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Molecular environment of the yellow hypergiant star HD 269953

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Resumen / Las hipergigantes amarillas son estrellas masivas, probablemente en una etapa evolutiva posterior a la de supergigante roja. En esta fase, se suelen dar eventos de pérdida de masa, en los cuales el material eyectado forma envolturas de gas y polvo alrededor de la estrella. HD 269953 fue sugerida como candidata a hipergigante amarilla. Aunque no se reportó ningún evento eruptivo en este objeto, en su entorno existe una gran cantidad de gas molecular de CO. Para entender la dinámica en la región de gas molecular, obtuvimos un espectro de alta resolución de HD 269953 en la banda K, usando IGRINS en GEMINI Sur. El espectro es rico en líneas en emisión. En particular, detectamos emisión en las bandas moleculares de ^{12}CO y ^{13}CO. La abundancia de esta última indica que la envoltura posee material procesado, eyectado por un objeto evolucionado. Además, identificamos emisión de vapor de agua caliente que resulta, de acuerdo a nuestro conocimiento, el primer reporte de detección de agua en el entorno de una estrella masiva evolucionada. Los resultados de nuestro análisis sugieren que el gas CO está confinado en un anillo que rota con velocidad proyectada en la línea de la visual de 9 ± 0.5 km s^{-1}. No se observa ensanchamiento rotacional en las líneas de vapor de agua, y su temperatura es alrededor de 400 K menor que la de las bandas de CO, lo que implica que la región de formación de las líneas de vapor de agua se encuentra algo más alejada de la estrella central que el anillo de CO.

Abstract / Yellow hypergiants are massive stars, most likely in post-red supergiant evolutionary state. Stars in this phase can undergo multiple outbursts, and the ejected material might enshroud the stars in gaseous and dusty shells or envelopes. The object HD 269953 has been suggested to be a candidate yellow hypergiant. Although no historic outburst has been reported for that object, its environment hosts a substantial amount of warm CO gas. To unveil the dynamics within the molecular gas we obtained a high-resolution ($R \sim 45\,000$) K-band spectrum of HD 269953 with IGRINS at GEMINI-South. We find that the spectrum is rich in emission features. In particular, we detect emission from the ^{12}CO and ^{13}CO molecular bands. The latter is strongly enriched, in agreement with the hypothesis that the environment contains processed matter that has been released from an evolved object. Moreover, we identified emission of hot water vapor, which is, to our knowledge, the first detection of water in the vicinity of an evolved massive star. The results from our analysis suggest that the CO gas is confined in a ring that rotates with a velocity of $9 \pm 0.5\,\mathrm{km\,s^{-1}}$, projected to the line of sight. No rotational broadening is seen in the lines of water vapor, and their temperature is about 400 K cooler than that of the CO bands implying that the line-formation region of water vapor is located slightly farther away from the star than the CO ring.

Keywords / stars: massive — supergiants — circumstellar matter

1. Introduction

Yellow hypergiants (YHGs) are evolved massive stars that were born with initial masses in the range of $20 - 40\,\mathrm{M_\odot}$. Stars in this category are supposed to have passed through their red-most evolutionary state and are now returning to the blue region of the Hertzsprung-Russell (HR) diagram. During this blue-ward evolution, instabilities can be excited and grow within the strongly inflated envelopes, leading to enhanced mass loss and eventually to ejections of the outer envelopes. Such outbursts have been recorded for a number of objects (Lobel et al., 2003; van Genderen et al., 2019; Kraus et al., 2019; Koumpia et al., 2020). Consequently, these stars are often embedded in gaseous and dusty shells or envelopes of ejected material (e.g. Jura & Kleinmann, 1990; Lagadec et al., 2011; Oudmaijer & de Wit, 2013).

The object HD 269953 resides in the Large Magellanic Cloud and was listed by de Jager (1998) as one of four YHG candidates in the Magellanic Clouds. Its position on the HR diagram suggests a progenitor mass of $35 - 40\,\mathrm{M_\odot}$ (Kourniotis et al., 2022). Previous studies of its infrared appearance revealed intense CO band emission from both ^{12}CO (McGregor et al., 1988) and its isotope ^{13}CO (Oksala et al., 2013) suggesting a significant amount of circumstellar gas. The detection of emission from the isotopic molecule ^{13}CO in medium-resolution observations is furthermore a clear indication for significant enrichment of the circumstellar matter by processed material from an evolved object (Kraus, 2009; Liermann et al., 2010), and the ratio of ^{12}CO/^{13}CO of about 10 obtained by Oksala et al. (2013) is in line with the hypothesis that HD 269953 might be evolving to-

Oral contribution

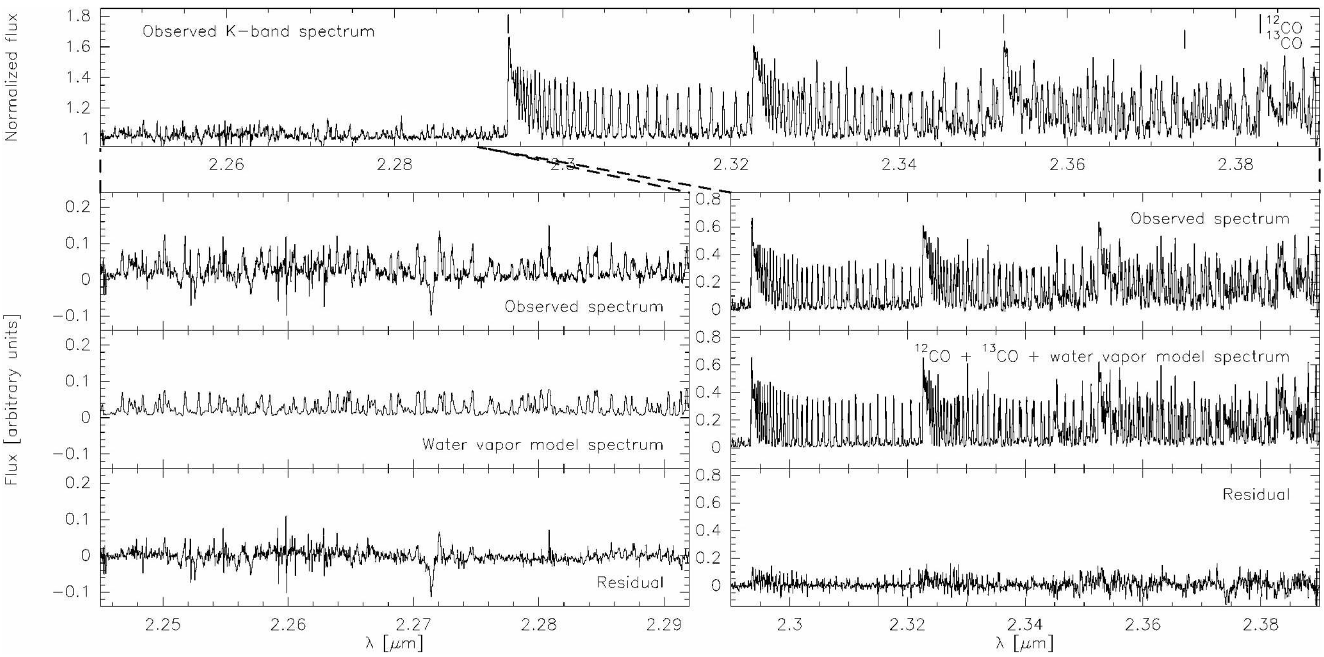

Figure 1: *Top:* Portion of the observed K-band spectrum of HD 269953 containing the first-overtone CO bands and emission from water vapor. *Bottom:* The left and right panels display the short respectively long-wavelength range of the observed spectrum (top), the synthetic spectrum (mid) and the residual spectrum (bottom).

wards the hot side of the HR diagram.

Although information about the star's light curve reaches back to 1987 (van Genderen & Sterken, 2005; Dorn-Wallenstein et al., 2019; Kourniotis et al., 2022), no variability exceeding 0.10 mag and, in particular, no outburst activity has been recorded during the past $\sim$ 45 yr. But the photometric coverage is sparse and outbursts might easily have been missed. In addition, nothing is known so far about the dynamics of the circumstellar matter of HD 269953. Hence, the prime goal of our current study is to obtain the missing information about the dynamics of the molecular gas based on an analysis of high-resolution near-infrared spectra.

2. Observations and data reduction

H- and K-band observations of HD 269953 (H_s = 8.328 mag; K_s = 8.021 mag Cutri et al., 2003) were acquired on 29 December 2020 using the Immersion GRating INfrared Spectrometer (IGRINS, Park et al., 2014) at Gemini-South (program ID: GS-2020B-Q-322). The instrument provides a resolving power of $R \sim 45\,000$ that is sufficient to resolve the profiles of individual ro-vibrational CO lines and the structure of the CO band head. The spectra were reduced using the IGRINS Pipeline Package (https://github.com/igrins/plp) and the *telluric* task from IRAF package*.

Observations were taken with an ABBA offset pattern. The basic reduction steps were, subtraction of the AB pairs, flatfielding, wavelength calibration and telluric correction. A telluric standard star observation was performed immediately after or before each science target observation to properly correct for telluric lines.

The portion of the K-band spectrum containing the CO bands is shown in the top panel of Fig. 1. Its signal-to-noise ratio was measured to be $\sim$ 160.

3. Results

3.1. CO band emission

The high spectral resolution of IGRINS allows us to resolve individual ro-vibrational lines of CO, in particular shortward of the second ^{12}CO band head. Their profiles appear double-peaked (see Fig. 2), suggesting rotation or equatorial in-/outflow of the gas. Based on our experience with CO emission around evolved massive stars, where the line-forming region is usually confined in a narrow rotating ring (e.g., Cidale et al., 2012; Oksala et al., 2012; Muratore et al., 2015; Kraus et al., 2016, 2020; Kourniotis et al., 2018; Torres et al., 2018; Arias et al., 2021), we adopt the scenario of a rotating ring of molecular gas for modeling the emission from HD 269953.

We utilize the code developed by Kraus et al. (2000) for the computation of CO band emission from a circumstellar disk, and modified by Kraus (2009) to add the emission of the isotopic molecule ^{13}CO. The model considers that the CO gas is in LTE, which is a suitable approximation for circumstellar environments. We restrict the model to a single ring with constant gas temperature and column density and a rotation velocity, projected to the line of sight, of $v_{\mathrm{rot,proj}} = 9 \pm 0.5\,\mathrm{km\,s^{-1}}$. Our best-fitting parameters are listed in Table 1, and the synthetic spectrum obtained for an isotopic ratio of

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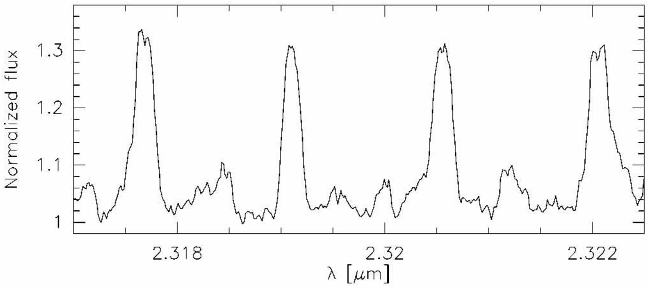

Figure 2: Resolved ro-vibrational lines of ^{12}CO displaying double-peaked line profiles.

12 ± 1 is included in the synthetic model spectrum in the middle right panel of Fig. 1.

3.2. Emission from water vapor

The K-band spectrum of HD 269953 displays many small emission features shortward of and within the CO bands, which we identified as lines from water vapor. Synthetic spectra were computed for a similar model as for CO, i.e., considering a ring of gas with constant temperature and column density, and using the line list, energy levels, and Einstein transition coefficients from Polyansky et al. (2018). The lines of water vapor show no indication for rotational broadening, so that we utilize a Gaussian profile with a velocity of $8 \pm 0.5\,\mathrm{km\,s^{-1}}$, which might be interpreted with turbulent motion of the gas. The best-fitting parameters are included in Table 1, and the synthetic spectrum of water vapor, which spreads over the full wavelength range, is shown in the middle left panel of Fig. 1. Obviously, most of the observed emission features can be identified with emission from water vapor. Its contribution to the red spectral portion is included in the synthetic spectrum shown in the middle right panel. Also worth mentioning is the fact that the numerous water vapor lines all overlap, forming a quasi-continuum, so that basically no line-free continuum is evident throughout the entire spectrum.

The residuals (bottom panels) contain some remnants from telluric correction, but they also display indication that the spectrum of HD 269953 contains besides CO band and water vapor emission also emission from some atomic species as well as photospheric absorption lines, which need to be further investigated.

4. Conclusions

Our high-quality K-band spectrum of HD 269953 reveals molecular emission from ^{12}CO, the isotope ^{13}CO, and a zoo of tiny emission lines that we identified as from water vapor. While water vapor has been reported from the environments of lower-mass giant stars such as IRC+10216 (Melnick et al., 2001) or W Hydrae (Neufeld et al., 1996), this is to our knowledge the first detection of water vapor from an evolved massive star.

The lower temperature found for water vapor and the narrower line profiles imply that the line-forming region is farther away from the star than the one of CO. This collocation agrees with a disk revolving around the central object and, together with the ^{13}CO enrichment, suggests that the material has been released from HD 269953, maybe during some mass-ejection episode.

Table 1: Best-fitting model parameters.

	CO	Water vapor
T [K]	2200 ± 200	1800 ± 200
N [10^{21} cm^{-2}]	2 ± 0.5	5 ± 0.5
$v_{\mathrm{rot,proj}}$ [km s^{-1}]	9 ± 0.5	–
v_{gauss} [km s^{-1}]	–	8 ± 0.5

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