GRO J1744-28, search for the counterpart: infrared photometry and spectroscopy

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ABSTRACT

Using ISAAC on the VLT, we have detected 2 candidate counterparts to the bursting pulsar GRO J1744-28, one bright and one faint, both within the X-ray error circles found using XMM-Newton and Chandra. Photometry and spectroscopy of the bright candidate indicate that it is most likely a G type giant. The spectrum does not show Brackett-γ emission, a known indicator of accretion, and dynamical calculations and comparison with the X-ray mass-function indicate that this star is most likely not the true X-ray source counterpart. Photometry of the fainter candidate indicates it is a K5 V star at a distance of 4 kpc. This fits the $L_{\text{Edd}}$ distance and the measured infrared extinction. If this star is the IR counterpart, dynamical calculations would require the system to be at very low inclination; however this source cannot be excluded without follow-up spectroscopy to detect emission signatures. The mass-function remains the tightest constraint for this system. The true counterpart most likely has a mass $M < 0.3 M_\odot$. Mass transfer in such a system will be by wind-accretion as the counterpart will not fill its Roche lobe given the observed $P_{\text{orb}}$. In this case, the derived magnetic field strength of $2.4 \times 10^{11}$ G is sufficient to inhibit accretion of captured material by the propeller effect.

Key words: pulsars: individual (GRO J1744-28) – X-rays: binaries – infrared: stars

1 INTRODUCTION

The Bursting Pulsar GRO J1744-28, was discovered with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory (CGRO) on 2nd December 1995 (Fishman et al., 1995; Kouveliotou et al., 1995) during a period of outburst. GRO J1744-28 was only the second system (after the Rapid Burster MXB 1730-335) to exhibit Type-II X-ray bursts. GRO J1744-28 displays properties of both a pulsar and a Type-II burster, making it a unique source for studying the properties of accretion onto neutron stars (NS) and the interaction of magnetic fields with accretion flows.

Finger et al. (1996) detected coherent X-ray pulsations with a period of 467 ms. The pulsation rate increased during their observations at a rate of $1.2 \times 10^{-11}$ Hz s$^{-1}$. They were able to determine the orbital period of the system to be $P_{\text{orb}} = 11.8337 \pm 0.0013$ days by fitting pulse phases. These measurements indicate that the system consists of a magnetised NS with a magnetic field $> 10^{13}$ G (Giles et al., 1996; Lewin et al., 1996), and that the accretion is spinning up the NS. Cui (1997) also measured the pulsations of GRO J1744-28 and was able to derive a magnetic field strength of $2.4 \times 10^{11}$ G, assuming that the source was entering the propeller regime at the end of its phase of outburst.

The system has undergone two periods of outburst: one lasting from 2nd December 1995 until 26th April 1996, the second lasting from 1st December 1996 until 7th April 1997 (Woods et al., 1999). During these periods of outburst, hard X-ray bursts were initially observed with durations typically between 8 and 30 s, and a frequency of $\sim 20$ per hour, falling to $\sim 1$ per hour after 1 day (Woods et al., 1999). It is believed that such outbursts are caused by instabilities in the accretion disc, leading to short intervals of increased accretion onto the surface of the NS (Lewin et al., 1996).

In 2001, GRO J1744-28 was in a quiescent state with a very low level of X-ray emission. Its $0.5 – 10$ keV luminosity was measured to be $2 – 4 \times 10^{33}$ erg s$^{-1}$ with Chandra.
Figure 1. Companion mass as a function of inclination angle based on the orbital constraints from Finger et al. (1996). Calculated for $M_x = 1.4M_\odot$.

(assuming the source is near the Galactic Centre (GC) at a distance of 8 kpc; Wijnands & Wang, 2002). More recently, Munu et al. (2007) re-observed GRO J1744-28. Its 2–8 keV luminosity was measured to be $6 \times 10^{33}\text{erg s}^{-1}$, about a factor of 3 higher than the previous measurements, indicating increased activity from the X-ray source. These measurements agree with models suggesting that quiescent X-ray transients exhibit luminosities of $10^{30} - 10^{34}\text{erg s}^{-1}$ in these bands.

The mass-function for GRO J1744-28 determined by Finger et al. (1996) is $f_c(M) = 1.36 \times 10^{-4}M_\odot$. Using this in conjunction with the $P_{\text{orb}}$ (also from Finger et al., 1996) we calculated the expected mass of the companion as a function of the inclination angle, assuming a neutron star mass of $M_N = 1.4M_\odot$ (Fig. 1). From this we find that unless we are observing the system almost pole-on (inclination angle < $10^\circ$), the companion will have $M_C \lesssim 0.3M_\odot$, in agreement with the calculations of Bildsten & Brown (1997).

Finger et al. (1996) used pulse phase analysis to determine $P_{\text{orb}}$ for GRO J1744-28. Pulse-phase shifting is attributed to Doppler shifts in the pulse arrival times due to the orbital motion of a system. Observation of this Doppler shift in the GRO J1744-28 system suggests that it is highly unlikely that the system has a low angle of inclination.

In this letter we describe the characteristics of two astrometrically selected candidate counterparts to the X-ray source and find that both are unlikely to be the true counterpart. From this we derive constraints as to the structure and composition of the binary system GRO J1744-28.

2 POSITION

The accuracy of the measured position of GRO J1744-28 has improved drastically over time as the astrometric precision of X-ray telescopes has improved. Initially, the position was only available with an error radius of ~ 6$^\circ$ at 1 $\sigma$ (Fishman et al., 1995). However, this was quickly refined and as new instruments and techniques were developed GRO J1744-28 had been revisited many times. The positional error has been a critical issue for those searching for the stellar counterpart to GRO J1744-28, as the GC has a very high stellar density, with an average stellar separation $\lesssim 1.94''$ in the $K$-band at a magnitude limit of $K_S = 20$ (Gosling et al., 2004). The current best measurement of the X-ray position is that of Wijnands & Wang (2002), obtained using Chandra.

Coles et al. (1997) and Augusteijn et al. (1997) announced the discovery of an optical/near infrared counterpart candidate based on the ROSAT position for GRO J1744-28. The positions reported by both groups were consistent within their errors. This counterpart was reported to show variability as it was present in only some of the observations for each telescope used. This candidate star was at the edge of the ROSAT error circle. More recently XMM-Newton (Daigne et al., 2002) and Chandra (Wijnands & Wang, 2002) observations of GRO J1744-28 have shown that this variable star cannot be the counterpart to GRO J1744-28 as these new, more accurate observations of the X-ray position are not coincident with the position of the previously proposed counterpart (see Fig. 2).

3 DATA AND REDUCTION

As part of a program of follow up study of the X-ray sources discovered by Wang et al. (2002), we have obtained IR imaging and spectroscopy of likely counterparts to the X-ray sources. The imaging is intended to select candidate counterparts astrometrically, and determine the colours of the general population of counterparts in comparison to the field population. To conclusively identify the counterparts to the X-ray sources, we are also undertaking a program of spectroscopic observations to identify accretion signatures in their spectra (Bandyopadhyay et al., 1997, 1999).

GRO J1744-28 was observed for both imaging and spectroscopy within this campaign during the period between the Chandra observations of 2001 and 2007 when the source was in a state of quiescence.

3.1 Imaging

In June and July of 2003, we observed 26 fields within the GC Chandra mosaic of Wang et al. (2002) using ISAAC, a 1024 x 1024 pixel Hawaii Rockwell detector on the ESO VLT. This provides a 2.5$^\prime\times$2.5$^\prime$ field of view on the sky with 0.1484 resolution per pixel. One of these locations was chosen to cover the region containing GRO J1744-28. This region was observed on the 26th July 2003. We obtained 6 minutes of exposure per pointing in each of the three near-IR bands, $J$, $H$ and $K_S$, on nights with seeing $\lesssim 0.6''$. The average magnitude limits of the images are $J = 23$ ($S/N = 5$), $H = 21$ and
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3.2 Spectroscopy

We obtained $K_S$ spectra for the candidate IR counterparts to 27 of the X-ray sources, identified in the imaging program described above. Spectra were obtained using the long slit mode on VLT/ISAAC with a 1" slit-width, $R = 450$, in service mode in period 75 (April - September 2005). O and B type standard stars were observed for each spectrum. The spectra for the brighter of the two candidate counterparts to GRO J1744-28 were obtained on the 2nd July and 4th September, each with 120 s integrations, giving a total integration time on source of 240 s.

<table>
<thead>
<tr>
<th>Line</th>
<th>$\lambda$ ($\mu$m ± 0.002)</th>
<th>Width (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na I (doublet)</td>
<td>2.207</td>
<td>5.98 ± 0.1</td>
</tr>
<tr>
<td>Ca I (triplet)</td>
<td>2.264</td>
<td>4.25 ± 0.1</td>
</tr>
<tr>
<td>Mg I</td>
<td>2.282</td>
<td>1.73 ± 0.1</td>
</tr>
<tr>
<td>$^{12}$CO (2-0)</td>
<td>2.295</td>
<td>7.43 ± 0.8</td>
</tr>
<tr>
<td>$^{12}$CO (3-1)</td>
<td>2.323</td>
<td>9.71 ± 0.6</td>
</tr>
<tr>
<td>Fe I</td>
<td>2.331</td>
<td>2.07 ± 0.1</td>
</tr>
<tr>
<td>$^{12}$CO (4-2)</td>
<td>2.353</td>
<td>6.77 ± 0.3</td>
</tr>
<tr>
<td>$^{12}$CO (3-1)</td>
<td>2.372</td>
<td>2.43 ± 0.1</td>
</tr>
<tr>
<td>$^{12}$CO (5-3)</td>
<td>2.383</td>
<td>9.43 ± 1.2</td>
</tr>
<tr>
<td>$^{12}$CO (4-2)</td>
<td>2.404</td>
<td>5.22 ± 0.2</td>
</tr>
<tr>
<td>$^{12}$CO (6-4)</td>
<td>2.415</td>
<td>10.38 ± 1.1</td>
</tr>
</tbody>
</table>

Table 1. Identified lines and measured equivalent widths from the combined spectrum of the bright source (Fig. 3).

The spectra were reduced using the IRAF routine “apsum” to extract the 1 d spectra. Atmospheric lines were removed by dividing by the standard star spectra using the IRAF routine “telluric”. The spectra were observed on non-photometric nights to increase the chances of the observations being performed so no flux standards were observed, therefore they cannot be flux calibrated. The spectra have been normalised to 1 by dividing by the mean of the flux values. Identified lines and equivalent widths measured in the combined spectrum of the brighter candidate star are listed in Table 1 and the spectrum is shown in Fig. 3.

4 EXTINCTION

The extinction towards the GC is very high and non-uniform, varying on scales of 5"-15" (Gosling et al. 2006).
Figure 3. Combined spectrum of the bright candidate counterpart to GRO J1744-28 from the two nights of observation. The prominent absorption lines have been indicated. The strong CO lines indicate that this source is a late type giant. The lack of Brackett-γ (line position indicated although not present) indicates that the star is not the X-ray source counterpart, or that the accretion signature is too weak to be distinguished from the noise.

Gosling et al., in prep.) and so a specific extinction calculation is needed for the GRO J1744-28 field. We extracted the colours of all the stars within 20″ of the position of the counterparts for which we had three-colour information (179 stars), and fit their location on a $K_S$ vs ($H-K_S$) colour-magnitude plot (Fig. 4). This line was used to measure the colour excess compared to the foreground stars in the field (extracted as those with $(J-H) < 1$). The colour excess was $E(H-K_S) = 1.12 ± 0.06$ ($3\sigma$ variation in excess is ±0.18). The extinction, $A_{K_S}$, was calculated using an extinction law $A_\lambda \propto \lambda^{-\alpha}$, with $\alpha = 1.99 ± 0.01$, as were the conversions to $A_J$ and $A_H$ ($A_J : A_H : A_K = 1 : 0.573 ± 0.009 : 0.331 ± 0.004$; Nishiyama et al., 2006). Thus, the measured extinction for the source is $A_{K_S} = 1.62 ± 0.08$, $A_H = 2.80 ± 0.15$ and $A_J = 4.88 ± 0.25$.

Dotani et al. (1996a) measured the column density to GRO J1744-28 to be $5.3 ± 0.1 \times 10^{22} \text{ cm}^{-2}$ for the persistent emission, and $6.1 ± 0.2 \times 10^{22} \text{ cm}^{-2}$ for the outbursts. Muno et al. (2007) measured the column density to be $6.5 ± 0.1 \times 10^{22} \text{ cm}^{-2}$. Using the formula from Bohlin et al. (1978) we can convert the value for the persistent emission to $A_V = 28.3$ mag, and using the formula from Rieke & Lebofski (1985) we get $A_K = 3.1$ mag. This is not in agreement with the value determined from the infrared observations. However, Bohlin et al. (1978) also state that in areas of dense clouds, the conversion of column density to magnitudes can be up to 3 times lower. Considering this, $A_K = 1.0 - 3.1$ mag are all possible. The variation in the measured column density, and as we show in Gosling et al. (2006) and Gosling et al. in prep., the extinction towards the Bulge is very variable with many dense clouds, and so the standard conversion of column density to IR extinction may not be adequate. We also see possibly unusual extinction in

Figure 4. The main diagram is the $H - K_S$ vs $K_S$ colour-magnitude diagram for the stars extracted within 20″ of GRO J1744-28; the smaller diagram inset is for the whole field, shown for comparison. The red line is the loci of the foreground stars $(J-H < 1)$ extracted as described in the text and the purple line is the fit to the stars within 20″ of GRO J1744-28 (with the same slope as the foreground population). The dark-blue circles mark theoretical values for un-reddened red giant stars (Philipp Podsiałowski, private communication). The green diamond indicates the reddened values for the bright candidate counterpart from this work; the red circle is the magnitudes of the same star as reported by Wang et al. (2007) for comparison. The blue square is the position of the faint candidate counterpart.
5 PROPERTIES OF THE CANDIDATE STARS

5.1 Bright star

Using the extinction derived in Section 3, the intrinsic magnitudes of the bright source are $J = 14.10 \pm 0.25$, $H = 12.89 \pm 0.15$ and $K_S = 12.82 \pm 0.08$, giving the star colours of $J - H = 1.21 \pm 0.29$, $J - K = 1.28 \pm 0.26$ and $H - K_S = 0.06 \pm 0.17$. Of these colours, only the $H - K_S = 0.06$ is a realistic value for a star (Cox 2000). It appears that the $J$ magnitude in this case is fainter than expected from the extinction law. We note the similarity of our magnitudes to those reported in Wang et al. (2007) (see Section 6) suggest that the faint $J$ is not the result of an error in our photometric calibration of the field. Possible explanations for this include:

- The $J$-band extinction is higher than the calculated value of $A_J = 4.88$. The high degree of complexity in the extinction (Gosling et al. 2000) could indicate that the extinction has a variable dependence on wavelength and hence we are under-estimating the $J$-band extinction in this case.
- There could be a degree of intrinsic extinction within the system due to a dense stellar wind or other effects, however Figure 6 shows the counterpart to be consistent with the whole field population.
- This star is actually a blend of two unrelated stars, where the second star is faint and redder than the brighter one. This would have the effect of boosting the $H$ and $K_S$ magnitudes but keeping the $J$ magnitude faint. From the image, there is no obvious evidence of blending of two sources such as elongation. However, as the second source would be faint, this cannot be ruled out.
- The star is part of a true binary system, and the colours are a mix of the two objects in the system as above.

We discuss these possibilities in more detail in Section 6.1

Based solely on the $H - K_S = 0.06$ colour, assuming it to be accurate, the possible spectral types for this candidate include F5 I, G0-8 III and G4-6 V (Cox 2000). Considering each of these possibilities:

- F5 I: A Iab supergiant would have an intrinsic $K_S$ app $\sim 9$, which is too bright to be consistent with the observed magnitude and extinction. (Note that type Iab would be even brighter, thus also not an option.)
- G4-6 V: Considering the extinction value measured towards GRO J1744-28, and the position of this brighter counterpart on the colour-magnitude diagram, the observed star is close to the GC if not within the Nuclear Bulge (Fig. 4). At such a distance, a G4-6 V main sequence star would be 5 magnitudes fainter than is observed, essentially undetectable in our imaging survey.
- G0-8 III: At the GC distance suggested from the colour-magnitude diagram of 8 kpc, this star should have a $K_S$ app $\sim 14$, approximately one magnitude fainter than observed. For the observed magnitude, the distance of the counterpart should be closer to 6±1 kpc. The position of the star on the colour-magnitude diagram suggests that it is at the near edge of the GC stars so such a distance is plausible.

We also obtained a spectrum for this brighter of the two stars, shown in Figure 8. From the absorption lines in the spectrum, it appears that this source is a late type giant. There are strong $^{12}$CO band-heads, some evidence of $^{13}$CO band-heads and Mg, Ca and Na absorption features.

We performed an optimal subtraction in order to improve our identification of the spectral type of the counterpart. We used the spectral library of standards from Wallace & Hinkle (1997), which includes stars of most spectral types from A–M giants. The resolution of the standards was $R = 3000$, so we had to resample them to match the lower resolution of our observed spectrum.

The optimal subtraction enabled us to exclude the possibility that the counterpart is of spectral type earlier than a G III type star. This is based on the absence of CO band-heads from the spectra of these earlier type stars. The CO band-heads are the most prominent feature of the observed spectrum and so the subtraction is strongly influenced by their presence. Of the G, K and M type spectra, later types of each (5-8) proved the best fits based on the strength of the CO features, with G8 IIIab, K5 III, and M7+ III proving the best fits for the respective spectral types as shown in Figure 5. The relatively low resolution of our target spectrum does not allow us to distinguish between these possibilities in a statistically significant way.

Brackett-$\gamma$ emission was not observed in the spectrum, nor any other emission lines, indicating the brighter source is not in an accreting system. Alternatively, the surface of the companion star is not being heated sufficiently to produce an observable emission line in our spectrum.

5.2 Faint star

The position of the faint source on the colour-magnitude diagram (Fig. 4) indicates that it is not actually at the distance of the GC, but is in fact closer. The colour excess for this star is 0.53 times that of the GC population in the field, therefore we have applied only half of the GC extinction correction for this star. In this case, the intrinsic magnitudes become $J = 19.04 \pm 0.27$, $H = 17.61 \pm 0.17$, and $K_S = 17.51 \pm 0.12$, giving the star colours of $J - H = 1.43 \pm 0.32$, $J - K = 1.54 \pm 0.30$ and $H - K_S = 0.11 \pm 0.21$. As with the brighter source, only the $H - K_S = 0.11$ corresponds to a realistic spectral type, and the same possible explanations could apply:

- The intrinsic $J$-band extinction for this field is higher than derived from the extinction law; or there could be a degree of intrinsic extinction in the system (see explanations for the bright source). The former is more likely than the latter as it would explain such anomalous colours in both the bright and faint sources.
- The anomalous colours could be due to blending of the observed star with a fainter background star, or a fainter binary companion producing an excess in $H$ and $K_S$. However, for this to occur in both the bright and faint candidate counterparts is very unlikely.
Based on an $H-K_S = 0.11$ colour and $K_S = 17.5$ and $H = 17.6$ magnitudes, the most likely spectral type for the faint candidate counterpart is a K5 V star (Cox, 2000). This colour and magnitude fit for a distance of 4 kpc which is consistent with the star’s position on the colour-magnitude diagram (assuming that the amount of absolute extinction is proportional to distance). However, the $J$-band magnitude and therefore $J-H$ and $J-K$ colours are still inconsistent with any spectral type.

6 DISCUSSION

For both the bright and faint stars, we find that the $J$ magnitude measured is anomalously faint, preventing identification of the spectral type using colours alone. This problem could be caused by some intrinsic property of the stars, a calibration error in our data, or uncertainties in the extinction. As we see this same effect in both stars, and as the candidate stars are consistent with the general field population (Figure 6), it is unlikely that there is some intrinsic property of both systems that causes their anomalously faint $J$ magnitude. Since these stars are not inconsistent with the stars of the entire field, there could be a calibration error in our data. However, Wang et al. (2007) has observed the bright candidate counterpart to GRO J1744-28, and their reddened magnitudes are similar to those of this work: $J = 19.21$, $H = 16.16$ and $K_S = 14.69, \pm 0.05$ compared to our values of $J = 18.98$, $H = 15.68$ and $K_S = 14.44 \pm 0.02$ (Fig. 6). While there is an offset between the two sets of magnitudes, Wang et al. (2007) use a different photometric calibration to ours (private communications) which accounts for the discrepancy. The fact that they independently observe similar magnitudes suggests that our results are valid and that $J$-band extinction is higher than the calculated $A_J$. That we observe higher extinction in $J$, the shortest wavelength of our observations, and that the X-ray column-density measured is higher than expected for a source at 4 kpc indicates that the extinction law may be steeper than 1.99.
6.1 Bright Star

Of the three spectral types allowed by the colours and magnitudes of the bright counterpart, a G type giant is the best candidate. This conclusion is also consistent with the observed spectrum.

If the counterpart is a G III, we can estimate some of the physical properties of the system. We use a NS of $M_\text{NS} = 1.4 \pm 0.1 M_\odot$, a companion G III mass of $M_\text{c} = 2.5 \pm 0.5 M_\odot$ and the orbital period of $P_{\text{orb}} = 11.8337 \pm 0.0013 \text{days}$ (Finger et al., 1996). From this we calculate the system would have a semi-major axis of $a = 34 \pm 4 R_\odot$, and the Roche lobe of the donor star would be $R_{\text{RL}} = 14 \pm 4 R_\odot$. In this case, if the bright star is the counterpart, then the $6 - 10 R_\odot$ radius of the G III giant is too small for accretion to be by Roche lobe overflow (RLOF), and any mass transfer will be by wind-accretion. A star of this mass is also consistent with the mass-function measured by Finger et al. (1996), unless the inclination angle $i < 4^\circ$, and we are observing the system nearly pole-on.

No Brackett-γ line was observed in the spectra, nor any other emission lines. Therefore if the brighter source is the counterpart to GRO J1744-28 then the surface of the star/outer accretion disc is not being illuminated and heated by the X-rays from the compact object, or if so then it is not strong enough to cause detectable line emission. The source may not be in an accreting phase; if so the observed X-rays could be the residual cooling of the NS surface, assuming the quiescent flux measured by Wijnands & Van der Klis (2002); Wang et al. (2007). If so, and this star is the companion, this would be in agreement with the theory put forward by Cui (1997) that GRO J1744-28 is in the propeller regime which is inhibiting accretion when it is in its quiescent state.

Based on our photometric and spectroscopic data, however, it seems unlikely that the bright star is the counterpart to the X-ray source GRO J1744-28.

6.2 Faint Star

For the fainter candidate counterpart, we only apply an extinction correction of half that used for a star at the GC based on the position of the star on the colour-magnitude diagram. The match to the $H - K_\text{S}$ colour and $H$ and $K_\text{S}$ magnitudes is a K5 V star. A companion star of this mass ($M_\text{c} = 0.67 \pm 0.1 M_\odot$ Cox, 2000) would still require a pole-on orientation of the system, $i < 7^\circ$. The system would be wind-accreting as a K5 V has a radius of $0.72 R_\odot$ (Cox, 2000), much less than the $R_{\text{RL}} \sim 8.8 R_\odot$ for such a system.

The magnetic field strength estimated by Cui (1997) $(10^{13} \text{G})$, requires a mass accretion rate $< 2.32 \times 10^{15} \text{kg s}^{-1}$ for the Alfvén radius to be greater than the co-rotation radius for this system, as required for the propeller effect. This is about 4 orders of magnitude greater than typical wind-accretion rates, so if the system is wind-fed then the observed quiescence could definitely be caused by the propeller effect as theorised by Cui (1997). However it is very unlikely that X-ray emission would be observed from a wind-accreting system containing a late main-sequence star as the stellar wind would result in very little mass transfer.

The distance calculated for this star, 4 kpc, agrees with the $L_{\text{Edd}}$ distance as calculated by Giles et al. (1996), as does the low value of extinction. However, this is at odds with the measured column density to the source that indicates that it should be at or near the GC (Dotani et al., 1996a; Giles et al., 1996; Munro et al., 2003, and others). The extinction towards the GC has a very complex distribution and it is possible that there is a cloud of material along the line of sight to GRO J1744-28, causing the anomalous colours and the high column density for such a distance.

This star was too faint to obtain a spectrum with the integration times used for our 2003 VLT ISAAC spectroscopy. In order to definitively rule out this star as the counterpart to GRO J1744-28, high S/N K-band spectroscopy, with significantly higher integration times, will be required.

6.3 Mass Function Constraints

The mass function is still the strongest constraint on the properties of the counterpart. Neither of the stars detected in the X-ray error circle are consistent with it unless the system is almost pole-on, in which case almost any spectral type is possible (Fig. 1). Finger et al. (1996) measured the orbital period by fitting pulse phases, caused by Doppler shifting due to orbital motion, which would be un-observable if the system were pole-on. Both the candidates described above would require the system to be almost pole-on and so are unlikely to be the true counterparts.

Assuming the system is not pole-on, the mass-function places an approximate upper limit on the mass of the counterpart at $\sim 0.3 M_\odot$ ($i > 15^\circ$), which equates to an M3 or later main sequence star (Cox, 2000), or an evolved star that has lost a significant portion of its mass (Rappaport & Joss, 1995). Both of these scenarios rule out RLOF as a method of accretion unless the system is pole-on. Thus, GRO J1744-28 is probably a wind accreter and as such in quiescence would have a minimal disc unlikely to affect the observed magnitude of the counterpart. Such a star, if at the distance of the GC, is too faint to be detected in our ISAAC images ($K_{\text{app}} > 20$). Therefore it may be that the counterpart is at the GC, as suggested by the X-ray column density measured to GRO J1744-28, and that deeper, vary-high spatial resolution observations would be needed to reveal it.

7 CONCLUSIONS

We detected two sources within the X-ray error circle of GRO J1744-28. The bright source has a position $R.A. = 17^h44^m35.07^s$, $Dec. = -28^\circ44'26.89''$ and the faint source has position $R.A. = 17^h44^m33.16^s$, $Dec. = -28^\circ44'27.41''$ with 0.1'' errors.

Based on photometry and spectroscopy, the bright candidate is most likely a late type G III star. The mass-function for the GRO J1744-28 system (Finger et al., 1996) means that if this is the counterpart, the system will be almost pole-on to the observer ($i < 4^\circ$) and it would be a wind-accreting system. The spectrum shows no sign of Brackett-γ, so, if this source is the counterpart, the illumination of the outer accretion disc or surface of the star is insufficient to produce an observable emission line. Based on this evidence, it is unlikely that this is the counterpart to the X-ray source GRO J1744-28.

Photometry of the faint star indicates that its most likely spectral type is K5 V. Although a more reasonable
possible counterpart based on comparison with the mass-function, it would still require the system to be almost pole-on ($i < 7^\circ$). The distance of this source (4kpc, see Fig. 4 & 6) agrees with the $L_{\text{Edd}}$ distance calculated by Giles et al. (1996) and the lower IR extinction. This value does not agree with the measured column densities which suggest the source is at the GC. However, as the distances derived from the measured column density and IR extinction vary greatly, we cannot rule out the possibility that the source is closer to us than the GC. This faint source thus cannot be ruled out as the counterpart, but further data is required, especially IR spectroscopy to investigate this possibility.

The mass-function is still the best constraint for GRO J1744-28, indicating that the counterpart has an $M < 0.3 M_\odot$ and could be an M3+ V (Cox, 2000) or evolved star that has been stripped (Rappaport & Joss, 1997). If the inclination is low ($i \leq 15^\circ$) and the candidate were a more massive star, we would have detected it in our survey. Based on the dynamics of such a system, the method of mass-transfer would have to be wind-accretion and the counterpart would not fill its Roche lobe. In this case, the magnetic field strength measured by Cui (1997) would mean that the propeller effect was inhibiting accretion explaining the quiescent state of GRO J1744-28 as observed since 1997.

8 ACKNOWLEDGEMENTS

AJG would like to thank the UK Particle Physics and Astronomy Research Council for his studentship. SAF acknowledges travel support provided by UNSW@ADF A and the Astronomical Society of Australia. This paper is based on observations made with the ESO VLT at Paranal under imaging programme ID 071.D-0377(A) and spectroscopic programme ID 075.D-0361(A). We would also like to thank the anonymous referee for the helpful comments made.

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