3D SMOOTHED PARTICLE HYDRODYNAMICS MODELS OF BETELGEUSE’S BOW SHOCK

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Abstract. Betelgeuse, the bright red supergiant (RSG) in Orion, is a runaway star. Its supersonic motion through the interstellar medium has resulted in the formation of a bow shock, a cometary structure pointing in the direction of motion. We present the first 3D hydrodynamic simulations of the formation and evolution of Betelgeuse’s bow shock. We show that the bow shock morphology depends substantially on the growth timescale for Rayleigh-Taylor versus Kelvin-Helmholtz instabilities. We discuss our models in light of the recent Herschel, GALEX and VLA observations. If the mass in the bow shock shell is low ($\sim$few $\times 10^{-3}$ $M_\odot$), as seems to be implied by the AKARI and Herschel observations, then Betelgeuse's bow shock is very young and is unlikely to have reached a steady state. The circular, smooth bow shock shell is consistent with this conclusion. We further discuss the implications of our results, in particular, the possibility that Betelgeuse may have only recently entered the RSG phase.

1 Introduction

From the shoulder of Orion ‘The Hunter’ (Greek mythology), to stories about the fierce, red lion (Southern African mythology), Betelgeuse has long been a prominent part of the night sky. As the nearest and brightest star of its kind, Betelgeuse is now considered the prototype red supergiant (RSG). Estimates of its mass range from 8 $M_\odot$ - 20 $M_\odot$ and although it is very cool ($T_{\text{eff}} \sim 3300$ K), it is highly luminous ($L_\star \sim 10^5 L_\odot$) due to its large stellar radius ($R_\star \sim 1000 R_\odot$) (see for example, Smith et al. 2009; Neilson et al. 2011). Its tenuous atmosphere is only loosely bound, consequently it loses $\sim 2 - 4 \times 10^{-6}$ $M_\odot$ yr$^{-1}$ via a slow, $\sim 17$ km s$^{-1}$ wind (Noriega-Crespo et al. 1997; Bernat et al. 1979). The mechanism by which this material is lost is still unclear, but the process has occurred for thousands of years forming an extensive circumstellar envelope (CSE) of gas and dust.

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Noriega-Crespo et al. (1997) successfully imaged the CSE at 60 and 100 µm using IRAS. They detected a bow shock arc ~6 arcmin in radius to the north-east of Betelgeuse and a mysterious linear 'bar-like' structure, located just ahead of the arc. A decade later, Ueta et al. (2008) confirmed the detection, imaging part of the bow shock arc and bar in the far-infrared with AKARI. More recently, high resolution Herschel observations revealed that the bow shock consists of multiple arcs (Cox et al. 2012, Decin et al. 2012). Le Bertre et al. (2012) identified a faint, GALEX far-ultraviolet arc at the same position as the outermost Herschel one. The bar, however, was not detected at these shorter wavelengths. With the VLA, they also found atomic hydrogen coincident with the bow shock and an inner, cometary shaped detached shell of HI emission ~4 arcmin in diameter.

Betelgeuse is moving supersonically relative to the local interstellar medium (ISM) and its bow shock is formed by the collision of its stellar wind with this medium. Assuming it has reached a steady state, the bow shock can be used to probe the physical properties of these interacting flows. The bow shock ‘radius’, known as the stand-off distance, $R_{SO}$, is the location where the ram pressures of the ISM and stellar wind are in equilibrium, and is given by:

$$\rho_{\text{ISM}} v^2 = \frac{\dot{M}_w v_w}{4\pi R_{SO}^2}, \quad (1.1)$$

(assuming a spherical wind) where $\dot{M}_w$ is the wind mass-loss rate, $\rho_{\text{ISM}}$ and $\rho_w$ are the density of the ISM and stellar wind, respectively; $v_*$ is the velocity of the star with respect to the ISM, and $v_w$ is the stellar wind velocity. Assuming momentum conservation and that the stellar wind and ISM mix and cool instantaneously (the thin-shell approximation), the shape of the bow shock is given by:

$$R(\theta) = R_{SO} \csc \theta \sqrt{\frac{1}{3} (1 - \theta \cot \theta)}, \quad (1.2)$$

where $\theta$ is the polar angle measured from the axis of symmetry (Wilkin 1996).

Utilising these analytic models and current estimates for Betelgeuse’s wind and distance, Ueta et al. (2008) derived a space velocity of $v_* = 40 n_H^{-1/2} \text{ km s}^{-1}$ with respect to the local ISM. Estimates of the ISM density, $n_H$, range from 0.3 cm$^{-3}$ to 1.5 - 1.9 cm$^{-3}$, thus Betelgeuse’s space velocity is likely to be between 73 km s$^{-1}$ and 28 km s$^{-1}$, respectively. Mohamed et al. (2012) simulated models for these parameters and compared the results to the IRAS and AKARI observations. In this paper, we highlight the main points of that study and discuss the conclusions in light of the recent Herschel, GALEX and VLA observations.

2 Model

The bow shock is modeled in 3D using Smoothed Particle Hydrodynamics (SPH), a Lagrangian method particularly suited to studying hydrodynamical flows with

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1Although Betelgeuse is the only RSG with a bow shock, theoretical models predict that up to 30% of RSGs can be runaway stars (Eldrige et al. 2011). The origin of the Betelgeuse’s high space velocity is unclear but may be due to a dynamical ejection from a cluster and/or a supernova kick.
Fig. 1. Evolution of the ratio of $R(0^\circ)/R(90^\circ)$ for a slow, $v_* = 32\, \text{km}\, s^{-1}$ model (magenta), and fast, $v_* = 73\, \text{km}\, s^{-1}$ model (dashed blue), compared to the analytic, steady state value, $1/\sqrt{3}$ (solid black line). The observed Herschel/AKARI ratio is $\sim0.7$ (arrows).

arbitrary geometries. Throughout this study we use the GADGET-2 SPH code (Springel 2005) which we have modified to include stellar winds (Mohamed & Podsiadlowski 2007), an ISM flow (Mohamed 2010), and atomic and molecular radiative cooling (Smith & Rosen 2003).

For numerical convenience, we select the stellar rest frame with the star located at the origin of a rectangular box $(x, y, z = 0, 0, 0)$. Given the uncertainty in Betelgeuse’s mass-loss mechanism, we do not model the wind acceleration in detail. Instead wind particles are injected isotropically at a radius, $R_{\text{inner}} \sim 10^{15} \, \text{cm}$, with velocity, $v_w \sim 17\, \text{km}\, s^{-1}$, and temperature $T_w \sim 1000\, \text{K}$. The result is a smooth, constant outflow of material at a rate of $3.1 \times 10^{-6}\, \text{M}_\odot\, \text{yr}^{-1}$. The ISM is also assumed to be homogeneous and flows past the star in the direction of the $x$ axis, interacting with the stellar wind as it does so. We model a range of ISM densities, $n_H = 0.3, 1.0, 1.5,$ and $1.9\, \text{cm}^{-3}$, with corresponding stellar velocities, $v_* = 73, 40, 32,$ and $29\, \text{km}\, s^{-1}$, respectively. These number densities lie at the boundary between typical values expected for either a warm or cold neutral ISM, so we assume temperatures based on the phase diagram of the standard model of Wolfire et al. (1995), e.g., their Fig. 3d. The temperatures, $T_{\text{ISM}}$, are $8000, 1600, 1000,$ and $650\, \text{K}$, respectively. Additional models are also run to investigate the effect of varying the ISM temperature, degree of cooling and numerical resolution.

The numerical method and model set up were tested with an adiabatic model. The results were consistent with both theoretical expectations and previous studies (e.g., Wilkin 1996, Brighenti & D’Ercole 1995).
3 Results

The simulations begin at the start of the RSG phase. As the stellar wind collides with the ISM, material accumulates at the contact discontinuity, where part of the kinetic energy of the gas is thermalised. The heated ISM and stellar wind expand outwards from either side of the contact discontinuity; the former pushes into the ISM, this is known as the forward shock, and the latter pushes into the stellar wind, known as the reverse shock. Although the stellar outflow is initially spherical, it becomes increasingly parabolic as the star moves through the ISM. Eventually a steady state is achieved at which point the global morphology is described by Eq. 1.2. From the models we derive the ratio of the bow shock radius at angles $\theta = 0^\circ$ and $\theta = 90^\circ$, $R(0^\circ)/R(90^\circ)$, as a function of time (shown in Fig. 1). It takes several dynamical timescales for the bow shock to achieve the equilibrium value $R(0^\circ)/R(90^\circ)=1/\sqrt{3}$.

Although all the models exhibit a similar global structure, the flow characteristics on smaller scales differ considerably due to the growth of Rayleigh-Taylor (R-T) and Kelvin-Helmholtz (K-H) instabilities (see Fig. 2). In the ‘slow’ models, $n_\text{H} \gtrsim 1 \text{ cm}^{-3}$ and $v_* \lesssim 40 \text{ km s}^{-1}$, the strong cooling reduces the thermal pressure of the gas enabling further compression in the forward and reverse shocks. The greater post-shock densities reduce the growth timescale for R-T instabilities. This, along with the slow space motion producing less shear, causes the R-T ‘fingers’ to develop faster than the K-H ‘rolls’. These bow shocks consist of a thin, smooth outer shock and a contact discontinuity that is highly distorted by R-T ‘fingers’. In the column density plots, the small-scale R-T instabilities result in a clumpy, knot-like sub-structure that becomes one of the dominant features of the bow shock, particularly when viewed at large inclination angles (see Fig. 3 [top]).

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2Rayleigh-Taylor instabilities are ‘finger-like’ protrusions that occur when a light fluid is accelerated into a denser fluid. Kelvin-Helmholtz ‘rolls’ or ‘eyes’ are excited by the shear produced in the relative motion of two adjacent fluid layers.
Fig. 3. Hydrogen column density (on a logarithmic scale) after 76 000 years for the slow, 32 km s$^{-1}$[top] and fast, 73 km s$^{-1}$ [bottom] models seen at different inclination angles, $i$. Increasing the inclination angle reduces the density contrast between the peak at the apex of the bow shock and the rest of the cometary structure, making the detection and identification of highly inclined systems more difficult.

By contrast, the ‘fast’ model, with $n_H = 0.3\, \text{cm}^{-3}$ and $v_*= 73\, \text{km\,s}^{-1}$, is dominated by K-H instabilities; the greater stellar motion increases the shear between the ISM and stellar wind, reducing the K-H growth timescale. The initially lower ISM density results in less cooling and thus less compression; it takes much longer to grow R-T instabilities and any excitations that do develop are quickly advected downstream. The ‘gentle’ fluctuations of the K-H instability results in a more layered, filamentary appearance (see Fig. 3[bottom]).

The appearance of the bow shock is also dependent on the emitting species (see Figs. 13 and 14, Mohamed et al. 2012). In our models, the total emissivity is a sum of the contributions from 15 different coolants, e.g., rotational and vibrational transitions of H$_2$, CO and H$_2$O, H$_2$ dissociative cooling and reformation heating, gas-grain cooling/heating, and atomic lines. While some species radiate from the entire bow shock surface, e.g., H$_2$O, others are almost entirely confined to the reverse shock or forward shock, e.g., CO. Emission primarily from a forward shock (hotter gas) results in a much smoother bow shock shell, e.g., the atomic line radiation, whereas emission from the reverse shock produces a more layered structure, e.g., collisional excitation of H$_2$O with H$_2$. Several coolants, such as gas-grain, rotational transitions of CO and H$_2$O, and the heating species produce a more ‘finger-like’, clumpy bow shock sub-structure.
Fig. 4. The minimum bow shock shell mass as a function of time for a slow model (points) and the fast model (lines). For both models, the RSG and ISM contributions are in red and blue, respectively, and their combined mass is plotted in black. The masses derived from the IRAS and AKARI observations are $\sim0.03M_\odot$ and $\sim0.003M_\odot$, respectively (indicated by arrows).

4 Discussion

Assuming no other energy sources are present and that during the collision all the kinetic energy of both the ISM and stellar wind is thermalised, the theoretical upper limit for the bolometric luminosity of the bow shock is given by $E_{\text{tot}} \approx \frac{1}{2} M_w v_w^2 + \frac{1}{2} M_r v_r^2$. For the parameters adopted in our models, $E_{\text{tot}}$ does not exceed $\sim6 \times 10^{33}$ ergs s$^{-1}$. In reality, however, only a small fraction of the kinetic energy is radiated from the bow shock; $\sim16\%$ and $\sim29\%$ for the fast and slow models, respectively. The AKARI ($65\mu$m) and the IRAS ($60\mu$m) luminosities are $\sim7 \times 10^{33}$ ergs s$^{-1}$ and $\sim5 \times 10^{34}$ ergs s$^{-1}$, respectively. The latter exceeds the theoretical upper limit for the bolometric luminosity by almost an order of magnitude, but is likely overestimated due to contamination from the bar and Betelgeuse itself, which is very luminous in the infrared. Whereas the more recent Herschel observations are in good agreement with the AKARI values (Decin et al. 2012). Although the luminosities based on these higher resolution observations are consistent with the theoretical upper limit, as discussed above, only a small fraction of the kinetic energy is thermalised. Furthermore, an even smaller fraction of this will be radiated in the far-infrared; from our simulations the combined luminosity from species thought to be responsible for the far-infrared emission, i.e. dust grains, C and O fine structure lines, is at least three orders of magnitude lower than the observed flux. The most likely explanation is that Betelgeuse’s radiation, and the radiation produced by hot gas in the bow shock itself, are absorbed and...
reemitted by the gas and dust in the far-infrared.

The evolution of the bow shock shell mass is shown in Fig. 4. Only shocked material with $x < 0$ in the bow shock head is included (recall, in the models the star is stationary and positioned at $x, y, z = (0, 0, 0)$ with the ISM moving in the direction of the $+x$ axis); this yields a lower limit for the mass in the bow shock at any particular time. Assuming the average mass-loss rate of the star has not varied significantly, we can compare the bow shock shell mass derived from the models with observational estimates and constrain the age of the bow shock. The bow shock mass derived from the IRAS flux is 0.033 M$_\odot$ and corresponds to a bow shock age of ~35,000 years (see Fig. 4 arrows). However, as discussed above, the IRAS flux is likely an overestimate, thus the age is an upper limit. The AKARI and Herschel bow shock masses are an order of magnitude lower, ~0.0033 M$_\odot$ and ~0.0024 M$_\odot$ (Decin et al. 2012), respectively, which would imply an age of ~10,000 years. If this is the case, however, the wind would not have had sufficient time to expand to the current bow shock radius. One possible solution is that the observed shell mass is underestimated due to uncertainties in the flux to mass conversion (e.g., the distance to the star, the gas-to-dust ratio, dust emissivity). In our models the shell takes ~20,000 years to reach the observed bow shock radius by which time the mass in the bow shock is approximately 0.02 M$_\odot$. This is higher than the value obtained from the far-infrared observations, but may be consistent within the uncertainties, and is in agreement with the masses based on 21cm neutral H observations (Le Bertre et al. 2012 Decin et al. 2012). Note, however, that at ~20,000 years none of our models are close to reaching a steady state.

The shape of Betelgeuse’s bow shock is more circular than parabolic. As shown in Fig. 3 the bow shock becomes increasingly circular with larger inclination angles, i.e. at large angles between the apex of the bow shock and the plane of the sky. Ueta et al. (2008) derived an inclination of 56° using Eqs. 1.1 and 1.2 (i.e. assuming a steady state) which is consistent with ~50° based on the tangential and radial velocities. However, an alternative explanation for the circular shape is that the bow shock has not yet reached a steady state. From the Herschel and AKARI observations, the ratio of $R(0^\circ)/R(90^\circ)$ is approximately 0.7, which is much greater than the equilibrium value and corresponds to an age of ≲30,000 years (Fig. 1).

The multiple arcs and even their bright knots in the Herschel observations closely resemble the filamentary structure of the fast model (Fig. 2[b]). The filaments arise when the K-H instabilities are seen projected onto the plane of the sky. This projection effect could account for some of the arcs and other structures observed at locations well inside the bow shock radius (although the very large mass of the HI detached shell would be difficult to explain). From the radial velocity and proper motion, the space velocity of Betelgeuse is unlikely to be as high as 73 km s$^{-1}$. (Understanding the origin of the far-ultraviolet emission may put constraints on the upper end of the stellar velocity.) The similarity between the observations and the fast model, and the lack of clumpy sub-structure that characterised the slow models, suggests that the bow shock is dominated by K-H rather than R-T instabilities. This situation could occur for the slow models if...
the RSG wind expands into a much lower density, hot ISM. These conditions reduce the cooling and hence compression in the bow shock, increasing the growth time for R-T instabilities. However, for the slow model, such conditions are not consistent with the relation $v_* = 40 \, n_{H}^{-1/2} \, \text{km s}^{-1}$, i.e. the ram pressures are not in equilibrium and the bow shock is not yet in a steady state. Thus the overall smooth appearance and lack of well-developed instabilities further strengthen the argument that the bow shock must be young.

5 Implications

We find that many of the physical and morphological characteristics of Betelgeuse’s bow shock, e.g., the smooth circular shape, the low shell mass and multiple arc substructure, are consistent with a young bow shock ($\lesssim 30,000$ years). Consequently, within this time frame, the local ISM through which the star is moving and/or the stellar wind must have undergone significant changes. In Mohamed et al. (2012) we proposed that such dramatic changes may have occurred if Betelgeuse only recently became a RSG, transitioning from either a main sequence (MS) star or a blue supergiant (BSG) (i.e. moving from the ‘blue’ to the ‘red’ in the Hertzsprung-Russell diagram). The radius of Betelgeuse’s MS or BSG wind bubble would have been $\sim 1 \, \text{pc}$, assuming typical wind mass-loss rates ($\sim 10^{-7} \, \text{M}_\odot \, \text{yr}^{-1}$) and wind velocities ($\sim 10^3 \, \text{km s}^{-1}$) for such hot, blue stars. A RSG phase of a $\sim \text{few} \times 10,000$ years would bring the star close to the edge of such a bubble; thus, the mysterious ‘bar’ ahead of Betelgeuse’s bow shock could be a remnant shell produced during this earlier phase of ‘blue’ evolution (Mohamed et al. 2012). A blue-red transition would also mean that the RSG wind expands into a MS or BSG bubble filled with low density, hot gas, precisely the conditions required to form the observed smooth, K-H dominated, multiple arc characteristics of Betelgeuse’s bow shock.

Mackey et al. (2012) carried out a detailed investigation of a BSG to RSG transition, including an evolving wind with a non-constant mass-loss rate and wind velocity. Their models reproduce the observed bow shock mass and multiple arcs. They also find that the receding BSG bow shock is a plausible candidate for the linear bar structure. More detailed comparisons of the models with the observations will require a more sophisticated treatment of dust, radiative transfer and possibly magnetic fields (see Decin et al. 2012).

Further observations are also required to reduce the number of free and uncertain parameters in the models. In particular, a more accurate distance to Betelgeuse ($197 \pm 45 \, \text{pc}$, see Harper et al. 2008) would reduce the uncertainty in several key areas, e.g., in deriving the space velocity of the star (to this end a more accurate proper motion and radial velocity are also needed). The bow shock mass also depends on the distance as well as the highly uncertain dust properties, e.g., composition, the dust-to-gas ratio and the dust temperature. Future observations, e.g., with ALMA, could constrain the gas density, temperature and velocity structure in the CSE. Indeed, tracing material from the stellar photosphere all the way to the bow shock would give us insight into the mass-loss history of Betelgeuse, a key ingredient in stellar evolution models.
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