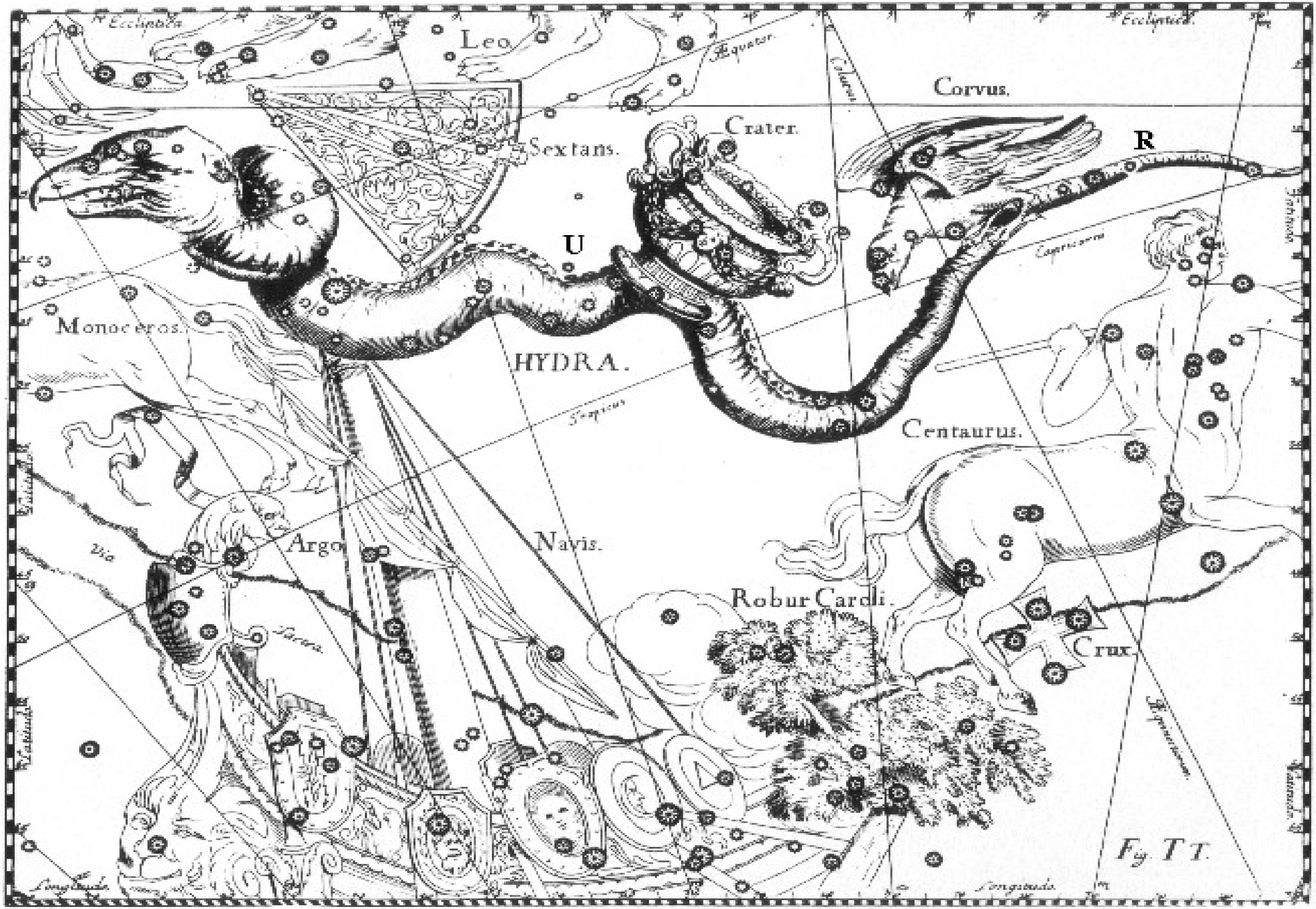


Figure 4. Hevelius' (1690a) chart of the region, showing both R Hya and U Hya. R Hya is the faint star in the tail of Hydra, to the right of the tail of the crow: it s just to the right of γ Hya and ψ Hya. U Hya is located between Sextans and Crater, just above the body of Hydra.

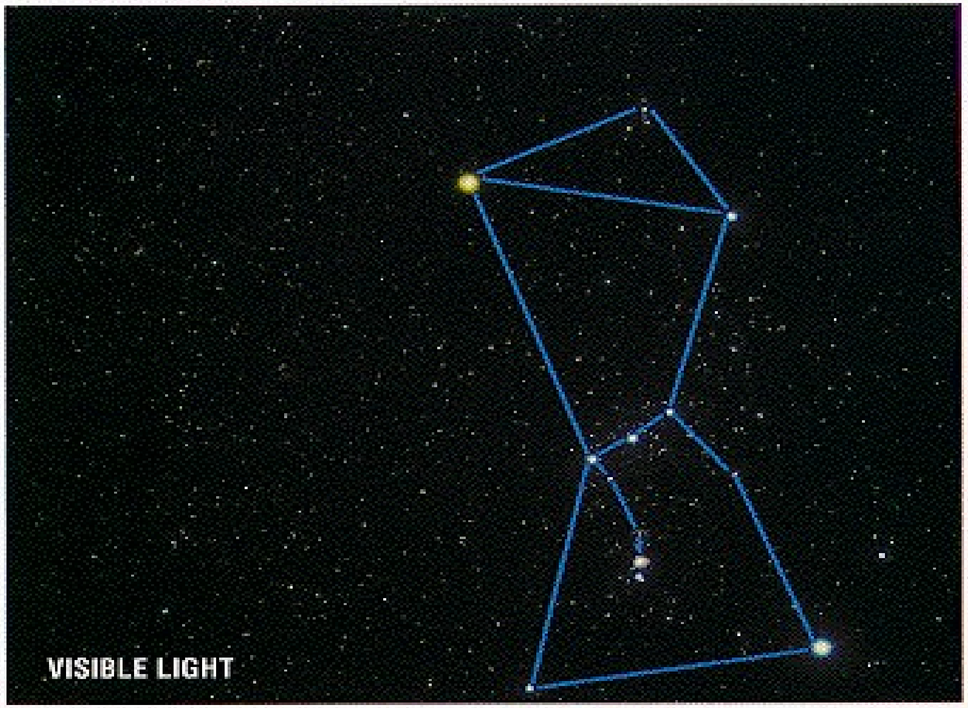
Star and Stellar Evolution

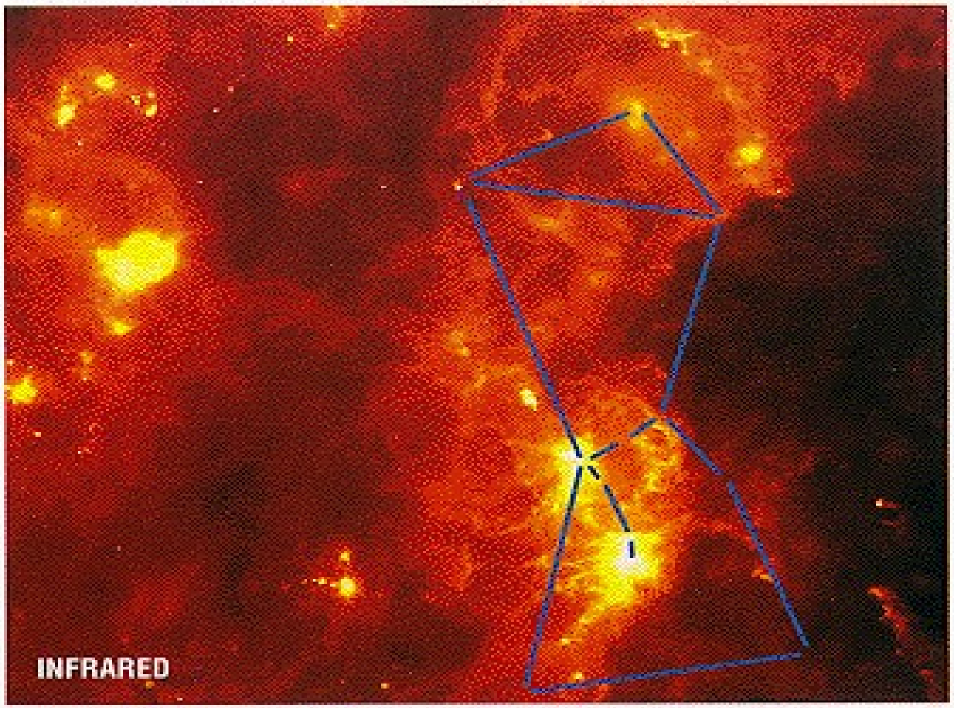
- Stars: are governed by simple physics
- Properties determined by
  - Mass
  - Composition
- Simple physics + simple properties give complex behaviour

Outline

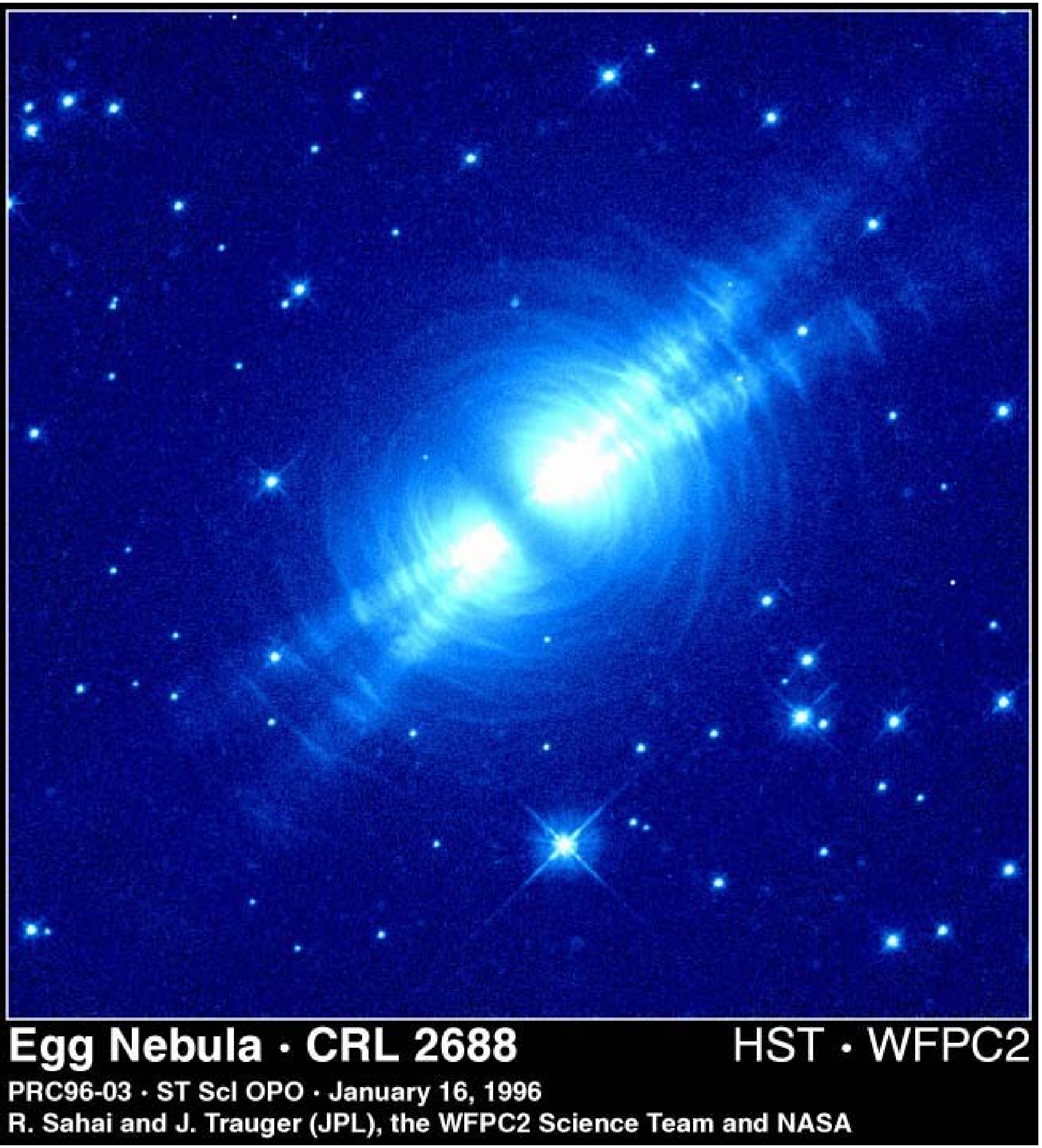
- Issues of stellar physics
- AGB evolution
- Mass loss
- Interacting winds
- Galactic ecology

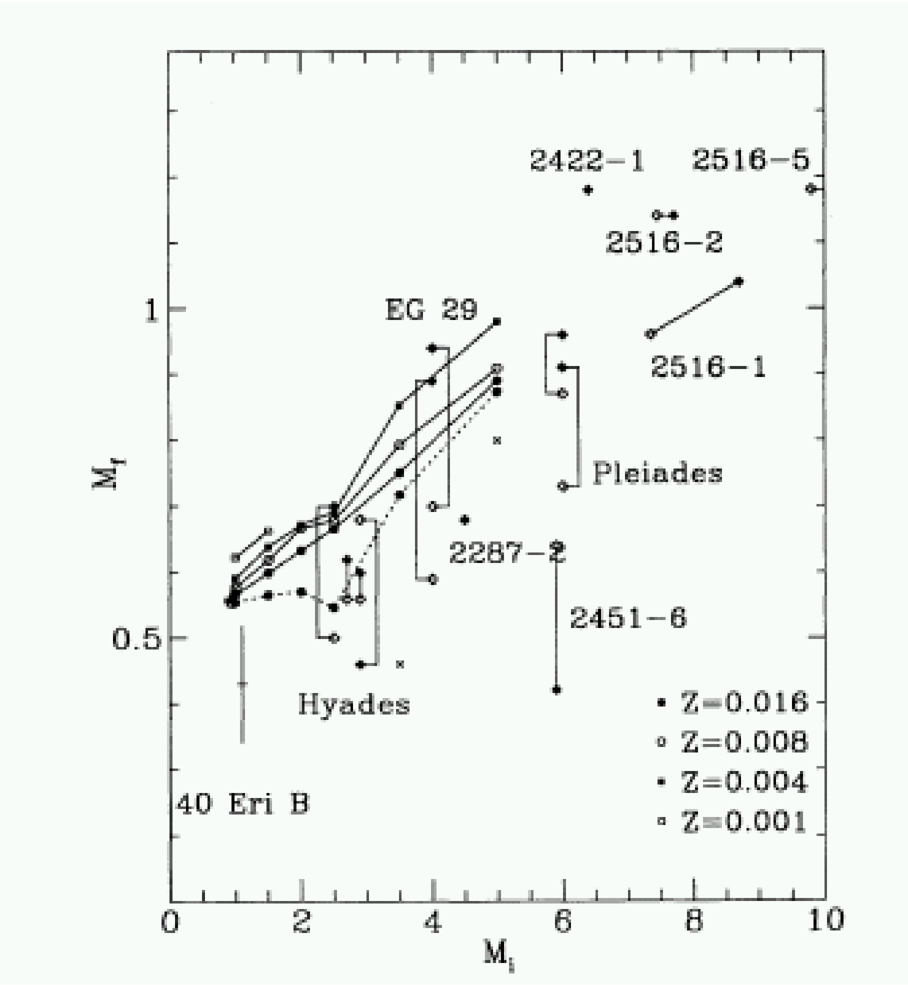
Stars begin and end their lifes within the interstellar medium (ISM)



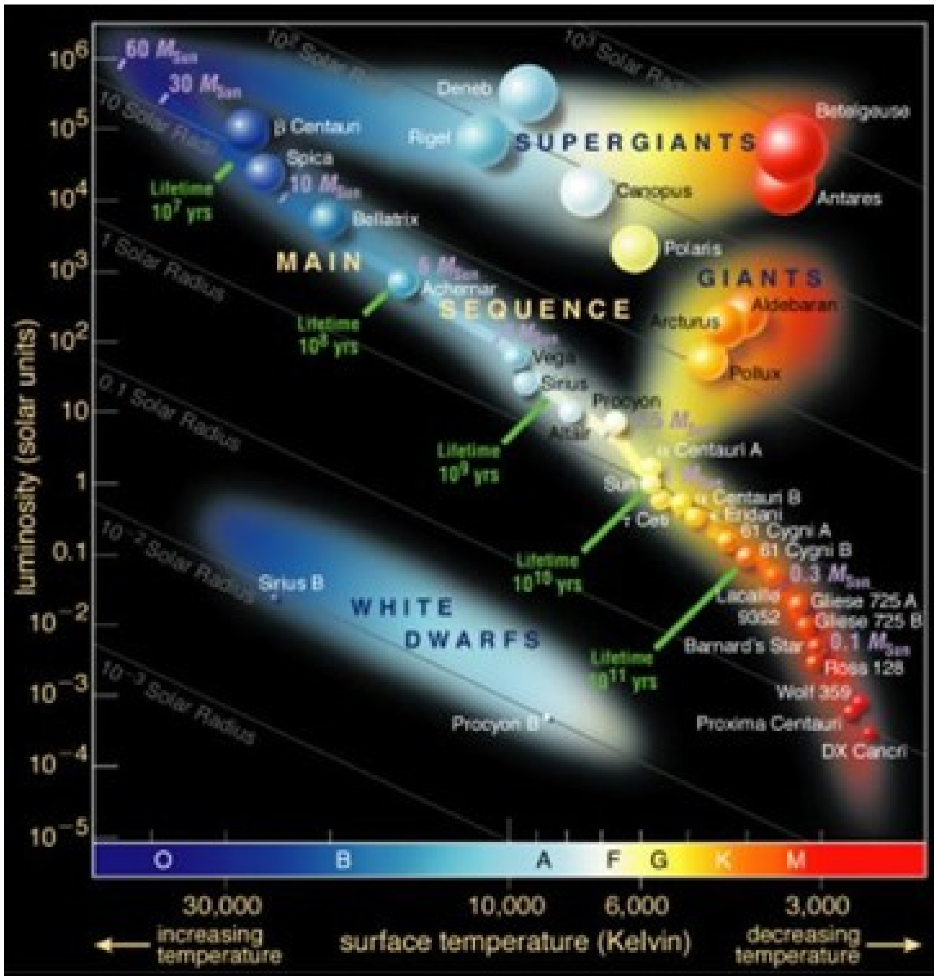


Orion's nursery


Egg Nebula · CRL 2688
HST · WFPC2
PRC96-03 · ST ScI OPO · January 16, 1996
R. Sahai and J. Trauger (JPL), the WFPC2 Science Team and NASA


2422-1
2516-5
2516-2
EG 29
2516-1
Pleiades
2287-2
2451-6
Hyades
40 Eri B
Z=0.016
Z=0.008
Z=0.004
Z=0.001
M_f
M_i
0.5
1
0
2
4
6
8
10

HR diagram



- Main sequence
- Evolved branches
- White dwarf branch

- large forbidden regions
- strict limits

HR physics

- Limits of the HR diagram
  - nuclear burning temperature (novae)
  - Hayashi track
  - : hydrogen-burning limit

- main sequence: L proportional to $M^{a:}$
  - $M < 7\ M_{o:}$ $a = 4.5$
  - $M > 7\ M_{o:}$ $a = 3$

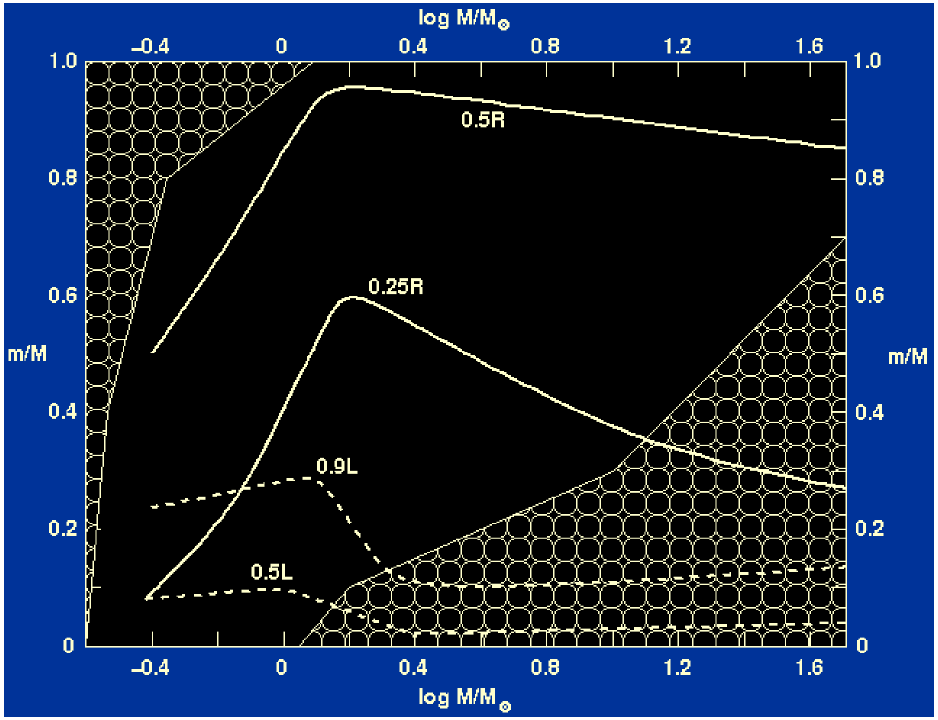
- Forbidden regions: traces stellar structure

Stellar physics

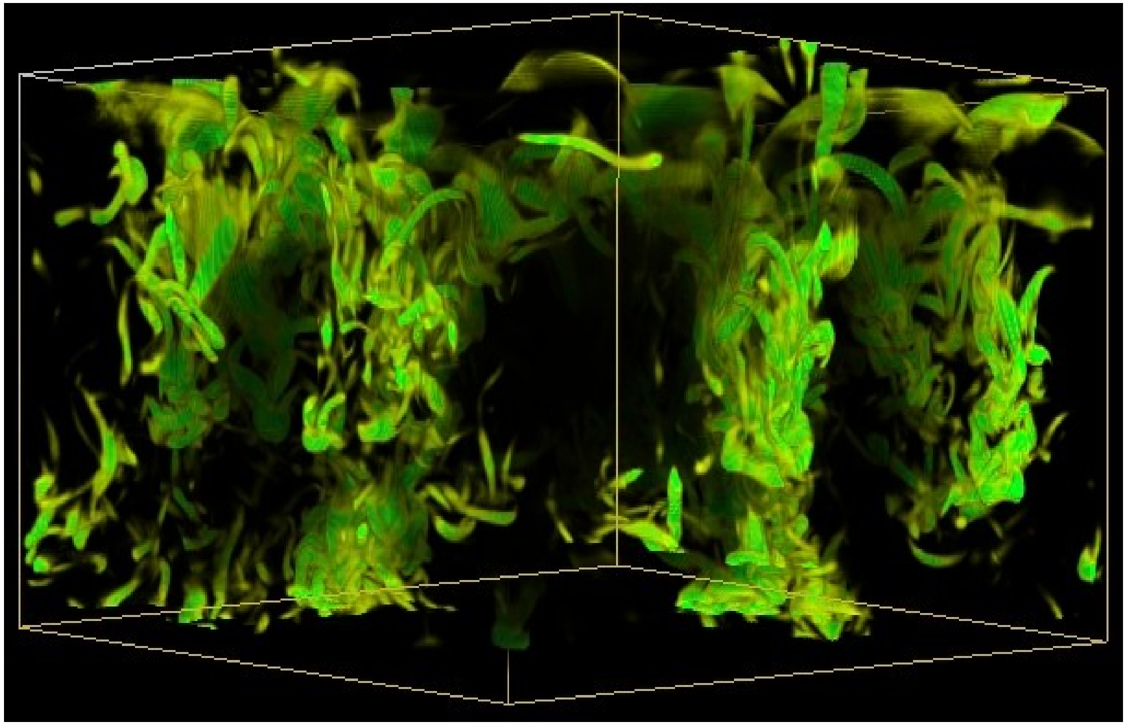
- Hydrostatic equilibrium
  - Gravity versus heat
  - Gravity versus equation of state
  - gaseous stars require an energy source
- Virial theorem
  - kinetic energy is minus half the potential energy
  - stars have negative heat capacity
  - less energy generation -> star becomes hotter
    - stablizes nuclear reactions

Energy transport

- radiative for small temperature gradient
- convective for steep temperature gradient
- most stars have both convective and radiative regions



Convection



- Turbulence itself is hard to model
  - chaotic
  - overshoot and undershoot
- Gives mixing and dredge-up

- predicts a fixed T-gradient
- convective star is easy to model

Stellar structure

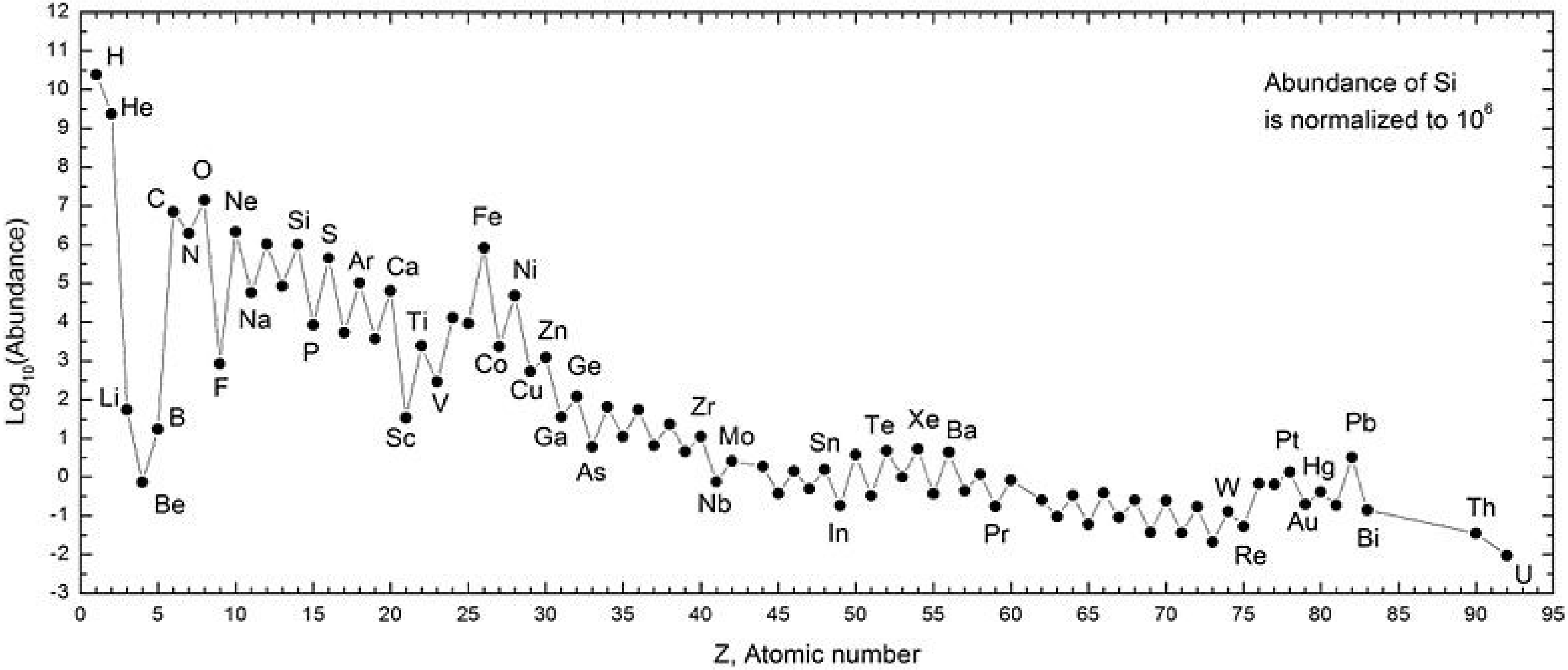
possible configurations

- Core burning
  - central temperature gradient
  - if convective: extended life expectancy
- Shell burning
  - no central temperature gradient
  - convective only above the nuclear burning zone
- Non-burning
  - degenerate

Nuclear burning

- deuterium: short-lived but inevitable
- hydrogen
  - pp, chain 1, 2 or 3 (<1.1Msun)
  - CNO
- helium burning: triple alpha
- C, O, Si burning
- s and r-process: neutron captures
  - not well understood

Elemental abundances



Dominant energy source

- f = E(nuclear)/U(gravity)
- low mass star (-> white dwarf)   f ~ 50
- high mass star (-> neutron star) f ~0.5

- Gravity is the main energy source in the Universe
- Nuclear burning is dominant during stable phases

Stellar winds

dominates evolution for

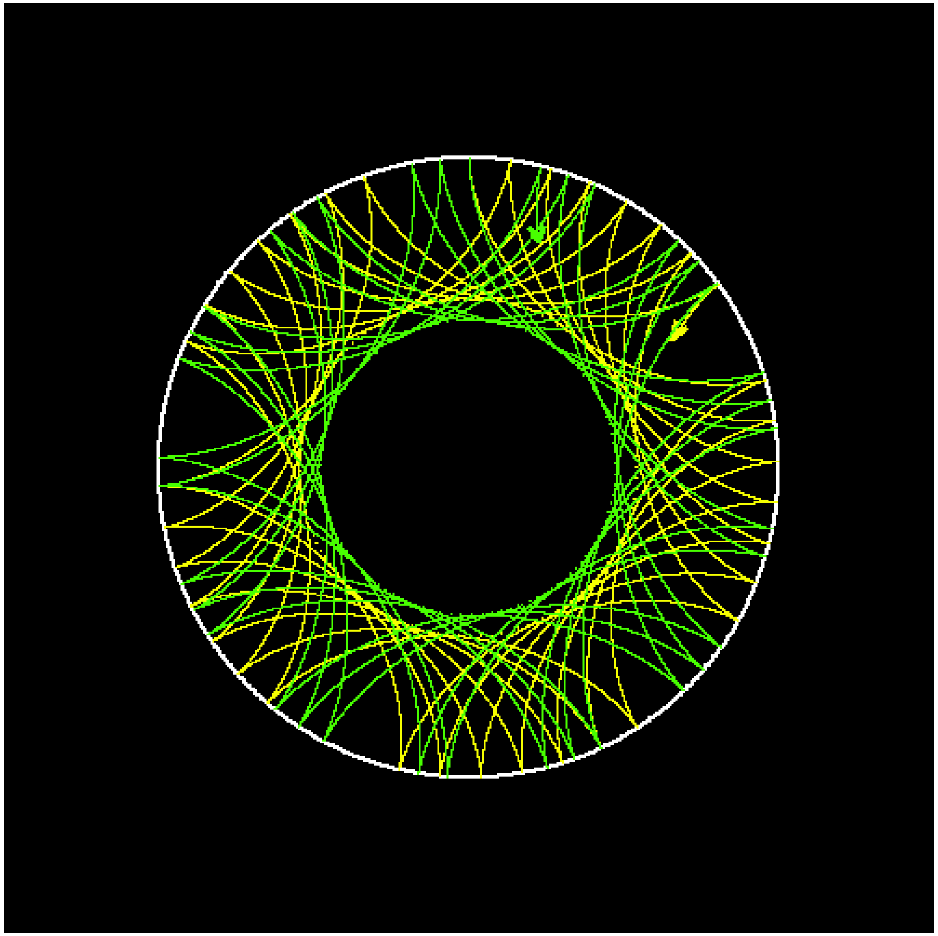
- high-mass stars
- evolved stars

main problem in stellar evolution

- mass loss rate
  - non-linear tracers
- wind energy
- wind composition
- driving mechanisms

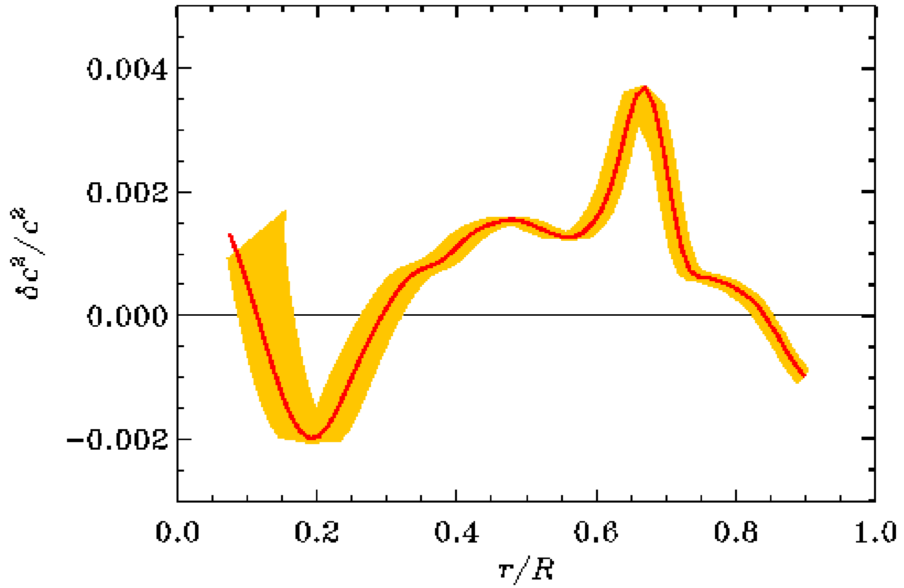
Asteroseismology

- oscillations induced by convection
- standing waves on the surface
- frequencies trace the temperature/density/rotation of the interior



The Sun

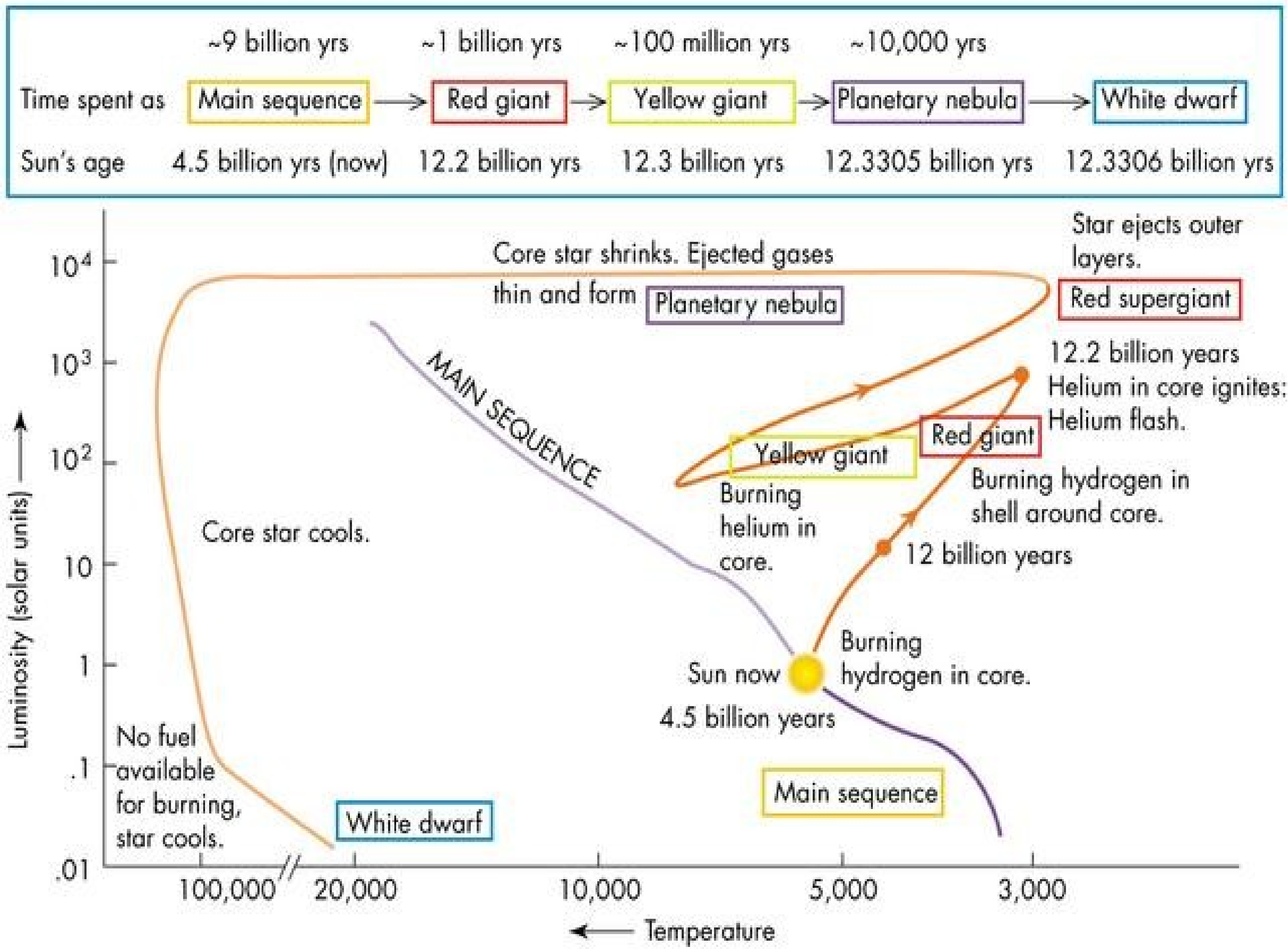
- Structure very well known
- Abundances rather uncertain
  - Z = 0.012 (spectrum)
  - Z = 0.016 (seismology)
  - Z = 0.02 (text books)
- Neutrino problem solved



Evolutionary phases

- core hydrogen burning: main sequence
- hydrogen shell burning: RGB
- core helium burning: HB
- helium shell burning: AGB
- helium flashes: thermal-pulsing AGB
- carbon core burning: super-AGB

More massive stars show multiple shell burning


~9 billion yrs
~1 billion yrs
~100 million yrs
~10,000 yrs
Time spent as
Main sequence
Red giant
Yellow giant
Planetary nebula
White dwarf
Sun's age
4.5 billion yrs (now)
12.2 billion yrs
12.3 billion yrs
12.3305 billion yrs
12.3306 billion yrs
Star ejects outer layers.
Core star shrinks. Ejected gases thin and form
Planetary nebula
Red supergiant
12.2 billion years
Helium in core ignites; Helium flash.
MAIN SEQUENCE
Red giant
Yellow giant
Burning helium in core.
Burning hydrogen in shell around core.
12 billion years
Core star cools.
Burning hydrogen in core.
Sun now
4.5 billion years
No fuel available for burning, star cools.
White dwarf
Main sequence
Luminosity (solar units)
10^4
10^3
10^2
10
1
.1
.01
100,000
20,000
10,000
5,000
3,000
Temperature

Schoenberner evolution

- AGB
  - Inert C/O core
  - He-burning shell, H envelope
- Thermal pulsing AGB
  - Regular He flashes
  - High mass loss
- Post-AGB
  - Mass loss ceases, photosphere collapses
  - Temperature increases
- Planetary nebula
  - Ionized ejecta
  - Inert white dwarf star

The University of Manchester
Jodrell Bank
Centre for Astrophysics

MANCHESTER 1824

TP-AGB evolution

- Semi-regulars
  - Period 50-150 days
- Mira variables
  - 15-500 days
- OH/IR stars
  - 300-1800 days
  - OH maser emission

- Increasing mass loss
  - 10^{-8} to 10^{-4} Msol/yr
- Increasing period
- Increasing amplitude

Third dredge may cause carbon-star formation

Hot bottom burning may prevent this

Dust

- AGB winds form dust
  - silicates
  - amorphous carbon
- Stars become highly self-obscured at optical wavelengths
- mid-infrared emission due to heated dust
- Missing million years of stellar evolution

Open problems

- Mass loss process
  - Driving force
  - Dependence on stellar properties
- Structure formation
  - Spherical winds
  - But ejecta show intricate structures
- Galaxy evolution
  - Carbon and dust enrichment of galaxy
  - Mass return at low metallicity
- Stellar evolution
  - Initial-final mass
  - Late helium flashes

Mass loss

Multi-step process

- Pulsations extend atmosphere
- Molecule/dust formation
- Radiation pressure on dust and molecules drive a wind

Mass loss depend on:

- pulsation
- stellar temperature
- surface gravity
- composition and metallicity

- No predictive parametrization exists

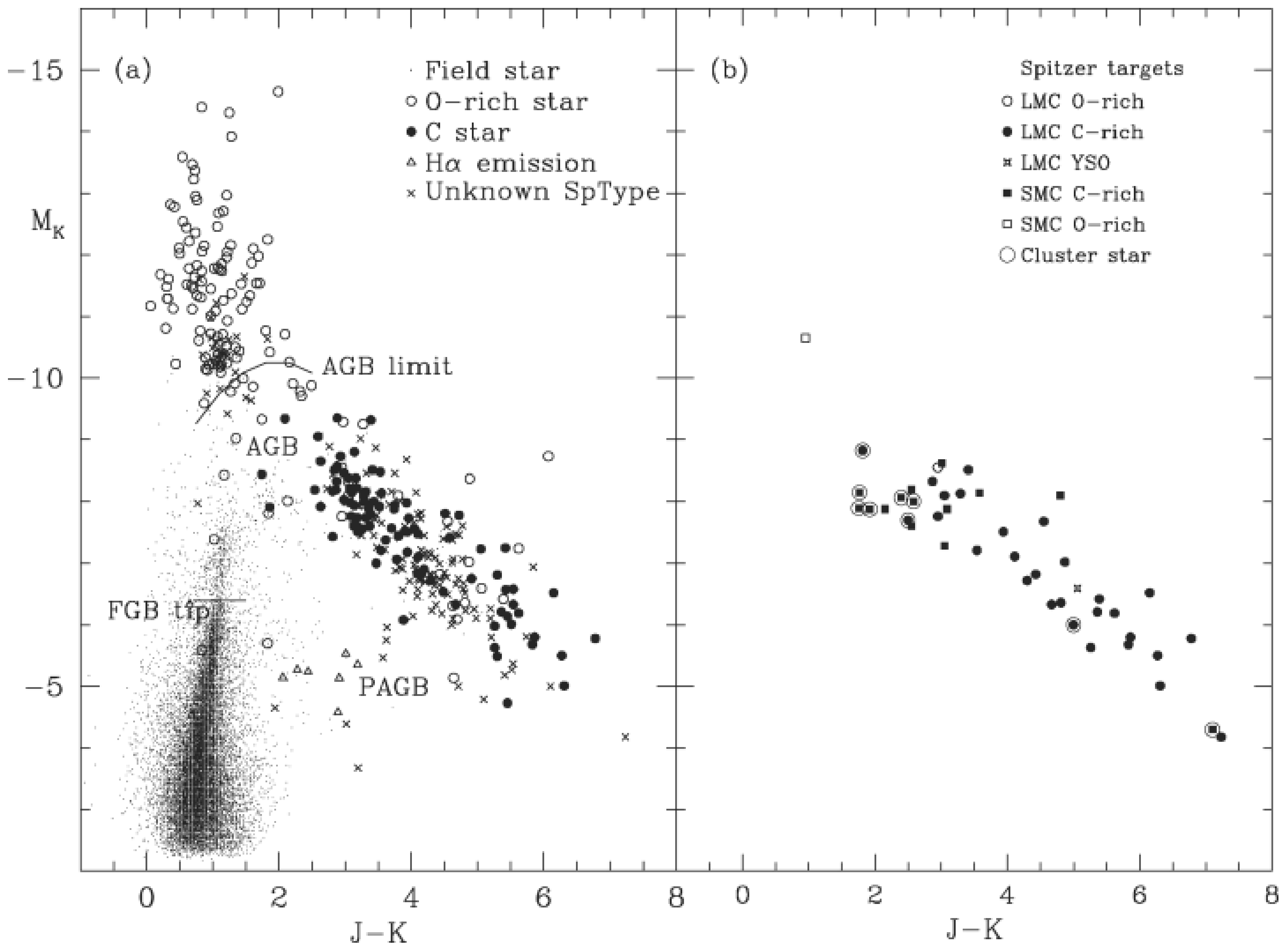
Mass loss parametrizations

(i)	$\log \dot{M}$	$=$	$a\,P + b$	Vassiliadis & Wood1993
(ii)	$\dot{M}$	$=$	$a\,M_{\rm i}^{-2.1}\,L^{3.1}\,R\,M^{-1}$	Bloecker 1995
(ii)	$\dot{M}$	$=$	$a\,L^{2.47}\,T^{-6.8}\,M^{-1.95}$	Wachter et al. 2002
(iv)	$\dot{M}$	$=$	$a\,L^{1.05}\,T^{-6.3}$	van Loon et al. 2005.

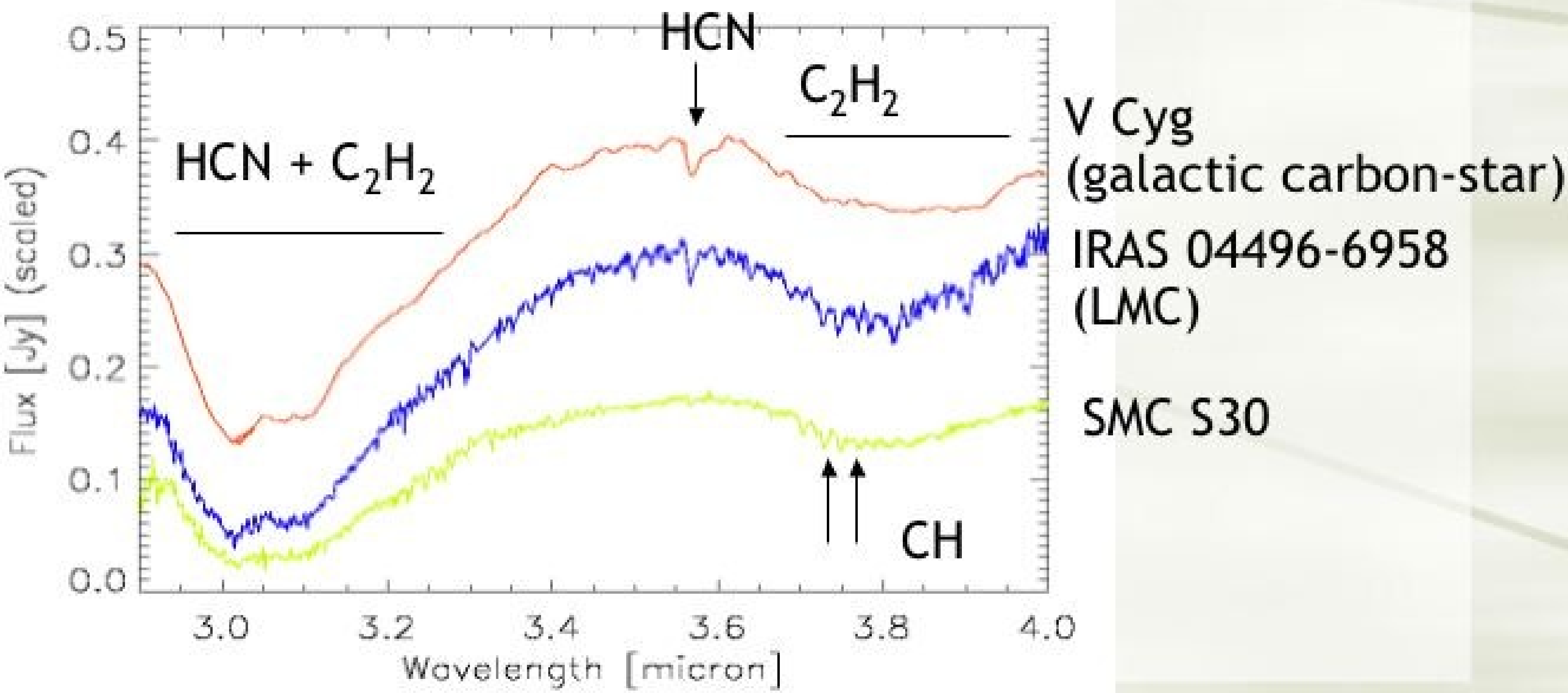
- Strong temperature dependence
- Period dependence is controversial
- Suggestive relation including radius:

$$\dot{M} \sim \left(\frac{M}{R}T\right)^{\alpha} L^{\gamma}$$

Mass losing AGB stars

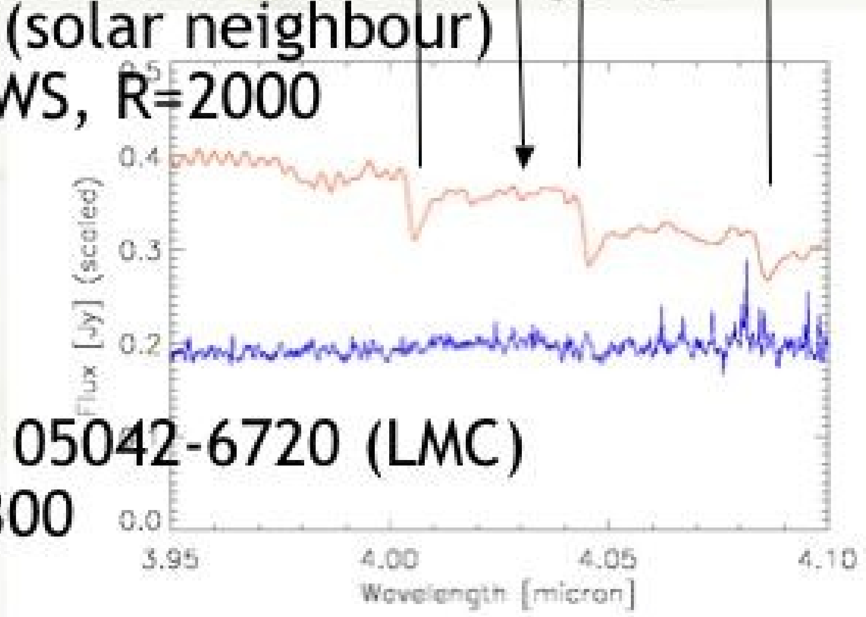


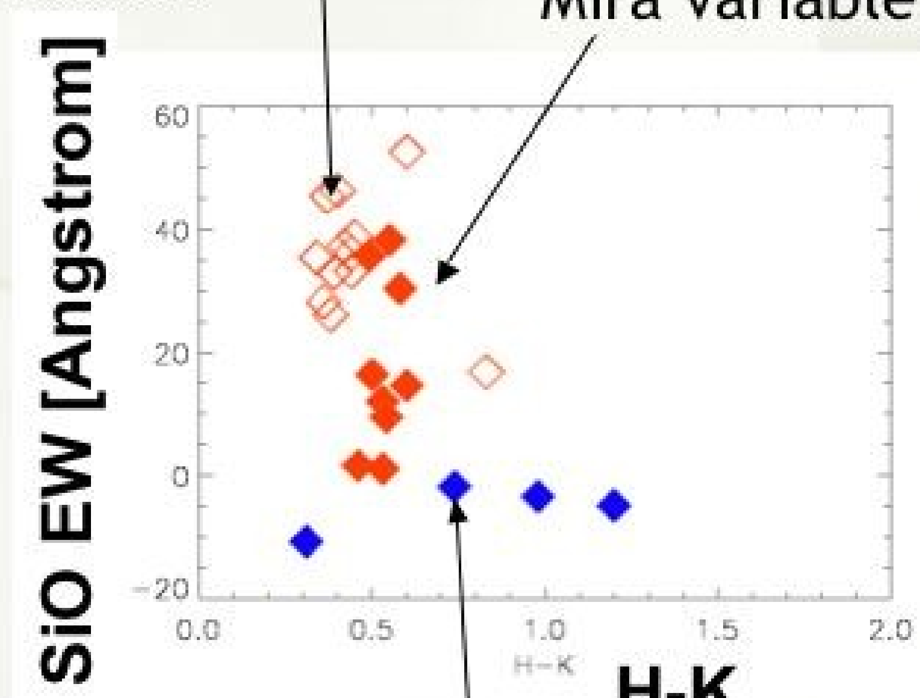
Spectra of carbon-rich stars

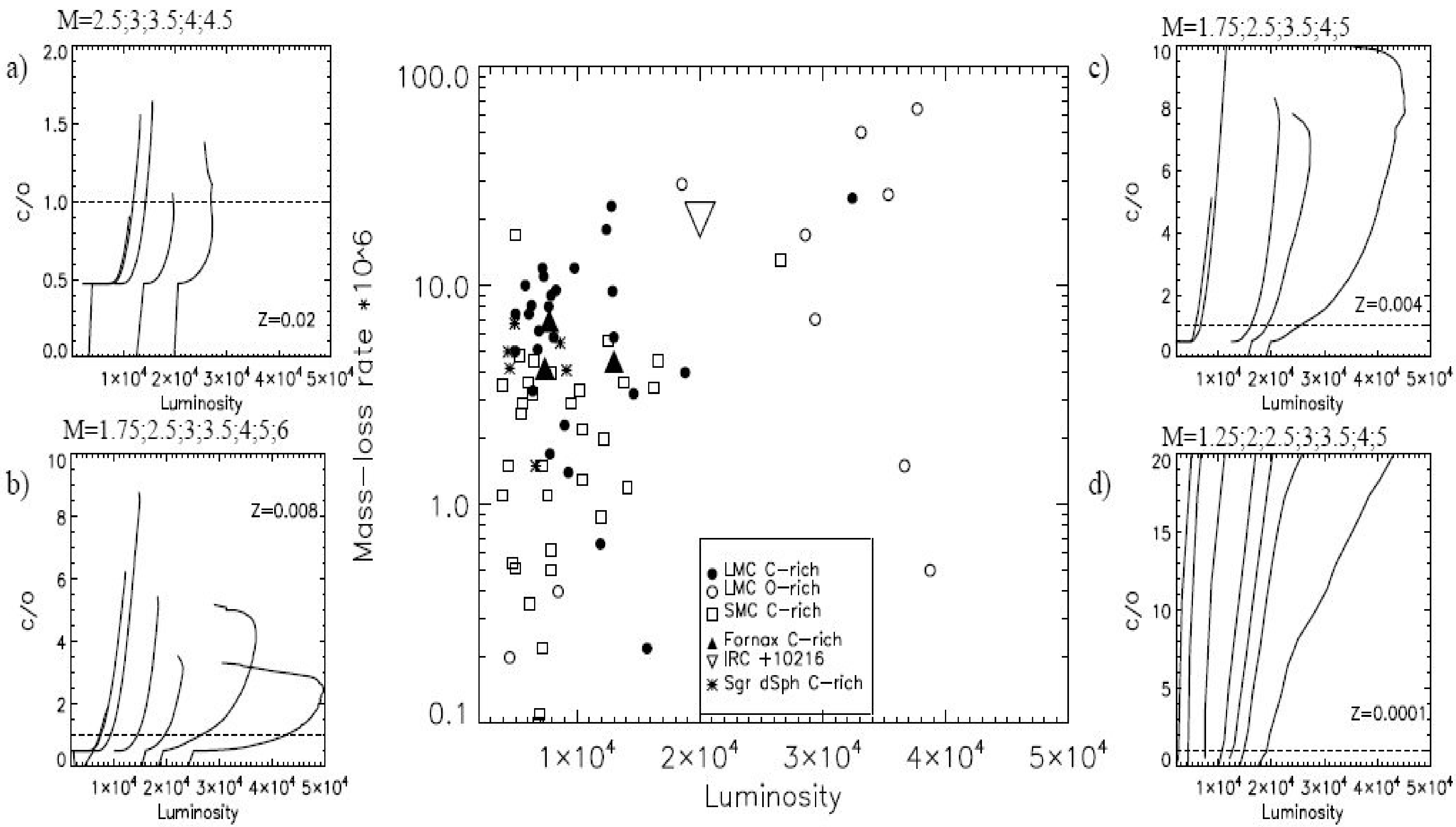


Matsuura et al.(2002); A&A in press

Oxygen-rich stars

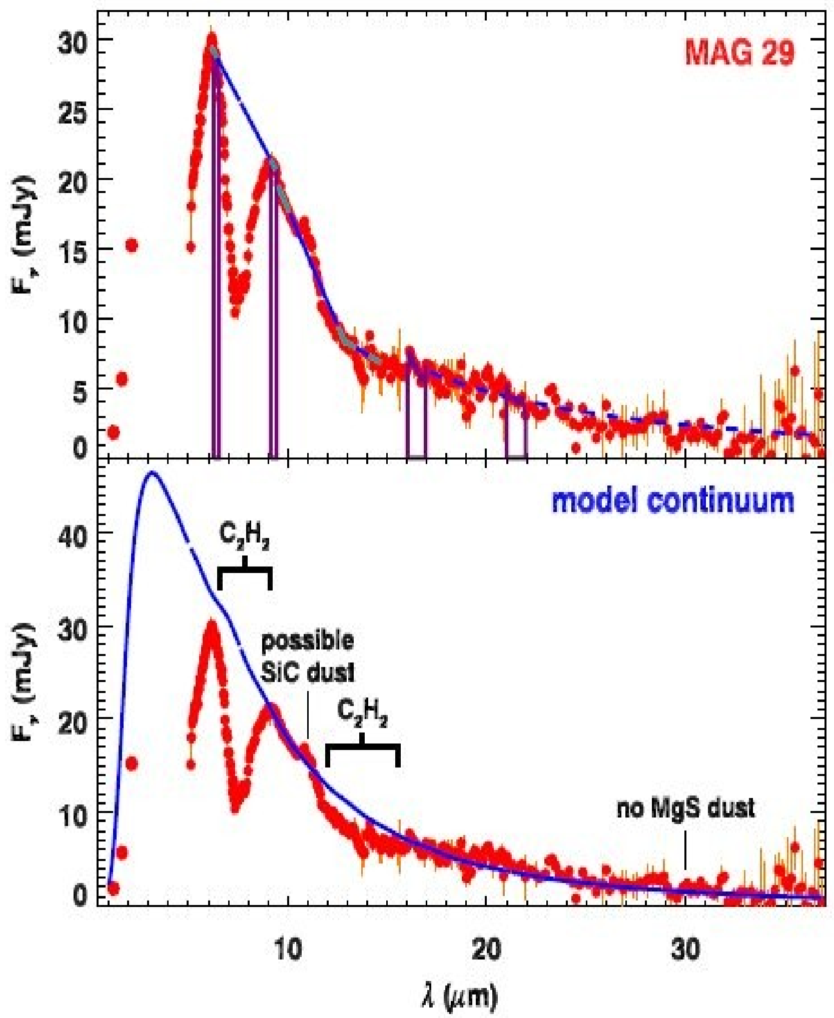


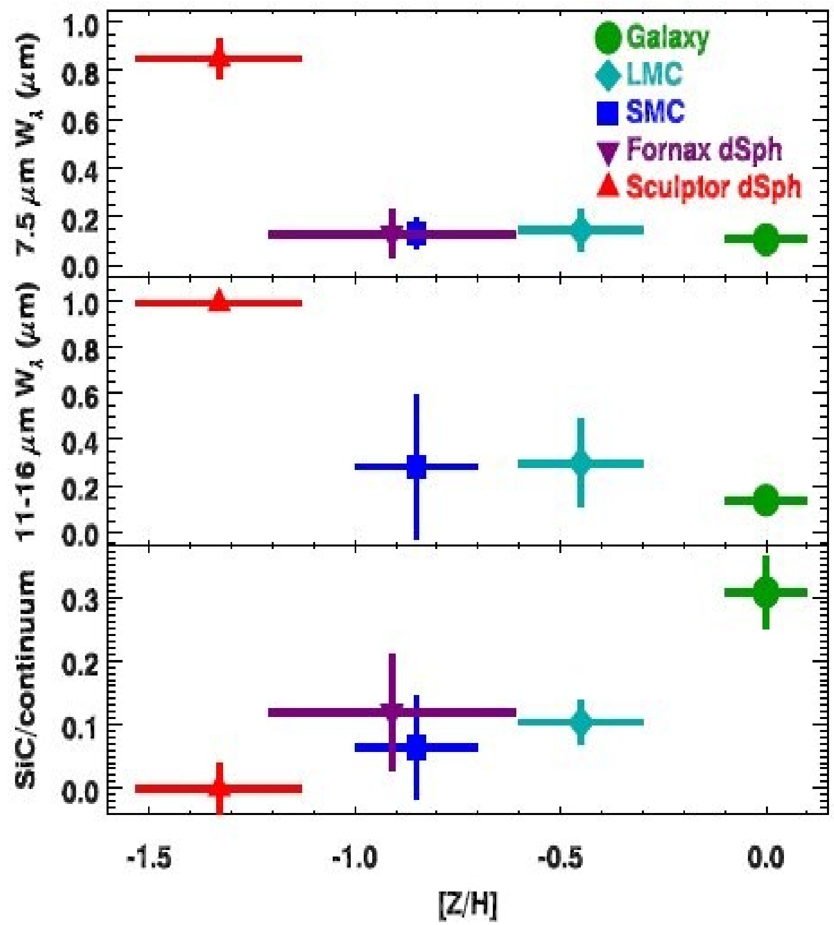




M=2.5;3;3.5;4;4.5
a)
Z=0.02
c/o
Luminosity
M=1.75;2.5;3;3.5;4;5;6
b)
Z=0.008
c/o
Luminosity
Mass-loss rate *10^6
Luminosity
LMC C-rich
LMC O-rich
SMC C-rich
Fornax C-rich
IRC +10216
Sgr dSph C-rich
M=1.75;2.5;3.5;4;5
c)
Z=0.004
c/o
Luminosity
M=1.25;2;2.5;3;3.5;4;5
d)
Z=0.0001
c/o
Luminosity

Spitzer spectra





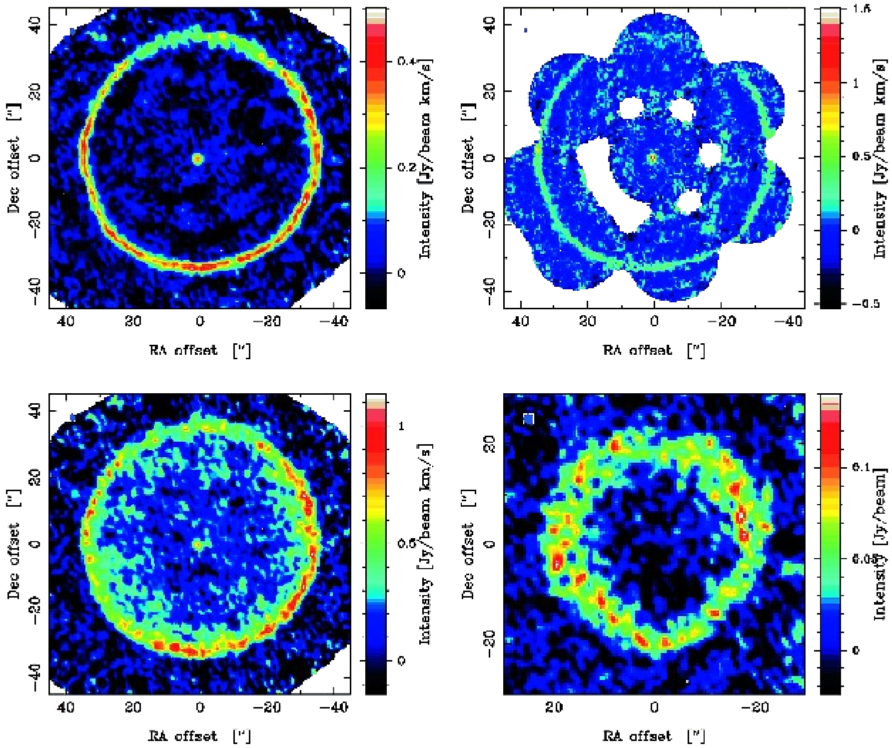
Superwind trigger

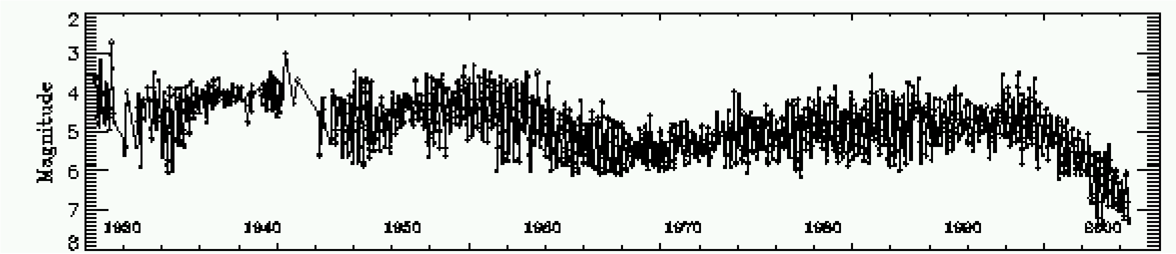
- Superwind occurs at all Z
- Mass loss for O-rich stars is metallicity-dependant
- Mass loss for C-rich stars is not

- Star evaporates if
- C – O higher than critical value
- L larger than critical value
  - $L \sim Z^{-4/3}$
- binary trigger

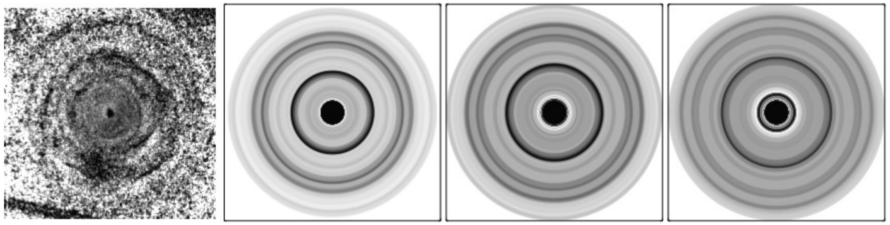
Mass loss variability
three time scales

- $10^{4\text{-}5}$ year: TP spikes
  - TT Cyg
- $10^{2\text{-}3}$ year: rings
- 10 year: extinction variations
  - L_2 Pup



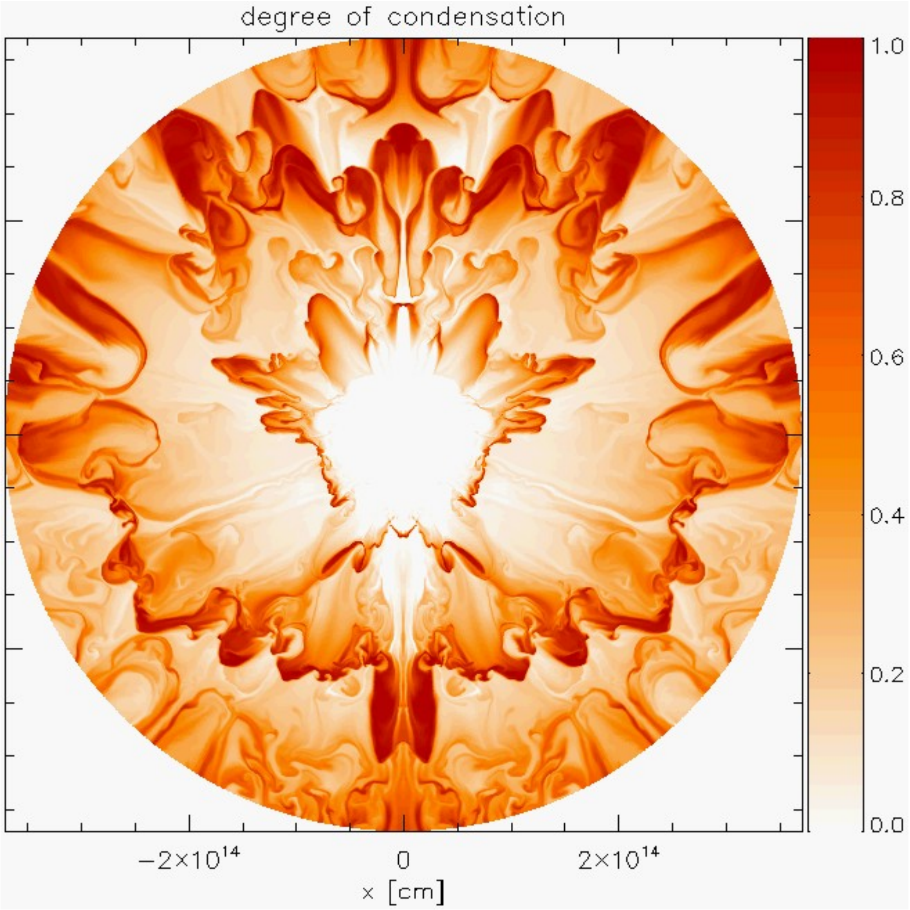


Dust driven instability



- 1-d models reproduce ring structure
- 2-d models indicate an irregular structure, not resembling rings
  - RT instabilities

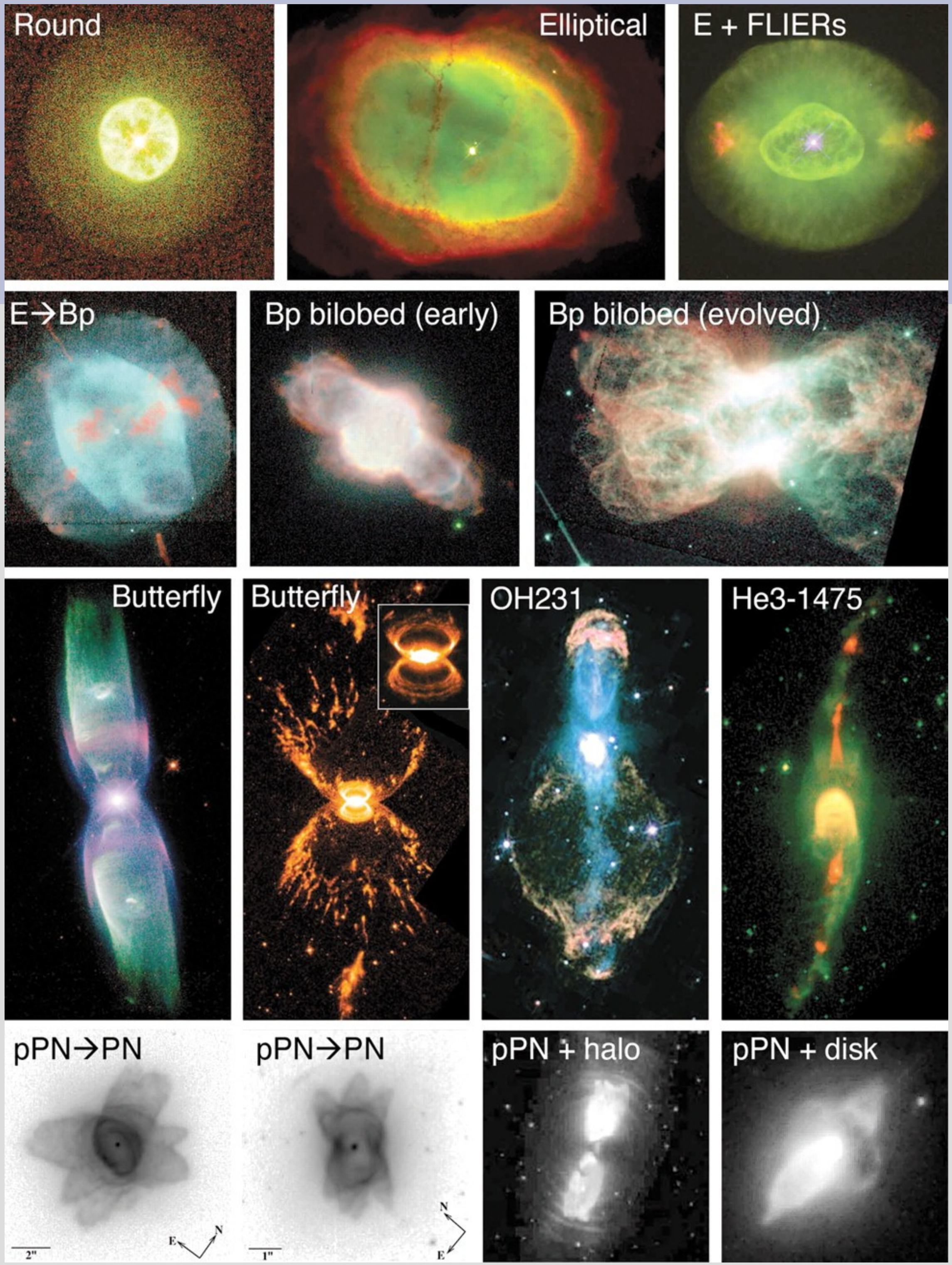
Woitke 2006



Shapes

- Round
- Elliptical
- Bipolar
- Multipolar

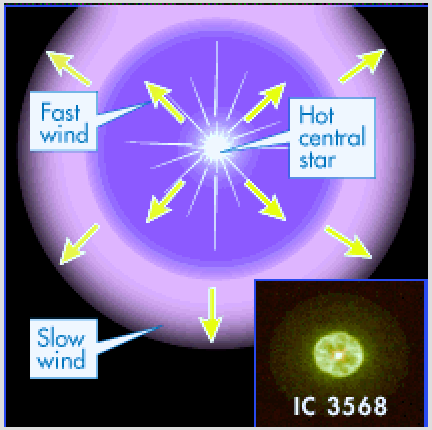
What did the star do?

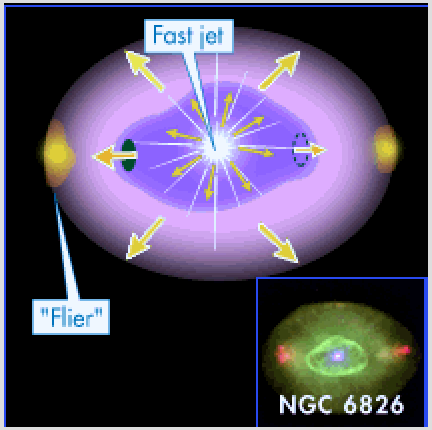


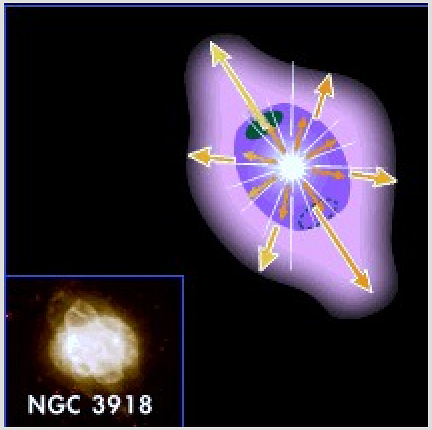
Interacting winds

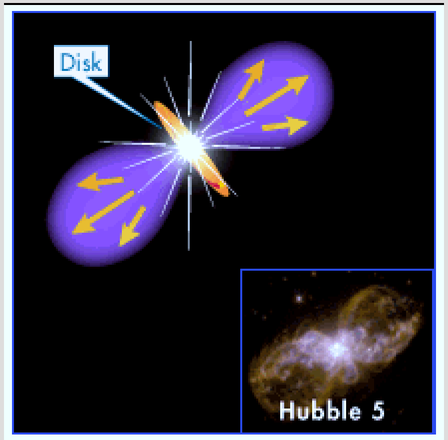
- Mira variable ejects a shell, at leisurely speeds
- Afterwards, the hot remnant blows a light wind at much higher speeds into the ejecta
- The fast wind sweeps up a shell of slower gas (snowplough)
- This amplifies initial asymmetries

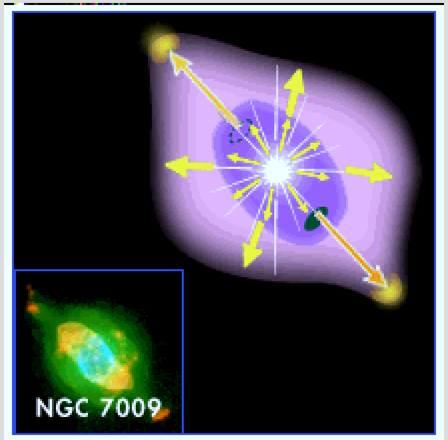
Interacting winds

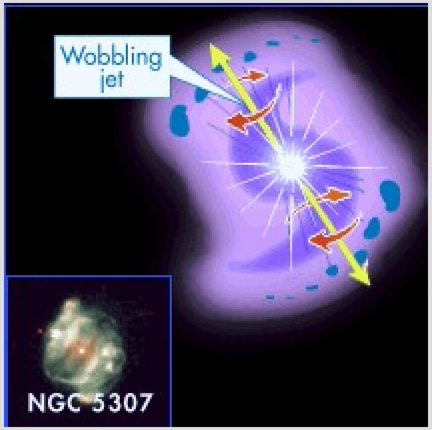




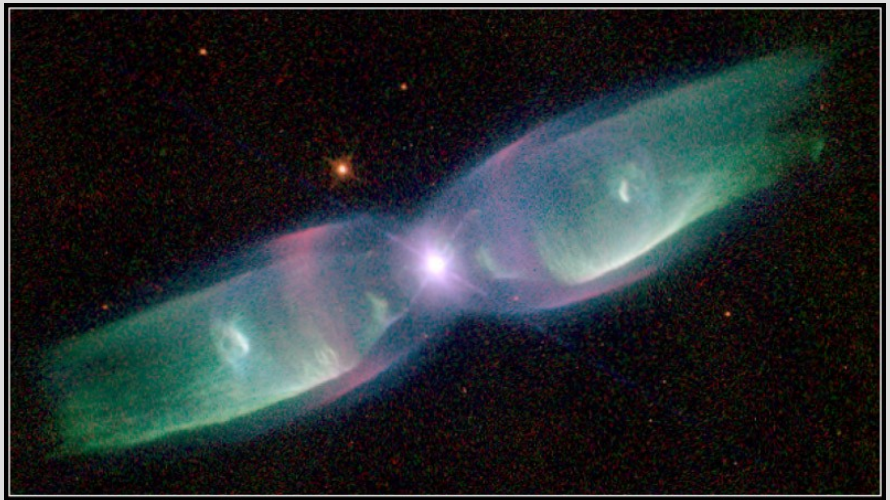








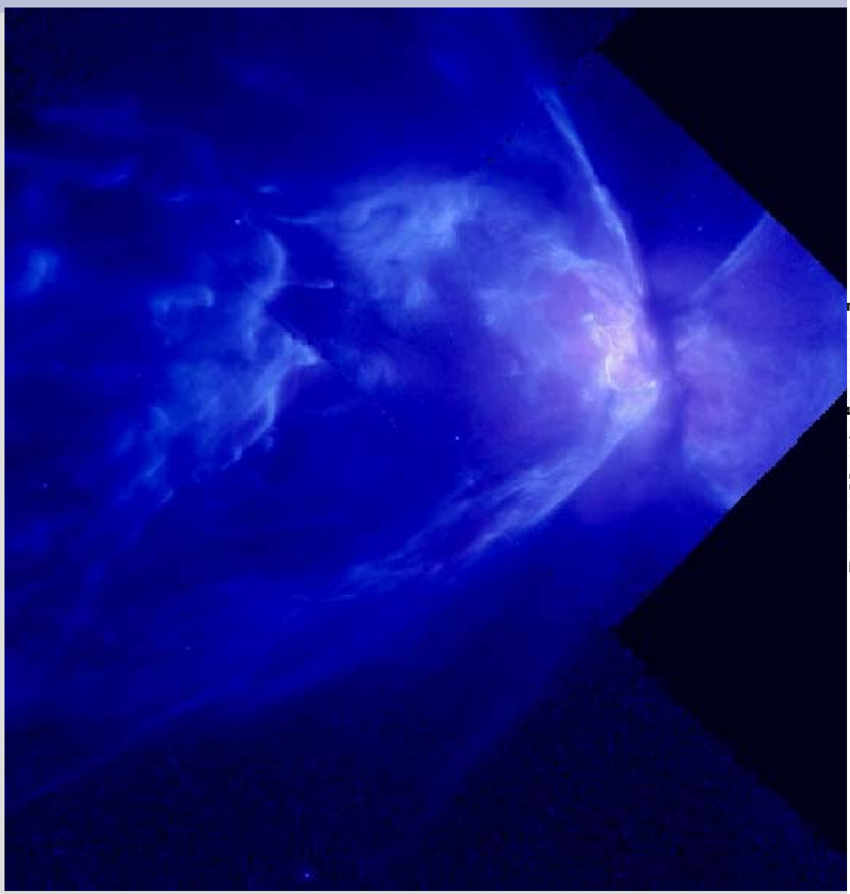
M2-9

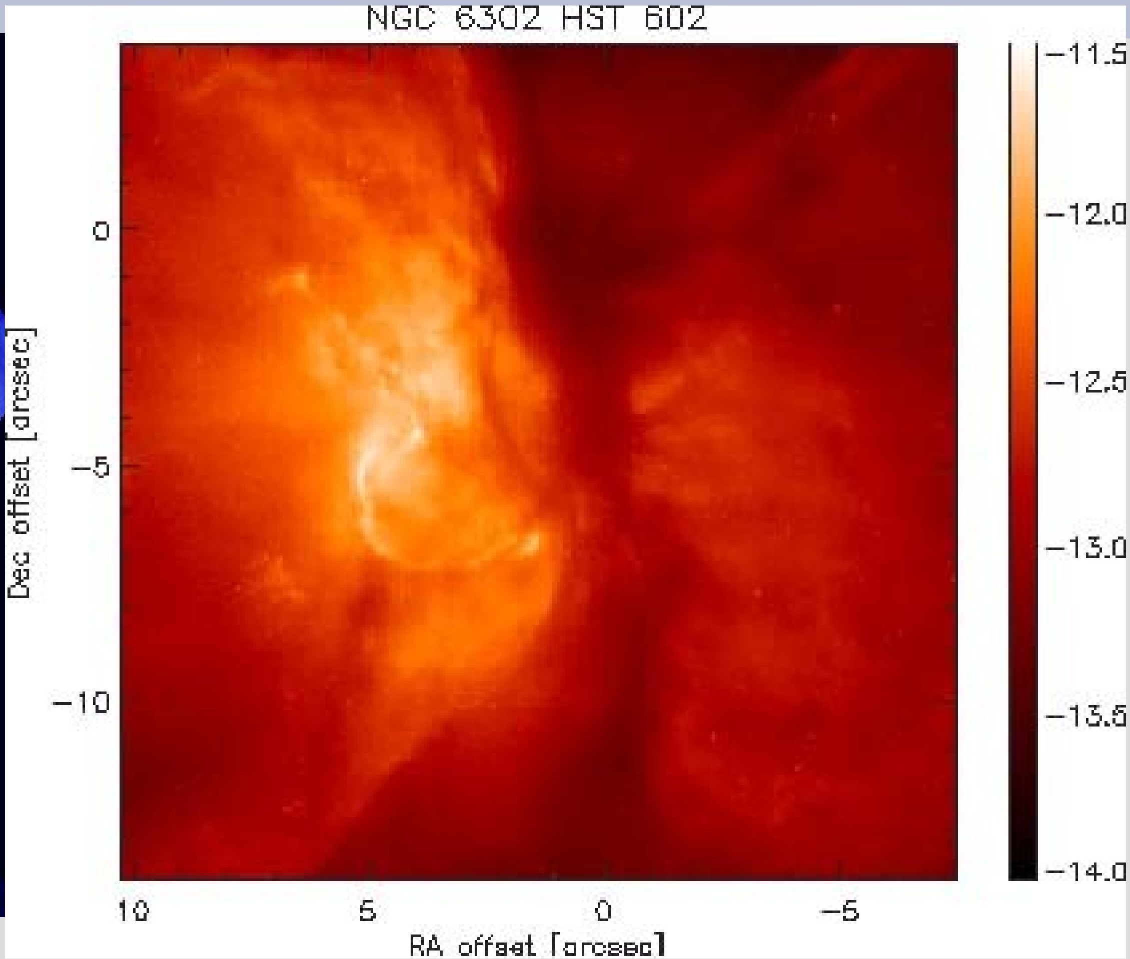


Planetary Nebula M2-9 HST • WFPC2
PRC97-38a • ST ScI OPO • December 17, 1997
B. Balick (University of Washington) and NASA

- Very fast winds
  - Hot region inside the nebula
  - Hot region tries to puncture the nebula
- Hydrodynamic models by Vincent Icke can fit many of the observed structures

NGC 6302: multipolar

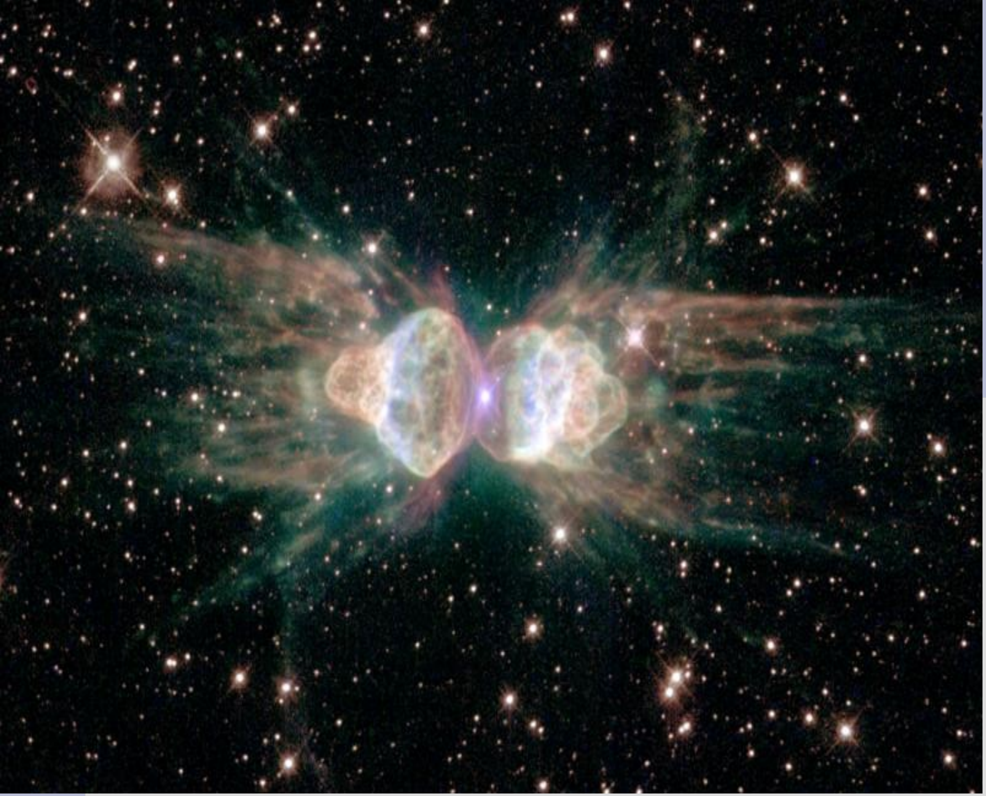




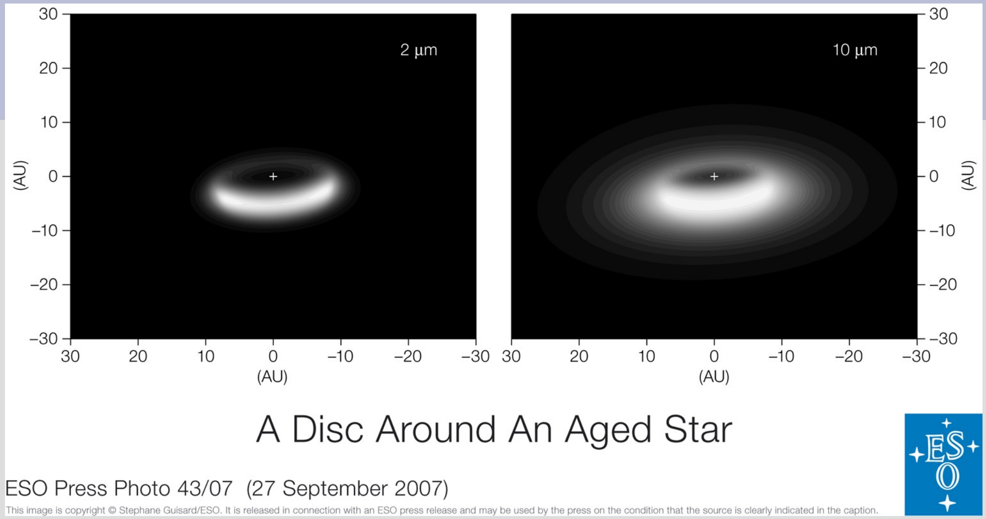
- Left: full HST image. Right: close up of the core

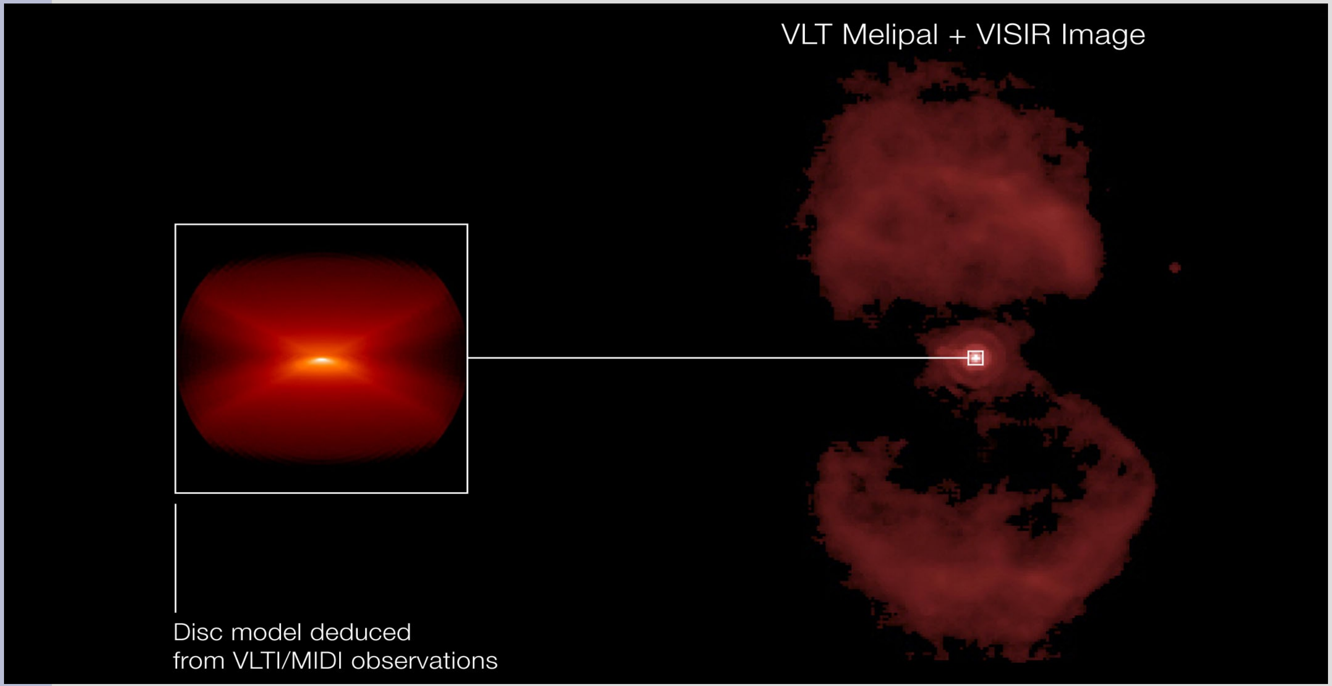
Initial asymmetries

- Hydrodynamical models require more mass ejected towards the equator than to the poles
  - Disk-like structure
- Observationally, not known for Mira variables
- could be caused by
  - Binaries
  - Cannibalized planets
- Work for the VLTI



Disk discoveries





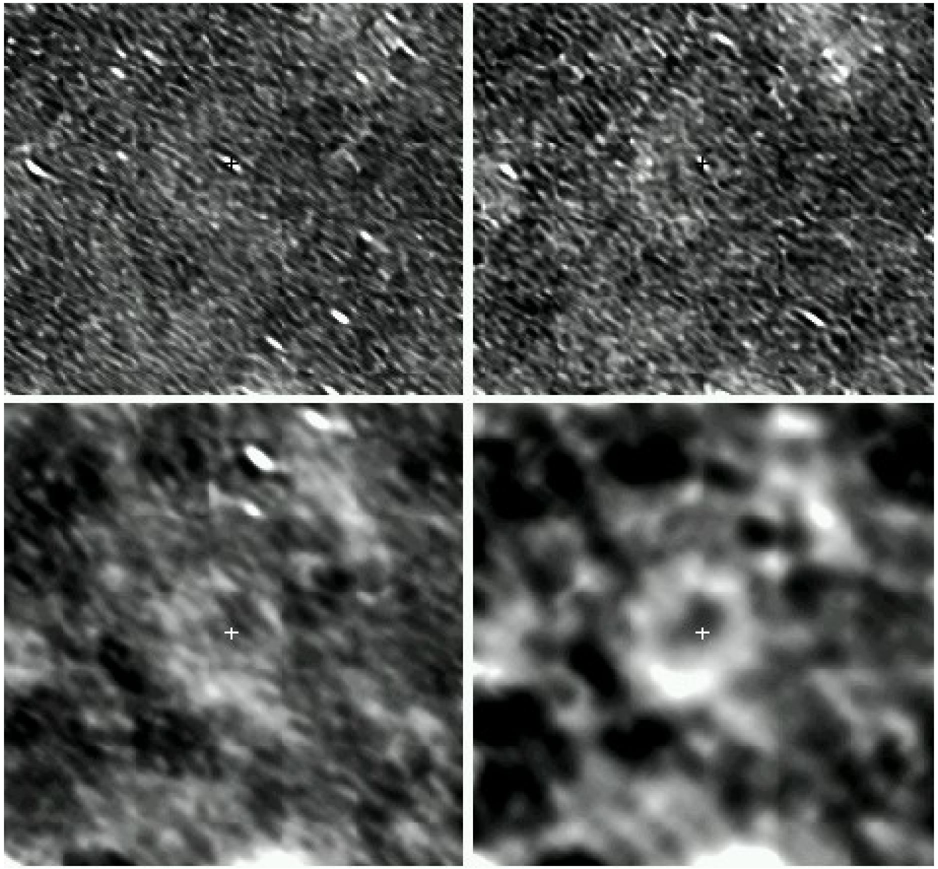
September 2007

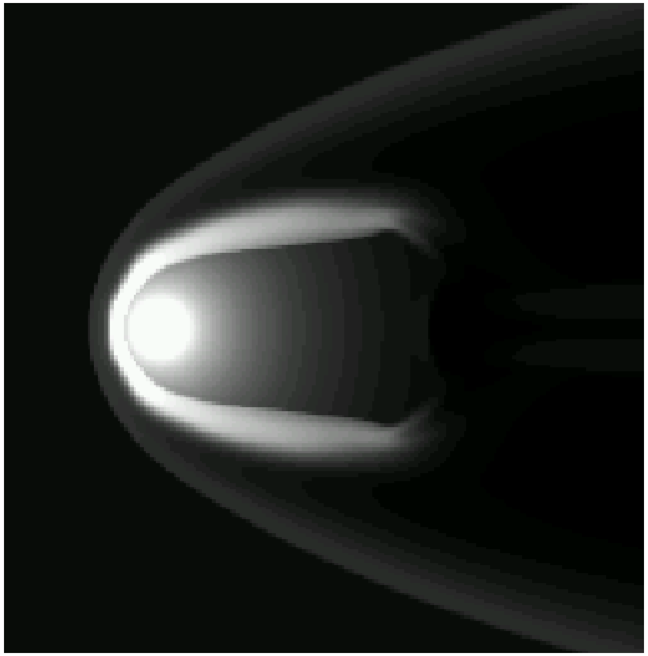
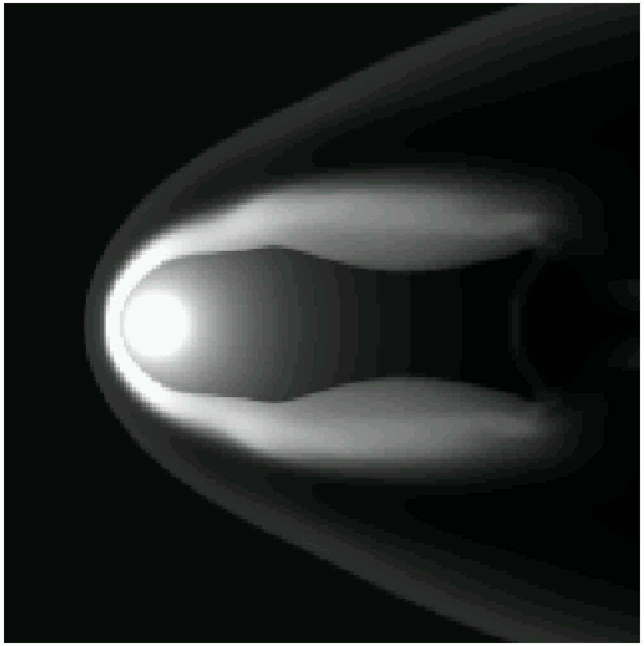
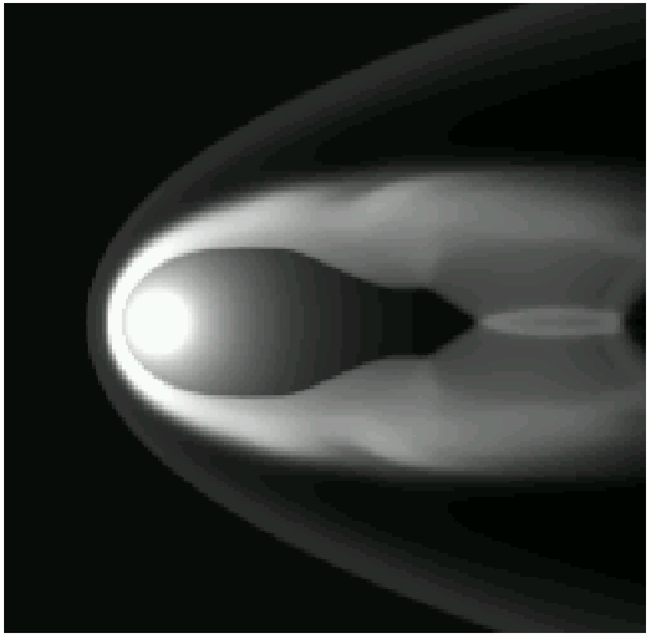
Angular momentum

- Shaping requires angular momentum
  - not possible from stellar rotation
- During stellar evolution, angular momentum is in cold storage
- Superwind taps angular momentum reservoir
  - binary orbits

AGB – ISM interface

- Stellar wind sweeps up ISM
  - stationary shock at 0.5-2 pc
  - interstellar wall
- Mixing occurs in the wall
- Wall is shaped by stellar motion

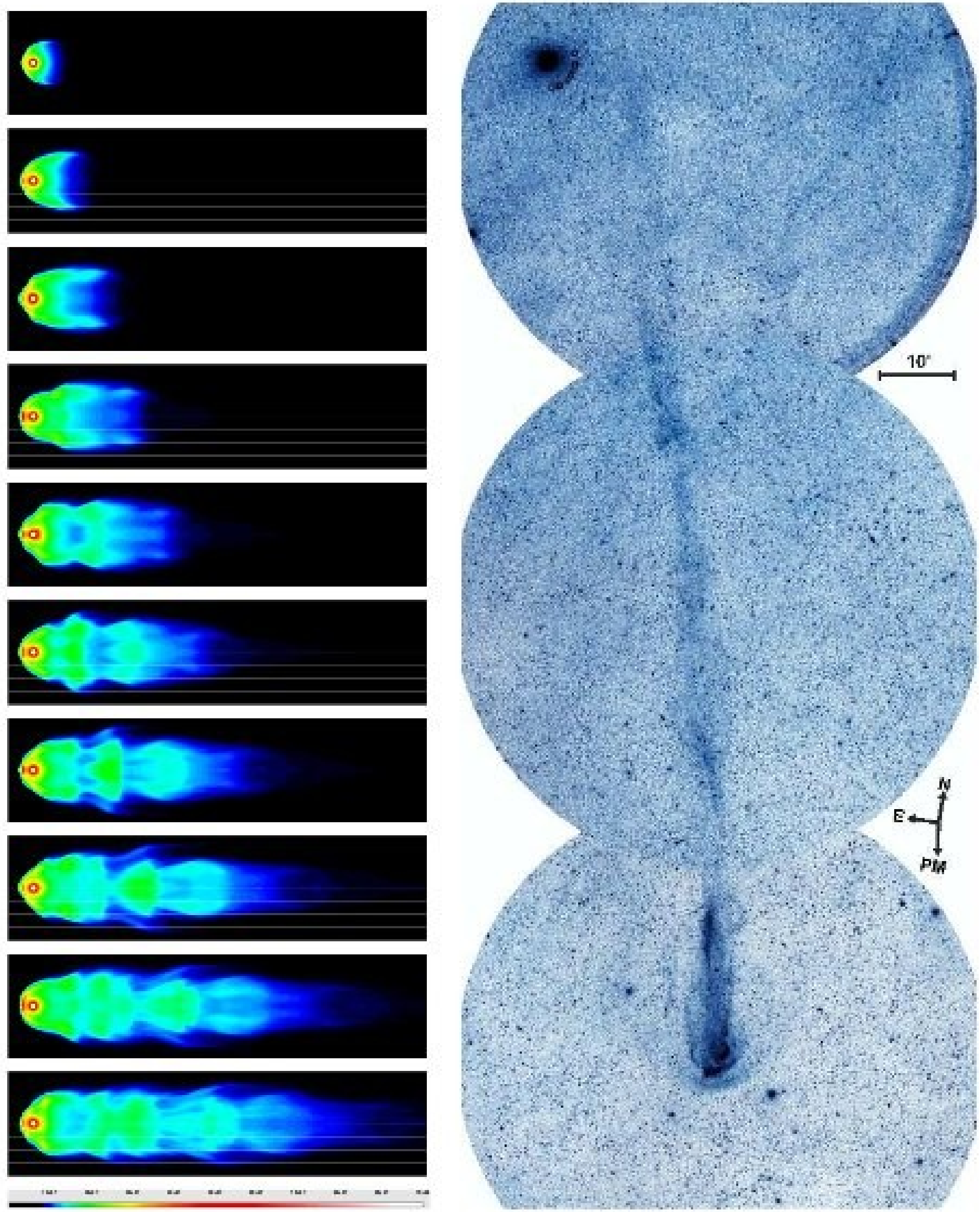


Mira: the wonderful

- Brightest, and oldest known, variable star
  - discovered 1584
  - probably known before
    (suggested candidate for star of Bethlehem)
- Moving at high speed through the Galaxy
  - expect bow shock and tail

- Mira's wonderful tail
  - 0.5 million year old
- caused by
  - stellar wind
  - blowing into the ISM



Galactic Ecology

- ISM conditions determine star formation
  - location, efficiency, metallicity, IMF, angular momentum
- Stars determine ISM conditions
  - energy deposition, ionization
- Stars re-form the ISM
  - Ejecta: gas, dust, kinetic energy
- ISM forms a new generation of different stars

Galactic evolution and stellar evolution intertwine