THE OPTICAL COUNTERPART OF THE ISOLATED NEUTRON STAR RX J1605.3+3249

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Submitted to ApJL

ABSTRACT

We have detected the optical counterpart to the nearby isolated neutron star RX J1605.3+3249 using observations from the Space Telescope Imaging Spectrograph aboard the Hubble Space Telescope. The counterpart, with $m_{50CCD} = 26.84 \pm 0.07$ mag and very blue colors, lies close to the ROSAT HRI error circle and within the Chandra error circle. The spectrum is consistent with a Rayleigh-Jeans tail whose emission is a factor of $\approx 14$ above the extrapolation of the X-ray blackbody, and the source has an unabsorbed X-ray-to-optical flux ratio of $\log(f_x/f_{opt}) = 4.4$, similar to that of other isolated neutron stars. This confirms the classification of RX J1605.3+3249 as a neutron star.

Subject headings: pulsars: individual (RX J1605.3+3249)—stars: neutron—X-rays: stars

1. INTRODUCTION

Thanks to ROSAT, a half dozen nearby neutron stars that emit no detectable radio emission have been identified (see Treves et al. 2000 for a comprehensive review). These objects have been eagerly studied using facilities such as the XMM-Newton Observatory, the Chandra X-ray Observatory, the Hubble Space Telescope (HST), Keck and the Very Large Telescope with the hope of determining the physical parameters, in particular radius and temperature, and to compare these to models of neutron stars. Independently, by their sheer proximity these objects play a pivotal role in assessing the neutron star demographics in the Galaxy. These two considerations highlight the virtue of detailed studies of nearby neutron stars.

RX J1605.3+3249 was identified in the ROSAT All-Sky Survey by Motch et al. (1999). The X-ray spectrum is well fitted by a blackbody with $kT \sim 90$ eV and low interstellar column density, $N_H \sim 10^{20} \text{ cm}^{-2}$, and is quite similar to those of well studied nearby neutron stars such as RX J1856.5−3754 and RX J0720.4−3125. Motch et al. (1999) obtained deep (B \sim 27 mag and R \sim 26 mag) images from the Keck telescope. Only one object (star C) was found within the 2'' High Resolution Imager (HRI) circle (we believe that the uncertainty of the HRI position was underestimated; see § 2.2). Optical spectroscopic observations carried out at the Canada-France-Hawaii Telescope (CFHT) showed that star C was a distant late-type M dwarf.

However, the soft spectrum and the stable X-ray emission are better accounted for by a model in which RX J1605.3+3249 is an isolated neutron star. If so, the optical counterpart would be below (or perhaps just at) the limit of the Keck observations. As a part of our investigation of nearby neutron stars with HST we undertook deep observations of this field. In this Letter we report the discovery of a faint blue optical star which we identify with the optical counterpart of RX J1605.3+3249. Our discovery confirms that RX J1605.3+3249 is a nearby neutron star.

2. OBSERVATIONS & DATA REDUCTION

2.1. Hubble Space Telescope Observations

We observed RX J1605.3+3249 with the Space Telescope Imaging Spectrograph (STIS) aboard HST in two modes: unfiltered CCD (50CCD aperture) and a longpass filter that transmitted photons longward of $\approx 5500$ Å; see Table 1. For each mode, the individual images were drizzled (Fruchter & Hook 2002) onto a single image with a pixel scale of 0.5. Thus final images had 0′′0254 pixels.

2.2. Keck Observations

For astrometric purposes we obtained imaging data from the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck II telescope; see Table 1. These images were reduced in a standard manner using tasks in MIDAS: bias subtraction, flat-fielding, and stacking of the exposures. We show the LRIS image in Figure 1.

After correcting the stellar positions measured in a 30-s LRIS image for geometric distortions1, we fit for plate-scale, zero-point, and rotation using 24 stars common to that and the 30-s image, getting rms residuals of 0′′09 in each coordinate (in what follows, astrometric uncertainties refer to rms values in each coordinate unless otherwise specified). We then determined the astrometric solution (plate-scale, zero-point, and rotation) of the full 30-minute LRIS image by using 24 stars common to that and the 30-s image, getting rms residuals of 0′′02. Finally, we used 21 stars on the deep LRIS image to determine the plate-scale, zero-point, and rotation of the drizzled STIS 50CCD image (shown in Fig. 2), getting rms residuals of 0′′04. The final uncertainty to which our STIS coordinates are on the ICRS is dominated by the 0′′3 uncertainty of the GSC-2.22.

We inspected all point sources on the STIS images that were within the PSPC error circle and found a very blue

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1 See http://alamoana.keck.hawaii.edu/inst/lris/coordinates.html.

2 See http://www-gss.stsci.edu/support/data_access.htm.

3 See http://www-gss.stsci.edu/gsc/gac2/calibrations/astrometry/astrometry.html.
source. As can be seen from Figure 3 this is the bluest source in the PSFC error circle. The source, hereafter “X”, is located at (J2000) \( \alpha = 16^h05^m18.52 \) \( \delta = +32^\circ49\arcmin18.70 \), with uncertainties of about 0.3, and lies 2.5 from the HRI position from Motch et al. (1999), outside the nominal 90% error circle.

However, we have found a problem in comparing positions referenced to the USNO-A2.0 (Monet 1998), like the HRI position, and those referenced to the GSC-2.2/ICRS (our optical data). In this field, there appears to be a systematic shift between the GSC-2.2 and the USNO-A2.0 of \( \delta_{\text{GSC}} - \delta_{\text{USNO}} = 0\arcsec65 \) (the shift in Right Ascension is a negligible 0.02). If we correct the HRI position to the GSC-2.2 reference frame, we find the new position to be (J2000) \( \alpha = 16^h05^m18.66 \) \( \delta = +32^\circ49\arcmin19.00 \). With this position, the error circle appears to be located properly with respect to star C, comparing with Fig. 4 of Motch et al. (1999).

Even with the updated position, X is slightly outside the 90% HRI error circle\(^4\). We have two possible explanations for this. First, RX J1605.3+3249 may have non-negligible proper motion, such as that seen for RX J1856.5–3754 (Walter 2001). In this case the offset between the HRI position (epoch 1998.3) and the STIS image (2001.6) could be real. However, the LRIS data are not of sufficient quality to detect X with any confidence, so we will have to wait for additional data. Second, we note that the quoted uncertainty of the HRI position may be underestimated: Motch et al. (1999) used 6 reference sources for the Pointing corrections and claim an uncertainty of 0.64 with no contribution from systematic effects. In comparison, Hasinger et al. (1998) use 32 sources and get typical HRI uncertainties of 1.0” that include a 0.5 systematic error to achieve good X-ray-to-optical matches.

In either case, the blue color of source X is similar to those of the counterparts of other isolated neutron stars (e.g. RX J1856.5–3754 and RX J1605.3+3249; Walter & Matthews 1997; van Kerkwijk & Kulkarni 2001b; Motch & Haberl 1998; Kulkarni & van Kerkwijk 1998). Thus we consider it likely that X is the counterpart of RX J1605.3+3249.

2.3. X-ray

While our identification based on color and position is plausible, the uncertainty in the ROSAT HRI position prevents us from being sure about the association (pulsations or a common proper motion would be definitive measurements). Fortunately, the availability of archival data from the Chandra X-ray Observatory offered us to opportunity to decrease the chance coincidence probability by a factor of 10. The Chandra observation (ObsID 2791) had a duration of 20-ks, and RX J1605.3+3249 was at the aim-point of the ACIS-I CCD array. Using standard processing steps\(^5\) we corrected for a systematic astrometric error of \( \Delta \alpha = -0\arcsec35 \) and \( \Delta \delta = -0\arcsec10 \). As a cross-check, we compared the positions of other X-ray sources to GSC-2.2 stars (which, since we used the GSC-2.2 as the reference for the optical astrometry, ensures that they are on the same system as our HST data) and found that the coordinates match to better than 0.5 arcsecond.

We then measured the centroid of RX J1605.3+3249 (with a count-rate of \( \approx 0.15 \) s\(^{-1} \), RX J1605.3+3249 is somewhat affected by photon pileup, but this should not affect the centroid) to be (J2000) \( \alpha = 16^h05^m18.50 \) \( \delta = +32^\circ49\arcmin17.4 \). We estimate a final 90% confidence radius of the X-ray position with respect to the STIS image of \( \approx 1\arcsec0 \). As can be seen in Fig. 2, source X is well within this radius, lending credence to our identification.

3. Analysis & Discussion

\(^5\) \text{http://asc.harvard.edu/cal/ASPECT/fix_offset/fix_offset.cgi.}
We rely on the spectral fits to the ROSAT PSPC data presented in Motch et al. (1999): \( kT = 92 \; \text{eV}, N_H = 1.1 \times 10^{20} \; \text{cm}^{-2}, \) and \( R_X = 3.3 d_{300}, \) where \( d = 300 d_{300} \; \text{pc} \) is the distance and the normalization assumes 0.9 counts s\(^{-1}\) in the PSPC. The absorption column density implies an extinction of \( A_V = 0.06 \; \text{mag}, \) (Predehl & Schmitt 1995) — while this value is uncertain, it is low enough to not make a large difference. The total Galactic hydrogen column density is \( 2.4 \times 10^{20} \; \text{cm}^{-2} \) (determined by COLDEX\(^6\); Dickey & Lockman 1990) so that the maximum extinction is 0.13 mag. This agrees with the extinction estimated from infrared dust emission (Schlegel, Finkbeiner, & Davis 1998), and confirms that the total extinction to RX J1605.3+3249 is low.

Within a 0\('\)′25-radius aperture, we measure magnitudes of \( m_{50\text{CCD}} = 27.03 \pm 0.07 \; \text{mag} \) and \( m_{F28X50\text{LP}} = 28.16 \pm 0.18 \; \text{mag} \) for source X in the STmag system. To correct the photometry to a nominal infinite aperture, we follow Kaplan, Kulkarni, & van Kerkwijk (2002a) and Kaplan et al. (2003). As X is bluer than all of the stars in the image, we used the bluest of the available aperture corrections: 0.183 mag at 0\('\)′25 radius for 50CCD and 0.214 mag at 0\('\)′25 radius for F28X50LP (T. Brown 2002, private communication). This then gives corrected magnitudes of \( m_{50\text{CCD}} = 26.84 \pm 0.07 \; \text{mag} \) and \( m_{F28X50\text{LP}} = 27.95 \pm 0.18 \; \text{mag} \), where we have incorporated a 0.02 mag uncertainty from the aperture corrections.

Since the STIS bandpasses are so wide we must use the shapes of the bandpasses to convert the measured magnitudes into fluxes. Following van Kerkwijk & Kulkarni (2001b), we find effective wavelengths \( (\lambda) \) of 5148 \( \text{Å} \) and 7137 \( \text{Å} \) and effective extinctions \( (A_{\lambda}/A_V) \) of 1.56 and 0.79 for 50CCD and F28X50LP, respectively. With these wavelengths, we can now apply the standard STmag conversion of \( F_{\lambda}(\lambda) = 10^{-((m_{\lambda} - 2.5)/2.5)} \; \text{ergs s}^{-1} \; \text{cm}^{-2} \; \text{Å}^{-1} \).

We plot the spectral energy distribution of source X in Figure 4. As one can see, the photometry appear to follow a power-law with spectral index \( \alpha \approx 2 \) (\( F_{\nu} \propto \nu^\alpha \)), appropriate for a Rayleigh-Jeans tail and similar to that of other isolated neutron stars (van Kerkwijk & Kulkarni 2001b; Kaplan et al. 2003). We also plot in Figure 4 the extrapolation of the best-fit ROSAT PSPC blackbody. The Rayleigh-Jeans fit to the STIS data has a normalization that is a factor of 14 \( \pm 2 \) above the extrapolation of the blackbody. Other power-law indices are possible, as found for RX J0720.4–3125 (Kaplan et al. 2003), but we do not believe that the current data warrant a full fit. The unabsorbed bolometric X-ray-to-optical flux ratio is \( \log(f_X/f_{\text{opt}}) = 4.4 \) (assuming that the X-ray spectrum is well described by a blackbody).

The blueness of source X and its X-ray-to-optical flux ratio, taken together with the X-ray spectrum of RX J1605.3+3249, virtually guarantee that X is the optical counterpart of RX J1605.3+3249 and that RX J1605.3+3249 is an isolated neutron star. It then joins 3 other sources (RX J1856.5–3754, RX J0720.4–3125, and possibly RX J1308.6+2127) that have soft X-ray blackbodies, blue optical counterparts, and no other emission; see Table 2. RX J1605.3+3249 stands out from the other sources in Table 2 by virtue of its relatively large optical excess: the optical flux is a factor of 14 above the extrapolated X-ray flux, where for the other sources the ratio is closer to 6 (this is despite the fact that the X-ray-to-optical flux ratio for RX J1605.3+3249 is within the range of the other sources). This can also be seen from the ROSAT data in Schwirazky et al. (1999), where RX J1605.3+3249 has a factor of 2 smaller count rate than RX J0720.4–3125 despite being hotter and having a comparable optical magnitude. There are two possibilities to explain the large excess of RX J1605.3+3249: either its X-ray emission is suppressed relative to the optical, or the

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\(^6\) See http://asc.harvard.edu/toolkit/colden.jsp.
optical emission is enhanced.

The first scenario implies that the blackbody radius (3.3×10^9 km, where the distance of ∼ 300 pc is predicted based on the optical flux; see Kaplan, van Kerkwijk, & Anderson 2002b) is significantly smaller than those of the other sources (typically 6 km). If the blackbody radius can be interpreted as the radius of a hot polar cap, perhaps RX J1605.3+3249 has a different magnetic field configuration leading to a smaller cap size, or RX J1605.3+3249 is in an orientation where only half of the cap is visible (although this is difficult when relativistic beaming is taken into account; Psaltis, Özel, & DeDeo 2000).

The second scenario could occur if there is a significant contribution to the optical emission from non-thermal emission likely linked to the spin-down luminosity, $\dot{E}$ (such as that seen for PSR B0656+14; Koptsevich et al. 2001). In this case, the high optical excess could indicate a large $\dot{E}$ for RX J1605.3+3249. While we cannot constrain the non-thermal emission from the current photometry, it may be difficult to reproduce the thermal-like spectrum observed in Figure 4 and to invoke significant non-thermal flux.

Future observations, such as higher-precision X-ray spectroscopy from Chandra and XMM, additional optical photometry, and improved X-ray timing (in order to determine $\dot{E}$ and the magnetic field $B$), should help to settle these issues. Our XMM data will answer some of these questions (van Kerkwijk et al., in preparation), and we are also searching for an Hα nebula around RX J1605.3+3249 (e.g., van Kerkwijk & Kulkarni 2001a). A definitive measurement would be the distance, which would determine the areas of the X-ray and optical emission regions, but a parallax measurement with HST would require a significant investment of observing time.

D. L. K. is supported by the Fannie and John Hertz Foundation and S. R. K. by NSF and NASA. Data presented herein were based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. Data presented herein were also obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Guide Star Catalog-II is a joint project of the Space Telescope Science Institute and the Osservatorio Astronomico di Torino. MIDAS is developed and maintained by the European Southern Observatory.

Fig. 4.—Spectral energy distribution for source X corrected for absorption with $A_V = 0.06$ mag. The STIS data are plotted as points. The extrapolation of the ROSAT blackbody (Motch et al. 1999) is the solid line (labeled “ROSAT BB”), and a Rayleigh-Jeans fit to the STIS data is the dashed line. The horizontal error-bars show the bandpasses of the filters.

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### Table 2

**Summary of Optically Detected Isolated Neutron Stars**

| Source            | Period (s) | $kT^a$ (eV) | $m_V^b$ (mag) | $\log f_X/f_V^c$ | Optical $^d$ Excess | References |
|-------------------|------------|-------------|---------------|------------------|---------------------|------------|
| RX J1856.5−3754   | ⋮          | 61          | 25.8          | 4.4              | 6                   | 1,2,3,4    |
| RX J0720.4−3125   | 8.39       | 81          | 26.8          | 4.6              | 6                   | 5,6        |
| RX J1308.6+2127   | 5.16       | 91          | 28.7          | 5.0              | 5                   | 7,8,9      |
| RX J1605.3+3249   | ⋮          | 92          | 27.1          | 4.4              | 14                  | 10,11      |

$^a$Temperature of the best-fitting blackbody.

$^b$V-band Vega magnitude, either measured or interpolated.

$^c$Absorption-corrected bolometric X-ray-to-optical flux ratio, assuming that the X-ray emission is a blackbody. The V-band flux is computed according to $f_V = 10^{-(V+11.76)/2.5}$ ergs s$^{-1}$ cm$^{-2}$, following Bessell, Castelli, & Plez (1998).

$^d$The ratio of the observed V-band flux to the extrapolated X-ray blackbody flux at 5500 Å.

**References.**— 1: Ransom, Gaensler, & Slane (2002); 2: Burwitz et al. (2002); 3: Drake et al. (2002); 4: van Kerkwijk & Kulkarni (2001b); 5: Haberl et al. (1997); 6: Kaplan et al. (2003); 7: Schwope et al. (1999); 8: Hambaryan et al. (2002); 9: Kaplan et al. (2002a); 10: Motch et al. (1999); 11: this work.