Letter to the Editor

The inhomogeneous submillimeter atmosphere of Betelgeuse

E. O’Gorman, P. Kervella, G. M. Harper, A. M. S. Richards, L. Decin, M. Montargès, and I. McDonald

1. Introduction

The mechanisms responsible for driving the relatively large mass-loss rates ($\dot{M} \sim 10^{-7} - 10^{-6} M_\odot \, yr^{-1}$) of red supergiants (RSGs) remain poorly understood. So too is the subsequent role these mechanisms play in driving the large mass-loss rates of these stars. Here we present ALMA long baseline observations of the free-free emission in the extended atmosphere of the M2 spectral-type supergiant Betelgeuse. The spatial resolution of 14 mas exclusively resolves the atmosphere, revealing it to have a mean temperature of 2760 K at $\sim 1.3 \, R_\star$, which is below both the photospheric effective temperature ($T_\text{eff} = 3690$ K) and the temperatures at $\sim 2 \, R_\star$. This is unambiguous proof for the existence of an inversion of the mean temperature in the atmosphere of a red supergiant. The emission is clearly not spherically symmetric with two notable deviations from a uniform disk detected in both the images and visibilities. The most prominent asymmetry is located in the north-east quadrant of the disk and is spatially resolved showing it to be highly elongated with an axis-ratio of 2.4 and occupying $\sim 3\%$ of the disk projected area. Its temperature is approximately 1000 K above the measured mean temperature at 1.3 $R_\star$. The other main asymmetry is located on the disk limb almost due east of the disk center and occupies $\sim 3\%$ of the disk projected area. Both emission asymmetries are clear evidence for localized heating taking place in the atmosphere of Betelgeuse. We suggest that the detected localized heating is related to magnetic activity generated by large-scale photospheric convection.

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hydrogen (Harper et al. 2001). At these wavelengths, the thermal source function is simply the Planck function in the Rayleigh-Jeans limit, which is linear with the gas (electron) temperature. The mean gas temperature can then be empirically estimated using the Eddington-Barbier relation if the emission is spatially resolved. If the thermal structure is inhomogeneous at small scales (i.e., much smaller than the restoring beam), the source function is an average of the temperatures; unlike the UV, where very small volumes of hot plasma can dominate the total emission.

2. Observations and analysis

Betelgeuse was observed with the Atacama Large Millimeter/submillimeter Array (ALMA) on 9 November 2015 during cycle 3 in band 7 (275–373 GHz) using an array configuration with projected baselines ranging from 0.078 to 16.076 km (project code: 2015.1.00206.S, PI: P. Kervella). The observations lasted for 75 min with 61 min spent on source. A total of 47 antennas were used to make the final calibrated visibility dataset. The observations were performed using five spectral windows (spws). Two spws were centered at 330.65 GHz and 332.55 GHz and covered a total bandwidth of 0.94 GHz and 1.88 GHz, respectively. The three other spws were centered at 343.19 GHz, 345.15 GHz, and 345.80 GHz covering a total bandwidth of 1.88 GHz, 0.94 GHz and 0.47 GHz, respectively.

The phase-reference source J0552+0939 was observed every 12 minutes and was used to check the absolute position of Betelgeuse. Gray contours are set to \( \pm 0.1 \sigma \), where \( \sigma \) is the image rms noise. The numbers within the contours are the flux density values they represent in mJy. The largest contour is displayed in red for clarity at 54 mJy or 635 \( \mu \)Jy beam\(^{-1}\). The filled ellipse in the lower left corner is the full width at half maximum (FWHM) of the restoring beam and has dimensions 15 \( \times \) 13 mas. The locations of the NE-peak and the east-extension are marked with “x” and “+”, respectively. The yellow circle is the size of the infrared H-band photosphere from Montargès et al. (2016).

We fitted a number of models to the complex visibilities to accurately quantify the basic properties of the main emission features such as position, morphology, and flux density, and also search for any underlying concealed substructure that might not be obvious in the images. The models included a uniform elliptical disk either with or without a combination of point sources, elliptical or circular Gaussians, and an elliptical ring. After each fit, the residual images (i.e., data - model) were inspected to help guide the next possible improved fit. Some of these residual images are shown in Appendix B along with further details of the fitting process. The model that produced the lowest reduced chi-squared statistic value as well as the lowest remaining residuals in the residual images is described in Table 1. It consists of one relatively large uniform elliptical disk that contains one resolved elliptical Gaussian at the position of the NE-peak, another resolved circular Gaussian at the position of the east-extension, and a thin (i.e., unresolved) elliptical ring outside of the uniform elliptical disk with the same center position and position angle (PA; measured east of north) as the main uniform elliptical disk.

The main uniform elliptical disk has a major axis of 57.8 mas, is mildly elongated with an axis ratio (major axis/minor axis) of 1.09 and has a brightness temperature, \( T_b \), of 2760 ± 140 K. The NE-peak was found to be highly elongated having a FWHM major axis of 19.8 mas and an axis ratio of 2.38. This elongation is clearly visible in both the continuum images and in the residual images where the component has not been subtracted (see the left panel of Fig. B.1). The total brightness temperature of the NE-peak was 3815 ± 165 K. This value is derived by adding its \( T_b \) value in Table 1 to the uniform elliptical disk value because the model fitting has shown the entire NE-peak lies directly on top of the uniform elliptical disk. The east-extension was characterized by a circular Gaussian profile centered almost exactly at the limb/edge of the main uniform elliptical disk. Its FWHM was 8.9 mas and its brightness temperature was 2260 ± 135 K. The total brightness temperature...
of the east-extension in reality will be higher than this value because a portion of it lies on top of the uniform elliptical disk. We attribute the thin ring of emission beyond the uniform intensity disk as emission that is not accounted for in the idealized uniform disk model. The ring is not located close to the limb of the main disk which suggests that it is not a result of limb brightening. The lack of a detection of limb brightening means that the thermal gradients are small on the scale height being probed when the finite resolution is accounted for.

The continuum data have only ~4% fractional bandwidth coverage but the high S/N allows the spectral index, $\alpha$ (i.e., $S_\nu \propto \nu^\alpha$), of the emission to be constrained. We find the global spectral index to be $\alpha = 1.67 \pm 0.09$ by separately imaging the lower (at 331.86 GHz) and upper (at 344.09 GHz) portions of the bandpass and calculating the integrated flux density in each image. This is slightly larger than the $\alpha = 1.57 \pm 0.05$ that can be derived from previous unresolved millimeter observations (Altenhoff et al. 1994; Harper et al. 2009; O’Gorman et al. 2012) and is much larger than the $\alpha = 1.33 \pm 0.01$ that can be derived from multi-epoch centimeter studies (O’Gorman et al. 2015a). We note that the NE-peak has a spectral index of $\leq 2$ in the spectral index image (from CASA’s clean parameter nterms = 2) but the error values per pixel may be underestimated due to the small fractional bandwidth coverage. Both the global and pixel spectral indices are in agreement with the emission being thermal free-free in nature, while the increasing $\alpha$ towards higher frequencies is a manifestation of probing smaller density scale heights at higher frequencies.

### 4. Discussion and conclusion

#### 4.1. Verification of a temperature inversion between the photosphere and chromosphere

Submm spatially resolved observations of thermal continuum emission from stellar atmospheres can act as an approximate linear thermometer. The continuum flux density, $S_\nu$, can be described as arising from an optically thick disk of angular size $\theta_0$ at some frequency $\nu$, and gas temperature $T_{\text{gas}}$ such that $S_\nu \propto T_{\text{gas}} \theta_0^2$. At these frequencies the free-free opacity varies as roughly $\nu^2$, so multi-frequency observations allow the temperature profile to be constructed. This method has been used by Lim et al. (1998) and O’Gorman et al. (2015a) to show that the mean gas temperature of Betelgeuse’s extended atmosphere declines from approximately 3600 K at $2R_\star$ to 1400 K at $6R_\star$, and is not as hot (~8000 K) as previously thought (e.g., Hartmann & Avrett 1984). These values are plotted in Fig. 2 along with our ALMA measurement of 2760 ± 140 K at ~1.3 $R_\star$. This value is below the photospheric effective temperature of 3690 ± 54 K (Ohnaka et al. 2011) and most of the temperature measurements between ~2 and 3 $R_\star$. Obviously, there is not a monotonic decrease in the mean gas temperature of the extended atmosphere derived from multi-epoch spatially resolved radio observations (Lim et al. 1998; O’Gorman et al. 2015a). The large black dashed rectangle is the approximate location and temperature range of the MOLsphere. The black filled square is our ALMA band 7 temperature which shows that the mean gas temperature has dropped well below the effective temperature at ~1.3 $R_\star$.

Lim et al. (1998) suggested that photospheric-like temperatures at small stellar radii (i.e., at ~2 $R_\star$), along with the monotonic decrease in temperature with increasing distance from the star, could be explained by the expansion and cooling of material elevated from the photosphere by large convection cells. In this scenario, the mean gas temperature should not drop below the effective temperature between 1 and 2 $R_\star$, but we find that it does. Our finding is in agreement with chromospheric modeling of all cool stars, which suggests that there is a trend of decreasing gas temperature above the photosphere which then rises again into the chromosphere (e.g., Basri et al. 1981).

#### 4.2. The source of the submm continuum asymmetries

At the depths probed by the 338 GHz emission the gas temperature will vary much more slowly with height above the surface, $z$, and the reason why our value at ~1.3 $R_\star$ is larger in comparison to MOLsphere values.
than the hydrogen (n_H) and electron (n_e) densities, respectively (Basri et al. 1981). Eddington-Barbier relations show that for temperatures varying slowly with optical depth \( T_b \approx T_{\text{gas}}(\tau = 1) \), where

\[
\tau(z) \propto \int_{\infty}^{z} n_e n_H \, dz' = n_e^2(z) H_p / 2
\]

where \( H_p \) is the density scale height. The latter equality follows if both \( n_e / n_H \) and \( H_p \) are approximately constant. This demonstrates that the submm opacity is dominated by the local densities and the local scale-height. Localized (i.e., non-uniform) heating will not only increase the gas temperature but it will also increase \( n_e \) (from photoionized metals), the density scale-height, and thus the total optical depth. This could explain why the NE-peak is the brightest feature in our image of Betelgeuse. On the stellar disk we are sampling \( T_{\text{peak}} \) is the brightest feature in our image of Betelgeuse. On the stellar disk we are sampling \( T_{\text{peak}} \) is the brightest feature in our image of Betelgeuse.

Indeed, Loukitcheva et al. (2015) have shown that this will happen when active regions on the Sun are observed at low spatial resolution with ALMA. Future multi-frequency ALMA observations with similar spatial resolution to that presented here could confirm our hypothesis if the brightness temperatures of the asymmetries increase with decreasing frequency as a result of the shifting of contributing heights to higher and hotter layers in the atmosphere.

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Appendix A: Continuum imaging

Continuum imaging was performed using the multi-frequency synthesis CLEAN algorithm with Briggs weighting and a robust parameter of 0, which resulted in a synthetic beam size of $15 \times 13$ mas at 338 GHz. Two Taylor coefficients were used to model the linear frequency dependence of the continuum emission. Additionally, we used the multiscale imaging option with scales approximately corresponding to 0, 1, and $3 \times$ the synthesized beam. Using these imaging parameters, three iterations of phase-only self-calibration were performed on the continuum emission until a S/N convergence was reached with a solution interval of 15 s. One final iteration was then performed, solving for both amplitude and phase. We note that self-calibrating the continuum data reduced the rms noise by approximately an order of magnitude. To investigate small-scale structure in the continuum emission we also created images using Briggs weighting with a robust parameter of $-1$ and uniform weighting. The achieved rms noise for the continuum images was 85 $\mu$Jy beam$^{-1}$ (robust 0 images), 138 $\mu$Jy beam$^{-1}$ (robust $-1$ images), and 255 $\mu$Jy beam$^{-1}$ (uniform images).

Appendix B: Residual images from uv-fitting

In Fig. B.1 we show three example residual images from our $uv$-fitting analysis. Residual images containing a lot of emission meant that the subtracted model did not describe the data well. In the left panel of Fig. B.1 a uniform intensity elliptical disk was fitted to the visibilities. The best fit model was then subtracted from them using CASA’s $uvsub$ task, and the residual visibilities were then imaged. The rms of the residual image within a circle of radius $\sim 3 R_*$ centered on the disk center was 1.345 mJy beam$^{-1}$. Clearly, excess emission remains in the residual image: a strong ($\sim \pm 60 \sigma_{rms}$) elongated feature in the north-east quadrant, another strong ($\sim \pm 40 \sigma_{rms}$) feature east of the disk center, and a weaker ($\sim \pm 10 \sigma$) ring-like feature beyond these. In the middle panel of Fig. B.1 we show the residual image after the best fit model of a uniform intensity elliptical disk plus a Gaussian profile have been fitted and subtracted from the visibilities. The emission feature in the north-east quadrant is now gone and the rms of the residual image within a circle of radius $\sim 3 R_*$ centered on the disk center was 0.817 mJy beam$^{-1}$. Finally, in the right panel of Fig. B.1 we show the residual image after the best fit model of a uniform intensity elliptical disk plus two Gaussian profiles plus a thin ring have been fitted and subtracted from the visibilities. All the main emission features present in the left panel of Fig. B.1 are now gone and the rms of the residual image within a circle of radius $\sim 3 R_*$ centered on the disk center was 0.367 mJy beam$^{-1}$. We note that a number of small-scale features with ($\sim \pm 5$–$10 \sigma_{rms}$) significance remain, which are probably the result of the thin ring not being a perfect match for the low brightness emission beyond the main elliptical disk.

We found that replacing the elliptical uniform intensity disk with a circular uniform intensity disk in the multi-component fits described previously produced larger chi-squared statistic values and increased the residual image rms. We also attempted fits by forcing the Gaussian components to have negative flux density values, but the fitted values were smaller than the fitting errors. Moreover, the large negative features in the left and middle panel are not present in our best fit model shown in the right panel and we conclude that they are simply artefacts.

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**Fig. B.1.** ALMA 338 GHz continuum residual (i.e., data – model) images of Betelgeuse. The filled ellipse in the lower left corner of the left panel is the FWHM of the restoring beam and has dimensions $15 \times 13$ mas while the orange circle is the size of the infrared $H$-band photosphere from Montargès et al. (2016). *Left panel*: the residual image after a uniform elliptical disk has been subtracted from the visibilities. *Middle panel*: the residual image after a uniform elliptical disk plus an elliptical Gaussian have been subtracted from the visibilities. *Right panel*: the residual image after a uniform elliptical disk, an elliptical Gaussian, a circular Gaussian, and a thin ring have been subtracted from the visibilities.