AN OPTICAL COUNTERPART CANDIDATE FOR THE ISOLATED NEUTRON STAR RBS 1774

S. Zane, R. P. Mignani, R. Turolla, A. Treves, F. Haberl, C. Motch, L. Zampieri, and M. Cropper

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1. INTRODUCTION

One of the most intriguing results of the ROSAT All Sky Survey has been the detection of seven close-by neutron stars (NSs), with particular characteristics (XDINSs in the following; see Haberl 2007; van Kerkwijk & Kaplan 2007 for recent reviews). These sources stand apart with respect to other known classes of isolated NSs detected at X-ray energies. Their X-ray spectrum is close to a blackbody, and no evidence of radio emission has been reported so far despite deep searches (e.g., Kondratiev et al. 2008). They are likely to be endowed with relatively strong magnetic fields. As a part of an ongoing campaign aimed at a complete identification and spectral characterization of XDINSs in the optical band, we performed deep imaging with the ESO Very Large Telescope (VLT) of the field of the XDINS RBS 1774 (1RXS J214303.7+065419). The recently updated FORS1 instrument mounted on the VLT provided the very first detection of a candidate optical counterpart in the B band. The identification is based on a very good positional coincidence with the X-ray source (chance probability $\sim 2 \times 10^{-3}$).

The source has $B = 27.4 \pm 0.2$ ($1\sigma$ confidence level), and the optical flux exceeds the extrapolation of the X-ray blackbody at optical wavelengths by a factor $\sim 35$ ($\pm 20$ at $3\sigma$ confidence level). This is barely compatible with thermal emission from the neutron star surface, unless the source distance is $d = 200$–300 pc, and the star is an almost aligned rotator or its spin axis is nearly aligned with the line of sight. At the same time, such a large optical excess appears difficult to reconcile with rotation-powered magnetospheric emission, unless the source has an extremely large optical emission efficiency. The implications and possible similarities with the optical spectra of other isolated NSs are discussed.

Subject headings: stars: individual (RBS 1774) — stars: neutron — techniques: photometric — X-rays: stars

Online material: color figure

ABSTRACT

Multiwavelength studies of the seven identified X-ray-dim isolated neutron stars (XDINSs) offer a unique opportunity to investigate their surface thermal and magnetic structure and the matter-radiation interaction in presence of strong gravitational and magnetic fields. As a part of an ongoing campaign aimed at a complete identification and spectral characterization of XDINSs in the optical band, we performed deep imaging with the ESO Very Large Telescope (VLT) of the field of the XDINS RBS 1774 (1RXS J214303.7+065419). The recently updated FORS1 instrument mounted on the VLT provided the very first detection of a candidate optical counterpart in the B band. The identification is based on a very good positional coincidence with the X-ray source (chance probability $\sim 2 \times 10^{-3}$).

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respectively. Additional optical ($B, V, r', i'$) and infrared ($J, H,$ and $K_s$) observations of RBS 1774 performed with the Keck, VLT, Blanco and Magellan telescopes were recently reported by Rea et al. (2007) exploiting the subarcsecond position obtained through a DDT Chandra observation. Again, no plausible optical and/or infrared counterpart for RBS 1774 was detected down to $r \sim 25.7$ and $J \sim 22.6$. Radio observations carried out with the Parkes 64 m telescope at 2.9 GHz and 708 MHz were also reported by Rea et al. (2007). However, they did not show evidence for radio pulsations down to a luminosity of $L = 0.02 \text{ mJy kpc}^2$ at 1.4 GHz. Very recently Kondratiev et al. (2008) placed more stringent upper limits on the radio luminosity of RBS 1774, $L_{1.4 \text{ GHz}} \sim 0.005$ and $\sim 7.6 \text{ mJy kpc}^2$ for pulsed and bursty emission respectively, which are the most stringent limits obtained to date from radio observations of XDINSs.

In this paper we present the first detection of a candidate optical counterpart to RBS 1774, obtained with the VLT. The observations and data analysis are described in § 2, while discussion and conclusions follow in §§ 3 and 4, respectively.

### 2. THE NEW VLT OBSERVATIONS

#### 2.1. Observations Description

We performed deep optical imaging of the RBS 1774 field with FORS1 (Focal Reducer Spectrograph), a multimode instrument for imaging and long-slit/multiobject spectroscopy mounted at the VLT Kueyen Telescope (Paranal Observatory). The instrument has been recently upgraded with the installation of a new detector which is the mosaic of two $2k \times 4k$ E2V CCDs, optimized for the blue range. Due to vignetting, the effective sky coverage of the two CCD chips is smaller than the projected detector field of view, and larger for the upper chip (dubbed “Norma”). Observations were carried out in Service Mode on 2007 July 11 and 21. FORS1 was set up in its default standard resolution mode, with a $2 \times 2$ binning, yielding a pixel size of 0.25″. The telescope pointing was set in order to position our target on the “Norma” CCD chip, and, thanks to its large effective sky coverage ($7' \times 4'$), to include a large number of reference stars for a precise image astrometry. The low-gain, fast read-out mode was chosen. Sequences of 590 s exposures were obtained through the $B$ Bessel filter ($\lambda = 429 \text{ nm}$; $\Delta \lambda = 88 \text{ nm}$), for a total integration time of 8850 and 2950 s in the first and second night, respectively. The observations were collected in dark time, with an average seeing of $\sim 0.7''$ and $\sim 0.9''$ and an air mass $\sim 1.17$–1.37 and $\sim 1.18$ on the first and second night, respectively.

#### 2.2. Data Reduction

The usual reduction steps (bias subtraction, flat-fielding) were applied to the data through the ESO FORS1 data reduction pipeline\(^8\) using calibration frames acquired as part of the FORS1 calibration plan. Then, single reduced images were aligned and co-added to filter out cosmic rays using the IRAF task imcombine. The photometric calibration was performed through the observation of standard stars from the fields PG 1323–086, PG 1633+099, SA 113–239 (Landolt 1992) at the beginning of the night. This yielded nominal extinction and color-corrected zero points of 28.16 $\pm$ 0.04 and 28.17 $\pm$ 0.04 for the first and the second night, respectively. The atmospheric extinction correction was applied using the extinction coefficients of the Paranal Observatory measured with the upgraded FORS1 ($k_B = 0.255$ for the “Norma” chip). Since the zero point computed by the FORS1 pipeline is in units of $e^{-} \text{ s}^{-1}$, while the flux on the image is measured in ADU $\text{ s}^{-1}$, we corrected the computed zero point by applying the detector electrons—to–ADU conversion factor ($\text{GAIN} = 0.45$). According to the Paranal Observatory sky monitor and weather report, sky conditions were photometric on the first night and at the beginning of the second night but they were then affected by the presence of thin, variable cirri. This means that the photometry of the second night is affected by a random, unknown uncertainty. We have tried to quantify this uncertainty by comparing the photometry of a number of reference field stars observed in the two nights. The star detection was performed using the SExtractor program and magnitudes were computed through customized aperture photometry (SExtractor parameter MAG_AUTO). In all sources detected at the flux level expected for our target ($B \geq 26$), we found an average offset of $\sim 0.1 \pm 0.5 \text{ mag}$ between the photometry of the two nights. Such a large scatter for faint objects is due to the fact that their flux measurement is more sensitive on the varying atmospheric conditions than that of the bright ones. Thus, if data of the two nights are combined, this would result in only a modest increase of the S/N ratio at the expenses of a worse photometric accuracy for our target. We thus decided not to use the data taken on the second night.

#### 2.3. Astrometry

The astrometry on the FORS1 image was computed using as a reference the coordinates of stars selected from the GSC-2 (ver. 3.2; Lasker et al. 2008). All stars from the UCAC-2 (Zacharias et al. 2004) are saturated in our images. Approximately 90 GSC-2 objects are identified in the FORS1 “Norma” field of view. After filtering out extended objects, stellar-like objects that are saturated or too faint to be used as reliable astrometric calibrators, objects falling close to the chip edges, and outliers, we performed our astrometric calibration using 20 GSC-2 reference stars, evenly distributed in the instrument field of view. Their pixel coordinates were measured by Gaussian fitting their intensity profiles with the GAIA (Graphical Astronomy and Image Analysis) tool,\(^9\) while the fit to the celestial reference frame was performed using the Starlink package ASTROM.\(^10\) This code is based on higher order polynomials, which account for unmodeled CCD distortions. The rms of the astrometric solution was determined as $\approx 0.11''$ per coordinate. Following Caraveo et al. (1998), we estimated the overall uncertainty of our astrometry by adding in quadrature the rms of the astrometric fit and the accuracy with which we can register our field on the GSC-2 reference frame. This is estimated as $\sqrt{3 \sigma_{\text{GSC}} / N}$, where the $\sqrt{3}$ term accounts for the free parameters ($x$-scale, $y$-scale, and rotation angle) in the astrometric fit, $\sigma_{\text{GSC}}$ is the mean radial error of the GSC-2 coordinates ($0.3''$; Lasker et al. 2008) and $N$ is the number of stars used for the astrometric calibration. The uncertainty on the reference stars centroids is well below 0.1 pixel and has been neglected. We also added in quadrature the radial uncertainty on the tie of the GSC-2 to the ICRF ($0.15''$; Lasker et al. 2008). Thus, the overall radial accuracy of our astrometry is $0.24''$ ($1 \sigma$).

#### 2.4. Results

Figure 1 shows a section of the co-added FORS1 $B$-band image of the RBS 1774 field. Figure 1 (right) shows a zoom with the Chandra position of RBS 1774 overlaid. The coordinates of

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\(^8\) See http://www.eso.org/observing/dfo/quality/FORS1/pipeline.

\(^9\) See http://star-www.dur.ac.uk/~pdraper/gaia/gaia.html.

\(^10\) See http://star-www.rl.ac.uk/Software/software.htm.
Fig. 1.—Left: B-band image (40\arcsec × 40\arcsec) of the RBS 1774 field obtained with FORS1 at the VLT Kueyen Telescope. The square corresponds to the 6\arcsec × 6\arcsec zoom shown in the right-hand panel. The intensity scale has been readjusted for an easier view of the brighter objects in the field. Right: 6\arcsec × 6\arcsec zoom of the same field. The circles correspond to the original (Rea et al. 2007) and revised (this work, § 2.4) Chandra position of RBS 1774, and are drawn at the 90% and 99% confidence levels. Their size (0.65\arcsec and 0.85\arcsec, respectively) also accounts for the uncertainty of the astrometric calibration of the FORS1 image. The object detected at the center of the error circles (B = 27.4 ± 0.2) is our candidate counterpart to RBS 1774. [See the electronic edition of the Journal for a color version of this figure.]

RBS 1774 were measured with high precision using Chandra HRC observations by Rea et al. (2007): \( \alpha = 21^h 43^m 03.38^s, \delta = +06^\circ 54' 17.53'' \) (J2000.0) with a nominal accuracy of 0.6\arcsec at the 90% confidence level (c.l.). The Chandra observation was recently reprocessed (2007 December) using updated calibration data products, and revised coordinates were obtained, \( \alpha = 21^h 43^m 03.40^s, \delta = +06^\circ 54' 17.79'' \) (J2000.0; with the same nominal accuracy; G. L. Israel 2007, private communication), which are consistent with the published ones. For comparison, in Figure 1 we show both the original and the revised error circles at the 90% and 99% c.l. The size of the error circles also accounts for the overall uncertainty of our astrometric calibration.

As is evident, a very faint object is detected about 0.2\arcsec from both the original and revised X-ray position. The object profile is pointlike and consistent with the measured PSF, which, at the level of the FORS1 spatial resolution, rules out the possibility of blending of fields object. We computed its magnitude through aperture photometry, by using a customized aperture and background region, following the same procedure described in the previous sections. The background was computed in an annular region centered on the target, in order to have the most reliable estimate close to the position of our source.

The measured value, corrected for the atmospheric extinction using the trended FORS1 extinction coefficients, is \( B = 27.4 \pm 0.2 \) (significant at \( \sim 9 \sigma \)) where the quoted error (1 \( \sigma \)) is purely statistical and does not include the much smaller errors on the zero point and on the atmospheric extinction correction. No other object is detected within or close to the Chandra position down to a 3 \( \sigma \) limit of \( B \sim 28.7 \). As pointed out in the previous sections, the FORS1 coordinates are tied to the ICRF within 0.15\arcsec so that we exclude an hypothetical shift with respect to the Chandra coordinates which are also tied to the ICRF.\(^{11}\) Thus, given its very good coincidence with the X-ray position, we regard this object as a viable candidate counterpart to RBS 1774.

3. DISCUSSION

In this paper we report the first detection of a likely optical counterpart for RBS 1774. Standardly, optical identifications of isolated neutron stars are robustly confirmed either by the detection of optical pulsations or by the measurement of a significant proper motion. In absence of such information we can base the optical identification only on the positional coincidence between the coordinates of our candidate counterpart and those of RBS 1774, as measured in the X-rays. In order to quantify the statistical significance, we estimated the chance coincidence probability that an unrelated field object might fall within the Chandra error circle. This can be computed as \( 1 - \exp(-\pi r^2) \) (see, e.g., Sevrenini et al. 2005), where \( r \) is the measured object density in the FORS1 “Norma” field of view and \( r \) is the registered radius of the Chandra error circle (0.65\arcsec, accounting for the uncertainty of the FORS1 astrometry while the uncertainty due to the unknown RBS 1774 proper motion is negligible given the small time span between the Chandra and VLT epochs). The measured density of stellar objects in the field with magnitude 27.2 \( \leq B \leq 27.7 \), i.e., comparable to that of our candidate counterpart, is \( \sim 0.0015 \) arcsec\(^{-2}\). This yields an estimated chance coincidence probability \( P \sim 2 \times 10^{-3} \), which shows that our association is robust.\(^{12}\) Thus, we are confident that we have identified a very likely optical counterpart to RBS 1774.

The flux of our candidate counterpart in the B band, after correcting for interstellar extinction, is \( F_B = (2.55 \pm 0.47) \times 10^{-7} \) keV cm\(^{-2}\) s\(^{-1}\) (the error is at 1 \( \sigma \)). To compute this value, we used the column density derived from the best fit to the XMM-Newton spectrum (\( N_H = 3.60 \times 10^{20} \) cm\(^{-2}\); Cropper 2006).

\(^{11}\) See http://cxc.harvard.edu/cal/ASPECT/celmon.

\(^{12}\) If we compute the chance probability by considering all objects brighter than \( B = 27.7 \), we get a very similar result, \( P = 2.3 \times 10^{-3} \).
We repeated this calculation by varying the distance between 200 and 500 pc\textsuperscript{15} and for \( r_o = 20, 15, \) or 10 km. Results show that this scenario is only barely compatible with our data and requires very small distances: \( d \approx 300–400 \) pc are only allowed within 3 \( \sigma \) and for neutron star radii as large as \( r_o = 20 \) km, while if \( r_o = 15 \) km the only allowed combinations require \( f = 15–22 \) and \( d \approx 200–250 \) pc. On the other hand, the lower the distance the smaller is the size of the X-ray-emitting region and the more difficult is to explain the small pulsed fraction observed in the X-rays (which is \( \approx 4\% \) in semiamplitude).

As we tested by assuming simple polar cap modeling and blackbody emission, if \( d = 300 \) pc the allowed parameter space is already confined to a very small region where the inclination angles of the line of sight and of the magnetic dipole axis with respect to the star spin axis are both \( \leq 20^\circ \). If \( d = 200 \) pc, the allowed region is even smaller and the only possible configurations require the star to be either a perfectly aligned rotator or viewed almost along its spin axis.

As discussed by Motch et al. (2003), Zane et al. (2004), and Ho et al. (2007) spectral models consisting of bare neutron stars surrounded by thin atmospheres may predict very different amount of optical excess. However, such models are affected by our poor knowledge of the properties of the condensed surface, and whether they can produce optical excesses as large as that measured here is still an open issue.

An alternative interpretation is that the optical emission is non thermal, probably of magnetospheric origin (Pacini & Salvati 1983). As it can be seen from Figure 2, a power-law spectral component with matching the \( B \) flux and with index \( \alpha \sim 0–1.4 \) is not in contradiction with the upper limits measured at longer wavelengths and, at the same time, is not expected to contribute significantly to the X-ray band. These constraints on the optical spectral index can be compared with the values derived from the optical spectra of rotation-powered neutron stars, which are all in the range 0–0.8 (see, e.g., Mignani et al. 2007a). In this respect, we note that for the XDINSs for which the spin down luminosity is measured (Cropper et al. 2004a; Kaplan et al. 2005a, 2005b; van Kerkwijk & Kaplan 2008) it is \( L_{\text{rot}}/E \approx 10^{-6} \) for the optical emission efficiency (as measured in old rotation-powered neutron stars by Mignani et al. 2004), this yields an optical luminosity of \( \approx 5 \times 10^{24} \) ergs \textsuperscript{-1}. If the case of RBS 1774 is analogous, and if we take \( L_{\text{opt}}/E \approx 10^{-6} \) for the optical emission efficiency (as measured in old rotation-powered neutron stars by Mignani et al. 2004), this yields an optical luminosity of \( \approx 5 \times 10^{24} \) ergs \textsuperscript{-1}. In order to reproduce the observed flux of our candidate counterpart, after accounting for the assumed interstellar extinction, RBS 1774 should be at an unrealistically small distance of \( \approx 25 \) pc. Thus, for the assumed value of \( E \), a purely rotation-powered optical emission is only compatible with a scenario in which our source is at least a 2 orders of magnitude more efficient optical emitter (see below). Similar conclusions can be reached if we consider the case in which the observed optical emission of RBS 1774 is due to a composite mechanism consisting of both thermal emission from the neutron star surface and a rotation-powered magnetospheric emission (as in the middle-aged neutron stars PSR B0656+14 and Geminga; e.g., Kargaltsev & Pavlov 2007).

A further, intriguing possibility is that the optical emission is nonthermal and powered by a mechanism different from rotation. Interestingly, at least in the IR domain, hints have been found for an increase of the low-energy emission efficiency with the dipole magnetic field strength (Mignani et al. 2007c). Indeed,\textsuperscript{16} we do not use the distance determination by Posselt et al. (2008) since their model is currently under revision for the case of RBS 1774 (B. Posselt 2007, private communication).

\textsuperscript{15} The Predehl & Schmitt (1995) relation is affected by uncertainties for close objects, due to the problems of modeling the ISM at small distance from the Sun where microstructures weight more. We checked that, when using the relations of Bohlin et al. (1978) as in Rea et al. (2007) and of Paresce (1984) extinction corrections are consistent within 0.04 mag, well below the pure statistical error on the source count rate.

\textsuperscript{16} Note, however, that when applied to other XDINSs this scenario often requires large neutron star radii.
in magnetars the efficiency is at least 2 orders of magnitude larger than in rotation-powered neutron stars and the spectra show a typical (and unexplained) flattening toward the infrared (Israel et al. 2003). It is interesting to note the magnetic field strength of RBS 1774 as inferred from the absorption feature in the X-ray spectrum is the highest among all XDINSs ($B \approx 10^{14}$ G), larger than the QED critical limit and comparable with that of magnetars. The optical emission of RBS 1774 could thus be powered by a magnetar-like process. If the spectrum of RBS 1774 shows a similar magnetar-like turn over, then the flattening is appearing blueward of the IR band.

4. CONCLUSIONS

We report here the deepest optical observations so far of the RBS 1774 field, performed with the upgraded FORS1 instrument at the VLT Kueyen Telescope. Based on the positional coincidence, we have identified a likely candidate counterpart. RBS 1774 would then be the fifth XDINS detected in the optical band, the second by the VLT. For the most reasonable distance range to the X-ray source, the measured brightness of the candidate counterpart ($B \approx 27.4$) is barely compatible with purely thermal emission from the neutron star surface, while, assuming a value of $\dot{E}$ similar to that of other XDINSs, rotation-powered emission from the magnetosphere (eventually in combination with a thermal component) requires RBS 1774 to have a very large optical efficiency ($\sim 3$ order of magnitudes larger than the Crab for $d = 400$ pc). If the optical emission is powered by a different process, the likely high magnetic field of RBS 1774 tantalizingly suggests magnetar-like magnetospheric emission as a viable option. New multiband observations, especially in the near-UV and in the near-IR, are required to characterize the counterpart spectrum and to assess the contribution of possibly different spectral components. At the same time, high-resolution optical astrometry of the candidate counterpart with the refurbished HST could yield the first direct estimate of the RBS 1774 parallax and distance, crucial to build the neutron star surface thermal map, and to provide confirmation of the optical counterpart through proper motion measurements.

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