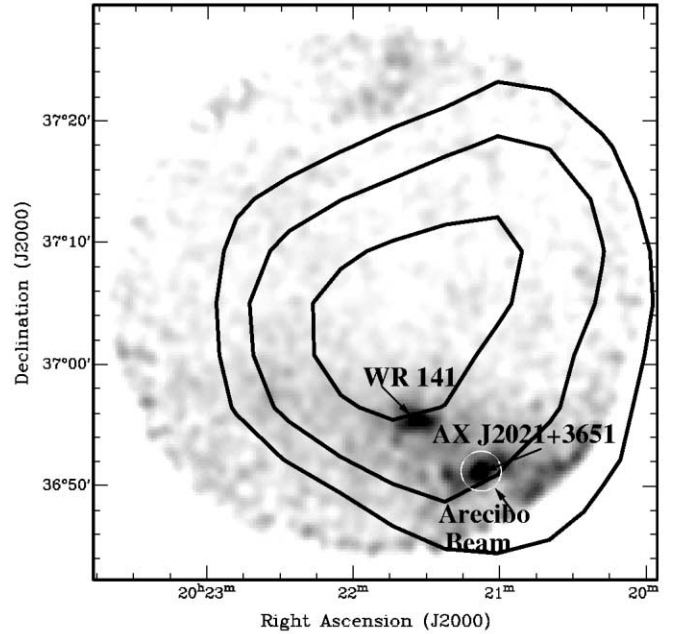


Fig. 2.—*ASCA* Gas Imaging Spectrometer 2–10 keV image of the γ -ray source region. Contours are the 68%, 95%, and 99% confidence regions of the γ -ray source position, derived from the greater than 1 GeV photons (RRK). WR 141 is a Wolf-Rayet star also in the field of view. Circle centered on AX J2021.1+3651 indicates the size of the 3' Arecibo beam.

used in the model. It is possible that there are further contributions from clouds in the Cygnus region not included in the model, where there is known to be excess gas at $d \sim 1.5$ kpc (J. Cordes 2002, private communication); however, there are no obvious H II regions within the Arecibo beam seen in either Very Large Array 20 cm radio images or Midcourse Space Experiment 8.3 μ m images (available from the NASA/IPAC Infrared Science Archive).

The high DM is somewhat surprising given the X-ray absorption quoted by RRK, $n_{\text{H}} = (5.0 \pm 2.5) \times 10^{21}$ cm⁻², where the errors represent the 90% confidence region. The total Galactic H I column density in this direction as estimated from the FTOOL nh (which uses the H I map of Dickey & Lockman 1990) is 1.2×10^{22} cm⁻². This should be a good approximation if the source is truly at the far edge of the outer spiral arm. Noting that the *ASCA* image shows faint, softer emission in the region (Fig. 2) and given the likely possibility of either associated thermal X-ray flux from a supernova remnant or a nearby massive star, we fitted the *ASCA* spectrum of RRK adding a thermal component to the absorbed power-law model. Accounting for $\sim 4\%$ of the photon flux with a MEKAL thermal plasma model (see Liedahl, Osterheld, & Goldstein 1995 and references therein) of temperature $kT \sim 0.1$ keV in XSPEC (Arnaud 1996) statistically improves the fit (F -test chance probability of 2.5%). The best-fit absorption for this three-component model is $n_{\text{H}} = 7.6 \times 10^{21}$ cm⁻² with a 90% confidence region of $(4.1\text{--}12.3) \times 10^{21}$ cm⁻², consistent with the total Galactic column density. The best-fit photon index is $\Gamma = 1.86$, still consistent with the 1.47–2.01 range in RRK derived from the simple absorbed power-law model. Hence, the X-ray absorption does not force us to adopt a smaller distance than is suggested by the DM.

For a distance $d_{10} = d/(10 \text{ kpc})$, the inferred isotropic X-ray luminosity is $L_{\text{X}} = 4.8 \times 10^{34} d_{10}^2$ (2–10 keV). The X-ray ef-

efficiency ($\eta_x = L_x/\dot{E}$) is $0.01d_{10}^2$. Compared to the total pulsar-plus-nebula X-ray luminosity of other spin-powered pulsars, this is somewhat high but is within the observed scatter (Posenti et al. 2002; Chevalier 2000).

The pulsar's positional coincidence with the error box of the hard-spectrum, low-variability EGRET γ -ray source GeV J2020+3658 coupled with the high inferred spin-down luminosity strongly suggests this pulsar emits pulsed γ -rays. Unfortunately, confirming this by folding archival EGRET data is problematic owing to the likelihood of significant past timing noise and glitches, which make the back-extrapolation of the rotational ephemeris uncertain. RRK noted that the chance probability of an X-ray source as bright as AX J2021.1+3651 in the EGRET error box was $\sim 10\%$, but the nearby Wolf-Rayet star WR141 was equally bright in X-rays and was also a potential γ -ray emitter. However, young pulsars remain the only firmly established class of Galactic EGRET sources. The known γ -ray pulsars cluster at the top of pulsar lists rank ordered by spin-down flux \dot{E}/d^2 , with γ -ray efficiencies $\eta_\gamma = L_\gamma/\dot{E}$ mostly between 0.001 and 0.03 (assuming 1 sr beaming) with a tendency to increase with pulsar age (Thompson et al. 1999). The exception is PSR B1055–52, with an apparent γ -ray efficiency $\eta_\gamma \sim 0.2$ given its nominal DM distance of 1.5 kpc. The inferred γ -ray efficiency for PSR J2021+3651 is $\eta_\gamma = 0.15d_{10}^2$ in the 100 MeV–10 GeV range. If the pulsar is located within the Perseus arm at a distance of 5 kpc, then the inferred X-ray and γ -ray luminosities would be fairly typical of the other pulsars with Vela-like spin-down luminosities. While there is currently no observational evidence for a distance this close, increased DM from an intervening source in this relatively crowded direction would not be surprising. We note that the DM-derived distance for another young pulsar recently discovered within an EGRET error box, PSR J2229+6114, also leads to an anomalously high inferred γ -ray efficiency (Halpern et al. 2001).

4.2. Upper Limits toward the Other Sources

Determining the fraction of radio-quiet versus radio-loud pulsars is important for our understanding of γ -ray pulsar emis-

sion mechanisms. The two leading classes of emission models, the outer gap (Romani 1996) and polar cap (Daugherty & Harding 1996) models, make very different estimates of the fraction of γ -ray pulsars that should be seen at radio energies. Out of the 25 brightest sources above 1 GeV not associated with blazars, ~ 10 are now known to either be energetic radio pulsars or contain such pulsars within their error boxes. Searching the brightest unidentified X-ray sources in five GeV error boxes, we detected radio pulsations at the ~ 0.1 mJy level from one of these with Arecibo; this flux density is similar to the limiting sensitivity of the Parkes observations. This is well below the average flux level expected for typical radio luminosities of young pulsars (Brazier & Johnston 1999) and distances to star-forming regions statistically associated with γ -ray sources (Yadigaroglu & Romani 1997). Two of the sources observed with Parkes, AX J1418.7–6058 (the Rabbit) and AX J1809.8–2333, have radio and X-ray properties that clearly identify them as pulsar wind nebulae (Roberts et al. 1999; Braje et al. 2002), and the third, AX J1826.1–1300, is an extended hard X-ray source that has few other source class options. Therefore, all three remain viable candidates for γ -ray loud, radio-quiet pulsars. Out of this same sample of 25 bright GeV sources, the total number of reasonable candidate neutron stars within the γ -ray error boxes that have now been searched deeply for radio pulsations without success is ~ 7 . A current “best guess” fraction of radio-loud γ -ray pulsars of $\sim \frac{1}{2}$ falls in between the predictions of the two main competing models.

We thank Jim Cordes for useful discussions. We acknowledge support from NSERC, CFI, an NSF CAREER Award, and a Sloan Fellowship. M. S. E. R. is a Quebec Merit fellow. S. M. R. is a Tomlinson fellow. J. W. T. H. is an NSERC PGS A fellow. V. M. K. is a Canada Research Chair. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation. The Parkes radio telescope is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

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