PSR J2021+3651: A GAMMA-RAY PULSAR AT THE EDGE OF THE GALAXY?

A New Pulsar in an Old $\gamma-$Ray Error Box

The identification of the Galactic sources of GeV emission has proven to be a difficult and often frustrating endeavor. Of the 25 brightest sources of GeV emission observed by EGRET at low Galactic latitudes, only 6 have firm identifications as pulsars. These six include Crab and Vela, which have bright pulsar wind nebulae which dominate the emission in radio and X-rays. A strategy of searching EGRET error boxes for hard X-ray sources followed by radio imaging and pulse searching has proven to be quite fruitful in recent years. Two bright GeV source positions (Roberts et al. 1999, Roberts et al. 2001, Roberts, Romani, & Johnston 2001, Braje et al. 2002) and one fainter one (Halpern et al. 2001ab) contain newly discovered pulsar wind nebulae. Several other EGRET sources have recently been found to contain radio pulsars or probable neutron stars (Torres, Butt, & Camilo 2001, Mirabal & Halpern 2001). However, many of the brightest sources with pulsar-like characteristics have no likely counterparts discovered to date.

The COS B source 2CG 075+00 has been one of the most reluctant sources to yield a likely counterpart, despite 20 years of multiwavelength observations. This source, also known as 2EG J2019+3719[1] or GeV J2020+3658, has been considered a probable pulsar due to its hard spectrum (Merck et al. 1996), proximity to star forming regions (Yadigaroglu & Romani 1997), and low variability (Tompkins 1999). However, earlier radio imaging (Özel et al. 1988), pulse searches (Nice & Sayer 1997), and X-ray imaging (Mukherjee et al. 2000) failed to find any interesting candidates consistent with the source of GeV emission.

Roberts, Romani, & Kawai (2001), reanalyzed the EGRET data using only > 1 GeV photons and including all known sources in the region. Pointing at the revised error contour, ASCA detected two unresolved sources embedded in a region of diffuse emission (Figure 1). One was associated with the Wolf Rayet/O star binary WR 141. The other, designated src2, is moderately bright ($F_{2-10keV} \sim 3.8 \times 10^{-12} \mathrm{ergs\,cm^{-2}\,s^{-1}}$) with a hard power law spectrum (photon index $\Gamma \sim 1.7$). The apparent elongation of the source is due to distortion of the PSF near the edge of the detector, where the aspecting is also poor, preventing the position to be determined to an accuracy better than $\sim 1'$ (Gotthelf et al. 2000). We observed this region at 20 cm with the VLA in D array,

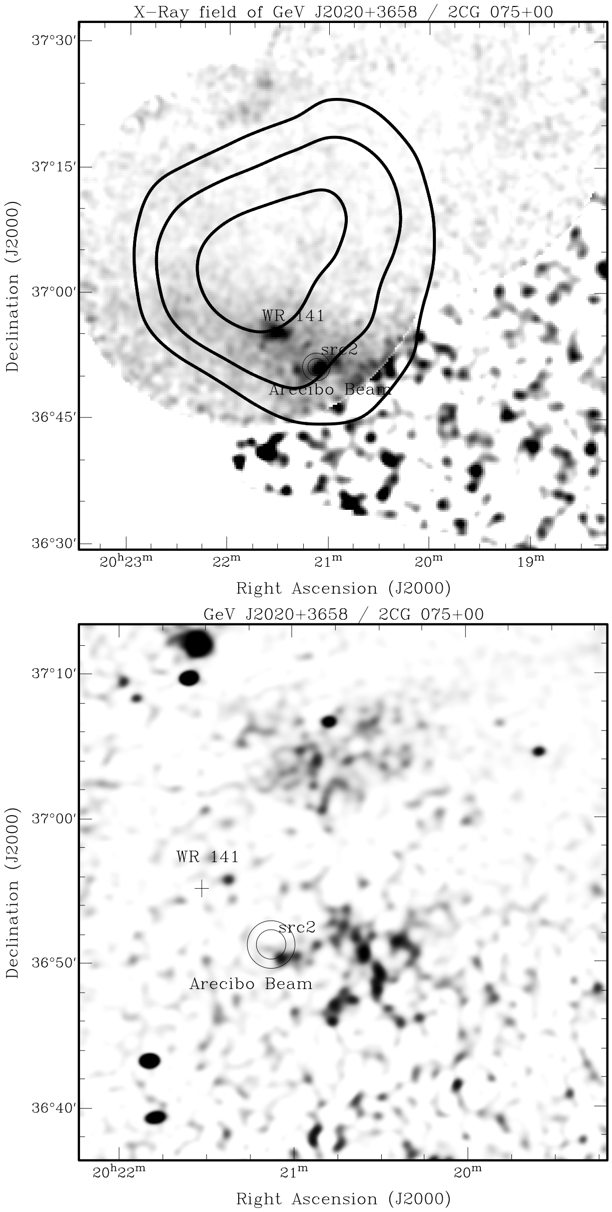

Figure 1: *Top:* ASCA GIS 2-10 keV image of the $\gamma-$ray source region, with Einstein IPC image at the edge. The contours are the 68%, 95%, and 99% confidence regions of the $\gamma-$ray source position, derived from the 1 GeV and above photons (Roberts, Romani, & Kawai 2001). *Bottom:* 20 cm VLA image of region. The smaller circle is the nominal ASCA X-ray position, while the larger circle is the Arecibo half-power beam width.

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[1] In the third EGRET catalog (Hartman et al. 1999) 2EG J2019+3719 was split into two sources, the harder 3EG J2021+3716 and the softer 3EG J2016+3657, with the latter now identified as a background blazar (Halpern et al. 2001c)

and find a faint (peak flux density ~ 20 mJy/beam, with a 51 by 38 arcsec beam) nebula near the X-ray position (Figure 1). A comparison with the Canadian Galactic Plane Survey suggests that this may be part of a large ridge of emission which is mostly resolved out by the VLA.

Using the upgraded Arecibo telescope and the new WAPP pulsar system at 20cm, our team performed a deep search for pulsations at the ASCA position of src2 in Jan. 2002. This resulted in the discovery of a new 103.7 ms pulsar (Figure 2), PSR J2021+3651. With a flux density of only ~ 0.1mJy, and a very high dispersion measure DM $\sim 360 \mathrm{pc\,cm}^{-3}$, the fact it was not found in previous surveys of the region is no surprise. The DM implies a distance of ~ 20 kpc using the model of Taylor and Cordes (1993) for the Galactic coordinates $l = 75.23°, b = +0.11°$. This is remarkably high for this longitude, which is a predominantly inter-spiralarm direction. The highest pulsar dispersion measure between $55° < l < 80°$ listed in the ATNF catalog of 1300 pulsars is DM $\sim 239 \mathrm{pc\,cm}^{-3}$. In fact, this DM suggests the pulsar is well past the last spiral arm used in the original Taylor and Cordes model! A revised model in preparation by Cordes and Lazio (Cordes 2001) includes an additional "Outer" arm at $d \sim 10$ kpc. However, that in itself is not enough to account for the excess DM, and there may be further enhancement by an HII region in the Cygnus region, which is known to have excess gas at 1.5 kpc (J. Cordes, private communication). On the other hand, while there is extended diffuse emission throughout much of the Cygnus region, we note that there are no obvious bright HII regions seen in the 20 cm radio or the MSX 8.3 micron images within the Arecibo beam.

Additional Arecibo observations made in March 2002 (just a few days before the Chandra deadline!) resulted in a pulse period measurement which allows us to determine the spin-down rate and hence a spin-down energy $\dot{E} \sim 5 \times 10^{36}$ ergs/s, and a characteristic age of $\tau_c \sim 12,000$ yr. This is very close to the Vela pulsar's $\dot{E} = 6.3 \times 10^{36}$ ergs/s. However, the ratio of $\dot{E}/d^2$, even at the 10 kpc distance of the spiral arm, is quite low, although similar to PSR B1055-52 which has an $\dot{E} \sim 3 \times 10^{34}$ ergs/s. This distance would imply an extremely high efficiency of $\gamma-$ray emission if it is the GeV source (~ 0.2 for $\pi-$sr beaming). In addition, the inferred X-ray luminosity at 10 kpc is extremely high, around 50 times that of the Vela PWN. Noting that the ratio of GeV flux to X-ray flux is almost identical to Vela, it may be more reasonable to assume a similar X-ray luminosity to that of the Vela pulsar wind nebula, which would imply a distance of ~ 3 kpc.

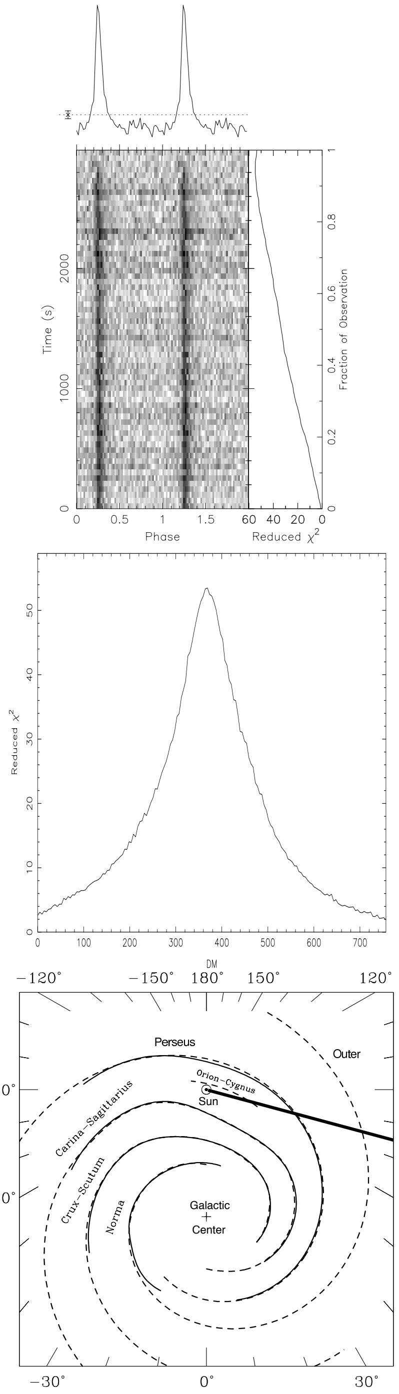

Figure 2: *Top:* Pulse profile as a function of time during the observation, and the average pulse profile. *Center:* Pulse significance as a function of dispersion measure. *Bottom:* An updated Galaxy model (Cordes 2001), where dashed lines are spiral arms not included in the original Taylor and Cordes (1993) model. The dark line indicates the direction of PSR J2021+3651.

Roberts, Romani & Kawai (2001) fit a simple absorbed power law to the spectrum of src2, measuring an absorption of $nH \sim 5 \times 10^{21}\,\mathrm{cm}^{-2}$, which is low considering the high dispersion measure. However, by adding a thermal shock component (PSHOCK in XSPEC) to the model, accounting for only 6% of the photons, the best fit absorption increases to $nH \sim 1 \times 10^{22}\,\mathrm{cm}^{-2}$, and the overall fit marginally improves. This is similar to the total Galactic absorption in this direction as given by the ftool nH (Dickey & Lockman 1990). Given that ASCA sees diffuse steep spectrum emission in the region, and that such thermal shock spectra are expected from supernova remnants, we think that multiple spectral components are likely within the $4'$ ASCA spectral extraction region.

Resolving the X-Ray Source

Our first objective is to obtain a precise location for the X-ray source, and see if it can be associated with any nearby sources at other wavelengths. There is also a possibility, although small given the size of the Arecibo beam, that the source in unrelated to the pulsar. A high precision timing position will likely be available around the time a Chandra observation takes place, which will allow confirmation that the X-ray source is truly the pulsar counterpart.

Our second objective is to determine the morphology of the surrounding pulsar wind nebula. If the diffuse X-ray emission is a result of the birth supernova remnant, it may not have moved far from its birthplace. We would therefore expect to see a torus/jet morphology, and it may be possible to scale features to estimate the distance. If it is far from the birth Supernova remnant, then it will likely have a bow-shock / trail morphology such as the pulsar associated with the Duck (Kaspi et al. 2001). Adopting the characteristic age of 12,000 years and a distance of 3 kpc, a tranverse velocity of $v_T \sim 350$ km/s, fairly typical for a pulsar, would mean it's birth-site was $\sim 5'$ away, and deep imaging in the direction indicated by the morphology may lead us to a birthsite, from which we might be able to estimate a distance. At a distance of 10 kpc or more, as suggested by the DM, the velocity would have to be very high to move it as far as $5'$ during its lifetime. A narrow Mach cone would with an extreme bow-shock morphology similar to the Guitar nebula (Romani, Cordes & Yadigaroglu 1997) would indicate a high velocity object.

The measured 2-10 keV flux of the X-ray source is among the higher of the "Vela-like" pulsars listed by Possenti et al. (2001). In all cases of X-ray luminosities of this magnitude, the bulk of the flux comes from a surrounding pulsar wind nebula. Although it seems point-like to ASCA's $50''$ resolution, if the X-ray source is associated with the pulsar, it will almost certainly be extended. If the physical extent of the PWN is similar to the Vela PWN, placing it at a distance of 3 kpc would give it an angular extent of $\sim 10''$. This can be well imaged by Chandra, but not with any other telescope such as XMM-Newton.

Quantitative studies of PWN require spectral information, so our third objective is to obtain good spectra of the nebula, the pulsar, and any ambient thermal emission from the supernova remnant. The indication from the ASCA data is that the photon spectral index is significantly less than two, and hence the peak of the energy output is above the ASCA band, as opposed to the Crab, but similar to Vela. However, if the pulsar is a significant fraction of the emission, and is predominantly emitting hard magnetospheric radiation, it would significantly skew the measurements. On the other hand, the pulsar surface itself might be a source of significant thermal emission. Spatially resolving the components is necessary to obtain reliable spectra. In addition to the intrinsic scientific interest of the observed quantities, separating the components will allow an unambiguous measurement of nH, and resolve the question of whether there truly is a significant discrepancy between the X-ray absorption and the high radio dispersion. Assuming 80% of the emission is in a nebular component we estimate using Webspec that $\sim$ 20ks of integration time would be adequate to rule out a photon index $\Gamma = 2.0$ if the best fit ASCA value of $\Gamma = 1.7$ is the true value, and would provide a good measure of the nH. This observation length would give us over 10 photons per resolution element for a $25''$ diameter object, and thus will be adequate to achieve our imaging goals as well.

However, there is one major caveat to the spectral fitting. PIMMS estimates a total ACIS-S count-rate of ~ 0.42 cps. Pile-up could therefore be a significant problem if the source is very compact or the pulsar emits a significant fraction of the total flux. If we assume 10% of the flux comes from the pulsar, a photon index $\Gamma = 1.5$ and an absorption of $10^{22}\,\mathrm{cm}^{-2}$, we would expect about 10% pile-up, which would significantly affect the spectral shape. For the nebula, if its diameter is smaller than $\sim 4''$, or it has sharp, bright features, pile-up could also be a problem. We will ameliorate this somewhat by observing with a half sub-array. Although the source would likely fit on an even smaller sub-array, the current uncertainty in the ASCA position makes us reluctant to shrink the FOV any further.

Fortunately, obtaining our final objective will also give us a second chance to measure the spectrum of regions with significant pile-up problems. The strength and pulse profile of magnetospheric X-ray emission is an important clue to the origin of high-energy emission (eg. Ray, A., Harding, A. & Strickman, M. 1999). With a second 20ks observation in continuous clocking mode, we can spatially resolve the image in one dimension and make pile-up negligible. In addition, we can search for X-ray pulsations and measure the pulsed spectrum. A hard pulsed component would support an identification with the $\gamma-$ray source, and its pulse profile would be an important observational constraint on pulsar emission models (eg. Romani and Yadigaroglu 1995). Since pile-up would not be a problem with continuos clocking data, it might also give us the best measurement of nH to the pulsar, since the unpulsed emission could be used as background and potential nebular contamination would be eliminated. If there are regions of the PWN which are piled up, the imaging data could be used to subtract off the local diffuse background along the clocking strip to obtain a relatively background free measure of the PWN spectra. If the total flux is 10% pulsed, and the pulsar has a spectral photon index of $\Gamma = 1.5$, then roughly 0.03 cps would be expected from the pulsar. If we assume a roughly equal contribution from the nebula (which is highly dependent on the morphology of the nebula) and a sinusoidal pulse profile (worst case scenario), we monte carlo the time needed for a 50% confidence chance of detecting the pulse assuming an intrinsic pulsed fraction of 50% and find it to be $\sim$ 20ks. We consider this a conservative time request that will give us a high probability of detection, noting that most magnetospheric pulse profiles are non-sinusoidal and thus significantly easier to detect. If there are significant pulsations, we estimate this observation length would also allow nH to be determined to a precision of $\sim 0.2 \times 10^{22}\,\mathrm{cm}^{-2}$.

In addition, we note that with the proper roll angle, significant serendipitous science would result. The extended diffuse emission runs in a roughly straight line and extends past the edge of the ASCA FOV and may be associated with supernova remnant birthplace. An Einstein IPC image shows the excess emission does not go much further than the field edge (Figure 1). Therefore, we may also be able to obtain a good X-ray image of the proposed remnant, and verify its nature. In the opposite direction is the X-ray bright Wolf-Rayet/O-star binary sytem WR 141, which has a 21.6 day orbit. Our proposed observations will allow its spectrum to be measured at two places on its orbit in addition to the ASCA observation, allowing the study of the shocked wind emission as a function of orbital phase. Since we consider these to be secondary to our prime objective of studying the compact pulsar emission (and possibly better accomplished with XMM-Newton), we only ask for a preferred roll angle, not a constrained observation.

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