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PSR J2229+6114: DISCOVERY OF AN ENERGETIC YOUNG PULSAR IN THE ERROR BOX OF THE EGRET SOURCE 3EG J2227+6122

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ABSTRACT

We report the detection of radio and X-ray pulsations at a period of 51.6 ms from the X-ray source RX/AX J2229.0+6114 in the error box of the EGRET source 3EG J2227+6122. An ephemeris derived from a single *ASCA* observation and multiple epochs at 1412 MHz from Jodrell Bank indicates steady spin-down with $\dot{P} = 7.83 \times 10^{-14}$ s s^{-1}. From the measured P and $\dot{P}$, we derive spin-down power $\dot{E} = 2.2 \times 10^{37}$ ergs s^{-1}, magnetic field $B_p = 2.0 \times 10^{12}$ G, and characteristic age $P/2\dot{P} = 10{,}460$ yr. An image from the *Chandra X-Ray Observatory* reveals a point source surrounded by centrally peaked diffuse emission that is contained within an incomplete radio shell. We assign the name G106.6+2.9 to this new supernova remnant, which is evidently a pulsar wind nebula. For a distance of 3 kpc estimated from X-ray absorption, the ratio of X-ray luminosity to spin-down power is $\approx 8 \times 10^{-5}$, smaller than that of most pulsars but similar to the Vela pulsar. If PSR J2229+6114 is the counterpart of 3EG J2227+6122, then its efficiency of γ-ray production, if isotropic, is 0.016 $(d/3\ \mathrm{kpc})^2$. It obeys an established trend of γ-ray efficiency among known γ-ray pulsars, which, in combination with the demonstrated absence of any other plausible counterpart for 3EG J2227+6122, makes the identification compelling. If confirmed, this identification bolsters the pulsar model for unidentified Galactic EGRET sources.

Subject headings: gamma rays: observations — pulsars: individual (PSR J2229+6114) — supernova remnants

1. INTRODUCTION

3EG J2227+6122 (Hartman et al. 1999) is one of a number of "unidentified" EGRET sources at low Galactic latitude, $(l, b) = (106.^\circ 6, 2.^\circ 9)$, for which a pulsar origin is the hypothesis favored by many authors (e.g., Halpern & Ruderman 1993; Kaaret & Cottam 1996; Yadigaroglu & Romani 1997). Emission attributed to this source was also detected by the imaging Compton telescope COMPTEL (Iyudin et al. 1997) and probably by *COS B* (Wills et al. 1980). We recently presented an X-ray, radio, and optical study of the error circle of 3EG J2227+6122 that revealed only one plausible candidate, a highly polarized, flat-spectrum radio shell superposed on a compact, nonthermal X-ray source with power-law photon index $\Gamma = 1.51 \pm 0.14$ and with no obvious optical counterpart (Halpern et al. 2001, hereafter Paper I). We concluded that the most likely interpretation was a young pulsar and associated wind nebula. The distance was estimated as 3 kpc from the X-ray absorption column density of $(6.3 \pm 1.3) \times 10^{21}$ cm^{-2}. At that distance, the spin-down luminosity required to power the X-ray and γ-ray luminosities of 1.7×10^{33} and 3.7×10^{35} ergs s^{-1}, respectively, would be similar to that of the younger known EGRET pulsars. In this Letter, we report follow-up observations that confirm a pulsar origin for RX/AX J2229.0+6114.

2. *CHANDRA* IMAGE

We observed the X-ray source RX/AX J2229.0+6114 for 17,728 s on 2001 February 14 with the *Chandra* imaging CCD array ACIS-I. The target was offset by $0.'5$ from the default ACIS-I pointing position in each direction in order to avoid the inter-CCD gaps. A point source was clearly detected, surrounded by diffuse emission with a centrally peaked morphology (Fig. 1). There is evidently an arc of emission that resembles similar structures in the Vela Nebula (Helfand, Gotthelf, & Halpern 2001), surrounded by fainter diffuse emission that is largely confined within the boundaries of the radio shell, which has a radius of $\approx 100''$. The radial profile of the X-ray flux is shown in Figure 2. The central point source accounts for 29% of the total flux within $100''$. The total 2–10 keV flux is 1.3×10^{-12} ergs cm^{-2} s^{-1}, only slightly smaller than the value of 1.56×10^{-12} ergs cm^{-2} s^{-1} that we found in Paper I using *ASCA*. It is possible that the *ASCA* Gas Imaging Spectrometer (GIS), with its large point-spread function, encompassed some extended diffuse emission that is not easily recovered in this short *Chandra* observation. In combination with the nonthermal spectrum of the X-ray nebula, the morphology indicates a "composite" supernova remnant (to which we assign the name G106.6+2.9), although the radio shell is probably a shock between the pulsar wind nebula (PWN) and the surrounding medium rather than a supernova blast wave (see § 6). No thermal emission has yet been detected from this remnant at X-ray or optical wavelengths.

There are eight X-ray sources in the ACIS (Advanced CCD Imaging Spectrometer) image that can be immediately identified by inspection with bright stars on the Palomar Observatory Sky Survey. Two of these are present on our optical CCD images of the field that were discussed in Paper I. We used them to derive a correction of $1.''5$ to the X-ray aspect solution, obtaining the precise position for the point source listed in Table 1, with an estimated uncertainty radius of $0.''5$.

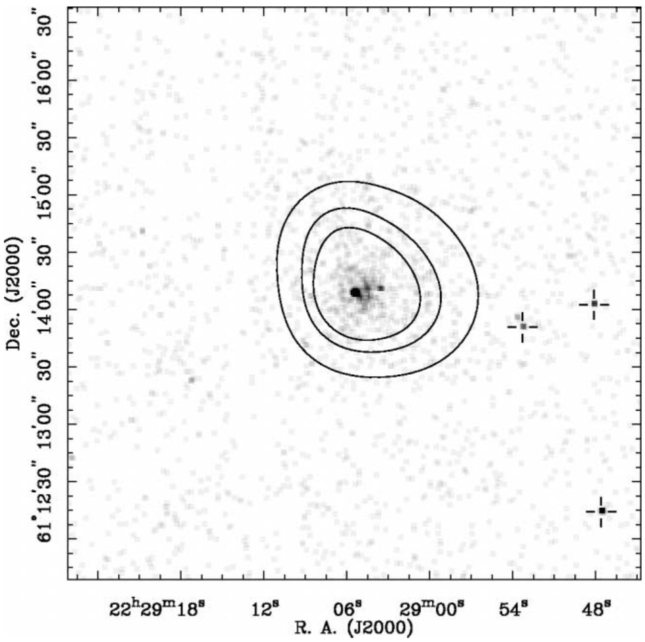

FIG. 1.—Portion of the *Chandra* ACIS-I image showing RX/AX J2229.0+6114. The image is binned into ≈1″ pixels and smoothed with a 3 pixel top-hat filter. It is displayed with square root intensity scaling with the contrast set to highlight faint diffuse structures. The linearly spaced overlaid contours correspond to an adaptively smoothed map. Also shown are the locations of X-ray point sources detected with greater than 2 σ confidence.

TABLE 1

PARAMETERS OF PSR J2229+6114

Parameter	Value
R.A. (J2000)	$22^h29^m05^s.28(7)$
Decl. (J2000)	$+61°14'09''.3(5)$
Galactic longitude (deg)	106.65
Galactic latitude (deg)	2.95
Period (s)	0.05162357393(6)
Period derivative (s s^{-1})	$7.827(2) \times 10^{-14}$
Epoch (MJD)	51980.0
Dispersion measure (cm^{-3} pc)	200(10)
Distance[a] (kpc)	∼3
Spin-down luminosity (ergs s^{-1})	2.2×10^{37}
Characteristic age (yr)	10460
Magnetic field (G)	2.0×10^{12}

[a] See text.

3. RADIO PULSAR

The position of RX/AX J2229.0+6114 was observed with the 76 m Lovell radio telescope at Jodrell Bank on 2001 February 27 and 28 for 1.5 and 2.4 hr, respectively. The observations used a cryogenic receiver at a central frequency of 1412 MHz and a filter-bank spectrometer with 64 channels, each 1 MHz wide, for each of two orthogonal polarizations. After square-law detection and summing of complementary polarizations, the total-power levels in each of 64 channels were integrated every 1 ms, 1 bit digitized, and written to tape for off-line analysis.

Standard search algorithms detected an unmistakable pulsed signal at a barycenter-corrected period $P = 51.6235$ ms and dispersion measure DM $= 200 \pm 10$ cm^{-3} pc with signal-to-noise ratio (S/N) of 13.9 and 18.6 on February 27 and 28, respectively. These S/N values are consistent with each other after scaling for the relative integration times, suggesting that the pulsar does not scintillate markedly. Based on this and the known telescope sensitivity, we estimate that the period-averaged flux density of the pulsar at this frequency is 0.25 mJy, with ∼30% uncertainty. This is a rather low value, fully consistent with its nondetection in previous "all-sky" surveys and with the median rms of 0.12 mJy reported for the Very Large Array image in Paper I. The radio pulse profile (Fig. 3) consists of one featureless peak with FWHM of 0.08 ± 0.02 cycles.

We began regular timing observations of this source, and a phase-connected solution to times of arrival spanning 11 days in 2001 March yields the period listed in Table 1, and $\dot{P} = (7.80 \pm 0.03) \times 10^{-14}$ s s^{-1}. The more accurate $\dot{P}$ listed in Table 1 is derived from a fit to this period in 2001 March and the period subsequently found in the X-ray data obtained 1.6 yr earlier (§ 4). Thus far, our data do not meaningfully constrain the amount of timing noise or glitch activity that may be present in PSR J2229+6114. If we assume a distance of 3 kpc as estimated from the X-ray spectrum in Paper I, the free electron/distance model of Taylor & Cordes (1993) would predict

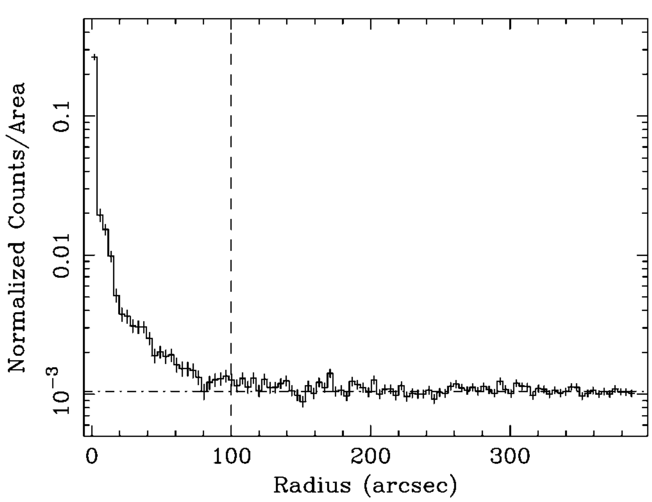

FIG. 2.—Radial profile of the *Chandra* ACIS-I image of RX/AX J2229.0+6114. Each radial bin is 8 ACIS pixels wide (3″.9). The profile is normalized by area and corrected for the instrument response across the focal plane, including mirror vignetting and inter-CCD chip gaps. The pulsar flux is confined to the central bin, around which is clearly evident at least two components of enhanced emission, one inside and one outside of 20″. The 1 σ error bar is shown for each data point. The dot-dashed line represents the estimated background level. The dashed line denotes the approximate outer boundary of the radio shell from Paper I.

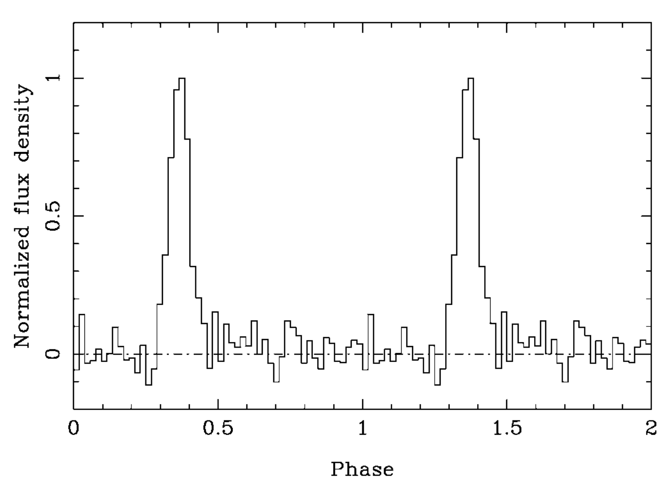

FIG. 3.—Radio pulse profile of PSR J2229+6114 at 1412 MHz. The instrumental resolution is ≈0.02 of the period. Phase zero is arbitrary.

DM = 75 cm^{-3} pc, significantly less than the observed DM = 200. Conversely, for the observed DM the model predicts a distance of 12 kpc. It is known that for individual objects the model distances/DMs can be wrong by a factor of a few, and this may be the case for PSR J2229+6114. In fact, the rule of thumb of 0.1 free electrons per hydrogen atom, combined with the measured DM, yields a predicted $N_H = 6 \times 10^{21}$ cm^{-2}, in exact agreement with the X-ray–measured value from the *ASCA* spectrum. While the conversion from column density to distance is itself uncertain, we tentatively retain the previous "X-ray" estimate of $d = 3$ kpc, while acknowledging that considerable uncertainty remains.

4. X-RAY PULSAR

Following the radio pulsar discovery in 2001 February, we searched the 113,700 s of *ASCA* GIS data obtained on 1999 August 4–7 for pulsations at periods slightly shorter than the radio, incorporating in the folding the $\dot{P}$ that would be necessary to connect to the radio period obtained 1.6 yr later. Using the Z_n^2-test (Buccheri et al. 1983) to gain sensitivity to n harmonics of the fundamental period, we found an unambiguous signal with $Z_7^2 = 99.4$ at $P = 51.6196134 \pm 0.0000005$ ms (MJD 51,394.365), requiring $\dot{P} = 7.827 \times 10^{-14}$ s s^{-1} to connect to the radio ephemeris. The Z_n^2 statistic is distributed as χ^2 with $2n$ degrees of freedom. The probability of a spurious detection is 6×10^{-15} per trial, while only $\sim 10^4$ independent trial periods were searched. Figure 4 shows the folded light curve in the 0.8–10 keV band, extracted from a region of radius 4′ around the source. There are evidently two pulses approximately 180° apart in phase, although they are not symmetric. The rise time of the higher pulse is unresolved; the bin size in Figure 4 (2.55 ms) is comparable to the instrumental time resolution. (Approximately half the data were obtained with 0.5 ms resolution, and half with 3.9 ms resolution.) Since most of the extracted flux is diffuse, it is not possible to measure the true pulsed fraction accurately. After subtracting background from an annulus surrounding the nebula, the *ASCA* GIS light curve has a pulsed fraction of 22%, but since the *Chandra* image indicates that only 29% of these photons are from the pulsar, the true pulsed fraction must be at least 75%.

5. OPTICAL OBSERVATIONS

Optical images of the location of PSR J2229+6114 from the MDM 2.4 m telescope were shown in Figure 3 of Paper I. The precise *Chandra* position of PSR J2229+6114 is now seen to fall only 1″.5 north of the $R = 17.3$ star marked A in that figure and a similar distance south of a fainter star of $R = 21.3$. Given the uncertainty of only 0″.5, the X-ray position is inconsistent with both of these stars. Star A is, in fact, a highly reddened A star as we determined using the KPNO 2.1 m telescope and Goldam spectrograph. The proximity to this bright star will make any further optical search for the pulsar difficult from the ground. Although our images reach a limiting magnitude of $R = 24.5$ in good seeing, a more conservative limit of $R > 23$ probably applies at the location of the pulsar in the wings of the bright star.

6. DISCUSSION

Applying the standard magnetic dipole model for rotation-powered pulsars, we can use the measured P and $\dot{P}$ of PSR J2229+6114 to derive the spin-down power $\dot{E} = I\Omega\dot{\Omega} = 2.2 \times 10^{37}$ ergs s^{-1}, the magnetic field $B_p = 3.2 \times 10^{19}(P\dot{P})^{1/2} = 2.0 \times 10^{12}$ G, and the characteristic age $\tau = P/2\dot{P} = 10{,}460$ yr. Compared to known γ-ray pulsars, PSR J2229+6114 is second only to the Crab in spin-down power, and it is significantly more luminous than the Vela pulsar (PSR B0833–45), which has $\dot{E} = 6.9 \times 10^{36}$ ergs s^{-1}. For a distance of 3 kpc estimated from X-ray absorption and radio pulse dispersion, the ratio of total 2–10 keV X-ray luminosity to spin-down power is $\approx 8 \times 10^{-5}$, smaller than that of most pulsars but similar to Vela (Helfand et al. 2001). If PSR J2229+6114 is the counterpart of 3EG J2227+6122, then its luminosity above 100 MeV is $\approx 3.7 \times 10^{35}$ ergs s^{-1} and its efficiency of γ-ray production, if isotropic, is 0.016 $(d/3\ \mathrm{kpc})^2$. For Vela, the same analysis gives a γ-ray efficiency of 0.03 $(d/500\ \mathrm{pc})^2$.

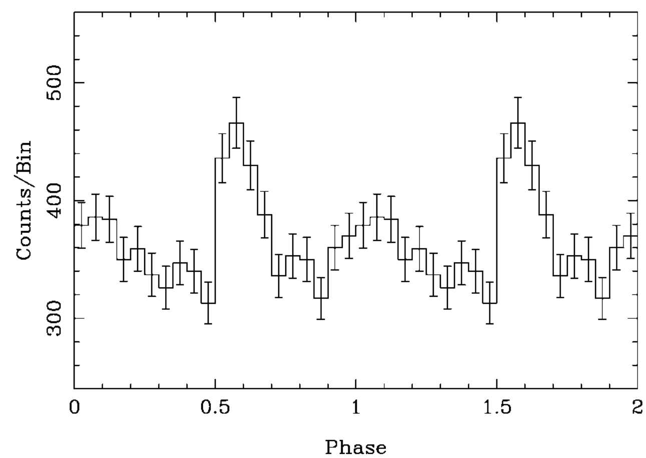

FIG. 4.—X-ray pulse profile of PSR J2229+6114 in the 0.8–10 keV band from the *ASCA* GIS. The instrumental time resolution is comparable to the width of one phase bin. Phase zero is arbitrary.

Among the pulsars that are either reliably or probably identified with EGRET sources, there is a trend (Thompson et al. 1997, 1999) in which the efficiency of greater than 100 MeV γ-ray production increases with decreasing spin-down power ($\dot{E} \propto B^2/P^4$), or equivalently, open field line voltage ($\Phi \propto B/P^2$). Their efficiencies range from 0.002 for the Crab to of order unity for the middle-aged pulsars Geminga and PSR B1055−52. As the source of 3EG J2227+6122, PSR J2229+6114 would have an efficiency in accord with the established pattern if its distance were close to our estimate of 3 kpc. If, on the other hand, the distance were as large as the DM estimate of 12 kpc, PSR J2229+6114 would have to be more efficient than either the Crab or Vela but not so much more as to rule it out as the source of 3EG J2227+6122. While PSR J2229+6114 is apparently similar to the Vela pulsar in γ-ray luminosity, its γ-ray spectrum is characterized as a power law of photon index $\Gamma = 2.24 \pm 0.14$ (Hartman et al. 1999). This is steep compared to Vela and all other EGRET pulsars except the Crab, for which $\Gamma = 2.19 \pm 0.02$. The X-ray pulse profile of PSR J2229+6114 is also reminiscent of that of the Crab, with its two unequal peaks.

Iyudin et al. (1997) reported the detection of a source in the 0.75–3 MeV band with COMPTEL, coincident with 3EG J2227+6122 but with a much larger error box. This detection is consistent in flux with an extrapolation of the EGRET spectrum, but it would exceed an extrapolation of the 2–10 keV spectrum of RX/AX J2229.0+6114 to 1 MeV. The soft γ-ray emission in this region therefore deserves more detailed study. PSR J2229+6114 may be one of the brightest pulsars at 1 MeV.

As a supernova remnant, G106.6+2.9 still has the peculiar property in the radio of shell morphology but with an extremely flat radio spectrum ($\alpha_r \approx 0.0$; Paper I). Since the X-ray emission appears to be largely confined within the radio shell, and since the shell is too small to be the blast wave of a 10^4 yr old supernova remnant, we conclude as was proposed in Paper I that the radio emission comes from a shock driven into the surrounding medium either by the motion of the pulsar or by the expansion of the PWN. In the bow shock interpretation, we can relate the now known spin-down power, $\dot{E} = 2.2 \times 10^{37}$ ergs s^{-1}, assumed to be carried almost entirely by the PWN, to the velocity of the pulsar v_p, the ambient density n_H, and the radius of the shock r_0 via $\dot{E} = 4\pi r_0^2 c \rho_0 v_p^2$. Thus,

$$\dot{E} = 2.2 \times 10^{37} \left(\frac{n_H}{0.01}\right) \left(\frac{d}{3 \text{ kpc}}\right)^2 \left(\frac{v_p}{90 \text{ km s}^{-1}}\right)^2 \text{ ergs s}^{-1}.$$

We measured 1'.7 for r_0, and we assume a relatively low-density medium, as might be appropriate at a z-height of 150 pc or in a cavity previously evacuated by a supernova explosion. However, the production of the particle energy spectrum needed to explain the flat radio spectrum is still not understood theoretically.

7. CONCLUSIONS AND FURTHER WORK

We have discovered the likely source of the γ-rays from 3EG J2227+6122, a young and energetic 51.6 ms pulsar that has properties in accord with those of known γ-ray pulsars. It may be possible to prove the association by finding the corresponding pulsed signal in the EGRET γ-ray photons. It is unlikely, however, that the ephemeris of such a young pulsar is stable enough to extrapolate back with phase coherence to the several epochs of EGRET exposure on this source. While we have ongoing radio and X-ray observations scheduled to assist in this analysis, considerable searching of parameter space will undoubtedly be necessary. Future observations with the *Gamma-Ray Large-Area Space Telescope* can definitively test the identification and can provide an excellent pulse profile for comparison with the X-ray and radio. Even so, it is important to realize that since, as described in Paper I, we have already made a sensitive search of the entire error circle of 3EG J2227+6122 without finding any plausible alternative X-ray counterpart to much fainter limits, it is more conservative to accept the identification with PSR J2229+6114 than to doubt it. The only other object that we are aware has been considered for identification with 3EG J2227+6122 is a Be star/X-ray binary with an unknown rotation period (SAX J2239.3+6116 = 4U 2238+60; in 't Zand et al. 2000), but since that X-ray source is 1°.5 from the γ-ray centroid, or 3 times the 95% error radius, it is an unlikely candidate. Meanwhile, PSR J2229+6114/G106.6+2.9 is sure to become a well-observed example of a young PWN, more of which are needed to study the poorly understood processes of particle acceleration in pulsars, spin-down evolution, MHD flows in PWNs, and interaction with the surrounding medium.

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