Accurate determination of accretion and photospheric parameters in Young Stellar Objects: the case of two candidate old disks in the Orion Nebula Cluster

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ABSTRACT

Context. Current planet formation models are largely based on the observational constraint that protoplanetary disks have lifetime ~ 3 Myr. Recent studies, however, show that a fraction of pre-Main-Sequence stars with signatures of accretion (strictly connected with the presence of circumstellar disks) appear to have photometrically determined ages of 30 Myr, or more. Here we present a detailed spectroscopic analysis of two of these “old” pre-Main-Sequence objects candidates in the Orion Nebula Cluster.

Aims. We use broad band, intermediate resolution VLT/X-Shooter spectra combined with an accurate method to determine the stellar parameters and the related age of the targets to confirm their peculiar age estimates and the presence of ongoing accretion.

Methods. The analysis is based on a multi-component fitting technique, which derives simultaneously spectral type, extinction, and accretion properties of the objects. With this method we confirm and quantify the ongoing accretion. From the photospheric parameters of the stars we derive their position on the HR Diagram, and the age given by evolutionary models. Together with other age indicators like the lithium equivalent width we estimate with high accuracy the age of the objects.

Results. Our study shows that the two objects analyzed are not older than the typical population of the Orion Nebula Cluster. Our results show that, while photometric determination of the photospheric parameters are an accurate method to estimate the parameters of the bulk of young stellar populations, those of individual objects with high accretion rates and extinction may be affected by large uncertainties. Broad band spectroscopic determinations should thus be used to confirm the nature of individual objects.

Conclusions. The analysis carried out in this paper shows that this method allows us to obtain an accurate determination of the photospheric parameters of accreting young stellar objects. We suggest that our detailed, broad-band spectroscopy method should be used to derive accurate properties of candidate old and accreting young stellar objects in star forming regions.

Key words. Stars: pre-main sequence — Stars: variables: T Tauri, Herbig Ae/Be — Stars: formation

1. Introduction

The formation of planetary systems is strongly connected to the presence, structure, and evolution of protoplanetary disks in which they are born. In particular, the timescale of disk survival sets an upper limit on the timescale of planet formation, becoming a stringent constraint for planet formation theories (Haisch et al., 2001; Wolf et al., 2012).

The observed timescale for the evolution of the inner disk around pre-Main Sequence (PMS) stars is of the order of a few Myr (e.g. Williams & Cieza, 2011). This timescale sets an upper limit on the timescales for planet formation, and, consequently, all models proposed to explain the gas giant planet formation (core accretion, gravitational instability) are generally constrained to agree with a disk timescale of much less than 10 Myr.

On the other hand, recent studies in different star forming regions show evidence that accretion processes, which are strictly connected with the presence of a circumstellar disk, may still be going on at ages of ~ 30 Myr and more. This has been found in both galactic (NGC 3603, Beccari et al. 2010; NGC 6823, Riaz et al. 2012; Orion Nebula Cluster (ONC), Da Rio et al. 2010, 2012; Taurus, White & Hillenbrand 2005; TW Hydrae, Bergin et al. 2013), and extragalactic (30 Dor and other regions of the Magellanic Clouds, De Marchi et al. 2010, 2011; Spezzi et al. 2012), environments. These older PMS accreting objects are found to be more spatially extended than the young (age < 10 Myr) PMS population in the cluster, suggesting that they may be tracing a previous episode of star formation, consistent with the larger age estimates. In these works the presence of ongoing accretion is usually studied through photometric detection of Hα excess emission. The age of the objects is derived from their position on the H-R Diagram (HRD), and thus subject to many biases due to observational and physical uncertainties (e.g. Da Rio et al., 2010b; Baraffe & Chabrier, 2010); those can be solved in many cases (e.g. edge-on disk presence, Huélamo et al. 2010) with a thorough analysis of individual targets.

These findings challenge our present understanding of protoplanetary disk evolution, and can imply a new scenario for
the planet formation mechanism, which could proceed on much longer timescales than previously thought. To verify the existence of older and still active protoplanetary disks we observed with the ESO/VLT X-Shooter spectrograph two candidate older PMS accreting stars in the ONC field. This is an ideal region for this study, given its young mean age (~2.2 Myr, Reggiani et al. 2011), its vicinity (d = 414 pc, Menten et al. 2007), the large number of objects (more than 2000, Da Rio et al. 2010, and the large number of previous studies (e.g. Hillenbrand, 1997; Da Rio et al., 2010, 2012; Megeath et al., 2012; Robberto et al., 2013). Our objective is to verify the previously derived age of these objects using different age indicators in the spectra, and the presence of an active disk by confirming ongoing accretion.

The structure of the paper is the following. In Sect. 2 we report the targets selection criteria, the observation strategy, and the data reduction procedure. In Sect. 3 we describe the procedure adopted to derive the stellar parameters of the objects, and in Sect. 4 we report our results. In Sect. 5 we discuss the implications of our findings. Finally, in Sect. 6 we summarize our conclusions.

2. Sample, observations, and data reduction

2.1. Targets selection and description

We have selected the two older PMS candidates from the sample of the HST Treasury Program on the ONC (Robberto et al., 2013). Our selection criteria were: clear indications of ongoing accretion and of the presence of a protoplanetary disk, an estimated isochronal age much larger than the mean age of the cluster, i.e. ≥ 30 Myr, location well outside the bright central region of the nebula in order to avoid intense background contamination, i.e. at a distance from θ1 Orionis C larger than 5′ (~0.7 pc), and with low foreground extinction (A_V ≤ 2 mag).

In order to find the best candidates, we have combined together HST broad-band photometry and spectroscopic data (Hillenbrand, 1997; Stassun et al., 1999; Da Rio et al., 2010, 2012), and with mid-infrared photometric data (Megeath et al., 2012). The presence of ongoing accretion has been estimated through the Hα line equivalent width (EW_Hα) reported in Da Rio et al. (2010), using as a threshold value EW_Hα > 20 Å, which implies not negligible mass accretion rates (M_accretion ≥ 10^{-8} M_☉/yr). The available Spitzer photometry (Megeath et al., 2012) has been used to confirm the presence of optically thick circumstellar disk, already suggested by the strong Hα emission, looking at the spectral energy distribution (SED) of the targets to see clear excess with respect to the photospheric emission in the mid-infrared wavelength range. Finally, using the data from Da Rio et al. (2010, 2012) we checked that the isochronal age was larger than 30 Myr for the older PMS candidates using different evolutionary models (D’Antona & Mazzitelli, 1994; Siess et al., 2000; Palla & Stahler, 1999; Baraffe et al., 1998), and that the foreground extinction was A_V ≤ 2 mag.

The two targets selected are OM1186 and OM3125, and we report in Table 1 their principal parameters available from the literature (Da Rio et al., 2010, and reference therein). Both targets are located on the HRD almost on the main sequence, as we show in Fig. 1, where the position of these sources is reported using green stars, and we also plot the position of other members of the ONC, shown with blue circles if their EW_Hα < 20 Å, and with red squares if EW_Hα ≥ 20 Å. Their position on the HRD clearly indicates that they have an isochronal age much larger than the bulk of the ONC population, with ages between ~ 60 Myr and ~ 90 Myr for OM1186, according to different evolutionary tracks, and between ~ 25 Myr and ~ 70 Myr for OM3125. The spectral type (SpT) of the two targets has been determined in Hillenbrand (1997) to be K5 for OM1186 and G8-K0 for OM3125. Using these values for the SpT and the photometric data from the WFPC2/HST ONC Treasury Program (Robberto et al., 2013), recently Manara et al. (2012) derived new stellar parameters for OM1186, namely A_V=1.16 mag, L/=0.77 L_☉, and age~6 Myr. This result, very different from the one obtained in Da Rio et al. (2010), shows that photometric analysis can lead to very different results on individual objects, and that the spectroscopic study we present is needed to shed light on the true nature of these objects.

2.2. Observations and data reduction

Observations with the ESO/VLT X-Shooter spectrograph have been carried out in service mode between February and March 2012 (ESO/DDT program 288.C-5038, PI Manara). This instrument covers simultaneously the wavelength range between ~300 nm and ~2500 nm, dividing the spectrum in three arms, namely the UVB arm in the region λι = 300-550 nm, the VIS arm between λι = 550-1050 nm and NIR from λι = 1050 nm to λι ~ 2500 nm (Vernet et al., 2011). The targets have been observed in slit-nodding mode, in order to have a good sky subtraction also in the NIR arm. For both targets we used the same slit widths (0.5'' in the UVB arm, 0.4'' in the other two arms) and the same exposure times (300s x 4 in all three arms), to ensure the highest possible resolution of the observations (R=9100, 17400, 10500 in the UVB, VIS and NIR arms) and enough S/N in the UVB arm. The readout mode used was in both cases “100.1x1.1h”. The seeing conditions of the observatory during the observations were 1'' for OM1186 and 0.95'' for OM3125.

Data reduction has been carried out using the version 1.3.7 of the X-Shooter pipeline (Modigliani et al., 2010), run through the EsoRex tool. The spectra were reduced independently for the three spectrograph arms. The pipeline takes into account, together with the standard reduction steps (i.e. bias or dark subtraction, flat fielding, spectrum extraction, wavelength calibration, and sky subtraction) also the flexure compensation and the
instrumental profile. Particular care has been paid to the flux calibration and telluric removal of the spectra. Flux calibration has been carried out within the pipeline and then compared with the available photometry (Robberto et al., 2013) to correct for possible slit losses, checking also the conjunctions between the three arms. The overall final agreement is very good. Telluric removal has been carried out using the standard telluric spectra that have been provided as part of the X-Shooter calibration plan on each night of observations. The correction has been accomplished using the IRAF\(^1\) task telluric, carefully normalizing the telluric standard spectra and removing the photospheric absorption lines with a multigaussian fitting procedure.

3. Method

The determination of SpT and stellar properties in accreting young stellar objects (YSOs) is not trivial for a variety of reasons. Firstly, YSOs are usually still embedded in their parental molecular cloud, which originates differential reddening effects in the region. This, together with the presence of a circumstellar disk surrounding the star, can modify the actual value of the extinction ($A_V$) on the central YSO from one object to another. Secondly, YSOs may still be accreting material from the protoplanetary disk on the central star. This process affects the observed spectrum of a YSO producing excess continuum emission in the blue part of the spectrum, veiling of the photospheric absorption features at all optical wavelengths, and adding several emission lines (e.g. Hartmann et al., 1998). The two processes modify the observed spectrum in opposite ways: extinction towards the central object suppresses the blue part of the spectrum, making the central object appear redder, thus colder, while accretion produces an excess continuum emission which is stronger in the blue part of the spectrum, making the observed central object look hotter.

For these reasons, SpT, $A_V$ and accretion properties should be considered together in the analysis of these YSOs. Here we present the minimum $X_{\text{dke}}$ method we use to determine SpT, $A_V$, and the accretion luminosity ($L_{\text{acc}}$) simultaneously. With this procedure we are able to estimate $L_*$, which is used to derive $M_*$ and the age of the target using different evolutionary models, and the mass accretion rate ($M_{\text{acc}}$). Finally, we determine the surface gravity ($\log g$) for the input object through comparison with synthetic spectra.

### 3.1. Multi-component fit: set of parameters

To fit the optical spectrum of our objects we consider three components: a set of photospheric templates which will be used to determine the SpT, and therefore the effective temperature ($T_{\text{eff}}$) of the input spectrum, different values of the extinction and a reddening law to obtain $A_V$, and a set of models which describe the accretion spectrum we use to derive $L_{\text{acc}}$.

**Photospheric templates.** The set of photospheric templates is obtained from the one collected in Manara et al. (2013). This is a sample of 24 well-characterized X-Shooter spectra of non-accreting (Class III) YSOs representative of objects of SpT classes from late K to M. We extend this grid with two new X-Shooter observations of non-accreting YSOs from the ESO programs 089.C-0840 and 090.C-0050 (PI Manara), one object with SpT G4 and the other one with SpT K2. In total, our photospheric templates grid consists of 26 non-accreting YSOs with SpT between G4 and M9.5. We use Class III YSOs as photospheric template, because synthetic spectra or field dwarf spectra would be inaccurate for this analysis for the following reasons. Firstly, YSOs are highly active, and their photosphere is strongly modified by this chromospheric activity, both in the continuum and in the line emission (e.g. Ingleby et al., 2011; Manara et al., 2013). Secondly, field dwarf stars have a different surface gravity with respect to PMS stars, which are subgiants. Using spectra of non-accreting YSOs as templates mitigates these problems.

**Extinction.** We consider in the analysis values of $A_V$ in the range [0-10] mag, with steps of 0.1 mag in the range $A_V = [0-3]$ mag, and of 0.5 mag at higher values of $A_V$. This includes all the possible typical values of $A_V$ for non-embedded objects in this region (e.g. Da Rio et al., 2010, 2012). The reddening law we adopt in this work is the one from Cardelli et al. (1989) with $R_V=3.1$, appropriate for the ONC region (Da Rio et al., 2010).

**Accretion spectrum.** To determine the excess emission due to accretion, and thus the $L_{\text{acc}}$, we use a grid of isothermal hydrogen slab models, which has already been used and proved to be adequate for this analysis (e.g. Valenti et al., 1993; Herczeg & Hillenbrand, 2008; Rigliaco et al., 2012; Alcalá et al., 2013). We describe the emission due to accretion with the slab model in order to have a good description of the shape of this excess and to correct for the emission arising in the spectral region at wavelengths shorter than the minimum wavelengths covered by the X-Shooter spectra, i.e. $\lambda \leq 330$ nm. In these models we assume local thermodynamic equilibrium (LTE) conditions, and we include both the $H$ and $H^+$ emission. Each model is described by three parameters: the electron temperature ($T_{\text{slab}}$), the electron density ($n_e$), and the optical depth at $\lambda=300$ nm ($\tau$), which is related to the slab length. The $L_{\text{acc}}$ is given by the total luminosity emitted by the slab. The grid of slab models we adopt covers the typical values for the three parameters: $T_{\text{slab}}$ is selected in the range from 5000 to 11000 K, $n_e$ varies from $10^{11}$ to $10^{16}$ cm$^{-3}$, and $\tau$ has values between 0.01 and 5.

**Additional parameters.** In addition to the 5 parameters just introduced, namely the photospheric template, $A_V$, and the three slab model parameters ($T_{\text{slab}}, n_e, \tau$), there is the need to include also two normalization constant parameters, one for the photospheric template ($K_{\text{phot}}$) and one for the slab model ($K_{\text{slab}}$). The first rescales the emitted flux of the photospheric template to the correct distance and radius of the input target, while the latter converts the slab emission flux as it would have been emitted at

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the stellar surface by a region with the area given by the slab parameters.

3.2. Multi-component fit: best fit determination

To consider the three components (SpT, $A_V$, $L_{\text{acc}}$) altogether, we develop a Python procedure which determines the model which best fits the observed spectrum. We calculate for each point of the model grid a likelihood function, which can be compared to the observed spectrum. The form of this function, that will be longer wavelengths, where the photospheric emission dominates, is mostly originated in the accretion shock, and regions at the model grid a likelihood function, which can be compared to the best fits the observed spectrum. We calculate for each point of the grid a likelihood function, which can be compared to the best fits the observed spectrum. We calculate for each point of the grid (SpT, $A_V$, $L_{\text{acc}}$) altogether, we develop a Python procedure which determines the model which best fits the observed spectrum. The features considered here are the Balmer jump ratio, defined as the ratio between the flux at $\sim 360$ nm and at $\sim 400$ nm, that is not reported, because this value itself should not be considered as an accurate estimate of the goodness of the fit. Whereas a fit with a value of $\chi^2_{\text{like}}$ much larger than the minimum one leads to a very poor fit of the observed spectrum, this function is not a proper $\chi^2$, given that it considers only the errors on the observed spectrum and only some regions in the spectrum.

The procedure is the following. For each photospheric template we deredden the observed spectrum with increasing values of $A_V$. Then, for each value of $A_V$, considering each slab model, we determine the value of the two normalization constants $K_{\text{phot}}$ and $K_{\text{slab}}$ by finding the values of these two constants which lead the flux at $\lambda \sim 360$ nm and at $\lambda \sim 710$ nm of the normalized sum of the photosphere and the slab model to better match the observed spectrum. After that we calculate the $\chi^2_{\text{like}}$ value using Eq. (1). This is done for each point of the grid (SpT, $A_V$, slab parameters). After the iteration on each point of the grid terminates, we find the minimum value of the $\chi^2_{\text{like}}$ and the correspondent values of the best fit parameters (SpT, $A_V$, slab parameters, $K_{\text{phot}}$, $K_{\text{slab}}$)

We also derive from the $\Delta \chi^2_{\text{like}}$ distribution with respect to the SpT of the photospheric templates and the different values of $A_V$ the uncertainties on these two parameters, and thus on $L_{\text{acc}}$. Indeed, these are the main sources of uncertainty in the determination of $L_{\text{acc}}$, which is in fact a measurement of the excess emission with respect to the photospheric one due to accretion. Most of the accretion excess ($\gtrsim 70\%$) is emitted in regions covered by our X-Shooter spectra, and originates mostly in the wavelength range $\lambda \sim 330-1000$ nm, while most of the excess emission at longer wavelengths is due to disk emission and is not considered in our analysis. To derive the total excess due to accretion, we need a bolometric correction for the emission at wavelengths shorter than those in the X-Shooter range, i.e. $\lambda \lesssim 330$ nm. This is calculated with the best fit slab model. Analyzing the slab models we derive that this contribution accounts for less than 30% of the excess emission, and that the shape of this emission is well constrained by the Balmer continuum slope. Different slab model parameters with reasonable Balmer continuum slopes, that would imply similarly good fits as the best one, would lead to values of $L_{\text{acc}}$ always within $10\%$ of each other, as it has been pointed out also by Rigliaco et al. (2012). Therefore, once SpT and $A_V$ are constrained, the results with different slab parameters will be similar. Other sources of uncertainty on the estimate of $L_{\text{acc}}$ are the noise in the observed spectrum, the uncertainties in the distances of the target, and the uncertainty given by the exclusion of emission lines in the estimate of the excess emission (see e.g. Herczeg & Hillenbrand 2008; Rigliaco et al. 2012; Alcalá et al. 2013). Altogether, typical errors on estimates of $L_{\text{acc}}$ with our method are of 0.2-0.3 dex.

As previously mentioned, the accretion emission veils the photospheric absorption features of the observed YSO spectrum. Those can be used to visually verify the goodness of the best fit obtained with the $\chi^2_{\text{like}}$ minimization procedure. In order to do that, we always plot the observed spectrum and the best fit one in the Balmer jump region, in the Ca I absorption line region at $\lambda \sim 420$ nm, in the continuum bands at $\lambda \sim 710$ nm, and in the spectral range of different photospheric absorption lines which depends mainly on the temperature of the star ($T_{\text{eff}}$), namely TiO lines at $\lambda \lambda$ 843.2, 844.2, and 845.2 nm, and the Ca I line at $\lambda \sim 616.5$ nm. The agreement between the best fit and the observed spectrum in the Balmer jump region, at $\lambda \sim 420$ nm, and in the continuum bands at $\lambda \sim 710$ nm is usually excellent. Similarly, the best fit spectrum reproduces very well the observed one also in the photospheric features at longer wavelengths.

3.3. Comparison to synthetic spectra

As an additional check of our results, and to derive the surface gravity ($\log g$) for the target, we compare its spectrum with a grid of synthetic spectra. In particular, we adopt synthetic BT-Settl spectra (Allard et al., 2011) with solar metallicity, $\log g$ in the range from 3.0 to 5.0 (in steps of 0.5), and $T_{\text{eff}}$ equal to that of the best fit photospheric template, using the SpT-$T_{\text{eff}}$ relation from Luhman et al. (2003), and also with $T_{\text{eff}}$ corresponding to the next upper and lower spectral sub-classes.

The procedure we use is the following. First, we correct the input spectrum for reddening using the best fit value of $A_V$. Subsequently, we remove the effect of veiling by subtracting the best fit slab model, rescaled with the constant $K_{\text{slab}}$ derived in the fit, to the dereddened input spectrum. Then, we degrade the synthetic spectra to the same resolution of the observed one ($R$=17400 in the VIS), and we resample those to the same wavelength scale of the target. We then select a region, following Stelzer et al. (2013), with many strong absorption lines dependent only on the star $T_{\text{eff}}$, and with small contamination from molecular bands and broad lines. This is chosen to derive the projected rotational velocity ($v\sin i$) of the target by comparison of its spectrum with rotationally broadened synthetic spectra. The region chosen is in the VIS arm, from 960 to 980 nm, and is characterized by several Ti I absorption lines, and by some shallower Cr I lines. The rotationally broadened and resampled synthetic spectra are then compared with the reddened and veiling-corrected target spectrum in two regions, which are chosen, always following Stelzer et al. (2013, and references therein), because they include absorption lines sensitive to both $T_{\text{eff}}$ and $\log g$ of the star. These are one in the wavelength range $\lambda \sim 500$ nm, where the Balmer lines are the strongest, and the other in the wavelength range $\lambda \sim 750$ nm.
from 765 to 773 nm, where the K I doublet (λ = 766-770 nm) is, and one in the range from 817 to 822 nm, where the Na I doublet (λ = 818.3-819.5 nm) is. The best fit log g is the one of the synthetic spectrum with smaller residuals observed-synthetic in the line regions.

3.4. Stellar parameters

From the best fit parameters determined with the procedure explained in this Section we obtain $T_{\text{eff}}$, $A_V$, and $L_{\text{acc}}$. The first corresponds to the $T_{\text{eff}}$ of the best fit photospheric template, converted from the SpT using the Luhrman et al. (2003) relation, derived with the multi-component fit and verified with the comparison with the synthetic spectra. $A_V$ is also derived in the multi-component fit, while $L_{\text{acc}}$ is calculated by integrating from 50 nm to 2500 nm the total flux of the best fit slab model, rescaled using the normalization constant $K_{\text{slab}}$ derived before. This total accretion flux ($F_{\text{acc}}$) is then converted in $L_{\text{acc}}$ using the relation $L_{\text{acc}} = 4\pi d^2 F_{\text{acc}}$, where $d$ is the distance of the target.

To derive $L_*$ of the input spectrum we use the values of $L_*$ of the non-accreting YSOs used as photospheric template for our analysis, which have been derived in Manara et al. (2013). From the best fit result, we know that $f_{\text{obs,dereddened}} = K_{\text{phot}} \cdot f_{\text{phot}} + K_{\text{slab}} \cdot f_{\text{slab}}$, where $f$ is the flux of the spectrum of the dereddened observed YSO ($\text{obs, dereddened}$), of the photospheric template ($\text{phot}$), and of the slab model ($\text{slab}$). The photospheric emission of the input target is then given solely by the emission of the photospheric template rescaled with the constant $K_{\text{phot}}$. Therefore, we use the relation:

$$L_\text{*,obs} = K_{\text{phot}} \cdot (d_{\text{obs}}/d_{\text{phot}})^2 L_\text{*,phot},$$

where $d$ is the distance, $L_\text{*,phot}$ is the bolometric luminosity of the photospheric template, and $L_\text{*,obs}$ that of the input object. With this relation we derive $L_*$ for the input YSO.

From $T_{\text{eff}}$ and $L_*$ we then derive $R_*$, whose error is derived by propagation of the uncertainties on $T_{\text{eff}}$ and $L_*$, $M_*$, and age are obtained by interpolation of evolutionary models (Siess et al., 2000; Baraffe et al., 1998; Palla & Stahler, 1999; D’Antona & Mazzitelli, 1994) in the position of the target on the HRD. Their typical uncertainties are determined allowing their position on the HRD varying according to the errors on $T_{\text{eff}}$ and $L_*$. Finally, using the relation $M_{\text{acc}} = 1.25 \cdot L_{\text{acc}} R_*/(GM_* )$ (Gullbring et al., 1998) we derive $M_{\text{acc}}$, and its error is determined propagating the uncertainties on the various quantities in the relation. We report always the values derived using all the evolutionary models, in order to show that the results are not model-dependent.

Another important quantity which can be used to assess the young age of a PMS star is the presence and the depth of the lithium absorption line at $\lambda \sim 670.8$. Given that veiling modifies substantially the equivalent width of this line (EW$_{\text{Li}}$), we need to use the reddening- and veiling-corrected spectrum of the target to derive this quantity. On this corrected spectrum we calculate EW$_{\text{Li}}$ integrating the gaussian fit of the line, which is previously normalized to the local pseudo-continuum at the edges of the line. The statistical error derived on this quantity is given by the propagation of the uncertainty on the continuum estimate.

4. Results

In the following we report the accretion and stellar properties of the two older PMS candidates obtained using the procedure explained in Sect. 3.

Fig. 2. Best fit for the object OM1186. Balmer jump, normalization region, Ca absorption feature, and photospheric features used to check derived veiling.

4.1. OM1186

The best fit for OM1186 is shown in Fig.2: the red line is the observed spectrum, the green one the photospheric template, the cyan line the slab model, and the blue the best fit. The region around the Balmer jump is shown in the upper plot, while the other panels show the normalization region around $\sim$710 nm, the continuum normalized Ca I absorption line at $\sim$422 nm, and the photospheric features at $\lambda \sim 616$ nm and $\lambda \sim 844$ nm. We clearly see that the agreement between the observed and best fit spectra is very good in all the region analyzed. This is obtained using a photospheric template of SpT K5, with $T_{\text{eff}}=4350$ K, which corresponds to $T_{\text{eff}}=4350$ K, and with $\log g=4.5$. In Fig. 3 both regions adopted for the log$ g$ analysis are shown, and the red line refers to the reddening- and veiling-corrected observed spectrum, while the black dotted line is the synthetic spectrum which better reproduces the observed one. We also report the residuals in the bottom panel.

From the best fit, we derive for this object a value of $L_*=1.15\pm0.36 L_\odot$. With this value and using $T_{\text{eff}}=4350$ K, we derive the mass and age for these objects with the evolutionary models of Siess et al. (2000); Baraffe et al. (1998); Palla & Stahler (1999); D’Antona & Mazzitelli (1994). The values derived are, respectively, $M_*=1.1\pm0.4$, $1.4\pm0.3$, $1.1\pm0.4$, $0.6\pm0.3$ $M_\odot$ and age $=[3.2^{+0.8}_{-0.7}, 4.7^{+0.2}_{-0.2}, 2.8^{+0.2}_{-0.2}, 0.8^{+1.4}_{-0.4}]$ Myr. Moreover, we derive $M_{\text{acc}}$ with the parameters derived from the fit and from the evolutionary models and, according to the different evolutionary
tracks, we obtain $\dot{M}_{\text{acc}} = [1.3 \pm 0.8, 1.1 \pm 0.6, 1.4 \pm 0.8, 2.4 \pm 1.8] \times 10^{-9} M_{\odot}/\text{yr}$ for this object. From the reddening- and veiling-corrected spectrum we derive $\text{EW}_{\text{Li}} = 658 \pm 85 \text{ mÅ}$. All the parameters derived from the best fit are reported in Table 2, while those derived using the evolutionary models in Table 3.

### 4.2. OM3125

Using the same procedure, we obtain for OM3125 a minimum $\chi^2_{\text{like}}$ value with a photospheric template of SpT K7, corresponding to $T_{\text{eff}} = 4060 \text{ K}$, with an uncertainty of 250 K, and $A_V = 1.2 \pm 0.3 \text{ mag}$. However, with this best fit model we do not reproduce very well the Ca I absorption feature at $\lambda \sim 616.5 \text{ nm}$, because the amount of veiling in this line is too high. Looking at the solutions with values of $\chi^2_{\text{like}}$ similar to the minimum value, we find that the best agreement between the observed and fitting spectrum in this feature is with a value of $A_V = 1.0 \text{ mag}$. We show this adopted best fit in Fig. 4, using the same color-code as in Fig. 2. The slab model used here leads to a value $L_{\text{acc}} = 1.25 \pm 0.60 L_{\odot}$. The effect of veiling in this object is stronger than in OM1186, and this is clearly seen both in the Balmer jump excess and in the Ca I absorption feature at $\lambda \sim 420 \text{ nm}$, which is almost completely veiled, and has emission on reversal of the very faint absorption feature. Moreover, also the other photospheric features are much more veiled, as it is shown in the bottom panels of Fig. 4. In the bottom right panel there is also an He emission line due to accretion in correspondence with the TiO absorption features normally present in the photosphere of objects with this SpT (see Fig. 2 for comparison).

In Fig. 5 we show, using the same color code as in Fig. 3, the synthetic spectrum analysis for this object. In this case the best agreement is found with a synthetic spectrum with $T_{\text{eff}} = 4000 \text{ K}$ and $\log g = 4.0$.

The luminosity derived for this object from its best fit is $L_x = 0.81 \pm 0.44 L_{\odot}$. With this value and using $T_{\text{eff}} = 4060 \text{ K}$, we derive the mass and age for these objects with the evolutionary models of Siess et al. (2000); Baraffe et al. (1998); Palla & Stahler (1999); D’Antona & Mazzitelli (1994). The values derived are, respectively, $M_x = [0.8 \pm 0.3, 1.2 \pm 0.2, 0.8 \pm 0.2, 0.5 \pm 0.2] M_{\odot}$ and age = $[2.2 \pm 0.6, 4.32 \pm 0.7, 2.4 \pm 1.3, 0.8 \pm 0.3] \text{ Myr}$. This object has, according to the different evolutionary models, $\dot{M}_{\text{acc}} = [1.2 \pm 0.9, 0.8 \pm 0.5, 1.2 \pm 0.7, 1.9 \pm 1.2] \times 10^{-9} M_{\odot}/\text{yr}$, and $\text{EW}_{\text{Li}} = 735 \pm 42 \text{ mÅ}$. These results are also reported in Table 2 and 3.
we will address possible reasons which lead to misclassification of these targets in the literature.

5.1. Age related parameters

Lithium abundance: using the values of EW\(_{\text{Li}}\) and the stellar parameters obtained in the previous section we calculate the lithium abundance (\(\log N(\text{Li})\)) for the two targets by interpolation of the curves of growth provided by Pavlenko & Magazzu (1996). We derive \(\log N(\text{Li}) = 3.324 \pm 0.187\) for OM1186 and \(\log N(\text{Li}) = 3.196 \pm 0.068\) for OM3125. These values are compatible with the young ages of the targets according to various evolutionary models (Siess et al., 2000; D’Antona & Mazzitelli, 1994; Baraffe et al., 1998). Indeed, these models predict almost no depletion of Lithium for objects with these \(T_{\text{eff}}\) at ages smaller than 3 Myr, meaning that the measured lithium abundance for younger objects should be compatible with the interstellar abundance \(\log N(\text{Li}) \approx 3.1-3.3\) (Palla et al., 2007).

Surface gravity: The derived values of the surface gravity for the two targets are compatible with the theoretical values for objects with \(T_{\text{eff}} \approx 4000-4350\) K and an age between \(\sim 1-4.5\) Myr. Indeed, both Siess et al. (2000) and Baraffe et al. (1998) models predict a value of \(\log g \approx 4.0\) for objects with these properties. Nevertheless, the derived value of \(\log g\) for OM1186 is also typical of much older objects, given that models predict \(\log g \approx 4.5\) at ages \(\sim 20\) Myr, with very small increase in the next evolutionary stages. However, the uncertainties on the determination of this parameter are not small, and the increase of this value during the PMS phase is usually within the errors of the measurements.

5.2. Sources of error in the previous classifications

Both targets have been misplaced on the HRD, but the reasons were different. For OM1186 we have confirmed the SpT available from the literature, but we found different values of \(A_V\) and \(L_{\text{acc}}\) with respect to Da Rio et al. (2010). In their work, they use a color-color \(BVI\) diagram to derive simultaneously \(A_V\) and \(L_{\text{acc}}\), with the assumption of the SpT. To model the excess emission due to accretion, they use a superposition of an optically thick emission, which reproduces the heated photosphere, and of an optically thin emission, which models the infalling accretion flow. From this model spectrum they derive the contribution of accretion to the photometric colors of the targets by mean of synthetic photometry. Their method assumes that on the \(BVI\) diagram the positions of the objects are displaced from the theoretical isochrone due to a combination of extinction and accretion.

5. Discussion

With the results presented in the previous section, we determine new positions for our target on the HRD. This is shown in Fig. 6 with green stars representing the two YSOs analyzed in this study and the other symbols the rest of the ONC population, as in Fig. 1. Their revised positions are compatible with the bulk of the population of the ONC, and their revised mean ages, i.e. \(\sim 2.9\) Myr for OM1186 and \(\sim 2.4\) Myr for OM3125, are typical ages for objects in this region, which mean age has been estimated around 2.2 Myr (Reggiani et al., 2011). We check also that the final results do not depend on the value we have chosen for the reddening law, i.e. \(R_V = 3.1\). With a value of \(R_V = 5.0\) we obtain ages which are systematically younger than the one obtained in our analysis by a factor \(\sim 30\%\) for OM1186 and \(\sim 50\%\) for OM3125. With the newly determined parameters, these objects are clearly not older than the rest of the population, and their status of candidate older PMS is due to an incorrect estimate of the photospheric parameters in the literature. In the following, we will analyze other derived parameters for these objects which confirm the age estimated with the HRD. Then,
With the assumption of the SpT, they can find the combination of parameters \( (A_v, L_{\text{bol}}) \) which best reproduces the positions of each target on the \( BVI \) diagram. With these values, they corrected the I-band photometry for the excess due to accretion, derived using the accretion spectrum model, and for reddening effects. Finally, they derived \( L_c \), from this corrected I-band photometry using a bolometric correction. Using this method, they found a solution for OM1186 with a large value of \( A_v \) and, subsequently, of accretion. Given the large amount of excess due to accretion they derive in the I-band, they underestimated \( L_c \), and assigned an old age to this target. On the other hand, our revised photospheric parameters are compatible with those of Manara et al. (2012). In their analysis, they use the same method as Da Rio et al. (2010), but they have at disposal also \( U \)-band photometric data, and thus used an \( UBI \) color-color diagram. Given that the excess emission due to accretion with respect to the photosphere in the \( U \)-band is much stronger, they were able to determine the accretion properties of the targets more accurately, and to find a unique correct solution.

Regarding OM3125, we derived with our analysis a different SpT with respect to the one usually assumed in the literature (G8-K0; Hillenbrand, 1997). This estimate was obtained using an optical spectrum covering the wavelength region from 300 nm to 900 nm, and their analysis did not consider the contribution of accretion to the observed spectrum. This was assumed not to be a strong contaminant for the photospheric features in this wavelength range. This is a reasonable assumption for objects with low accretion rates, but it has been later shown not to be accurate for stronger accretors (Fischer et al., 2011), as we already pointed out for this target. Hillenbrand (1997) marked this SpT classification as uncertain, and they reported also the previous classification for this object from Cohen & Kuhi (1979), who classified it as being of SpT K6, a value which is in agreement with our finding. This previous classification is obtained using spectra at shorter wavelengths (\( \lambda \sim 420-680 \) nm) with respect to Hillenbrand (1997), and still with no modeling of the accretion contribution. The difference in the classification is most likely due to the fact that some TiO features at \( \lambda \lambda \sim 476, 479 \) nm, which are typical of objects of spectral class late-K, were covered in the spectra of Cohen & Kuhi (1979). Given the large amount of veiling due to accretion that is present in the spectrum of this object, it represents a clear case where the detailed analysis carried out in our work is needed. We conclude that even optical spectra covering large regions of the spectra, like those used in Hillenbrand (1997) and in Cohen & Kuhi (1979), can lead to different, and sometimes incorrect, results if the veiling contribution is not properly modeled.

5.3. Implications of our finding

Accretion veiling, extinction and spectral type are difficult to estimate accurately from limited datasets, especially if mostly based on only few photometric bands. In particular, when classifying young stellar objects the difficulty increases, given that accretion and extinction may modify substantially the observed spectra. For this reason, the use of few photometric bands where accretion, extinction and spectral type effects can be very degenerate (e.g. \( B-I \) band range) or of spectra covering only small wavelength regions (e.g. \( \lambda \sim 500-900 \) nm) can lead to different solutions, which may be incorrect.

With our work we show that an analysis of the whole optical spectrum which includes a detailed modeling of the various components of the observed spectrum leads to an accurate estimate of the stellar parameters. Our work also implies that single objects which deviate from the bulk of the population could be affected by an incorrect estimate of the photospheric parameters especially in cases where the determination is based on few photometric bands. In order to verify their real properties, a thorough analysis like the one we carried out in this work is needed.

When dealing with objects located in regions less affected by extinction effects, e.g. \( \sigma \)-Ori, we expect the amount of misclassified objects to be smaller. Nevertheless, also spectra of single YSOs in these regions can be modified by the presence of anomalous extinction, originated for example by edge-on disks (e.g. Huelamo et al., 2010).

When good quality and intermediate resolution spectra with large wavelength coverage, i.e. from \( \lambda \sim 330 \) nm to \( \lambda \sim 1000 \) nm, are not available, we suggest that a combination of photometric and spectroscopic data in the \( U, B, R, \) and \( I \)-band, i.e. around the Balmer jump and around \( \lambda \sim 700 \) nm, together with spectra in selected wavelength regions where photospheric lines sensitive to \( T_{\text{eff}} \) and/or \( \log g \) are present, can lead to a robust estimate of the stellar parameters of the targets independently of their SpT.

6. Conclusion

We have observed with the ESO/VLT X-Shooter spectrograph two candidate old (age>10Myr) accreting PMS in the ONC in order to confirm previous accretion rate and age estimates. Using a detailed analysis of the observed spectra based on a multicomponent fit, which includes the photospheric emission, the effect of reddening, and the continuum excess due to accretion, we derived revised accretion rates and stellar parameters for the two targets. We confirm that the objects are accretors as from previous studies, but the revised photospheric parameters place these objects in the same location as the bulk of the ONC young stellar population (age~2-3Myr). Therefore, they cannot be considered older PMS, but they are classical accreting YSOs. In particular, we confirmed the previously estimated SpT for OM1186, but we derived different values of \( A_v \) and \( L_{\text{bol}} \) with respect to previous works in the literature, finding that the real position of this object on the HRD leads to a mean age estimate of ~2.9 Myr. On the other hand, we derived a different SpT for OM3125 with respect to the usually assumed value in the literature. This, together with the other parameters, moved this target to a position on the HRD leading to age ~2.4 Myr. The analysis of the lithium abundance confirms this finding, and that of the surface gravity also, even if the uncertainties for the latter are large.

We showed that with our analysis we are able to accurately determine the stellar parameters of YSOs, while the use of few photometric bands or spectra covering small wavelength regions can lead to large errors in the derived position on the HRD. We thus suggest that single objects whose position on the HRD is not compatible with the bulk of the population in their region could be misplaced, especially if there is the suspicion of high optical veiling connected to large values of the accretion rate. The nature of these individual objects will need to be verified using a detailed analysis similar to the one we report in this study, in order to verify the existence and study the properties of long-lived disks around young stellar objects.

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