Turbulent Structure in the Upper Chromospheres of Cool Supergiants

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1. Studying α Ori via Other Supergiants

Analyses of stellar photospheres tend to disregard the chromosphere and the impact it has upon photospheric line profiles, save for somewhat resigned statements that computed line profiles never fit observed line cores 'because of chromospheric effects'. However, while the contribution of a chromosphere to the total *flux* may be small, it plays a vital role as the interface between the star and IS space, as it is where the stellar wind originates. Moreover, those outermost layers of a star are expected to be turbulent, so assigning even a 'representative' value to the chromosphere will hardly be realistic. Understanding and modelling what the chromosphere is actually like can provide some of the most valuable information about the way the star is evolving and how it may be discarding mass, and any evidence that can offer information in those directions may have fundamental significance, particularly in the case of a cool supergiant.

The nearest we can get to understanding what the outermost regions of Betelgeuse itself may be like, and how its wind is generated and expelled, is to examine other stars in a similar category. Serious limitations still occur, because the number of cases in which we can directly examine a cool-supergiant chromosphere is limited to just a handful—the eclipsing systems of the ζ Aurigae type. Three ζ Aur systems contain late-K giants of luminosity class Ib or II; all three are bright, and all three have been well studied at different eclipses. All three present strong evidence that a cool-giant chromosphere undergoes substantial changes, on both long and short time-scales.

2. Observing and Analysing Chromospheric Eclipses

A chromospheric eclipse offers a unique and extremely powerful tool for isolating and studying a stellar chromosphere. First recognized in the case of ζ Aur itself some 85 years ago, and observed persistently in many of the eclipses that have occurred since, a chromospheric eclipse provides arguably the most dramatic of spectroscopic phenomena that can be easily observed at visible wavelengths. The typical ζ Aur binary is a detached system containing a late-type (super)giant primary plus a hot dwarf of type B or A; the period is necessarily fairly long—of the order of years; ζ Aur itself has a period of 8/3 years, so only 1 eclipse in 3 occurs at a time of year when the star is well placed for observing. Of the other two bright systems (31 and 32 Cyg), 32 Cyg has a period of just over 3 years, while that of 31 Cyg is 10 years. These eclipses are therefore relatively rare events.

The eclipse of most significance here is the primary one, when the hot secondary (which dominates the UV flux) is occulted by the primary. When it is near to the limb of the giant it shines through the giant's chromosphere; the chromosphere absorbs the secondary's flux selectively, depending on the physical properties of its material in the line of sight, and adds its own absorption lines to the observed spectrum. A cool supergiant's chromosphere can extend well beyond its own radius, which may be some 30 or 40 times that of the dwarf. As a general approximation, the orbiting hot dwarf moves through a projected distance corresponding to its own diameter in one or two days. We can therefore resolve the chromosphere of the supergiant quite finely; observations at nightly intervals sample nearly fresh but contiguous heights in the chromosphere. Series of spectra during ingress and egress reveal if the chromosphere is spherical, has even approximate symmetry, or is a confusion of individual of clouds.

In the visible region, by far the richest feature to monitor for information aout a star's chromosphere is the Ca II K line. Because of the relatively high abundance of Ca and its low I.P., calcium is a dominant constituent of the chromosphere, so chromospheric structure can be traced to a significant height by monitoring the K line. Close to the cool-giant's limb the chromosphere is mainly just an extension of the photosphere, so the K line there is deep and broad; at those phases lines of Fe I and Ti I are also visible as very narrow features. However, if the line of sight to the hot star is more than ∼0.1 of the giant's radius from the giant's limb, the only obvious signature of the chromosphere is the K line, and it is the behaviour of that feature which describes well the conditions in the outermost regions of the chromosphere—and, by extrapolation, possibly in those of α Ori too.

The three stars included in this study reveal evidence of inhomogeneity and motions in the outer chromosphere that are markedly different, not just from star to star but also from eclipse to eclipse in the same system. In 31 Cyg, where the eclipse trajectory is at a latitude of nearly 60^o on the supergiant primary, the outer chromosphere is characterized by large clouds of gas that split, diverge, and move rapidly through the line of sight. In 32 Cyg the picture is interestingly different because the eclipse is grazing, so spectra effectively sample the 'polar plumes'. In ζ Aur the K line in the outer chromosphere also shows evidence of activity, but of a strangely restrained kind. According to SIMBAD all three supergiants have similar spectral classifications: K2 II (31 Cyg), K3 Ib-II (32 Cyg) and K4-5 II (ζ Aur), but the chromospheres which atmospheric eclipses probe do not reflect very much similarity. The advantage of that diversity in the present context is to offer evidence of a broad range of conditions, any or all of which can be relevant to α Ori.

Series of spectra of the K-line region have been observed with the DAO's 1.2-m coudé spectrograph during eclipse ingress and egress of those three systems whenever possible during the past 15 or so years. Selected series of eclipse spectra were shown during the Workshop to help explain the presentation; one of those is reproduced here (Figure 1) by way of illustration; many of the others are to be published in due course. The richness of each series has depended both on allocations of observing time and on the position of the star in the sky at corresponding dates (as well as on the vagaries of the DAO weather). Thus, while it is certainly important to monitor each binary through ingress and egress of the same eclipse event, in practice the most useful sets of ζ Aur spectra were obtained in late August and September, but for egress only. The DAO plate archive contains numerous photographic spectra of past eclipses, though their observers tended to restrict their monitoring to dates near to conjunction, and to be unaware of the astrophysical significance of spectra at phases that are a little more removed.

3. Monitoring a Chromospheric Eclipse

The observed spectra of these binary systems necessarily include the photospheric spectra of both stellar components, with chromospheric features overlaid, and they cannot easily be studied quantitatively in such composite form. However, the spectrum of the respective cool giant can be obtained by observing the system during total eclipse, and when we subtract that from each composite spectrum observed during a chromospheric-eclipse phase we isolate the spectrum of the hot component, together with the features originating in the chromosphere. Since the hot star in each of these three systems is early- or mid-B type it has only a vestigial K line of its own, and is otherwise nearly featureless in the K-line region. Spectrum separation is therefore effective for extracting the chromospheric K line cleanly during ingress or egress.

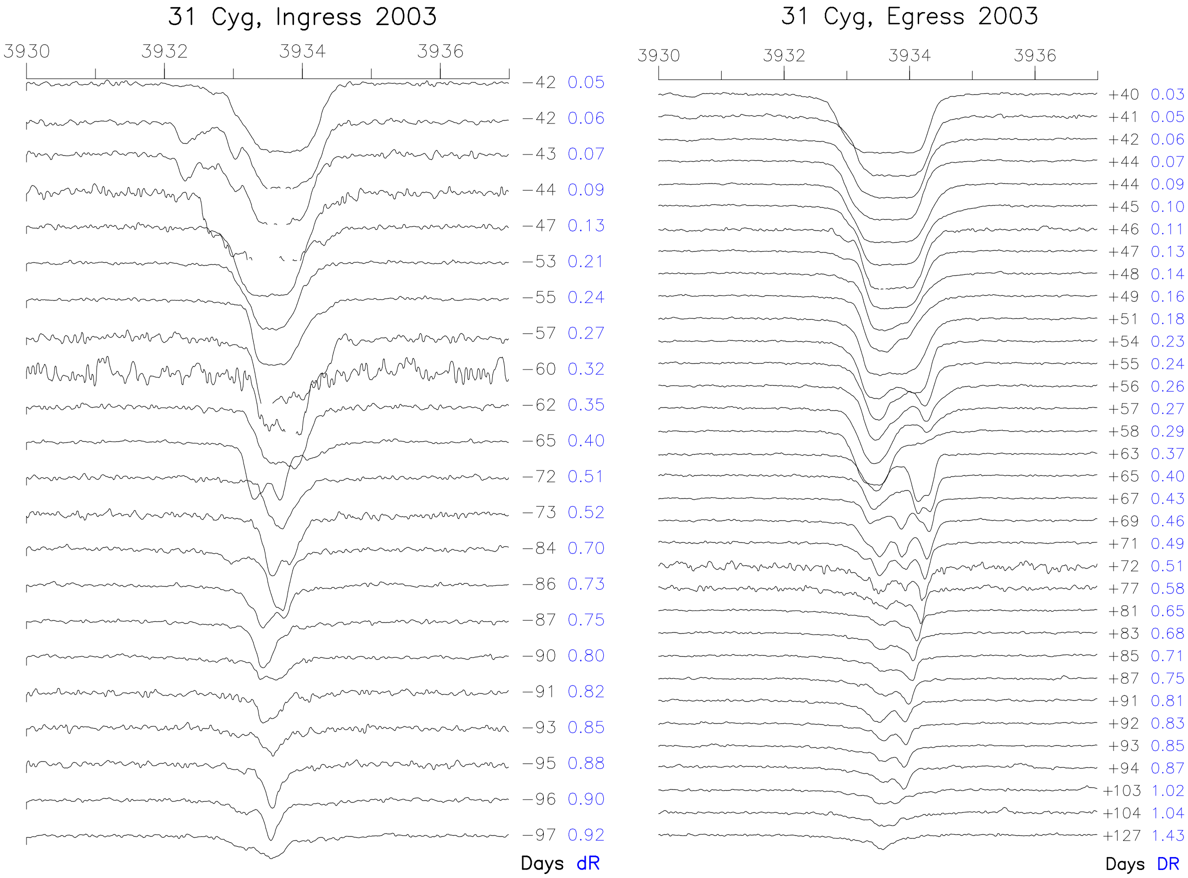

Figure 1: The chromospheric K line in 31 Cyg during ingress (left) and egress (right) of the 2003 eclipse. ‘Days’ measures the interval of each observation from mid-eclipse; dR gives the distance from the supergiant’s limb, as a fraction of the latter’s radius. The direction of time is opposite in the two plots, in order to range the two series at roughly corresponding heights.

(a) 31 Cyg

The period of 31 Cyg is 10.35 years. The latest eclipse (and the first to be monitored at the DAO with CCD spectroscopy) was in 2003; data for all earlier ones are photographic. Rich coverage of the 2003 event revealed interesting differences in the properties of the chromospheric material between ingress and egress: see Figure 1. Most ‘activity’, as measured in terms of the number of independent moving clouds and their respective velocities, seems to have been concentrated at heights between about 0.2 and 0.8 R_1 above the supergiant’s limb, R_1 being the supergiant’s radius. Isolated clouds travelled at velocities of some 30 to 60 $\mathrm{km\,s^{-1}}$ past one another, while an occasional one low in the chromosphere moved at 100 $\mathrm{km\,s^{-1}}$ and another at 45 $\mathrm{km\,s^{-1}}$ (relative to the supergiant), but in ingress only. The fact that the features only persisted for one or two days and then vanished demonstrates that the cloud diameters were not much larger than that of the B star itself. During egress a complex set of clouds was mapped at heights of $\sim$0.4 to 0.5 R_1, the most extreme travelling at a radial velocity of +56 $\mathrm{km\,s^{-1}}$. At greater heights, that same cloud became a more persistent feature, with a velocity that dwindled to $\sim$23 $\mathrm{km\,s^{-1}}$ at a height of $\sim$0.9 R_1. Its relative longevity suggests a cloud with a much larger structure than was seen at smaller heights, and could perhaps represent the top of a fountain of material that was pouring back onto the photosphere. Most of the other clouds encountered showed little systematic behaviour, their velocities ranging at random and their sizes (as suggested by their brief appearances on single or only two adjacent days) often smaller than the B-star radius. The turbulence was not seen at heights much above 1 R_1, at least in the Ca II K line, but that does not imply that it ended there, as the dominant ionization state of Ca may be Ca III where the atmosphere is sufficiently rarefied.

(b) 32 Cyg

The orbital period of 32 Cyg is 3.14 years, so the dates of eclipse slowly migrate round the seasons. Series of spectra were obtained in 2003, 2006, 2009 and 2012. The 2003 and 2006 series showed numerous small clouds, some initially moving with velocities of 100 $\mathrm{km\,s^{-1}}$ or more and traceable through several days as they described fountains, changing from upflows to downflows. The degree of random turbulence and velocity extremes was more marked in 32 Cyg than in 31 Cyg. However, in 2009 the activity was substantially less random, while in 2012 hardly any individual clouds were seen at all, the picture being one of steady, uniform growth and decline throughout both ingress and egress. When the randomness decreased, as in 2009 and 2012, the prime chromospheric feature appeared to be stronger than in previous eclipses. The reason for the change from intense clumpiness to an orderly smoothness may be related to the fact that an eclipse in 32 Cyg is grazing, so the B star samples the material at the pole of the giant star. If the distribution of chromospheric material and its degree of activity is related to magnetic activity, as in the case of the Sun, we might infer that 32 Cyg is currently at 'spot minimum', compared to the raised magnetic activity that it was experiencing in 2003 and 2006. The increased strength of the prime chromospheric component in 32 Cyg would correspond to the smooth sheet-like 'wings' that characterize the solar corona at sunspot minimum, and the mass of smaller individual clouds seen at the two earlier eclipses would correspond to the large number of small streamers seen during sunspot maximum. The challenge now is to obtain other eclipse series (the historic photographic spectra at the DAO are currently being digitized) in order to look for a cyclic variation in the level of chromospheric activity in this system; cyclic changes, if they occur, will contain valuable information regarding magnetic forces on the surface of the supergiant.

(c) ζ Aur

The orbital period of ζ Aur is close to 2.67 years, and eclipses are locked in an 8-year pattern with just a 5.5-day migration round the calendar. One eclipse currently occurs in November, when the star can in principle be monitored well in both ingress and egress but winter observing is also at the mercy of the local weather. The other eclipses currently occur in March and July, so each can only be monitored in either ingress or egress but not both. In consequence, the series of spectra to hand provide excellent cover in some respects but are rather patchy in others. According to its spectral type the primary of ζ Aur is nearest in T_{eff} to α Ori, and only 32 Cyg is suggested (by SIMBAD) as being more luminous than ζ Aur, yet the chromosphere of ζ Aur is much less turbulent than in the other two cases. The hot dwarf is of sufficiently late-B type to have its own K line, though it is only a small feature, and the only evidence of clouds or clumps occurs around heights of $\sim$0.75 to 1 R_1, when the K line sometimes splits into two. The velocity separation between those two K-line components is sufficient to displace the chromospheric line completely from that of the B-star's photosphere, but between 1998 and

2011 (the events monitored with DAO CCD spectra) there has been an almost total lack of any satellite features that were much more displaced in velocity. For practical reasons more series have been observed in egress than in ingress, but so far the splitting of the K line has only been observed in egress, never in ingress. Moreover, the size of the split, in terms of velocity, is curiously regular: the width of the split does not vary—the components do not merge or widen, and as the phases pass one component simply grows or fades. One interpretation is that the chromosphere consists of fountains whose contents rise and fall back in a well-constrained manner, and that there is abundant empty space between them. The fountains themselves will be randomly spaced, or occur at random intervals, and if there is no fountain along the projected eclipse trajectory at the critical moment then a series of eclipse spectra will not record any extra absorption.

4. In Summary

What information can this evidence offer as regards the outer structure and wind of Betelgeuse? It shows that K-supergiant chromospheres can be extremely turbulent, are likely to contain discrete, isolated and possibly randomly moving clouds of material, and that the region of the chromosphere up to about 1 stellar radius above the limb can contain as much empty space as chromospheric material. The chromosphere may be influenced by varying magnetic fields on the stellar surface (as evidenced by cyclical 'spot' formations), and may vary in both density and extent as a result. The picture thus emerging is one of almost infinite possibilities, but it seems likely that the mechanisms for wind generation, which may be inferred from the above evidence in the case of different late-K supergiants, will be present in an M supergiant as well.

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