

## PSR J2021+3651: a new $\gamma$ -ray pulsar candidate

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### Abstract

The *COS B* high energy  $\gamma$ -ray source 2CG 075+00, also known as GeV J2020+3658 or 3EG J2021+3716, has avoided identification with a low energy counterpart for over 20 years. We present a likely identification with the discovery and subsequent timing of a young and energetic pulsar, PSR J2021+3651, with the Wideband Arecibo Pulsar Processor at the Arecibo Observatory. PSR J2021+3651 has a rotation period  $P \sim 104$  ms and  $\dot{P} \sim 9.6 \times 10^{-14}$ , implying a characteristic age  $\tau_c \sim 17$  kyr and a spin-down luminosity  $\dot{E} \sim 3.4 \times 10^{36}$  erg s<sup>-1</sup>. The pulsar is also coincident with the *ASCA* source AX J2021.1+3651. The implied luminosity of the associated X-ray source suggests the X-ray emission is dominated by a pulsar wind nebula unresolved by *ASCA*. The pulsar's unexpectedly high dispersion measure ( $DM \sim 371$  pc cm<sup>-3</sup>) and the  $d \geq 10$  kpc DM distance pose a new question: is PSR J2021+3651 an extremely efficient  $\gamma$ -ray pulsar at the edge of the Galaxy? This is a question for *AGILE* and *GLAST* to answer. © 2004 COSPAR. Published by Elsevier Ltd. All rights reserved.

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### 1. Introduction

Finding low energy counterparts to  $\gamma$ -ray sources is difficult because they have large positional uncertainties, typically  $\sim 1^\circ$  across. Consequently, the majority of the high energy  $\gamma$ -ray sources observed by *COS B* and *EGRET* remain unidentified (Hartman et al., 1999). Young pulsars are viable candidates for many of these sources and they remain the only discrete Galactic source class (other than the Sun) unambiguously shown to emit radiation in the 100 MeV–10 GeV range. The increased sensitivity to pulsars with high dispersion measure (DM), provided by new pulsar backends such as the Parkes multibeam system (Manchester et al.,

2001), has led to a number of discoveries recently of young pulsars coincident with known  $\gamma$ -ray sources (D'Amico et al., 2001; Camilo et al., 2001; Halpern et al., 2001). The recent detection of a young, low luminosity, radio pulsar in the supernova remnant 3C58 (Camilo et al., 2002) suggests many more faint radio pulsars await discovery in deep, targeted, searches.

The *COS B* source 2CG 075+00 has long been considered a pulsar candidate due to its hard spectrum. *EGRET* resolved it into two sources. The fainter one, 3EG J2016+3657, was identified as a probable blazar by Mukherjee et al. (2000). A *ROSAT* image and an *ASCA* GIS image based on the second *EGRET* catalog position of the brighter source, 3EG J2021+3716, failed to yield any obvious candidates. These sources are in the crowded Cygnus region and the likelihood analysis used to find  $\gamma$ -ray source positions is sensitive to the assumed number of surrounding sources. Roberts et al. (2001) (hereafter, RRK) noted that the catalog of sources

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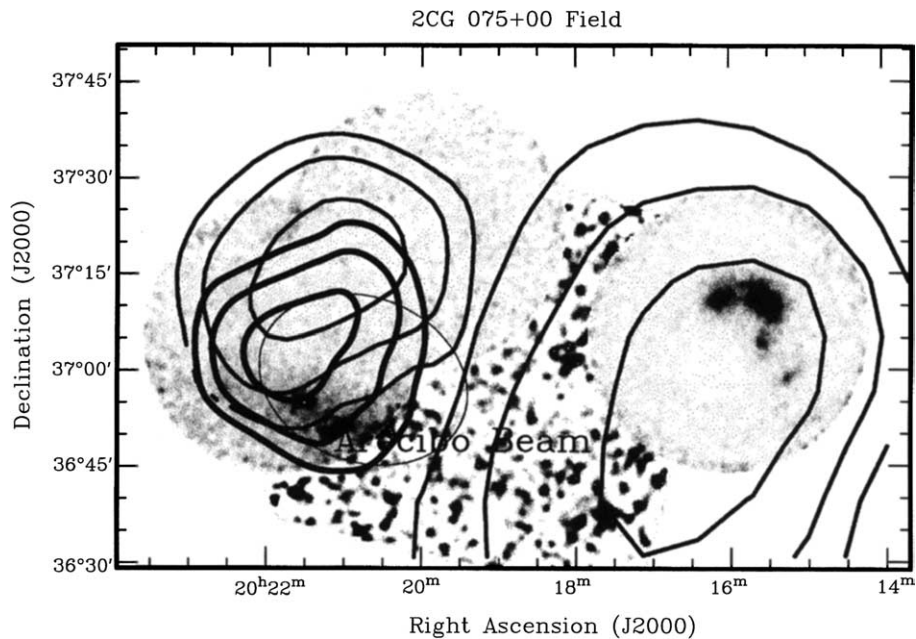


Fig. 1. ASCA GIS 2–10 keV Images of the COS B region 2CG 075+00 superimposed on an Einstein IPC 0.1–4.5 keV image. The light grey contours are the 68%, 95% and 99% confidence regions of the third *EGRET* catalog sources 3EG J2021+3716 (left) and 3EG J2016+3657 (right). The dark contours are for the source GeV J2020+3658 and are derived from the  $>1$  GeV photons only (Roberts et al., 2001). The oval is the positional error derived for GeV J2020+3658 by Lamb and Macomb (1997). The circle centered on AX J2021.1+3651 indicates the size of the 3' Arecibo beam.

above 1 GeV (Lamb and Macomb, 1997) contained two sources in this region that were not in the list of  $3\sigma$  sources, based on 100 MeV and above maps, used to construct the 3rd *EGRET* catalog. They rederived the positional contours of 3EG J2021+3716 using 1 GeV and above maps and all of the known nearby sources in their analysis. An *ASCA* image of the new position yielded two hard point-like sources (Fig. 1), embedded in softer extended emission. One is identified with the Wolf-Rayet + O-star binary system WR 141. The second, AX J2021.1+3651, is moderately absorbed ( $n_{\text{H}} = 5 \times 10^{21} \text{ cm}^{-2}$ ) with a hard, power-law spectrum (photon index  $\Gamma = 1.7$ ).

By targetting the X-ray source AX J2021.1+3651 with the Arecibo radio telescope, we have discovered the young and energetic pulsar PSR J2021+3651 (Roberts et al., 2002). Here we present a timing solution of the pulsar based on eight months of monitoring with Arecibo and discuss the likely prospect that this is the counterpart to 2CG 075+00, which has eluded identification for over 20 years.

## 2. Observations and analysis

PSR J2021+3651 was observed 17 times between MJD 52305 and 52545 using the Wideband Arecibo Pulsar Processor (WAPP) at the Arecibo Observatory. 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

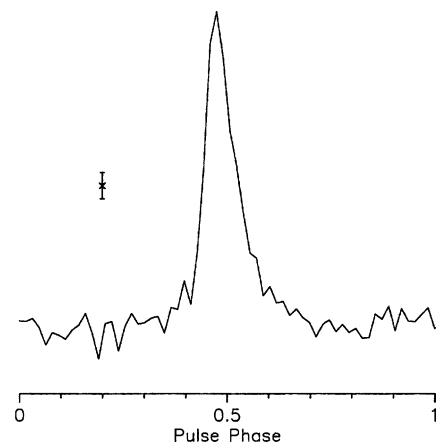


Fig. 2. 1.4 GHz pulse profile for PSR J2021+3651 adopted from Roberts et al. (2002). The error bar represents the  $1\sigma$  uncertainty.

et al., 2000). Our observations were made at 1.4 GHz with 100 MHz of bandwidth, 512 lags, 200  $\mu\text{s}$  sampling and summed polarizations. The 16-bit samples were written to a disk array and then transferred to magnetic tape for later analysis.

Analysis of the observations was done using the PRESTO software suite (Ransom, 2001).<sup>1</sup> Integrated pulse profiles (Fig. 2) from our observations were convolved with a template profile to extract 69 topocentric times of arrival (TOA). Using TEMPO,<sup>2</sup> the topocentric

<sup>1</sup> <http://www.physics.mcgill.ca/~ransom/>.

<sup>2</sup> <http://pulsar.princeton.edu/tempo>.

Table 1  
Measured and derived parameters for PSR J2021+3651

Parameter	Value
Right ascension $\alpha$ (J2000)	20 <sup>h</sup> 21 <sup>m</sup> 05 <sup>s</sup> .214(51)
Declination $\delta$ (J2000)	36° 51′08″.42(72)
Galactic longitude $l$	75.°23
Galactic latitude $b$	+0.°11
Pulse period $P$ (s)	0.103722225646(12)
Period derivative $\dot{P}$	$9.56118(60) \times 10^{-14}$
Pulse frequency $\nu$ (s <sup>-1</sup> )	9.6411351933(11)
Frequency derivative $\dot{\nu}$ (s <sup>-2</sup> )	$-8.88726(54) \times 10^{-12}$
RMS residual	292 $\mu$ s
Epoch (MJD)	52407.389
Dispersion measure DM (pc cm <sup>-3</sup> )	369.12(58)
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)	$\sim 0.1$
Spin-down luminosity $\dot{E}^a$ (erg s <sup>-1</sup> )	$3.4 \times 10^{36}$
Surface dipole magnetic field $B^b$ (G)	$3.2 \times 10^{12}$
Characteristic age $\tau_c \equiv \frac{1}{2}P/\dot{P}$ (kyr)	17

<sup>a</sup>  $\dot{E} = 4\pi^2 I \dot{P} / P^3$  with  $I = 10^{45}$  g cm<sup>2</sup>.

<sup>b</sup> Assuming standard magnetic dipole spindown:  $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$  G (Manchester and Taylor, 1977).

TOAs were converted to TOAs at the solar system barycenter at infinite frequency and fit simultaneously for pulsar period, period derivative, DM, RA and Dec with a residual rms of 292  $\mu$ s. Table 1 gives the measured and derived parameters for PSR J2021+3651 and is updated from Roberts et al. (2002). The quoted errors are three times those given by TEMPO in order to compensate for systematic errors otherwise unaccounted for.

### 3. Discussion

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 inter-spiral arm direction. Using the recent Cordes and Lazio (2002) update to the Taylor and Cordes (1993) dispersion measure model gives a distance of  $\sim 12.4$  kpc, at the outer edge of the last spiral arm 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 (Cordes, private communication, 2002). However, there are no obvious HII regions within the Arecibo beam seen in either very large array (VLA) 20 cm radio or midcourse space experiment (MSX) 8.3  $\mu$ m images (available from the NASA/IPAC Infrared Science Archive).

The likelihood, that PSR J2021+3651 is unrelated to the X-ray source is extremely small given the rarity of such young, energetic, pulsars and the consistency of the timing position with the  $\sim 1'$  positional uncertainty of the *ASCA* source. However, the high DM is somewhat surprising given the X-ray absorption quoted by RRK ( $n_H = (5.0 \pm 0.25) \times 10^{21}$  cm<sup>-2</sup>), where the errors repre-

sent the 90% confidence region. The total Galactic HI column density in this direction as estimated from the FTOOL nh, which uses the HI map of Dickey and Lockman (1990), is  $1.2 \times 10^{22}$  cm<sup>-2</sup>. 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. 1) and given the likely possibility of either associated thermal X-ray flux from a supernova remnant or a nearby massive star, we fit 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 et al. (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  $n_H = 7.6 \times 10^{21}$  cm<sup>-2</sup> with a 90% confidence region of  $(4.1-12.3) \times 10^{21}$  cm<sup>-2</sup>, 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 and the value of  $n_H$  may be contaminated by thermal emission. Upcoming *Chandra* observations of the source may well clarify this.

For a distance  $d_{10} = d/10$  kpc, the inferred isotropic X-ray luminosity  $L_X = 4.8 \times 10^{34} d_{10}^2$  erg s<sup>-1</sup> (2–10 keV). The X-ray efficiency  $\eta_X = L_X/\dot{E}$  is  $0.01 d_{10}^2$ . Compared to the total pulsar plus nebula X-ray luminosity of other spin-powered pulsars, this is somewhat high, but within the observed scatter (Possenti et al., 2002; Chevalier, 2000). Upcoming *Chandra* observations will determine what fraction of the X-ray flux comes from a compact nebula and will allow us to search for X-ray pulsations.

2CG 075+00 = 3EG J2021+3716 = GeV J2020+3658 is the 10th brightest Galactic source above 1 GeV. It has a hard (photon index  $\Gamma = 1.86 \pm 0.10$ ) spectrum with no sign of a break out to 10 GeV and has low variability, similar to the known  $\gamma$ -ray pulsars. PSR J2021+3651's position is outside the 99% contour of the 3EG catalog position, but consistent with the 95% contour of both the Lamb and Macomb (1997) GeV catalog position and the RRK position. The only other potential counterpart within any of the error contours is WR 141. Although such binary systems have the potential for producing  $\gamma$ -rays from colliding winds, no convincing association with a known high-energy ( $>100$  MeV)  $\gamma$ -ray source has yet been made for a Wolf-Rayet system (Romero et al., 1999). The pulsar's positional coincidence coupled with the high inferred spin-down luminosity strongly suggests this pulsar emits  $\gamma$ -rays. Unfortunately, confirming this by folding archival *EGRET* data is problematic due to the likelihood of significant past timing noise and glitches, which make the back-extrapolation of the rotational ephemeris uncertain.

Assuming the distances given by the Cordes and Lazio (2002) model, the known  $\gamma$ -ray pulsars have  $\gamma$ -ray efficiencies  $\eta_\gamma = L_\gamma/\dot{E}$  mostly between 0.0001 and 0.03 (assuming 1 sr beaming). Assuming the  $\gamma$ -rays are 100% pulsed, the inferred  $\gamma$ -ray efficiency for PSR J2021+3651,  $\eta_\gamma = 0.15d_{10}^2$  in the 100 MeV–10 GeV range, would be by far the most efficient  $\gamma$ -ray pulsar. Note however that PSR B1055-52 (Thompson et al., 1999) has a similar efficiency if one uses the DM distance given by Taylor and Cordes (1993), instead of the newer Cordes and Lazio (2002) model. PSR B1706-44, which has nearly identical spin parameters, has a  $\gamma$ -ray efficiency of  $\sim 0.01$ , while Vela with a similar spin-down energy has a low efficiency of  $\sim 0.0004$ . Even if the pulsar is located within the Perseus arm at a distance of 5 kpc, it would still be very efficient. If it is the  $\gamma$ -ray source, it would further strain the relationship of efficiency to spin-down energy  $\eta_\gamma \propto L_{sd}^{-1/2}$  expected from theory (Zhang and Harding, 2000). While there is currently no observational evidence for a closer distance, increased DM from an intervening source in this relatively crowded direction would not be surprising. We note that the DM derived distances for several other young pulsars recently discovered within *EGRET* error boxes, if the true counterparts, also tend to have high inferred  $\gamma$ -ray efficiencies (Roberts, 2002).

We plan to continue timing observations of this source, which will refine the position, provide a contemporaneous timing solution for future high-energy pulse searches and allow us to monitor for glitches. *AGILE* and *GLAST* should be able to unambiguously determine if the pulsar is the counterpart of the  $\gamma$ -ray source.

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