Massive young stellar objects in high-mass star-forming regions

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Abstract. High-quality K-band spectra of point sources, deeply embedded in massive star-forming regions, have revealed a population of 20 young massive stars showing no photospheric absorption lines, but only emission lines. The K-band spectra exhibit one or more features commonly associated with massive Young Stellar Objects surrounded by circumstellar material: a very red color $(J - K) = 2$, CO bandhead emission, hydrogen emission lines (sometimes doubly peaked), and FeII and/or MgII emission lines. The CO emission comes from a relatively dense ($\sim 10^{10} \text{cm}^{-3}$) and hot ($T \sim 2000$–$5000$ K) region, sufficiently shielded from the intense UV radiation field of the young massive star. Modeling of the CO-first overtone emission shows that the CO gas is located within 5 AU of the star. The hydrogen emission is produced in an ionized medium exposed to UV radiation. The best geometrical configuration is a dense and neutral circumstellar disk causing the CO bandhead emission, and an ionized upper layer where the hydrogen lines are produced. We argue that the circumstellar disk is likely a remnant of the accretion via a circumstellar disk.

Keywords. infrared: stars, stars: formation, early-type, circumstellar matter, pre-main-sequence

1. Introduction

Although over the past decades significant progress has been made in unraveling the formation process of low-mass stars (Shu *et al.*, 1987), it is not well understood how massive stars form. The contraction timescale is short, so that already very early in the formation process massive stars will produce a copious radiation field that may hamper or even reverse the accretion process (e.g. Wolfire & Cassinelli, 1987). These difficulties have led to the suggestion that stars more massive than ~ 10 M$_\odot$ cannot form through (spherical) accretion alone, but instead form by collisions of intermediate-mass stars (Bonnell *et al.*, 1998). Alternatively, non-spherical accretion through a disk could solve the "radiation pressure problem" (Yorke & Sonnhalter, 2002). Therefore, the detection and characterization of circumstellar disks around young massive stars is regarded as an essential step in understanding the formation of the most massive stars. Observational evidence is growing that rotating circumstellar disks are present around high-mass protostars in the hot core phase (Minier *et al.* 1998, Shepherd *et al.* 2001, Beltrán *et al.* 2004, Chini *et al.* 2004).

Already before arriving on the main sequence, the young massive star produces a strong UV radiation field ionizing its surroundings. At this stage the object will become detectable at far-infrared and radio wavelengths through the heated dust and recombina-
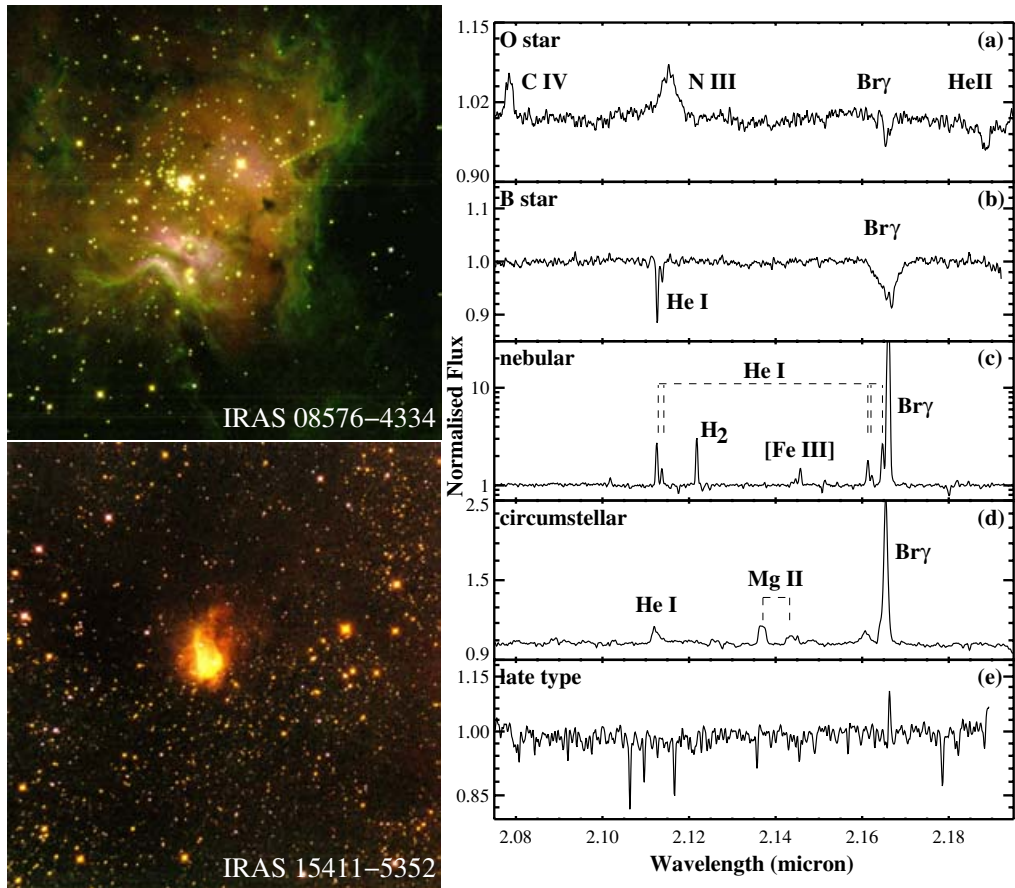
Figure 1. *Left:* Near-infrared images of 2 of the high-mass star-forming regions in our sample. *Right:* Examples of the different types of spectra obtained in our spectroscopic survey. Panels (a) and (b) show the photospheric K-band spectra of O and B stars. Panel (c) shows a spectrum dominated by nebular emission from the UCHII region. The emission lines are narrow and not resolved. This in contrast to the spectrum displayed in panel (d) where the emission lines are resolved. This object shows characteristics of a massive YSO. Panel (e) displays a spectrum of a late type (fore-/background) star.

tion of hydrogen in the expanding hyper- or ultra-compact H II region (e.g. Churchwell, 2002). In the mean time, the same UV radiation field will impact on the extended circumstellar disk and start to destroy it (Hollenbach *et al.* 1994). The disk destruction timescale is so short ($\sim$100,000 yr) that it becomes an observational challenge to detect and measure any remnants of the formation process of massive stars.

The near-infrared is the only wavelength range where the dust obscuration is reduced and the dust emission is not dominant yet. This favours the detection of the photospheric and circumstellar emission of the young massive star. We have carried out an extensive near-infrared survey of fields centered on southern ultra-compact H II regions detected at far-infrared and/or radio wavelengths, with SOFI on the ESO *New Technology Telescope* (Bik, 2004; Kaper *et al.*, 2005). These narrow-band imaging observations have revealed embedded, young stellar clusters ($A_V \sim$ 10–50 magnitudes) containing newly formed massive stars. (left panel of Fig. 1).

High-resolution (R = 10,000) K-band spectroscopy of members of those clusters have been obtained with ISAAC mounted on the VLT. The spectroscopic targets have been selected based on their K-band magnitude and $(J - K)$ color. Spectra have been taken of the brightest and most reddened cluster members. The obtained K-band spectra can be divided in different classes (see right panel of Fig. 1 for an example of the different spectra). Forty objects turn out to be late-type (fore- or background) stars, with K-band spectra dominated by many absorption lines (Fig. 1e). These stars are a natural by-product of our selection criteria. They emit the bulk of their radiation in the (near) infrared and have a red intrinsic color. The other three classes are different types of objects connected with star-forming regions. Thirty-eight objects show the spectral features indicative of OB stars (Fig. 1a,b). These stars are discussed in Bik *et al.* (2005a) . The second type of objects are the near-infrared counterparts of the UCHII regions with nebular K-band spectra (Fig. 1c). We focus on the spectroscopic properties of the third class; 20 objects that differ from normal main-sequence OB stars and exhibit features commonly associated with massive Young Stellar Objects (YSOs).

2. Massive Young Stellar Objects

Based on the K-band spectra of the massive YSOs candidates in our sample we find evidence for the prescence of a circumstellar disk. The massive YSO candidates show emission line spectra and are selected based on the presence of Brγ in their spectrum (Bik *et al.*, 2005b). These objects are the reddest members of their respective clusters. This red color indicates that the object is highly obscured and/or has a strong K-band excess. We cannot easily separate these two contributions as we observed in the J and K-band only. In some cases, however, we were able to determine the intrinsic (J-K) of a neighboring star in the young cluster based on its K-band spectrum, so that we can measure the interstellar extinction in that sight-line. The Brγ full width at half maximum (FWHM) is large (and spectrally resolved), ranging from 100 to 230 km s^{-1}. The large FWHM indicates that the emission has a circumstellar and not a nebular origin. One object shows a double-peaked Brγ profile, with a peak separation of 95 km s^{-1}. Such a profile suggests formation in a rotating disk. The Brγ profile in several other targets displays an asymmetry.

Some objects exhibit an Fe II emission line (2.089 μm), and/or show broad Mg II emission (2.138, 2.144 μm). The Mg II emission is likely produced by the excitation through Lyβ fluorescence. Like the Fe II emission, the Mg II emission lines point to a dense and warm (several 1000 K) circumstellar environment. In a few objects hydrogen Pfund-lines are observed. The Pf-line emission indicates a line forming region of ionized gas with high density ($N_e \sim 10^8 \text{cm}^{-3}$).

2.1. *CO bandheads*

CO first-overtone emission has been detected and analyzed in a number of high- and low-mass stars (e.g. Scoville *et al.*, 1979 and Chandler *et al.*, 1995). Modeling efforts have been hampered by the small number of observed J-lines, or a low resolving power and moderate signal-to-noise.

Of our massive YSO sample, 15 objects are observed in the "CO setting", of which 5 show the CO first-overtone bands in emission (Fig. 2). The shape of the bandhead varies from source to source. The rise of the first bandhead is sharp in the spectrum of 08576nr292 and 11097nr1218 whereas in that of 16164nr3636 and 18006nr766 a blue wing is clearly present. The expected profile from a spherical stellar wind has a flat-topped
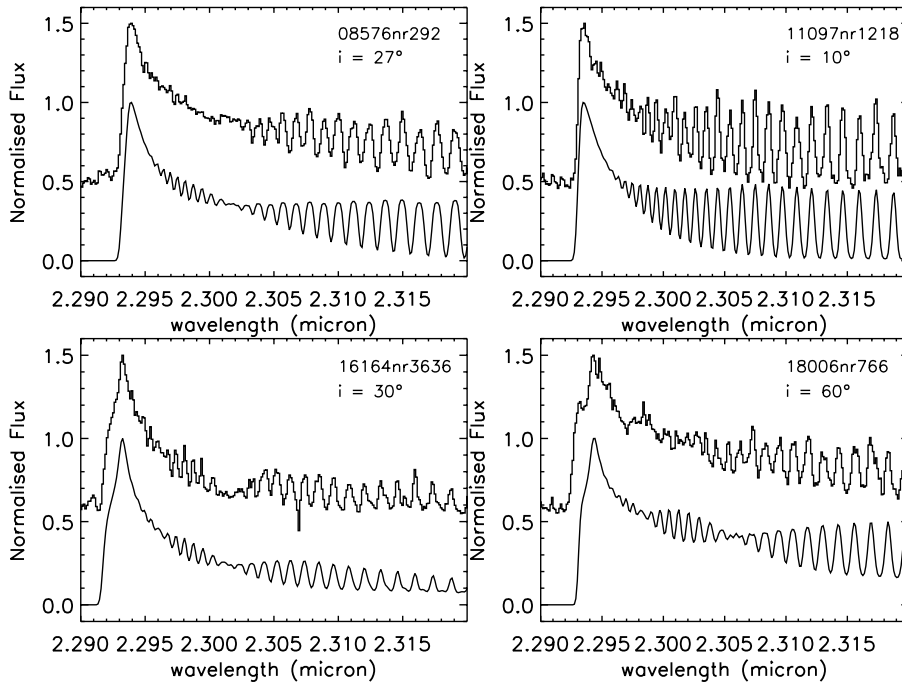
Figure 2. CO first-overtone bands in four objects (upper spectra) shown along with the best-fitting model (lower spectra). The object name and adopted inclination are given.

shape and cannot account for the wing seen in two of the objects. The favored model to explain the blue wing consists of a keplerian disk and/or a disk-wind (Chandler *et al.*, 1995), although the disk model provides the best match.

In Bik & Thi (2004) we explore the possibility that the CO bandhead emission arises from a disk in keplerian rotation around the massive star. Synthetic CO bandhead spectra are generated using a standard parametric disk model for a range of gas temperatures, column densities, turbulent velocities and disk viewing angles. The population of the CO rotational levels within each vibrational level is assumed to be in local thermodynamic equilibrium, with an excitation temperature given by the local vibrational temperature, specific for each bandhead; a temperature gradient within the line-forming region is neglected. Typical column densities derived from the model fitting are 10^{20}–10^{21} cm^{-2} and excitation temperatures are found to be in the range of 1700–4500 K.

The different observed profiles of the CO-bandhead emission can be explained by a difference in inclination angle of the disks. It turns out that the CO is located in the inner disk regions (within 5 AU), very close to the central star (see Bik & Thi, 2004 for more details). The maximum distance at which the CO bandheads are emitted depends on the inclination, which is not a well constrained parameter, but even for a wide range of possible inclinations the hot CO molecules are located within a few AU from the star. Similar results are found by Blum *et al.* (2004) who performed an analysis of a number of massive YSOs located in giant HII regions.

In the absence of extinction by dust grains, the CO molecules should be photodissociated by the stellar ultraviolet photons. However, the derived column densities (10^{20}–10^{21} cm^{-2}) are well above the required value for the CO molecules to self-shield (N(CO) $\sim 10^{15}$ cm^{-2}, van Dishoeck & Black, 1988). Moreover, gas phase chemical models show
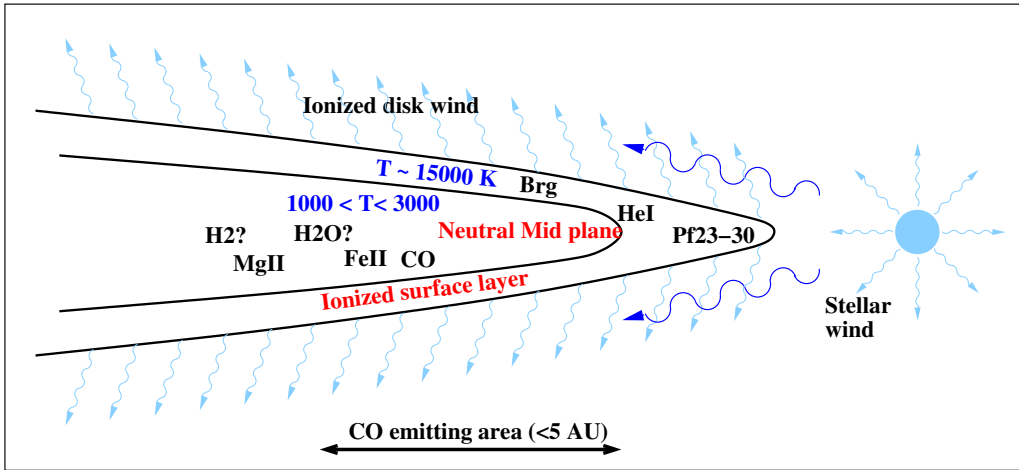
Figure 3. A schematic view of the different line-forming regions in the circumstellar disk surrounding a massive YSO. The CO is located in the dense mid plane of the disk, while the hydrogen lines are emitted by the ionized surface layer and/or disk wind.

that CO molecules can rapidly form in the gas phase to compensate for their destruction (Thi & Bik, 2005).

2.2. *Line-forming regions*

The different emission lines discussed above require different physical conditions to be emitted. The CO first-overtone emission requires the material to be neutral, dense and a temperature of a few thousand K. On the other hand, the hydrogen emission requires ionized material and to emit the Pfund lines a high electron density is required ($N_e \sim 10^8 cm^{-3}$). This means that the different lines are formed at different locations in the circumstellar environment.

The Pfund lines are much broader than Brγ. If the Pf-lines would originate in a keplerian rotating disk, they are likely formed in the high-density inner disk region, while Brγ would be formed over a more extended region of the disk. This would explain the difference between the width Pf-lines and Brγ. Brγ will be dominated by the more slowly rotating outer parts of the disk (larger surface area) and will have a smaller FWHM.

Another possibility is that Brγ is formed in a disk wind. The FWHM of the Brγ lines does not correlate with the width of the CO lines of which modeling shows that these lines are formed in a circumstellar disk. The FWHM of the Brγ lines for the objects with the steep CO bandheads is similar to those of the objects where the CO bandheads are broad. In the disk wind scenario the outflow velocity is higher than the rotation velocity and widths of $\sim$200 km s^{-1}are expected for lines formed in a disk wind (Drew *et al.*, 1998); no correlation between the FWHM of Brγ and disk inclination is expected.

3. The nature of the cirumstellar mater

We have presented several arguments that the emission-line objects contained in our sample are surrounded by a dense, circumstellar disk in keplerian rotation: broad and sometimes double-peaked hydrogen emission lines, Mg II emission, CO first-overtone band emission likely arising from a keplerian disk and a strong near-infrared excess. Fig. 3 gives a schematic view of the disk geometry and the proposed locations of the different line forming regions.

After correction of the interstellar extinction, the location of the massive YSO in the (J-K) vs K color-magnitude diagram suggests that they are of early spectraltype. The majority of the objects have photometric properties similar to the Herbig Be stars, suggesting that those objects are likely B-type stars. Hanson *et al.* (1997) were able to detect the I-band spectrum of some of the massive YSOs in M17 resulting in a B-star classification. They found that the O stars in M17 do not show evidence for circumstellar disks. This is confirmed by observations of massive stars in giant H II regions by Blum *et al.* (1999, 2000, 2001) and Figuerêdo *et al* (2002, 2005). In our sample only a few objects show evidence that the central star is of O spectral type.

The disks around the objects in our sample might be the remnants of the large accretion disks (∼10 000 AU) detected in the millimeter around younger high-mass protostars. Although the near-infrared only probes material upto a few AU of the star, the disks around the objects in our sample are likely much smaller than those around the high-mass proto stars (∼1000 AU). The FUV radiation and the strong stellar wind of the stars start to rapidly disrupt the inner regions and photo-evaporate the outer regions of the circumstellar disk as soon as it has formed (e.g. Hollenbach *et al.*, 2000). The detection of only a few O stars surrounded by circumstellar matter is consistent with these photo-evaporation and disk destruction models as well. The disks around O stars are destroyed much more rapidly than those around B stars. This suggests that the few objects for which the central star is likely an O star are the youngest objects in our sample (few 100,000 years).

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