VLT observations of GRS 1915+105

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Abstract. We present near infrared spectroscopy of the super-luminal microquasar GRS 1915+105 obtained with the first unit of the VLT [1] and the ISAAC spectro-imager. The emission features detected in the VLT data have been identified as He I, Br γ, He II and Na I. The detection of Na I is reported here for the first time, while our confirmation of weak He II emission provides support to previous marginal detections of this feature. By comparing the observed spectra with those of massive stars, we find that our results are very consistent with GRS 1915+105 being a high mass X-ray system with an early type primary, as previously proposed by Chaty et al. (1996) and Mirabel et al. (1997). The VLT spectra also provide evidence of P Cygni profiles, that turn into blue emission wings when the system is in outburst. This observed line profile evolution implies that GRS 1915+105 must be surrounded by an expanding envelope, that is partially blown out during the X-ray outbursts. The presence of such circumstellar gaseous material around GRS 1915+105 is more naturally understood in the context of a massive luminous star than if the system was a low-mass X-ray binary.

Key words: stars: individual: GRS 1915+105 – infrared: stars – radio continuum: stars – X-rays: stars

1. Introduction

The X-ray transient GRS 1915+105 was first discovered by Castro-Tirado et al. (1992) using the WATCH all-sky monitor on board the Russian satellite GRANAT. Special attention to this source increased enormously a few years later when Mirabel & Rodríguez (1994) reported that GRS 1915+105 was producing repeated ejections with apparent superluminal motion. These events could be first followed at radio wavelengths thanks to the Very Large Array interferometer of NRAO and represented a phenomenon never observed before in the Galaxy. There are only two confirmed galactic superluminal sources known, the other one being GRO J1655−40 (Hjellming & Rupen 1995;

Tingay et al. 1995). Both of them have been classified as 'microquasar' systems, i.e., a selected group of radio emitting X-ray binaries whose physics and external appearance is strongly reminiscent of quasars and active galactic nuclei. We refer the reader to the review by Mirabel & Rodríguez (1999) for an updated account.

Since the discovery of superluminal episodes in GRS 1915+105, this object has been under strong surveillance by several observers at different wavelengths. In spite of this work, the nature of the X-ray binary system in GRS 1915+105 is still a matter of debate. The strong interstellar absorption towards the source, that implies optical extinctions of $A_V \sim 27$ magnitudes (Chaty et al. 1996), appears as the main cause of this uncertainty. Therefore, it is not surprising that the best approaches to the problem have come from imaging and spectroscopic studies at infrared wavelengths, where the effects of extinction are much less severe ($A_K \sim 3.0$ mag). Infrared results, however, have not yet reached an unanimous consensus. GRS 1915+105 has been proposed to be a low-mass X-ray binary (LMXRB) by Castro-Tirado et al. (1996) and an high-mass X-ray binary (HMXRB) by Chaty et al. (1996) and Mirabel et al. (1997), who favour an Oe/Be spectral type. There is also a discussion on the reality of weak emission lines of He II, that have been marginally detected by Castro-Tirado et al. (1996) and Eikenberry et al. (1998a).

The existence, or not, of He II lines is relevant because they are naturally expected in LMXRBs as a result of excitation from the hard photons of the accretion disk. The prototypical LMXRB Sco X-1 is a good example of this statement (Bandyopadhyay et al. 1999). In contrast, He II is seldom observed in HMXRBs. In massive systems, accretion often proceeds directly from the stellar wind and photons from typical companion photospheres would not be energetic enough to ionize helium atoms. However, the He II criterion is not a reliable one to distinguish between high and low mass systems. Indeed, a few objects in the HMXRB group do exhibit He II lines in emission. The best representative is certainly A0538−66 (Charles et al. 1983) in the Large Magellanic Cloud. This B2 III-IV system has been observed to produce strong and variable He II 4648 Å emission when in outburst. An interesting property of some emission lines in A0538−66 (e.g. C IV and He II) is that they alternate between a
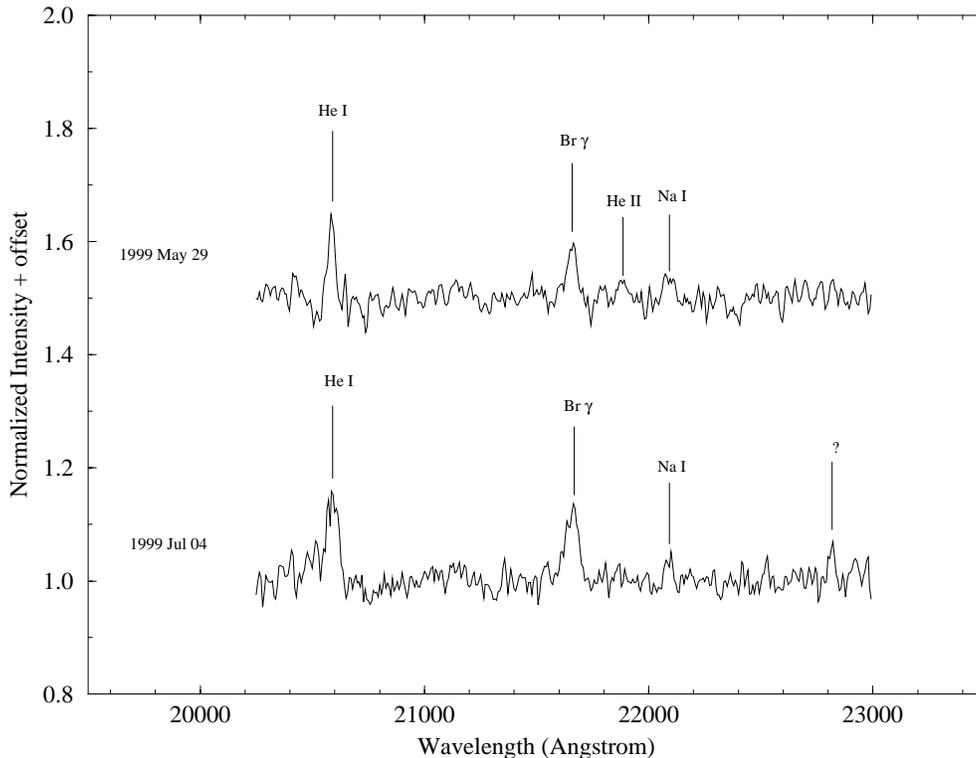

Fig. 1. VLT low resolution spectra of GRS 1915+105 obtained on 1999 May 29 (before a radio outburst) and 1999 July 04 (during a radio outburst) using the SK filter with ISAAC. The emission line identifications are indicated.

P Cygni profile and a noticeable blue wing in emission when in quiescence and outburst, respectively. We advance here that the same behavior may be present in GRS 1915+105. Another case of massive He II emitter is the classical black hole candidate Cygnus X-1, whose spectrum displays He II 4846 Å emission believed to form in the stellar wind above the substellar point of the O9.7 Iab primary (Gies & Bolton 1986).

In this context, we present new infrared spectroscopic observations of GRS 1915+105 obtained with the first 8.2 m unit (Antu) of the Very Large Telescope (VLT) of the European Southern Observatory (ESO). The VLT spectra show, among others ones, possible evidence for He II and a newly detected doublet of Na I, both in emission. When taking all these features into account we find compelling evidence that a HMXRB scenario, with a surrounding envelope, provides a very likely interpretation for GRS 1915+105.

2. Observations and results

We observed GRS 1915+105, in service mode, on two different epochs using the ISAAC spectro-imager at the VLT (see Cuby 1999 for a description). The first epoch was on 1999 May 29 (JD 2451327.84) under good weather conditions. The second observation took place on 1999 July 04 (JD 2451363.77) under less favorable weather conditions. In both dates, we carried out low resolution ($R \sim 450$) spectroscopy with the SK filter and an integration time of 30 minutes. The $1''$ slit was selected, with position angle of $90°$ in order to avoid bright nearby stars. The frames were acquired with the detector integration time (DIT) set at the recommended value of 60 s. Each observing epoch consisted of acquiring a total of 30 of such frames. The usual

Table 1. Emission line parameters observed in GRS 1915+105

Date 1999	Line Id. (μm)	Observed λ (μm)	Relative Flux	EW (Å)	FWHM (Å)
May 29	He I 2.0587	2.0585	0.88	−6.1	36
	Brγ 2.1661	2.1658	1.00	−5.5	55
	He II 2.1891	2.1886	0.49	−2.7	63
	Na I 2.206-9	2.2087	0.57	−2.9	58
July 04	He I 2.0587	2.0589	0.87	−10.8	67
	Brγ 2.1661	2.1658	1.00	−10.0	73
	He II 2.1891	−	−	−	−
	Na I 2.206-9	2.2087	0.24	−2.2	42
	?	2.2817	0.29	−2.4	32

technique of nodding the telescope was used, so that the target is placed at different slit positions in each frame.

The data were reduced using the IRAF package, including bias and dark current subtraction, flat field division and frame combination. The wavelength calibration was performed by means of the OH sky lines in the range 1.9-2.25 μm. The atmospheric absorption was corrected by observing the G4 V star HIP 99727, at an air mass as close as possible to that of GRS 1915+105. This star was observed by the telescope staff as a part of the ESO calibration plan. The final target spectrum was obtained as the ratio of the absorbed spectrum to that of the solar type star. The only intrinsic stellar absorption present in the K-band, namely Br γ, was adequately removed by interpolation of the nearby continuum prior to computing the ratio.

The main results of this paper are presented in Figs. 1 and 2. The absorption correction worked acceptably well for the first
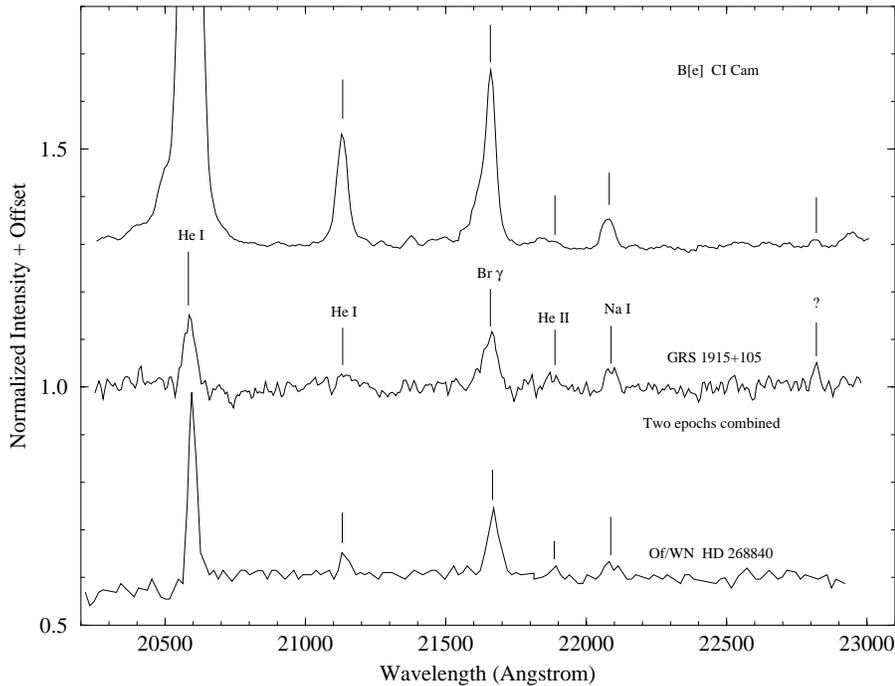
Fig. 2. Combined VLT spectrum of GRS 1915+105 (middle) obtained by averaging the data of the two epochs to increase signal-to-noise ratio in order to better detect any weak persistent features. The He II line in GRS 1915+105 appears barely visible because it is not present in the second epoch, while the faint He I feature may have some contribution from N III. The two comparison spectra are those of the B[e] system CI Cam (top) and the Ofpe/WN9 star HD 268840 (bottom) adapted from Clark et al. (1999) and Morris et al. (1996), respectively. The common features are identified on all plots and labeled for GRS 1915+105.

spectrum. The second one suffered from less good atmospheric conditions and a slight mismatch ($\lesssim$0.1) of air masses between the target and HIP 99727. The absorption correction close to the $\sim 2.0\,\mu$m region, with strong telluric features, was consequently difficult but we still consider it acceptable.

The vertical axes in the spectra of Figs. 1 and 2 are expressed in terms of relative flux plus an arbitrary offset. No absolute calibration could be performed. This is because HIP 99727 does not have yet K-band magnitudes available in the literature. Nevertheless, a relative comparison of the continuum level and line fluxes can actually be obtained. During the second epoch, the continuum was $\sim$ 6% brighter than during the first one. This implies a photometric variation of $\Delta K \simeq 0.^m1$, that may be consistent with zero. In contrast, the emission line parameters of GRS 1915+105 do seem to have varied significantly by a factor of $\sim$ 2. We derived them by fitting a Gaussian profile and the corresponding results are also given in Table 1. The likely error of the fits is estimated to be less than 1 pixel ($\lesssim$10 Å) in wavelength and $\sim$ 10% in the relative flux, equivalent width (EW) and full width half maximum (FWHM), respectively. The following subsections are devoted to comment on the different emission lines listed and identified in Table 1.

2.1. Apparent P Cygni and asymmetric emission profiles in the He I and Br γ lines

The infrared spectra for the two epochs in Fig. 1 confirm the detection of the He I (2.0587 μm) and Br γ (2.1661 μm) emission lines, both without significant Doppler shifts. These lines have been reported before on different epochs by Castro-Tirado et al. (1996), Mirabel et al. (1997) and Eikenberry et al. (1998a). The line ratios He I/Brγ seem to be often in the range 0.96-1.16 as derived from these previous detections. In both our two VLT

spectra we find that He I/Br γ is practically 0.9, i.e., a value not far from this range.

On the first epoch, He I appears to display a P Cygni profile corresponding to an expansion velocity of ~ 2000 km s^{-1}. The same type of profile may also be present in Br γ, although it is not so obvious. In contrast, during the second epoch we find that the He I and Br γ lines have changed their appearance to a noticeable asymmetric profile. The asymmetry is particularly evident in He I. A blue wing component in emission seems to have emerged in *both lines* also extending up to $\sim$ 2000 km s^{-1}. Hereafter, we will proceed under the assumption that this is a real effect because the two lines appear to show it. Furthermore, the skewness of the He I profile for 1999 May 29 is -0.35 ± 0.27, consistent with no significant asymmetry, while that of 1999 July 04 gives a skewness of -0.73 ± 0.14, indicating the presence of a blue asymmetry significant at the 5-σ level. Nevertheless, it will be interesting to obtain future confirmation of it that safely rules out any possible small error when correcting for atmospheric transmission.

2.2. Confirmation of He II emission

In our first epoch spectrum, we detect a weak feature in emission close to 2.1891 μm. This is the expected wavelength of the He II 10-7 transition marginally detected by Castro-Tirado et al. (1996) and Eikenberry et al. (1998a). The plausible He II/Br γ ratios derived from their spectra are about 0.53 and 0.23, respectively. We find this ratio in our case to be about 0.49, hence well within this range. The He II emission is, once more, detected at a marginal level. However, the fact that this is the third independent marginal detection gives us confidence about its reality.

2.3. Other emission lines

The two VLT spectra seem also to contain a feature in emission centered at 2.2087 μm. This could be consistent with the Na I doublet at the wavelengths of 2.206-9 μm. The significance of this detection improves noticeably if one averages the two individual spectra, as we show in Fig. 2. This combined plot also contains some possible evidence for the complex of He I lines located at 2.112-3 μm. At the resolution and signal-to-noise ratio of our spectra, it is difficult to discriminate if this marginal feature could also be due to N III at the nearby wavelength of 2.116 μm. Finally, an unidentified emission feature at 2.2817 μm is apparent in the 1999 July 04 spectrum.

3. Multi-wavelength behaviour of GRS 1915+105 during the VLT runs

It will be useful for discussion purposes to provide an overview of the X-ray and radio behaviour of GRS 1915+105 at the times of our VLT observations. This information is displayed in the panels of Fig. 3. From top to bottom, we plot here the 2.3 GHz, 1.5-12 keV and 20-100 keV light curves of GRS 1915+105. These multi-wavelength data have been obtained thanks to the public monitorings available from the Green Bank Interferometer (GBI), the All Sky Monitor (ASM) on board the Rossi X-Ray Timing Explorer (RXTE) and the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory (CGRO), respectively.

We see in Fig. 3 that the first epoch of observation was just prior to the onset of an ejection event, with a ~ 0.25 Jy amplitude in the radio, and a minor soft X-ray maximum. The second epoch was obtained soon after another strong ejection event had taken place. Its amplitude was similar to that of the May event and it also had a noticeable soft X-ray counterpart. The second run of VLT observations coincided with the early decay of the flare. It has been proposed that the ejections in GRS 1915+105 involve the destruction and ejection of the inner accretion disk and corona, as evidenced by previous multi-wavelength observations (Mirabel et al. 1998; Fender & Pooley 1998; Eikenberry et al. 1998b).

4. Discussion

4.1. Interpretation of P Cygni and asymmetric wing emission profiles

The apparent P Cygni profile detected on 1999 May 29 (see Fig. 1) corresponds to an epoch when GRS 1915+105 was not yet in outburst. This profile is naturally understood in terms of an expanding shell or extended atmosphere around the companion, whose approaching (and therefore blueshifted) regions are seen in absorption against the stellar disk. It is appropriate to remind here that evidences of surrounding material around GRS 1915+105 have been reported in the past (Mirabel et al. 1996).

Several weeks later, the ~ 0.25 Jy outburst that peaked ~ 2 d before our second spectrum seems to have altered considerably the quiescent picture. The shell around GRS 1915+105 is likely
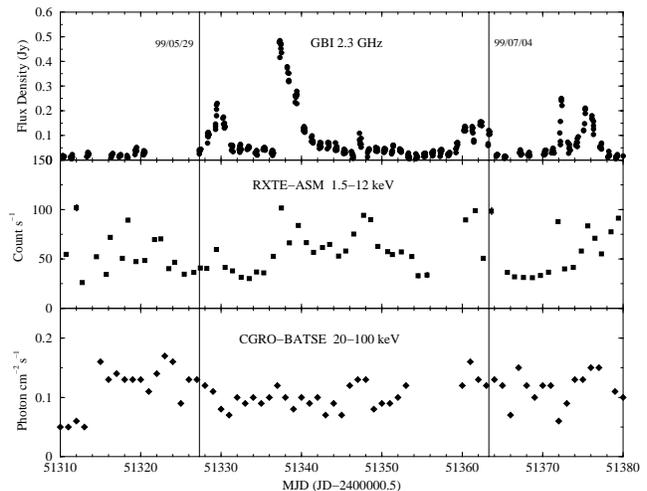

Fig. 3. Top. The radio behavior of GRS 1915+105 during our observations as recorded by the daily GBI monitoring. The vertical lines indicate the precise dates when the VLT-ISAAC spectra were obtained. **Middle.** The same kind of plot but showing the soft X-ray light curve of GRS 1915+105 from the RXTE-ASM data. **Bottom.** Another similar plot with the hard X-ray light curve of GRS 1915+105 from the CGRO-BATSE Earth occultation monitoring.

to have experienced a considerable injection of energy from the outburst, with part of its material being blown out. It is this blown out material that we believe is producing the strong blue emission wing in the July 04 spectrum. The evolution from quiescent P Cygni profiles to blue emission wings is, in fact, not a new phenomenon in the context of X-ray binaries. The same behavior has been very well observed in other outbursts of different sources. As mentioned in the introduction, the B2 III-IV system A0538−66 is one of such cases (Charles et al. 1983). A more recent example can be found in the 1998 outburst of CI Cam, which has been classified as a B[e] HMXRB by Clark et al. (1999). Their K-band spectra of CI Cam in outburst clearly shows the blue wing effect, specially in the He I and Br γ lines (see Fig. 2).

Further evidence of blue wing emission, with superimposed P Cygni profiles, is also present in the K-band spectrum of GRS 1915+105 by Mirabel et al. (1997) of 1995 September 4. The blue asymmetry in the He I line in Fig. 1 of this paper is even more pronounced. The GBI monitoring was not available at that time, but the contemporaneous BATSE light curve displays a sharp drop ~ 3 d before that date, and we know that the sudden drops in the BATSE flux are associated to major ejection events.

4.2. The HMXRB versus LMXRB scenarios

One of the important results provided by the VLT spectra is an independent confirmation of the weak He II emission line, at least on the first epoch spectrum. We do not have a reliable detection of He II on the second epoch, although this could be due either to line variability or to the lower quality of the night.

As mentioned before, the debate on the origin of the He II line has important consequences on the nature of the GRS

1915+105 companion. Since no ordinary star is able to generate it, Castro-Tirado et al. (1997) and Eikenberry et al. (1998a) attribute its detection to the accretion disk around the compact object rather than the atmosphere of a Be star or other massive companion. However, when doing so another interesting possibility is excluded. He II emission can actually be excited in the atmosphere of the hottest stars in the spectral sequence. For instance, the spectra of some O-type stars are well known to exhibit He II both in absorption and emission. There is actually a sequence between pure absorption O stars and stars with both He II and N III in emission, that are known as Of stars (Kaler 1989). Therefore, the detection of He II emission does not necessarily rule out that we are dealing with a HMXRB in GRS 1915+105 provided that the primary is of very early type.

The challenging HMXRB possibility, with an early type companion, fits nicely with the expanding envelope evidences based on P Cygni and asymmetric wing profiles. The idea also appears further supported when comparing our VLT spectra with those of massive stars (see Fig. 2). Excellent samples of spectra of luminous stars belonging to the classes of Of, Wolf-Rayet (WR), Be, B[e] and Luminous Blue Variables (LBV) can be found, e.g., in the works by Morris et al. (1996), Hanson et al. (1996) and Clark & Steele (1999). The discrimination between these different classes of stars on the basis of 2 μm spectroscopy is not always straightforward, because of significant overlap in their spectral morphology. Individual stars have also been observed to change their spectral morphology with time and move from one class to another on timescales of a few years. Our situation is further worsened here due to the low signal-to-noise ratio of the spectra. However, even with these limitations, it should be still possible to recognize the HMXRB nature of GRS 1915+105 and to provide a tentative spectral classification from comparison with spectral atlases of hot, luminous stars in the infrared.

With these cautions into account let us consider the contents of Table 8 in the Morris et al. (1996) paper, where the different spectral characteristics of massive stars in the K-band are listed. We find here that the observed properties of Br γ emission with $EW \sim 10$ Å, as well as emission lines of He I at 2.112-3 μ, N III at 2.116 μm, He II at 2.1891 μm and Na I at 2.206-9 μm are simultaneously present only for stars of the Of and WR nitrogen (WN) classes. Interestingly, this seems to be in good agreement with the most likely spectral features observed or suspected in our VLT spectra.

The presence of Na I implies that part of the stellar wind of the proposed Of/WN companion has to be shielded from direct stellar radiation because of the low ionization potential of sodium, perhaps in a cooler dusty region of the star atmosphere. Na I is also a typical feature in the related HMXRBs of the Be type (Everall et al. 1993). Concerning the strong He I line at 2.0587 μm, it is often excluded as a classification criterion because of several factors that make it unreliable (difficult telluric correction, optical depth variability, bad indicator to distinguish between OB and WR subtypes, etc.). He I in emission is believed to be related to luminosity class I, but this is a rule with several known exceptions.

Another issue that strengthens the relationship between GRS 1915+105 and massive luminous stars is again provided by the comparison of our spectra with those of CI Cam. As GRS 1915+105, CI Cam has been observed to undergo violent ejection events that are able to produce bipolar collimated jets with relativistic velocities (Hjellming & Mioduszewski 1998). The evidence so far available strongly suggests that CI Cam may be another member of the microquasar group. It is then appropriate to remind here that the B[e] stars in the infrared are sometimes hard to distinguish from the Of/WN status and viceversa, e.g., as discussed by Morris et al. (1996) in the cases of WR 85a and WR 122. With these thoughts in mind, the infrared spectrum of CI Cam by Clark et al. (1999) compares remarkably well with our GRS 1915+105 spectrum as evidenced in Fig. 2. All of them are coincident again at displaying emission from Brγ, He II 2.1891 μm, the Na I doublet and the He I 2.0587 μm line. From this comparison, it appears very plausible to us that both GRS 1915+105 and CI Cam are HMXRBs in closely related evolutionary stages.

4.3. The He II line and the accretion disk

The fact that a very massive early-type companion can produce the He II emission does not exclude the possibility that the accretion disk is also contributing to this feature. It is conceivable as well that the recurrent creation and disruption of the inner accretion disk during the ejection events is responsible for most of the observed variability of this line. The fact that we better detect enhanced He II emission on the first epoch could be understood considering that GRS 1915+105 was then prior to a strong ejection event (see Fig. 3). Therefore, the accretion disk at that time should be well extended up to the latest stable orbit. In contrast, the second epoch almost coincided with the peak of another ejection episode (see again Fig. 3). The inner accretion disk from which the ejecta is formed may have not been yet refilled, hence the lower He II emission.

4.4. HMXRBs among galactic radio jet sources

To complete our discussion, it is interesting to point out that there seems to be a majority of HMXRBs or intermediate mass systems among the list of confirmed radio jet sources in the Galaxy. This selected group includes with great confidence SS 433, Cyg X-3, Cir X-1 and GRO J1655−40. The first three of these objects are widely believed to be bona fide HMXRBs. The last one has been reported to be a system of intermediate mass, with the optical companion being in the range 1.7-3.3 $M_\odot$ (Shahbaz et al. 1999). Add the recently discovered massive jet source CI Cam and the idea of GRS 1915+105 being also a HMXRB does not come with great surprise.

However, given that GRS 1915+105 is a remarkable binary system with a very luminous accretion disk and relativistic ejections, other origins for the observed lines different from a massive companion cannot be strictly ruled out at present. In particular, the fast variability in the infrared emission lines observed by Eikenberry et al. (1998a) is difficult to explain with a normal

stellar atmosphere, unless it is being directly affected by the X-ray flares and jets. Indeed, GRS 1915+105 is a complex object where interactions between the massive outflows from the companion star and relativistic ejections from the compact object are likely to occur. In any case, additional studies on the nature of the companion of the collapsed object should be pursued.

5. Conclusions

1. We have presented the first VLT infrared spectra of the superluminal source GRS 1915+105. The strong emission line of He I at 2.0587 μm provides suggestive evidence of a P Cygni profile evolving into a blue wing in emission when the system goes from quiescence to outburst. A similar trend is also likely to occur for Br γ. This behavior is consistent with what is observed during the outbursts of other HMXRBs and points towards the existence of an expanding shell or atmosphere around the GRS 1915+105 companion. We speculate that the appearance of such shell is changing depending on the state of activity of the high energy source.

2. The GRS 1915+105 companion is very likely to be a massive star. Not only the presence of an extended envelope is a clue of its HMXRB nature, but also the comparison of the GRS 1915+105 spectrum with infrared spectral atlas supports this interpretation. The newly discovered line features, specially Na I, as well as those previously detected show a strong resemblance with the spectra of such massive stars. We are also able to propose a tentative spectral classification of the primary as an Of/WN star.

3. In this context, the long discussed He II line should be excited by the photons of the massive and luminous companion star, although we cannot rule out completely that the accretion disk is also playing a role. In any case additional sensitive observations, in different states of activity of the source, would be very valuable to settle definitively this issue and to provide a more accurate spectral type.

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