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Infrared spectroscopy of low-mass X-ray binaries

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ABSTRACT

Using CGS4 on UKIRT, we have obtained the first 2.05–2.45 μm infrared spectra of the Galactic bulge low-mass X-ray binaries (LMXBs) GX1 + 4 and GX13 + 1. We report the detection of Brackett gamma emission from the accretion disc in both systems, confirming the identification of the IR counterpart to GX13 + 1. In addition, both spectra show CO molecular bands and metal lines in absorption, representing the first infrared spectroscopic detection of the secondary in a heavily obscured bulge source. We also present a *JHK* spectrum of the LMXB Sco X-1, which shows strong H I, He I and He II emission.

Key words: accretion, accretion discs – binaries: close – binaries: spectroscopic – infrared: stars – X-rays: stars.

1 INTRODUCTION

In low-mass X-ray binaries (LMXBs), mass is transferred from a late-type star to its highly compact companion, either a neutron star or a black hole, via an accretion disc. These systems can be classified according to location within the Galaxy, accretion characteristics, and luminosity (e.g. van Paradijs & McClintock 1995). Mapping of the X-ray sky has revealed a band of bright X-ray sources within 15° longitude and 2° latitude of the Galactic Centre (see e.g. Warwick et al. 1988). Known as the 'Galactic bulge' or 'bright bulge' sources (henceforth referred to as GBS), these LMXBs are among the most luminous X-ray sources in the Galaxy (typical $L_X \sim 10^{38}$ erg s^{-1}). However, the GBS remain the most poorly understood class of LMXB because of the heavy obscuration in the direction of the Galactic bulge which makes optical study nearly impossible. To date, little is known about the GBS, save for the discovery of quasi-periodic oscillations (QPOs) in several systems (e.g. van der Klis 1989). GBS have shown no X-ray bursts, and attempts to detect orbital variability have generally been unsuccessful, suggesting that their periods may be longer than those of canonical LMXBs (Charles & Naylor 1992, hereafter CN92).

With the recent advances in infrared (IR) detector technology, it has become possible to study LMXBs at *JHK* wavelengths. Observing LMXBs in the IR has two main advantages: the late-type secondaries are brighter relative to the accretion discs, and, more importantly for the GBS, the ratio of *V*- to *K*-band extinction is nearly 10 (Naylor, Charles & Longmore 1991, hereafter NCL91). Only in IR wavelengths, then, does it become possible to undertake a detailed study of these systems.

Over the past six years, we have developed a program of IR observations of LMXBs. This began with the discovery, via colours or variability, of candidates for the IR counterparts to the GBS X-ray sources using the precise X-ray and radio locations now available (NCL91). Following this photometric survey, we are now engaged in one of the first IR spectroscopic surveys of LMXBs. As well as observing the GBS, we are also observing better-known LMXBs for the dual purpose of comparison with the GBS and further understanding of the LMXBs themselves.

In this paper, we present the spectra of three systems: the LMXB Sco X-1, the GBS GX1 + 4, and the GBS GX13 + 1. The prototype LMXB Sco X-1 is the brightest steady LMXB and has been well-studied for three decades. Here we present the first high-resolution *JHK* spectrum. As a result of its lower reddening, GX1 + 4 is the only GBS to have been extensively studied in the optical, and is the

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brightest of the bulge sources at $K=8.1$. The secondary in this system has been identified as an M6III (Davidsen, Malina & Bowyer 1977). The brightness of GX1 + 4 makes it an excellent candidate both for a detailed spectroscopic study and as a template for comparison with the less-thoroughly observed GBS. GX13 + 1, by contrast, is completely obscured in the optical. An IR study of the field mapped by the *Einstein HRI* in X-rays revealed a variable IR source at the Grindlay & Seaquist (1986) radio position of GX13 + 1 (CN92). The observed variability made this IR source a very strong candidate for being the counterpart to GX13 + 1. We present here the *K*-band spectrum of this candidate, whose emission feature confirms the identification.

2 OBSERVATIONS

We obtained *K*-band (2.05–2.45 μm) spectra of GX1 + 4 and GX13 + 1 using the Cooled Grating Spectrometer (CGS4) on the 3.8-m United Kingdom Infrared Telescope on Mauna Kea during the night of 1995 June 29 UT. The 75 line mm^{-1} grating was used with the 150-mm camera and the 256 × 256-pixel InSb array. Target observations were bracketed by observations of A-type stars for removal of telluric atmospheric features. The *JHK* spectra of Sco X-1 were obtained on the nights of 1992 May 29 and 30 UT, using the earlier 58 × 62 InSb array on CGS4. A journal of observations is presented in Table 1.

The standard procedure of oversampling was used to minimize the effects of bad pixels (Wright 1995). The 1995 spectra were sampled over two pixels by mechanically shifting the array in 0.5-pixel steps in the dispersion direction, giving a full width at half maximum (FWHM) resolution of 34 Å (~ 460 km s^{-1} at 2.25 μm). We employed the non-destructive readout mode of the detector in order to reduce the readout noise. The slit width was 1.23 arcsec, which correpsonds to 1 pixel on the detector. In order to compensate for the fluctuating atmospheric emission lines, we took relatively short exposures and nodded the telescope primary so that the object spectrum switched between two different spatial positions on the detector. Throughout the observing run the slit orientation was north–south. Details of the design and use of CGS4 can be found in Mountain et al. (1990).

The Sco X-1 spectra were oversampled by 3 pixels, producing a resolution of 63 Å. The slit width was 3.1 arcsec (corresponding to 1 pixel) and was at a position angle of 45°. Further details of the 1992 May observations can be found in van Kerkwijk et al. (1996).

Table 1. Journal of observations.

Object	Date	UTC (hrs)	Exposure time (secs)	Band
Sco X-1	29/5/1992	7:18	360	K
	30/5/1992	7:25	360	H
	30/5/1992	12:50	360	J
GX1+4	29/6/1995	8:34	640	K
GX13+1	29/6/1995	11:44	2400	K

3 DATA REDUCTION

The CGS4 data reduction system performs the initial reduction of the 2D images. These steps included the application of the bad pixel mask, bias and dark subtraction, flat-field division, interlacing integrations taken at different detector positions, and co-adding and subtracting the nodded images (see Daly & Beard 1994). All of the 1995 2D images were inclined by about 30° from vertical because of a fault in the slit wheel. This slant was corrected by tracing the inclination of the arc spectra and then fitting each line with a polynomial in order to transform the lines to the vertical. The resulting coefficients were then used to transform all of the other spectra. The residual sky background was then removed from each spectrum. Finally, 1D spectra were extracted by summing the counts in the three rows containing the object flux. Further reduction was performed in the following three stages.

(i) First we performed a wavelength calibration using argon arc lamp exposures. We fitted the arc spectrum with a second-order polynomial. The rms scatter of the fits was $\sim 1/3$ of a pixel (=5 Å). With three coefficients fitted to about 14 lines, the statistical uncertainty in the wavelength scale is of the order 1/7 of a pixel, corresponding to a velocity uncertainty of 30 km s^{-1}.

(ii) The next step was to remove the ripple arising from variations in the star brightness (a result of changes in the seeing and sky transparency, and the slight motion of the stellar image relative to the slit) between integrations at the different detector positions. The ripple amplitude varied between 2 and 3 per cent of the flux level for any given spectrum. Fourier transforms of the individual spectra revealed a 2.5-pixel periodicity. We subtracted this ripple from each of the spectra by first computing the Fourier transform of the spectrum and then subtracting the ripple at the observed frequency and amplitude.

(iii) The telluric atmospheric features were removed by dividing the spectra to be calibrated by the spectrum of an A-type star, observed at a similar airmass (within 0.05). A-type (most frequently A0) stars were used because these show only one prominent feature in the *K*-band, namely Brackett γ absorption, which is easily masked out. Finally, for flux calibration we multiplied the observed flux standard spectrum by the known flux of the standard at each wavelenth as fitted to a blackbody function (see e.g. Daly & Beard 1994). This spectrum was then used to flux calibrate all the other spectra.

4 RESULTS

4.1 Sco X-1

Our *JHK* spectrum of Sco X-1 is shown in Fig. 1. Strong emission lines of H I, He I and He II from the accretion disc dominate the features; no absorption features from the secondary star can be distinguished. A list of identified lines is found in Table 2.

The X-ray luminosity of Sco X-1 ($L_X \sim 3 \times 10^{37}$ erg s^{-1}, Bradt & McClintock 1983) indicates a high rate of mass transfer and an intensely heated accretion disc. Little is known about the mass-losing secondary; however, the long orbital period of the system ($P=18.9$ h) indicates that the

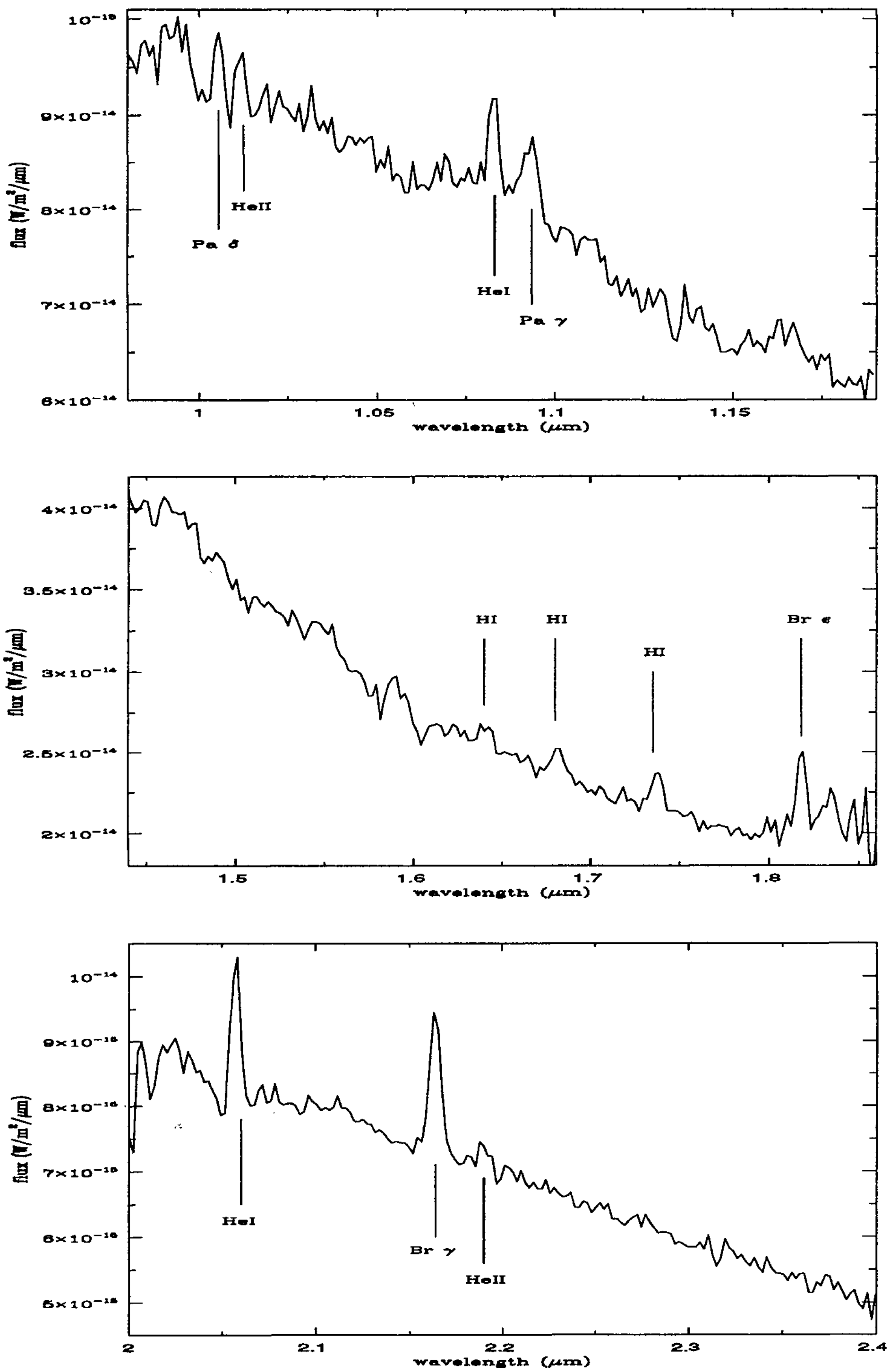

Figure 1. *J*-, *H*- and *K*-band spectra of Sco X-1. Strong emission lines of H I, He I and He II are evident, but no absorption features can be distinguished.

secondary is evolved. Both the long period and the high mass-transfer rate favour the formation of a large accretion disc (see Beall et al. 1984); consequently, we expect to see emission from the disc in the IR. Indeed, as in the optical spectroscopy of Sco X-1 (see e.g. Schachter, Filippenko & Kahn 1989), our *JHK* spectrum does not show the prominent absorption features expected from a late-type star but instead shows only emission lines from the heated disc. The lack of evidence for features arising from the secondary may be due in part to continuum noise resulting from variable atmospheric absorption. However, the continuum of our *K*-band Sco X-1 spectrum does not show noise fluctuations large enough to obscure the CO bandheads and metal absorption lines expected from the secondary.

Table 2. Equivalent widths of features identified in the LMXB spectra.

Line	Wavelength (μm) [a]	Sco X-1 (Å)	GX1+4 (Å)	GX13+1 (Å)
Pa δ	1.006	-2.1±0.4		
HeII	1.012	-1.5±0.4		
HeI	1.083	-4.8±0.4		
Pa γ	1.093	-5.4±0.5		
HI	1.641	-3.6±0.8		
HI	1.682	-6.1±0.9		
HI	1.737	-8.4±0.8		
Br ϵ	1.818	-15.1±0.8		
HeI	2.057	-18.0±0.8		
Br γ	2.164	-23.1±1.2	-10.8±0.6	-5.5±0.8
HeII	2.191	-4.7±0.8		
NaI	2.199		1.5±0.6	1.7±0.6
NaI	2.204		2.5±0.6	
FeI	2.225		1.8±0.4	
FeI	2.236		0.7±0.4	
CaI (triplet)	2.261		4.0±0.5	2.4±0.9
MgI	2.281		1.0±0.5	
^{12}CO (2,0)	2.293		20.5±0.6	6.2±1.0
^{12}CO (3,1)	2.322		20.9±0.7	
^{13}CO (2,0)	2.343		3.4±0.5	
^{12}CO (4,2)	2.352		28.0±0.8	4.4±1.2
^{13}CO (3,1)	2.375		8.2±0.7	
^{12}CO (5,3)	2.382		14.5±1.0	
^{13}CO (4,2)	2.405		5.5±0.8	
^{12}CO (6,4)	2.413		13.9±1.0	

[a]Typical wavelength calibration errors are approximately ± 0.002 μm.

The non-detection of the mass-losing star despite the relatively low reddening ($E(B-V)=0.3\pm0.05$: Vrtilek et al. 1991) indicates that the secondary cannot be very luminous, i.e. it is not a giant. Assuming the secondary fills its Roche lobe, its mean density (0.31 g cm^{-3}) implies that it cannot be a late-type main-sequence star; a main-sequence star of that density would be type A3 or earlier (Allen 1973). The secondary is therefore most likely a subgiant. Several long-period X-ray binaries, e.g. Cen X-4 ($P=15.6$ h, Shahbaz, Naylor & Charles 1993) and Aql X-1 ($P=19.1$ h, Shahbaz et al. 1996, hereafter S96), are known to have subgiant secondaries, suggesting that Sco X-1 may be similar in this respect.

In order to determine whether or not we would expect to see absorption features from a late-type subgiant secondary at the measured Sco X-1 distance of 2.0 ± 0.5 kpc (Vrtilek et al. 1991), we have modelled the appearance of two spectral template stars (K0IV and G5III) in the *K*-band at the distance and reddening of Sco X-1. The depths of the CO bands in a G5III are similar to those in a G5IV; the giant serves in lieu of a good quality subgiant spectrum, which is not yet available. After modelling the flux of the spectral template stars at 2.0 kpc, we degraded the spectra by a factor of 2 to correspond to the lower resolution of the Sco X-1 spectrum, obtained with the earlier CGS4 array. We then added a simulated accretion disc (a blackbody spectrum $\sim\nu^{1/3}$, with noise) to the template stars, bringing the combined spectrum to the flux level observed in our *K*-band Sco X-1 spectrum. The resultant spectra are seen in Fig. 2, normalized for ease of comparison. The simulated spectra indicate that for K0IV and G5III(IV) secondaries, we should be able to see CO band features in the Sco X-1 spectrum. Of course, it is not certain that secondary stars in LMXBs will evolve in an identical way to single stars of the same spectral type, i.e. a star the size of which is fixed by the Roche lobe may actually have the gravity and temperature of a much larger star. Consequently, the modelling of this system to determine spectral type has an inherent uncertainty. However, if the Roche lobe-constrained secondary star does indeed have the temperature characteristics of a larger star, i.e. it is *cooler* than expected for its type, then the molecular bands should be *more* rather than less prominent in the *K*-band spectrum. Therefore, it is more likely that the Sco X-1 secondary star is of a spectral type which shows little or no CO features, which for a subgiant constrains its spectral type to be earlier than G5 (see e.g. the spectral atlas

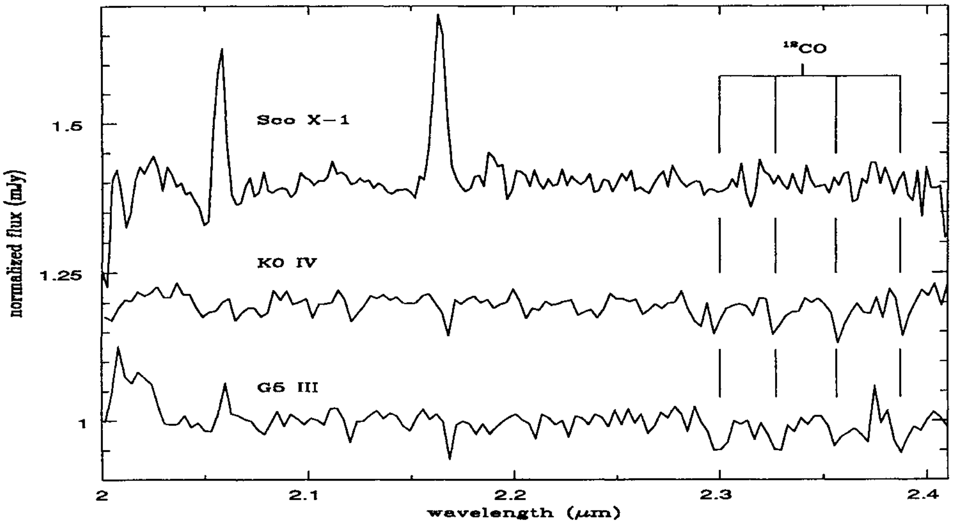

Figure 2. *K*-band Sco X-1 spectrum plotted with the K0IV and G5III template stars with simulated accretion disc added. Note that the CO bands are still visible in the latter two spectra, where they are not in Sco X-1. The flux level has been normalized for ease of plotting.

of Kleinmann & Hall 1986, hereafter KH86). The next step will be to obtain a new *K*-band spectrum of Sco X-1 with longer integration times combined with the higher resolution of the larger CGS4 array to search for the metal lines which should still be present in subgiants earlier than G5.

4.2 GX1 + 4

Fig. 3 shows our *K*-band spectrum of GX1 + 4. The spectrum shows Brackett γ emission, along with a number of prominent absorption features. Most noticeable are the five ^{12}CO bands and three ^{13}CO bands which are characteristic of evolved late-type single stars (KH86). Also visible are neutral metal lines including Na I, Fe I, Ca I and Mg I. Due to the lack of available M giant standard IR spectra of comparable resolution to our data, we have not attempted any exact verification of the spectral type of the companion. However, the depth of the ^{12}CO bands together with the prominence of ^{13}CO lines are clearly inconsistent with a main-sequence star, and strongly support the existing classification via optical spectroscopy of the secondary as an M giant (Davidsen et al. 1977; S96). Brackett γ emission is expected to arise from both the accretion disc and the X-ray-heated face of the secondary. As the optical spectrum of GX1 + 4 is totally dominated by the secondary star (S96), we expect the accretion disc contamination to be negligible in the *K*-band; indeed, the absorption features seen in the spectrum are intrinsic features of the companion. The line identifications, measured wavelengths, and equivalent widths are listed in Table 2.

The ratio of the equivalent widths of ^{12}CO to ^{13}CO depends upon luminosity class (see e.g. Dhillon & Marsh 1995), ranging from 90 in main-sequence stars to approximately 10 in giants (Campbell, Lambert & Maillard 1990). In our GX1 + 4 spectrum, the ^{13}CO bands are prominent, consistent with its classification as a giant. Unfortunately, the resolution of the spectrum is insufficient to accurately calculate the ^{12}CO/^{13}CO ratio. To obtain a rough estimate of this ratio, we measured equivalent widths by first establishing the continuum as a linear function between marked points on either side of each feature. The flux was then determined by summing the pixels within the marked area and subtracting the continuum. Measurement of the ratio of the most clearly resolved ^{12}CO and ^{13}CO pair, the (2,0) bandheads, yielded a value of ~ 8, which is comparable to that expected for a field giant. Although it is clear that higher resolution spectra are required to determine the ^{12}CO and ^{13}CO ratio accurately, our GX1 + 4 spectrum shows that using this ratio to constrain the luminosity class of LMXB secondaries is feasible.

4.3 GX13 + 1

Our *K*-band spectrum of GX13 + 1 is presented in Fig. 4. The most prominent feature in this spectrum is the Brackett γ emission line from the accretion disc. The presence of this line directly confirms the proposed identification of the IR counterpart to the X-ray source (CN92). This spectrum has rather poor signal-to-noise ratio compared with that of GX1 + 4. This is related to both the relative faintness of the source ($K \sim 12$) and the difficulty in adequately correcting for atmospheric absorption over the long (40 min) exposure. This is especially noticeable in the region of 2.28–2.38 μm, where changeable atmospheric conditions severely limit our ability to resolve the CO bands satisfactorily. Nevertheless, CO bands are present, as may be Na I and Ca I. A complete list of the lines seen in this spectrum is found in Table 2.

This spectrum represents the first detection of the mass-donating star in a heavily obscured GBS. In a statistical study of a flux-limited sample of LMXBs, Naylor & Podsiadlowski (1993) asserted that the GBS distribution is associated with that of M giants in the Galactic bulge. Indeed, the presence of CO absorption bands in the spectrum indicates that the secondary must be a late-type star (later than G2 for a giant or later than G5 for a main-sequence star, KH86). Groot et al. (1996) have observed a possible 12.6 ± 1 d period for GX13 + 1; assuming the secondary star fills its Roche lobe, its approximate spectral type would therefore be K0III (Allen 1973). In addition, Garcia et al.

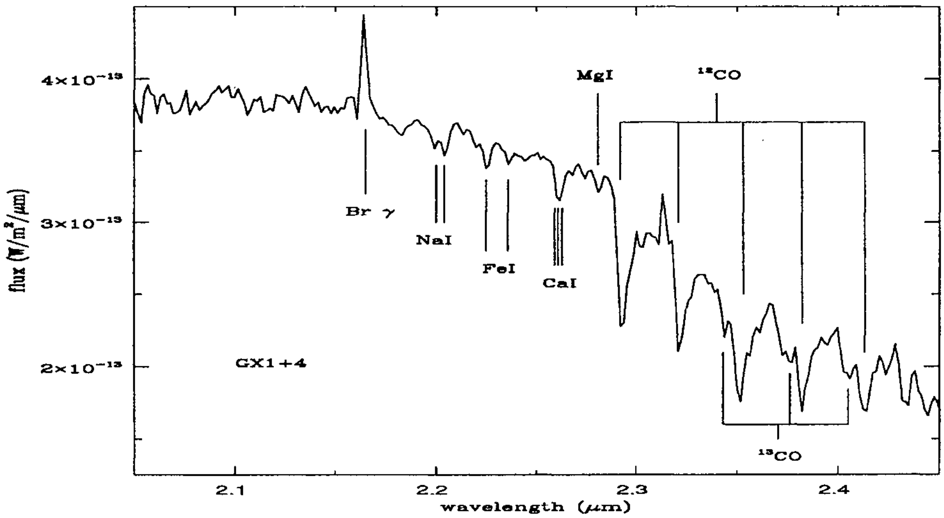

Figure 3. *K*-band spectrum of the GBS GX1 + 4 ($K = 8.1$). Bracket γ and the metal lines are clearly delineated.

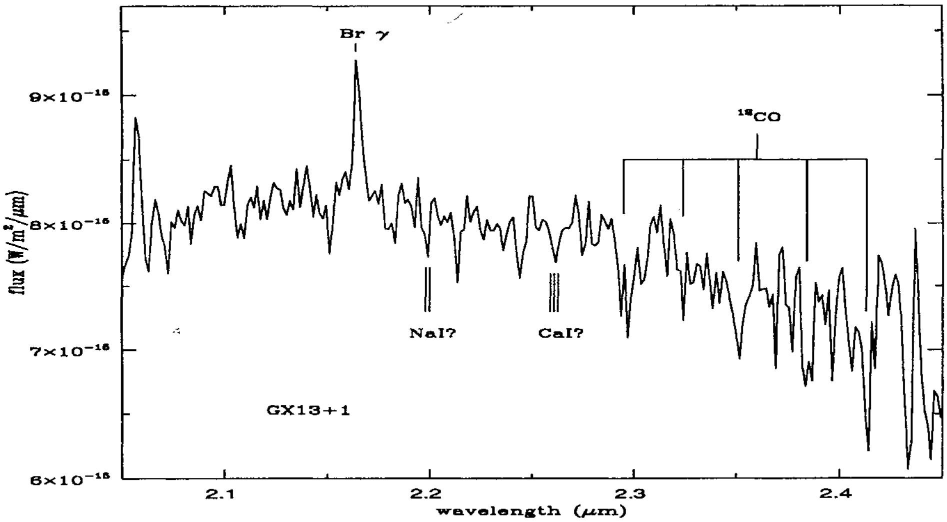

Figure 4. *K*-band spectrum of the GBS GX13 + 1 ($K = 11.8$), 40-min exposure. Bracket γ emission is clearly visible, confirming the identity of the IR counterpart to the X-ray source. Possible features arising from the secondary are also indicated.

(1992) have previously estimated the secondary to be a K2III. Using an approximate distance to GX13 + 1 of 9 kpc and an apparent magnitude $K = 12$ (CN92) together with a colour excess $E(B-V) = 5.7$ (van Paradijs 1995), we calculate an absolute magnitude $M_K = -4.6$ for GX13 + 1. Assuming no accretion disc contamination, a main-sequence star with this M_K would be of type O6 (Allen 1973), clearly inconsistent with our spectrum. We note that even a 40 per cent error in our value of M_K (from uncertainties in the distance and reddening of GX13 + 1 and the possibility of an accretion disc contribution in K) would indicate a main-sequence secondary star no later than B2. We can therefore rule out a main-sequence secondary for this system. For a giant secondary, $M_K = -4.6$ implies an approximate spectral type of M1. With a 40 per cent uncertainty, possible spectral types range from K2III to M5III, in general agreement with previous estimates. Our spectrum is consistent with these possibilities, but the obscuration by noise of the absorption features prevent us from placing any further constraint on the spectral type. However, as features arising from the secondary are seen, future observations of GX13 + 1 with a longer integration time should resolve absorption features sufficiently to allow comparison with template stars to accurately determine the spectral type of the secondary.

5 CONCLUSIONS

We have presented the first high-resolution *K*-band spectra of two Galactic bulge LMXBs, GX1 + 4 and GX13 + 1, and a complete *JHK* spectrum of the classic LMXB Sco X-1. The IR spectrum of Sco X-1 exhibits the emission features expected from a luminous accretion disc but does not show any absorption features arising from the system secondary, reinforcing the probability that the secondary is a late-type subgiant, most likely of spectral type G5 or earlier. The *K*-band spectrum of GX1 + 4 exhibits both Brackett γ emission arising from the accretion disc and a variety of metal absorption lines and CO bands from its M6III secondary. An estimate of the ^{12}CO to ^{13}CO ratio in the spectrum is consistent with that expected from a late-type giant star. The spectrum of the proposed counterpart to GX13 + 1 shows Brackett γ emission from the accretion disc, confirming the identification. The spectrum also has several absorption features arising from the secondary which indicate that it must be a late-type star. A calculation of the absolute *K* magnitude of GX13 + 1, together with the features seen in our spectrum, has eliminated the possibility of a main-sequence secondary star. We therefore suggest that the secondary is a giant, with a spectral type between K2 and M5, in agreement with previous estimates. It is clear from our spectra that IR spectroscopy has an enormous potential for enhancing our understanding of the enigmatic GBS and LMXBs in general, and future observations are planned to take advantage of this new opportunity.

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