Imaging Spectroscopy of Betelgeuse in the Ultraviolet

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Abstract:
The bright supergiant Betelgeuse has been imaged in the ultraviolet continuum and with spectroscopic resolution using the Faint Object Camera (FOC) and the Goddard High Resolution Spectrograph (GHRS) on the \textit{Hubble Space Telescope (HST)}. FOC images were obtained on two separate occasions, in March 1995 and October 1996. A single bright unresolved area is found in both sets of observations, although with different position and contrast.

Spatially resolved spectroscopy obtained with the GHRS in March 1995 shows the chromospheric emission in the Mg\textsc{ii} h and k lines reaches a diameter of \(~300\) mas, about twice the size of the ultraviolet continuum images. The signature of the bright spot observed in the March 1995 FOC images occurs in the spectrum as an asymmetry in the intensity measured across the disk at constant wavelength. On the basis of the small number of such hotspots that are present at any one time, and their signature in the Mg\textsc{ii} resonance lines, as observed with the GHRS, we argue that these spots are not the consequence of convective flows as hypothesized by Schwarzschild (1975). Differences in the spatial distribution of the flux between the h and k lines, rather suggest that we are observing a non-spherically symmetric shock wave that propagates radially outward. Because the spectra were obtained scanning across the stellar image, it is possible to determine the axis of rotation of Betelgeuse and estimate its rotational speed. The bright spot in March 1995 appears congruent with the pole of the star suggesting that its angle of inclination is \(~20^\circ\) to the line of sight.

1. Introduction

Because of its large size and relative proximity the red supergiant Betelgeuse (\(\alpha\) Orionis, HD 39801, spectral type M2Iab) has been everyone's favorite object for observational techniques that require large amounts of photons, such as polarimetry and interferometric imaging. Despite the fact that it has, therefore, been frequently observed with these techniques it is surprising that so little about the star's physical properties is known. Undoubtedly, this is due in part to the irregular variability of the star, which makes it difficult and confusing to compare observations obtained at different epochs. In this paper we give a brief overview of existing observations, discuss our recent images and spectroscopic

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observations of Betelgeuse obtained with the Hubble Space Telescope (HST), and attempt to establish a coherent picture.

One uncertainty in the interpretation of α Ori observations has recently been eliminated by the determination of the supergiant’s distance at 131^{+36}_{-23} pc with the European Space Agency’s Hipparcos mission (ESA 1997, see also the Hipparcos homepage^3). Using the canonical value for its diameter in the optical of 50 mas (milliarcsecond), would give the star a radius of approximately 700 solar radii.

2. Observations

Betelgeuse is known to vary in all its observable quantities: visible magnitude, UV flux, radial velocity, and percentage and orientation of polarization. Sometimes these variations (for instance between 1984 and 1988) seem regular with a well-defined period. Dupree et al. (1987) found a period of about 1.15 year close to the expected period of fundamental pulsations of a star of the mass of Betelgeuse (10 M_☉). More recently fluctuations in the UV as measured with the IUE satellite have had much lower amplitude and less well-defined periods, although radial velocity measurements from photospheric metal lines still show considerable variation (see Figure 1).

2.1. Interferometric Techniques and Polarization Measurements

Because of its apparent brightness and large size α Ori is ideally suited for interferometric techniques, which have been employed to measure its diameter and detect surface features. Recent examples of imaging with speckle interferometry are given by Hebden et al. (1986), Christou et al. (1988), and Klückers et al. (1997), and with non-redundant masking techniques by Buscher et al. (1990), Wilson et al. (1992), and Tuthill et al. (1997). Typically, these imaging techniques find evidence for one, two, or sometimes three “hotspots” on the disk of Betelgeuse. These hotspots contribute at most a few tens of percent to the total flux of the star and seem to change on the time-scale of months. They sometimes appear very similar in different wavelengths (see, for instance, Tuthill et al. 1997 who compare images in the 710 nm TiO band and the neighboring continuum at 700 nm in their Figure 5), or they look differently at different wavelengths (see, for instance, the images at 710 and 700 nm in Wilson et al. 1992, Figures 4b and 5c, respectively).

The presence of inhomogeneities in the α Ori atmosphere has also been suggested by polarimetric studies. The integrated stellar light may be polarized by several mechanisms. First, consider the simple case of circumstellar material scattering the light of a homogeneous photosphere. The polarization of the scattered light is parallel to the limb of the stellar disk, and the integrated polarization in this simple case will be zero. However, when there is an inhomogeneity in the photosphere, such as a bright spot, the polarization due to scattering right over the spot will dominate the net polarization which will be non-zero with a polarization vector that is 90 degrees rotated from the position angle of the spot.

Figure 1. Variations in UV continuum and Mg II k line flux (both from IUE), and photospheric velocity over a 13 year period. Notice the clear periodicity in both UV fluxes between 1984 and 1988 and the low amplitude of the flux variations after 1990. An overall decline in flux is also apparent. The radial velocity amplitude seems to remain of similar magnitude throughout the 13 year period (Dupree et al. 1997).

Similarly, there may be an inhomogeneity in the scattering material, with the same result. On the other hand there may be a darker area in the photosphere giving rise to a deficit in the scattered light over that area. This again causes a net polarization vector with an angle 90 degrees off the position angle of the dark spot. As the amount of polarization changes strongly with wavelength, for instance through the TiO band at 710 nm (see Tinbergen et al. 1981; Schwarz & Clarke 1984), it seems unlikely that the scattering that causes α Ori’s net polarization is due to dust. Moreover, Bester et al. (1996) found that the inner
most dust shell, as observed with 11 μm interferometry, lies about 0.1" away from the star.

Hayes (1980, 1981, and 1984) has reported ordered changes in the linear polarization in the $B$-filter band (centered around 440 nm) during four consecutive observing seasons from 1979 to 1983. Although the changes appear ordered over time-scales of several months, it is difficult to distinguish a fixed pattern in the changes of polarization strength and position angle. One thing to remark is that the position angles tend to cluster in the second quadrant of the $U-V$ plane with position angles between 90 and 180 degrees. The largest polarization percentages are found mainly for these angles.

More recently, polarimetric observations of Betelgeuse (Figure 2) have been done with the Wisconsin HPOL polarimeter (see Nordsieck et al. 1994 and the HPOL web page). The highest polarizations (above 0.35%) occur only around a

![Figure 2. Plot of position angle versus polarization percentage in the $R$ and $I$ band measured with the Wisconsin HPOL polarimeter for the period of 1989 through 1994 (Nordsieck et al. 1994).](image)

position angle of 150 degrees, consistent with Hayes' results. This indicates that the strongest inhomogeneities on the stellar surface occur on a line from disk center towards the limb perpendicular to the direction of polarization, i.e., at a position angle of 240 degrees (measured counter-clockwise from North through East) on the sky.
3. **HST Observations**

3.1. **FOC Images**

We have observed α Ori twice now with the FOC, in March 1995 and October 1996. The March 1995 observations are described in detail by Gilliland & Dupree (1996b). Images were obtained in two UV filterbands around 253 and 278 nm. These images show a limb-darkened stellar disk of about 108 mas FWHM and an unresolved bright spot in the South-West quadrangle of the disk (see Figure 3). Fitting the 1995 FOC image in the 253 nm band with a limb darkened disk and Gaussian shaped spot provides the following parameters for the position of the spot: a position angle of 235 degrees and a separation of 16.5 ± 3.4 mas from disk center. The spot in the 278 nm FOC image (see Table 1 in Gilliland & Dupree 1996b), which has a 24% contribution from the MgⅡ resonance lines, has a slightly larger offset of 20 ± 1.1 mas with a disk size of 96 mas.

![Image of FOC image](image.png)

Figure 3. The FOC image in the 253 nm obtained in March 1995 (left panel). The right panel shows the orientation of the star and hotspot as derived from the simultaneously obtained GHRS spectra.

3.2. **GHRS Spectra**

On 3 March 1995 (1100–1500 UT) a total of 56 spectra of α Ori were obtained with the G270M grating of the GHRS (Gilliland & Dupree 1996b). The wavelength range was centered on the MgⅡ h&k resonance doublet at 280.27 and 279.55 nm, respectively. The integration time for each spectrum was 120 s. Although the projection of the GHRS Small Science Aperture on the sky (200 mas across) is of similar dimension as the stellar disk, a certain degree of spatial resolution was achieved by taking spectra at a series of different offset pointings. The pointings were organized in four strips distributed over two perpendicular directions from North-West to South-East, and North-East to South-West (Gilliland & Dupree 1996a). Within each strip the offsets were separated by 27.5 mas. A similar set of observations was obtained for the reference star η UMa in order to calibrate the response of the stepping method to a true point source. For
the sake of brevity we only show results here from the two long central scans crossing the center of the disk in the two perpendicular directions. We checked the repeatability of the scan positions by comparing the spectra at the locations where the strips cross each other. The spectra were essentially identical in each pair of three positions of overlap.

The spectra were corrected for the most important instrumental effects that may influence the apparent positions of the lines. Among these are aperture pulling, geomagnetic image motion, thermal drift, and Doppler shifts due to the spacecraft's proper motion. A full reduction of the spectra of the point-source reference star η UMa indicated that, within an rms of 0.5 km s⁻¹, all artificial wavelength shifts could be accounted for.

Figure 4 shows the composite of spectra along the two central scans in the NW–SE (bottom panel) and NE–SW (top panel) directions, respectively. One immediately notices that the chromosphere extends over at least the whole spatial range in each of the two scans in the Mg II resonance lines. Since the spatial extent in the spectra represents the convolution of the stellar disk with the 200 mas wide small science aperture of the GHRS this means that the chromospheric disk in these strong lines has at least a diameter of 300 mas, approximately six times that in the optical.

Figure 4. Composite of 19 spectra of the spatial scan in the Northwest–Southeast direction (bottom panel) and 19 spectra of the Northeast–Southwest scan (top panel).

Over the whole disk, the h&k lines show a blue–red asymmetry with a dominant red emission peak in the k line, and a dominant blue peak in the h
line. This is not typical for α Ori. The star shows variable asymmetry in the h line and constant asymmetry in the k line. The reversed asymmetry suggests the presence of a velocity gradient with opposite sign in the formation regions spanned by each of the two lines (velocity increasing with radius in the k line, and decreasing in the h-line formation region) during the time of the GHRS observations. The IUE archive shows that the two lines usually have profiles with asymmetries of the same sense, but occasionally the asymmetry of the h line is reversed (see Figure 5).

![Betelgeuse spectra](image)

**Figure 5.** Three high-resolution IUE spectra of the Mg II h&k lines. Notice the reversal of the asymmetry in the h line (at λ280.27 nm) on an 8-month time scale.

The bright spot visible in the FOC images of March 3 1995 is also detected in the GHRS spectra, and it behaves differently at different wavelengths. This is best seen when plotting the intensity versus position across the disk for different wavelength bands. Figure 6 shows the behavior of intensity for wavelengths in the continuum, the Fe II line at 277.55 nm, and the Mg II h&k lines. The bottom left panel in Figure 6 also shows the variation of the intensity for the point-source reference star η UMa (dashed curve). All curves are normalized to a maximum value of one. The intensity profile of the reference star of Figure 6 is essentially the point spread function of the telescope/spectrograph combination (with a FWHM of 38 mas) convolved with the 200 mas boxcar of the GHRS small science aperture. The intensity profiles for α Ori have a much more rounded top indicating that the star is resolved in all four wavelength bands. It is clear that the overall shape changes, when going from the continuum formation height via
Figure 6. The curves show the run of intensity across the stellar disk in four wavelength bands: the continuum (lower right panel), the Fe II line at 277.55 nm (bottom right), and the h (middle right) and k (middle left) lines. Solid curves are for the NW–SE scan and the dotted curves for the NE–SW scan. The upper panels show the central sections of the two middle panels for the h and k line.
the Fe II line to the chromospheric h&k lines, due to the increase in the apparent size of the disk.

The shapes near the top of the curves for the two (NW–SE and NE–SW) scans are different due to the off-center position of the bright spot. The NW–SE scan (solid curves) is symmetrical around the maximum while the NE–SW scan (dotted curves) is clearly skewed towards the SW. This means that the direction of the first scan is perpendicular to the line disk center – bright spot, and that the spot lies in the southwest quadrant of the disk, in agreement with the UV image in the 253 nm filter. The amount of asymmetry in the dotted curves changes with wavelength. In the continuum the asymmetry is largest, while it is almost absent in the curve for the k line. This indicates the spot is larger in the lower regions of the atmosphere and is smaller at progressively higher altitudes. Notice that in the continuum the solid curve of the NW–SE scan is slightly asymmetric towards the left, which means that the spot in the UV continuum is positioned a little towards the NW of the line that goes through disk center and is perpendicular to the scan direction.

We also measured the wavelength offset of two photospheric lines in the spectra displayed in Figure 4. The results for the two scan directions are plotted in Figure 7 in terms of a Doppler shift. If we interpret the observed shift in the lines as being due to rotation then the rotation axis should be parallel to the direction of the NE–SW scan where there is no systematic shift with position. If in addition we interpret the position of the bright spot as being on the pole (see the next section for arguments in favor of the hypothesis) we can determine the inclination \( \theta \) of the rotation axis from the offset of the spot from disk center. In the 253 nm image the offset is 16 mas and the radius of the (limb-darkened) disk is 54 mas, so the inclination \( \theta \) with respect to the line of sight would be approximately 20 degrees in this case. The right hand panel in Figure 3 shows

![Graph](image-url)

**Figure 7.** Rotational velocities measured across the \( \alpha \) Ori disk in the two perpendicular scan directions (see right panel of Figure 3).
the orientation of the star in the sky under these assumptions.

4. Convection or Pulsation?

In an often quoted paper Schwarzschild (1975) investigates the characteristic scale of convective elements in red giants and supergiants. On the basis of typical scales of quantities relevant for solar granulation and supergranulation, and the assumption that convective elements are approximately three times as wide as they are deep, he estimates the physical scale of convection elements in red giants from the size of corresponding physical quantities like the superadiabatic temperature gradient in giant and supergiant envelope models. Schwarzschild’s main conclusion is that only a modest number of convection elements will exist at any one time on the entire surface of the star, a stark contrast with the roughly two million granules on solar surface. For a 15 $M_\odot$ supergiant model he specifically finds that “These data indicate that about 90 such large elements would occupy the surface of a red supergiant.” The small number of these elements would then be able to explain the irregular variations in the magnitudes of giants and supergiants.

In this paper we propose that convection seems an unlikely cause of the single bright spot observed in the March 1995 UV images and GHRS spectra. First of all, the presence of only one single convection element on the visible hemisphere stretches Schwarzschild’s arguments considerably, even allowing for an order of magnitude error in his estimate. Moreover, images obtained with interferometric techniques like non-redundant masking show only one or two bright areas at any one time indicating that our March 1995 observations are not an exception. These interferometric techniques, and variations in visible magnitude indicate that the time scales for changes in the brightness pattern are of the order of a couple of months. Schwarzschild argues that time-scale estimates by Stothers & Leung (1971) who derived characteristic convection times of order 2000 days in supergiants can be shortened to 150 days if elements are considered that do not go all the way to the bottom of the convection zone. However, the presence of only a few elements at any one time would require elements with sizes close to the upper limit, and thus would imply longer time scales than the phenomena we observe exhibit.

Secondly, convective heat transport vanishes at the photosphere where, by definition, the transport of energy is taken over by radiation. In the GHRS spectra we clearly observe the bright spot in the Mg II h line and to a lesser extent in the k line. These lines form at heights in the atmosphere where the continuum optical depth is much less than one, i.e., considerably above the photosphere. It seems unlikely that temperature variations at this altitude in the atmosphere could be induced by convection. One could argue that the brightening might be caused by magnetic field concentrations governed by the convective flow in the same way the magnetic network on the solar surface is shaped by the supergranulation, but there is no further evidence for magnetic fields in the form of X-ray or EUV emission (Basri et al. 1981). Finally, there are episodes where the brightening of $\alpha$ Ori seems to take place with a regular period, which would not be expected if the variations were caused by the stochastic appearance and disappearance of convection elements.
We propose here instead that the bright spots as observed with interferometric techniques, the FOC, and the GHRS are more likely to be shockwaves running through the atmosphere induced by pulsations of the stellar envelope. As argued above in § 3.2. there is evidence that the bright spot we observe in our 1995 FOC images is located on one of the poles of the star. Polarization measurements seem to corroborate this evidence by showing that incidences of high polarization percentage always occur at a position angle close to 150 degrees, consistent with the atmospheric inhomogeneity causing the polarization being in the place where we observed it in March 1995 with HST. A proper hydrodynamic theory to explain the bright spots, therefore, needs to explain why they appear preferentially at the pole.

We propose the following working hypothesis here. The pulsations that occur in the envelope of the star generate shockwaves in its atmosphere. These shockwaves deposit energy in the atmosphere, greatly increasing the density scale height: the atmosphere puffs up (see Bowen 1988). In such an extended atmosphere rotation will induce asymmetry between the poles and the equator where gravity is partially balanced by centrifugal forces and the atmosphere, as a consequence, is even more extended. Due to this asymmetry the shockwaves that run through the atmosphere are more likely to appear first at the poles and be more vigorous there, leading to anisotropic mass ejection (e.g., Asida & Tuchman 1995).

The irregularities in the period of $\alpha$ Ori indicate that different pulsation modes interact in the envelope transferring energy between them. This may lead to non-spherical excitation of shockwaves in the atmosphere, and might explain why bright areas appear in different locations or seem more extended. Even rotation itself might change the fundamental pulsation properties of the envelope to non-radial behavior (Clement 1981).

5. Conclusions

We have observed the supergiant $\alpha$ Ori with the HST FOC and the (now removed) GHRS. In combination with ground-based observations, in particular interferometric imaging and polarimetry, we are now able to sketch a more coherent picture of the star than before. The GHRS spectra obtained in March 1995 show us that the hotspot observed with the FOC in the UV changes properties with height in the atmosphere. Since the intensity enhancement is observed in the MgII h & k lines which form far above the photosphere, it seems unlikely that convective flows are the cause of the atmospheric inhomogeneity. In addition, the number of these hotspots, which also have been reported in interferometric imaging, and the time-scale on which they seem to evolve, are not in agreement with estimates (be they crude) given by Schwarzschild (1975) for such phenomena if they were to be the result of convective motions.

If we, instead, interpret the hotspots as the result of shockwaves traveling through the atmosphere and induced by envelope pulsations we find reason to believe that the March 1995 spot demarcates one of the poles of the star. This would be consistent with the interpretation of the variation of the shift of photospheric lines across the stellar disk to be due to rotation. The axis of rotation would then lie in the NE–SW direction in the sky. The inferred inclination of
the rotation axis would be approximately 20° in this case, the rotational velocity
15 km s⁻¹ (with a projected velocity of \( v \sin(i) = 5 \) km s⁻¹, see Figure 7), and
the period 7 year. This is a fast rotation for a highly evolved star like Betelgeuse
and definitely needs further thought.

We are scheduled to observe \( \alpha \) Ori again with the FOC in September 1997
and with the newly installed Space Telescope Imaging Spectrograph (STIS) in
the beginning of 1998. Hopefully coordinated observations from the ground can
be made for radial velocity, polarization, and interferometric imaging, so that
we have simultaneous observables which can be compared directly.

Discussion

Carole Jordan: This is a comment regarding the Mg II profiles. I believe that
there are a number of blends with other lines causing the odd profiles in cool
supergiants (in addition to wind and interstellar absorption).

Don Luttermoser: To elaborate on Carole’s comment, the Mg II h&k lines in
Betelgeuse and later type giants show overlying absorption from Mn I and Fe I
(from a circumstellar shell) which eats away the blue side of the k-line emission.
Don’t you need to worry about this when discussing the asymmetries between
the k and h lines.

Han Uitenbroek: This is a problem mostly with the low resolution IUE spectra.
In the G HRS spectra the interstellar lines are clearly distinguishable and
asymmetries can be determined independently of them.

Peter Tuthill: I would like to point out that interferometric imaging is sensitive
to spots facing you on the disk (where they are less limb-darkened and foreshort-
ened), whilst polarimetry is sensitive to spots near to the limb. Correlating these
two is therefore difficult.

Han Uitenbroek: This is true. However, if the spot is located midway between
disk center and limb it will still contribute to the polarization and be visible
with imaging, be it with direct techniques or with interferometry. In fact we
have started modeling the polarization at CfA using Monte Carlo techniques.
Our first results indicate that the calculated polarization is less than we expect
on the basis of the observed intensity contrast, so this definitely merits more
attention.

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Imaging of Betelgeuse

ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Rachel Osten seemed to enjoy the posters.
Andrea “crowned” by Lynda Williams.
Our valiant organizers, Sara Yorke and Stephanie Deeley.

Rafael Rebolo and Ramon García–López as the announcement that CS11 will be hosted by Instituto de Astrofísica de Canarias is made.
Lynda Williams (sans Corona).

Speaking of Corona, this beer dates from CS5. Yes, Jeff did drink it.
More scenes from the banquet.
Stellar Coronae: Preparations for $AXAF$ and $XMM$