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# THE SIZE AND SURFACE BRIGHTNESS OF THE CIRCUMSTELLAR GAS SHELL SURROUNDING BETELGEUSE

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## ABSTRACT

We have obtained direct images of the K I gas shell surrounding the M supergiant Betelgeuse using a two-dimensional television system and a 2 Å bandpass filter. The emission extends to at least 50″.

*Subject headings:* stars: circumstellar shells — stars: individual — stars: supergiants

### I. INTRODUCTION

The M supergiants are known to possess extensive gas and dust shells. Expanding gas shells have been inferred through the presence of narrow, blueshifted absorption cores superposed on the stellar photospheric spectrum (Deutsch 1956; Bernat 1977). Difficult to infer, and of major importance, is the location of this gas along the line of sight. Bernat and Lambert (1975, 1976), Lynds, Harvey, and Goldberg (1977), and Bernat *et al.* (1978) directly detected and mapped the presence of K I λ7699 emission from Betelgeuse, M2 Iab. This emission results from resonance-line scattering of stellar photospheric radiation by the neutral potassium atoms in the circumstellar shell. Bernat and Lambert (1976) and Lynds, Harvey, and Goldberg (1977) obtained observations at numerous position angles around the star out to 5″ from disk center; Bernat *et al.* (1978) extended the observations to 29″ with a two-dimensional television detector. In this paper we report direct images of the shell obtained with this television detector and a narrow band filter.

### II. OBSERVATIONS

The detector used to produce the images is a 40 mm S-1 I-SIT vidicon operated at −40°C temperature. The detector performance characteristics are given by Sandford, Gow, and Jekowski (1976), and details of the data reduction procedure can be found in Gow *et al.* (1976).

The α Ori shell is imaged onto the vidicon through the apparatus shown schematically in Figure 1. First, a dichroic beamsplitter deflects the blue light to an eyepiece for guiding. The red light (including K I 7699 Å) passes through a narrow-band interference filter centered at λ7699 before reimaging onto the vidicon. Use of the filter to isolate the emission line is essential to increase the contrast between the shell light and scattered photospheric continuum light. The two-cavity filter has a full width at half-maximum (FWHM) of 2.0 Å when used at normal incidence, and it is necessary to collimate the light to avoid broadening the profile. The filter temperature coefficient is +0.17 Å per degree Celsius, and the collimator-filter assembly is thermostated to within 0.2° C. The filter can be accurately tilted within the collimator assembly, and a combination of temperature and tilt are used to "tune" the filter to accommodate the radial velocity of the star. The filter can also be tilted "off-line" to secure an image of the scattered photospheric light in the stellar continuum adjacent to 7699 Å. These measures of scattered photospheric light (uncontaminated by shell light) are used to correct the scattered plus shell images for the fraction of scattered light, as described in § III. A typical "off-line" image exposed at 7695 Å requires a filter tilt of 4°, which degrades the profile from 2.0 Å FWHM at normal incidence to a 2.3 Å FWHM. The dependencies of the central wavelength and width of the filter on temperature and tilt were

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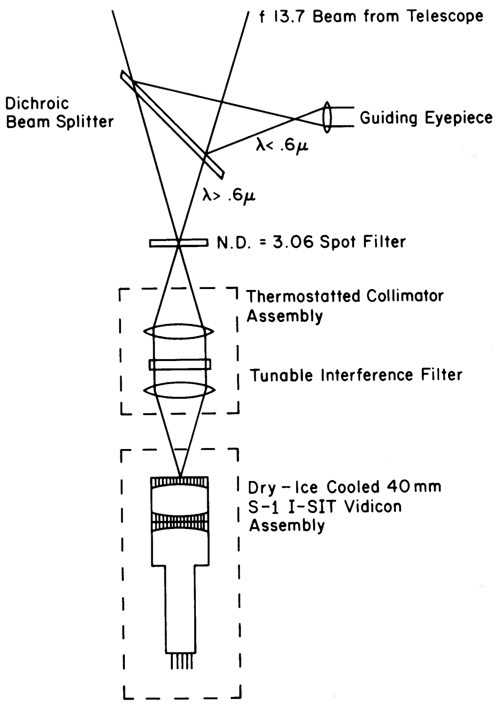


FIG. 1.—The instrumental setup

determined by direct measurement using the coudé scanner of the McDonald 107 inch (2.7 m) telescope, at a resolution of 0.2 Å.In addition, nightly checks were made on the zero point of these calibrations using a potassium hollow-cathode lamp as a source.

Over a 1 Å bandpass at 7699 Å the shell light per arcsec$^2$ is only $10^{-3}$ to $10^{-4}$ times the photospheric light. Since the multiple reflections and scattered light in a two-cavity interference filter are expected to exceed $10^{-3}$, it is necessary to block out most of the photospheric light before it reaches the filter. This is accomplished by placing a "spot" filter in the telescope focal plane consisting of a 3.06 density aluminum spot 2 mm in diameter (14″.5 at the McDonald 82 inch [2.1 m] telescope) deposited on glass. Enough stellar light is transmitted through the spot to obtain a measurement of stellar flux simultaneous with the shell flux exposure. Since the shell light is due to resonance scattering of radiation originating from the photosphere, the quantity of interest is the ratio of shell light to photospheric light. The images therefore contain information (in the same part of the dynamic range of the detector) on both shell and photospheric fluxes—no additional flux calibrations are needed.

## III. DATA REDUCTION

The data used here were obtained at the Cassegrain focus of the McDonald 82 inch reflector in 1977 March. Seven pairs of on-line and off-line images with exposure times from 5 to 15 minutes were retained for use in the final analysis. These 14 images (plus appropriate calibration frames) were digitized onto a 325 × 410 grid at EG&G, Los Alamos Division, and an initial correction for background and flat field (following the procedures outlined in Gow *et al.* 1976) was applied at Los Alamos Scientific Laboratory. These images were then transferred via magnetic tape to Indiana University, where they were subjected to further analysis involving (principally) image registration and correction for scattered light. These reductions were accomplished using the image analysis system of the Astronomy Department at Indiana University, described by Honeycutt, Kephart, and Henden (1979).

The correction for scattered light is made by assuming that the off-line image is a measure of the *shape* of the scattered light component of the on-line image. Apart from the shell contribution, the off-line image is generally brighter than the on-line because it is exposed in a brighter part of the photospheric continuum, largely outside the photospheric K I absorption line. The off-line image is therefore scaled by a multiplicative factor $K < 1$ before being subtracted from the on-line image. $K$ is evaluated by requiring that the central photospheric image transmitted through the spot filter cancel in the net shell image. For those longer exposures where the central image is saturated, we used a fainter ghost image (due to the dichroic beamsplitter) which appears about 30″ south of the primary stellar image. Examples of the on-line and off-line images are shown in Figure 2.

The longer exposures are saturated in the brighter parts of the shell but are better than the shorter exposures at faint levels. Therefore the seven net shell images were averaged into a grand mean image using a weighting function that ensures the "best" part of the dynamic range of each image is used. Because this mean image (shown in Fig. 2) covers a large dynamic range, we have displayed gray scales proportional to the log of the shell intensity. The shell is seen to be rather symmetrical except for increased brightness in the northwest quadrant (Fig. 3). This increase may partially reflect velocity structure in the K I shell emission profiles in the northwest quadrant, as reported by Bernat and Lambert (1976). We find no firm evidence for any other structure in the map of shell intensities.

For a qualitative comparison with previous work and with theoretical models the data were reduced to the "standard" units of the ratio of shell intensity in K I 7699 over 1 arcsec$^2$ to the photospheric flux over 1 Å centered at K I λ7699. After taking into account the filter width and the pixel size, the run of shell intensity with radial distance from the star was computed and is shown in Figure 4 along with a comparison to our previous work. We have chosen not to plot the earlier Bernat and Lambert (1976) data as their observations were obtained with a slit spectrograph and were essentially uncorrected for seeing.

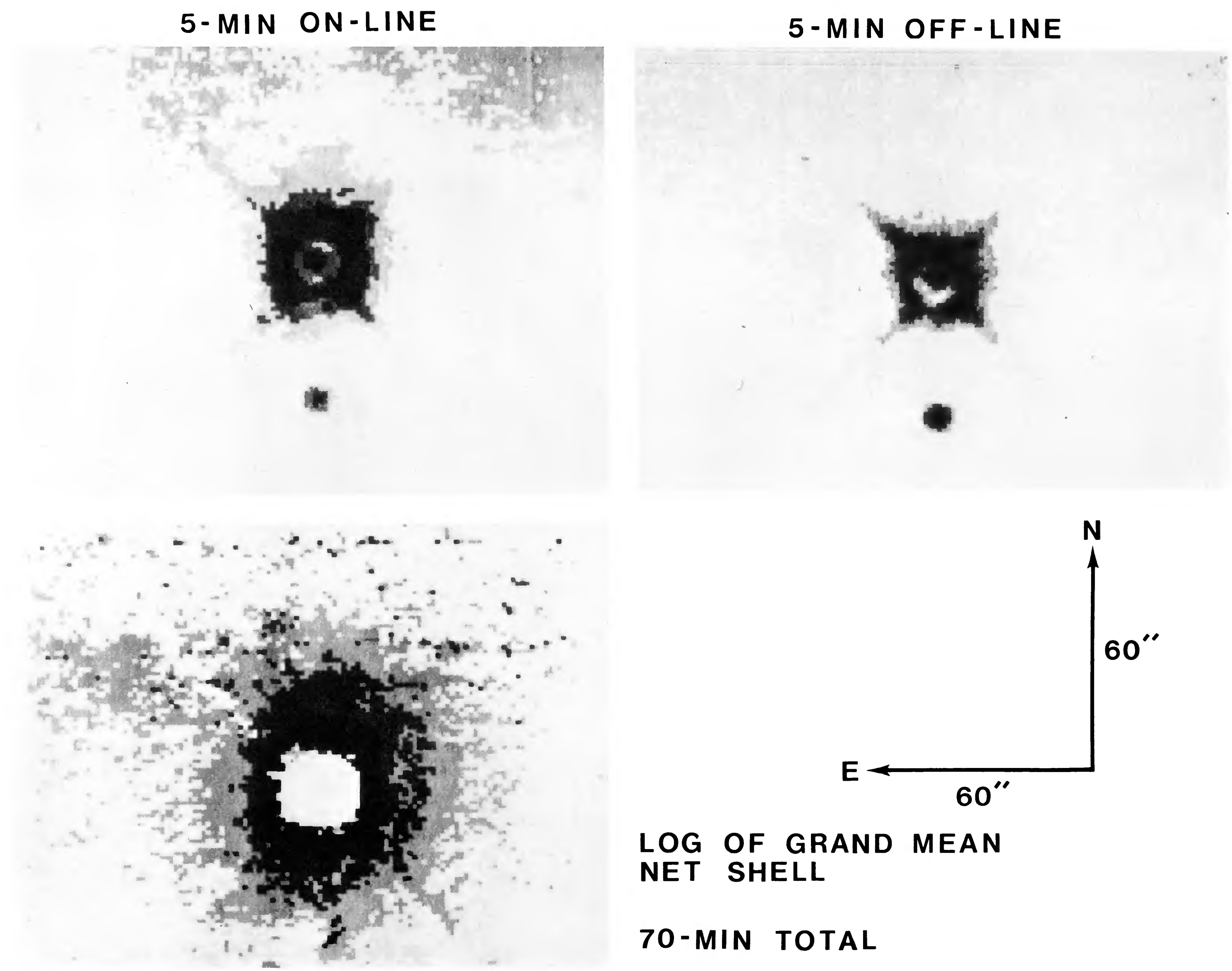


FIG. 2.—Top two images are examples of short exposure on-line and off-line raw data. The object just south of center is a secondary image of α Ori due to the beamsplitter. The grand mean image incorporates seven pairs of on-line and off-line exposures; the gray scales in the mean image are proportional to the logarithm of the net shell intensity. The "feature" in the northeast quadrant is a ghost image of instrumental origin, and some residual noncancellation of the diffraction spikes is also apparent.

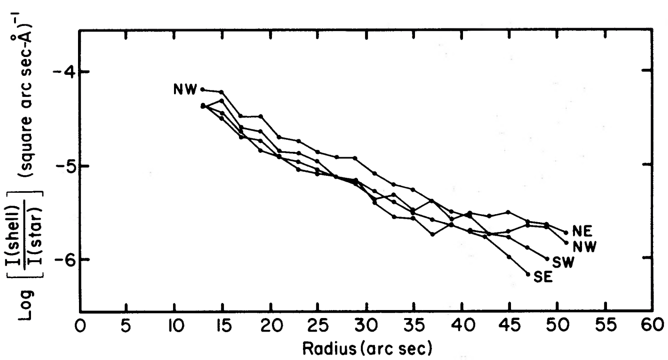


FIG. 3.—Resultant shell intensities as a function of quadrant

## IV. DISCUSSION

We have now directly detected the gas shell surrounding Betelgeuse out to a radius of 50″. At a stellar distance of 190 pc (Weymann 1962), this corresponds to a radius of 9500 AU or 55 light-days. At a constant expansion velocity of 10 km/s (Weymann 1962), the outermost potassium observed would have been ejected 4500 years ago.

Our observations confirm the results of Bernat and Lambert (1976)—the northwest quadrant of the shell shows more intense K I emission. This might be due to either an asymmetrical mass ejection (hence denser shell) or an asymmetrical stellar surface intensity (hence more K I photons to be scattered).

The best (in the $\chi^2$ sense) power law fit to our data gives

$$\frac{I(\text{shell})}{I(\text{star})} = \frac{0.044(+0.020,\ -0.024)}{\phi^{2.65(\pm 0.20)}}, \qquad (1)$$

where $\phi$ is the radius in arc seconds and the 1 $\sigma$ errors are determined following Avni (1976). $I$(shell) is per arcsec$^2$, and $I$(star) is per steradian.

For a static, spherically symmetric shell, power law density, and single scatterings we find by integrating along a line of sight through the shell (Bernat 1976)

$$\frac{I(\text{shell})}{I(\text{star})} = \frac{\tau_0}{4\pi}\left(\beta\frac{r_0}{r_*}\right)^{\theta-1}\int_{-\infty}^{\infty}\frac{dy}{(\phi^2+y^2)^{(\theta+2)/2}}, \qquad (2)$$

where $\tau_0$ is the optical depth of the shell along the line of sight to the star, $\beta$ is the stellar angular radius (0″.025), $r_0$ is the inner radius of the shell, $r_*$ is the stellar radius, and $\theta$ is the power law fit to the density, i.e.,

$$n = n_0(r_0/r)^\theta .$$

Evaluating the integral in equation (2) for any specific value of $\theta$, we find that the $\phi$ dependence of shell

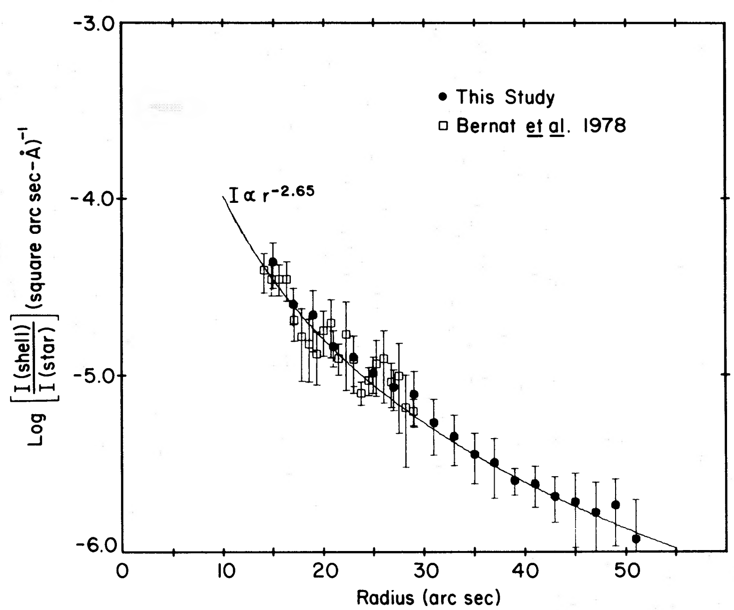


FIG. 4.—Angle averaged shell intensities compared with our previous work. The solid line gives the least squares fit of a power law to all of the data.

brightness is

$$\frac{I(\text{shell})}{I(\text{star})} \propto \frac{1}{\phi^{\theta+1}} .$$

Thus equation (1) implies $\theta = 1.65 \pm 0.20$. Integrating equation (2) for this value of $\theta$ leads to

$$\frac{r_0}{r_*} = \frac{1}{\beta}\left[\frac{4\pi}{\tau_0}\frac{0.044}{1.69}\right]^{1/0.65} . \tag{3}$$

Betelgeuse displays two shell components: S1 for which $\tau_0$ (K I 7699) = 4.5 and $V_{\text{expansion}} = 11 \text{ km s}^{-1}$, and S2 for which $\tau_0 = 0.56$ and $V_{\text{expansion}} = 17 \text{ km s}^{-1}$ (Goldberg *et al.* 1975; Bernat 1976). The weaker shell S2 is considerably cooler, hence is formed at larger radii (Bernat *et al.* 1979). It is unclear which of these shells (or combination thereof) our present observations relate to. The alternate choices lead to

$$r_0/r_* = 0.72 \pm 0.64 \quad (\text{S1})$$
$$= 17 \pm 15 \quad (\text{S2}) .$$

The S1 result is consistent, to within the error, with the stellar radius; both values are in disagreement with $r_0 \gtrsim 50\, r_*$ as derived from the Ca II infrared triplet lines (Bernat and Lambert 1975; see also Goldberg 1979). The implication is that the simple picture of smooth flows and ionization equilibrium is far from accurate. Study of the region closer to the star (speckle?) should be fruitful.

Derivation of a mass loss rate requires, in addition to $r_0$, a large correction for ionization (K I is a very minor species). Since $r_0$ and fractional ionization are both still uncertain, we will not burden the literature with yet another highly uncertain mass loss rate.

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