Numerical Models For Betelgeuse’s Circumstellar Medium

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6 February 2013

MPIfR/AlfA Lunch Colloquium

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Outline

• Motivation for our work - massive stars and their feedback effects.

• Introduction to the circumstellar medium (CSM) around Betelgeuse.

• Simulations of CSM around a runaway star evolving from blue to red.

• Conclusions.


Betelgeuse is “Evolved” and “Evolving”!

Wednesday 6 February 2013
Massive Star Evolution

- Massive star evolution is not very well understood (e.g. Langer 2012).
- But it is a key driver of galaxy evolution...
- Metallicity, binarity, rotation, and magnetic fields are all important.
- Some mass-loss rates are uncertain at order-of-magnitude levels.
- Assigning masses to nearby evolved massive stars is very difficult.
- CSM studies can help to constrain mass-loss rates, and evolutionary sequences.
Runaway Stars / Exiles

- About 15-25% of O stars are isolated (Gies, 1987).
- Most of these are classical runaway stars ($V>30\text{km/s}$) or lower velocity “exiles” (Gvaramadze+, 2012).
- Ejected from star clusters, or from binaries when the primary explodes.
- Usually isolated, and in the diffuse ISM.
- CSM reaches a “steady” state in a “short” time (about 0.1 Myr).
- CSM shaped mostly by stellar wind and ionising photons.

Introduction to Betelgeuse

- H-alpha map of Orion (right).
- D~200pc, 2nd nearest RSG to sun (Harper+, 2008).
- Proper motion and bow shock (Ueta+, 2008) implies V=28-73 km/s, moving to ~Northeast.
- Mass ~11-20 M⊙. Teff ~3300K. (e.g. Neilson+, 2011).
- Has mid-IR bow-shock and “bar” upstream from bow shock (Noriega-Crespo+, 1997).
- Size similar to the full moon.
• DSS POSS2 Blue image (right).

• Optical/NIR imaging is very difficult!

• CSM first discovered in far-IR data.
• WISE 22um all-sky survey data.
• Can just make out the bow shock, and also a linear feature to the NE.
- IRAS 60 um image
- Noriega-Crespo et al. (1997)
- Total mass of wind and bow shock $M \sim 0.033 \, M_{\odot}$ for $d=200\, \text{pc}$.
✧ AKARI data 
(Ueta+, 2008, PASJ)
✧ Bow-shock has 
M~0.0033 $M_\odot$
based on AKARI
flux 
• Herschel image (70, 100, 160 um)
• Bow shock mass is $M \sim 0.002 \, M_\odot$ from this data.

• HI 21cm data from VLA (2.4 km/s).

• Detached shell of emission with 2’ radius (0.12pc)

• HI 21cm data from VLA (3.7 km/s).

• Detached shell of emission with 2’ radius (0.12pc)

HI 21cm data from VLA.

Detached shell of emission with 2’ radius (0.12pc)
Mohamed, Mackey & Langer (2012): Constant Wind Models

✦ The first 3D SPH simulations of a constant RSG wind interacting with ISM, generating a bow shock.

✦ Different ISM densities, stellar space velocities.

✦ Bow shock is clumpy and unstable, and mass is $M > 0.1 \, M_\odot$ in steady state.

✦ If $M = 0.0033 \, M_\odot$, bow shock must be <30 kyr old, or even younger if $M = 0.002 \, M_\odot$.

✦ So maybe the wind is evolving?
Mohamed, Mackey & Langer (2012): Constant Wind Models
Evolving wind model


- 15 $M_{\odot}$ model.

- Computed to have RSG properties similar to Betelgeuse (see Neilson+2011).

- Simulation starts at 11.4 Myr, shown by asterisk.

- Blue section lasts 75 kyr (from 11.832 to 11.907 Myr).
Stellar Wind Properties

- Last 75 kyr of evolution (blue region of previous plot).
- $M_{\text{dot}}, V_w$, and wind density plotted.
- Kink is due to luminosity dip.
2D Hydrodynamical Simulations

- 2D simulations of (z,R) plane with rotational symmetry.
- Use the pion code (Mackey & Lim, 2010, 2011).
- Collisional ionisation equilibrium gas cooling (Wiersma+2009).
- Star has \( V^* = 50 \text{ km/s} \), through ISM with \( n(\text{H}) = 0.2 \text{cm}^{-3} \).
- Star is static on grid, ISM flows past (right to left).
- Freely-expanding wind imposed in region \( r < 0.05 \text{ pc} \) (Freyer+, 2003).
Shell Mass

- Mass of inner shell measured from simulations during time between BSG reverse-shock collapse and contact discontinuity collapse.
- Mass ~50% lower than AKARI mass estimate, but within a factor of 2.
- Similar to Decin+(2012) estimate, but not Cox+(2012).
Shell Masses

- Inner shell much less massive than remnant of outer BSG bow shock, and inner RSG wind.
  - Le Bertre+(2012): $M_{\text{wind}} \sim 0.068 \, M_\odot$ (VLA 21cm data)
  - Decin+(2012): $M_{\text{wind}} \sim 0.02-0.07 \, M_\odot$ (also 21cm), $M_{\text{bar}} \sim 0.002-0.029 \, M_\odot$, $M_{\text{arc}} \sim 0.0024 \, M_\odot$.
  - Cox+(2012): $M_{\text{arc}} \sim 0.16-0.28 \, M_\odot$ (different dust + distance).
Dust Emission

- Projected dust luminosity (above), and mass surface-density below.
- Fairly standard assumptions about dust absorption/emission/abundance.
- Dust is simply re-radiating stellar flux.
• Decin et al. (2012) Herschel image again.
• Simulation overlaid on roughly the same scale.
• Decin et al. (2012) Herschel image again.

• Simulation overlaid on roughly the same scale.
Conclusions

15-20 M⊙ runaway stars evolving from MS/BSG to RSG can produce multiple bow shocks/shells during transition.

They are a generic feature of blue-to-red transitions, and may be visible for 50-100 kyr (depending on parameters).

Our model can match Betelgeuse’s bow shock in terms of location (~0.35pc upstream) and mass (~0.002 M⊙).

May be the simplest explanation for its low mass.

And provides a natural explanation of the upstream bar.

If Betelgeuse was recently a BSG, with our model it would be ~15 kyr from supernova.

Caveats: uncertain masses of shocks, curvature of bar, stellar velocity in the model, HI shell at 2’ from star.
What Can We Learn?

• If star is **not** evolving rapidly, bow shock size and shape constrain wind and ISM properties.

• H II region also constrains ISM properties (if star is hot).

\[ R_0 = \left[ \frac{\dot{M}v_\infty}{4\pi n(\mu m_H v_*^2 + 2kT)} \right]^{1/2} \]

• If star **is** evolving, bow shock may not be in steady state, and CSM is more complicated.

• Combines historical variations in stellar wind (and ionising photon luminosity) with hydrodynamical evolution.
Bow Shock Models

- Bow shock standoff distance, $R_0$, obtained by equating ISM ram and thermal pressure with wind ram pressure (e.g. Baranov et al. 1971).

\[
R_0 = \left[ \frac{\dot{M} v_\infty}{4\pi n (\mu m_H v^*_s + 2kT)} \right]^{1/2}
\]

- Here $n$ is the ISM number density, $v^*_s$ is the star’s space velocity, $\mu = 1.27$ is the mean molecular weight, $m_H$ is the H atom mass.

- For large Mach numbers $M = v^*_s / c_i$, the $kT$ term drops out (where $c_i$ is the ionised gas sound speed).

- $R_0$, $v^*_s$, can be measured with good data; $T$ is not so important; the wind velocity, $v_\infty$, can be measured.

- Only $n$ is difficult to constrain (cf. Kobulnicky+2010).

- If we know $n$ we can constrain $\dot{M}$ (e.g. Gull & Sofia, 1979)
Supersonic Stars

- Simple picture of CSM around star moving supersonically, from centre outwards:
  - Freely-expanding wind;
  - reverse/termination shock;
  - Shocked wind (hot bubble) \( R \sim 0.1-3 \) pc;
  - Contact discontinuity between wind and ISM gas;
  - Shocked ISM;
  - Forward Shock driven into ISM.

Asymmetric CSM around a supersonically-moving star (Credit: N.Cox, KU Leuven)

N.B. Reaches steady state in finite time! (if stable)
Our line of reasoning

✦ If the bow shock is really young, then either Betelgeuse or the ISM has changed.
✦ We consider the first possibility.
✦ The CSM shows relics of previous mass loss, rather like tree rings showing climate history.
✦ We can learn about Betelgeuse’s past, and therefore (maybe) also its future.
✦ We know so little about its fundamental parameters, so any constraints are valuable.