HEARTBEAT OF THE MOUSE: A YOUNG RADIO PULSAR ASSOCIATED WITH THE AXISYMMETRIC NEBULA G359.23−0.82

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ABSTRACT

We report the discovery of PSR J1747−2958, a radio pulsar with period $P = 98$ ms and dispersion measure $\text{DM} = 101 \text{ cm}^{-3} \text{ pc}$, in a deep observation with the Parkes telescope of the axially-symmetric “Mouse” radio nebula (G359.23−0.82). Timing measurements of the newly discovered pulsar reveal a characteristic age $P/2P = 25 \text{ kyr}$ and spin-down luminosity $\dot{E} = 2.5 \times 10^{39} \text{ erg s}^{-1}$. The pulsar (timing) position is consistent with that of the Mouse’s “head”. The distance derived from the DM, $\approx 2 \text{ kpc}$, is consistent with the Mouse’s distance limit from H$\alpha$ absorption, < 5.5 kpc. Also, the X-ray energetics of the Mouse are compatible with being powered by the pulsar. Therefore we argue that PSR J1747−2958, moving at supersonic speed through the local interstellar medium, powers this unusual non-thermal nebula. The pulsar is a weak radio source, with period-averaged flux density at 1374 MHz of 0.25 mJy and luminosity $\sim 1 \text{ mJy kpc}^2$.

Subject headings: ISM: individual (G359.23−0.82) — pulsars: individual (PSR J1747−2958)

1. INTRODUCTION

The “Mouse” (G359.23−0.82; Yusef-Zadeh & Bally 1987) is among the few known non-thermal radio nebulae with axial symmetry (see Fig. 2), consisting of a bright “head” and a long “tail” that is highly linearly polarized. It is also an X-ray source (Predehl & Kulkarni 1995; Sidoli et al. 1999). The few other examples known in this class are manifestations of a pulsar bow shock: the relativistic wind of a neutron star confined by ram pressure due to the supersonic motion of the pulsar through the local interstellar medium (ISM). The detailed study of such objects can lead to constraints on the local ISM density and pulsar velocities, ages, spin and magnetic field evolution, and winds (Chatterjee & Cordes 2002; van der Swaluw et al. 2002), as exemplified by the study of the “Duck” nebula and its pulsar (Gaensler & Frail 2000). Also, relatively few young nearby pulsars are known. Detecting other such nearby pulsars, as is likely to be lurking inside the Mouse, is important for accurately determining pulsar birth rates, beaming fractions and luminosity distributions (e.g., Brazier & Johnston 1999).

The Mouse has therefore been the object of considerable interest since its discovery. While its interpretation as a pulsar-powered nebula is appealing (Predehl & Kulkarni 1995), no central engine had been detected in previous radio pulsation searches. In this Letter we report the discovery of a faint young pulsar coincident with the Mouse’s head, confirming that the Mouse is a synchrotron nebula powered by a high velocity neutron star.

2. OBSERVATIONS

The most sensitive previous pulsar search at the position of G359.23−0.82 was the Parkes Multibeam Pulsar Survey of the inner Galactic plane (Manchester et al. 2001). The Mouse is only one degree away from the Galactic center, where background synchrotron emission degrades considerably the system sensitivity, and we estimate that the flux density limit at the position of G359.23−0.82 was no better than 0.6 mJy at a frequency of 1374 MHz. Following the recent discovery at Parkes of the very faint pulsar J1124−5916 located in the supernova remnant (SNR) G292.0+1.8 (Camilo et al. 2002b), we began the deepest searches possible at Parkes of a number of good young pulsar candidates, including the Mouse.

On 2002 February 1 we searched the head of the Mouse using the center beam of the multibeam receiver at a central frequency of 1374 MHz. The observing setup was identical to that used in the discovery of PSR J1124−5916, with total-power signals from 96 frequency channels, spanning a total band of 288 MHz for each of two polarizations, sampled at 1 ms intervals and recorded to magnetic tape for off-line analysis. The total observation time was 9.4 hr. The data were reduced in standard fashion using an FFT-based code (see Lorimer et al. 2000 for details) to search for periodic signals in de-dispersed time series with trial dispersion measures (DMs) in the range 0–8800 cm$^{-3}$ pc. For further details, see Camilo et al. (2002b). A clear periodic and dispersed signal with period $P = 98.8$ ms was detected with maximum signal-to-noise ratio of 15.1 at DM $\approx 105$ cm$^{-3}$ pc.

We confirmed the pulsar with a 3 hr observation on February 3 and thereafter began similar regular timing observations, thus far having obtained 17 times-of-arrival (TOAs) spanning 6 months. We have used the TEMPO code and the TOAs to derive the ephemeris listed in Table 1. Based on the coordinates of this pulsar, we designate it as PSR J1747−2958. The observed flux density of the pulsar is somewhat variable, in a manner consistent with interstellar scintillation. We formed a...
mean pulse profile, shown in Figure 1, by averaging all available observations. This shows that the pulsed emission covers about 50% of the pulse period, rising slowly to the peak and falling sharply after it. This profile was calibrated (for details, see Manchester et al. 2001), taking into account the measured sky brightness temperature at the Mouse position (18 K), to derive a flux density of $S = 0.25 \pm 0.03$ mJy. The radio luminosity $Sd^2$ for a distance $d = 2$ kpc (see § 3) is $\sim 1$ mJy kpc$^2$. This is a very low value, but is similar to those of four young and energetic pulsars discovered recently (Halpern et al. 2001; Camilo et al. 2002a–c), highlighting that such pulsars can be very faint radio sources.

On 2002 May 15 we attempted, unsuccessfully, to measure the position of the pulsar independent of pulsar timing by performing pulsar-gated radio imaging with the Australia Telescope Compact Array (ATCA). We observed the field of the Mouse in the 6A array configuration simultaneously with two $32 \times 4$-MHz bandwidths centered at frequencies of 1.4 and 1.7 GHz for an effective on-source integration time of about 11 hr. PKS 1934–638 was the primary flux density calibrator and PKS 1748–253 was the secondary phase calibrator. While pointing at PSR J1747–2958, data for each baseline were integrated into 32 pulse phase bins coherently with the topocentric period of the pulsar. We also made a number of 5 min integrations on a strong pulsar, PSR B1641–45. The data were analyzed in standard fashion with the MIRIAD$^7$ software (see, e.g., Stappers, Gaensler, & Johnston 1999) eventually yielding “on-pulse − off-pulse” images. While PSR B1641–45 was detected easily, PSR J1747–2958 was not, with an upper limit on the flux density averaged over $\sim 0.1$ of the period of about 2 mJy. This is comparable to the expected peak flux density of the pulsar.

In Figure 2 we display two radio images of the Mouse. In the left panel we show a 42$'$ × 42$'$ field taken from the MOST Galactic Center Survey (MGCS; Gray 1994), with the field-of-view of our Parkes observation overlaid. In the right panel we show a higher resolution image of the head of the Mouse, expanded by a factor of 30 with respect to the left panel. This was obtained from an observation with the Very Large Array (VLA) in its A configuration on 1999 October 8 at a frequency of 8.4 GHz, using a bandwidth of 100 MHz with an on-source integration time of 3 hr, and analyzed in standard fashion.

3. DISCUSSION

The $P$ and $P$ measured for PSR J1747–2958 imply a relatively large spin-down luminosity $\dot{E} = 4\pi^2 IP/P^3 = 2.5 \times 10^{36}$ erg s$^{-1}$ (where the neutron star moment of inertia $I \equiv 10^{45}$ g cm$^2$), small characteristic age $\tau_c = P/2P = 25$ kyr, and surface magnetic dipole field strength $B = 3.2 \times 10^{13}(P/10^3)^{1/2} = 2.5 \times 10^{13}$ G. These parameters place PSR J1747–2958 in the group of $\approx 20$ “Vela-like” pulsars now known (those with $\dot{E} \gtrsim 10^{36}$ erg s$^{-1}$ and $10 \lesssim \tau_c \lesssim 100$ kyr). In the remainder of this section we discuss the evidence linking PSR J1747–2958 with the Mouse.

With the present positional accuracy (Table 1 and Fig. 2), the offset between the pulsar’s timing position and that of the head of the Mouse seen in the right panel of Figure 2 is $7'' \pm 37''$, and the area of the error ellipse is $5 \times 10^{-5}$ deg$^2$. With approximately 1000 pulsars known in an area $\approx 1000$ deg$^2$ along the inner Galactic plane ($260^\circ \lesssim l \lesssim 100^\circ$; $|b| \lesssim 2.5^\circ$), the probability of finding one by chance this close to the Mouse’s head is about $5 \times 10^{-5}$. We therefore regard the positional match of both sources as highly suggestive of an association. Eventually a more precise position for the pulsar will be obtained from timing, and possibly from Chandra observations.

We now consider distance indicators. The measured DM, together with the Cordes & Lazio (2002) model for the Galactic distribution of free electrons, implies a pulsar distance of 2 kpc (the older model of Taylor & Cordes 1993 yields $2.1 \lesssim d \lesssim 2.8$ kpc). The distance to the Mouse has been investigated using HI absorption measurements. Owing to the lack of absorption against a ring located 3 kpc from the Galactic center, Uchida et al. (1992) infer that the Mouse is located at $< 5.5$ kpc from the Sun. This is consistent with the pulsar distance determination, and hereafter we consider both objects to be located at $\approx 2$ kpc and parametrize the distance in terms of $d_5 = d/2$ kpc.

The head of the Mouse has been detected in X-rays, although with limited statistics (Priedehl & Kulkarni 1995) and angular resolution (Sidoli et al. 1999). Sidoli et al. model the source with a power-law spectrum having unabsorbed $2–10$ keV flux $\approx 3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Assuming this flux to be isotropic implies a luminosity $L_x \approx 1.4 \times 10^{34}$ $d_5^2$ erg s$^{-1}$, or an efficiency for conversion of spin-down luminosity into X-ray emission of $L_x/\dot{E} \sim 0.005$ $d_5^2$. This is apparently a factor of $\approx 4$ larger than the comparable efficiency in the PSR B1757–24/Duck pulsar wind nebula (Kaspi et al. 2001), a system displaying a bow-shock morphology (Gaensler & Frail 2000) and seeming in many respects similar to the Mouse/PSR J1747–2958, including a pulsar with comparable spin parameters. Only X-ray observations with higher sensitivity and resolution will settle the issue, but the presently available data do indicate that the X-ray emission observed from the direction of the Mouse’s head is certainly compatible with an origin in this system, located at a distance of $\approx 2$ kpc.

Given the positional coincidence, consistency in distance indicators, and energetics compatible with a common source, we regard the PSR J1747–2958/Mouse association as secure. The morphology of the Mouse (bright head, coincident with PSR J1747–2958, trailed to the west by a $12'$-long cometary tail; Fig. 2) suggests fast motion of the pulsar through the ambient ISM. The tail (length $L \approx 7$ $d_5$ pc) presumably results from synchrotron radiation produced by the pulsar relativistic wind in the nebular magnetic field. For a typical field of tens of $\mu$G, the lifetime of the radiating particles is $\approx 10^6$ yr. The non-thermal spectrum steepens away from the pulsar location likely due to synchrotron losses (Yusef-Zadeh & Bally 1987). Much can be learned about the pulsar and the local ISM through a detailed study of the Mouse’s head and tail, as we now outline.

As the pulsar moves supersonically through the ambient medium producing a bow shock, the morphology of the Mouse’s head is expected to be shaped by ram-pressure balance between the pulsar relativistic wind and the local ISM. In particular, the standoff radius of the shock, $R_0$, for a neutron star moving with velocity $V$ through a medium of density $\rho$, is determined from $\rho V^2 = E/(4\pi c R_0^2)$ (see, e.g., Chatterjee & Cordes 2002). We assume that the pulsar wind is radiated isotropically, and hereafter neglect projection effects. We have not measured the standoff angle $\theta_0 = R_0/d$, but infer a crude estimate from Figure 2 as follows. The width of the Mouse’s head in the presumed direction of motion (west to east) is about 176. It is likely that the pulsar lies within this region of intense synchrotron emission and that the apex of the bow shock lies just outside (Bucciantini 2002). Thus we estimate $\theta_0 \sim 1''$. 

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7 See http://www.atnf.csiro.au/computing/software/miriad.
parametrized as $\theta = \theta_0/1''$. With $\rho = 1.37 m_H n$, where $n$ is the medium’s number density, $m_H$ is the mass of the H atom, and the numerical factor derives from assuming a cosmic abundance of He in the ISM (Chatterjee & Cordes 2002), we obtain $V \sim 570/(d_2 \theta_0 n^{1/2})$ km s$^{-1}$, where we have used the $E$ measured for PSR J1747–2958. For a reasonable pulsar velocity ($1000 \gtrsim V \gtrsim 100$ km s$^{-1}$; e.g., Lyne & Lorimer 1994), this implies an ISM of high density, $0.3 \lesssim n \lesssim 30$ cm$^{-3}$. In turn this suggests the pulsar is moving (rapidly) through a warm or cold phase of the ISM (e.g., Heiles 2001), with attendant small sound speed $C$, and hence that its Mach number should be high, $V/C \gg 10$. We now extend our attention to the Mouse’s tail.

We can obtain a crude estimate of the pulsar’s age $\tau$ by considering that it has traveled the observed length of the tail in its lifetime, $\tau = L/V \approx 12 d_2 V_{570} / 570$ kyr, where $V = 570 V_{570}$ km s$^{-1}$. The age may differ significantly from this if only part of the tail has been detected or if the tail is instead caused by a relatively recent pulsar backflow (e.g., Kaspi et al. 2001). The actual age compares to the pulsar characteristic age of $\tau_c \approx 25$ kyr. These are related by $\tau = 2 \tau_c (1 - P_0/P)^{n-1}/(n-1)$ under the assumption of constant magnetic moment, where $P_0$ is the initial period and $n$ is the braking index of rotation (Manchester & Taylor 1977). A number of factors may cause $\tau$ to be larger, or smaller, than $\tau_c$. $P_0 \ll P$, and $n = 3$, appropriate to magnetic dipole braking, are usually assumed. However for some pulsars $n < 3$ (Mereghetti et al. 2002 and references therein). Also, $P_0$ may be large, up to perhaps $\approx 90$ ms (e.g., Camilo et al. 2002b). In light of these issues, we regard the pulsar’s characteristic age as approximately consistent with that inferred from the length of the tail, confirming this source as a relatively young pulsar.

In summary, while it appears that the nature of the source powering the Mouse has finally been uncovered with the discovery of PSR J1747–2958, much remains to be understood about this fascinating object, requiring further observational efforts. A key measurement to be made is the proper motion of the pulsar, $\mu = 60 V_{570}/d_2$ mas yr$^{-1}$. This may be possible through Chandra observations and, depending on the amount of “timing noise” present in the neutron star, via radio timing. The pulsar–bow-shock standoff distance is also of great interest. Finally, further study of the Mouse’s tail, independent characterization of the local ISM, and any improvement to the distance estimate, would be most useful.

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Table 1
PARAMETERS OF PSR J1747–2958

| Parameter                              | Value                                      |
|----------------------------------------|--------------------------------------------|
| R.A. (J2000) [pulsar]                  | 17$^h$47$^m$16$^s$.1(4)                   |
| R.A. (J2000) [nebula]                  | 17$^h$47$^m$15$^s$.8(1)                   |
| Decl. (J2000) [pulsar]                 | $-29^\circ$58$'$07$''$.37(37)             |
| Decl. (J2000) [nebula]                 | $-29^\circ$58$'$00$''$.2(2)               |
| Galactic coordinates [nebula]          | 359$^\circ$.305, $-0^\circ$.841            |
| Period, $P$ (ms)                       | 98.81275773(5)                             |
| Period derivative, $\dot{P}$           | $6.136(5) \times 10^{-14}$                |
| Epoch (MJD [TDB])                      | 52383.0                                    |
| Dispersion measure, DM (cm$^{-3}$ pc)  | 101.5(16)                                  |
| Flux density at 1374 MHz (mJy)         | 0.25 $\pm$ 0.03                            |
| Pulse FWHM at 1374 MHz (ms)            | 7 $\pm$ 1                                  |
| Distance, $d$ (kpc)                    | $\approx 2$                                |
| Derived parameters:                    |                                            |
| Characteristic age, $\tau_c$ (kyr)    | 25.5                                       |
| Spin-down luminosity, $\dot{E}$ (erg s$^{-1}$) | $2.5 \times 10^{36}$                        |
| Magnetic field strength, $B$ (G)       | $2.5 \times 10^{12}$                       |
| Luminosity at 1400 MHz (mJy kpc$^2$)   | $\sim 1$                                   |

Note. — Numbers in parentheses represent 1$\sigma$ uncertainties in the last digits quoted and, except as noted, are equal to twice the formal errors determined with TEMPO.

*Derived from timing measurements. Uncertainty in Decl. is much larger than in R.A. due to the low ecliptic latitude ($\beta = -6^\circ$) of the pulsar.

Derived from VLA measurements (see Fig. 2). Position (uncertainty) is that of center (extent) of head of the Mouse, an ellipse oriented at P.A. $\approx 0^\circ$. This position is coincident with that of the X-ray source detected by ROSAT with $\approx 8''$ uncertainty (Predehl & Kulkarni 1995).
Fig. 1.— Mean pulse profile of PSR J1747–2958 at 1374 MHz, based on 56 hr of Parkes observations.
Fig. 2.— Radio images of the Mouse. *Left:* Large scale view at 0.8 GHz from the MGCS with an angular resolution of $43''$, showing the Mouse's bright head and long tail, and the unrelated (Uchida, Morris, & Yusef-Zadeh 1992) SNRs G359.1–0.5 (west) and G359.0–0.9 (south). *Right:* Detailed view of the Mouse’s head from VLA observations at 8.4 GHz with resolution of $0''9 \times 0''4$ and r.m.s sensitivity of 20 $\mu$Jy beam$^{-1}$. The head is clearly resolved in this image. At the estimated distance of 2 kpc (see § 3), $0''5$ corresponds to a linear size of 1000 AU. Notice the relatively faint “wake” of nearly triangular shape, with apparent (semi) opening angle $\sim 30^\circ$. The ellipse denotes the current positional uncertainty of PSR J1747–2958, determined from timing observations (Table 1).