Modelling multiwavelength observational characteristics of bow shocks from runaway early-type stars

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ABSTRACT
We assess the multiwavelength observable properties of the bow shock around a runaway early-type star using a combination of hydrodynamical modelling, radiative transfer calculations and synthetic imaging. Instabilities associated with the forward shock produce dense knots of material which are warm, ionized and contain dust. These knots of material are responsible for the majority of emission at far infrared, Hα and radio wavelengths. The large-scale bow shock morphology is very similar and differences are primarily due to variations in the assumed spatial resolution. However infrared intensity slices (at 22 microns and 12 microns) show that the effects of a temperature gradient can be resolved at a realistic spatial resolution for an object at a distance of 1 kpc.

Key words: stars: early-type – ISM: general.

1 INTRODUCTION
Stars with large velocities (>40 km s −1) relative to the surrounding interstellar medium (ISM) are termed runaway stars (Blaauw 1961; Cruz-González et al. 1974; Tetzlaff, Neuhäuser & Hohle 2011). Space velocities up to 200 km s −1 were observed by Blaauw (1961) and if conditions in the ISM are favourable the velocity of a runaway star relative to the ISM will be supersonic (Huthoff & Kaper 2002) leading to the formation of a bow shock (Baranov, Krasnobaev & Ruderman 1976). Runaway early-type stars have strong stellar winds and experience a particularly strong interaction with the ISM, due to the high space velocity of the star and the high velocity of the wind. A number of high velocity early-type stars are identified by Blaauw (1961) and Cruz-González et al. (1974). Bow shocks have also been identified around evolved stars, e.g. red supergiants (Noriega-Crespo et al. 1997b; Cox et al. 2012; Gvaramadze et al. 2014; Meyer et al. 2014a). These bow shocks are similar to those around early-type, main-sequence stars albeit with a lower stellar wind velocity.

It has been proposed that runaway stars are produced by binary supernovae (Blaauw 1961) or result from dynamical interactions between stars in a cluster (Poveda, Ruiz & Allen 1967). There is evidence that, in practice, runaway stars are produced by both mechanisms (Portegies Zwart 2000; Hoogerwerf, de Bruijne & de Zeeuw 2000, 2001). Runaway stars with velocities of a few 100 km s −1 can be generated by both the binary supernova (Portegies Zwart 2000) and dynamical ejection scenarios (Poveda et al. 1967; Leonard 1991). Moreover, ejection from the Galactic Centre, due to interaction with the supermassive black hole, has been cited as a mechanism for the formation of hypervelocity stars with even higher spatial velocities (Hills 1988; Brown et al. 2012). In addition to bow shocks around stars with large peculiar velocities, young stars in a cluster can drive outflows, which cause ISM velocities to deviate from the local standard of rest, and bow shocks can be generated without ejecting stars from the cluster (Povich et al. 2008).

The formation of isolated massive stars is an important factor in discriminating between different star formation mechanisms. In the competitive accretion paradigm massive stars form by accreting material in a cluster environment (Zinnecker 1982; Larson 1992; Bonnell et al. 1997; Bonnell, Vine & Bate 2004) whereas in the core accretion paradigm massive stars are able to form in isolation (Wolfire & Cassinelli 1987; Yorke & Sonnhalter 2002; Krumholz et al. 2009). When searching for evidence of isolated massive star formation runaways need to be excluded, as they are likely to be found far from where they formed (de Wit et al. 2005; Bressert et al. 2012). Runaway stars can sometimes be identified through proper motion observations or line-of-sight velocity measurements but the presence of a bow shock is also a valuable indication that a star is a runaway. Stellar bow shocks yield not only kinematic information but the stand-off distance of the shock has been used as a diagnostic of stellar wind and ISM properties (Brown & Bomans 2005; Povich et al. 2008; Kobulnicky, Gilbert & Kiminki 2010; Cox et al. 2012). As well as using bow shocks as diagnostics it is important to understand the observable properties of stellar bow shocks, as they may produce an infrared excess which could be confused with emission from a circumstellar disc (Gáspár et al. 2008; Povich et al. 2008).

Observational studies have detected stellar bow shocks in various regions of the spectrum, most notably in the mid-infrared (Noriega-Crespo, van Buren & Dgani 1997a; van Buren & McCray...
Bow shocks from runaway early-type stars

A multiwavelength study of the O5 star HD 192281 by Arnal et al. (2011) revealed an Hβ structure consistent with formation by a bow shock, with counterparts seen in infrared, radio continuum and CO (1–0) observations. The radio emission had a thermal spectrum with ionization as the proposed source. Non-thermal radio emission, from relativistic particles, has been detected in observations of BD+43° 3654 by Benaglia et al. (2010) and non-thermal X-ray emission from the AE Aur bow shock was detected by López-Santiago et al. (2012).

Analytical expressions can be derived for some bow shock properties, given certain simplifying assumptions. Wilkin (1996) treats the bow shock as an axisymmetric thin shell and calculates analytical expressions for the shape, mass column density and velocity of the shocked gas. However when the simplifying assumptions are relaxed numerical modelling is required. In their study of ultracompact H II regions, Mac Low et al. (1991) use a numerical model of a shell in momentum balance. This gives a two-dimensional solution which they use to produce synthetic radio observations. Raga et al. (1997) use two-dimensional models, with hydrodynamics and a radiative transfer approximation, to produce synthetic dust and H α emission maps for a runaway O star. A number of subsequent studies have also made use of two-dimensional hydrodynamics to study the physics of bow shocks around runaway massive stars, e.g. Comeron & Kaper (1998) and Cox et al. (2012). More recently (Meyer et al. 2014b) modelled an evolving main-sequence star, using a two-dimensional hydrodynamics code, and generated synthetic H α observations.

In this paper, we model the bow shock caused by a runaway early-type star and determine the observational properties of the resulting structure. To achieve this, we combine hydrodynamical modelling (described in Section 2) with Monte Carlo radiative transfer calculations (described in Section 3) to model the radiation influenced region around the star. We generate synthetic observables, as described in Section 4, focussing on the infrared, H α and radio regimes where successful detections of stellar bow shocks have already been made. We discuss our results in Section 5, where we compare them to synthetic observations in the literature, and discuss assumptions and potential improvements to the model. We close with our conclusions in Section 6.

2 HYDRODYNAMIC CALCULATION

The formation of the bow shock structure was modelled using the VH-1 hydrodynamics code (Blondin, Mezzacappa & DeMarino 2003; Hawley et al. 2012), a grid-based code which uses the Piecewise-Parabolic Method (Colella & Woodward 1984) and provides good resolution of shocks in complex flows. The gas is treated as an ideal gas with radiative cooling implemented as a cooling curve. The radiative cooling in the hydrodynamic calculation is modelled using an analytic fit to the results of Schure et al. (2009), assuming a solar metallicity plasma. Radiation pressure is not included and no additional physical viscosity is added.

The simulation grid uses two dimensional, cylindrical polar coordinates, with the direction of motion of the star aligned with the z-axis. The grid size is 10^{18} cm in each linear dimension with 1000 grid cells. The star is placed on the z-axis and ISM material flows on to the grid at a fixed velocity of 100 km s^{-1} (i.e. the simulation is performed in the frame of reference of the star). The star has a wind which causes material to flow radially outwards and meet the incoming ISM in the upstream direction. The stellar wind is implemented as a region with a constant outflow velocity which is imposed within a fixed radius of 50 grid cells from the star. The density in the outflow region decreases with radius such that the mass loss rate is constant. The wind radius must be large enough to ensure that the wind remains spherical but needs to be smaller than the minimum extent of the bow shock region. The main model parameters are listed in Table 1. Dust mass is not included in the hydrodynamical simulations, where its contribution to the mass is negligible. However radiation pressure can have a significant impact on dust dynamics which could influence the gas if the dust and gas are dynamically coupled (Villaver, Manchado & García-Segura 2012; Gratier et al. 2014; Ochsendorf et al. 2014). Dust opacity is included in the radiative transfer calculation, where the effect is significant (see Section 3).

The density distribution is plotted in Fig. 1 (top-left) and shows a two shock structure with a forward shock, where the ISM shocks, and an inner shock where the stellar wind terminates. This is similar to the structures seen in other simulations (e.g. Comeron & Kaper 1998; Cox et al. 2012; Mackey et al. 2012; Meyer et al. 2014b) where the two shocks bound a contact discontinuity. However our model does not show a clear separation between the forward shock and contact discontinuity. If the shocked ambient gas cools very rapidly, as expected due to the high ISM density, then the outer layer of hot material is not present, as described by Comeron & Kaper (1998).

Bow shocks from runaway early-type stars

The forward shock is subject to instabilities which result in the formation of denser knots of material. Similar instabilities have been seen in other numerical models of stellar bow shocks (e.g. Comeron & Kaper 1998, Cox et al. 2012 and Meyer et al. 2014b). A number of different mechanisms can generate these instabilities (e.g. Kelvin–Helmholtz instabilities, non-linear thin shell instabilities (Vishniac 1994) and transverse acceleration instabilities (Dgani, van Buren & Noriega-Crespo 1996)) as discussed by Comeron & Kaper (1998).

An analytical expression for the shock stand-off distance $R_0$ can be derived by determining the distance at which the stellar wind ram pressure and the ISM ram pressure are equal (Wilkin 1996)

$$R_0 = \sqrt{\frac{M_W V_W}{4\pi\rho_{\text{ISM}} V^2_\infty}}$$

(1)

where $\rho_{\text{ISM}}$ is the ISM mass density and other symbols are defined in Table 1. We assume the ISM is composed of hydrogen and helium with a 10:1 ratio and is fully ionized. The ISM number density $n_{\text{ISM}}$ is the sum of the hydrogen ion, helium ion and electron number densities (i.e. $n_{\text{ISM}} = n_H^+ + n_{\text{He}}^++ + n_e$) and $\rho_{\text{ISM}} = \frac{1}{3}n_{\text{ISM}} m_H$ where $m_H$ is the mass of a hydrogen atom. For the parameters used in this simulation the calculated stand-off distance is $R_0 = 0.10$ pc.

Wilkin (1996) derives an analytical expression for the shape of the bow shock

$$R = \frac{R_0}{\cos \theta} \sqrt{3(1 - \theta \cot \theta)}$$

(2)

where $R$ is the distance from the star and $\theta$ is the polar angle from the axis of symmetry. The analytical solution is shown in Fig. 1 as

**Table 1. Parameters of the hydrodynamical simulation.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellar mass-loss rate</td>
<td>$\dot{M}_W$</td>
</tr>
<tr>
<td>Stellar wind velocity</td>
<td>$V_W$</td>
</tr>
<tr>
<td>Stellar velocity</td>
<td>$V_*$</td>
</tr>
<tr>
<td>ISM number density</td>
<td>$n_{\text{ISM}}$</td>
</tr>
<tr>
<td>Grid size</td>
<td>$10^{18}$ cm</td>
</tr>
<tr>
<td>Number of grid cells</td>
<td>1000^2</td>
</tr>
</tbody>
</table>
a black curve overlaid on the density plot. In our model the z-axis location of the stand-off distance is between the forward shock and the wind termination (inner) shock. The shape of the forward shock follows the analytical solution but is located further from the star. The post-stellar wind material in our model is at a high temperature and the density ratio is approximately 4 which suggest an adiabatic shock with inefficient cooling of the shocked gas. Comeron & Kaper (1998) note that if cooling of the shocked stellar wind is inefficient then a layer of hot, low-density gas lies between the stellar wind and the bow shock, causing the bow shock to move forward of $R_0$. 

**Figure 1.** Density (top-left) in gm cm$^{-3}$, dust distribution (top-right), gas temperature (bottom-left) in K, and dust temperature (bottom right) in K, at the end of the photoionization equilibrium calculation. The star is located at the origin of the grid. The black curve shown on the density plot is the Wilkin analytical solution. The dust distribution plot shows dust fraction by mass and is black where dust is present and white where there is no dust.
The density distribution from the hydrodynamical calculation, described in Section 2, is used as input to the T"ORUS\textsuperscript{1} radiative transfer code (Harries 2000). The \textit{VH-1} density field is mapped on to a T"ORUS grid comprising 256 × 256 cells.\textsuperscript{2} This density field is used to calculate temperature and ionization equilibrium using an iterative Monte Carlo method, similar to that of Ercolano et al. (2003) and Wood, Mathis & Ercolano (2004). The photoionization component of T"ORUS has been described in detail by Haworth & Harries (2012) and Haworth et al. (2015). For the calculations presented in this paper the photoionization calculation operates stand-alone (without a T"ORUS hydrodynamics calculation) using a static density distribution derived from the \textit{VH-1} calculation. Consequently we are able to use a more computationally expensive determination of equilibrium temperature (based on the balance between ionization, recombination and forbidden line cooling) rather than the simplified thermal balance calculation of Haworth & Harries (2012). Like Haworth & Harries (2012) we use a polychromatic radiation field and explicitly represent the diffuse radiation field (i.e. there is no on-the-spot approximation). A total of 22 species are included in the photoionization calculation, with abundances from Ferland (1995) as shown in Table 2. The star is represented by a blackbody source with a temperature of 40 000 K and a luminosity of $L = 1.41 \times 10^{6} \ L_{\odot}$ which produces an ionizing photon flux of $7.45 \times 10^{49} \ s^{-1}$. The effects of dust opacity are included in the radiative transfer calculation, and separate gas and dust temperatures are calculated as the gas and dust are not expected to be thermally coupled. The dust grains are Draine and Lee silicates with a uniform size of 0.1 $\mu$m and a density of 3.6 $g \ cm^{-3}$. The total opacity (solid line), absorption opacity (dashed line) and scattering opacity (dotted line) per gramme of gas, plotted as a function of wavelength, for the 0.1 $\mu$m silicate dust grains used in the radiative transfer calculation.

The results from the photoionization calculation were used to generate synthetic observations (infrared, H $\alpha$ and radio images and infrared SEDs). The temperature, density, abundance and dust distributions at the end of the photoionization calculation are used to populate the T"ORUS grid with emissivities at the appropriate wavelength. A Monte Carlo sampling technique (Harries 2000) is then used to sample the emission with a number of photon packets which are propagated through the grid (accounting for scattering and absorption events) to determine the flux in a prescribed image plane. The method has previously been applied to output from T"ORUS photoionization calculations by Haworth, Harries & Acreman (2012).

### 4 SYNTHETIC OBSERVATIONS

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#### 4.1 Infrared images and SEDs

For generating infrared images and spectral energy distributions (SEDs) the emissivity of a grid cell $\epsilon_{\lambda}$ at a wavelength $\lambda$ is given by

$$\epsilon_{\lambda} = B_{\lambda}(T) \kappa_{\lambda,\text{ISM}}$$

\begin{table}
\centering
\caption{Elements and species included in the photoionization calculation with elemental abundances relative to hydrogen.}
\begin{tabular}{lll}
Element & Species & Abundance \\
\hline
H & LII & 1 \\
He & LII,III & 0.1 \\
C & LII,III,IV & $2.2 \times 10^{-4}$ \\
N & LII,III & $4 \times 10^{-5}$ \\
O & LII,III & $3.3 \times 10^{-4}$ \\
Ne & LII,III & $5 \times 10^{-5}$ \\
S & LII,III,IV & $9 \times 10^{-6}$ \\
\end{tabular}
\end{table}

\footnote{1 \url{www.astro.ex.ac.uk/people/th2/torus_html/homepage.html}}

\footnote{2 The number of cells in each dimension of the T"ORUS grid must be a power of 2 as T"ORUS uses a tree structure to store the grid.}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure2.png}
\caption{Total opacity (solid line), absorption opacity (dashed line) and scattering opacity (dotted line) per gramme of gas, plotted as a function of wavelength, for the 0.1 $\mu$m silicate dust grains used in the radiative transfer calculations.}
\end{figure}
where $B_\lambda(T)$ is the Planck function at temperature $T$, $\kappa_\lambda$ is the wavelength-dependent absorption opacity from dust, and $\rho_{\text{ISM}}$ is the ISM gas density. Referring to Fig. 1 we see that the emissivity will be zero in the stellar wind (both shocked and unshocked regions), as there is no dust and hence $\kappa_\lambda = 0$. The highest emissivities will be in the high-density parts of the forward shock where the density and temperature (hence $B_\lambda(T)$) are high.

4.1.1 Images

Synthetic images at 22 microns and 12 microns are shown in the first and second rows of Fig. 3 respectively. The size of the images corresponds to 2.25 arcmin at a distance of 1 kpc and the colour scale is in distance independent units of MJy sr$^{-1}$. To represent the effect of spatial resolution the 22 micron images have been smoothed with
Bow shocks from runaway early-type stars

4.1.2 SEDs

SEDs, as seen at 0° inclination (face-on; solid line) and 90° inclination (side-on; dashed line) are shown in Fig. 4. The assumed distance is again 1 kpc. The top figure plots the SEDs as \( \lambda F_\lambda \), and shows that at wavelengths shorter than 5 \( \mu m \) the emission is dominated by the star, and at wavelengths longer than 5 \( \mu m \) emission from hot dust in the bow shock dominates. This is consistent with the infrared images which show bow shock emission at 12 and 22 \( \mu m \), but not at 3.4 or 4.6 \( \mu m \). At 90° inclination the star is unobscured by bow shock material and the SED is similar to that of a star with an accretion disc viewed face-on (the optical depth along the path from the star to the observer is 0.427 at 0.1 \( \mu m \)). At 0° inclination bow shock material obscures the star and the SED appears more like an SED from a star-disc system where the disc partially blocks direct stellar radiation (the optical depth along the path from the star to the observer is 2.57 at 0.1 \( \mu m \)). The total luminosity of the SED is 1.22 \( \times 10^5 \) L_\odot, compared to the stellar luminosity of \( L = 1.41 \times 10^6 \) L_\odot.

The lower figure plots the SEDs in mJy over the range 1–100\( \mu m \) and solid points are from candidate 7 of the Kobulnicky et al. (2010) sample, where circles are detections and triangles are upper limits. Candidate 7 is the most massive and energetic star in their sample and consequently is the best comparison to our model. In Fig. 4 the assumed distance is changed to 2.1 kpc to match the distance to candidate 7 in the Kobulnicky et al. (2010) sample. Kobulnicky et al. (2010) find their SED is consistent with a temperature of 40 000 K and \( \log (L/L_\odot) = 6.15 \), so is about 4.4 times more luminous than at 22 microns as the spatial resolution is higher (6.5 arcsec compared to 12 arcsec). Infrared observations of bow shocks show a crescent-shaped structure ahead of the star frequently with a bright spot near the apex (Kobulnicky et al. 2010; Perie et al. 2012). These structures are similar to our synthetic observations at 60° and 90° inclinations.

Figure 4. SEDs from the star and bow shock viewed at 0° inclination (face on; dashed line) and 90° inclination (side on; solid line). Top: SED in SI units plotted as \( \lambda F_\lambda \) versus wavelength in microns, bottom: SED in mJy versus wavelength in microns. At wavelengths shorter than 5 \( \mu m \) the emission is dominated by the star and at wavelengths longer than 5 \( \mu m \) emission from hot dust in the bow shock dominates. Solid circles are photometric points from Kobulnicky et al. (2010) and solid triangles show upper limits. Open circles and open triangles show the Kobulnicky et al points scaled by a factor of 4.4 to account for our more luminous star.

with a similar temperature.\(^3\) Open circles and open triangles show the Kobulnicky et al. (2010) candidate 7 points scaled by a factor of 4.4 to account for our more luminous star. Compared to the observed photometric data points we have higher levels of emission, more than the factor of 4.4 in the stellar luminosity, although we have not included extinction effects in our model SED. The peak in the SED due to the bow shock appears at shorter wavelengths in our model SED than in the SED fitted to candidate 7 by Kobulnicky et al. (2010). However the model has a smaller shock stand-off distance (∼0.1 pc for the model compared to a projected distance of 0.53 pc for candidate 7) so it is reasonable to expect higher temperature material in the model bow shock (hence a shorter wavelength peak in the SED) and for more stellar radiation to be reprocessed through the bow shock (hence higher levels of emission). Meyer et al. (2014b) find that the bow shock luminosity scales strongly with stand-off distance in their models (stronger that \( R_0^3 \)), according to their fig. 24). Such a strong dependence on \( R_0 \) indicates that a quantitative

\(^3\) The higher luminosity of our model star is required in order to be consistent with the stellar wind parameters used in Section 2.
comparison between observed and model SEDs requires tuning the model parameters to produce a similar shock stand-off distance to the observed object, as well as the inclusion of extinction.

### 4.2 Hα images

When calculating Hα images the emissivity of a grid cell is the sum of the recombination line emissivity and the dust emissivity (the latter is described in Section 4.1). For this model the dust emissivity from the bow shock is negligible in comparison to the recombination emissivity (the emission at 0.66 μm seen in the SED shown in Fig. 4 is from the star and not the dust). However scattering from dust is significant at this wavelength (see Fig. 2), affecting emission in bright regions of the synthetic image by several per cent, so dust opacity is included in the calculations.

The Hα line intensities are calculated using values from Hummer & Storey (1987), scaled according to the temperature dependence of the recombination coefficient in Table 1 of Storey & Hummer (1987). The Hummer & Storey (1987) line intensities are calculated relative to the Hβ line intensity given by

$$\epsilon_{H\beta} = 1.235 \times 10^{-25} n_e n_H^2 \left( \frac{T}{10^4 K} \right)^{-0.87}$$  (4)

where the constant term is the emission measure given in Hummer & Storey (1987). The fiducial values are the case B values from Hummer & Storey (1987) for a density of $n = 10^5$ cm$^{-3}$ and a temperature of 10$^4$ K.

All the gas in our model is highly ionized so the Hα emissivity is effectively a function of temperature (to the power $-0.87$) and density squared. The emissivity of the stellar wind region is low due to the low density and high temperature. Hα emission is expected to originate predominantly from the dense material at the forward shock. This region is bright in both infrared emission and Hα emission as it is dense, ionized, and contains dust.

Hα images are shown in the third row of Fig. 3. The images have been blurred with a 1 arcsec Gaussian filter, representative of a high spatial resolution Hα survey (e.g. IPHAS). The elliptical bands of emission seen at 30 and 60° inclinations, and the stripes seen at 90° inclination, are due to viewing a 2D simulation rotated about the axis of symmetry. The same effect was seen in the synthetic images of Raga et al. (1997) shown in their fig. 5. In reality, and in a 3D simulation, we would expect these features to show bright knots of emission associated with instabilities at the forward shock (see Fig. 1).

The bow shock is more clearly identifiable in the Hα images, with a more prominent bow morphology, due to the higher spatial resolution. If the Hα images are smoothed to the same resolution as the infrared images then the bow shock morphology is very similar. This is unsurprising given that the infrared and Hα emission both originate from the same region.

### 4.3 Radio images

When generating radio images we calculate thermal free–free emission from ionized hydrogen and the emissivity of a grid cell is given by

$$\epsilon_{\nu} = n_e^2 \alpha_{\nu,k} (\nu, T) \exp \left( -\frac{h\nu}{kT} \right) \frac{2h\nu^3}{c^2}$$  (5)

where $\alpha_{\nu,k}(\nu, T)$ is the free–free absorption coefficient for hydrogen at a frequency $\nu$ in a cell with temperature $T$ (Mihalas & Mihalas 1984) and $n_e^2$ is the electron density. The dependance of the emissivity on the square of the electron density means that dense, ionized material within the forward shock again dominates the emission.

Synthetic radio observations at 1.4 GHz are shown in the fourth row of Fig. 3. These images have not been spatially smoothed and hence show the sharpest features. Bands of emission associated with the 2D geometry are again seen, which in reality would correspond to knots of emission at the forward shock.

### 4.4 Emission slices and shock stand-off distance

Slices of intensity are shown in Fig. 5 for 12μm (solid line), 22 μm (dashed line) and Hα (dotted line) for 30°, 60° and 90° inclinations. For each slice the intensity has been normalized, by dividing by the maximum intensity, to enable the shape of the profiles to be more easily compared. The stand-off distance $R_0$, projected by the inclination angle, is shown as a solid vertical line. The x-axis is shown in parsecs and also arcseconds at a distance of 1 kpc.

At 90° inclination the peak of the 22μm emission is very close to the calculated stand-off distance of 0.1 pc. For the 12μm and Hα emission the peaks are at a slightly greater distance but are also very close to 0.1 pc. The peaks of emission are closer to the calculated stand-off distance than might be expected given the position of the Wilkin analytical solution relative to the forward shock (see Fig. 1). At 60° inclination the infrared peaks are in approximately the same location as at 90° inclination but the Hα slice no longer shows a clear maximum. At 30° inclination the infrared peaks are clearly separated with the 12μm peak closer to the star. Fig. 6 again shows the 12μm (solid line) and 22μm (dashed line) intensity slices (previously plotted in the top-left panel of Fig. 5) but also shows a 22μm slice smoothed to the same resolution as the 12μm slice (dotted line). This shows that the differences in the 12μm and 22μm profiles are not just due to resolution. The z-axis temperature profile in the region ahead of the star is shown in the bottom-right panel of Fig. 5 (the star is at $z = 0$). A temperature gradient is seen with temperature decreasing in the upstream direction, consistent with the 12μm emission peaking closer to the star than the 22μm emission.

### 5 DISCUSSION

#### 5.1 Comparison with previous synthetic observations

Synthetic Hα and dust continuum maps of a runaway star have been previously published by Raga et al. (1997), also using 2D hydrodynamical and radiative transfer calculations. Compared to our simulations Raga et al. (1997) have a much lower ISM density (1 cm$^{-3}$ compared to 1000 cm$^{-3}$). In reality the ISM is far from homogeneous and a runaway star will encounter a range of ISM properties along its trajectory, hence both these regimes are of interest. Raga et al. (1997) also see the highest Hα emissivity from the forward shock (see their fig. 4), and their Hα and dust continuum maps (see their fig. 5) show significant similarities (although they note that the dust continuum has more extended emission in the bow shock wings).

Synthetic radio images were presented by Mac Low et al. (1991) and compared to observations of ultracompact H II regions. In their model the emission emanates from a limb-brightened ionized shell, giving a similar morphology to our synthetic radio images. However their model does not form dense knots of material (the result of instabilities in the forward shock/contact discontinuity region)
which give rise to the smaller scale structures seen in our synthetic observations.

More recently Meyer et al. (2014b), in their models of main-sequence stars, find that ‘most of the emission by radiative cooling comes from shocked ISM gas which cools as the gas is advected from the forward shock to the contact discontinuity’. In our model the contact discontinuity and forward shock are not separated so there will not be advection from the forward shock to the contact discontinuity. However in both our model and the models of Meyer et al. (2014b) most infrared emission is from dense regions associated with the forward shock.

5.2 Future model developments

Although our synthetic observations show an encouraging similarity in morphology to observations, and are consistent with previous synthetic observations, there are aspects of the model which will require further development if all relevant physical processes are to be taken into account.

The location and composition of the dust are subject to significant uncertainties but could have a significant influence on observables in the infrared regime. Dust does not necessarily follow the gas distribution in a stellar bow shock (van Marle et al. 2011) with larger dust grains penetrating into the unshocked stellar wind, and

Figure 5. The first three panels show intensity slices along the z-axis at 12 µm (solid line), 22 µm (dashed line) and Hα (dotted line), for inclinations of 30° (top-left), 60° (top-right) and 90° (bottom left). For each slice the intensity has been normalized by dividing by the maximum intensity. The standoff distance $R_0$, projected by the inclination angle, is shown as a solid vertical line. The bottom-right panel shows the dust temperature along the z-axis. The assumed distance is 1 kpc and the star located is at z = 0.

Figure 6. Intensity slices along the z-axis at 12 µm (solid line) and 22 µm (dashed line) for a 30° inclination angle. The dotted line is the intensity slice from the 22 µm synthetic image smoothed to the same resolution as the 12 µm synthetic image (i.e. 6.5 arcsec) to show resolution effects. The standoff distance $R_0$, projected by the inclination angle, is shown as a solid vertical line.
even the smaller grains can reach the wind termination shock (van Marle et al. 2015). Variations in dust composition, and presence of PAHs, can have a significant impact on infrared observables (Kobulnicky, Gilbert & Kiminki 2010; Pavlyuchenkov, Kirsanova & Wiebe 2013). Variations in composition can be driven by a number of mechanisms in addition to the effects described by van Marle et al. (2015) e.g. differing destruction time-scales and the effects of radiation pressure (Ochsendorf et al. 2014).

Although our model provides a thorough treatment of radiative transfer in the gas and dust, and accounts for the effects of shock heating, it does not self-consistently couple the hydrodynamics and radiative transfer. It is considerably more computationally expensive to run such a coupled calculation using Monte Carlo radiative transfer, however such calculations have already been shown to be tractable in 3D using the TORUS code (Haworth & Harries 2012). Our current hydrodynamical model also does not include magnetic fields. van Marle, Decin & Meliani (2014) examine the effects of magnetic fields on the bow shock around an AGB star. They conclude that the main effect is suppression of instabilities, rather than an influence on the larger scale morphology. As our model involves significantly higher speeds for both the star and the stellar wind we will have a much higher ram pressure from both these components. Consequently the influence of the ISM magnetic field on the large scale structure will be even smaller than that seen by van Marle et al. (2014). However if magnetic fields are effective at suppressing instabilities this will affect the formation of the dense knots of material seen in our model, which are associated with prominent observable features.

6 CONCLUSIONS

We have generated synthetic images in infrared, H α and radio regimes for a runaway O star passing though a high-density ISM. In all cases the emission is dominated by knots of dense material formed by instabilities at the forward shock. This region contains dust but is also ionized so it is seen not only at infrared wavelengths (due to emission from warm dust) but is also seen in the H α recombination line and free–free radio emission. Differences in bow shock morphology are largely due to differing spatial resolution and the fundamental morphology is very similar (particularly as we have assumed that the dust distribution follows the gas distribution outside the stellar wind).

Synthetic infrared SEDs show a similar shape to observed bow shock SEDs (Kobulnicky et al. 2010) but with higher levels of emission. This can be attributed partly to our model star being brighter than the observed stars but also to a smaller shock stand-off distance. Achieving a better quantitative match to specific observations would require selecting model parameters which better represent the target of the observation. Variations in dust properties and the presence of PAHs may also need to be taken into account in order to achieve a quantitative match with observations.

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