i-process nucleosynthesis in super-AGB stars

Carolyn Doherty (Budapest)

P. Gil-Pons (Barcelona), S. Campbell (Monash), P. Banerjee (Shanghai), J Gutiérrez (Barcelona), A. Heger (Monash), L. Siess (Brussels)
Overview

★ Super-AGB stars, Red Supergiants & Thorne-Zytkow objects
★ “i”-process - neutron densities & potential sites
★ Dredge-out nucleosynthesis in super-AGB stars
★ Potential to help constrain the lowest mass supernovae boundary
Super-AGB stars

★ Mass range ~6-12 $M_\odot$
★ Bridge the divide between low/intermediate-mass and massive stars.
★ Off-centre carbon ignition prior to a thermally pulsing phase
★ ONe Core vs CO core
★ Many 10-1000s of thermal pulses.
★ Red, cool (3000-4000K),
★ Large envelopes ~ 1000 $R_\odot$
★ Very luminous: Due to efficient Hot Bottom Burning they exceed the Paczynski luminosity limit of $M_{bol}$$\sim$-7.1
★ Low metallicity can reach $M_{bol}$$\sim$-8.2 (150,000 $L_\odot$)

Pioneering evolution models for the first TPs by Garcia-Berro, Iben & Ritossa (1994-1999)

Numerically challenging and only recently have full calculations along TP-Super-AGB phase
How do super-AGB stars die?

Either as ONe white dwarfs, or as neutron stars* after undergoing an electron capture supernova (EC-SN)?

OR

Competition between the growth of the core and the mass loss from the envelope during the super-AGB phase determines the stars fate. If the core reaches $M_{EC} \sim 1.375 \, M_\odot$ (Nomoto 1987) an EC-SN will occur.

* Debate rages over final fate of an EC-SN either as neutron star or ONeFe remnant (Isern+1991, Canal+1992, Jones+2016)

Review by Doherty, Gil-Pons, Siess & Lattanzio 2017 PASA
Hiding in plain sight?

Super-AGB stars, Red Supergiants (RSG) & Thorne-Zytkow Objects (TZO)

No observationally confirmed Super-AGB star!

How do we find them?

Very similar temperature, luminosity and radius as RSG* & TZO**

Can surface composition help distinguish these types of star?

Only some super-AGB star models find 3DU and s-process enhancement

*Red supergiant - Late stage of massive star (core He or further burning)

**Thorne-Zytkow Objects
(Thorne & Zytkow 1975/77)
Neutron star at the center of a RSG
irp-process - Mo & Rb (no Ba?)
Levesque+2014 HV2112 in SMC
Tout+2014
Beasor+2018

\[ \frac{A}{B} = \log_{10}\left( \frac{n(A)}{n(B)} \right) - \log_{10}\left( \frac{n(A)}{n(B)} \right)_\odot \]

Doherty+2017
Heavy element production - s, i, r-processes

With “intermediate” neutron densities the abundances can venture far from beta stability (Cowen & Rose 1977)

Neutron densities

\[
\begin{align*}
\text{s-process} & \sim 10^{8-13} \text{ n cm}^{-3} \\
\text{i-process} & \sim 10^{14-16} \text{ n cm}^{-3} \\
\text{r-process} & > 10^{20} \text{ n cm}^{-3}
\end{align*}
\]
i-process conditions/sites & observations

Selection of studies and proposed sites:

★ Red giants undergoing He shell places - Cowan & Rose 1977
★ Very late thermal pulses - Herwig+ 2011 (Sakurai’s object)
★ Carbon-enhanced metal poor stars s/r (i) Dardelet+ 2015, Hampel+2016
★ Post-AGB stars Lugaro+ 2015, Hampel+2018 In prep. (P#49)
★ Low metallicity low-mass stars (proton ingestion episodes) Cristallo+ 2009/16 Campbell+2010
★ Rapid accreting white dwarfs Dennisenkov+ 2017
★ Low metallicity massive stars - Banerjee+2017, Clarkson+2018 (P#111)
★ **Super-AGB stars** - dredge-outs Doherty+ 2015, Jones+2016
★ **Super-AGB stars** - thermal pulses Jones+ 2016

![Graphs showing isotopic abundance ratios and trends](image)
Dredge-out event

- In most massive super-AGB stars ~ 0.3 $M_\odot$ below SN boundary
- Convective He burning region mergers with inward moving convective envelope
- When the zones meet protons are mixed down (proton ingestion episode) to high temperature He (and C) regions
- $H$ flash $\sim 10^{6.9} \, L_\odot$
- $^{12}C(p,g)^{13}N$ reaction occurs
- $^{13}N(e^+\nu_e)^{13}C$ decays in $\sim 10$ min
- Neutron source
  - $^{13}C(a,n)^{16}O$
- Heavy element production

Siess 2007
Dredge-out event - Mass ejection?

- Mixing and burning occur on similar timescales
- 1D calculations may miss important features in this convective/reaction event
- MultiD hydrodynamic models performed for proton ingestion episode (albeit not dredge-outs)
- Jones+2016 suggested that a dredge-out may cause a global oscillation of shell-H ingestion (GOSH) event (Herwig+2014) which may lead to mass ejection of the entire envelope at this point

Herwig+2011/14, Woodward+2015

Hydrodynamic picture of H-entrainment into He-shell flash convection near the luminosity peak of the flash for a very late thermal pulse.
Can these events produce a unique nucleosynthetic signature?

Ritossa+1999 (IBEN CODE)

Jones+ 2016 (MESA)

Siess 2007 (STAREVOL)

Takahashi+ 2013

Doherty+ 2018 (in prep) (KEPLER)

Doherty+ 2015 (MONSTAR)
(Very) Preliminary results

- First heavy element study for dredge-out events
- Using KEPLER 1D stellar evolution code (Heger+)
- Adaptive nuclear network ~ 1000+ species
- Spontaneous ingestion of protons
- Peak neutron densities > $3 \times 10^{14} \text{n/cm}^3$
- Temperature ~ 250MK, Density ~ 500g/cm$^3$

**Elements heavier than Rb produced**

Yield at base of He convective zone

Different signature than standard thermal pulses

Banerjee+2017 25Msun Massive star

Z=0, [Z] = $-5, -4, -3, -2$.  

[Graph showing yield vs. atomic number]
Summary/Future Work

★ Dredge-out events in Super-AGB stars make heavier elements (up to even Pb) compared to the (potential) mainly Rb during the thermal pulsing phase

★ Heavy element abundances may help us positively identify a super-AGB star compared to other unusual objects such as Thorne-Zytkow Objects

★ Currently computing detailed models for a range of metallicities and mixing prescriptions

★ Can the dredge-out cause an edjection of the stellar envelope?
★ Multi-dimensional hydrodynamic simulations of this event are crucial!