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 is just to the right of $\gamma$ Hya and $\psi$ 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 lives within the interstellar medium (ISM)
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
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 \( M^a \):
  – \( M < 7 \, M_\odot \): \( a = 4.5 \)
  – \( M > 7 \, M_\odot \): \( a = 3 \)

• 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
    - Stabilizes nuclear reactions
Energy transport

- radiative for small temperature gradient
- convective for steep temperature gradient
- most stars have both convective and radiative regions
Turbulence itself is hard to model
- chaotic
- overshoot and undershoot

Gives mixing and dredge-up

Convection
- 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

- $f = \frac{E(\text{nuclear})}{U(\text{gravity})}$
- low mass star (→ white dwarf)  $f \sim 50$
- high mass star (→ neutron star)  $f \sim 0.5$

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

main problem in stellar evolution

- mass loss rate
  - non-linear tracers

- wind energy

- wind composition

- driving mechanisms

dominates evolution for

- high-mass stars

- evolved stars
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
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
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) \[ \log \dot{M} = a P + b \]

(ii) \[ \dot{M} = a M_1^{-2.1} L^{3.1} R M^{-1} \]

(iii) \[ \dot{M} = a L^{2.47} T^{-6.8} M^{-1.95} \]

(iv) \[ \dot{M} = a L^{1.05} T^{-6.3} \]

Vassiliadis & Wood 1993

Bloecker 1995

Wachter et al. 2002

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

V Cyg
(galactic carbon-star)
IRAS 04496-6958
(LMC)
SMC S30

Matsuura et al. (2002); A&A in press
Oxygen-rich stars

$^{28}\text{Si}^{16}\text{O}$

$^{29}\text{Si}^{16}\text{O}$

Galactic stars: semi-regular variables

Mira variables

g Her (solar neighbour)
ISO/SWS, $R=2000$

IRAS 05042-6720 (LMC)
$R=3300$

$\text{SiO EW [Angstrom]}$

$H-K$

$\text{LMC}$
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
    - \( \sim Z^{-4/3} \)
- binary trigger
Mass loss variability
three time scales

- $10^{4-5}$ year: TP spikes
  - TT Cyg
- $10^{2-3}$ 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**

- 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

A Disc Around An Aged Star

ESO Press Photo 43/07 (27 September 2007)

VLT Melipal + VISIR Image

Disc model deduced from VLT/MIDI observations

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