Structure and Evolution of Stars

Lecture 16: The IMF, Lithium Burning, P Cygni Profiles and Mass Loss

- The Initial Mass Function

- Star of the Week #4: VY Canis Majoris
  - Lithium Burning, star-Brown Dwarf discriminant, pre- and post-main sequence discriminant
  - P Cygni line profiles
  - Evidence for mass loss
  - Mass loss during post-main sequence evolutionary phase

The Initial Mass Function

• In Lecture 15, considered briefly the Jeans' criterion for stability against gravitational collapse

• Really want birth function – number of stars with masses $M \rightarrow M+dM$ per unit volume. Simplest to assume a function of mass only

• Ed Salpeter determined the power-law index, =-2.35, 60 years ago now

• The Initial Mass Function (IMF) is the standard parameterisation – the amount of mass contained in stars with mass $M \rightarrow M+dM$

$$dN = \Phi(M)dM$$

$$\Phi(M) \propto M^{-2.35}$$

$$MdN = \xi(M)dM$$

$$\xi(M) \propto \left(\frac{M}{M_{sun}}\right)^{-1.35}$$

Initial Mass Function

Behaviour at low and high masses continues to be the subject of current research

Straightline portion of this determination:

$$\log \xi = -1.7 \log m + 1.75$$

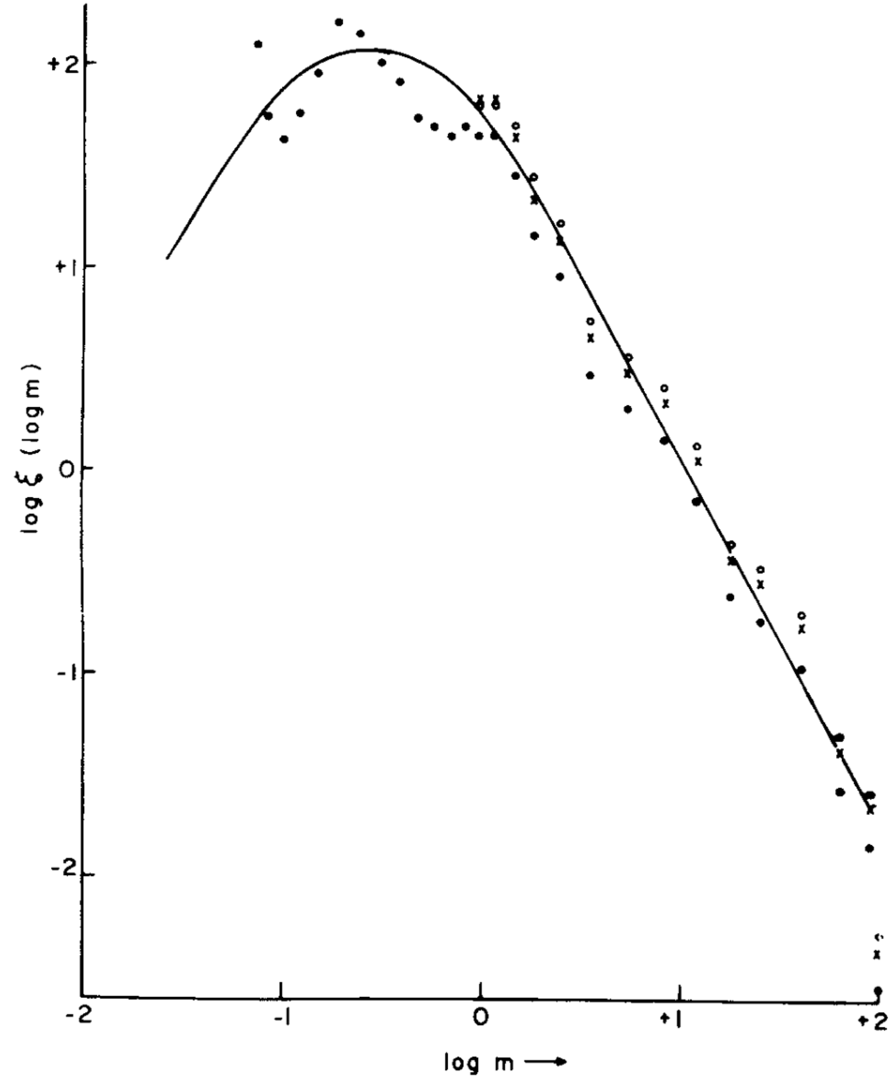


Figure 12.9 The initial mass function, ξ, shows the number of stars per unit area of the Milky Way's disk per unit interval of logarithmic mass that is produced in different mass intervals. Masses are in solar units. (Figure adapted from Rana, *Astron. Astrophys.*, *184*, 104, 1987.)

The Initial Mass Function

• Negative index means that there are far fewer stars at high masses than there are at low masses
• The IMF describes the way the ZAMS is populated as the result of the collapse of molecular cloud
• It is difficult to perform observations that provide direct measures of the IMF for an individual system over a large dynamic range in mass – unless very massive cloud/cluster then few if any massive stars; most massive stars very short lived; for systems at large distances cannot see the low mass objects; still major uncertainties in the luminosity (i.e. what is observed) to mass conversion at low masses
• Still the case that while the exact form of the original Salpeter IMF has changed somewhat, there is little convincing evidence that the IMF varies as a function of metallicity, location…

The Initial Mass Function

- The *fragmentation* of a collapsing molecular cloud is expected to be a complicated process involving the interplay between
  - o angular momentum
  - o magnetic fields
  - o mass-loss due to radiation pressure
  - o stellar winds and radiation from recently formed stars
  - o supernovae
  - o Jeans' criterion
  - o opacity
- Form of the IMF really not understood, although numerical simulations just reaching the point where quantitative progress possible

- Somewhat surprising that there is no definitive evidence for dependence of form of IMF on any parameter whatsoever!

Star of the Week #4: VY Canis Majoris

(Humphreys et al. 2005, *Astrophysical Journal*, 129, 492
Shenoy et al. 2013 *Astronomical Journal*, 146, 90) and 2016

- Extreme red supergiant at a distance of ~1.2kpc with a luminosity $L \approx 2.7 \times 10^5 L_{sun}$, $R = 2100 R_{sun}$, at the extreme of the HR-diagram

- Associated with a well-studied star-forming region (star cluster NGC 2362) including an HII region and a molecular cloud

- Some researchers have identified VY Canis Majoris as a pre-main sequence star
- Other researchers have identified VY Canis Majoris as a post-main sequence object, close to the end of its life

- Presence of large, 10 arcsec, asymmetric nebula associated with the star has been cited as evidence of both interpretations

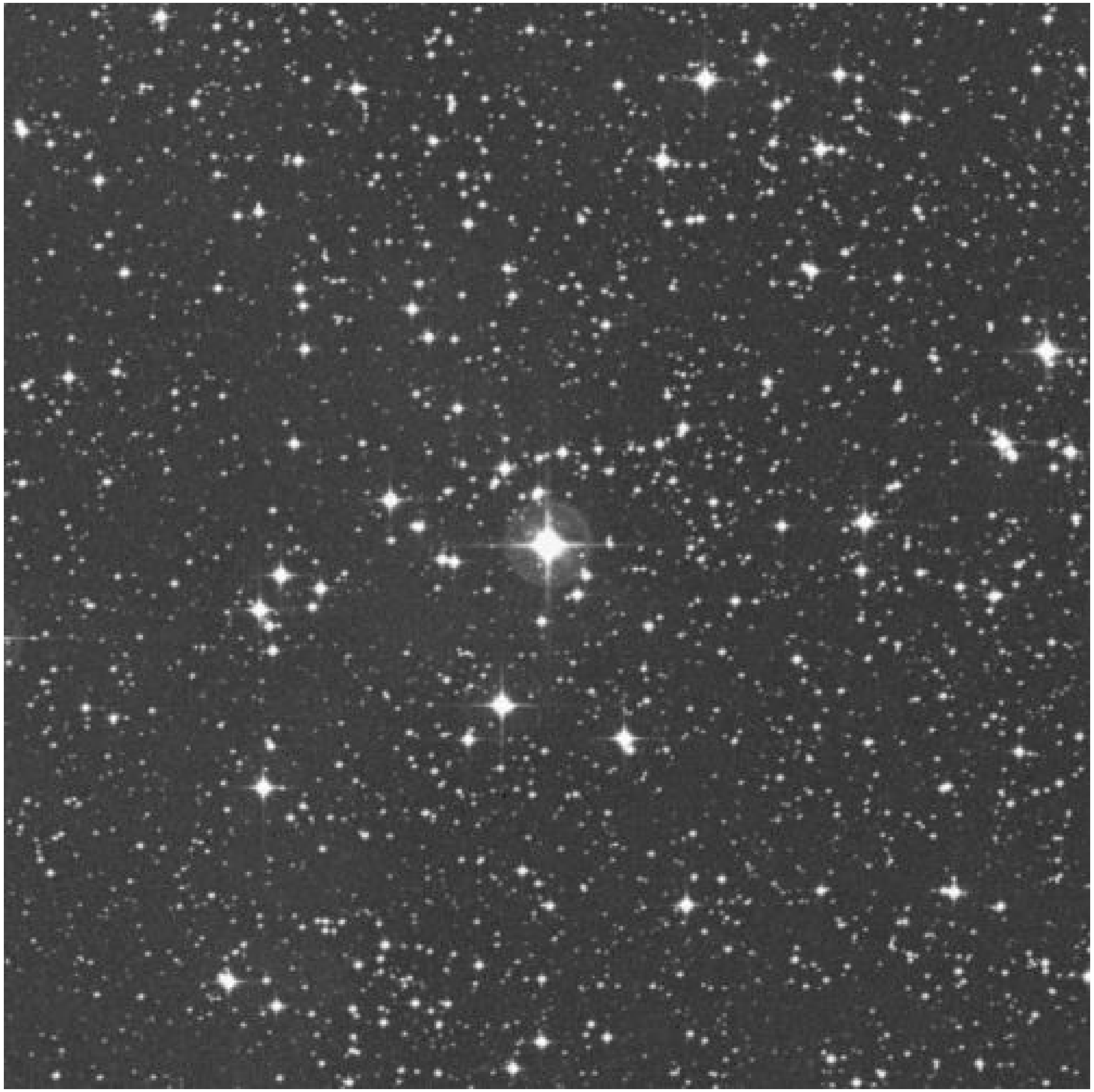
VY Canis Majoris

Photographic B-band image of 10 arcmin on a side

V=7.95
B-V=2.24

Spectral Type: M4II
T_{eff}≈3000K

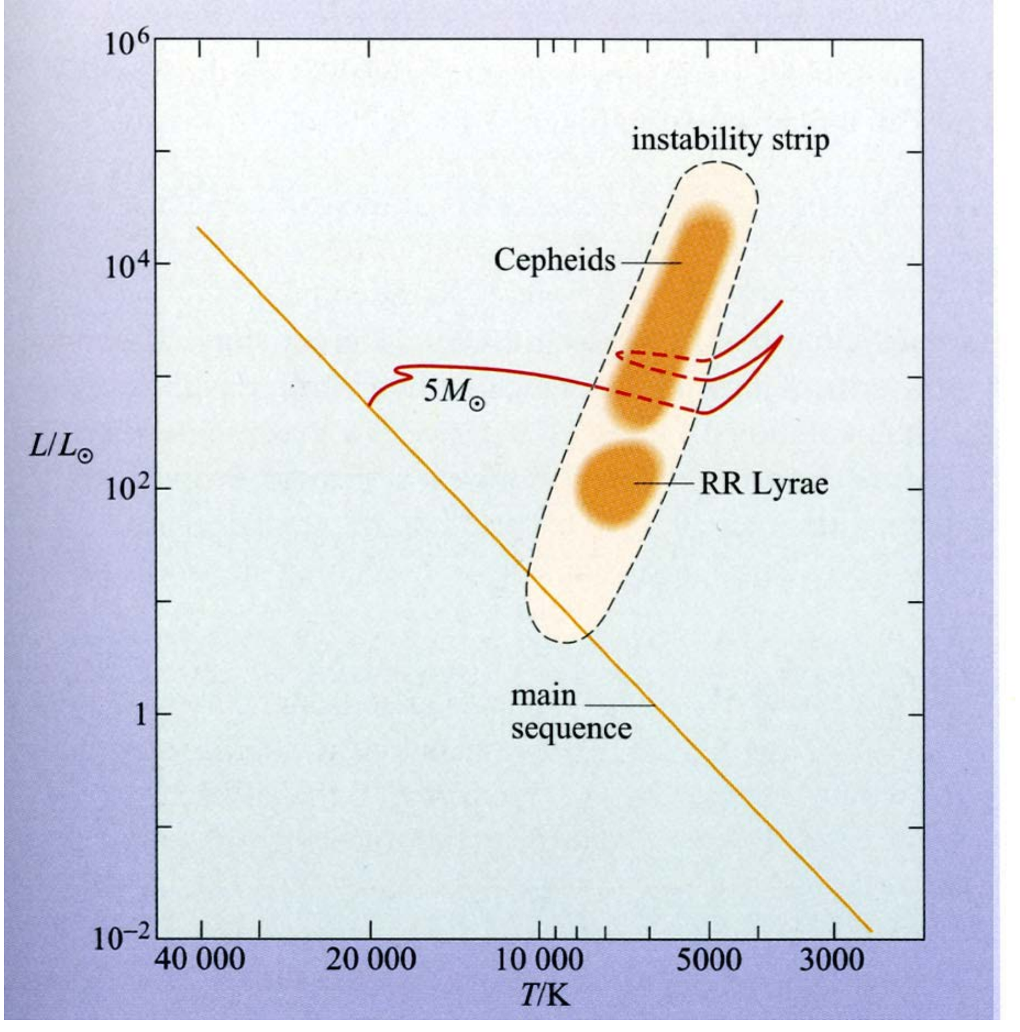
Significant reddening – star is cocooned

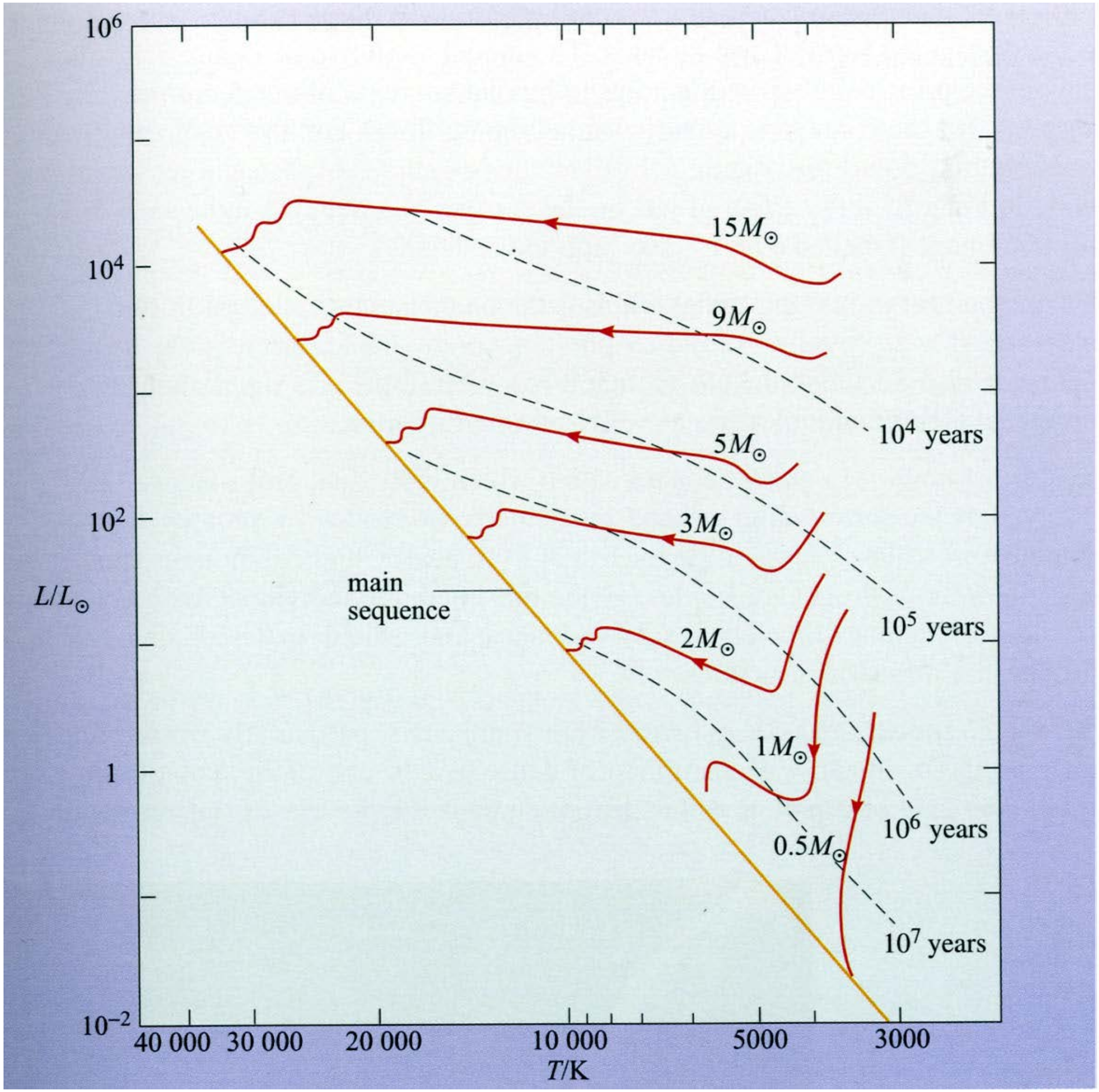


Location of VY CMa in the HR-diagram

Red supergiant star that has evolved off main-sequence in last phases of life?

Luminous convective protostar that is very young and has not initiated nuclear burning? (Top of Hayashi Track discussed in Lecture 15)





10^6
10^4
10^2
1
10^{-2}
$L/L_\odot$
$15M_\odot$
$9M_\odot$
$5M_\odot$
$3M_\odot$
$2M_\odot$
$1M_\odot$
$0.5M_\odot$
10^4 years
10^5 years
10^6 years
10^7 years
main sequence
40 000
30 000
20 000
10 000
5000
3000
T/K

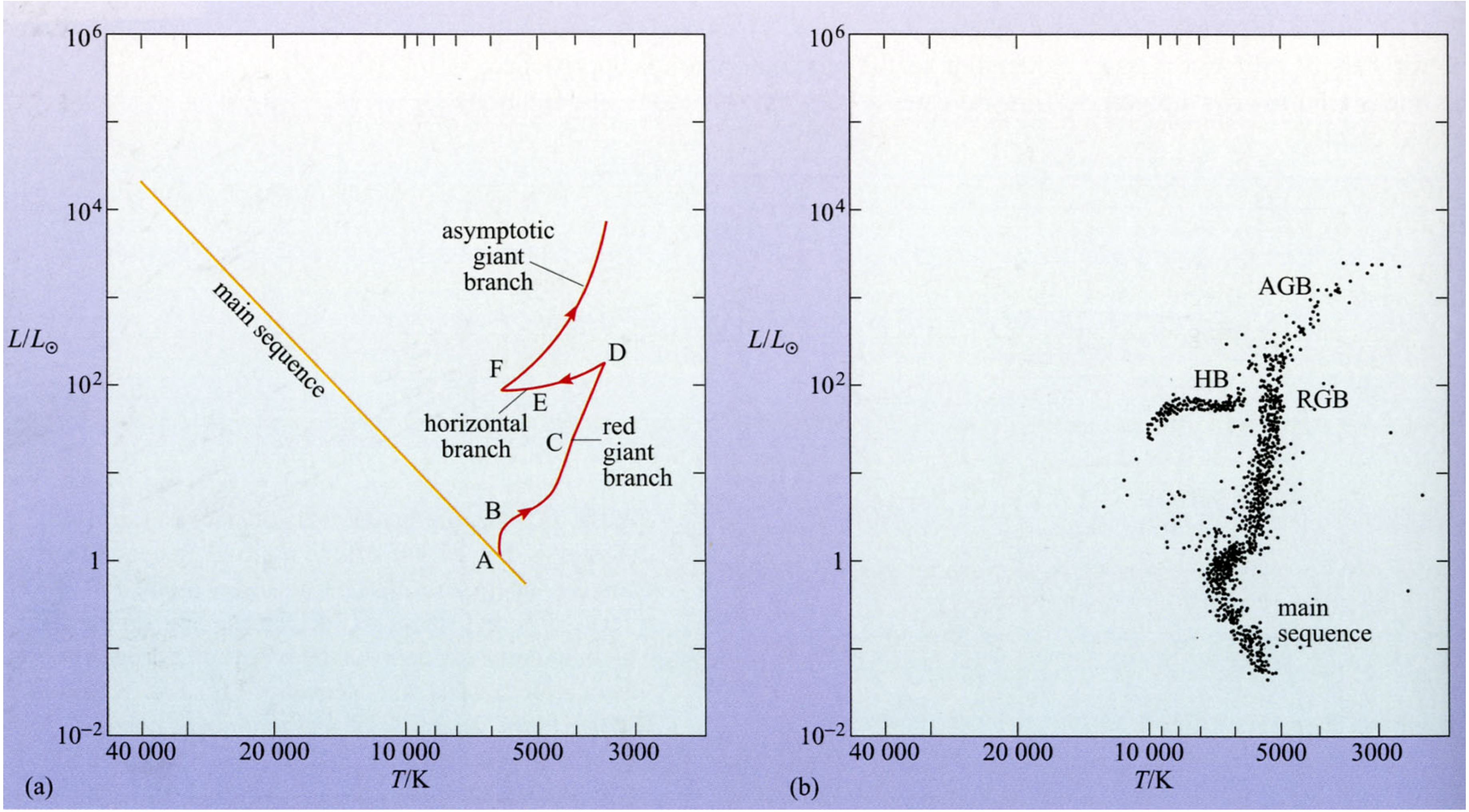


Figure 7.3 (a) The predicted path of a $1 M_\odot$ star, plotted on the same scale with the same labels as Figure 7.2, (A) hydrogen core fusion; (B) onset of hydrogen shell fusion; (C) hydrogen shell fusion continues; (D) helium core fusion starts; (E) helium core fusion continues; (F) helium shell fusion starts. (b) The H–R diagram of a globular cluster which illustrates how stars tend to concentrate in these regions.

Lithium Burning: Star-Brown Dwarf Boundary

• Potential energy source at relatively low *T* is the fusion of Lithium to produce Helium

• Lithium produced in Big Bang – next element after Helium

• *T*-required is low because Coulomb barrier not high and reaction rate is fast relative to first step in the p-p chain because no proton decay involved

• Lithium burning involves creation of He and Be via 2-body interactions with protons

• Subsequent Be decay produces two He nuclei

$$^{6}_{3}\mathrm{Li}+^{1}_{1}\mathrm{H}\rightarrow^{3}_{2}\mathrm{He}+^{4}_{2}\mathrm{He}$$

$$^{7}_{3}\mathrm{Li}+^{1}_{1}\mathrm{H}\rightarrow^{8}_{4}\mathrm{Be}+\gamma$$

$$^{8}_{4}\mathrm{Be}+\gamma\rightarrow^{4}_{2}\mathrm{He}+^{4}_{2}\mathrm{He}$$

Additional Li via :

$$^{9}_{4}\mathrm{Be}+^{1}_{1}\mathrm{H}\rightarrow^{4}_{2}\mathrm{He}+^{6}_{3}\mathrm{Li}$$

Lithium Burning: Star-Brown Dwarf Boundary

- Deuterium burning occurs first. Only 1:100000 deuterium ions but for very low mass stars can fuel object for ~100 million years
- Additional reactions between protons and low-mass nuclei can also generate energy

$$ {}^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma $$

$$ {}^{10}_{5}\mathrm{B} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{7}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} $$

$$ {}^{11}_{5}\mathrm{B} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} + \gamma $$

- Collapsing protostars are fully convective, i.e. well-mixed
- If *T* reaches threshold for Lithium burning then all (the small amount) the Lithium is rapidly consumed
- Presence/absence of Lithium in atmospheres is the accepted diagnostic for classification of object as a star or brown-dwarf

VY Canis Majoris

• The Lithium-test for classification as star or brown dwarf works for stars on or close to the main sequence – relatively strong neutral Lithium absorption line at 6707A usually employed

• Can also use Lithium test to discriminate between post-main sequence object and one at the start of protostellar collapse – in latter case, Lithium has not been burned and 6707A absorption should be strong

• Failure to detect Lithium 6707A in VY CMa confirms post-main sequence identification

• Extended nebula surrounding VY CMa provides information on key mass-loss phase during period as red supergiant

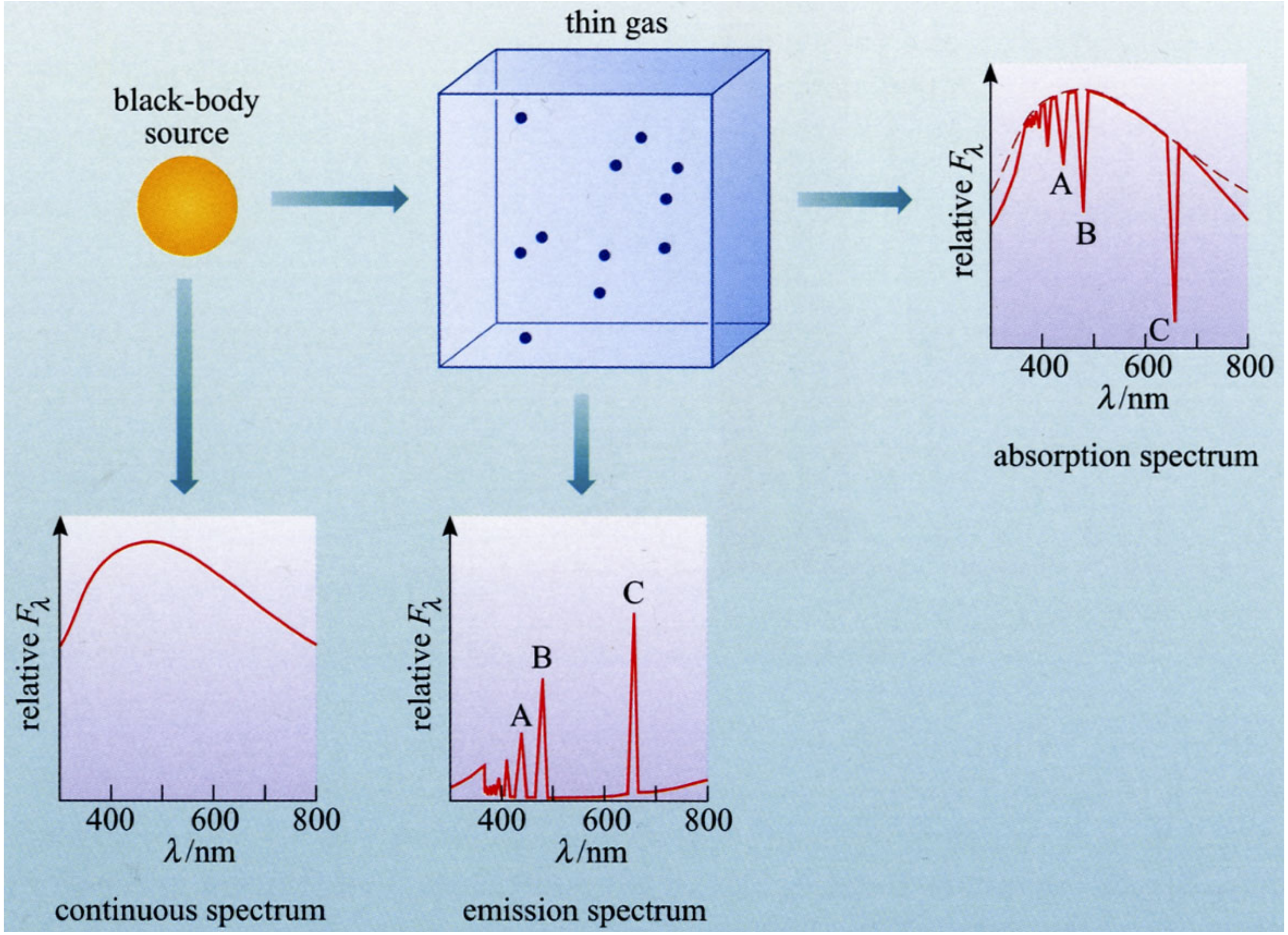
VY Canis Majoris: Mass Loss

• Will look in more detail at the question of mass loss in a later lecture but stars with main sequence masses as high as ~$8M_{sun}$ produce remnants, white dwarfs, with masses $<1M_{sun}$ – mass loss is critical to understanding the post-main sequence phases of stellar evolution

• Stars with such masses are not radiating at the Eddington Luminosity on the main-sequence, therefore, the mass loss must occur during the relatively short period of post-main sequence life prior to the stellar core becoming revealed as a hot white dwarf

• Basic principles behind mass loss, such as the Eddington Luminosity, understood but details of the process very poorly constrained

Continuum, emission and absorption spectra



What do we expect if we observe a spectrum of a star experiencing mass-loss due to Luminosity exceeding the Eddington Luminosity at the stellar photosphere?

P Cygni Profiles

• Observe Blackbody-like continuum spectrum from stellar photosphere

• If star is surrounded by low-density gas, continuum absorbed at particular wavelengths, corresponding to electron energy level differences, and re-emitted to produce emission feature as electron returns to lower energy state – if gas and star appear unresolved, observe additional emission along with the stellar continuum

• Blackbody continuum absorption occurs due to presence of surrounding gas along line-of-sight to the stellar photosphere

• At what wavelength does the absorption appear for gas accreting onto star (protostar perhaps) and for material that is present due to mass loss as Eddington Luminosity exceeded?

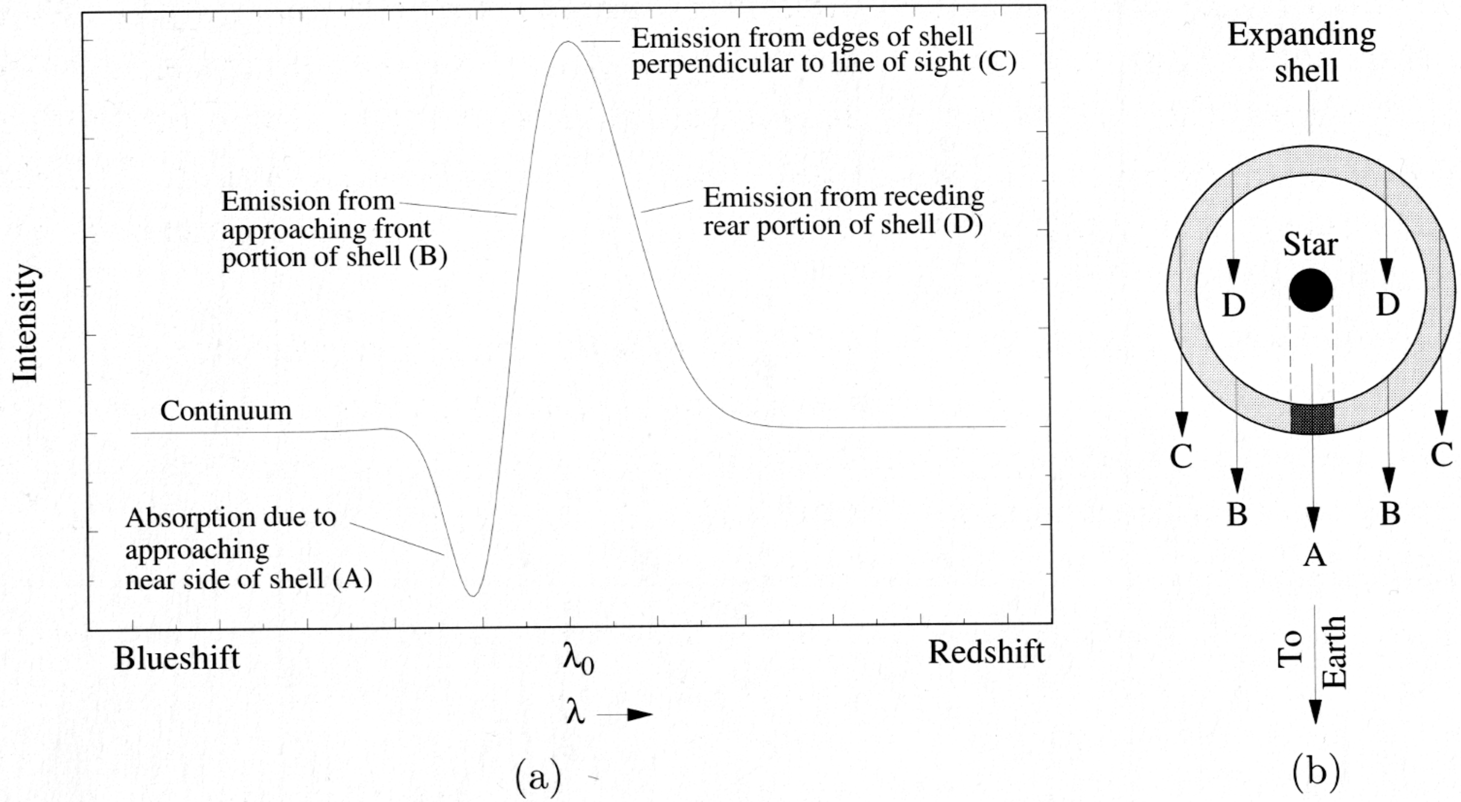
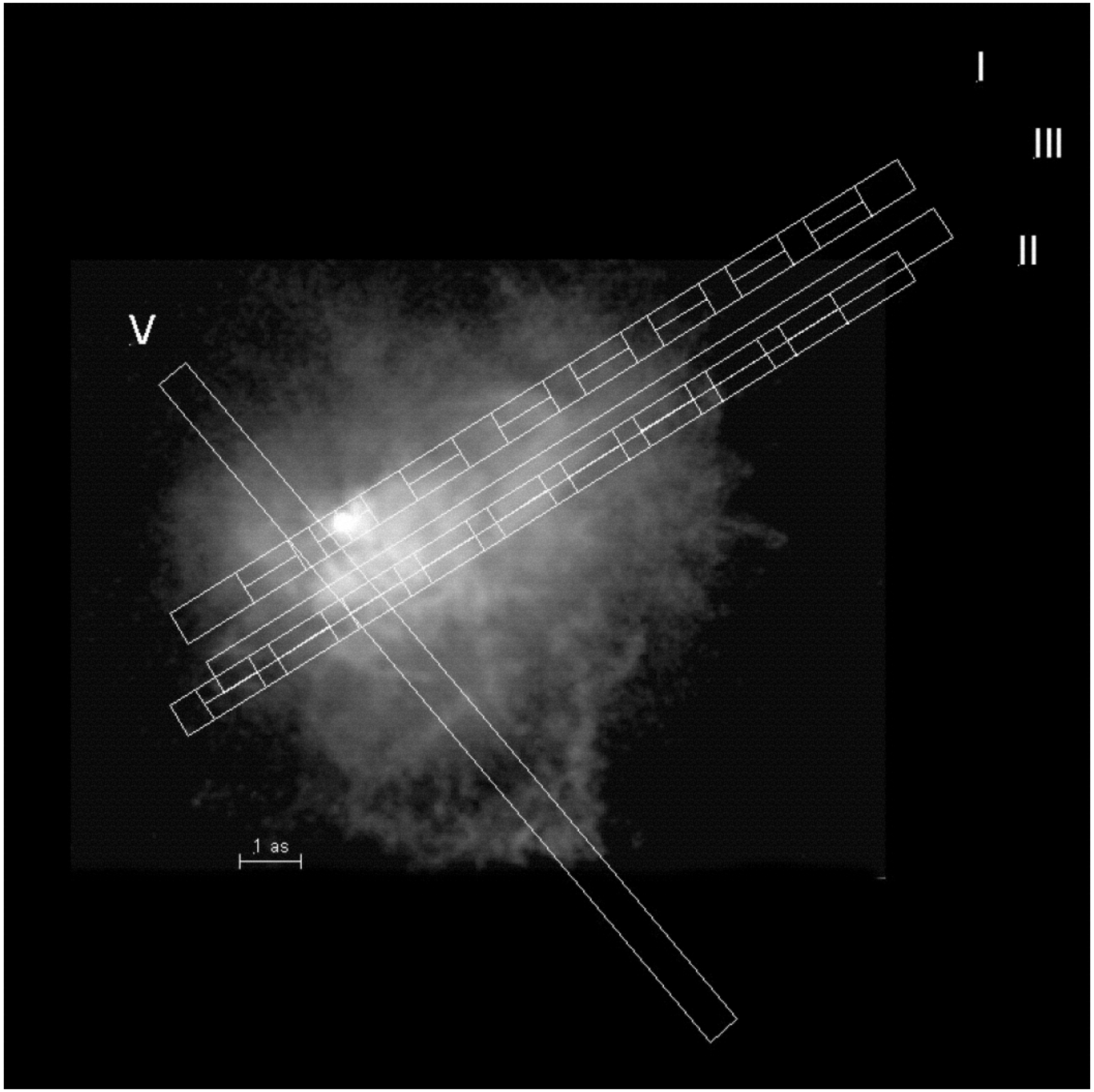


Figure 12.12 (a) A spectral line exhibiting a P Cygni profile is characterized by a broad emission peak with a superimposed blueshifted absorption trough. (b) A P Cygni profile is produced by an expanding mass shell. The emission peak is due to the outward movement of material perpendicular to the line of sight, while the blueshifted absorption feature is caused by the approaching matter in the shaded region, intercepting photons coming from the central star.

Hubble Space Telescope WFPC2 V-band image of VY CMa showing the inner nebula emission

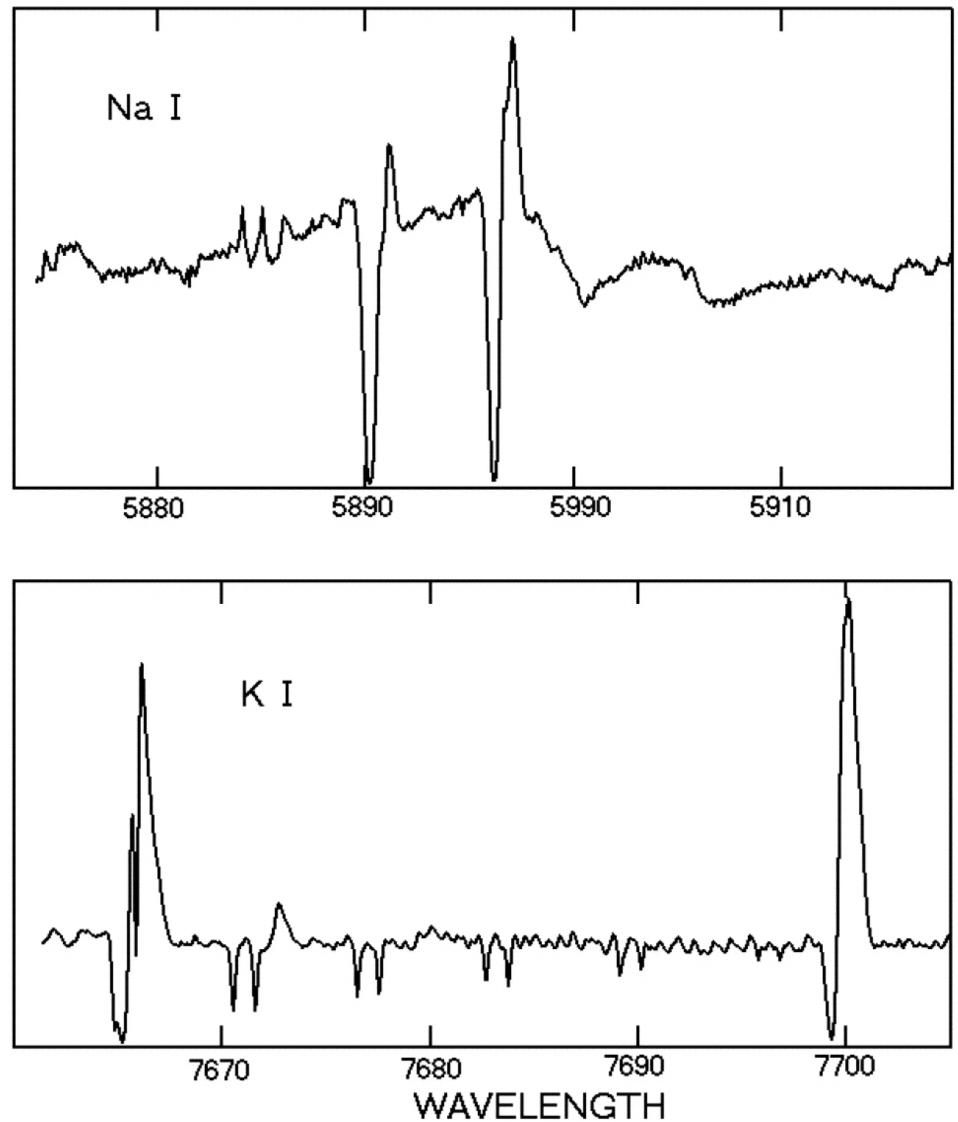
Scale bar is 1 arcsecond

Rectangular outlines indicate locations of slits used in the spectroscopic observations



Spectra of VY CMa including transitions due to Sodium and Potassium that show the characteristic signature of P Cygni profiles

Note location of absorption, blueward of emission, which shows the material is outflowing

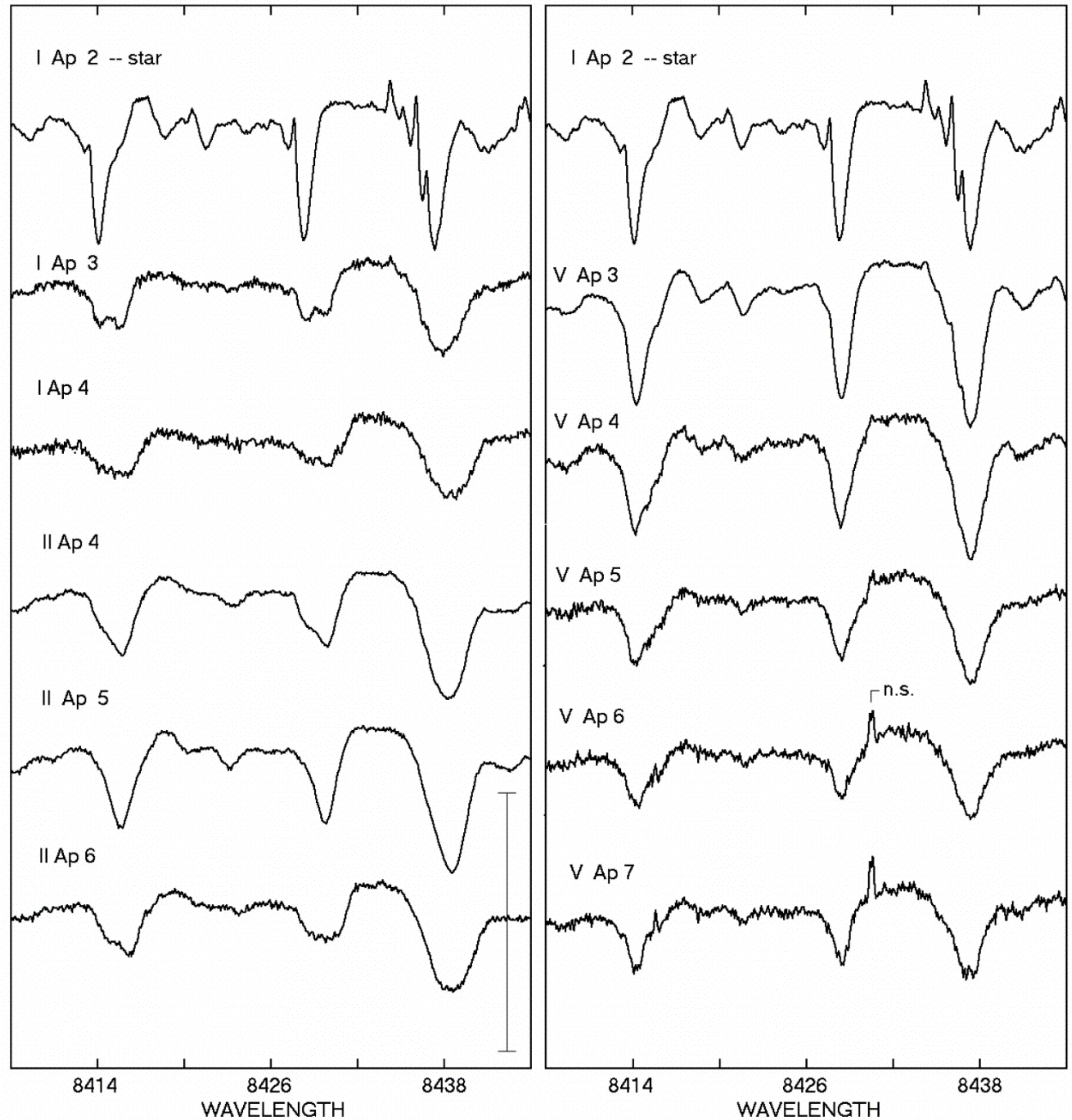


Absorption line profiles of transitions in neutral Fe and Ti towards the star and at distances further out across the nebula

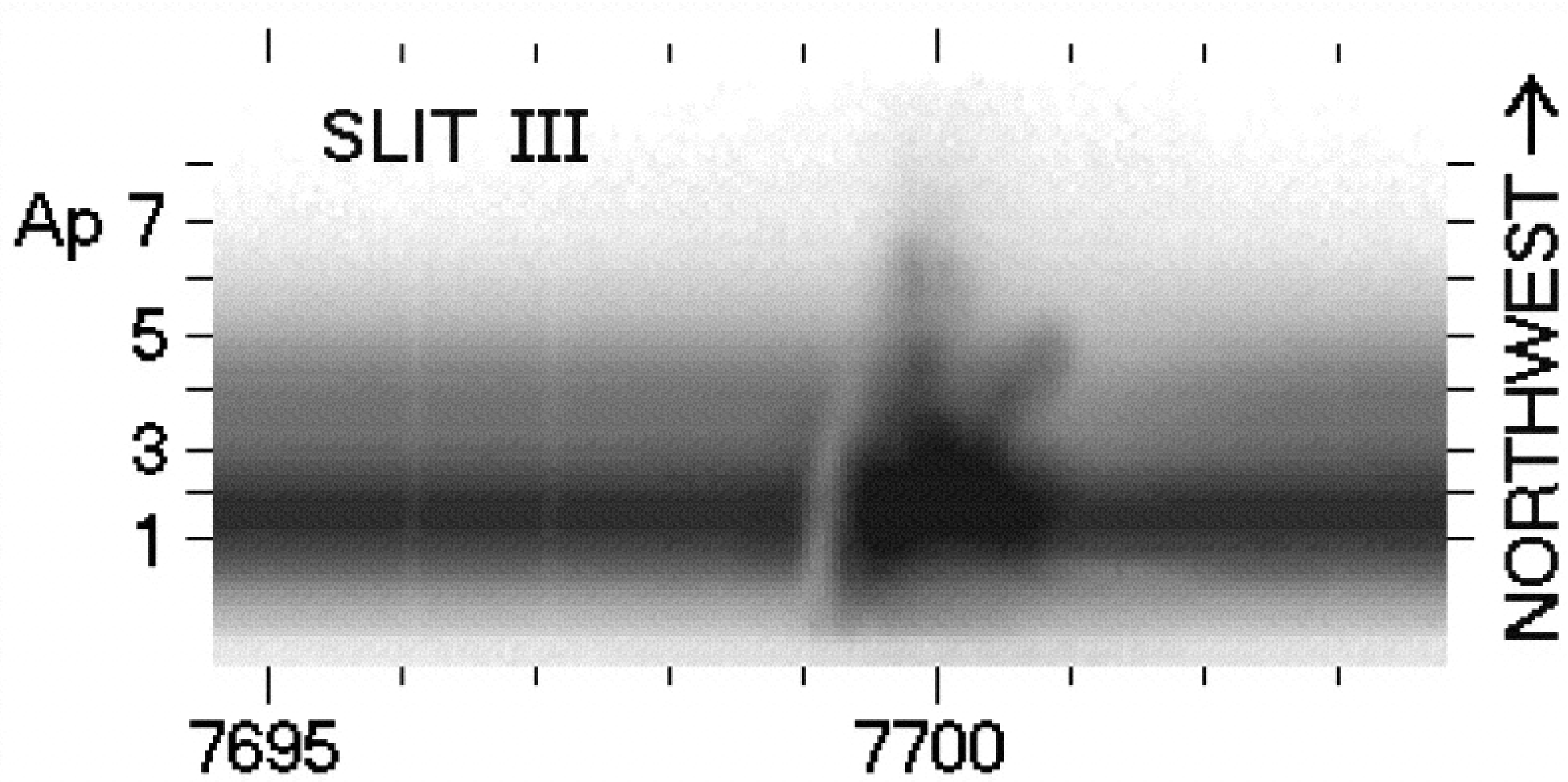
Note the sharp features present in the direct line of sight to the star.

Smeared profiles in the nebula due to additional velocity dispersion within the nebula - FWHM≈100km/s

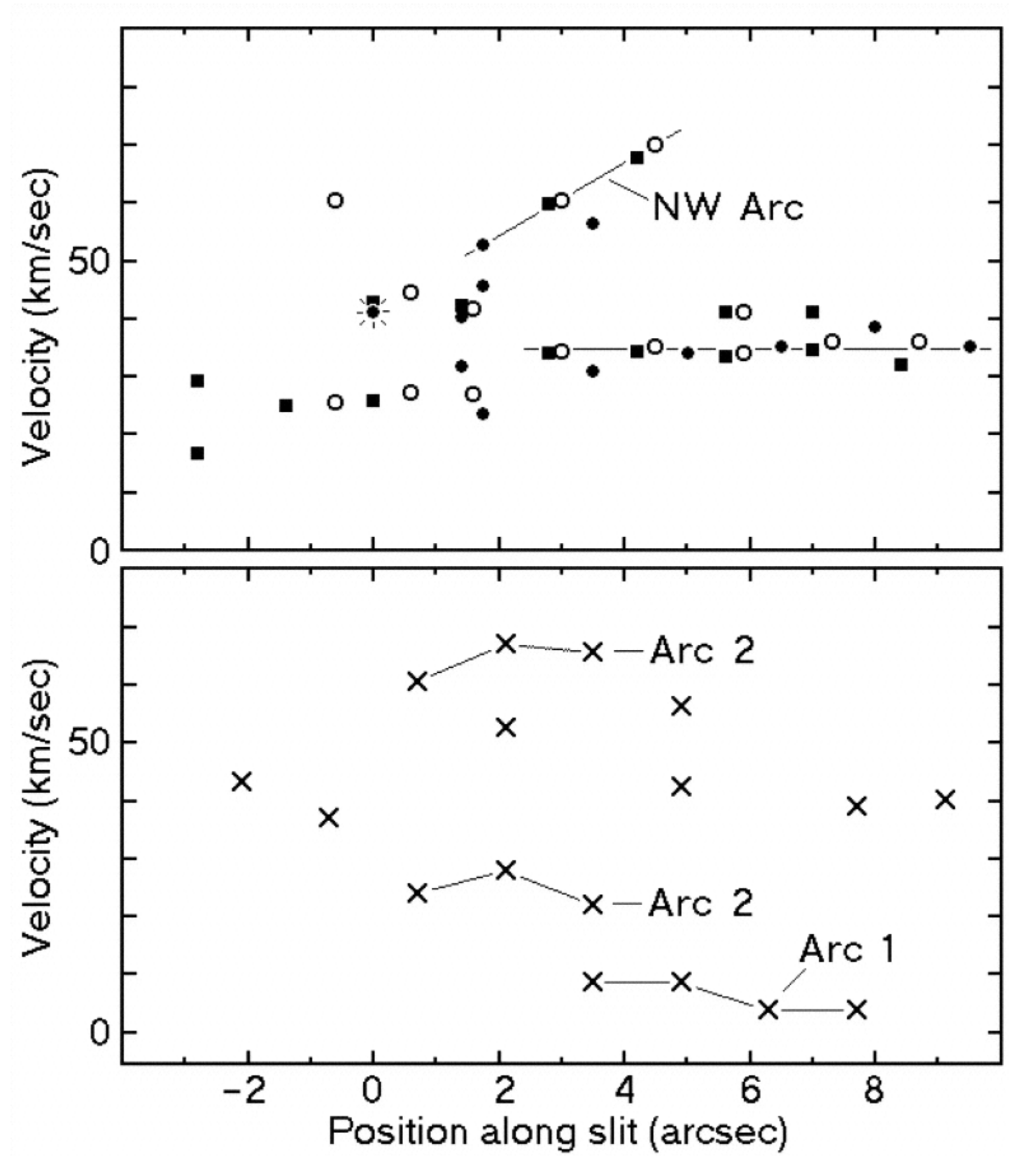
Note mean wavelength shift as well



Two-dimensional image of wavelength (x-axis) against position (y-axis) along slit, showing velocity trends in the neutral potassium emission. Systematic velocity gradient along northwestern arc feature clearly seen



Coherent outflows evident in position versus velocity diagrams for the emission. Three additional “streams” also evident in the lower plot.
However, the essentially stationary emission (relative to the systemic velocity of the system – indicated by horizontal line at 35km/s in top plot) over extended range of radii does not fit expectations for the post-main sequence mass-loss hypothesis

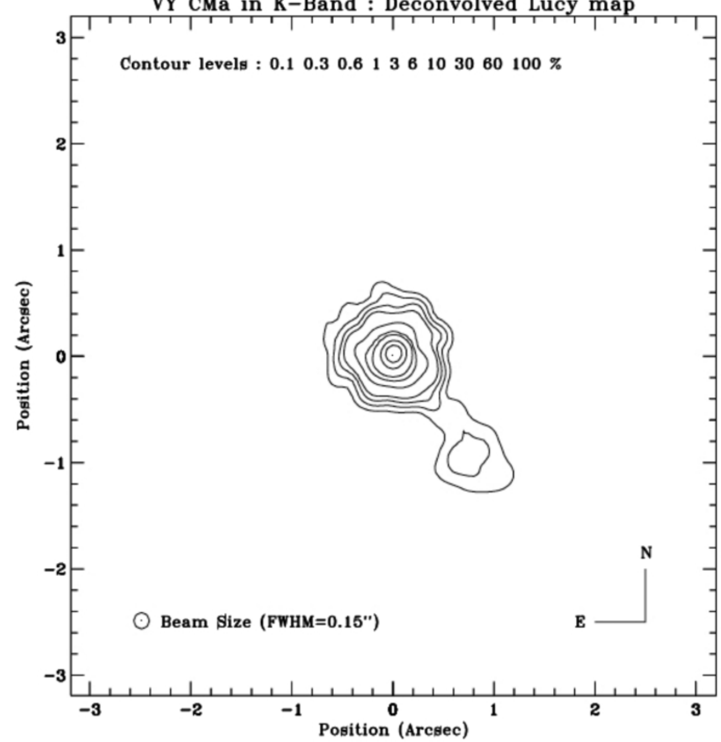


VY Canis Majoris: Extreme post main sequence mass-loss?

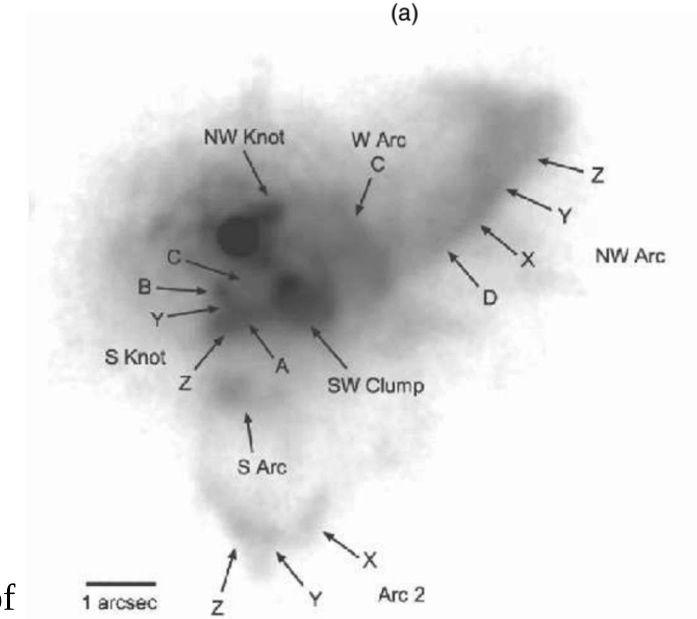
- Evidence for kinematically distinct outflows – discrete mass-loss episodes (strongly asymmetric)
- Expansion velocities ~40-50km/s
- Kinematic age estimates for features, from distance/velocity, are ~200, 400 and 900 years
- Smallest discrete knots only 0.5 arcsec from star would have ages of ~70 years if velocity also ~50km/s

- Historical evidence for photometric variability
  - 1872-1880: 1.5 magnitude decline in brightness. Dust formation at ~100AU where $T \approx 1000$K
  - 1984-1995: 1-2 magnitude variability perhaps related to pulsations of ~1000 days

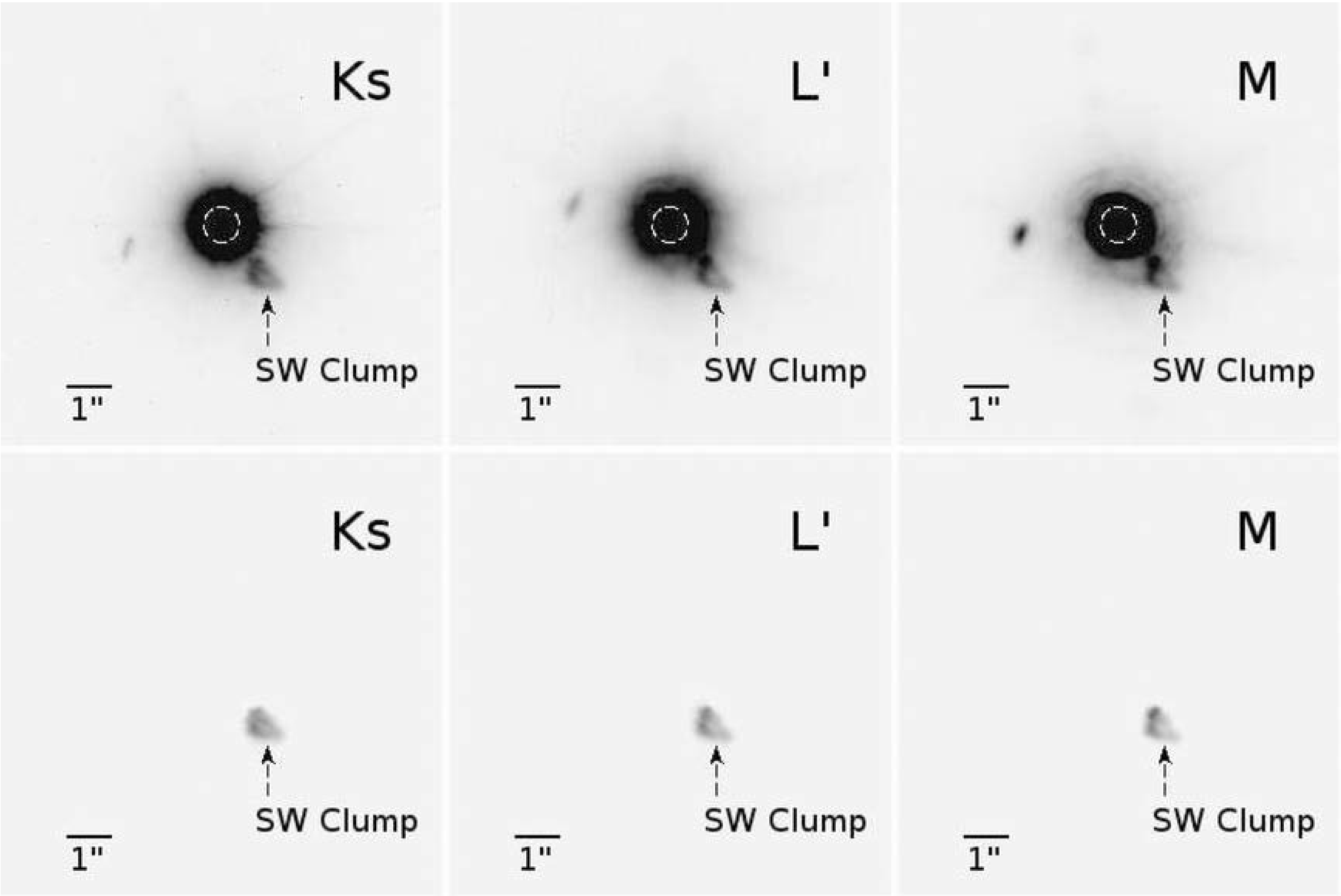
Recent K, L and M-band imaging (2.2-4.8µm)
HST 1µm image below with best possible infrared imaging in 1994 at top – can just make out one extension, the SW-clump.
Possible geometric mass loss – could be related to rotation of star?



(a)



(b)



2013 adaptive-optics images – no counter (NE) clump

VY Canis Majoris: Extreme post main sequence mass-loss

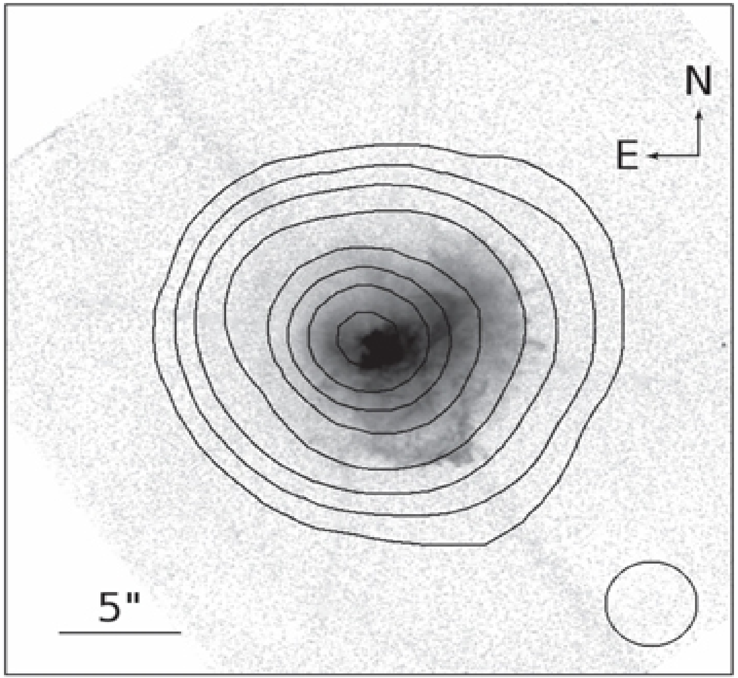
- From estimates of T and ρ in material ejected – use spectroscopic properties – the mass ejected is $3\times10^{-3}M_{sun}$ with kinetic energy 10^{44} ergs (cf stellar luminosity $L\sim6\times10^{46}$ergs/yr)

- Average mass loss rate, assuming one event every 50 years, is $\sim2\times10^{-4}M_{sun}$ per annum. The asymmetric and stochastic nature of the mass loss confirms the complexity of understanding the actual mechanism

- VY Canis Majoris is definitely one of the most extreme stars known. In the post-main sequence mass-loss interpretation have evidence for significant evolution on incredibly short timescales

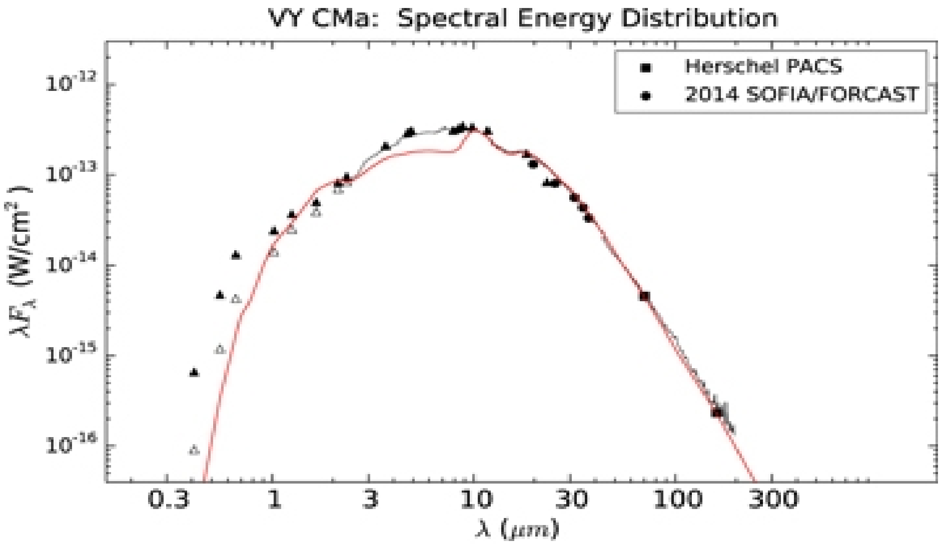
- The stationary ejecta is a problem though – consistent with pre-MS interpretation but post-MS identification favoured

Figure 7 from Searching for Cool Dust in the Mid-to-far Infrared: The Mass-loss Histories of the Hypergiants μ Cep, VY CMa, IRC+10420, and ρ Cas
Dinesh Shenoy et al. 2016 AJ 151 51 doi:10.3847/0004-6256/151/3/51



New, 2016, 27μm image shows extensions to the NW and SW as seen in shorter wavelength observations – Blackbody temperature
Sensitivity from Wien;s Law?

Figure 8 from Searching for Cool Dust in the Mid-to-far Infrared: The Mass-loss Histories of the Hypergiants μ Cep, VY CMa, IRC+10420, and ρ Cas
Dinesh Shenoy et al. 2016 AJ 151 51 doi:10.3847/0004-6256/151/3/51



Construct simple model with dust composition, temperature and mass compatible with the optical-infrared spectral energy distribution.

Allow for the interstellar line-of-sight extinction, A_V=1.5 mag, which is small compared to the extinction associated with the material resulting from the mass loss.

Need a gas to dust ratio

The optical depth of the feature causing the extension is τ(37μm)~0.2 – which tells us what about the observation?

Mass in ejecta ~0.7M_{sun} and mass loss estimate $6\times10^{-4}M_{sun}$ per annum

Lecture 16: Summary

- Initial Mass Function describes amount of mass contained in stars of a given. Simple power-law form overextended mass range and little good evidence for significant variation as function of any physical parameter
- Presence of Lithium in objects is direct evidence for lack of sufficient temperatures to initiate nuclear burning leading to classification of object as a Brown Dwarf or protostar at the very earliest stages of collapse
- Mass loss is a major factor in post-main sequence evolution with stars more massive than the Sun losing most of their mass prior to reaching their final state – white dwarf, neutron star, blackhole
- P Cygni profiles give direct evidence for mass loss and mass accretion

Picture Credits

- Slides 8, 9, 10 and 15 © from Green and Jones, CUP
- Slides 3 and 17 © Ostlie and Carroll
- Slide 7 © Digital Sky Survey, STScI
- Slides 18, 19, 20, 21, 24 and 25 © *Astrophysical Journal*