The structure and temperature of Betelgeuse's extended atmosphere

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The highly extended atmospheres of evolved M supergiant stars such as Betelgeuse have complex properties which are not clearly understood, nor are the processes responsible for elevating their atmospheres to form massive cool outflows. Alfvén waves[1–4], acoustic waves[1,2,5–7], and radial pulsations[8] are regarded as likely driving mechanisms, which act by strongly heating the atmosphere at low heights and transferring wave momentum. Observations with the Hubble Space Telescope indeed show Betelgeuse's atmosphere to be heated to chromospheric temperatures out to a radius of at least $\sim 6R_*$ (ref. 9) (the photospheric radius $R_* \approx 22.5$ mas; ref. 10), with an inferred temperature of $\sim$5000 K at $\sim 3R_*$ (ref. 11). Here we present a radio image of Betelgeuse's atmosphere at a radius of $\sim 2R_*$, and report direct temperature measurements of its atmosphere from 2–$7R_*$. The stellar atmosphere at $\sim 2R_*$ has an irregular structure and a temperature of just 3450 ± 850 K (consistent with the stellar photospheric temperature of $\sim$3600 K), decreasing steadily to 1370 ± 330 K at $\sim 7R_*$. This previously unknown cool gas therefore spans the same height range as the hot chromospheric gas, but to dominate the stellar radio emission must be much more abundant. Our results are consistent with the idea that large convection cells distributed inhomogeneously over the stellar surface elevate photospheric gas into the atmosphere. Radiation pressure on dust grains condensed from the dense cool gas may then drive Betelgeuse's outflow.

We observed Betelgeuse for 11 hrs on 21 December 1996 with the Very Large Array (VLA) in its highest-resolution (A) configuration. At 7 mm, the angular resolution achieved is sufficient to have resolved Betelguese's optical disk, which subtends the largest angular diameter of any star visible in the night sky from the northern hemisphere. Because Betelguese's radio emission is purely thermal and optically thick (as demonstrated below), such spatially resolved radio observations also act as a pure thermometer of the stellar atmosphere. This is in contrast to observations in the ultraviolet continuum or optical and ultraviolet spectral lines, where the gas temperature is derived by comparison with theoretical model atmospheres. The VLA is presently equipped with 7 mm receivers on 13 of its 27 antennas. We used the remaining 14 antennas to observe at the longer wavelengths of 1.3, 2, 3.6, and 6 cm, where we found Betelgeuse to be partially resolved. Fig. 1 shows the final image obtained at 7 mm. Betelgeuse's atmosphere becomes opaque at very different heights when observed at different wavelengths, and at 7 mm the average diameter is approximately twice that measured in the optical. The radio surface is clearly not spherically symmetric, nor does it appear to be axially symmetric.

To quantify the total flux and area of the 7 mm surface and hence its brightness temperature, we fitted circular and elliptical disks to the measured visibilities. The best fit was provided by a uniformly-bright ellipse with dimensions of 95 ± 2 mas $\times$ 80 ± 2 mas at a position angle of $67° \pm 7°$ (measured east from north), and a total flux density of 28.0 ± 5.6 mJy; the uncertainty in the flux measurement is dominated by the uncertainty in the absolute flux calibration of the VLA at 7 mm, estimated to be $\pm 20\%$. Although this model ellipse does not provide a perfect fit to the observed disk structure, the residuals are small and approximately cancel in flux indicating that the total flux and area of the fitted ellipse nevertheless closely match that of the observed stellar radio disk. The implied brightness temperature is 3450 ± 850 K (the uncertainty here, dominated by the uncertainty in the absolute flux calibration, represents extreme limits; elsewhere the quoted uncertainty refers to $\pm 1\sigma$), consistent with the stellar photospheric temperature of $\sim$3600 K (ref. 10). At the longer radio wavelengths where Betelgeuse's atmosphere appears increasingly larger while our angular resolution becomes progressively poorer, we derived just the average diameter and total flux density of the stellar radio disk by fitting uniformly bright circular disks to the measured visibilities at each wavelength. The increase in size with radio wavelength implies that the observed radio surfaces are optically thick, and hence have brightness temperatures reflecting the local gas temperature. In Fig. 2 we plot the measured brightness temperature of Betelgeuse's atmosphere as a function of stellar radius. The temperature of the atmosphere can be seen to decrease steadily with increasing radius from 3450 ± 850 K at $\sim 2R_*$ to 1370 ± 330 K at $\sim 7R_*$.

Our results are at odds with current theoretical and empirical models for the structure and temperature of Betelgeuse's atmosphere. Theoretical models which invoke the dissipation of Alfv́en waves[1–4], shocks produced by acoustic waves[1,2,5–7], or shocks produced by radial pulsations[8] to elevate the stellar atmosphere all predict a globally spherically-symmetric structure, contrary to that actually observed. Empirical models constructed to fit previous ultraviolet and radio data predict a spatially extended hot chromosphere[12,13], consistent with the idea that strong heating at low heights elevates the stellar atmosphere. The ultraviolet image of Betelgeuse taken with the HST clearly shows its chromosphere to have a diameter of 125 ± 5 mas in the continuum at 2550Å, which is inferred to be formed at a temperature of $\sim$5000 K (ref. 11). Our radio measurements, however, show that the hot chromospheric gas is not the only component at this height in Betelgeuse's atmosphere. The 2550Å height is above that which we probed at 7 mm, but is almost identical to that probed at 1.3 cm (diameter of 114 ± 4 mas). The temperature measured at 1.3 cm, however, is only 3180 ± 350 K, formally below the photospheric temperature. From scans of the ultraviolet disk with the HST, the chromosphere observed in the Mg II h and k emission lines is inferred to extend to an even larger diameter of at least 270 mas (ref. 9). This surface is roughly comparable in diameter to that which we and others[13] have probed at 6 cm (diameter of 310 ± 30 mas), but here the temperature measured in radio is just 1370 ± 330 K. An earlier speckle image of Betelgeuse's chromosphere observed in the Hα absorption line, which should be formed at a slightly higher temperature than the 2550Å continuum, showed a diameter of $\sim$95 mas (ref. 14). This is comparable in diameter to our 7 mm measurement, but again the temperature measured in radio is much lower than is required for Hα absorption. Clearly, there are significant differences over the same height range between the temperature of the atmosphere inferred from optical and ultraviolet observations and the temperature directly measured in our radio observations.

We therefore conclude that the relatively cool gas responsible for the observed stellar radio emission spans the same height range as the hotter gas responsible for the optical and ultraviolet chromospheric signatures. To determine the conditions under which the cooler gas component can dominate the observed radio emission, we refer to the recent work by Reid & Menten[15] who studied the radio opacity of late-type giant star atmospheres. They showed that the radio opacity of gas significantly below 4000 K is provided by the interactions of electrons, obtained predominantly from elements with low ionization potentials such as potassium and sodium, with neutral atomic and molecular hydrogen. At temperatures above 4000 K, corresponding to that of the hot chromospheric gas, scattering of electrons by protons (i.e., ionized hydrogen atoms) provides the dominant source of radio opacity. Since the electron-neutral absorption per neutral particle is a factor of about 10^3 smaller than the electron-ion free-free absorption per ion, the preferential detection of the cooler gas component in our radio observations implies that it must be more than 3 orders of magnitude more abundant than the chromospheric gas. Under these circumstances, it seems unlikely that the diffuse chromospheric gas plays an important role in elevating Betelgeuse's atmosphere.

Instead, the irregular structure and predominantly low temperatures of Betelgeuse's atmosphere suggest the following alternative mechanisms for elevating its atmosphere and driving its mass outflow. Over 20 years ago, Schwarzschild[16] proposed that late-type giant and supergiant stars possess very large convection cells, a few of which may be present on the stellar surface at any one time. The existence of such large convection cells has since gained wide acceptance in order to explain the polarized optical light commonly seen from these stars (ref. 17 and references therein), as well as photospheric bright spots seen on the few red supergiants imaged[18−21], most notably Betelgeuse. Optical images of Betelgeuse show that the morphology of its photosphere changes with time, but at any given time can be well fit by the superposition of one or more bright spots (which are not always required) on a circular stellar disk[18−21]. The HST ultraviolet image of Betelgeuse's atmosphere also appears to show a bright spot superposed on a circular disk[11]. Such large convection cells could elevate photospheric material into the stellar atmosphere[16,21] and, if distributed inhomogeneously over the stellar surface, produce an asymmetric atmospheric structure. The elevation of photospheric material into the stellar atmosphere naturally explains our measurements of photospheric-like temperatures at small stellar radii, while the smooth decrease in temperature with increasing radius may represent expansion and cooling of the elevated material. Radiation pressure on dust grains condensed from the dense cool gas could then drive Betelgeuse's massive outflow. This mechanism has long been postulated for driving the massive cool outflows of late-type giant and supergiant stars[22], but faces severe difficulties if an extended inner region of the stellar atmosphere is entirely heated to chromospheric temperatures. Dust grains would then be required to form at relatively large stellar radii, where the gas density may in fact be too low for dust to condense effectively, or where radiation pressure may not be sufficiently intense to drive a massive outflow even if dust formation is possible. These problems are alleviated on Betelgeuse by the presence of dense cool gas in its inner atmosphere; indeed, dust has been detected to form episodically at radii as small as $\sim 4R_*$ (ref. 23). Finally, the vigorous expulsion of gas into Betelgeuse's atmosphere would be expected to produce shock waves[21], which could heat localized but spatially distributed (and therefore extended) regions of its atmosphere to chromospheric temperatures.

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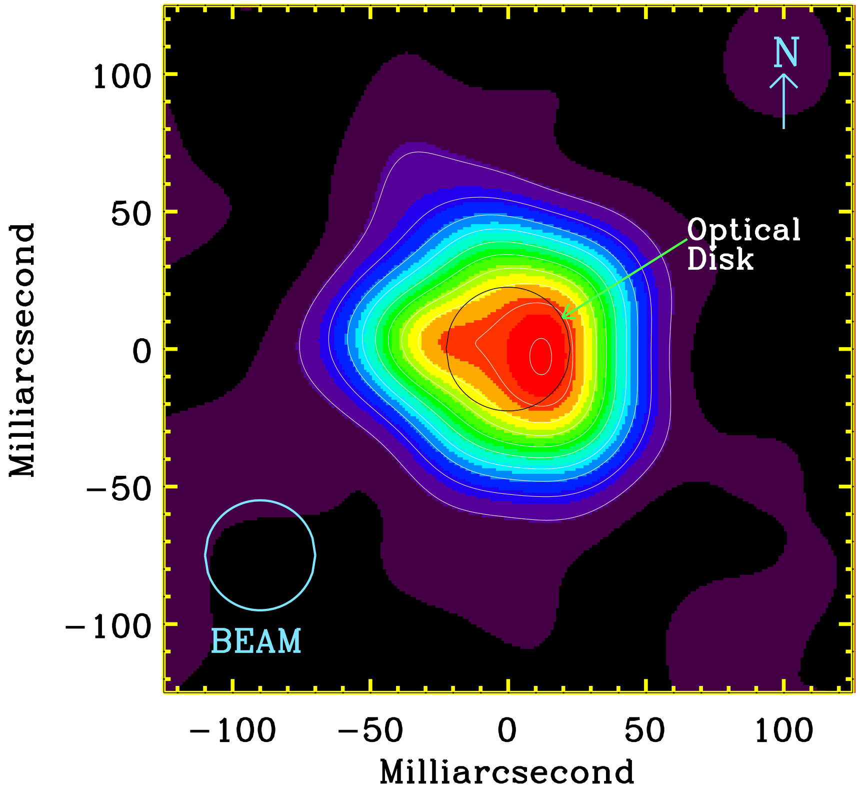

Figure 1: An image of Betelgeuse's atmosphere observed at 7 mm with the VLA with an angular resolution of 40 mas (blue circle at bottom left corner). White contour lines are plotted at 10%, 20%, ..., 90%, and 99% of the peak flux of the false-colour radio image. Betelgeuse's 7 mm surface has an average diameter approximately twice as large as its optical surface of diameter 45 mas (black circle with its center placed coincident with the intensity-weighted center of the radio disk), and is clearly not spherically symmetric. To make this image, we removed fast tropospheric phase fluctuations using a newly-implemented "fast–switching" observing mode[24] at the VLA which allowed us to observe a nearby calibrator frequently without losing too much observing time. We therefore switched between Betelgeuse and an unresolved extragalactic object, 05528+03135 (used as our calibrator), located 4°.2 away, with a cycle time of only ∼2.5 mins. To check the effectiveness of the amplitude and phase corrections, we also switched between 05528+03135 and another unresolved extragalactic object, 05326+07327 (used as our control source), located 5°.3 away, at two intervals during the observation with the same cycle time; this yielded an unresolved image for the control source. We set the flux density scale using the primary flux calibrator 3C286. The final image includes a single iteration in phase self-calibration to correct for small residual phase errors: this self-calibrated image has a ∼60% lower noise fluctuation level than the original image (consistent with the overall system noise), but is morphologically identical. Also, the final image was constructed using natural weighting of the visibilities but restored with a synthesized beam of size corresponding to that obtained using uniform weighting. The uniform weighted image is identical except for a slightly (35%) higher noise level, demonstrating the robustness of our conservative implementation of the super-resolution technique.

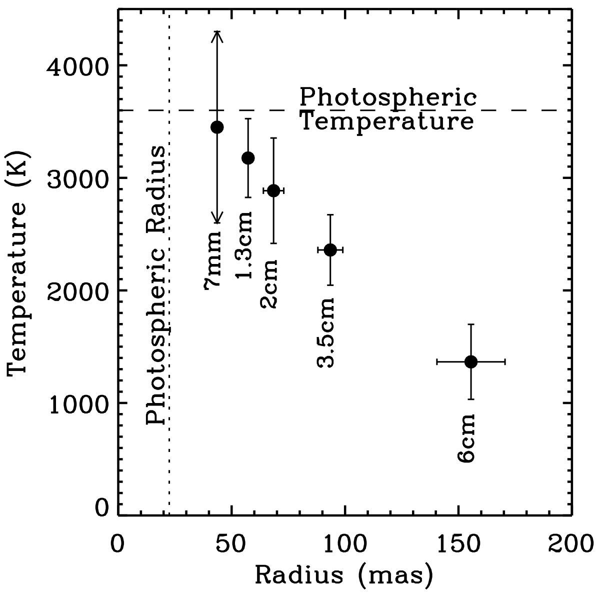

Figure 2: The temperature profile of Betelgeuse's atmosphere measured at the radio wavelengths indicated below each point. All the points have $\pm 1\sigma$ error bars, except for the 7 mm data point where the error bar with arrows indicate extreme limits (see text). The photospheric radius of 22.5 mas is indicated by a dotted line, and the photospheric temperature of 3600 K indicated by a dashed line. The stellar radius at 7 mm corresponds to the average radius measured in the spatially-resolved image of Fig. 1. At the longer radio wavelengths, we derived the stellar radius by fitting a uniformly-bright circular disk to the measured visibilities at each wavelength. The brightness temperature at each wavelength was calculated using the equation $T_b = 2.0\ S_{mJy}\ (\lambda_{cm})^2/(\theta_{maj}\theta_{min})$ K, where S_{mJy} is the total flux density, λ_{cm} the observing wavelength, and θ_{maj} and θ_{min} the major and minor axes of the stellar radio disk, respectively, in arcseconds. Note that the derived brightness temperature is independent of any assumptions such as the distance to the star.