

A PROBABLE OPTICAL COUNTERPART TO THE ISOLATED NEUTRON STAR RX J1308.6+2127

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ABSTRACT

Using a very deep observation from the *Hubble Space Telescope* Space Telescope Imaging Spectrometer, we have searched for an optical counterpart to the nearby radio-quiet isolated neutron star RX J1308.6+2127 (RBS 1223). We have identified a single object in the 90% *Chandra* error circle that we believe to be the optical counterpart. This object has $m_{50\text{CCD}} = 28.56 \pm 0.13$ mag, which translates approximately to an unabsorbed flux of $F_\lambda = (1.7 \pm 0.3) \times 10^{-20}$ ergs s⁻¹ cm⁻² Å⁻¹ at 5150 Å or an X-ray-to-optical flux ratio of $\log(f_x/f_{\text{opt}}) = 4.9$. This flux is a factor of ≈ 5 above the extrapolation of the blackbody fit to the X-ray spectrum, consistent with the optical spectra of other isolated neutron stars. Without color information, we cannot conclude that this source is indeed the counterpart to RX J1308.6+2127. If not, then the counterpart must have $m_{50\text{CCD}} > 29.6$ mag, corresponding to a flux that is barely consistent with the extrapolation of the blackbody fit to the X-ray spectrum.

Subject headings: pulsars: individual (RX J1308.6+2127) — stars: neutron — X-rays: stars

1. INTRODUCTION

Neutron stars have been regarded as natural laboratories for matter denser than can be obtained by heavy-ion accelerators. The basic physics is summarized by the mass and radius, with larger radii for a given mass favoring stiffer equations of state (Lattimer & Prakash 2000). It is against this backdrop that one recognizes that one of the major outcomes of the all-sky survey undertaken by the X-ray satellite *ROSAT* was the systematic identification of the nearest neutron stars (see reviews by Motch 2001 and Treves et al. 2000).

RX J1308.6+2127 (also known as RBS 1223) was identified as a candidate neutron star from the *ROSAT* Bright Survey by Schwöpe et al. (1999) on the basis of its soft X-ray spectrum (blackbody with $kT \approx 100$ eV), constant X-ray flux, and lack of optical counterpart. It now joins six other similar objects (RX J1856.5–3754, RX J0720.4–3125, RX J1605.3+3249, RX J2143.0 +0654, RX J0806.4–4123, and RX J0420.0–5022; Walter, Wolk, & Neuhäuser 1996; Haberl et al. 1997; Motch et al. 1999; Haberl, Pietsch, & Motch 1999; Zampieri et al. 2001) and three previously known pulsars (Geminga, PSR B0656+14, and PSR B1055–52) in the sample of nearby 10^6 yr neutron stars detected by the *ROSAT* Bright Survey.

Of these objects, the five brightest (in terms of soft X-ray count rate) have been well studied. PSR 0656+14 and PSR B1055–52 are well-known radio pulsars, not particularly remarkable in any other way. Geminga, first identified via γ -ray emission (and thereby dramatically demonstrating that radio pulsars can lose a large fraction of their energy via γ -rays), is now generally considered to be an ordinary pulsar whose radio beam we happen to miss.

In contrast, RX J1856.5–3754 and RX J0720.4–3125 are mysterious. Both sources have (as expected) faint, blue, optical counterparts (Walter & Matthews 1997; Kulkarni & van Kerkwijk 1998), with X-ray-to-optical flux ratios of $\log(f_x/f_{\text{opt}}) \sim 5$. RX J1856.5–3754 shows no significant pulsations (Ransom, Gaensler, & Slane 2002), and despite significant investment of *Chandra* time, the X-ray spectrum is featureless (Drake et al. 2002). There is no evidence of any nonthermal emission (van

Kerkwijk & Kulkarni 2001b). Conventional models for this source include a weakly magnetized cooling neutron star (van Kerkwijk & Kulkarni 2001a) or an off-beam radio pulsar (like Geminga, but without the γ -ray emission; Braje & Romani 2002). In contrast, RX J0720.4–3125 shows 8.4 s pulsations. It too exhibits a featureless X-ray spectrum (largely thermal; Paerels et al. 2001). Again, conventional possibilities include an off-beam radio pulsar, but the long period would require that the neutron star be born with either an unusually long period or an unusually large magnetic field (Kaplan et al. 2002a; Zane et al. 2002).

Thus, the five brightest (in soft X-rays) and presumably nearest neutron stars show a stunning diversity. Our understanding of the nature of two (or perhaps even three) of these sources is quite incomplete.

In this Letter, we redetermine the position of RX J1308.6+2127 from archival *Chandra* analysis. We present radio observations of RX J1308.6+2127, and we then discuss very deep optical observations aimed at detecting its optical counterpart. This source exhibits long-period pulsations with $P = 5.16$ s. However, unlike RX J0720.4–3125, a large period derivative has been measured (Hambaryan et al. 2002). If this is ascribed to magnetic braking, then the implied dipole field strength is $B \geq 10^{14}$ G, and RX J1308.6+2127 is a magnetar. Kulkarni & van Kerkwijk (1998) and Heyl & Kulkarni (1998) advocated the magnetar model for nearby long-period pulsators because magnetars have an additional source of heat (their magnetic fields) and thus are warmer than ordinary neutron stars for a longer duration.

2. OBSERVATIONS AND DATA REDUCTION

2.1. X-Ray

We used the 10 ks observation of RX J1308.6+2127 from the *Chandra X-Ray Observatory* described in Hambaryan et al. (2002) to determine the position of the X-ray source. The main change from the analysis presented by Hambaryan et al. (2002) was that we corrected the spacecraft aspect by 0".23

TABLE 1
SUMMARY OF OPTICAL OBSERVATIONS

Telescope	Instrument	Date (UT)	Exposure (s)	Band
Keck II	ESI	2000 May 3	3500	<i>R</i>
<i>HST</i>	STIS	2001 Jul 22	5264	50CCD
	STIS	2001 Aug 4	15880	50CCD
Palomar	LFC	2002 Mar 5	375	<i>r</i>

according to the *Chandra* X-ray Center prescription.¹ We measured the centroid of the X-ray source to be (J2000): $\alpha = 13^{\text{h}}08^{\text{m}}48^{\text{s}}.27$, $\delta = +21^{\circ}27'06''.78$, with statistical uncertainties of $\pm 0''.05$ in each coordinate. This position is consistent with the position determined by Hambaryan et al. (2002) and with the *ROSAT* HRI position, but it has been tied (at least statistically) to the International Celestial Reference System (ICRS) and is therefore preferable for comparison with other data sets. Overall, the positions of X-ray sources that have been corrected for aspect errors match the optical positions (from the ICRS or Tycho) with a 90% confidence radius of $0''.6$, with a distribution that is highly non-Gaussian.²

2.2. Radio

We observed RX J1308.6+2127 with the Very Large Array at 1.4 GHz on 2001 February 12–14, with a total integration time of 173 minutes. Observations were done in the BnA configuration with 2×50 MHz bandwidths, giving a final beam size of $1''.2 \times 3''.8$. All data sets were independently calibrated using AIPS and then combined for imaging. Imaging and self-calibration were performed in DIFMAP. The data were repeatedly cleaned and self-calibrated (phase corrections only) until the solution converged. After cleaning, we found the rms map noise to be 0.032 mJy.

No emission from RX J1308.6+2127 was found, giving a 3σ upper limit to the flux of a point source of 0.10 mJy. This implies a radio luminosity limit for RX J1308.6+2127 of $0.05d_{700}^2$ mJy kpc², where the distance is $d = 700d_{700}$ pc (Kaplan, van Kerkwijk, & Anderson 2002b). Such a limit is a factor of 10 below the luminosity for PSR J0205+6449 in 3C 58 (Camilo et al. 2002) and a factor of 2 above the limit for Geminga (Seiradakis 1992). In fact, it is below virtually all of the radio pulsars younger than 10^6 yr (Motch 2001).

2.3. Optical

Schwabe et al. (1999) unsuccessfully searched for an optical counterpart to RX J1308.6+2127 and determined limits of $B \geq 26$ mag and $R \geq 26$ mag from observations at Keck. The large X-ray-to-optical flux ratio inferred from the ground-based data strongly favored a neutron star origin for RX J1308.6+2127. Accordingly, we obtained data from the Space Telescope Imaging Spectrometer (STIS) aboard the Hubble Space Telescope (*HST*), listed in Table 1. The data were taken with the CCD without a filter (50CCD aperture), which gives an extremely broad spectral response from 3000 to 9000 Å. For these data, we drizzled (Fruchter & Hook 2002) all the individual exposures onto a single image, for a total exposure of 21,144 s (eight orbits). We used a pixel scale of 0.5, so that the final image had $0''.0254$ pixels. For astrometric purposes,

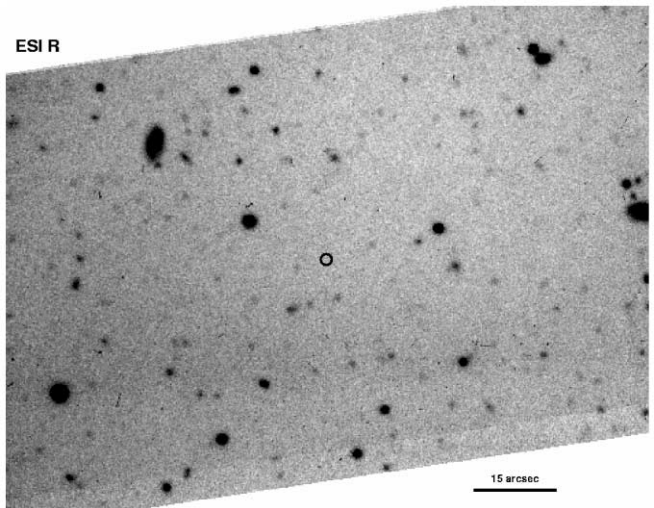


FIG. 1.—Keck ESI image of the field around RX J1308.6+2127. The image is $\approx 2'$ on a side, with north up and east to the left. The $1''.0$ radius *Chandra* error circle is shown.

we also obtained data with the Echelle Spectrograph and Imager (ESI; Sheinis et al. 2002) at the Keck II telescope and with the Large Format Camera (LFC) at the Palomar 200 inch telescope. We performed the standard reduction of the ground-based data in IRAF, subtracting bias images, flat-fielding, and stacking the exposures. We referenced the astrometry to the latest version of the Guide Star Catalog (GSC 2.2).³ After applying a distortion solution (M. Hunt 2002, private communication),⁴ we identified 142 unsaturated stars on the LFC image, solved for the rotation, zero point, and plate scale (the same terms were used for all subsequent astrometric solutions), and got residuals of $0''.4$ in each coordinate.

We used 13 sources on the LFC image to transfer the astrometric solution to the ESI image, with residuals of $0''.14$ in each coordinate. From the ESI image (Fig. 1), we identified 10 stars that we used to go to the STIS image and obtained residuals of $0''.06$ in each coordinate. Assuming a $0''.3$ intrinsic uncertainty⁵ for the GSC 2.2, we then have overall uncertainties of $0''.3$ in each coordinate for the STIS image. With the $0''.6$ 90% radius for the X-ray astrometry, we estimate a final 90% confidence radius of $\approx 1''.0$.

3. ANALYSIS AND DISCUSSION

In the following, we use the results of the spectroscopic fits of Hambaryan et al. (2002) to the *Chandra* data. Specifically, we take $N_{\text{H}} = (2.4 \pm 1.1) \times 10^{20} \text{ cm}^{-2}$, $kT = 91 \pm 1 \text{ eV}$, and $R = (6.5 \pm 0.3)d_{700} \text{ km}$, where the normalization comes from the *Chandra* count rate. This spectrum implies an unabsorbed flux of $(3.5 \pm 0.3) \times 10^{-21} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$ at 5150 Å.

There is only one optical source inside the *Chandra* error circle. This source, marked X in Figure 2, is a possible counterpart to RX J1308.6+2127. There are no other potential counterparts visible in Figure 2, the next closest unresolved source being $\approx 4''$ from the *Chandra* position (source B in Fig. 2).

Without color information, it is difficult to accurately pho-

¹ See http://asc.harvard.edu/cal/ASPECT/fix_offset/fix_offset.cgi.

² See <http://asc.harvard.edu/cal/ASPECT/celmon>.

³ See http://www-gsss.stsci.edu/support/data_access.htm.

⁴ See <http://wopr.caltech.edu/~mph/lfcrcd>.

⁵ See <http://www-gsss.stsci.edu/gsc/gsc2/calibrations/astrometry/astrometry.htm#method>.

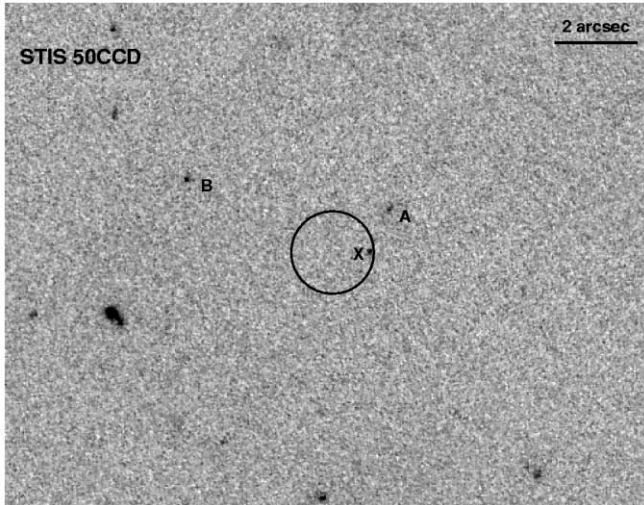


FIG. 2.—*HST*/STIS image of the field around RX J1308.6+2127. The image is $\approx 15''$ on a side, with north up and east to the left. The $1'\!0$ radius *Chandra* error circle is shown. Source X, the likely counterpart of RX J1308.6+2127, and the unrelated sources A and B are also indicated. Source A is extended.

tometer the 50CCD data. This is because its wide bandwidth makes the aperture corrections and zero-point fluxes color-dependent, leading to uncertainties of greater than a factor of 2 for the flux coming from stars ranging from type M to type O. In what follows, we follow the analysis of D. L. Kaplan, S. R. Kulkarni, M. H. van Kerkwijk, D. A. Frail, H. L. Marshall, & B. A. Jacoby (2002, in preparation) for RX J0720.4–3125. We assumed that X is the counterpart and therefore has blue colors (similar to RX J1856.5–3754 and RX J0720.4–3125; van Kerkwijk & Kulkarni 2001b; Kulkarni & van Kerkwijk 1998). Then we used the bluest of the available aperture corrections: 0.183 mag at $0\!^{\circ}\!254$ radius (T. Brown 2002, private communication). This correction is for a star with $B-V = -0.09$ mag, compared with an expected $B-V = -0.3$ mag for RX J1308.6+2127, and is therefore not quite right. However, the scattered light that contributes to the color dependence of the STIS aperture corrections is predominantly red. For blue sources, the dependence of the correction on color is relatively small: for a star with $B-V = 0.05$ mag, the correction changes by about 0.01 mag from that for a source with $B-V = -0.09$ mag. So the aperture correction used here should be reasonably appropriate, and to account for any remaining differences, we have added a 0.02 mag systematic uncertainty into the photometry for RX J1308.6+2127.

With this correction, we find a magnitude of $m = 28.56 \pm 0.13$ mag for X at infinite aperture. The 3σ limiting magnitude is ≈ 29.6 mag. These magnitudes are in the STMAG system, where $F_{\lambda} = 10^{-(m+21.1)/2.5}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$. Assuming a spectrum similar to a Rayleigh-Jeans tail, this relation holds at $\lambda \approx 5148$ Å (this is the wavelength at which a Rayleigh-Jeans spectrum has the same flux as a flat spectrum that produces the same number of counts in the 50CCD band; see Appendix A of van Kerkwijk & Kulkarni 2001b).

From this, we find $F_{\lambda}(X) = (1.4 \pm 0.2) \times 10^{-20}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$ at 5148 Å. We estimate $A_V = 0.14 \pm 0.06$ mag, using the hydrogen column from above and the relation from Predehl & Schmitt (1995). Again, assuming a Rayleigh-Jeans spectrum, we convert A_V to the extinction appropriate for the

50CCD bandpass (again, see van Kerkwijk & Kulkarni 2001b) and find that $A_{50CCD} = 0.22 \pm 0.09$ mag. This gives us an unabsorbed flux of $(1.7 \pm 0.3) \times 10^{-20}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$.

The optical flux of X is then a factor of ≈ 5 higher than the extrapolation of the X-ray blackbody of RX J1308.6+2127, smaller than the value of 16 found for RX J1856.5–3754 (van Kerkwijk & Kulkarni 2001b), but very similar to the values found for RX J0720.4–3125 and PSR B0656+14 (D. L. Kaplan, S. R. Kulkarni, M. H. van Kerkwijk, D. A. Frail, H. L. Marshall, & B. A. Jacoby 2002, in preparation; Koptsevich et al. 2001). Likewise, the unabsorbed X-ray-to-optical flux ratio is $\log(f_X/f_{\text{opt}}) = 4.9$ (where the X-ray flux has been integrated over the entirety of the blackbody spectrum). The similarity of these values to those for other isolated neutron stars suggests that source X is the optical counterpart of RX J1308.6+2127.

While a blue color would assure us that X is the counterpart of RX J1308.6+2127, without color information we cannot be certain. Source X is very similar to the counterparts of RX J0720.4–3125 and RX J1856.5–3754, but it is possible that it is an unrelated source and that no counterpart was detected. If that is the case, then any counterpart would have $m_{50CCD} > 29.6$ mag [$\log(f_X/f_{\text{opt}}) > 5.3$] or an optical flux just consistent with the extrapolation of the X-ray blackbody fit.

Aside from color information (difficult to obtain given its faintness), another good test for the nature of source X is proper motion. Neutron stars have significantly higher proper motions than the stellar population, with velocities of ~ 100 km s $^{-1}$ typical for the general population of neutron stars (Arzoumanian, Chernoff, & Cordes 2002). Such high velocities have been found for the local neutron star population as well (e.g., Migani, De Luca, & Caraveo 2000; Walter 2001). Assuming a velocity of 100 km s $^{-1}$, the proper motion of RX J1308.6+2127 would be $30d_{700}^{-1}$ mas yr $^{-1}$. While the absolute astrometry from the STIS image does not have this precision, we expect to be able to perform relative astrometry with at least ~ 20 mas precision (the limiting factors are the distortion correction and modeling of the point-spread function, which is color-dependent), although this has not been tested for STIS. If this is the case, then in the next few years proper motion of source X may be detectable, and if so source X would almost certainly be a neutron star (if X were instead a star, it would have to be many kiloparsecs away and would therefore have negligible proper motion and be out of the Galaxy, given its Galactic latitude of $b = 83^{\circ}$).

In the P - \dot{P} plane, RX J1308.6+2127 appears very similar to the anomalous X-ray pulsars (AXPs; Mereghetti 2001). However, whether or not we have detected the counterpart of RX J1308.6+2127, the X-ray-to-optical flux ratio is considerably higher than those found for AXPs (Hulleman, van Kerkwijk, & Kulkarni 2000; Hulleman et al. 2001; Wang & Chakrabarty 2002): for 4U 0142+61, $\log(f_X/f_{\text{opt}}) \approx 4.1$ (where the X-ray flux is measured from 0.5 to 10 keV; Juett et al. 2002). The optical emission from AXPs, which has a nonthermal spectrum, is thought to arise from the magnetosphere. Therefore, the lack of an active magnetosphere would significantly decrease the optical flux. Scaling the nonthermal X-ray emission of 4U 0142+61 by the optical flux of RX J1308.6+2127, we would predict an X-ray power law for RX J1308.6+2127 that would have been easily visible with *Chandra* (2×10^{-3} photons s $^{-1}$ cm $^{-2}$ keV $^{-1}$ at 1 keV). Since this power law is not seen (Hambaryan et al. 2002), it appears that despite its rapid spin-down, RX J1308.6+2127 does not have an active magnetosphere. Without an active magnetosphere, the optical emis-

sion from RX J1308.6+2127 would likely be similar to those of RX J1856.5–3754 and RX J0720.4–3125, suggesting that we have indeed found the counterpart to RX J1308.6+2127.

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