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First firm spectral classification of an early-B pre-main-sequence star: B275 in M 17*

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ABSTRACT

The optical to near-infrared (300–2500 nm) spectrum of the candidate massive young stellar object (YSO) B275, embedded in the star-forming region M 17, has been observed with X-shooter on the ESO Very Large Telescope. The spectrum includes both photospheric absorption lines and emission features (H and Ca II triplet emission lines, 1st and 2nd overtone CO bandhead emission), as well as an infrared excess indicating the presence of a (flaring) circumstellar disk. The strongest emission lines are double-peaked with a peak separation ranging between 70 and 105 km s⁻¹, and they provide information on the physical structure of the disk. The underlying photospheric spectrum is classified as B6–B7, which is significantly cooler than a previous estimate based on modeling of the spectral energy distribution. This discrepancy is solved by allowing for a larger stellar radius (i.e. a bloated star) and thus positioning the star above the main sequence. This constitutes the first firm spectral classification of an early-B pre-main-sequence (PMS) star. We discuss the position of B275 in the Hertzsprung-Russell diagram in terms of PMS evolution. Although the position is consistent with PMS tracks of heavily accreting protostars (M_ac ≳ 10⁻³ M_☉ yr⁻¹), the fact that the photosphere of the object is detectable suggests that the current mass-accretion rate is not very high.

Key words. stars: formation – stars: pre-main-sequence – stars: massive – stars: variables: T Tauri, Herbig Ae/Be

1. Introduction

Observational and theoretical evidence is accumulating that the formation process of massive stars is through disk accretion, similar to low-mass stars. This persists despite the strong radiation pressure and ionizing power produced by the massive young stellar object (YSO) that may reverse the accretion flow and prevent matter from accreting onto the forming star (e.g., Keto et al. 2006; Krumholz et al. 2009). Given the short main-sequence lifetime of massive stars, the mass accretion rate must be high (up to ∼ M_☉ yr⁻¹), and they provide information on the physical structure of the disk. The underlying photospheric spectrum is classified as B6–B7, which is significantly cooler than a previous estimate based on modeling of the spectral energy distribution. This discrepancy is solved by allowing for a larger stellar radius (i.e. a bloated star) and thus positioning the star above the main sequence. This constitutes the first firm spectral classification of an early-B pre-main-sequence (PMS) star. We discuss the position of B275 in the Hertzsprung-Russell diagram in terms of PMS evolution. Although the position is consistent with PMS tracks of heavily accreting protostars (M_ac ≳ 10⁻³ M_☉ yr⁻¹), the fact that the photosphere of the object is detectable suggests that the current mass-accretion rate is not very high.

* Based on observations performed with the ESO Very Large Telescope on Cerro Paranal, Chile, as part of the X-shooter Science Verification program 60.A-9402(A).
no definite photospheric features other than hydrogen, so that the nature of this source remained uncertain. The spectral energy distribution (SED), though, indicated spectral type late-O or early B, at an adopted distance of 1.3 kpc. We set out to exploit the high efficiency and broad wavelength coverage of the new medium-resolution spectrograph X-shooter on the ESO Very Large Telescope (VLT) to (i) detect the photospheric spectrum of B275 in M 17; (ii) determine its effective temperature in order to place the candidate massive YSO unambiguously onto recent evolutionary tracks; and (iii) search for ongoing accretion activity and investigate the structure of the disk.

2. VLT/X-shooter observations of B275

VLT/X-shooter spectra were obtained of the massive YSO B275 in M 17 (CEN 24, RA(2000.0) = \(18^h20^m25.13^s\), Dec(2000.0) = \(-16^\circ10'24''.56\), \(V = 15.55\) mag, \(K = 8.05\) mag, Chini et al. 1980; Skrutskie et al. 2006) on August 11, 2009 at 03h20 UT, during the first science verification run (PI Chini). The observations in the UVB arm (300–600 nm) were binned (2 pixels) in the wavelength direction in order to increase the signal-to-noise ratio of this part of the spectrum, while still oversampling the resolution element. The 1.6′ slit was used resulting in resolving power \(R = 3300\). For the VIS (550–1000 nm) and the NIR arm (1000–2500 nm) a 0.9′ slit was used (\(R = 8800\) and 5600, respectively). The total exposure time was 45 min, resulting in a typical signal-to-noise ratio of 70. For more details on the X-shooter instrument and its performance, see D’Odorico et al. (2006); Vernet et al. (2011). The observing conditions were good (0.6′′ seeing in V and 76% Moon illumination). The spectra were obtained by nodding the star on the slit, allowing for background subtraction. The standard procedures of data reduction were applied using the X-shooter pipeline version 0.9.4 (Goldoni et al. 2006; Modigliani et al. 2010). For flux calibration and telluric absorption correction, the standard stars EG274 and HD 180699 were used.

3. Results

In the following we present the results for the accurate classification of the photospheric spectrum, analyze the interstellar spectrum to determine the extinction, model the SED using the flux-calibrated X-shooter spectrum, and describe the emission-line spectrum produced by the circumstellar disk.

3.1. Spectral classification

Hydrogen absorption lines were detected by Hanson et al. (1997) in the blue spectrum of B275, but do not allow for an accurate spectral classification. As shown in Fig. 1, a number of helium and metal lines can be used to classify the photospheric spectrum. The He \(i\) 400.9 nm and C \(\Pi\) 426.7 nm, prominent down to spectral type B3, are very weak. The He \(i\) 447.1 nm/Mg \(\Pi\) 448.1 nm ratio is a useful spectral indicator for mid- to late-B stars (Gray & Corbally 2009) as the neutral helium line disappears towards lower temperature (A0) and the magnesium line strengthens. When also considering another line ratio, Si \(\Pi\) 412.8 nm/He \(i\) 448.1 nm, the spectral type becomes B6 (±one subtype).

The spectral type and luminosity class of B275 are further constrained by comparison of the observed H \(i\) and He \(i\) line profiles (as well as the shape of the SED, see Sect. 3.3), to model profiles produced with FASTWIND (Puls et al. 2005). This code calculates non-LTE line-blanketed stellar atmosphere models and is especially suited to modeling stars with strong winds, but it can also be used to examine \(T_{\text{eff}}\) and \(\log g\) dependent photospheric lines of H and He. We constructed a grid of models (in varying \(T_{\text{eff}}\) and \(\log g\) of B6–B8 dwarf and giant stars. The synthetic H \(i\) and He \(i\) profiles resulting from the models are convolved with the corresponding instrumental and rotational profiles. We adopt \(v_i \sin i = 100\) km s\(^{-1}\). An acceptable fit is obtained for a B7 V model (Fig. 2); however, the best fit is obtained for a B7 III model, with \(T_{\text{eff}} = 13000 \pm 500\) K and
log $g = 3.5 \pm 0.3$. This is the first time that the spectral type of a candidate massive YSO has been accurately determined.

### 3.2. Interstellar spectrum

The optical spectrum of B275 includes several interstellar features: atomic resonance transitions (e.g., Ca ii H&K, Na i D) and diffuse interstellar bands (DIBs). The DIB strengths provide a measure of the interstellar extinction. For the DIBs centered at 578.0, 579.7, and 661.4 nm, we measure an equivalent width of 0.063, 0.014, and 0.021 nm, respectively, with a typical error of 10%. Using the relations from Cox et al. (2005), we arrive at an $E(B-V)$ of 1.0 ± 0.1 mag. For an average value of $R_V = 3.1$, these DIB strengths yield $A_V = 3$ mag of visual extinction. This is less than the determination of $A_V = 6.1$ mag from reddening the SED (Sect. 3.3). Hanson et al. (1997) note that the DIB features in spectra of M 17 stars do not show large variations in strength, despite the fairly wide range in total extinction, from $A_V = 3 - 10$ mag. We consider their explanation likely that the DIBs are mostly tracing the foreground dust and that the (unidentified) DIB carriers may only exist in the diffuse medium, not in the dark cloud environment of M 17.

### 3.3. Spectral energy distribution

Figure 3 shows the flux-calibrated X-shooter spectrum (300–2500 nm) of B275. The photometric data points demonstrate the accuracy of the spectrophotometric calibration. The long standing debate over the distance to M 17 (ranging from 1.3 to 2.1 kpc) has recently been settled by the measurement of the trigonometric parallax of the CH3OH maser source G15.03–0.68 (Xu et al. 2011), resulting in a distance of $1.98^{+0.15}_{-0.12}$ kpc so that M 17 is likely located in the Carina-Sagittarius spiral arm.

We deredden the flux-calibrated X-shooter spectrum of B275 (Fig. 3) using the parameterization of the extinction law by Cardelli et al. (1989). The dereddened spectrum is fit to a Kurucz model (Kurucz 1979, 1993) based on an iterative procedure, with fixed parameters $T_{\text{eff}} = 13000$ K, log $g = 3.5$, $d = 1.98$ kpc and $R_V = 3.3$ (an effective value resulting from interstellar and local extinction). This yields independent best-fit values of $A_V = 6.1 \pm 0.6$ mag and $R_\star = 8.1 \pm 0.8$ $R_\odot$. Note that this radius is much larger than that of, e.g., a B5 zero-age main sequence (ZAMS) star (2.7 $R_\odot$, Hanson et al. 1997). An additional constraint is provided by the height of the Balmer jump, which also varies with $T_{\text{eff}}$ and $R_\star$: Fig. 3 demonstrates that the Balmer jump (as well as the Paschen jump) is nicely fit to the observed spectrum. Thus, with a larger radius the discrepancy between the classification of the photospheric spectrum and the dereddened SED is solved. The consequence is that B275 is not on the main sequence but is a so-called bloated star, where the appropriate spectral type would be B7 III. The corresponding luminosity is $L_\star / L_\odot = 3.2$.

### 3.4. Accretion signatures

A pronounced, double-peaked emission feature is detected in the strongest H Balmer lines, the Ca ii triplet and the O i 844.6 nm line (Fig. 1). The measured peak-to-peak separation ranges from 71 ± 7 km s$^{-1}$ (O i 844.6 nm) to 103 ± 3 km s$^{-1}$ (Ca ii 849.8 nm), and is centered at the rest-frame velocity of the star. The Ca ii triplet lines are probably produced in an optically thick medium, since their strength ratio is not 1:9:5. The strongest lines of the H i Paschen and Brackett series also exhibit a central emission component, though it is single-peaked. The higher series members include a weaker emission component that may be double-peaked. A number of metallic emission lines (e.g., C i and Fe ii) are detected throughout the spectrum, albeit very weak.

Prominent CO 1st-overtone emission bandheads are detected at 2.3 $\mu$m, with clear evidence of a blue shoulder. We also confirm the presence of 2nd-overtone CO bandhead emission at 1.5 $\mu$m (Hanson et al. 1997). CO is easily dissociated so must be shielded from the strong UV flux of the young massive star. On the other hand, to produce 1st overtone emission, CO must be excited, requiring a temperature in the range between 1500 and 4500 K (Bik & Thi 2004). This temperature might even be higher, considering the unprecedented detection of 2nd overtone emission. These conditions can be met in the plane of a dense circumstellar disk where the CO molecules can be formed, excited, and protected from dissociation through self-shielding.
The relative strength and shape of the CO bandheads can be modeled by an optically thin Keplerian disk (Bik & Thi 2004; Blum et al. 2004), where the blue shoulder would imply a relatively high inclination angle of the disk (“edge-on”). Blum et al. (2004) model the CO 2–0 first-overline transition rotational bandhead at 2294 nm of B275 resulting in $\nu \sin i = 109.7 \pm 0.6$ km s$^{-1}$ (at the inner edge of the CO emission zone) and surface density $N_{\text{CO}} = 3.5 \pm 0.2 \times 10^{12}$ cm$^{-2}$. The double-peaked emission profiles, as shown in Fig. 1, are very similar to the emission-line profile of a single line obtained by Blum et al. (2004).

We find no evidence for veiling of the optical spectrum or any strong indications of active “heavy” accretion and/or jets, such as those observed in some other systems (e.g., Ellerbroek et al. 2011). The [O ii] 630 nm line very likely has a nebular origin.

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