ON THE BINARY NATURE OF 1RXS J162848.1−415241

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ABSTRACT

We present spectroscopy of the optical counterpart to 1RXS J162848.1−41524, also known as the microquasar candidate MCQC J162847−4152. All the data indicate that this X-ray source is not a microquasar and that it is a single-lined chromospherically active binary system with a likely orbital period of 4.9 days. Our analysis supports a K3 IV spectral classification for the star, which is dominant at optical wavelengths. The unseen binary component is most likely a late-type (K7−M) dwarf or a white dwarf. Using the high-resolution spectra, we have measured the K3 star’s rotational broadening to be \( v \sin i = 43 \pm 3 \text{ km s}^{-1} \) and determined a lower limit to the binary mass ratio of \( q (= M_2/M_1) > 2.0 \). The high rotational broadening together with the strong Ca ii H and K/H\alpha emission and high-amplitude photometric variations indicate that the evolved star is very chromospherically active and responsible for the X-ray/radio emission.

Subject headings: binaries: close — stars: individual (RX J1628−41) — X-rays: stars

1. INTRODUCTION

X-ray binaries are binary systems where a neutron star or a black hole accretes matter from its companion star. Of \( \sim 280 \) known X-ray binaries, 15 show persistent or episodic relativistic radio jets and are called microquasars as they are reminiscent of active galactic nuclei (AGNs; see, e.g., Paredes [2005] for an inventory and Mirabel & Rodrı́guez [1999] and Fender [2003] for a review of their properties). Microquasars are of great interest because they may provide a unique opportunity to gain insight into the mechanisms ruling the formation and evolution of relativistic outflows coupled to accretion phenomena. In this regard, the variations observed in microquasars are perceptible on human timescales, which allows studies impossible to perform for the more plentiful (but slowly varying) extragalactic relativistic jet sources. 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In § 3 we estimate the orbital ephemeris, and in § 4 we discuss the spectrum of the secondary star. Note that hereafter we call the visible star in the binary the “secondary” and the invisible stellar component the “primary,” in analogy with the terminology used in the study of binaries harboring compact objects. In § 5 we derive an upper limit to the extinction toward J1628. In § 6 we describe the emission lines observed in the spectrum. Finally, in § 7 we discuss our results, and a summary is given in § 8.

2. OBSERVATIONS AND DATA REDUCTION

The observations of J1628 were obtained using different spectrographs mounted on the 6.5 m Magellan Baade and Clay telescopes at LCO.

The Boller & Chivens Spectrograph (B&C) was used to acquire low-resolution spectra. A 0.7 slit width and a 600 (1200) line mm$^{-1}$ grating yielded a spectral resolution of 2 pixels and a dispersion of 1.56 (~0.80) Å pixel$^{-1}$. The spectral interval covered by the B&C was set depending on the requirements of the observer’s scientific program and can be found in Table 1.

The Inamori-Magellan Areal Camera and Spectrograph (IMACS; Bigelow & Dressler 2003) was employed in short-camera mode to obtain intermediate-resolution spectra dispersed along the long axis of two of the eight SITe CCDs in the IMACS detector. Using a 600 line mm$^{-1}$ grism and a 0.55 slit width yielded a dispersion of 0.48 (CCD No. 2) and 0.58 Å pixel$^{-1}$ (CCD No. 5) in the spectral intervals 5670–7620 and 7695–10025 Å, respectively. The spectral resolution was ~2 pixels FWHM.

High-resolution spectra were acquired with the Magellan Inamori Kyocera Echelle (MIKE; Bernstein et al. 2003). During 2002 May, data were obtained using a 0.7 slit and the CCD detector binned by 2 in the spatial direction. In the blue, the useful wavelength range covered from 3360 to 4700 Å over 32 echelle orders. The dispersion was of 0.017–0.023 Å pixel$^{-1}$ and the spectral resolution ~5.4 pixels FWHM. In the red, the useful wavelength range covered the 4775–8500 Å interval over 31 echelle orders with a dispersion varying between 0.034 and 0.060 Å pixel$^{-1}$. The spectral resolution was ~4.5 pixels FWHM. In 2004 July a new dichroic and CCD were available. High-resolution spectra were obtained using again a 0.7 slit, but this time the CCD detector was binned by 2 in both the spatial and spectral directions. With this configuration the wavelength interval 3325–5070 Å was covered over 35 orders and the interval 4705–7260 Å over 25 orders. The 0.7 slit yielded a dispersion of 0.033–0.050 Å pixel$^{-1}$ and a spectral resolution of 2.7 pixels FWHM in the blue and 0.066–0.10 Å pixel$^{-1}$ and 2.2 pixels FWHM in the red.

Table 1 provides a detailed journal of the J1628 observations. In addition to the spectra of J1628, spectra of several radial velocity standards, flux standards, and other stars were acquired during the observations.

The B&C and IMACS images were bias and flat-field corrected with standard IRAF1 routines. The spectra were extracted from each CCD frame with the IRAF KPNOSLIT package. The pixel-to-wavelength calibration was derived from cubic spline fits to HeNe or HeNeAr arc lines. The rms deviation of the fit was ~0.07 Å and ~0.02 Å for the data acquired with the B&C and IMACS, respectively. Checks for the stability of the wavelength calibration were made using the strongest atmospheric emission lines present in the spectrum. For the spectra acquired with B&C we made use of the [O i] λ5577.34 line and estimated an accuracy in the wavelength calibration ≤0.30 Å (600 line mm$^{-1}$ grating) and <0.08 Å (1200 line mm$^{-1}$ grating). In the case of IMACS, we made use of the [O i] λ6300.3 line and the OH emission blend at 7316.3 Å (Osterbrock et al. 1996). The accuracy estimated in this way was ≤0.08 Å for the wavelength calibration of the spectra recorded in CCD No. 2.

The MIKE data were processed with IRAF and the spectra extracted with the IRAF ECHELLE package and the aid of IRAF tasks developed and kindly provided by Professor Jack Baldwin. A dispersion solution was derived from a two-dimensional fit to the ThAr comparison lamp spectra. More than 400 lines were included in the fit, and residuals were typically ~0.0012 Å in the blue and ~0.0023 Å in the red. No corrections for terrestrial lines were applied to the data. The atmospheric Na D emission at 5889.95 and 5895.92 Å and the atmospheric O$_2$ bands with wavelengths provided in Pierce & Breckinridge (1973) were used to establish an accuracy of the fit <0.02 Å.

3. RADIAL VELOCITY MEASUREMENTS

The first task was to measure the radial velocities of the optical counterpart. These were measured from the spectra by the method of cross-correlation with a template star (Tonry & Davis 1979). Because no common template star was observed with all setups, we decided to use for the cross-correlation the spectrum of a template star from the Indo-US library of cool feed stellar spectra (Valdes et al. 2004). This library contains spectra of 1273 stars at a dispersion of 0.4 Å pixel$^{-1}$ and 1 Å FWHM resolution. On the basis of the preliminary results for the spectral

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1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
class of J1628 (Torres et al. 2004b), we selected the spectrum of a K3 III star (HD 169191) for the cross-correlation. Prior to the cross-correlation, the B&C and IMACS spectra were resampled onto a logarithmic wavelength scale and normalized by dividing with the result of fitting a low-order spline to the continuum. The archival K3 III spectrum was resampled onto the same logarithmic wavelength scale as for the B&C and IMACS target spectra, broadened to match the IMACS/B&C spectral resolution using a Gaussian function with the appropriate width and normalized to the continuum. In the case of the MIKE spectra, we chose two orders covering the wavelength intervals 6055–6225 and 6400–6580 Å to measure the radial velocities. These spectral ranges contain a number of moderately strong lines and blends useful not only for the radial velocity measurements but also for the spectral type/luminosity classification and rotational broadening measurement (see next section). Both orders were rebinned to match the template logarithmic wavelength scale and rectified to the continuum as explained above.

Individual velocities were extracted by cross-correlation with the archival template star in the range 4900–5560 Å (B&C; 2002 October), 4990–6540 Å after masking the interstellar Na D lines (B&C; 2003 May 12), 6400–6545 Å (IMACS), and the MIKE data after masking the Hα emission line. To obtain an estimation of the systematic errors caused by the use of the archival template, we proceeded as follows: First, we obtained the radial velocities for each night (when more than one target spectrum was available) using now a template spectrum observed during the respective night. Next, we calculated for each night the radial velocity differences and compared the values (night per night) with the radial velocity differences obtained using the archival template. We found in this way rms errors of 2 km s\(^{-1}\) and a maximum deviation of 5 km s\(^{-1}\).

We performed least-squares sine fits to our radial velocity data using the photometric period \(P_{ph} = 4.9364\) days and \(2P_{ph}\) as initial guesses for the orbital period. A spectroscopic period of 4.93956 ± 0.00025 days provided the lowest value of the \(\chi^2\) per degree of freedom (dof), being 5 times lower than that obtained for \(2P_{ph}\). This value is consistent with the deepest minimum at \(\sim 0.2\) cycles day\(^{-1}\) observed in the \(\chi^2\) periodogram of the radial velocities. Furthermore, this period agrees with the photometric period within 1.8 \(\sigma\). Nevertheless, the orbital period is not determined unambiguously because the spectroscopic data set is also consistent with several alias periods. In this work we adopt the following parameters of the radial velocity curve:

\[
K_2 = 33.3 \pm 0.6 \text{ km s}^{-1},
\]
\[
\gamma = 14.7 \pm 0.6 \text{ km s}^{-1},
\]
\[
P_{ap} = 4.93956 \pm 0.00025 \text{ days},
\]
\[
T_0 = \text{HJD 2, 452, 575.11 ± 0.03}.
\]
The zero phase is defined as the time of closest approach of the secondary to the observer. All quoted uncertainties are 1σ and were obtained after increasing the error in the radial velocities in order to give $\chi^2 = 1$. The phase-folded radial velocity curve is shown in Figure 1. Orbital phases of the observations, radial velocity measurements with their associated statistical errors, and residuals to the circular orbit solution are given in Table 2. Adopting the values of $K_1$ and the orbital period, a mass function of $f(M_1) = 0.019 \pm 0.001 M_\odot$ is obtained.

A 4.9 day orbital period rules out an ellipsoidal modulation of the optical light curve (Buxton et al. 2004) and suggests a chromospherically active binary scenario for J1628 where an evolved stellar component is covered with starspots that modulate the photospheric light with stellar rotation. The 0.30 mag modulation observed in the $V$-band light curve is at the high end for chromospherically active binaries: only 13 of 206 binaries listed in Strassmeier et al. (1993) have shown a modulation in the $V$ band with an amplitude $\geq 0.3$ mag.

4. SPECTRAL TYPE, LUMINOSITY CLASS, AND ROTATIONAL BROADENING

In a preliminary report based on the analysis of the first B&C and MIKE data sets (Torres et al. 2004b), the spectra of J1628 were compared visually with the spectra of K subgiants and main-sequence stars acquired during the observations and also compared with the spectra of G- and K-type V/IV/III stars from the Indo-US Library of coude' feed stellar spectra. Based on the depth of the TiO bands at 6080–6390 Å, a spectral type in the range K3 $\pm$ 1 was supported. A luminosity class III–IV was suggested because of the strength of the Ca i 6450 line with respect to the metallic lines in the interval 6420–6530 Å and by comparing the relative intensities of the multiplet 33 Ti i lines $\lambda\lambda$8379, 8382 and Fe i 6450 line with respect to the metallic lines in the interval 6420–6530 Å and by comparing the relative intensities of the multiplet 33 Ti i lines $\lambda\lambda$8379, 8382 and Fe i 6450 line.

To verify our visual classification and determine the rotational broadening of the secondary star, we made a more detailed analysis of the spectra acquired with MIKE during 2004 as they have a higher signal-to-noise ratio in the red than the 2003 MIKE data due to the binning in the dispersion direction and the use of a new dichroic. We focused our analysis in the wavelength interval 6350–6530 Å where there are several temperature- and gravity-sensitive lines for F, G, and K stars (Strassmeier & Fekel 1990; Strassmeier & Schordan 2000). We used the technique outlined in Marsh et al. (1994) that is based on the search of the lowest residual obtained when subtracting a set of templates from the Doppler-corrected average spectrum of the target. The template spectra are broadened prior to subtraction to determine the rotational broadening of the lines. This technique also allows the possibility of a continuum contribution from an accretion flow when searching for the parameters of the secondary star. To implement this procedure, we used a set of K dwarf and subgiant template spectra taken with MIKE during 2004 and a set of K giant spectra observed with MIKE in 2003 March (see Martini & Ho 2004).

We proceeded as follows. First, the target spectra were Doppler corrected to the rest frame of the secondary star by subtracting the radial velocity obtained from the cross-correlation with the template. Next, we produced an average spectrum after assigning different weights to the individual spectra in order to maximize the signal-to-noise ratio of the sum. The template spectra were then broadened from 37 to 47 km s$^{-1}$ in steps of 0.05 km s$^{-1}$ through convolution with the rotational profile of Gray (1992). We adopted a linearized limb-darkening coefficient of 0.65. Each broadened version of the template spectrum was multiplied by a factor $f$ (representing the fractional contribution of light from the secondary star) and subtracted from the target Doppler-corrected average. Then a $\chi^2$ test on the residuals was performed in the range 6400–6548 Å and the optimal values of $f$ and $v \sin i$ were provided by minimizing $\chi^2$. The results from the $\chi^2$ minimization are listed in Table 3, with quoted uncertainties corresponding to $\chi^2_{\text{min}} + 1$ (Lampton et al. 1976). The minimization of $\chi^2$ in the V/IV luminosity class templates shows that the spectral type of the secondary star in J1628 is most likely not later than K3. Additionally, for a single-lined chromospherically active binary star the fractional contribution of the secondary must be $\leq 1.0$. This rules out a main-sequence star and constrains the spectral type to be K3 IV/III. The high $f$-value as determined from the $\chi^2$ minimization using the IV/III templates together with the fact

![Image](https://example.com/image.png)

FIG. 2.—Averaged spectrum of J1628 and the template spectra after being artificially spun up using the rotational broadenings listed in Table 3. The spectra have been vertically shifted by a constant value for the sake of clarity. The spectrum of HD 43827 (K3 III) has been superimposed onto that of J1628 (dashed line).

### TABLE 3

| Template | Spectral Type | $v \sin i$ (km s$^{-1}$) | $\chi^2$ (dof = 1645) | $f$ |
|----------|---------------|-------------------------|-----------------------|-----|
| HD 88284 | K0 III        | 42.5 ± 0.2              | 2.58                  | 1.14 ± 0.01 |
| HD 95272 | K1 III        | 43.0 ± 0.2              | 2.64                  | 1.14 ± 0.01 |
| HD 43827 | K3 III$^a$    | 42.8 ± 0.2              | 2.46                  | 1.01 ± 0.01 |
| HD 217880 | G8 IV       | 42.7 ± 0.3              | 3.29                  | 1.50 ± 0.02 |
| HD 215784 | K1 IV       | 42.9 ± 0.2              | 2.41                  | 1.10 ± 0.01 |
| HD 163197 | K4 IV       | 43.4 ± 0.3              | 3.51                  | 0.91 ± 0.01 |
| HD 223282 | K0 V        | 43.2 ± 0.3              | 3.78                  | 1.71 ± 0.02 |
| HD 223121 | K1 V        | 42.4 ± 0.2              | 2.83                  | 1.18 ± 0.01 |
| HD 218279 | K2 V        | 42.5 ± 0.2              | 2.64                  | 1.18 ± 0.01 |
| HD 217580 | K4 V        | 42.1 ± 0.2              | 2.72                  | 1.15 ± 0.01 |
| HD 130992 | K5 V$^b$     | 42.4 ± 0.3              | 3.28                  | 1.10 ± 0.01 |

$^a$ Spectral types adopted from Jasiewicz et al. 1999 and Robinson & Cram 1990.
that the primary star is not detected in the nightly averaged spectra (which have a signal-to-noise ratio of about 70) suggest that the visual luminosity of the primary star and/or the accretion flow can be at most a few percent of the flux of the secondary star.

A rotational broadening measurement ($v \sin i$) of 43 km s$^{-1}$ was obtained from the K3 III template. To check the systematic errors introduced by the choice of the linearized limb-darkening coefficient (which is only suitable for the continuum; Collins & Truax 1995), we have allowed it to vary in the range 0.0–1.0. This leads to 7% changes in the resulting value of $v \sin i$ (i.e., ~3 km s$^{-1}$) and $f$. Therefore, it is the uncertainty in the limb-darkening coefficient and not the statistical noise that limits our accuracy. We therefore adopt a value of $v \sin i = 43 \pm 3$ km s$^{-1}$, which encompasses all $v \sin i$ values obtained for the templates in Table 3. Figure 2 shows a comparison of the spectra over the range 6400–6475 Å. It is clear that there is some excess absorption in the Ca ii lines (in particular Ca ii λ6439.1). This could be caused by differences in the spectral luminosity or/and metallicity between template and target spectrum.

5. INTERSTELLAR EXTINCTION UPPER LIMIT

An estimate of the upper limit to the color excess of 0.78 mag is derived from the weighted average Hα column within 1° along the line of sight to J1628 ($N_H = 4.51 \times 10^{21}$ cm$^{-2}$; Dickey & Lockman 1990) and the relation between $N_H$ and $E(B - V)$ of Bohlin et al. (1978). For this reddening we should expect the λ6196, 6203 diffuse interstellar bands (DIBs) to have EWs of about 78 and 220 mÅ, respectively (Herbig 1975). However, the EWs of the absorption features close to these wavelength positions are about 10 mÅ, indicating that the extinction toward J1628 is significantly lower.

We have searched all medium- (IMACS) and high-resolution spectra (MIKE) for other DIBs and atomic interstellar lines. The only interstellar features we were able to identify unambiguously in the forest of absorption lines originating in the secondary were the Na D λλ5889.95, 5895.92 and K i λ7699 lines blended with the namesake broader photospheric lines (see Fig. 3). The profile of these interstellar lines shows a single component. Taking into account that double or multiple components in the profile of the K i λ7699 line appear when its EW is ≥0.15 Å (Munari & Zwitter 1997), the upper limit to $E(B - V)$ can be reduced to ~0.6 mag according to the relation between reddening and EW for this interstellar line (Munari & Zwitter 1997). We have measured an EW of 0.08 ± 0.01 Å for the K i interstellar line after fitting the K i blend with a two-Gaussian model (with one Gaussian to account for the photospheric absorption line and the other to account for the interstellar component). Using the calibration of Munari & Zwitter (1997), we derived an interstellar extinction of $E(B - V) = 0.30 \pm 0.04$. For this reddening, the λ6196, 6203 DIBs should be stronger than observed (Herbig 1975; see also Fig. 5 in Jenniskens & Désert 1994). This discrepancy suggests that our fit is overestimating the EW for the interstellar line. Given the unreliable utility of Herbig’s calibrations for low reddening and our uncertain fit to the K i blend, we conservatively adopt for the remaining of this paper $0.0 \leq E(B - V) \leq 0.6$.

6. EMISSION LINES IN THE SPECTRUM OF J1628: CHROMOSPHERIC ACTIVITY INDICATORS

Observational evidence of a chromosphere in the visible spectrum of active stars relies commonly on the existence of emission in the cores of the Ca ii H and K lines. Apart from this hallmark active stars can reveal filling-in or strong emission lines in photospheric lines like H i Balmer lines and the Ca ii infrared triplet (see, e.g., Linsky 1980; Thatcher & Robinson 1993 and references therein). In this regard, there is clear manifestation of stellar activity in the spectra of J1628.

The Ca ii H and K lines have emission cores with absorption reversal at the top of the emission that give them a double-peak shape (see Fig. 4). Both Ca ii H and K emission profiles exhibit variations in the strength of the violet ($V'$) and redward ($R'$) peaks, the violet peak being stronger than the redward peak ($V'/R' > 1$) except on 2004 June 9, when the red peak becomes stronger ($V'/R' < 1$). Single K dwarfs and giants hotter than spectral type K3 commonly show $V'/R' > 1$ asymmetries as observed in the integrated disk of the Sun. This is often interpreted to be an indication that they have coronae and chromospheres dynamically similar to the Sun. The $V'/R'$ ratios < 1 observed in giants cooler than K4 are considered to be related to mass outflow in the chromosphere (Stencel 1978). The temporal variability of the Ca ii peak asymmetries is well documented for Arcturus ($\alpha$ Boo; K2 III). Arcturus has shown transitions from $V'/R' > 1$ to $V'/R' < 1$ in the Ca ii K emission core ratio (Chiu et al. 1977; Gray 1980). Temporal variations of the Ca ii emission cores have been observed in other late-type stars and are described in Rebolo et al. (1989), García López et al. (1992), and references therein. In the case of binary systems, Baliunas & Dupree (1982) found that the strength of the Ca ii emission profile for the single-lined (G8 III–IV) chromospherically active binary λ Andromedae increases (decreases) at the time of continuum light minimum (maximum), which corresponds to the time when spotted (unspotted) regions dominate the stellar disk. Moreover, they found $V'/R' < 1$ only at maximum light and $V'/R' > 1$ at other phases and suggested an explanation of the variations in the profile asymmetry as due to differential downward and upward motions in the stellar atmosphere. Unfortunately, our observations of J1628 are insufficient to corroborate the above correlation and explanation. Clearly, high-resolution spectroscopy with a better sampling of an orbital cycle and a simultaneous light curve are required.
The mean emission line width $W_0(K)$ measured for the Ca II K line in the MIKE spectra is 0.82 $\AA$, which yields $W_0(K) = 62.5$ km s$^{-1}$ after the quadratic correction of the instrumental broadening (18.3 km s$^{-1}$). From $W_0(K)$, we estimated an absolute visual magnitude of 2.0 for the secondary of J1628 by using the Wilson-Bappu relation for chromospherically active binaries (Montes et al. 1994):

$$M_V = 0.16 \log W_0(K) + 30.79,$$

where $W_0(K)$ is expressed in km s$^{-1}$. However, J1628 may deviate significantly from the Wilson-Bappu law due to the influence of its high rotational broadening. Montes et al. (1994) found that $M_V$ was overestimated for large values of $v \sin i$, up to 2 mag when $v \sin i \sim 40$ km s$^{-1}$ (see Fig. 5 in their paper). Therefore, $M_V$ could be $\sim 4.0$ for the secondary in J1628. In any case, these estimations of $M_V$ are in between the values for a K3 dwarf ($M_V = 6.8$; Gray 1992) and a K3 giant ($M_V = 0.3$). This result is in agreement with the expected evolved secondary for J1628.

The H$\alpha$ line is in emission above the continuum (see Fig. 4) with EW values between 0.3 and 1.3 $\AA$, except on the night of 2003 May 6, when the EW increases to 4 $\AA$. This may be due to intrinsic activity variations, like a flare eruption. The H$\alpha$ profile obtained from the high-resolution spectra has an FWHM $\sim 160$–250 km s$^{-1}$ and shows a self-reversal core during some of the nights. Variable broad H$\alpha$ emission (for an insight on the broadening mechanism see, e.g., Byrne et al. 1995) sometimes with a self-reversal core has been observed among the most extreme chromospherically active binary stars, for instance, UZ Lib (K0 III, $P_{sp} = 4.76$ days; Bopp et al. 1984), II Peg (K2 IV, $P_{sp} = 6.72$ days; Byrne et al. 1995), EZ Peg (G5 IV–III/K0 V, $P_{sp} = 11.6$ days; Montes et al. 1998), XX Tri (K0 III, $P_{sp} = 24$ days; Bopp et al. 1993), and HD 6139 (K2 IV–III, $P_{ph} = 31.95$ days; Padmakar et al. 2000). The EW of the observed H$\alpha$ emission line measured in these systems is of the order of 1 $\AA$ (see the above references). For comparison, the H$\alpha$ EWs measured in X-ray novae in quiescence are of the order of tens to hundreds of angstroms. For instance, V404 Cyg (K0 IV, $P_{sp} = 6.47$ days, $v \sin i = 38$ km s$^{-1}$) and Cen X-4 (K3–5 V, $P_{sp} = 0.63$ days, $v \sin i = 43$ km s$^{-1}$) have H$\alpha$ EWs of 38 (Casares et al. 1993) and 35 $\AA$ (Torres et al. 2002), respectively.

7. DISCUSSION

Tidal theory (Zahn 1977) predicts that late-type stars in close binary systems rotate in synchronization with the orbital motion because tidal interactions are effective in forcing synchronization on timescales shorter than the evolutionary lifetime of the systems. A purely hydrodynamical mechanism based on the effects of meridional currents in the atmospheres of the stellar components and due to their nonspherical shape also explains the synchronism observed in close binary systems (Tassoul & Tassoul 1992). The estimated spectroscopic (orbital) and photometric (rotational) periods for J1628 are nearly identical, implying synchronism. The small difference (if real) could be due to changes in the spot pattern over the years. Using the measured rotational broadening ($\xi$ 4) and assuming that the secondary star is spherical, we can obtain a lower limit for the...
\[ v \sin i = K_2(1 + q) \frac{0.49d^{2/3}}{0.6a^{2/3} + \ln(1 + q^{1/3})} . \]

From the values of \(v \sin i\) and \(K_2\) found for J1628, we derive a lower limit of \(q > 2.0\), which implies a velocity semi-amplitude of the primary \(K_1 = qK_2 > 67\) km s\(^{-1}\). These are lower limits because the radius of the secondary in J1628 may be smaller than its Roche lobe and the latter increases its size with \(q\). Assuming mild mass exchange/loss during the evolution of the system (Popper & Ulrich 1977; Dupree 1986), the mass of the secondary should be in the range of masses expected for K3 V to K3 II stars, i.e., 0.7–1.1 \(M_\odot\) (Lang 1992). Hence, \(M_1 = M_2/q < 0.5M_2 \leq 0.6 M_\odot\). On this basis, the unseen primary of J1628 is probably a dwarf (if not a white dwarf) of spectral type K7 or later. A stringent lower limit for the binary inclination of \(i \gtrsim 41^\circ\) is derived from the mass function \(f(M_1) = (1 + q)^{-3}M_1 \sin^3 i\) when using the upper limit for \(M_1\), the lower limit for \(q\), and the value of \(f(M_2)\). The radius of the secondary is thereby \(R_2 \sin i < 41^\circ/6.4 R_\odot\). In short, \(4.2 R_\odot \leq R_2 \leq 6.4 R_\odot\) for the visible stellar component in J1628. These constraints on the radius can be used in conjunction with the constraint in the spectral type of the secondary (\(\S \) 4) to obtain its absolute visual magnitude by applying equation (2) of Popper (1980). Using the visual absolute flux (surface brightness parameter) for a K3 V/III star (Table 1 in Popper 1980), we derive \(2.0 < M_V < 3.8\) in harmony with the absolute magnitudes estimated from the Wilson-Bappu relationship (\(\S \) 6). From \(M_V\), the apparent magnitude \(V = 13.4\), and the constraints to the reddening obtained in \(\S \) 5, we find 350 pc \(d < 1.9\) kpc for the distance to J1628.

We made use of PIMMS to convert the ROSAT PSPC count rates to an unabsorbed flux of \(8.5 \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) \(< f_x \approx 4.4 \times 10^{-12}\) ergs cm\(^{-2}\) s\(^{-1}\) (0.1–2.4 keV) by applying an absorbed Raymond-Smith model with log \(T = 7\), assuming a metal abundance of 0.2 times the solar value and \(0.0 < N_H \lesssim 3.48 \times 10^{21}\) cm\(^{-2}\) (see Yi et al. [1997] regarding the utility of using this one-temperature model to obtain X-ray fluxes). Furthermore, for each possible value of \(N_H\) and \(M_V\) we can evaluate the distance toward J1628 using the distance modulus and (as above) the corresponding intrinsic X-ray flux. This yielded an intrinsic X-ray luminosity of \(6.6 \times 10^{31}\) ergs s\(^{-1}\) \(< L_X \approx 6.4 \times 10^{32}\) ergs s\(^{-1}\), well above the averaged X-ray luminosity observed in chromospherically active binaries (\(\sim 1 \times 10^{30}\) ergs s\(^{-1}\); Padmakar et al. 2000), but consistent with the X-ray luminosities for RS CVn stars (\(10^{30.2}–10^{32.2}\) ergs s\(^{-1}\)). This range of X-ray luminosities for RS CVn stars was derived from observations with Einstein IPC (energy band 0.16–4 keV) and ROSAT PSPC (see Drake et al. 1989, 1992; Dempsey et al. 1993). The differences in the X-ray flux due to the different bandpasses are expected to be \(\pm 10\%\) (Dempsey et al. 1993; Benz & Güdel 1994).

An upper limit to the quiescent radio flux density of 0.3 mJy was obtained from observations (Slee et al. 2002; Rupen et al. 2004) and can be used to check if the radio flux is consistent with that expected for a quiescent chromospherically active binary. We compared this with the quiescent radio luminosity found for chromospherically active binaries of \(L_{\text{rad}} = (1.37 \pm 0.09) \log L_X = 26.38\) (Padmakar et al. 2000; see also Drake et al. 1989; Benz & Güdel 1994). In this way we derived 0.2 mJy \(< f_{\text{rad}} < 2.0\) mJy for J1628. While this range is consistent with the observed upper limit, the range is due almost entirely to our uncertainty in the X-ray luminosity: the correlation between \(L_X\) and \(L_{\text{rad}}\) is rather tight. If the true X-ray luminosity is at the high end of our range, then the quiescent radio flux is inconsistent (the predicted radio flux is larger than the observed upper limit). In this regard, the hard X-ray emission observed for J1628 (ROSAT hardness ratio HR1 = 1.00) is common for RS CVn stars undergoing an X-ray flare (see, e.g., Graffagnino et al. 1995). The radio counterpart to J1628 occasionally increases its flux density to 0.35–13.8 mJy at 8.6 and 4.8 GHz (Tsarevsky et al. 2001; Rupen et al. 2002, 2004; Slee et al. 2002). Transient radio brightenings with amplitude similar to or larger than those observed in J1628 are frequent in chromospherically active binary stars (Slee et al. 1987; Drake et al. 1989).

Finally, we considered the possibility that a foreground object could be the source of the radio and X-ray emission. We searched the images obtained with IMACS during the acquisition of the spectra to find a fainter optical source nearby GSC 07861–01088, the proposed (brighter) optical counterpart (see Fig. 5). We performed an analysis of optical astrometry from one of the images to check the positional coincidence of GSC 07861–01088 and its radio counterpart (Rupen et al. 2004). The agreement between the optical and radio position is well within the subarcsecond astrometric error, and we rule out the possibility that the nearby fainter object, which is located 2\" south at R.A. = 16h28m47s27 and decl. = −41°52′41″0 (J2000.0), is the radio source.
Optical spectroscopy obtained for other microquasar candidates has shown that they are mostly extragalactic in nature and, in the few stellar cases, likely chromospherically active stars/binary (Martí et al. 2004a, 2004b; Torres et al. 2004a; Tsarevsky et al. 2005). Hence, the search for microquasars using X-ray and radio surveys has not provided so far any new and secure microquasars. This suggests that there are few microquasars with persistent bright radio/X-ray emission to be found with the RASS Bright Source Catalogue. Apart from the discovery of X-ray transient microquasars (e.g., García et al. 2003), the progress in understanding relativistic outflows in X-ray binaries depends largely on observations of known X-ray binaries using current and future instruments with higher sensitivity and angular resolution. Suitable targets are, for instance, radio-emitting X-ray binaries where jets have not been resolved yet (see, e.g., Mirabel & Rodríguez 1999; Fender 2004) and X-ray transients in quiescence where radio jets are expected at a level of a few microjansky (see, e.g., Gallo et al. 2003, 2005).

8. CONCLUSIONS

We have presented comprehensive optical spectroscopy of the microquasar candidate 1RXS J162848.1—41524. From the analysis of the absorption-line spectrum, we have determined an orbital period of $P_{\text{orb}} = 4.93956 \pm 0.00025$ days and a radial velocity semi-amplitude of the secondary of $K_{2} = 33.3 \pm 0.6$ km s$^{-1}$. The implied mass function is $f(M_{2}) = 0.019 \pm 0.001 M_{\odot}$. We have established the rotational broadening of the secondary star to be $e \sin i = 43 \pm 3$ km s$^{-1}$. This provides an upper limit to the mass ratio of $q > 2.0$. A $χ^{2}$ test applied to the residuals obtained by subtracting different template stars from the high-resolution spectra (§7), the limits to the absolute visual magnitude (§§6 and 7), and the constraints to the stellar radius (§7) support a K3 IV secondary. The emission lines observed in the spectrum of J1628 are consistent with those observed in chromospherically active binaries. This fact, together with the results presented above, indicates a chromospherically active binary and not a microquasar nature for J1628, where the X-ray and radio emission is powered by the stellar chromosphere and the periodic photometric variability reported by Buxton et al. (2004) would be due to cool surface spots. No trace of the primary has been found in the photospheric spectrum, leading to the conclusion that it is a low-luminosity object, possibly a late-type K dwarf or white dwarf. Our analysis is hampered, however, by the fact that our spectroscopic observations do not have the required temporal coverage to determine unambiguously the orbital period of J1628. Therefore, a better sampled radial velocity curve is still necessary to confirm the parameters derived in this paper for J1628. Photometric observations at different epochs will be enlightening: if J1628 is a chromospherically active binary system, it should show significant changes in the shape and amplitude of the light curve due to variations in the starspot distribution over the surface of the secondary.

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