Mass loss

- up to now we assumed stellar mass *M* to be constant.

- Sun, for example, looses, however, $\sim 10^{-14}\,M_\odot/y$ via solar wind (400-800 km/s), CMEs, flares, etc., which can safely be ignored.

- in other stars, and during later evolutionary stages, however, mass loss can be as large as $10^{-8}\,M_\odot/y$ or even beyond, e.g. for stars with $\geq 50\mathrm{M}_\odot$ and during AGB phase of $5\mathrm{M}_\odot$ stars.

- mass loss ranges from being irrelevant up to 50% loss of its original mass.

- note that mass loss due to nuclear transmutations is about of similar magnitude in the Sun (and other stars) as the solar wind.

Mass loss

- evidence of mass-loss from direct detection of circumstellar matter and spectral line signatures (Doppler shifts, line shapes).

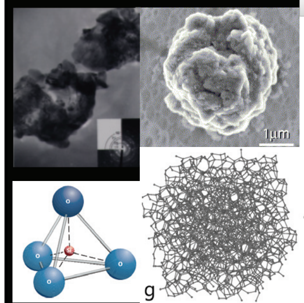
- stellar wind velocities: ~ 5 … 1000 km/s .

- stellar winds result typically from interaction of photons (photosphere) with atoms, molecules, dust grains → complicated radiation-hydrodynamics problem.

Composition of dust

Gall et al. (2014, Nature)

- Compositions
  - Carbon rich
  - Oxygen rich



Dust species	Chemical definition	T_c [K][a]	Spectral characteristics, prominent bands [μm][b]
Carbon-rich environment			
Amorphous carbons, a-C:H	sp^2/sp^3, H	$\gtrsim$1700	≈0.2, 3.4, 6.85, 7.25
PAH	fusions of C_6H_6[c]	$\lesssim$1700	0.2–0.26, 2–50
Graphitic carbon	sp^2	~1600	~0.22
Silicon carbide	SiC	$\gtrsim$1700	~10–13
Oxygen-rich environment			
Olivine	$[Mg, Fe]_2SiO_4$[d]	~1300	~0.7–1.5, 9, 10–11.6, 18, 20
Forsterite	Mg_2SiO_4	~1300	~10, 11.3, 69
Fayalite	Fe_2SiO_4	~1000	~10.6, 11.4, 93–94, 110
Pyroxene	$[MgFe]SiO_3$[d]	~1300	~10–20, 40.5
Enstatite	$MgSiO_3$	~1300	~9.7, 19.5, 26–30
Magnetite	Fe_3O_4	~800	~17, 25
Corundum	Al_2O_3	~1700	broad at ~13 (12.5–14)
Spinel	$MgAl_2O_4$	~1200	~0.3, 0.5, 2, 13, 17, 32
Calcite	$CaCO_3$	~800	~6.8, 11.4, 44, 92
Dolomite	$CaMg[CO_3]_2$	~800	~6.6, 11.3, 60–62
Iron	Fe	~900	featureless

Mass loss

- mass-loss estimates from direct detection of circumstellar matter and spectral line signatures (Doppler shifts, line shapes).

- stellar wind velocities: ~ 5 … 1000 km/s .

- stellar winds result typically from interaction of photons (photosphere) with atoms, molecules, dust grains → complicated radiation-hydrodynamics problem.

- well-understood **models** for stellar winds available **only** for either hot stars (radiation-driven) or cool stars (dust-driven models).

- because of lack of thorough theoretical models, use of empirical models for various types of star, e.g. Reimers (1975)

$$\dot{M}_\mathrm{R} = -4\cdot 10^{-13}\eta\frac{L}{gR}\cdot\frac{g_\odot R_\odot}{L_\odot}$$ … for red giants with large *Z* .

$(\mathrm{M}_\odot/y)$

Mass loss

$\dot{M} \sim X_{\rm res}^{1/2}$

Reimers (1975):

$$\dot{M}_{\rm R} = -4 \cdot 10^{-13} \eta \frac{L}{gR} \cdot \frac{g_\odot R_\odot}{L_\odot}$$ ... for red giants with large *Z*.

$(M_\odot/y)$

for Z<< → 0.2,...,1.0 to account for other stars (η)

i.e. $\dot{M}_{\rm R} \propto L$ and $\dot{M}_{\rm R} \propto \frac{1}{GM/R}$. ← gravitational potential

Schröder & Cuntz (2005, for cool stars):

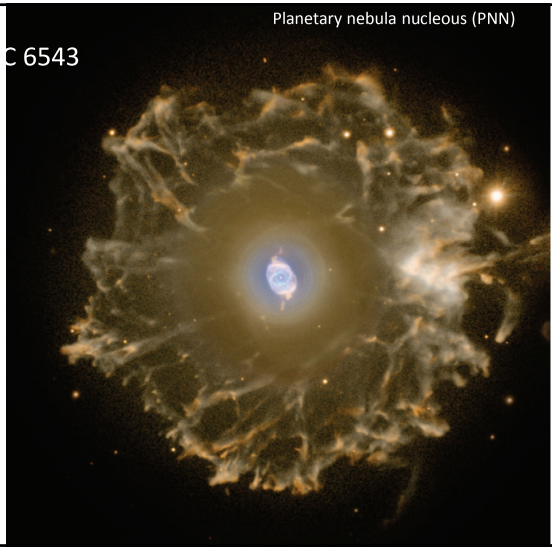
$$\dot{M}_{\rm SC} = -8 \cdot 10^{-14} \frac{LR}{M} \frac{M_\odot}{L_\odot R_\odot} \left(\frac{T_{\rm eff}}{4000\,{\rm K}}\right)^{3.5} \left(1 + \frac{g}{4300 g_\odot}\right) .$$

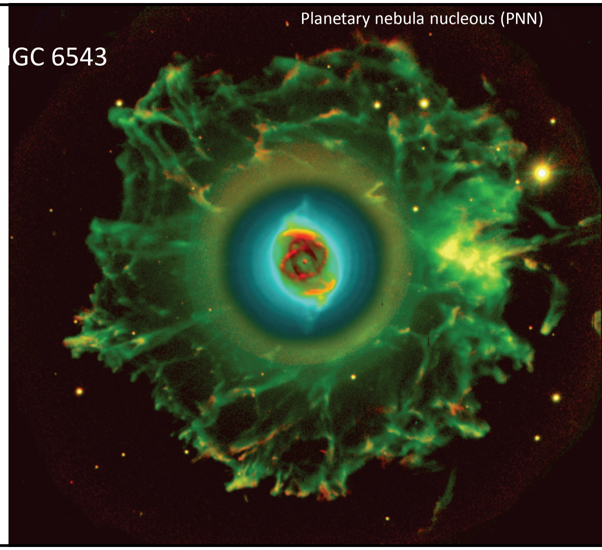
Blöcker (1995, AGB stars, from obs. & dust-driven wind theory):

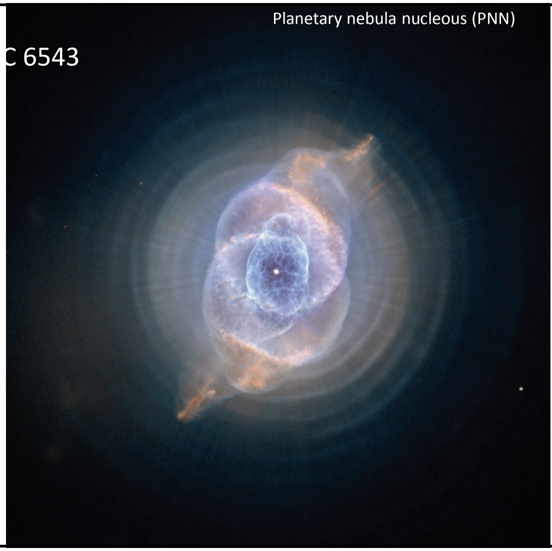
$$\dot{M}_{\rm B} = -4.83 \cdot 10^{-9} \dot{M}_{\rm R} (M_\star/M_\odot)^{-2.1} (L/L_\odot)^{2.7}$$

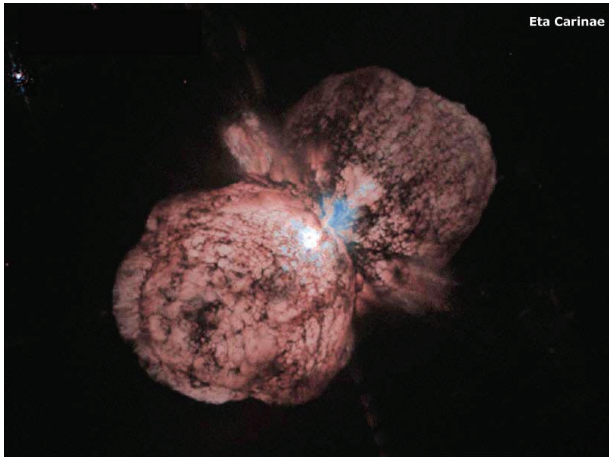
Lamers (1981, O, B tars, emperical):

$$\dot{M}_{\rm L} = -1.48 \cdot 10^{-5} \left(\frac{L}{1000 L_\odot}\right)^{1.42} \left(\frac{R}{30 R_\odot}\right)^{0.61} \left(\frac{30 M_\odot}{M}\right)^{0.99}$$






Planetary nebula nucleous (PNN)
C 6543


Eta Carinae