Molecular emission of CO in BI Cru with high resolution spectroscopy

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Resumen / En este trabajo analizamos un espectro infrarrojo de alta resolución ($R \sim 45\,000$) de la estrella simbiótica BI Cru. Este espectro fue obtenido con el espectrógrafo IGRINS montado en Gemini Sur y abarca el rango espectral comprendido entre 1.5 a 2.5 μm. A partir del modelado de la banda de emisión de CO observada en la región de los 2.3 μm, obtenemos información detallada de la cinemática y propiedades físicas del medio molecular circunestelar.

Abstract / In this work we analyze a high-resolution infrared spectrum ($R \sim 45\,000$) of the symbiotic star BI Cru. This spectrum was obtained using IGRINS spectrograph mounted in Gemini South and ranges from 1.5 to 2.5 μm. From the modeling of the observed CO band emission in the 2.3 μm region, we obtained detailed information of the kinematics and the physical properties of the molecular circumstellar medium.

Keywords / binaries: symbiotic — infrared: stars

1. Introduction

Symbiotic stars are interacting binaries formed of a red giant, a hot compact star (usually a white dwarf), and a dense nebula. The study of this dense circumstellar material represents a natural laboratory to examine physical processes such as collimation of stellar winds, formation of jets (Tomov, 2003), formation of bipolar planetary nebulae (Corradi, 2004), among others. In addition, the complex circumstellar environments detected around some supernovae (Dilday et al., 2012) provide evidence that supports the hypothesis that symbiotic stars are possible supernovae Ia progenitors (Munari & Renzini, 1992).

Symbiotic stars are classified according to their appearance in the near-infrared in D-type (dust), if they contain a highly evolved Mira variable embedded in warm dust with periods greater than 50 days; and in S-type (stellar), if their infrared continuum is dominated by stellar emission from a late giant star with orbital periods of the order of a few years (generally less than 15 years).

BI Cru is a D-type symbiotic object and is also so far the only symbiotic star in which molecular emission of CO was detected in the near infrared at 2.3 μm (McGregor et al., 1988) which seems to be stable over long time intervals (Marchiano et al., 2015). This CO emission is associated with the existence of a dense disk that would form after one or more episodes of intense mass loss from the red giant (the mass transfer occurs because the M giant fills its Roche lobe, Verhoelst, T. et al., 2007), while another scenario could be that CO emission originates in the wind interaction region of the colliding winds (Hinkle et al., 2013). McCollum et al. (2008) reported an IR shell of BI Cru more than 5 times larger in arc size than the star's optical lobe. The temperature of this dust emission associated with our object was estimated to 1 300 K (Marchiano et al., 2013; Henize & Carlson, 1980).

A recent study of observations at 4.8 and 8.64 GHz (C and X bands, Dickey et al., 2021) made it possible to determine the characteristic size of 2 800 AU for the region of the radio emission source. The authors used data obtained from Gaia Data Release 3 and estimated a distance of 2.96 kpc for BI Cru.

In this work, we present the first high-resolution first-overtone CO band spectrum of BI Cru that arises in the near-infrared redward of 2.3 μm. From our modeling of the emission spectrum we derive the properties of the hot molecular gas surrounding the object, and we propose possible scenarios that complement previous studies of this object.

2. Observations

We obtained high-resolution ($R \sim 45\,000$) spectroscopic observations of BI Cru in the 2.3 μm region on April 2018 using IGRINS (Immersion Grating Infrared Spectrometer, Park et al., 2014) spectrograph mounted on Gemini South (Program ID: GS-2018A-Q-231).

During all observations, several ABBA sequences, with an on-slit separation of 2.5" between the two positions, were taken in order to subtract the AB pairs to remove the sky contribution adequately.

The basic steps of the reduction process were carried out with IRAF⋆ (Image Reduction and Analysis Facil-

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⋆IRAF was distributed by the National Optical Astron-

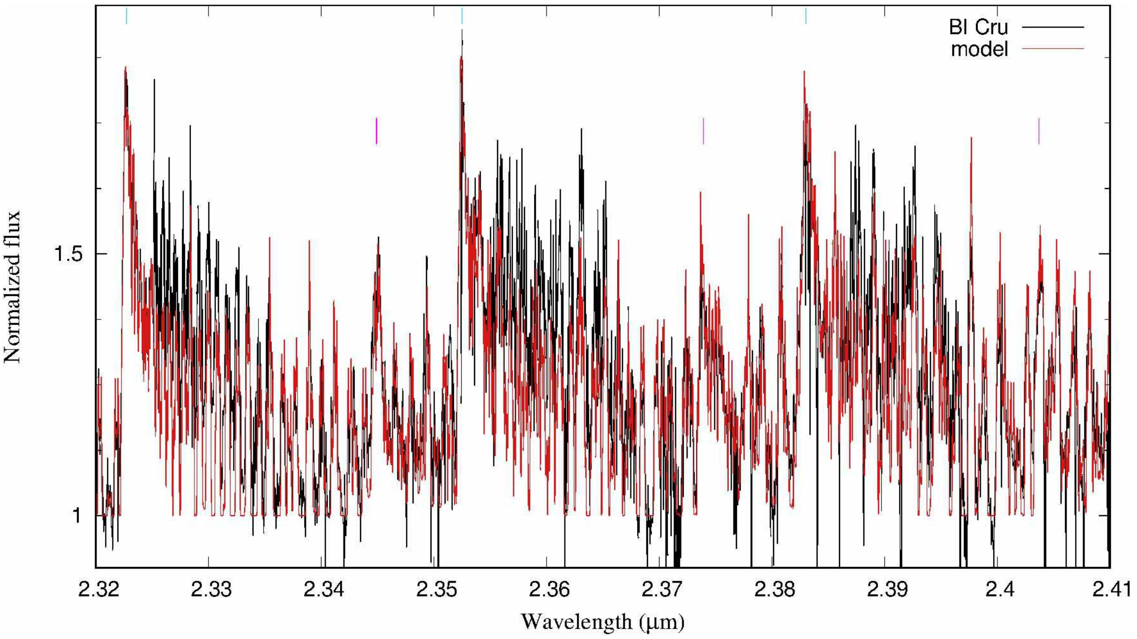

Figure 1: Portion of the K-band spectrum of BI Cru with CO emission (black). The synthetic spectrum is plotted in red. Blue and magenta tics show the position of ^{12}CO and ^{13}CO band heads, respectively.

ity) software package. These included the subtraction of AB pairs, the flat-fielding, the telluric correction and the wavelength calibration.

3. Results

The infrared spectrum of the CO molecule corresponds to ro-vibrational transitions of the first-overtone bands. The high spectral resolution of IGRINS allows us to resolve the shape of the first band head as well as individual ro-vibrational lines of CO, in particular bluewards of the second band head, and hence to identify the type of line broadening. It can be noted from Fig.2 that the line profiles are double-peaked, indicating rotational broadening.

To reproduce the observed molecular band emission, we used the model proposed by Kraus et al. (2000). This model assumes that the emission comes from a rotating ring or disk with the CO molecule in local thermodynamic equilibrium, and the ^{12}CO as well as the ^{13}CO isotopes were considered. A disk in Keplerian rotation results in a characteristic band head shape, displaying a blue shoulder and a red peak, and the separation between these two, when observed with high spectral resolution, corresponds to twice the line-of-sight rotational velocity. In addition, the strength of the band heads is very sensitive to the density and temperature of the CO gas. Therefore, this model not only delivers information on the rotation velocity of the disk through the shape of the double peak, but also allows us to constrain parameters such as the temperature and column density of the CO gas.

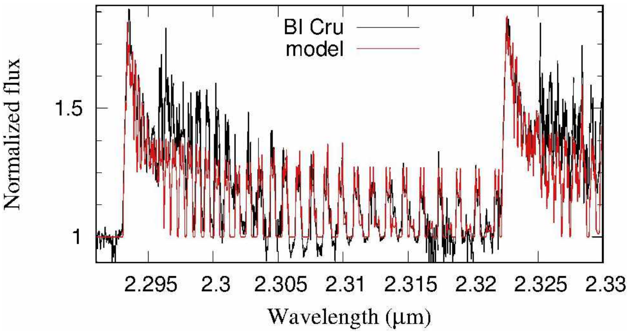

Figure 2: Zoom-in to the first two band heads showing double peaked features.

The best fitting to the CO band spectrum is overplotted to the observed spectrum in Figs. 1 and 2. More precisely in Fig. 2 we can observe the double-peaked lines clearer. This fitting has been achieved for a thin rotating disk of molecular gas whose parameters are listed in Table 1 where $v_{\rm rot,los}$ is the line-of-sight rotation velocity, $T_{\rm CO}$ is the temperature of the molecular forming region and $N_{\rm CO}$ is the column density. The second row shows the errors for each parameter.

In Fig. 1 a molecular residue can be observed overlaying the modeled CO emission. To identify it, it will be necessary to have information from a greater spectral

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omy Observatory, which was managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

Table 1: Parameters of the molecular gas region.

$T_{\rm CO}$ $[K]$	$N_{\rm CO}$ $[cm^{-2}]$	^{12}CO / ^{13}CO	$v_{\rm rot,los}$ $[km\ s^{-1}]$
3 100	2.5×10^{21}	10	21
±100	$\pm 1 \times 10^{21}$		±3

range.

It is interesting to note that there are some peaks at 2.3448, 2.3739 and 2.4037 μm which coincide with the positions of ^{13}CO. These features are well fitted assuming a ^{12}CO / ^{13}CO ratio of 10, a value typical of an evolved object where the circumstellar material is enriched by ^{13}CO(Kraus, M., 2009).

With our fitting to the K-band spectrum for BI Cru we were able to determine that:

- The CO emitting region is confined in a thin ring of molecular gas rotating with a line-of-sight velocity of 21 ± 3 km s^{-1} for a close-to edge-on view (inclination < 10 degrees).
- From the fact that CO band emission always traces the hottest ring of molecular gas (Kraus, M., 2009), the temperature of $3\,100 \pm 100$ K found from our modeling is cool compared to the dissociation temperature of CO, which is of the order of $5\,000$ K.
- From the results obtained using our model we were able to estimate the internal radius of the disk. If we consider a disk in Keplerian rotation and use the velocity value derived with our CO fitting, we can estimate the value of the distance of the CO-emitting ring from the center of gravity (Kraus et al., 2000; Cidale et al., 2012). Therefore, assuming that the central star is a M-type giant star with a mass of 1.2 $M_{\odot}$, we find that the inner radius of the disk is located at 2 AU ($\sim$ 430 $R_{\odot}$). In this case, the temperature in the disk indicated in Table 1 (3 100 K) is similar to that of the M star. It is important to note that a Mira variable has variations in its radius between 200 and 400 $R_{\odot}$.Then, this result suggests that the CO disk could be surrounding the cool star but a CO band monitoring over the pulsation cycle of the Mira will be required to test our hypothesis.

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