LETTER TO THE EDITOR

X-shooter observations of the accreting brown dwarf J053825.4-024241

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ABSTRACT

We present the first observations of a probable brown dwarf, obtained with the new spectrograph X-shooter mounted on the UT2@VLT. The target (2MASS J053825.4-024241) is a 0.06 M⊙ object in the star-formation region σ Ori. The X-shooter spectrum covers simultaneously the whole range from UV to NIR (300–2500 nm). The J053825.4-024241 spectrum is rich in emission lines that are typical of accreting young object and clearly shows the Balmer jump. Moreover, many photospheric atomic and molecular absorption lines yield the spectral type and confirm that the object is young. We compute the mass accretion rate from all available observed accretion diagnostics. We find that there is a large spread in the Ṁacc values (up to a factor 40) that is not caused by variability; some of this spread may be intrinsic, i.e., owing to different physical conditions of the emitting region for the same Macc. However, within the large error bars all Macc measurements agree, and the mean value is logṀacc ∼−9.86 ± 0.45 M⊙yr−1. The hydrogen Balmer lines are clearly detected up to n = 25. Their ratios suggest that the emitting region is cold (T ∼ 2000–3000 K), dense and in thermal equilibrium (LTE), and that the lines are optically thick up to n ∼ 21. We briefly discuss the implications of this result for magnetospheric accretion models.

Key words. stars: formation – accretion, accretion disks

1. Introduction

Accretion and ejection of matter play a fundamental role in shaping the structure and evolution of proto-planetary disks. In the last years, our understanding of these processes has progressed significantly, confirming the role played by accretion and magnetic fields, but at the same time raising new questions. A large number of observational diagnostics need to be observed simultaneously to avoid the problems related to the time variability that characterize pre-main sequence stars. X-shooter, the new spectrometer at VLT/ESO, is the optimum instrument for this purpose, with its large wavelength range (300–2500 nm) that is covered simultaneously.

This letter reports the first observations of a brown dwarf carried out with X-shooter. The target J053825.4-024241 (J0538 in the following) in the σ Ori star-forming region (D ∼ 360 pc, Béjar et al. 2001), was first identified as a photometric substellar candidate by Béjar et al. (2004), and was then extensively studied by Caballero et al. (2006), who concluded that J0538 is a likely cluster member, with heliocentric radial velocity vR = 32 ± 13 km s−1, spectral type M6 ± 1, and a mass estimated from evolutionary models of M ∼ 0.06 M⊙. J0538 is detected by Spitzer at all IRAC wavelengths and at 24 μm with MIPS (Hernández et al. 2007). Its spectral energy distribution (SED) shows a clear excess over the photospheric emission from the K band, which is indicative of a circumstellar disk surrounding the brown dwarf.

2. Observations and analysis

The observations were obtained with X-shooter within the INAF/GTO program on star-forming regions. Observations were performed in visitor mode during the night of the 2009 December 23; exposure time was 6 × 900 s, which allows us to reach a signal-to-noise ratio in the continuum from ∼7 (UVB-arm) to ∼30 (VIS-arm) and ∼80 (NIR-arm), depending on the echelle order.

The target was observed with the 11′′ × 1.0′′ slit in the UVB-arm and with 11′′ × 0.9′′ slit in the VIS and NIR-arms. The spectral resolution R is ∼5100 over the UVB and the NIR-arm, and ∼8800 in the VIS-arm. Raw data were reduced using the EsoRex pipeline (version 0.9.4) following the standard steps, which include bias subtraction, flat-fielding, optimal extraction, wavelength calibration, sky subtraction, and flux-calibration.

The extraction of the 1D spectra and the subsequent data analysis was performed with the IRAF1 package. The flux calibration of the star was performed using a spectrophotometric

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mass star in jump. Dashed L6, page 2 of 4

J0538 (SO500 in Hernández et al. 2007) shows spectroscopic Fig. 2. The properties of some selected lines are given in Table 1.

The NIR hydrogen recombination lines Paβ and Pay have also been extensively used as proxy of the accretion luminosity (e.g., Muzerolle et al. 1998); mass accretion rates from these lines have been derived using the relationships in Natta et al. (2004) and Gatti et al. (2008). All these values of $M_{\text{acc}}$ are given in Table 1.

4. Mass accretion rate

The X-shooter spectrum of J0538 is rich in emission in lines and continuum, which are powered by processes related to the accretion from the circumstellar disk onto the central object. These diagnostics are used to derive the mass accretion rate from the width of the Hα line at 10% of the peak intensity (see, e.g., Herczeg & Hillenbrand 2008, hereafter HH08, and references therein). These relations were calibrated on a relatively small sample of well-studied objects, mostly T Tauri stars, for which the accretion luminosity was derived by fitting the observed optical veiling with magnetospheric accretion models (Gullbring et al. 1998; Calvet et al. 2004), or, for brown dwarfs, the Hα profiles (Muzerolle et al. 2005).

We compute the $M_{\text{acc}}$ values from the Hα luminosity according to the relation in Fang et al. (2009), the Hβ luminosity (Fang et al. 2009), the Hγ luminosity (HH08), the NaI D line luminosity (HH08) and the HeI line luminosity (Fang et al. 2009). An independent value of the mass accretion rate ($\log M_{\text{acc}} = 9.6 \pm 0.5 M_\odot$/yr) is derived from the width of the Hα line at 10% of the peak ($\sim 340$ km s$^{-1}$), using the relation derived by Natta et al. (2004).
The presence of forbidden lines such as [O i] λ630.0 nm and [S ii] λλ671.6,673.1 nm is an indication of jets or outflows from the system (e.g., Hartigan et al. 1995; Whelan et al. 2009). The most prominent optical forbidden line detected in the J0538 spectrum is the [O i] line, while the [S ii] lines are not detected. At the resolution of X-shooter, the [O i] line shows an asymmetric profile, with stronger red-shifted than blue-shifted emission (see Fig. 1). From the [O i] line luminosity we derive an average mass loss rate of $M_{\text{wind}} \sim 4.5 \times 10^{-12} M_\odot/\text{y}$, following Hartigan et al. (1995), including their assumptions that $V_w \sim 150$ km s$^{-1}$ for the outflow velocity, that the electron density is $n_e \sim 7.0 \times 10^4$ cm$^{-3}$ (used because [S ii] lines are not detected), and that the outflow fills our 1-arcsec beam ($l_1 \sim 5.4 \times 10^{15}$ cm).

The value of $M_{\text{wind}}$ is rather uncertain, given the assumptions on $V_w$, $l_1$, and $n_e$. However, the inferred ratio of the mass loss rate to the mass accretion rate ($\sim 0.03$) is typical of T Tauri stars (Hartigan et al. 1995; White & Hillenbrand 2004) and agrees with the expectation of accretion-driven jets and winds (e.g., Shu et al. 1994; Pudritz et al. 2007).

6. Physical condition of the emitting gas

The many hydrogen emission lines detected in the J0538 spectrum can provide information on the physical conditions of the emitting gas.

Figure 4 shows the ratio of the Balmer line fluxes normalized to H$\delta$, the strongest line with an almost symmetric profile. For comparison, we computed the expected ratios for optically thick, LTE lines over a large range of temperatures, as well as the Case B predictions, which assume that all lines are optically thin (Storey & Hummer 1995) for different temperatures and electron densities. We show in the figure the best-fitting curves.

The line ratios are well fitted by optically thick, LTE emission at relatively low temperature (2000–3000 K). The highest Balmer lines ($n \geq 21$) are weaker than predicted when compared to H$\delta$, probably because they become more and more optically thin. The Case B models do not provide an equally good fit. The infrared lines are relatively weak, with Br$\gamma$ not detected. The observed values of Pa$\beta$/H$\gamma$ ($\sim 0.2$) and Pa/H$\delta$ ($\sim 0.4$), which refer to lines coming from the same upper levels, are higher than expected in the optically thin case, but much lower than expected if all lines were optically thick and coming from the same physical region. The observed ratio Pa$\beta$/Pa$\gamma$ ($\sim 0.9$) is consistent with
optically thick, LTE gas at $T \sim 3000$ K. Our interpretation is that the hydrogen recombination lines come from dense, relatively cold gas in thermal equilibrium, with different lines sampling regions of a different physical size.

The physical conditions of the emitting gas inferred from the hydrogen spectrum are not consistent with the predictions of the magnetospheric accretion models, in which the lines form at temperature of several thousand degrees ($6000 \lesssim T \lesssim 12\,000$ K, Muzerolle et al. 2001, 2005) in the column of gas accreting onto the star. Gatti et al. (2006) found that at low mass accretion rates the region emitting the hydrogen lines is more likely to be the shocked photosphere, where the infalling matter impacts onto the star.

7. Conclusions

We present the first observations of a young, accreting brown dwarf in the σ Ori (J053825.4-024241) obtained with the new spectrograph X-shooter, which provides a simultaneous, medium resolution, high-sensitivity spectrum over the entire wavelength range from $\sim 300$ to $\sim 2500$ nm. The spectrum shows a large number of lines and excess continuum emission, which are typical signatures of the accretion-related phenomena that dominate the spectrum of young stars, as well as a number of absorption features that allow us to classify the object ($M_7 \pm 0.5$), estimate its mass ($M \sim 0.06 M_\odot$), and confirm its youth.

We estimate the mass accretion rate from 12 different accretion indicators simultaneously observed with X-shooter. The accretion rate determinations have a minimum-maximum spread of a factor of 30 for the different methods; when using all values, we significantly reduce the uncertainty and obtain $\log M_{\text{acc}} = -9.86 \pm 0.45 M_\odot/\text{yr}$, similar to the non-simultaneous determination from the $U$-band excess emission (Rigliaco et al. 2011). J0538 is one of the most variable objects observed among very low-mass stars and brown dwarfs in the σ Ori cluster (Caballero et al. 2006); the X-shooter spectrum proves that the large discrepancies between $M_{\text{acc}}$ values found by different techniques by various authors do not only depend on variability, but also on the uncertainties of the relations between the observed properties, such as line luminosities, and $L_{\text{acc}}$.

The spectrum of J0538 shows emission in the [O I] 630.0 nm line, which we interpret as evidence of mass ejection with $\log M_{\text{wind}} \sim -11.4 M_\odot/\text{yr}$. The ratio $M_{\text{wind}}/M_{\text{acc}}$ is $\sim 0.03$, which is low, but within the range observed in T Tauri stars (Hartigan et al. 1995).

The large number of hydrogen recombination lines in the X-shooter spectrum allows us to study the physical conditions of the emitting gas. We find that Balmer lines (up to $n \sim 21$) are optically thick and likely produced in a cold ($\sim 2000$–$3000$ K) dense region where LTE conditions hold. These conditions are

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