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OPTICAL OBSERVATIONS OF THE ISOLATED NEUTRON STAR RX J0720.4−3125

S. R. KULKARNI
Palomar Observatory 105-24, California Institute of Technology, Pasadena, CA 91125; srk@astro.caltech.edu
AND
M. H. VAN KERKWIJK[1]
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England, UK; mhvk@ast.cam.ac.uk
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ABSTRACT

RX J0720.4−3125 is an unidentified bright, soft X-ray source that shows pulsations at an 8.39 s period and has a thermal spectrum. We present deep *B*- and *R*-band images of its X-ray localization. We find one possible counterpart in the X-ray error box, with magnitudes $B = 26.6 \pm 0.2$ and $R = 26.9 \pm 0.3$. The very high X-ray–to–optical flux ratio confirms that this object is an isolated neutron star. We discuss possible models, and we conclude that only two are consistent with the data and at the same time are able to draw from a large enough population to make finding one nearby likely. In our opinion, the second criterion provides a stringent constraint but appears to have been ignored so far. The first model, suggested earlier, is that RX J0720.4−3125 is a weakly magnetized neutron star accreting from the interstellar medium. The second is that it is a relatively young, highly magnetized neutron star, a "magnetar," which is kept hot by magnetic field decay.

Subject headings: stars: individual (RX J0720.4−3125) — stars: magnetic fields — stars: neutron — X-rays: stars

1. INTRODUCTION

The population of defunct radio pulsars far exceeds that of active ones. It is believed that the Galaxy has about 2×10^5 radio pulsars. The neutron star birthrate is estimated to be between one per 30 yr and one per 100 yr. Assuming a constant pulsar production rate and an age of the disk of 10^{10} yr, one infers a Galactic neutron star population of $\sim 2 \times 10^8$, 3 orders of magnitude larger than that of the active radio pulsar population.

It is not easy to detect old neutron stars. While the nearest few intermediate-age pulsars can be identified by their cooling radiation, which peaks in the soft X-ray/EUV band, the defunct pulsars will have become too cool to be observable. A small fraction of them, however, may be in a position to accrete matter from the interstellar medium (ISM). These will then get reheated and reappear in the X-ray sky.

Quite independent of this discussion, there has been a growing recognition of a population of highly magnetized neutron stars. The circumstantial evidence for this class comes from studies of soft gamma-ray repeaters (SGRs) and long-period pulsars in supernova remnants (Vasisht & Gotthelf 1997). Thompson & Duncan (1995) have introduced the term "magnetars" for neutron stars with field strengths significantly larger than 10^{12} G, the typical field strength inferred for radio and X-ray pulsars. The birthrate of SGRs has been estimated to be roughly 10% that of ordinary pulsars (Kulkarni & Frail 1993; Kouveliotou et al. 1994).

The relevance of magnetars to the discussion at hand is as follows. Unlike the situation for ordinary neutron stars, magnetic field decay is expected to be significant in highly magnetized neutron stars. This decay could reheat the magnetar (Thompson & Duncan 1996), making it hotter than an ordinary neutron star and thus brighter in soft X-rays.

Two of the best candidates for this general class of neutron stars have emerged from the *ROSAT* mission: RX J185635−3754 (Walter, Wolk, & Neuhäuser 1996) and RX J0720.4−3125 (Haberl et al. 1997). Both are bright *ROSAT* objects with very soft X-ray spectra. Walter & Matthews (1997) have provided compelling evidence for the identification of a faint blue optical counterpart of RX J185635−3754. In this Letter, we present deep *B* and *R* observations of the localization of RX J0720.4−3125.

2. RX J0720.4−3125

The basic X-ray properties are described by Haberl et al. (1997). A brief summary now follows. With a Position Sensitive Proportional Counter (PSPC) count rate of 1.67 s^{-1}, the source is one of the brighter in the *ROSAT* All-Sky Survey. The PSPC spectrum is fitted very well by a blackbody with $kT_{\mathrm{eff}} = 79 \pm 4$ eV absorbed by a column density $N_{\mathrm{H}} = (1.3 \pm 0.3) \times 10^{20}\ \mathrm{cm}^{-2}$. The observed flux in the 0.1–2.4 keV *ROSAT* band is $1.15^{+0.3}_{-0.14} \times 10^{-11}$ ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. Using PIMMS (Portable Interactive Multimission Simulator),[2] we estimate, for the blackbody model mentioned above, an unabsorbed flux of 1.8×10^{-11} ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the range 0.010–2.4 keV.

Perhaps the most remarkable fact about the source is neither its high count rate nor its soft X-ray spectrum, but the presence of pulsations with a 8.39 s period. The period is very stable: from observations done over a 3 yr period, Haberl et al. find a period derivative $\dot{P} = (-2.6 \pm 3.4) \times 10^{-12}\ \mathrm{s\ s}^{-1}$. This argues for the period to be the rotation period of the star. The shortness of the period rules out all models save those involving a neutron star or a white dwarf.

Haberl et al. found no optical counterpart within the *ROSAT* HRI error circle and noted an X-ray–to–optical flux ratio of $\gtrsim 500$. Such a high value is barely compatible with a model involving an accreting low-mass X-ray binary and certainly excludes any model based on an accreting white dwarf binary.

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[1] Present address: Astronomical Institute, Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands: M.H.vanKerkwijk@astro.uu.nl.

[2] PIMMS is available at http://legacy.gsfc.nasa.gov, which is maintained by NASA Goddard Space Flight Center.

We note that an isolated hot white dwarf (planetary nebula nucleus) would be incompatible with the high inferred blackbody temperature.

3. OPTICAL OBSERVATIONS

We imaged the field containing RX J0720.4−3125 with the Low-Resolution Imaging Spectrograph (Oke et al. 1995), mounted at the Cassegrain focus of the Keck II telescope, on the nights of 1997 November 28 and 29 (UT). The detector was a 2048 × 2048 pixel Loral CCD that was read out with two amplifiers. The skies appeared to be clear on the second night, but the first night was plagued by cirrus. A log of the observations is given in Table 1.

During the second night, four flux-standard fields from Landolt (1992) were observed (defocusing the telescope to avoid saturation of pixels). We took care to place our targets and most of the standards on the same side of the CCD chip, thereby ensuring that the same amplifier was used. From the standard stars, which had a range in $B - R$ from -0.4 to 1.7, we determined the color and extinction coefficients. The rms residual around the calibration is about 0.02 mag in both B and R.

The reduction was done using MIDAS (Munich Image Data Analysis System). Individual frames were bias-subtracted and then flat-fielded using twilight flats. For the RX J0720.4−3125 images, a fixed region around the target's position was extracted and cleaned of cosmic rays, and these images were added together by band and by night. The result is shown in Figure 1. The two X-ray position estimates from Haberl et al. (1997) are overdrawn, using astrometry relative to the USNO-A1.0 catalog (Monet et al. 1996; see also Table 2). Note that these are close to, but not exactly at, the position shown in Figure 7 of Haberl et al. We do not know the reason for this discrepancy.

As can be seen in the figure, only one source (hereafter "X") is found within the union (and intersection) of the two HRI error circles. It is well detected in the B image but barely detected in the R band. Scattered light from some nearby stars results in a strong gradient in the local sky. This made application of the standard photometric packages difficult. We proceeded by using a simplified point-spread function fitting, as follows. First, we used aperture photometry to measure the magnitudes for four relatively isolated, brighter "secondary" stars (22, 24, A, B; see Fig. 1 and Table 2). Next, we extracted the stellar images of these four stars, as well as those of candidate X and of star C, within a 21 × 21 pixel (4″.5 × 4″.5) region centered on each source, and fitted these to a two-dimensional Gaussian on top of a plane with an arbitrary tilt. From the fit, we determined the average FWHM for the four secondary stars. We then refitted all objects, keeping the FWHM fixed at the average, and used the amplitudes of the Gaussians to determine relative magnitudes. Finally, the difference with the aperture results for the secondary stars was used to calculate instrumental B and R magnitudes for stars X and C, and all magnitudes were calibrated using the solution found from the secondary stars.

In summary, our observations have identified only one source, star X, within the HRI localization region. This source is a plausible optical counterpart of RX J0720.4−3125. Its magnitudes are $B = 26.6 \pm 0.2$ and $R = 26.9 \pm 0.3$ (Table 2). It is moderately blue: $B - R = -0.3 \pm 0.4$.

TABLE 1
LOG OF OBSERVATIONS

Field	Filter	UT	$t_{\rm exp}$	sec z
RX J0720.4−3125	R	12:44	2 × 300	1.60
	B	12:58	4 × 600	1.60
	R	13:47	3 × 300	1.63
RX J0720.4−3125	B	12:27	3 × 900	1.60
	R	13:18	7 × 300	1.62
PG 2336+004 (A, B)	B	08:28	20	1.50
	R	08:32	5	1.52
SA 95 (41, 42)	R	08:38	5	1.10
	B	08:45	20	1.10
PG 1047+003 (PG, A, B, C)	R	14:08	5	1.33
	B	14:10	20	1.33
Ruben 149 (Ru, B, C, E, F, G)	B	15:43	10	1.35
	R	15:45	2 × 2	1.36

NOTE.—The UT date is 1997 November 28 for the first three entries and 1997 November 29 for all others. All exposure times are in seconds. The standard fields are from Landolt 1992; the stars actually used for the photometric calibration are listed in parentheses. The seeing (as measured in the R band) on the first night was 1″ and improved to 0″.8 on the second night.

4. THE NATURE OF RX J0720.4−3125

A straightforward conclusion we can draw from our observations is that the X-ray–to–optical flux ratio[3] is $f_{\rm X}/f_V \gtrsim 2 \times 10^5$. The approximate equality is applicable if source X is the optical counterpart of RX J0720.4−3125. The high value for the ratio rules out the possibility that RX J0720.4−3125 is an accreting neutron star binary, leaving only a single neutron star as a viable option. The X-ray spectrum is highly suggestive of thermal emission from a hot surface. If so, $f_{\rm X}$ constrains the distance to the source to be less than $450R_6$ pc, where R_6 is the radius of the neutron star in units of 10^6 cm.

RX J0720.4−3125 must be nearby since the inferred column density is rather small, 1.3×10^{20} cm^{-2}. As pointed out by Haberl et al. (1997), the source is in the general direction of the open cluster Collinder 140 (Claria & Rosenzweig 1978). FitzGerald, Harris, & Miller (1980) carried out extensive spectroscopic observations and derive $E_{B-V} = 0.04$, a distance of 410 ± 30 pc, and an age of 20 ± 6 Myr. Using the usual relation between dust and gas, the inferred total column density is 2.8×10^{20} cm^{-2}. RX J0720.4−3125 is within the confines of the cluster; thus, following Haberl et al. (1997), we place an upper limit of 410 pc on the distance to RX J0720.4−3125.

Accepting the conclusion that RX J0720.4−3125 is an isolated and nearby neutron star, we now turn to the question of why its surface is hot.

4.1. *A Young Neutron Star*

In this model, RX J0720.4−3125 is a nearby young neutron star. According to Umeda et al. (1993), an isolated neutron star, even with internal frictional heating, will cool down to $kT = 80$ eV at an age $\tau_{\rm cool} = 4 \times 10^5$ yr. For a given neutron star birthrate $B_{\rm ns}$, the expected number of neutron stars with an age less than $\tau_{\rm cool}$ and within a distance projected on the Galactic plane less than $\rho_{\rm lim}$ is $B_{\rm ns}\tau_{\rm cool}\pi\rho_{\rm lim}^2$. We make the assumption that most neutron stars are born as ordinary pulsars. Lyne et al. (1998) estimate the local birthrate of pulsars with a 400 MHz luminosity above 1 mJy kpc^2 as 2.8 ± 1.7 Myr^{-1} kpc^{-2}. Taking into account that many pulsars will not be beamed

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[3] In computing the X-ray–to–optical flux ratio, it is traditional to compute the optical flux using the following relation: $f_V = 10^{-0.4(V+13.42)}$ ergs cm^{-2} s^{-1} (see Maccacaro et al. 1988). We assumed $V \simeq B$ for source X.

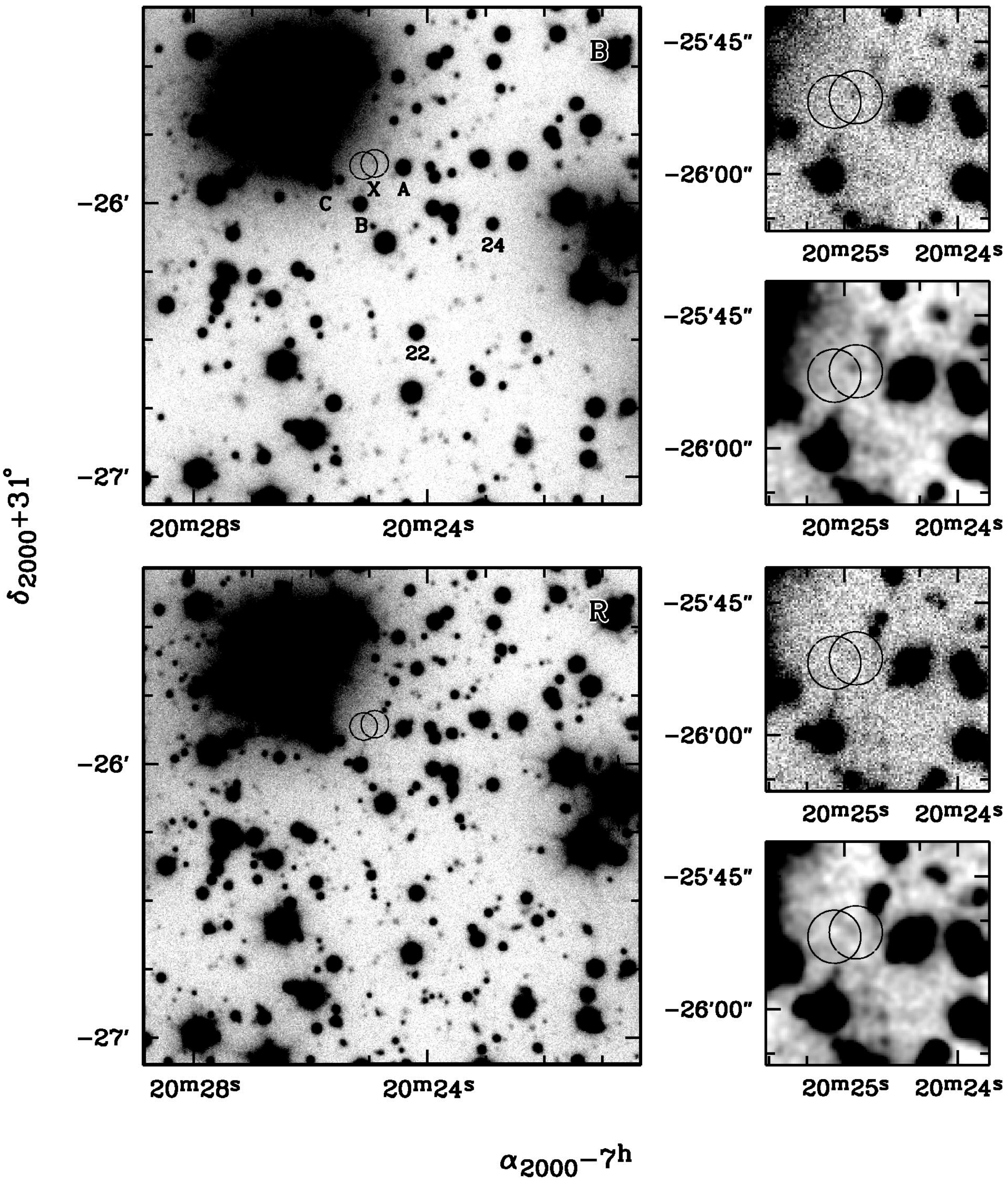

FIG. 1.—Summed *B* (*top*) and *R* (*bottom*) images of the localization of RX J0720.4−3125. The left-hand panels show an overview. The two circles represent the two HRI X-ray positions derived by Haberl et al. (1997). The stars mentioned in the text are labeled below their image in the top panel. The right-hand panels show an enlarged view of the region around the localization for each band. For these enlargements, the local sky was subtracted (determined by fitting a two-dimensional, second-order polynomial to the image with stars masked out). In the lower panels for each band, the image has furthermore been convolved with a Gaussian with a width approximately matching the seeing (FWHM of 4 pixels, 0.″85).

toward us, they derive a total birthrate of 10 ± 6 $\mathrm{Myr}^{-1}\,\mathrm{kpc}^{-2}$. Lyne et al. claim that the luminosity function flattens below 20 mJy kpc^2. If so, B_{ns} is well constrained. Hence, for $\tau_{\mathrm{cool}} = 0.4$ Myr and $\rho_{\mathrm{lim}} = 0.4$ kpc, we expect a total of 1.2–3.2 young nearby pulsars showing strong thermal emission. Geminga, at 160 pc, is perhaps the nearest example of a middle-aged cooling neutron star (Caraveo et al. 1996; Halpern & Wang 1997), while PSR B0656+14 (Finley, Ögelman, & Kiziloğlu 1992) and PSR B1055−52 (Ögelman & Finley 1993), both at ~500 pc, are examples of neutron stars whose radio emission is beamed toward us.

A problem for the young pulsar model, however, is the very

TABLE 2

Photometry and Astrometry of the Candidate Counterpart of RX J0720.4−3125 and Selected Stars in the Field

Star	B	R	α_{J2000}	δ_{J2000}
X	26.6(2)	26.9(3)	7 20 24.92	−31 25 50.9
A	20.52	19.42	7 20 24.40	−31 25 52.3
B	20.79	19.62	7 20 25.15	−31 26 00.3
C	21.23	18.85	7 20 25.76	−31 25 55.6
22	20.37	19.22	7 20 24.18	−31 26 28.4
24	21.49	20.13	7 20 22.88	−31 26 04.6

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The uncertainty in the photometry for star X is indicated by the number in parentheses. For the other stars, it is $\lesssim 0.02$ mag in both B and R. Comparing our measured $B-R$ with the main-sequence colors (Johnson 1966), we conclude that the spectral types of A and B are both roughly G2, quite consistent with what is indicated by the spectra of Haberl et al. 1997. Haberl et al. classified star C as M based on its spectrum; from both color and spectrum, we believe it is a little earlier, roughly K7. The V magnitudes inferred using these spectral types are consistent with the range quoted by Haberl et al. The uncertainty in the astrometry is dominated by the systematic uncertainty in the USNO-A1.0 catalog.

long spin period of 8.39 s. There is little evidence that normal pulsars are born with such long periods, and it would have taken too long to spin down from an initially short period. Thus, we consider this model to be unlikely.

4.2. *A Neutron Star Accreting from the ISM*

In this picture, already extensively discussed in the literature (Konenkov & Popov 1997; Wang 1997; Haberl et al. 1997), it is assumed that the neutron star is heated by matter being accreted from the ISM. An advantage compared with the young pulsar model is that one can draw on the entire old neutron star population. The principal uncertainty is whether all the conditions for accretion are met. These include (1) the unknown and small filling factor of a moderately dense interstellar medium, (2) the small fraction of neutron stars with sufficiently low velocity ($\lesssim$10%; Cordes & Chernoff 1998), and (3) the combination of dipole field strength and spin period needed to accrete matter. Accretion can proceed only if the Alfvén radius (the radius at which accretion flow pressure balances the magnetospheric pressure) is inside the corotation radius. For RX J0720.4−3125, Wang (1997) infers $B < 10^{10}$ G. Thus, if the field originally was similar to that observed in present-day young neutron stars, it must have decayed substantially. There is little evidence for any decay in ordinary pulsars. Indeed, Kulkarni & Anderson (1996) argue that the existence of long-period pulsars in clusters is incompatible with a field decay by more than a factor of 10 over a Hubble time. For this reason, we neglect this model.

Haberl et al. (1997) suggested an interesting possibility that might alleviate points 2 and 3 mentioned above, namely, that RX J0720.4−3125 is an evolved member of the group of so-called anomalous X-ray pulsars (Mereghetti & Stella 1995). These systems have similar pulse periods and are found close to the plane, often associated with young supernova remnants. If these systems are formed in common-envelope evolution of high-mass X-ray binaries, as suggested by van Paradijs, Taam, & van den Heuvel (1995), their space velocities are likely low, and their magnetic fields may be reduced because of accretion. For a birthrate of anomalous pulsars of about one per 3×10^3 yr (van Paradijs et al. 1995), there should be $\sim 1.6 \times 10^3$ descendants within $\rho_{\rm lim} < 0.4$ kpc. If all of these have suitably low velocity, the fraction visible as X-ray sources will depend only on the filling factor f of a dense ($\gtrsim 1$ cm^{-3}) interstellar medium. Even for an unrealistically low $f \sim 0.01$, we expect to see many accreting systems. Thus, this is a plausible model, subject only to the assumed birthrate of anomalous pulsars and whether they indeed evolve to low-velocity, low magnetic field, single neutron stars.

4.3. *A Magnetar*

The long period of 8.39 s is expected if the object is not a normal young pulsar but a magnetar. This possibility is briefly mentioned by Wang (1997) and considered in more detail by Heyl & Hernquist (1998). In the framework of the rotating magnet (vacuum) model for pulsars, one has $P\dot{P} \propto B_d^2$; here P is the rotation period and B_d is the strength of the dipole component of the magnetic field. Assuming that the neutron star was born with a period much shorter than the current period, we find $\dot{P} \equiv P/\tau = 3 \times 10^{-13}\tau_6^{-1}$ s s^{-1}, where the age of the magnetar is $\tau = 10^6\tau_6$ yr. This leads to $B_d \sim 5\tau_6^{-1/2} \times 10^{13}$ G.

Earlier we had stated that it has been argued that soft gamma-ray repeaters are young magnetars and that their birthrate is about 10% of that of the ordinary pulsars. With one magnetar for every 10 ordinary pulsars, the probability of finding a middle-aged magnetar is small but not negligible. Observationally, if we associate RX J0720.4−3125 and RX J185635−3754 with magnetars, the local number density of magnetars would be comparable to that of middle-aged ordinary pulsars. This would indicate that magnetars are brighter and/or longer lived as soft X-ray sources. Heyl & Hernquist (1998) have studied the thermal evolution in the presence of magnetic fields in detail. Curiously, their cooling timescales appear insensitive to the field strength when $kT_{\rm eff} \lesssim 100$ eV. However, their models neglect the influence of magnetic field decay. For these high field strengths, decay is expected (Thompson & Duncan 1996; see also Goldreich & Reisenegger 1992). We believe this field decay is what sets magnetars apart from and could make them brighter than ordinary neutron stars. Therefore, we would argue that RX J0720.4−3125 could well be a magnetar.

5. THE NATURE OF STAR X

We now discuss the nature of star X. There are two possibilities. The first is that X is unrelated to RX J0720.4−3125. If so, X has to be a distant star, with spectral type no later than F2 ($B - R < 0.72$; 3 σ limit). Combined with the apparent B magnitude of 26.6, it could only be a white dwarf (a main-sequence star would be well outside even the extended halo of our Galaxy). A white dwarf would have $M_V \lesssim 13.2$ (Allen 1973) and be at a distance $\gtrsim$4 kpc, $\gtrsim$0.6 kpc above the plane. It would have to be a disk white dwarf, since white dwarfs in the halo would be too cool. The scale height of disk white dwarfs is 275 ± 50 pc, and the local density is 0.6×10^{-3} pc^{-3} (Boyle 1996). At the latitude of RX J0720.4−3125, $-7\overset{\circ}{.}8$, we would thus expect about one white dwarf per 4 arcmin^2. Hence, the probability of finding one within the 80 arcsec^2 HRI error box is $\sim 6 \times 10^{-3}$. We conclude that it is possible, though not very likely, that X is a distant white dwarf. A better color determination could settle this issue; if the object really has $B - R < 0$, the putative white dwarf would have to be much brighter and thus be well outside the disk.

This brings us to our second hypothesis, that star X is the optical counterpart of RX J0720.4−3125. The observed B and R magnitudes correspond to fluxes of 92 ± 14 and 53 ± 17 nJy, respectively. Here we used the effective wavelengths and absolute calibration given by Bessel (1992): $\lambda_{\rm eff}(B, R) =$

0.436, 0.638 μm and $F_\nu(B, R = 0) = 4.00, 3.06$ kJy. We can compare these fluxes with those expected from the *ROSAT* data, by extrapolating the best-fit, $kT_{\rm eff} = 80$ eV, blackbody spectrum (see § 2). Using the Rayleigh-Jeans formula, $f_\nu = 2\pi kT_{\rm eff}(\nu/c)^2(R/d)^2$, and $(R/d)^2 \simeq f_{\rm X}/\sigma T_{\rm eff}^4$, where $f_{\rm X}$ is the unabsorbed flux in the *ROSAT* band (§ 2); the predicted *B*- and *R*-band fluxes are 18 and 8 nJy, respectively. The observed optical flux is a factor of 5 larger. A similar excess is seen in RX J185635−3754 (Walter & Matthews 1997).

There are several possible causes for the apparent excess. Perhaps the simplest is that the surface does not have a uniform temperature; a two-component model, one component with $kT_1 = 80$ eV and the other with $kT_2 \ll 80$ eV but occupying $4T_1/T_2$ times more area, would satisfactorily account for both the optical and X-ray measurements. An alternative is that the excess is only apparent; the emergent X-ray spectrum depends on the composition in the neutron star atmosphere, and thus the effective temperature may well be different from that inferred by fitting a blackbody spectrum (Pavlov et al. 1996). Finally, the optical excess could be due to nonthermal emission, similar to what has been inferred for PSR B0656+14 (Pavlov, Welty, & Córdova 1997; Kurt et al. 1998; Shearer et al. 1997) and Geminga (Bignami et al. 1996).

The measurement of $\dot{P}$ would clearly be the most elegant way to discriminate between the two models for RX J0720.4−3125. For the magnetar, one would expect steady spin-down, at a few 10^{-13} s s^{-1} (§ 4.3). For the accreting old neutron star model, Wang (1997) estimates a spin-down rate $\lesssim 10^{-16}$ s s^{-1}. However, this ignores the torques exerted by the accreting matter, which might lead to either spin-up or spin-down, at a much larger rate (Lipunov & Popov 1995). Other future observations (improved position and better spectrum: *AXAF*; accurate optical and UV photometry: *Hubble Space Telescope*; radio emission: VLA) will be of great interest no matter what the object turns out to be.

While revising this Letter, we became aware of a preprint by Motch & Haberl (1998) reporting optical observations of RX J0720.4−3125. They propose two candidates, X1 and X2. X1 is our star X. X2 is about 3″ northwest of X1 (see Fig. 1) and is nominally outside the HRI error circles based on our astrometry. It is easily detected in *R* but fainter than X1 in *B*. Given the abundance of such faint red objects, it is our opinion that X2 is most likely a background object.

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