Photoionized winds of cool stars

Jonathan Mackey
Argelander-Institut für Astronomie (aifa), Uni. Bonn

Collaborators:
Shazrene Mohamed (SAAO, Cape Town)
Vasilii Gvaramadze (Lomonosov Moscow State University, Russia)
Norbert Langer (aifa, Bonn)
Rubina Kotak (Queen’s University Belfast)
Dominique Meyer (aifa, Bonn)
Takashi Moriya (aifa, Bonn)
Hilding Neilson (East Tennessee State University, USA)

22 October 2014, MPIfR/AIfA Lunch Colloquium
Outline

- Photoionized red supergiant (RSG) winds:
  - observational motivation: Betelgeuse, IRC-10414, W26
  - Formation of photoionization-confined shells
  - Shell properties for different progenitors
  - Estimates of supernova interaction with shells
All of the bright stars in Orion are evolved Giants or Supergiants, with masses 8-30 $M_\odot$, and all are closer to us than M42 or the Horsehead Nebula.
Introduction to Betelgeuse

• H-alpha map of Orion (right).

• D=200 pc, closest RSG to the sun (Harper +,2008). (or 2nd closest, after Antares?).

• Proper motion and bow shock implies $V=28$-73 km/s (Ueta+,2008), moving to Northeast.

• Mass $\sim 11$-20 $M_\odot$. $T_{\text{eff}} \sim 3300$K. (e.g. Neilson+,2011).

• Has mid-IR bow-shock and “bar” upstream from bow shock (Noriega-Crespo+,1997).

• Circumstellar structures are similar in size to the full moon.
Herschel’s view of Betelgeuse

- Far infrared emission shows dust emission from re-radiated starlight.

- The “bar” may be circumstellar (Mackey+, 2012) or interstellar (Decin+, 2012) in origin.

- The bow shock marks the interaction of the RSG wind with the surrounding medium (Mohamed+, 2012).

- What is the inner shell? Discovered in HI 21cm emission by Le Bertre+ (2012)

Herschel image (PACS 70 μm) of Betelgeuse’s surroundings (Decin+2012)
Herschel’s view of Betelgeuse

• Far infrared emission shows dust emission from re-radiated starlight.

• The “bar” may be circumstellar (Mackey+, 2012) or interstellar (Decin+, 2012) in origin.

• The bow shock marks the interaction of the RSG wind with the surrounding medium (Mohamed+, 2012).

• What is the inner shell? Discovered in HI 21cm emission by Le Bertre+ (2012)
## Circumstellar Medium (CSM) structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>radius</th>
<th>radius</th>
<th>mass</th>
<th>interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>bar</td>
<td>0.5 pc</td>
<td>9’</td>
<td>0.002–0.029 M</td>
<td>interstellar/circumstellar?</td>
</tr>
<tr>
<td>bow shock</td>
<td>0.35 pc</td>
<td>6-7’</td>
<td>0.0024–0.03 M</td>
<td>wind-ISM interaction</td>
</tr>
<tr>
<td>Inner shell</td>
<td>0.12 pc</td>
<td>2’</td>
<td>0.09 M</td>
<td>Photoionization-confined shell</td>
</tr>
</tbody>
</table>


- We propose the inner shell is confined because the outer parts of the wind are photoionized by an external radiation field.
- The outer wind is hot (∼10⁴K), inner wind is colder (∼100K).
- Pressure gradient across D-type ionization front drives a shock.
Two related problems

• Betelgeuse has an unexplained static shell around it, not caused by eruptions or extreme mass loss.
• About 10% of core-collapse supernovae show evidence of very dense circumstellar medium (shells?), type IIln and overluminous SNe.
• Origin of this dense CSM is unclear; one possibility is luminous blue variable (LBV) eruptions, but LBVs are not thought to be direct SN progenitors.
• Betelgeuse’s shell may provide an explanation for this very dense CSM.
Other photoionized RSG winds

IRC-10414 (Gvaramadze+, 2014; Meyer+, 2014)

- Bow shock discovered in Hα + [NII] filter using the SuperCOSMOS Hα Survey.
- Spectra with SALT showed that [NII] is stronger than Hα, indicating photoionization.
- Hydrodynamical models with postprocessing showed that only a photoionized RSG wind could produce the observed emission.

See also NML Cyg (Morris & Jura, 1983), and W26 in Westerlund 1 (Wright+, 2014).

Left: Hα+[NII] surface brightness (Rayleigh)
Right: Line ratio [NII]/Hα
Other photoionized RSG winds

W26 in Westerlund 1
(Wright+, 2014)

- Ring-shaped emission nebula about 0.03 pc from W26, a massive RSG (about 40 $M_\odot$) in Westerlund 1.
- One interpretation is that the wind is photoionized by the nearby O, B, and WR stars.
- Could also be shock ionization by wind-wind collision.
Photoionization-confined (PICO) shells

- Schematic diagram for Betelgeuse's bow shock and PICO shell.
- PICO shell is an “inside-out” HII region.

Photoionization-confined shells

Classic D-type ionization front (e.g. Kahn, 1954; Mihalas & Mihalas, 1984)

- Structure of the shell.
- Data from a 1D radiation-hydrodynamics simulation.
- Photoionization heats the wind to $T \sim 10^4$ K.
- Wind is much hotter at large radius than small radius.
- Ionization front is D-type, so thermal pressure drives a shock into the neutral wind.
- The standing shock accumulates mass, trapping 20-35% of the RSG wind.
Photoionization-confined shells

- Animation of the shell growth from the simulation.
Photoionization-confined (PICO) shells

- Steady-state shell radius (Morris & Jura, 1983):

\[
R_{IF} = \left( \frac{\alpha_B}{3F_\gamma} \right)^{1/3} \left( \frac{X_H \dot{M}}{4\pi v_n m_p} \right)^{2/3}
\]

\[
= 0.018 \text{ pc} \left( \frac{\dot{M}}{10^{-4} M_\odot \text{ yr}^{-1}} \right)^{2/3} \left( \frac{F_\gamma}{10^{13} \text{ cm}^{-2} \text{ s}^{-1}} \right)^{-1/3} \left( \frac{v_n}{15 \text{ km s}^{-1}} \right)^{-2/3}
\]

- Shell mass once the hydrodynamics reaches a steady state:

\[
M_{\text{shell}} = \left( \frac{\alpha_B X_H^2}{162\pi^2 m_p^2} \right)^{1/3} \frac{a_i}{a_n^2} \left( 1 - \left[ \frac{v_n}{2a_i} \right]^{3/2} \right) \dot{M}^{5/3} F_\gamma^{-1/3} v_n^{-2/3}
\]

\[
= 9.2 M_\odot \left( \frac{\dot{M}}{10^{-4} M_\odot \text{ yr}^{-1}} \right)^{5/3} \left( \frac{F_\gamma}{10^{13} \text{ cm}^{-2} \text{ s}^{-1}} \right)^{-1/3}
\]
Equilibrium shell positions

• Steady-state shell radius (Morris & Jura, 1983):

\[ R_{IF} = \left( \frac{\alpha_B}{3F_\gamma} \right)^{1/3} \left( \frac{X_H \dot{M}}{4\pi v_n m_p} \right)^{2/3} \]

\[ = 0.018 \text{ pc} \left( \frac{\dot{M}}{10^{-4} \text{ M}_\odot \text{ yr}^{-1}} \right)^{2/3} \left( \frac{F_\gamma}{10^{13} \text{ cm}^{-2} \text{ s}^{-1}} \right)^{-1/3} \left( \frac{v_n}{15 \text{ km} \text{ s}^{-1}} \right)^{-2/3} \]

• Shell mass once the hydrodynamics reaches a steady state:

\[ M_{\text{shell}} = \left( \frac{\alpha_B X_H^2}{162\pi^2 m_P^2} \right)^{1/3} \frac{a_i}{a_n^2} \left( 1 - \left[ \frac{v_n}{2a_i} \right]^{3/2} \right) \dot{M}^{5/3} F_\gamma^{-1/3} v_n^{-2/3} \]

\[ = 9.2 \text{ M}_\odot \left( \frac{\dot{M}}{10^{-4} \text{ M}_\odot \text{ yr}^{-1}} \right)^{5/3} \left( \frac{F_\gamma}{10^{13} \text{ cm}^{-2} \text{ s}^{-1}} \right)^{-1/3} \]
Equilibrium shell masses

- Steady-state shell radius (Morris & Jura, 1983):

\[
R_{IF} = \left( \frac{\alpha_B X_H}{3 F_{\gamma}} \right)^{1/3} \left( \frac{X_H \dot{M}}{4 \pi v_n m_p} \right)^{2/3}
\]

\[
= 0.018 \text{ pc} \left( \frac{\dot{M}}{10^{-4} \text{ M}_\odot \text{ yr}^{-1}} \right)^{2/3} \left( \frac{F_{\gamma}}{10^{13} \text{ cm}^{-2} \text{ s}^{-1}} \right)^{-1/3} \left( \frac{v_n}{15 \text{ km s}^{-1}} \right)^{-2/3}
\]

- Shell mass once the hydrodynamics reaches a steady state:

\[
M_{\text{shell}} = \left( \frac{\alpha_B X_H^2}{162 \pi^2 m_P^2} \right)^{1/3} \frac{a_i}{a_n^2} \left( 1 - \left[ \frac{v_n}{2 a_i} \right]^{3/2} \right) \dot{M}^{5/3} F_{\gamma}^{-1/3} v_n^{-2/3}
\]

\[
= 9.2 \text{ M}_\odot \left( \frac{\dot{M}}{10^{-4} \text{ M}_\odot \text{ yr}^{-1}} \right)^{5/3} \left( \frac{F_{\gamma}}{10^{13} \text{ cm}^{-2} \text{ s}^{-1}} \right)^{-1/3}
\]
Maximum mass of shells

- Shell mass increases approximately linearly with time until it approaches its equilibrium mass.
- Stars like Betelgeuse can have shells with masses \( \sim 0.1-1 \, M_\odot \).
- Stars like W26 will lose up to \( 20 \, M_\odot \) in the RSG phase, and so can have shells with \( \sim 4-7 \, M_\odot \).
- Final mass depends on mass-loss rate and total mass lost.
Supernova—shell interaction

- Analytic model assumes SN shock is always radiative and that 50% of kinetic energy is radiated in the postshock gas (Moriya+, 2013).

- Bolometric luminosity evolution of supernovae interacting with PICO shells.

- Choose massive shells, with ionizing fluxes such that the shell is at $2 \times 10^{16}$ cm (lower mass shell) and $4 \times 10^{16}$ cm (higher mass shell).

- Calculations for explosions with $10^{51}$ and $5 \times 10^{51}$ ergs (1B and 5B).

- Ejecta mass 15 $M_\odot$.

- Find strong rebrightening and long “plateau” phase, although much of this may not be optical emission.
Supernova—shell interaction


Luminosity (erg s\(^{-1}\))

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1000</td>
<td>(10^{40})</td>
</tr>
<tr>
<td>1000-2000</td>
<td>(10^{41})</td>
</tr>
<tr>
<td>2000-3000</td>
<td>(10^{42})</td>
</tr>
<tr>
<td>3000-5000</td>
<td>(10^{43})</td>
</tr>
<tr>
<td>5000-7000</td>
<td>(10^{44})</td>
</tr>
</tbody>
</table>

Absolute magnitude


SN 2004et (SN IIP)
Analytic model assumes SN shock is always radiative and that 50% of kinetic energy is radiated in the postshock gas (Moriya+, 2013).

- Bolometric luminosity evolution of supernovae interacting with PICO shells.
- Choose massive shells, with ionizing fluxes such that the shell is at $2 \times 10^{16}$ cm (lower mass shell) and $4 \times 10^{16}$ cm (higher mass shell).
- Calculations for explosions with $10^{51}$ and $5 \times 10^{51}$ ergs (1B and 5B).
- Ejecta mass $15 \, M_\odot$.
- Find strong rebrightening and long “plateau” phase, although much of this may not be optical emission.
Model limitations and future work

- Assume isothermal neutral gas, so the discontinuities are sharper than in reality (finite cooling length). We are working on follow-up models with more realistic heating/cooling rates.

- Anisotropic radiation fields. As an extreme case, what about WD-RG binary systems? Lower mass and asymmetric shell, but how much lower mass?

- Detailed calculations of SN-shell interaction, including predictions of X-ray, IR, optical emission.

Requirements for a photoionization-confined shell:

1. a cool star with a dense and slow wind (<20 km/s).
2. located in an ionized region of space so the wind can be photoionized from outside.

RSGs are best candidates because they live near O and B stars. AGB and RG stars by chance (up to 30% of ISM is hot ionized gas), or because they have a hot binary companion.
NML Cyg (Morris & Jura, 1983)

- Ionized from one side by hot stars from the nearby Cyg OB2 association.
- Detected by Habing + (1982) as an arc-shaped HII region in radio free-free emission.
- Simple model of photoionized wind fits the data very well.

Another example is IRS 7 in the Galactic centre (Yusef-Zadeh & Morris, 1991)
Conclusions

• We explain the shell around Betelgeuse as a photoionization-confined shell, from diffuse ionizing radiation in the Orion-Eridanus superbubble.

• Predict that these shells should be common around RSGs.

• Shell mass scales with mass-loss rate

• Shells can have up to 7 M\(_{\odot}\) at solar metallicity.

• Strong influence on SN lightcurves, relating to IIIn and SLSN

• Alternative model to the LBV \(\rightarrow\) SN scenario for SN IIIn.

• Shell should be almost static (\(V_{\text{exp}}<\sim 1\) km/s), although subsequent evolution (e.g. Wolf-Rayet) may cause expansion and/or clumping.