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The Post-Red Supergiant IRC +10420

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Abstract. In this contribution we review the properties of the post-red supergiant IRC +10420. Its A-type supergiant spectral classification, high wind outflow velocities, strong infrared excess combined with its abundances typical of massive evolved stars strongly indicate that IRC +10420 is a post-Red Supergiant. Indeed, the object can be classed as a genuine evolved "A[e]" supergiant, and as such may provide important clues to the understanding of the B[e] phenomenon. We give an update on the photometric evolution of the star and present new spectropolarimetric data. These imply that the Hα line forming region deviates from spherical symmetry.

1. Intro : IRC +10420 as a Massive Evolved A[e] Supergiant

IRC +10420 occupies a special place at a workshop dedicated to stars with the B[e] phenomenon, and the evolved massive B[e] supergiants in particular. This is because it shows all the characteristics of the B[e] phenomenon as listed by Lamers et al. (1998). As we will discuss below, it has strong Balmer lines, displays many low excitation permitted lines from low ionization metals such as FeII, as well as having the forbidden lines in [FeII] and [OI], while it also has a near-infrared excess due to hot dust. The only thing IRC +10420 does not have, by virtue of being an A-type star, is a B-type spectrum! Yet, that is where IRC +10420 may hold the key in understanding the evolutionary place of the B[e] supergiants as it seems to bear all the hall-marks of a progenitor.

More than 250 papers in the literature cite this object and the majority deals with the far-infrared and millimetre wavelengths tracing the cool dust shell surrounding the star. IRC +10420 is one of the brightest mid-infrared sources around, and it is often a target for new techniques to be applied to. In the following we will discuss the features of the object and then move on to some recent results that we obtained.

The circumstellar dust shell Let us first discuss the circumstellar dust shell. The dust fitting of the spectral energy distribution (SED) by Oudmaijer et al. (1996) and Blöcker et al. (1999) indicate that the mass loss of the object has been enormous. Mass loss rates of order $10^{-4} M_{\odot}\mathrm{yr}^{-1}$ are derived. These

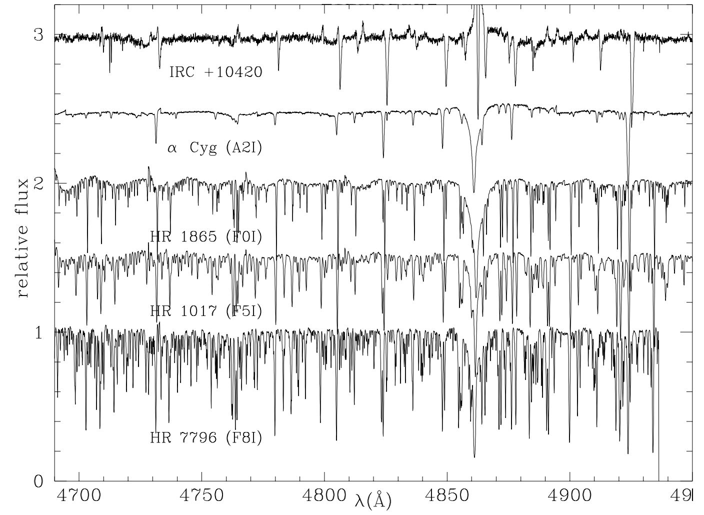

Figure 1. IRC +10420 (*top*), and spectra of a selection of supergiants at high spectral resolution. These data indicate that IRC +10420's spectral type is best described as an early A-type supergiant. The emission lines that can be seen in the spectrum are due to permitted transitions of FeII, TiII and CrII (from Oudmaijer 1998).

models also show that the luminosity of the object is 25,000 $L_{\odot} \times (d/\mathrm{kpc})^2$. As estimates of the distance d to the object average around 3kpc, it is clear we deal with an intrinsically luminous and massive object. The mass loss rates suggest that the object was recently in a cool mass losing, dust forming phase. The high wind outflow velocities found in the CO rotational lines ($40\,\mathrm{km\,s^{-1}}$, much higher than found for the lower mass AGB stars, Oudmaijer et al. 1996) point towards a phase where the surface gravity was fairly low, and it is fair to assume that the object was recently in the Red Supergiant phase of evolution.

Many yellow hypergiants are known (e.g., Lobel et al. 2003) but IRC +10420 is the only one with an infrared excess due to cool dust, and as such it is the only object known to be in this evolutionary phase in the transition to the Wolf-Rayet or Luminous Blue Variable phase (e.g. Jones et al. 1993). For completeness, we mention HD 179821, a G-type star with infrared excess but without an emission line spectrum, which has on occasion been suggested to be in a similar phase of evolution (Jura & Velusamy 2001; Kastner & Weintraub 1995). Other, more exotic evolutionary scenarios may also be possible (e.g. Lamers, these proceedings), but the post-Red Supergiant scenario strikes us as the simplest explanation for the observed properties. In any case, IRC +10420 provides a unique opportunity to study the late stages of evolution of massive stars.

The star's photosphere Spectral classifications have been sparse for this object. Based on the G-band, Humphreys et al. (1973) assigned an F8I$^+$ classification, a spectral type that still often creeps up in listings of this object. A blue spectrum taken in the mid-nineties showed beyond doubt that the spectral

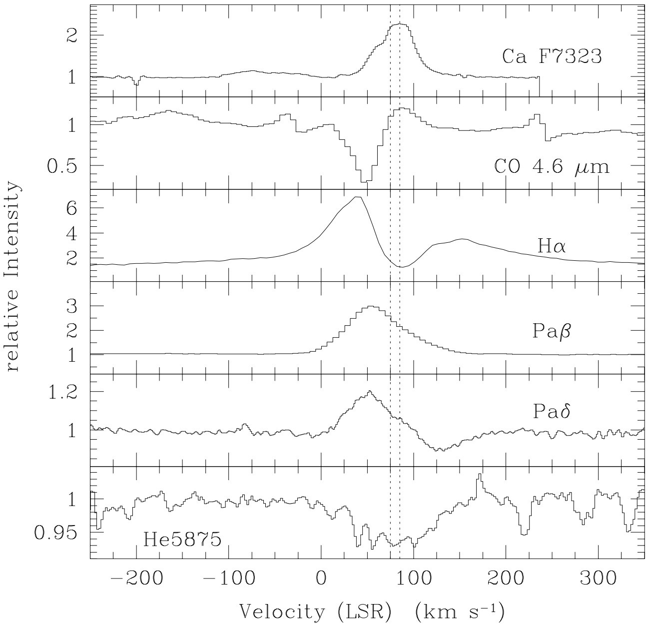

Figure 2. Example of the variety of different line profiles in the spectrum of IRC +10420. Tentatively plotted as originating from the outside inwards from top to bottom, it appears that the CO ro-vibrational line at 4.6μm exhibits a P Cygni line profile, while the Pa lines reveal an inverse P Cygni profile. The dashed lines indicate respectively the systemic velocity and the central dip in the Hα line.

type is early A (see Fig. 1; Oudmaijer 1998). This is confirmed by the abundance study that was performed by Klockkova et al. (1997) using our blue data. They found that the star is 8500 K, implying that the object became hotter by about 1000-2000 K in only 10 years. We are pursuing getting new high quality blue spectra to revisit the star. The N overabundance (Klockkova et al. 1997) provides additional evidence that IRC +10420 is massive and evolved.

The emission lines IRC +10420's spectrum displays many emission lines, often from permitted and forbidden transitions of singly ionized metals such as CaII, FeII etc. The Hα line is several times the continuum, and the spectrum adheres to the criteria laid out by for example Lamers et al. (1998), the star can be truly considered to be an A[e] star.

The interpretation of the geometry of the emission line forming regions, i.e. the inner regions close to the star, has been based on indirect observations, mostly of the Hα line. The results have been ambiguous however. For example, Hα emission has been proposed to be due to rotating disks (Jones et al. 1993), bi-polar flows (Oudmaijer et al. 1994), but also spherically symmetric shells (Humphreys et al. 2002). That these hypotheses are so different has much to do with the large variety of emission lines in the spectrum of IRC +10420. Figure 2 gives a selection of the different line profiles that can be found. The only symmetric absorption line that can be found in our spectrum of IRC +10420 is the HeI 5876 Å line shown in the bottom panel. That this is a credible detection stems from the fact that is has been observed on many occasions, and always at the systemic velocity traced by the CO rotational lines (e.g., Oudmaijer et al. 1996), represented by the leftmost dashed line. The forbidden emission lines as well as the central absorption in the Hα line (indicated by the right hand dashed line) are slightly red-shifted. As an example of the inverse P Cygni lines, Paδ is shown. Many more lines have this profile (Oudmaijer 1998), and the blue-shifted absorption is very persistent, having been present for over more than a decade (starting in Oudmaijer et al. 1994, through to Klockkova et al. 1997; 2002, and the spectra shown in the following section). The CO fundamental ro-vibrational lines at 4.6μm, arising from cool material and of which one example is shown, display bona fide P Cygni profiles.

So, at face value one would interpret the spectral features of IRC +10420 as being due to large scale outflow and infall of material. However, although inverse P Cygni profiles have been observed regularly in the spectra of massive evolved stars, it is always transient. The published interpretations of such features as due to phases of infall of material when the, pulsating, star is in a contracting phase for example (e.g., Wolf & Stahl 1990) leave no room for such an extended period of time.

Oudmaijer (1998) mentioned infall of material as well, but the much larger timespan in which these features are now observed makes the interpretation fraught with more difficulty, but not necessarily impossible. A ten year long period of some sort of infall combined with the notion that we may, perhaps, look at a clearing pseudo-photosphere (Humphreys et al. 2002) could go a long way in explaining the observed spectrum.

2. The Photometry

The photometric evolution of the object has been discussed extensively by Jones et al. (1993) and Oudmaijer et al. (1996). Let us give an update on the long term variability. We have collected some more photometry ourselves (see below), gathered data from the literature and were kindly provided with an epoch of observations by Anatoly Miroshnichenko. The data are plotted in Fig. 3. The K band data show a steady faintening starting in the mid-seventies, and this may be partly explained by the clearing of the expanding dust shell. However, Oudmaijer et al. (1996) found that the K band excess emission had remained constant until then. This is because the faintening is mimicked by the, more sparsely sampled, J band data. As the J band traces the stellar photosphere, the excess at K stayed roughly the same. When we realize that the V band magnitude also remained more or less constant, the best explanation for the photometric changes at J is that they are due to bolometric correction effects associated with an increase in stellar temperature - consistent with the spectra. The data are not conclusive with respect to the more recent years. It could be that the J band has reached a plateau implying a constant temperature, or that it is still gradually faintening, revealing a steady temperature increase of the star.

Optical multi-colour photometry of IRC +10420 is lacking. A problem in the determination of optical colours, especially when dealing with data from

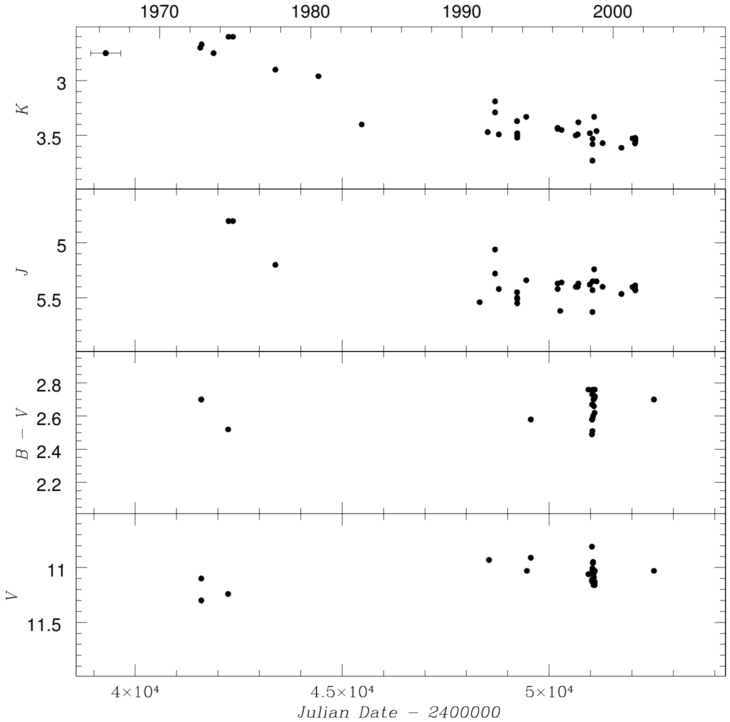

Figure 3. An updated version from the photometric variations presented in Oudmaijer et al. 1996. Especially the change in the *J* band, tracing the stellar photosphere, indicates the temperature increase of the star.

different telescopes, is that the object is extremely red. The use of even slightly different filters will affect the deduced colours significantly (see e.g., Humphreys et al. 1997, on the HST photometry). To circumvent this we have initiated a new programme to obtain spectro-photometric data using carefully selected "standard stars" located in close proximity, within 1.5°, of IRC +10420 itself. By bracketing observations of the target obtained with a wide slit with observations of these standard stars in the same set-up, we are avoiding seeing and airmass effects. Even if the observations are taken during moderately cloudy nights, they should still guarantee fairly precise spectro-photometry which can then be used to fold with filter profiles to obtain equivalent broad-band photometric data. Our initial test observations indicate that accuracies at the per cent level can be reached, some data points resulting from this method are plotted in the graph.

3. Probing the Inner Parts of the Ejecta

HST imaging by Humphreys et al. (1997) reveals evidence for a complex structure with dust condensations located in the equatorial region. An open question, however is whether the larger scale asymmetry is due to the mass lost during the transition, or earlier. Blöcker et al. (1999) performed speckle interferometry on the 6m telescope. Sixty per cent of the *K* band emission was unresolved, while the resolved 40 per cent was best fitted with a ring. The ring's size is consistent

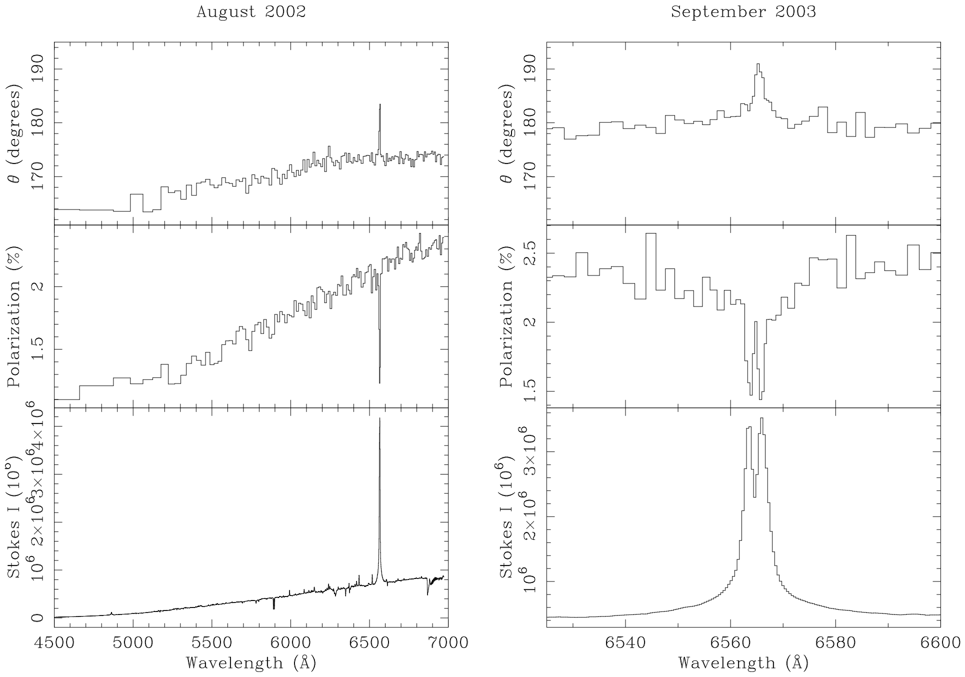

Figure 4. Spectropolarimetry of IRC +1042 at two different epochs. The left hand panel shows low resolution spectral data and cover a wide wavelength range, while the right hand panel shows data taken a year later. At its higher resolution, the line profile is resolved. The lower panel shows the intensity spectrum, the middle panel shows the polarization and the upper panel displays the polarization angle. The data are rebinned to bins containing equal errors in polarization. The 2002 data are rebinned to 0.05%, and the 2003 data are rebinned to 0.1%.

with the SED modelling and the dust condensation radius which is around 30 mas for reasonable stellar parameters. The unresolved source is identified with the stellar photosphere by Blöcker et al. (1999), who estimated it to be around 1 mas in size. This agrees with the observations by Monnier et al. (2004) who, using Keck + IOTA, find an upper limit to the source's diameter of 3 mas.

To learn more about the smaller scales, we have performed spectropolarimetric observations of the object on several occasions, and two of our results are shown in Fig. 4. The 2002 data shown in the left hand panel have a wide wavelength coverage from ∼4500-7000 Å. It can be seen in the middle panel that the polarization steeply increases with wavelength by more than 1% while the polarization angle rotates over 10-15°. This is not what is observed for normal field stars, where interstellar polarization (ISP) due to intervening dust is responsible for most of the observed polarization. In these cases the polarization angle remains constant, and the maximum polarization is found within the wavelength range covered by our data. The peak wavelength gives a typical size scale for the size of the dust grains involved.

The fact that IRC +10420 does not adhere to the ISP picture immediately implies the presence of intrinsic sources of polarization. Obvious candidates are scattering due to dust or electrons, particles which IRC +10420 has abundantly available in its circumstellar material. The increasing polarization towards the red can not be explained by electron-scattering alone, which has a more or less constant magnitude. So, dust scattering will have an increasingly large contribution to the polarization, indicating that the typical grain sizes are larger than in the interstellar medium (cf. Kastner & Weintraub 1995).

We also find a decrease in polarization across the Hα line, which is even clearer in the high resolution 2003 data shown in the right hand panel. This so-called line-effect indicates aspherical material in the electron-scattering region. The continuum radiation from the star will be scattered by the many free electrons in the ionized wind whereas the Hα line photons, originating from further out, will undergo less scattering. In case of a deviation from circular symmetry on the sky, the continuum light will have a net polarization, and the line emission will be less polarized (see e.g., Oudmaijer & Drew 1999; Davies et al. 2005). Additional information provided by such data is that we can work out the intrinsic polarization angle of the scattering material at 22°. This is the same value for both epochs.

We note that the polarization increased by about 0.5% at Hα between the two datasets. As the equivalent width of the emission line also increased by 25% (compare also the Hα profiles in Figs. 2 and 4, the red wing has increased in strength over the last 10 years), it would appear that the wind has become more ionized and therefore that electron scattering contributes more to the total polarization. We are in the process of obtaining more monitoring data to test this hypothesis further - one of the predictions would be that the variability is predominately in one plane (as opposed to Davies et al. these proceedings, who find signatures of clumping in their data of Luminous Blue Variables).

4. Conclusion

We have presented some properties of the post-red supergiant IRC +10420, and show that it can be considered as an evolved A[e] supergiant and similiar to the B[e] supergiants. Although optical photometry does not reveal very strong changes over the past years, the marked change in polarization observed within one year reveals that the ionization conditions close to the star strongly vary. The change in polarization over the Hα profile indicates that the electron-scattering region is aspherical.

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Jon Bjorkman and René Oudmaijer chatting about this and that.