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Published in:
Astronomy & Astrophysics

DOI:
10.1051/0004-6361/201118089

Citation for published version (APA):
Letter to the Editor

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


Astronomical Institute Anton Pannekoek, University of Amsterdam, Science Park 904, PO Box 94249, 1090 GE Amsterdam, The Netherlands
E-mail: ochsendorf@strw.leidenuniv.nl; L.Kaper@uva.nl

ESO 2011

DOI: 10.1051/0004-6361/201118089
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1 Astronomical Institute Anton Pannekoek, University of Amsterdam, Science Park 904, PO Box 94249, 1090 GE Amsterdam, The Netherlands
2 Astronomisches Institut, Ruhr-Universität Bochum, Universitätsstrasse 150, 44780 Bochum, Germany
3 Instituto de Astronomía, Universidad Católica del Norte, Antofagasta, Chile
4 SRON, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

Received 14 September 2011 / Accepted 25 October 2011

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 (Ṁₚₕ ≳ 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 10⁻³ M⊙ yr⁻¹, Hosokawa et al. 2010) to ensure that the star is not leaving the main sequence before the accretion process has finished.

Evidence of accretion must come from the detection of circumstellar disks, and possibly bipolar jets, as observed around forming low-mass stars (e.g., Appenzeller & Mundt 1989). Disks and outflows around massive YSO candidates are being reported (e.g., Chini et al. 2004; Kraus et al. 2010; Ellerbroek et al. 2011), but the physical properties of the forming massive stars remain uncertain. The mass of the central object has to be estimated from the emerging flux, and the direct detection of the photospheric spectrum turns out to be very difficult at this early stage of evolution (e.g., Testi et al. 2010).

Infrared surveys have revealed several hundred candidate massive YSOs, based on luminosity arguments (e.g., Urquhart et al. 2011). A (K-band) spectrum has been obtained for only a few of these (Hanson et al. 1997, 2002; Bik et al. 2006), and they show a red continuum, likely due to hot dust, and an emission-line spectrum that includes Brγ and, often, CO 2.3 μm bandhead emission. The latter emission can be modeled as being produced by a Keplerian rotating disk surrounding the young, potentially massive star (Bik & Thi 2004; Blum et al. 2004; Wheelwright et al. 2010).

As massive stars show most spectral features in the UV and optical ranges, the study of their photospheric properties would strongly benefit from extending the spectral coverage as far to the blue as possible. Obviously, extinction by the surrounding gas and dust makes this an observational challenge. Only in rare cases have spectra of candidate massive YSOs been obtained at optical wavelengths. Hanson et al. (1997) obtained optical and near-infrared spectra of candidate massive YSOs in M 17, one of the most massive nearby star-forming regions in the Galaxy (Hoffmeister et al. 2008; Broos et al. 2007; Povich et al. 2009).

For the “normal” OB stars Hanson et al. (1997) found a good correspondence between the optical and K-band spectra, but the massive YSO optical spectra remained inconclusive. For four massive YSO candidates, they registered the optical spectrum from 400 to 480 nm, indicating a high mass and luminosity. The blue spectrum of the strong CO emission source B275 showed...
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 spec-
trum 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°20′25″13, Dec(2000.0) =
−16°10′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 observa-
tions 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, re-
spectively). 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 classifica-
tion of the photospheric spectrum, analyze the interstellar spec-
trum 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 accu-
rate 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 II 426.7 nm, prominent
down to spectral type B3, are very weak. The
He I 447.1 nm/Mg II 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 II 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 eff and log g dependent pho-
tospheric lines of H and He. We constructed a grid of models
(in varying T 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 vi 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 eff = 13 000 ± 500 K and

Fig. 1. Top left: the blue spectrum of B275 in M 17 shown next to B main-sequence-star spectra (Gray & Corbally 2009). Bottom left: the
1st and 2nd overtone CO emission bands. Zero velocity corresponds to the first component in the series (at 2294 and 1558 nm, respectively).
Right: a sample of the emission line profiles in the spectrum of B275. The Ca II triplet lines and O I 845 nm are superposed on hydrogen Paschen
series absorption lines. The flux of the Hα line is scaled down by a factor 5; the structure near the peak is a remnant of the nebular-line subtraction.

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The B7 III model provides the best fit with the observed profiles. Likely that the DIBs are mostly tracing the foreground dust and at 578.0, 579.7, and 661.4 nm, we measure an equivalent width, a measure of the interstellar extinction. For the DIBs centered and die.

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 strength provides 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 dereddening 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 CH$_3$OH maser source G15.03–0.68 (Xu et al. 2011), resulting in a distance of $1.98^{+0.12}_{-0.15}$ 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 $A_V = 6.1$ ± 0.6 mag and $R_*= 8.1 ± 0.8 R_\odot$. 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 $R_*$. 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 log $L_*/L_\odot = 3.2$.

3.4. Accretion signatures

A pronounced, double-peaked emission feature is detected in the strongest H Balmer lines, the Ca ii H&K, Na ii i, and di.

Fig. 3. The flux-calibrated X-shooter spectrum of B275 from 300–2500 nm (black) along with the photometric data (red triangles, black error bars) from Chini et al. (1980) (UVBRI), 2MASS (Skrutskie et al. 2006, JHK), Spitzer GLIMPSE (Benjamin et al. 2003, 3.6, and 5.8 μm), and Nielbock et al. (2001) (N, Q). When dereddened ($A_V = 6.1$ mag, orange line, blue diamonds), the SED is described well by a B7 III Kurucz model (blue, dashed line). The excess flux at 500–800 nm is an instrumental feature.

log $g = 3.5 ± 0.3$. This is the first time that the spectral type of a candidate massive YSO has been accurately determined.

**Fig. 2.** FASTWIND model profiles of He (top) and He i 447.1 nm (bottom) lines for B6–B8 giants (left) and main-sequence stars (right). The B7 III model provides the best fit with the observed profiles.
Fig. 4. The location of B275 (red parallelogram) in the HRD next to PMS tracks from Hosokawa & Omukai (2009) with the ZAMS mass labeled and open symbols indicating lifetimes. The thin dashed and thin dot-dashed lines are the birth lines for accretion rates of 10^{-4} M_\odot yr^{-1} and 10^{-5} M_\odot yr^{-1}, respectively; the thick solid line is the ZAMS (Schaller et al. 1992). The filled and open circles represent stars in M 17 for which a spectral type has been determined (Hoffmeister et al. 2008), within a radius of 0.5 and 1.0, respectively; dots are other stars in M 17. B275 is on its way to becoming a 6–8 M_\odot ZAMS star.

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- overtone ro-vibrational bandhead at 2294 nm of B275 resulting in v sin i = 109.7 ± 0.6 km s^{-1} (at the inner edge of the CO emission zone) and surface density N_{CO} = 3.5 ± 0.2 \times 10^{18} 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.

4. Discussion

The accurate spectral classification and SED fit result in a well-defined position of B275 in the Hertzsprung-Russell diagram (HRD, Fig. 4). It is located well above the ZAMS, demonstrating its PMS nature. If B275 is contracting towards the ZAMS, the final ZAMS mass would be 6–8 M_\odot (spectral type B1–B2), assuming that no additional mass is accreted.

To be visible at this location in the HRD, the star must have experienced an average accretion rate of at least 10^{-5} M_\odot yr^{-1} in its recent history. B275 may thus be the long-sought-for example of an early-B PMS star. Figure 4 also shows other nearby stars in M 17. Hanson et al. (1997) derive an age of ~1 Myr for the M 17 cluster and Hoffmeister et al. (2008) estimate that the PMS objects are less than 5 \times 10^5 yr old. Based on its location on the HRD we estimate the age of B275 at 10^5 yr.

B275 bears some resemblance to a classical Be star. However, we note that Be stars do not emit CO 1st and 2nd overtone emission. In addition, B275 would be classified as a luminous Herbig Be star according to the definition discussed in Carmona et al. (2010), but our analysis of the photospheric spectrum allows for a more quantitative classification.

B275 has a significant amount of infrared excess, starting at 1 \mu m, and a flat SED between 2 and 10 \mu m (Nielbock et al. 2001). This indicates the presence of a flaring circumstellar disk in which the dust has not settled yet. However, the visibility of the photosphere, the small number of optical gas emission lines and the absence of a jet lead us to believe that the current mass-accretion rate is not very high. Nevertheless, the CO (2–0) and (3–0) emission originates in a dense and highly excited inner part of the disk. Either the system is in an intermittent phase between accretion episodes, or it is on the verge of photo-evaporating its disk. Either scenario is consistent with its location in the HR-diagram: an intermediate-mass, visible star in M 17 on its way to becoming an early-B main-sequence star.

Acknowledgements. We thank Takashi Hosokawa for kindly providing the PMS tracks. The ESO Paranal staff is acknowledged for obtaining the X-shooter spectrum of B275. We thank the anonymous referee for useful comments and suggestions.

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