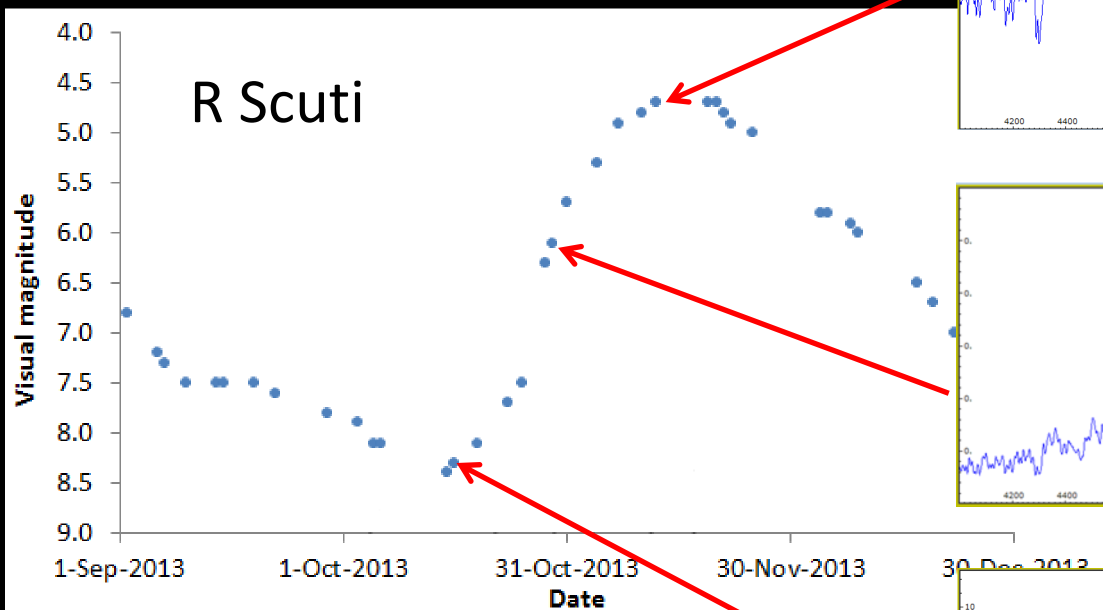
What you can learn about variable stars from spectroscopy

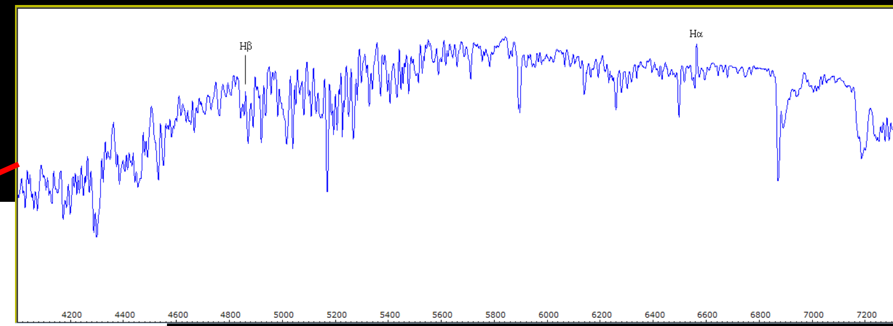
- and how to do it

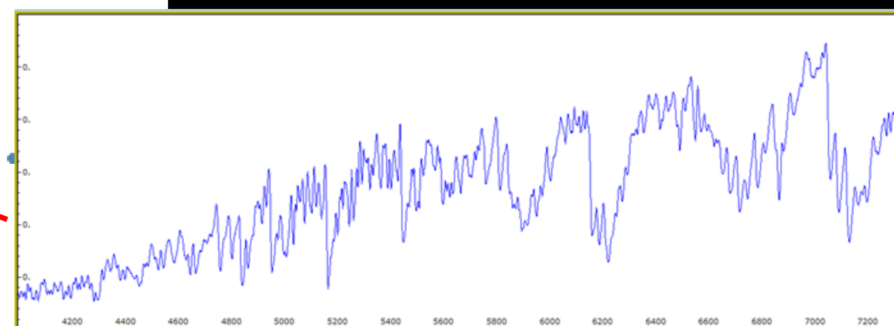
David Boyd

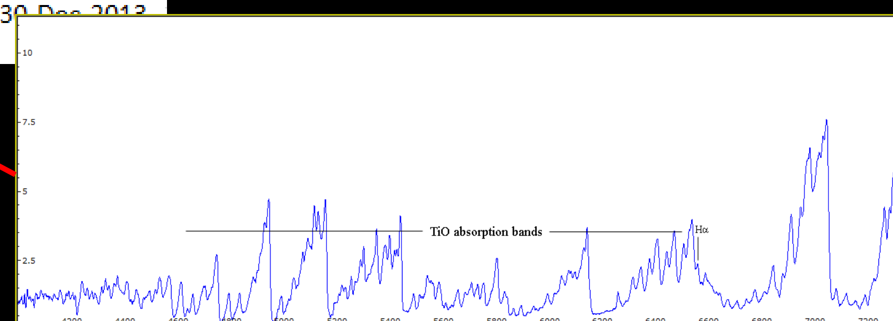
How spectroscopy can tell you more

Photometry reveals changes in a star’s brightness.



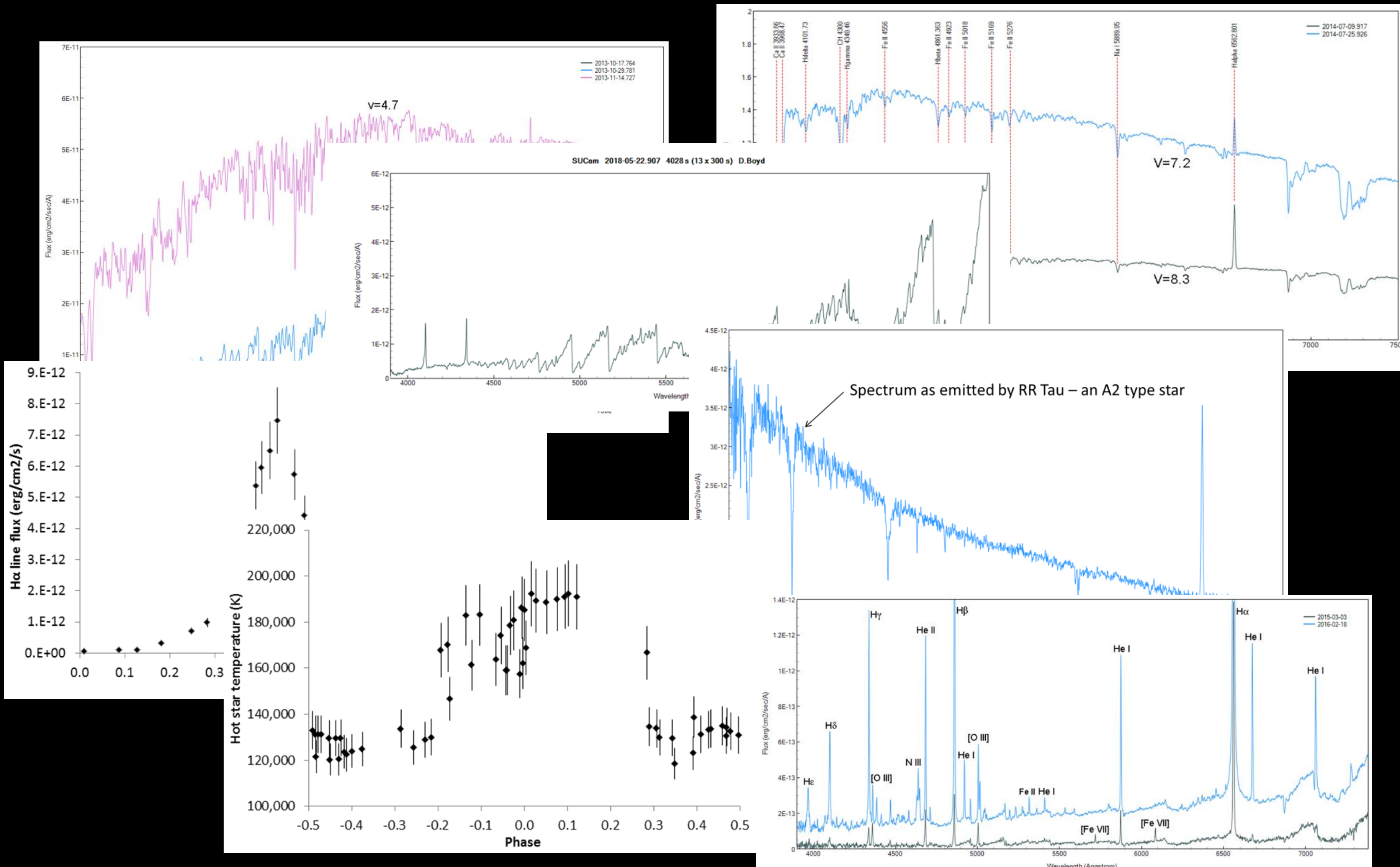






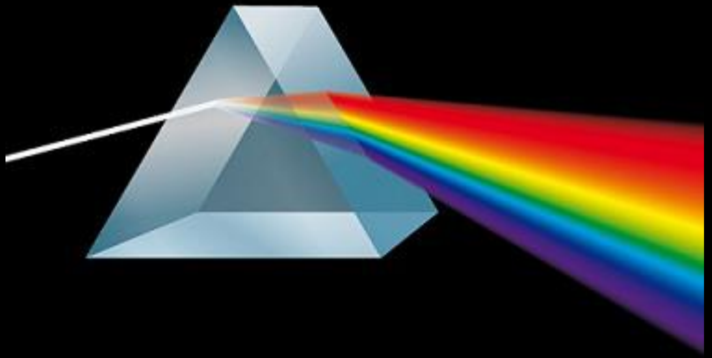
Spectroscopy reveals what is happening as the star brightens.

But first we'll look at how to record spectra

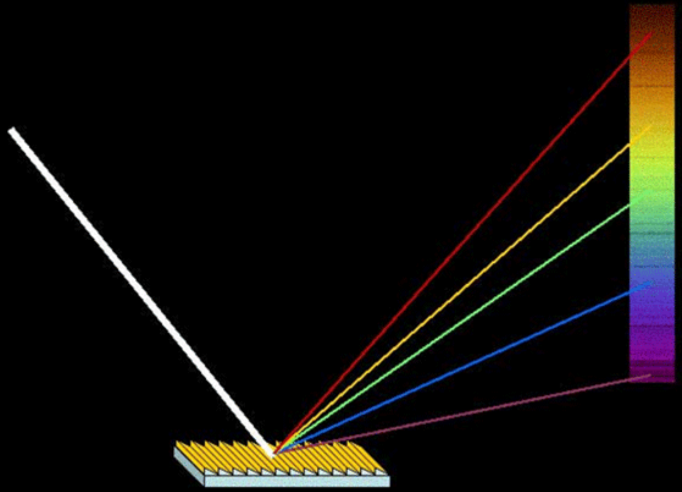


Creating a spectrum

Two devices are typically used to create a spectrum:



- a prism refracts white light and splits it into its component colours
  dispersion is non-linear



- a diffraction grating diffracts white light using a set of fine lines etched onto a surface
  dispersion is ~ linear

a diffraction grating may either reflect or transmit light

How do you record a stellar spectrum?

You need three components:

- optical system (to gather as much light as possible)
- spectroscope (to split the light into different wavelengths) using either
  - a prism (or multiple prisms)
  - a diffraction grating (either transmitting or reflecting)
  - a combination of both prism and grating (a grism)
- camera (to record the spectrum)

Spectroscopy is more difficult than photometry!

The main problem is the relative faintness of the dispersed light - so spectroscopes are typically attached to large telescopes

The challenge for amateurs is to achieve good results with small telescopes

This usually involves long exposures so guiding becomes important

There are two approaches:

a) spectroscopy without a slit (slitless)

b) spectroscopy using a slit

Slitless spectroscopy is a good starting point

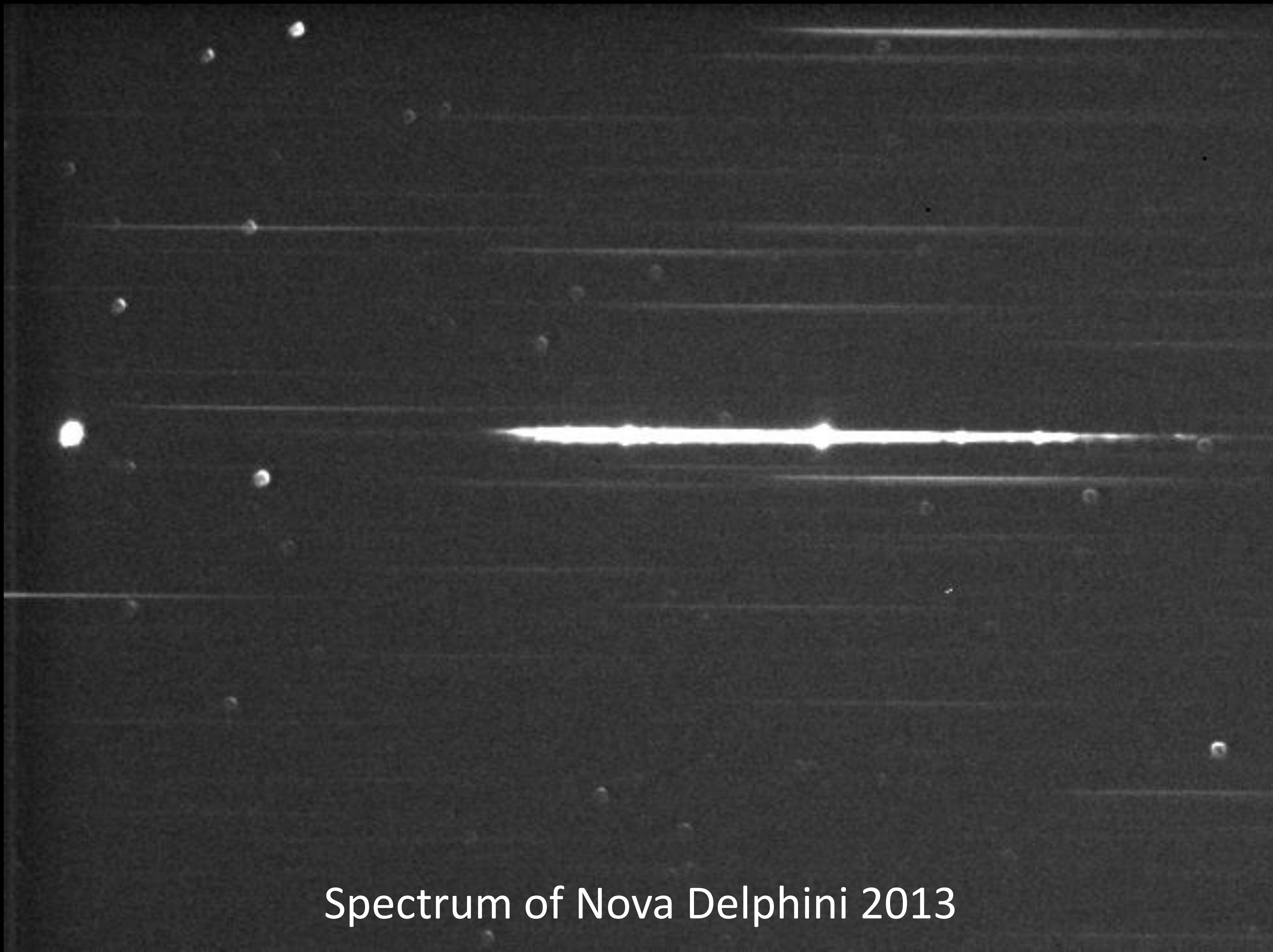
This uses the Star Analyser SA100 transmission diffraction grating.

(manufactured by Paton Hawksley)

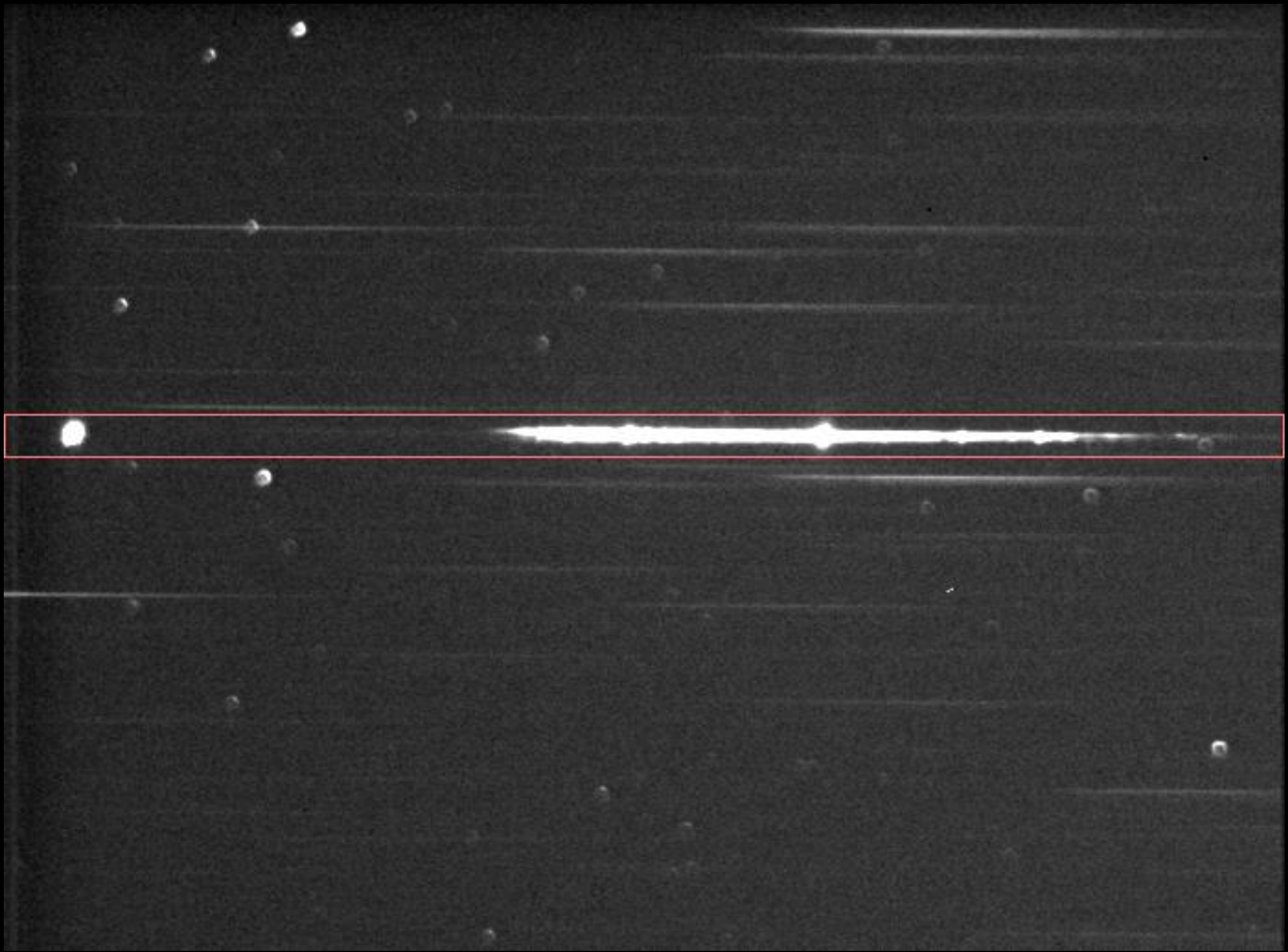
- 100 lines/mm and mounted in a 1¼” holder like a normal filter
- designed to be mounted in front of a camera or behind a telescope
- simple to use
- cost relatively low ~£100

Photo courtesy of Robin Leadbeater

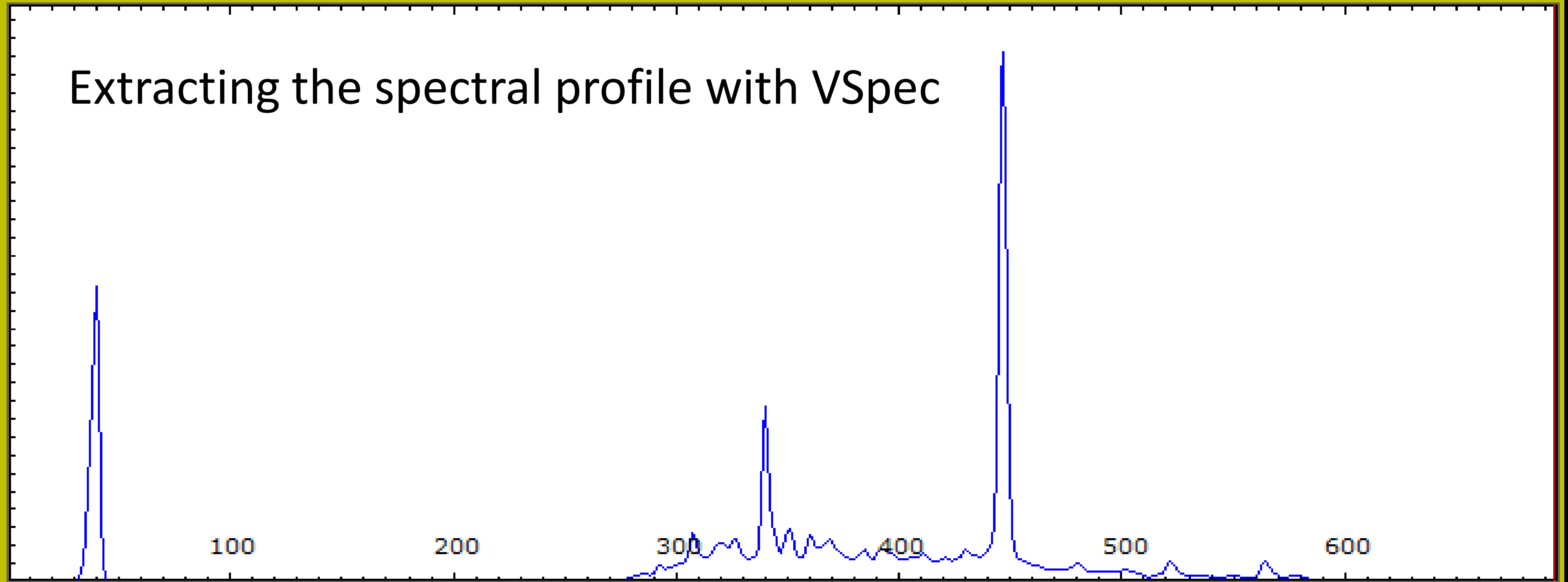
The SA100 produces spectra of all stars in the field of view



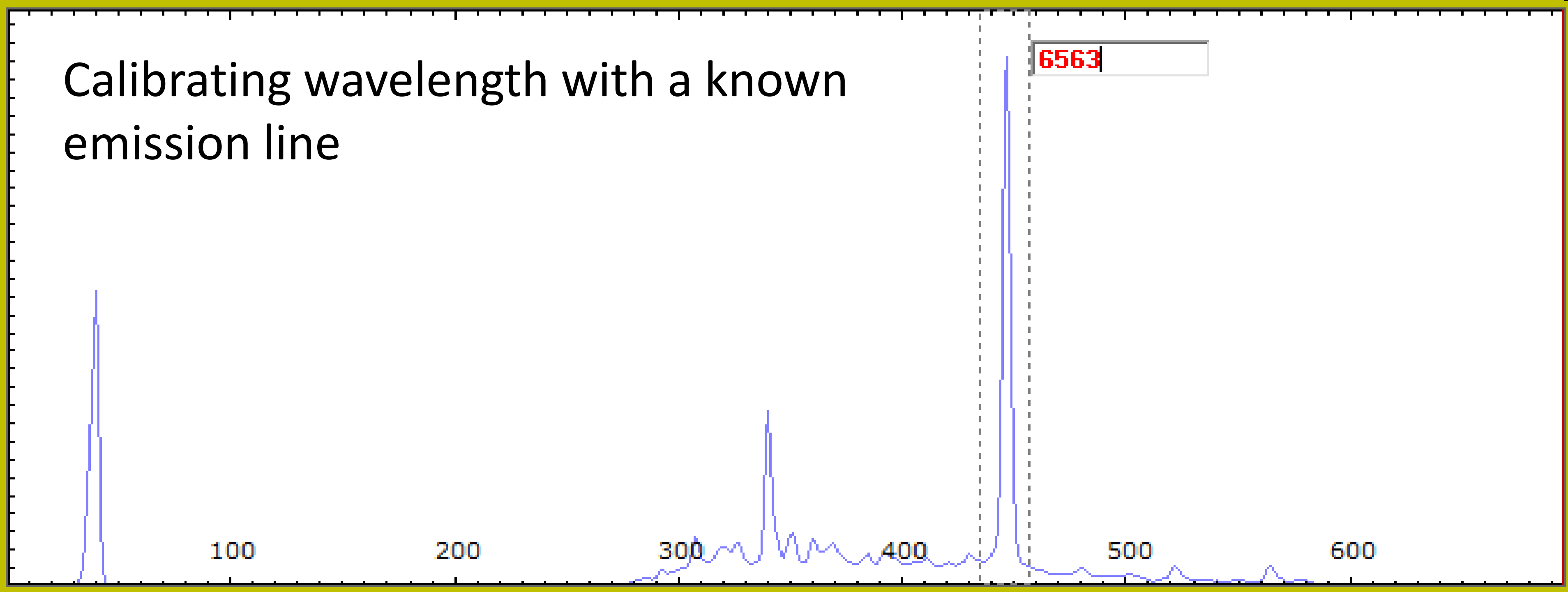
Using VSpec to identify zero order image plus first order spectrum

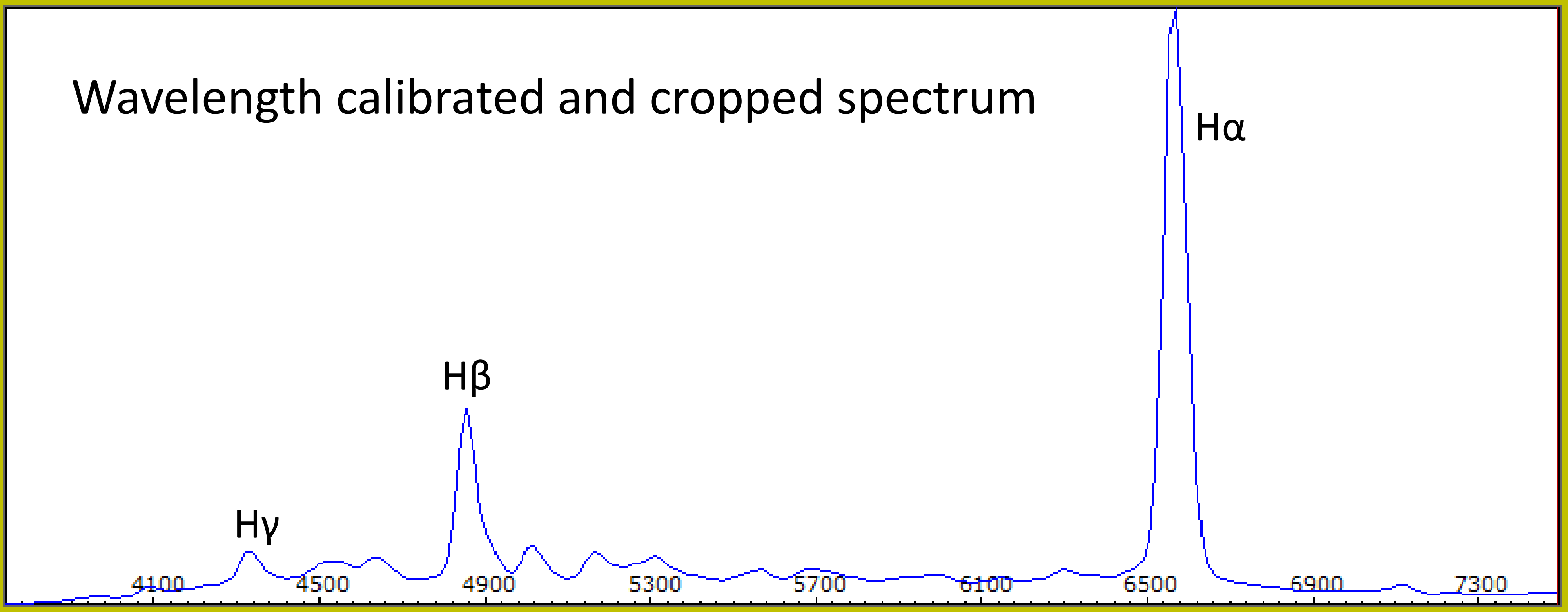


Extracting the spectral profile with VSpec



Calibrating wavelength with a known emission line

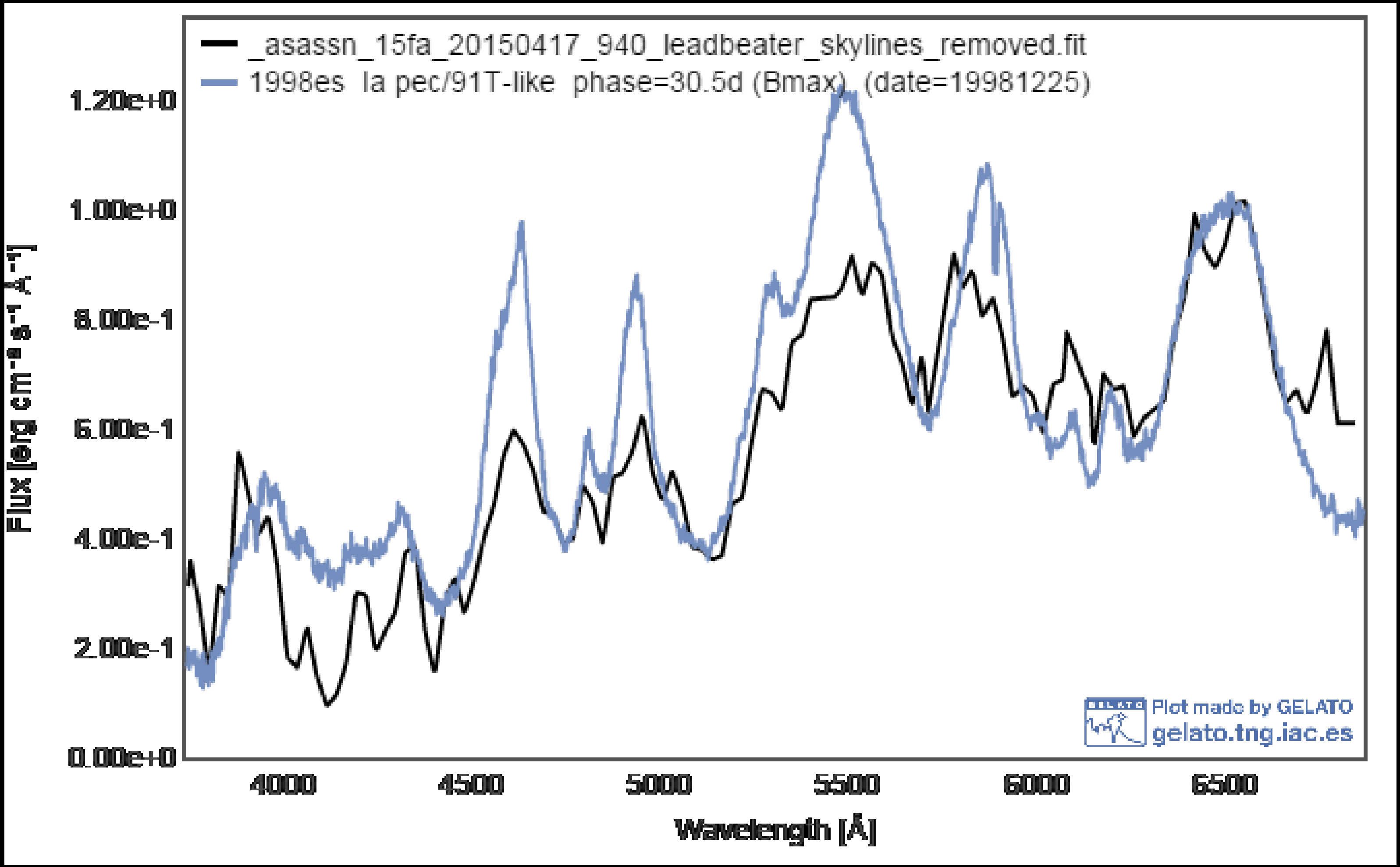




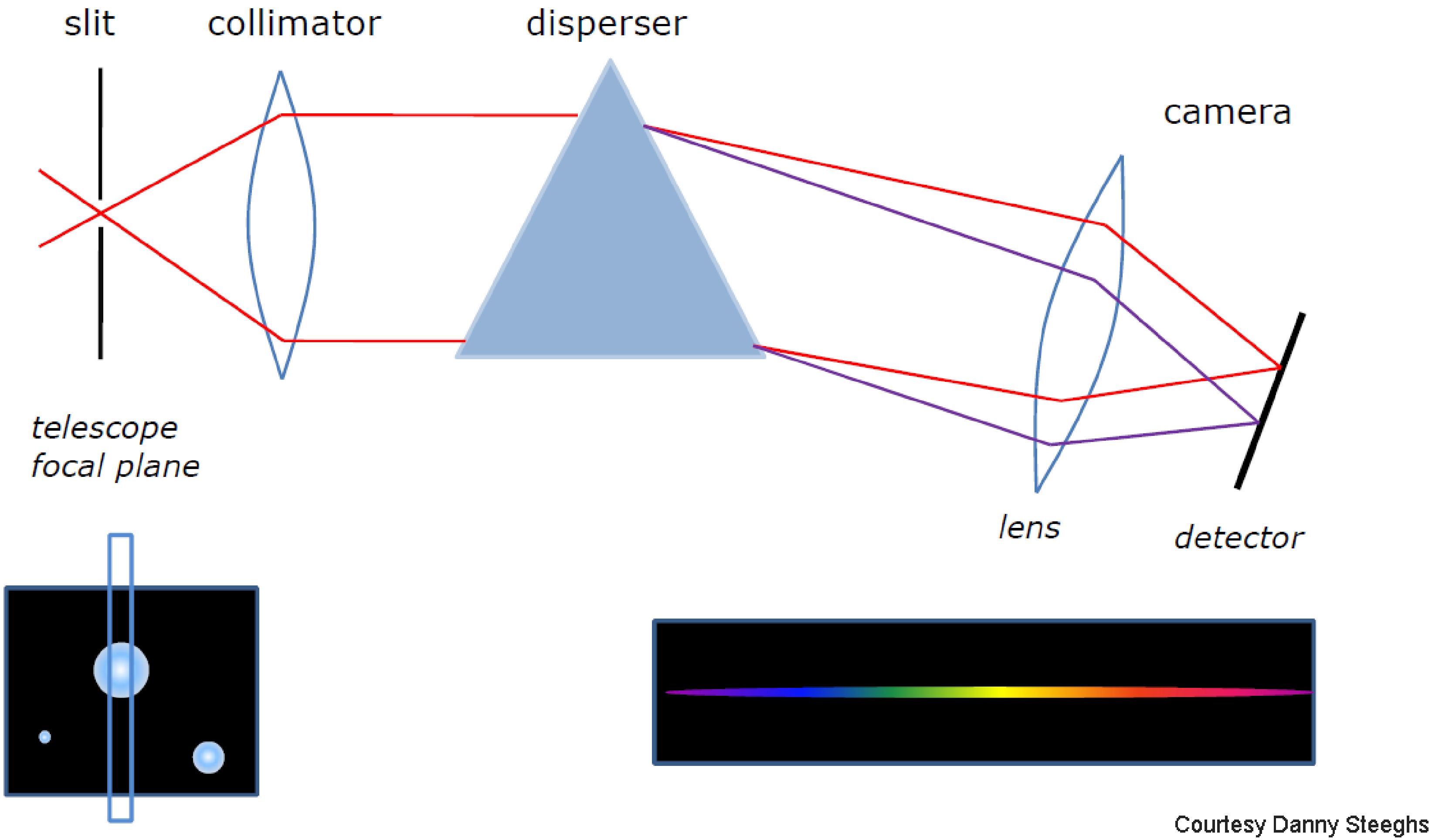
- Offers an inexpensive entry into amateur spectroscopy
- Enables recognition of the types of many variable stars
- Spectral lines are broad because the resolution is low
- Has limited scientific potential, but . . .

Robin Leadbeater has used the SA200 and equipment derived from it to identify the type of bright supernovae ahead of professional astronomers

ASASSN 15fa in NGC 6319 – type 1a supernova

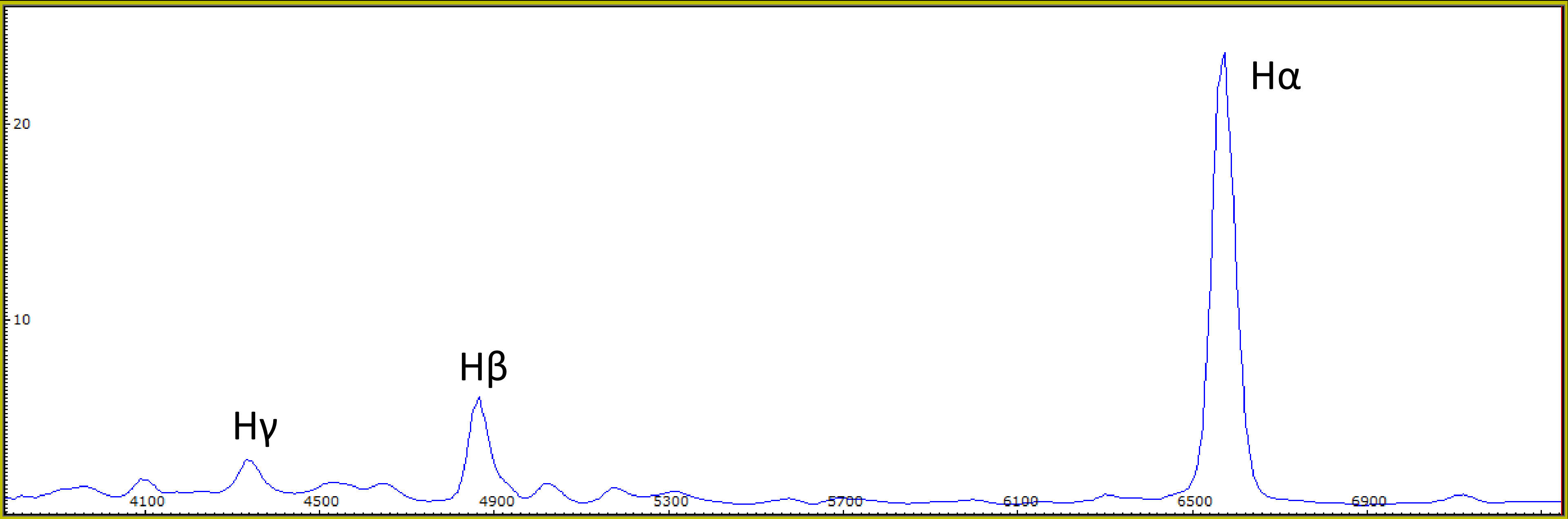


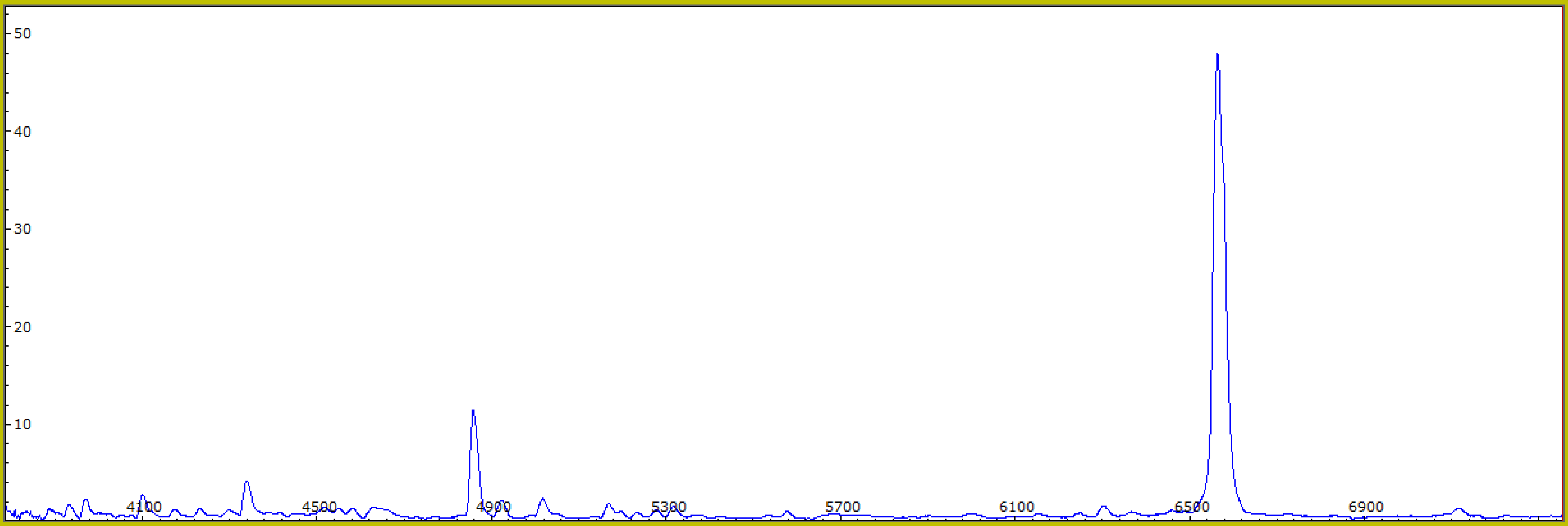
The basic slit spectrograph



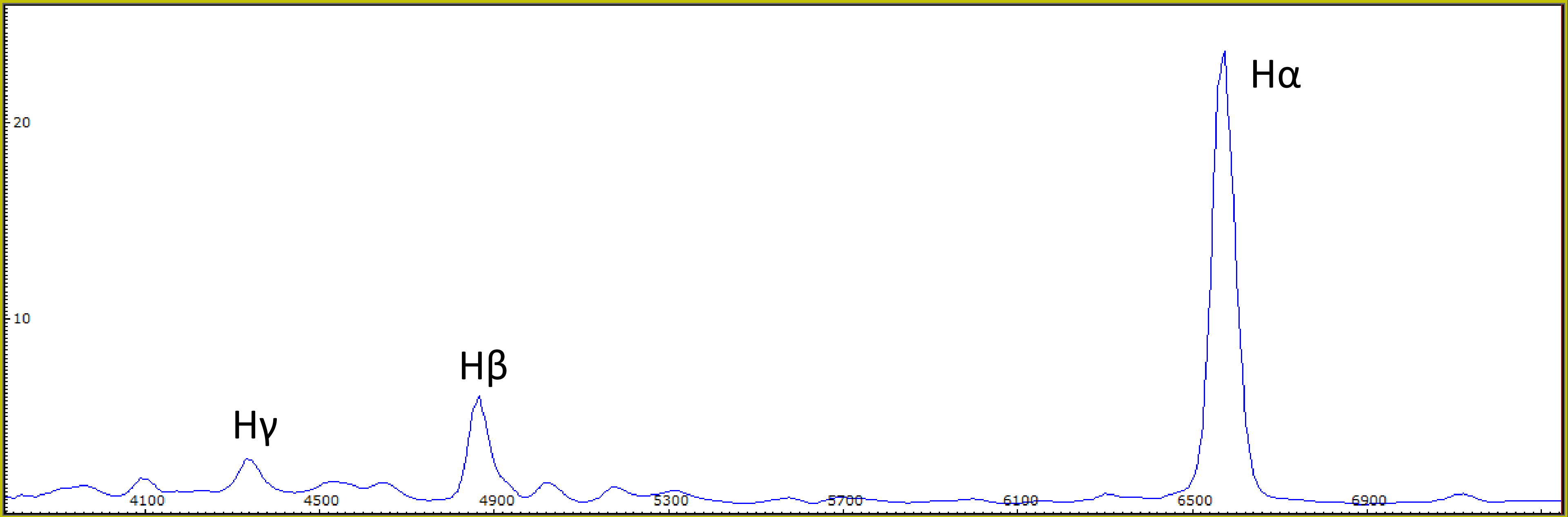
Slit gives higher resolution with sharper lines and better rejection of sky background => greater scientific potential

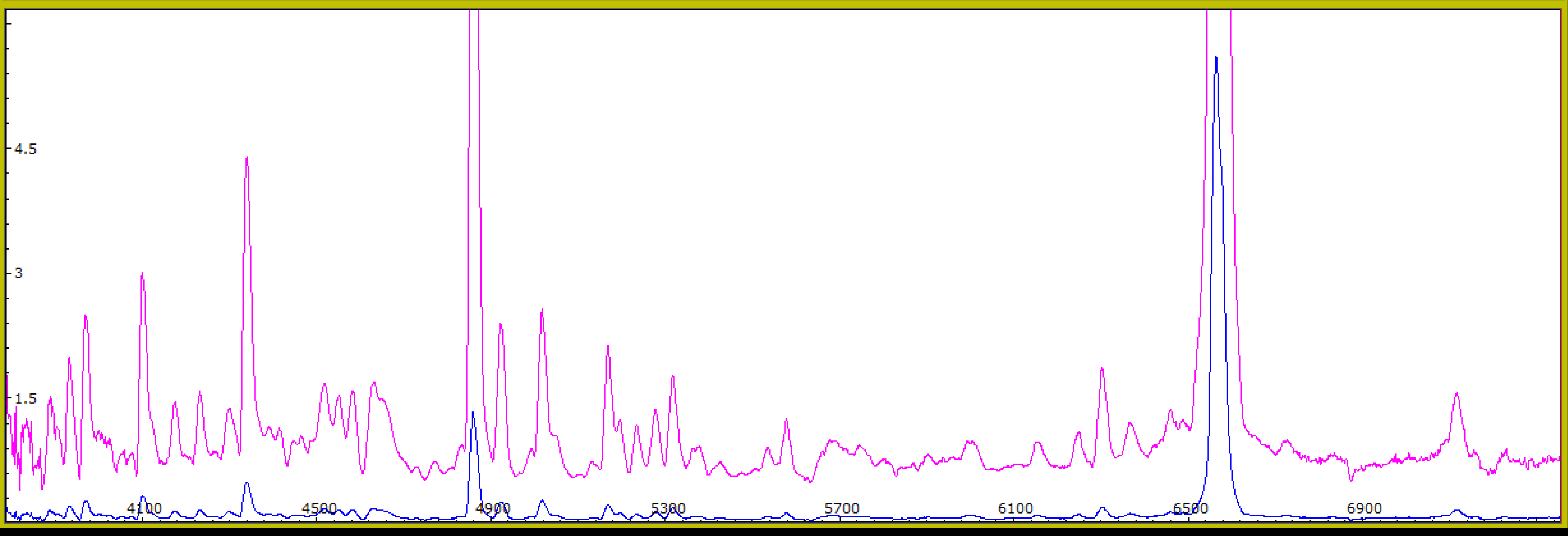
Comparison of slitless vs slit spectra of Nova Delphini 2013





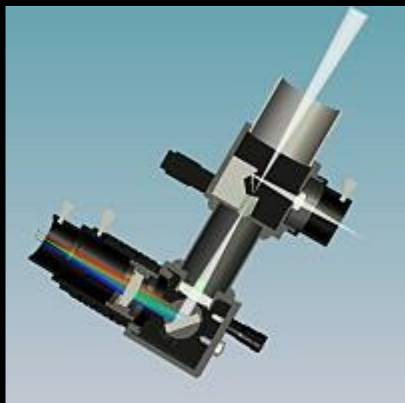
Comparison of slitless vs slit spectra of Nova Delphini 2013





Some commercial amateur spectrographs

$R = \lambda / \Delta\lambda$



DADOS R~500

ALPY R~600

CCDSPEC R~400

LHIRES R~17000

LISA R~1000

ECHELLE R~10000

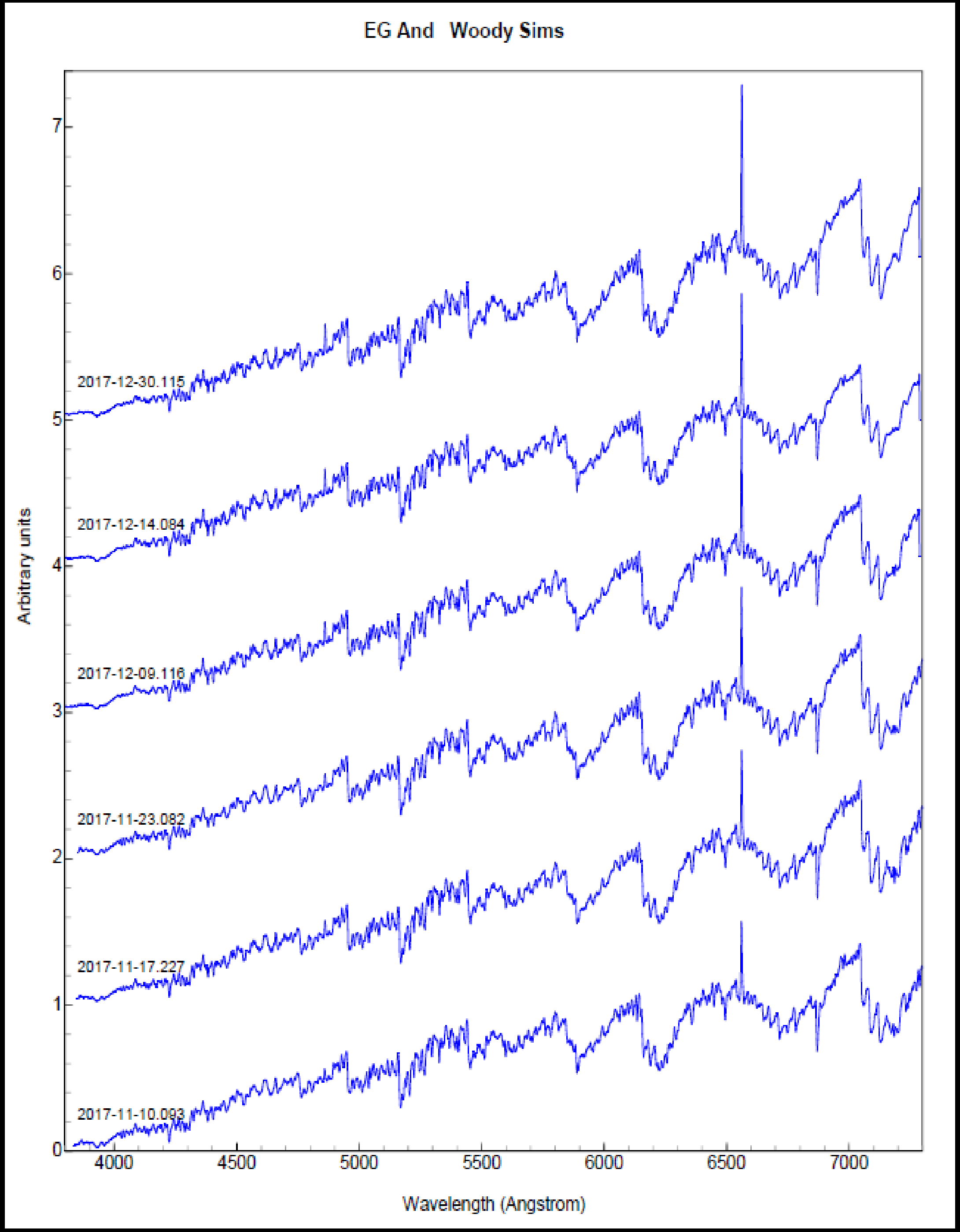
There are choices to be made . . .

Low resolution	High resolution
Wide wavelength range	Narrow wavelength range*
Lower level of detail	Higher level of detail
Fainter stars accessible	Limited to brighter stars
Somewhat less expensive	Can be very expensive

* Echelle spectrographs can achieve both high resolution and wide wavelength range – but at substantial cost!

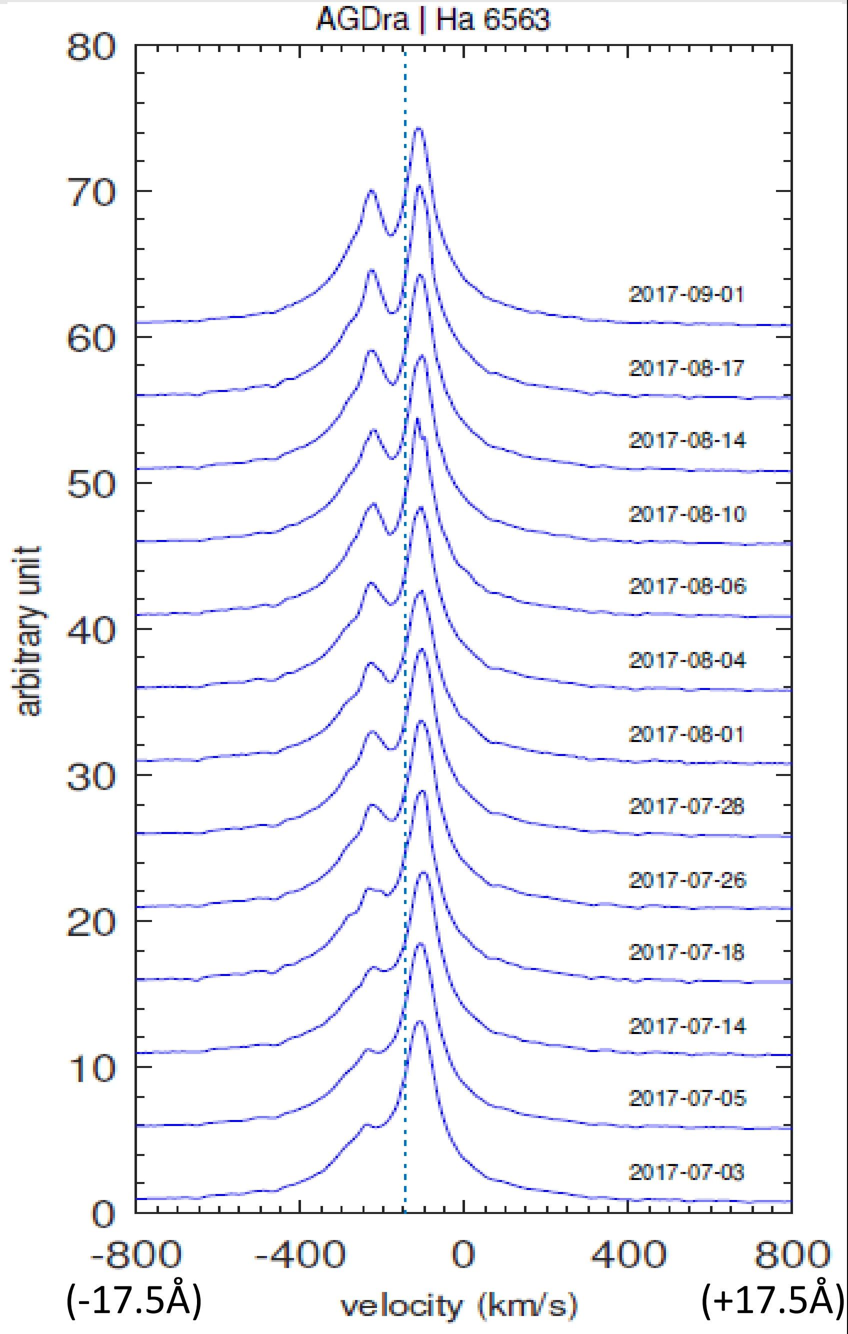
Example of low resolution spectroscopy

Series of spectra of symbiotic star EG And obtained by Woody Sims with a LISA at R ~1000 showing increasing intensity of the Hα emission line over 7 weeks



Example of high resolution spectroscopy

Changing velocity profile of the Hα emission line in the symbiotic star AG Dra recorded by Joan Guarro, Tim Lester and Francois Teyssier using echelle spectroscopes operating at R ~10000



Processing spectra

Several software packages are available for processing amateur spectra

- RSpec – easy to use commercial package (Tom Field)
- Visual Spec (VSpec) – basis set of analysis tools (Valérie Desnoux)
- BASS – full range of processing functions (John Paraskeva)
- ISIS – very comprehensive analysis software (Christian Buil)
- IRAF – professional software, steep learning curve (Linux-based)
- PlotSpectra – spectral analysis and plotting program (Tim Lester)

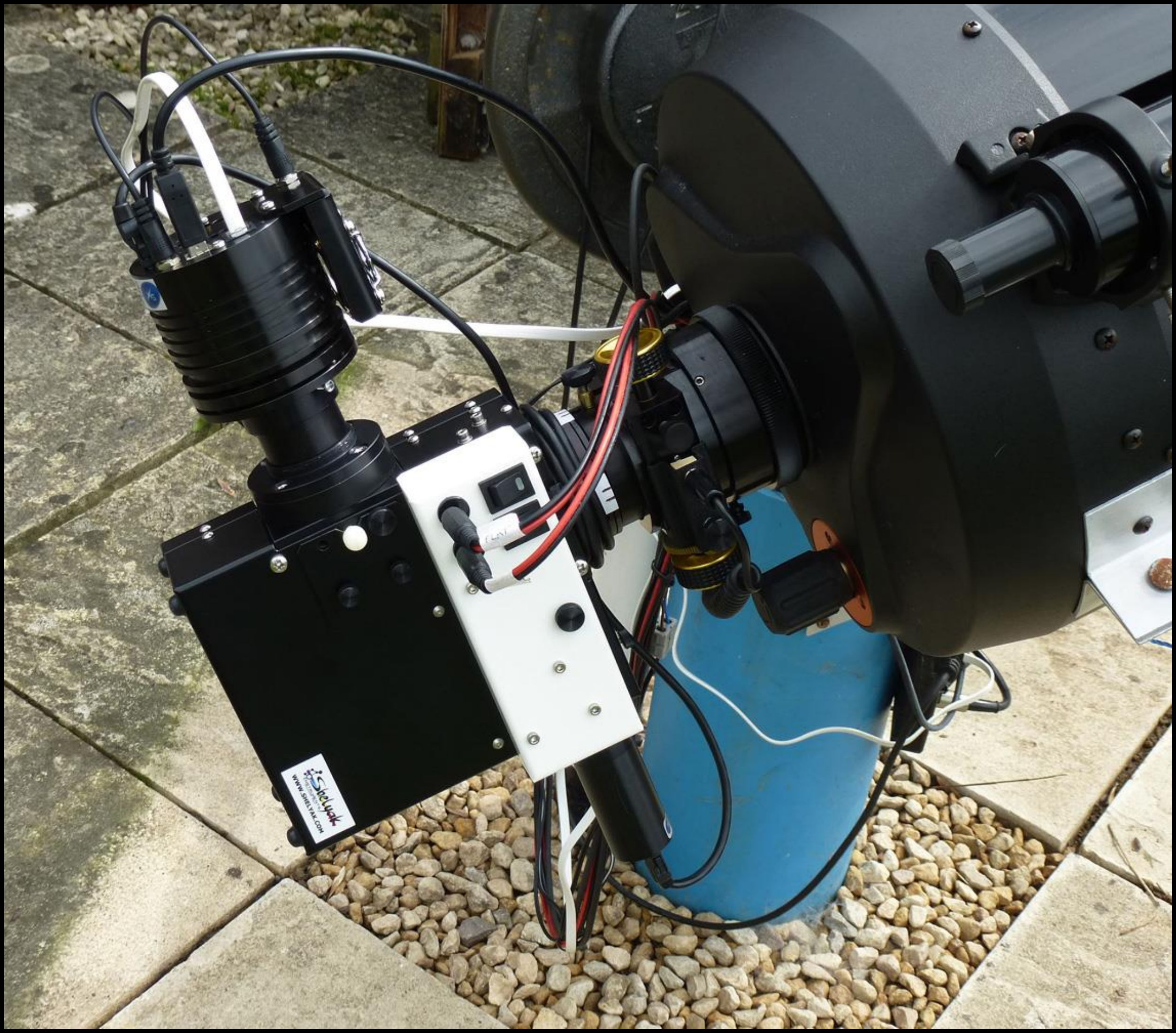
Basic processing steps

- Subtraction of bias and dark images
- Division by flat image
- Replacement of pre-identified hot pixels
- Sky background subtraction
- Wavelength calibration (using built-in calibration lamp)
- Correction for instrument and atmospheric response (using nearby reference star with known spectrum)
- [Flux calibration to put spectrum on an absolute flux scale]

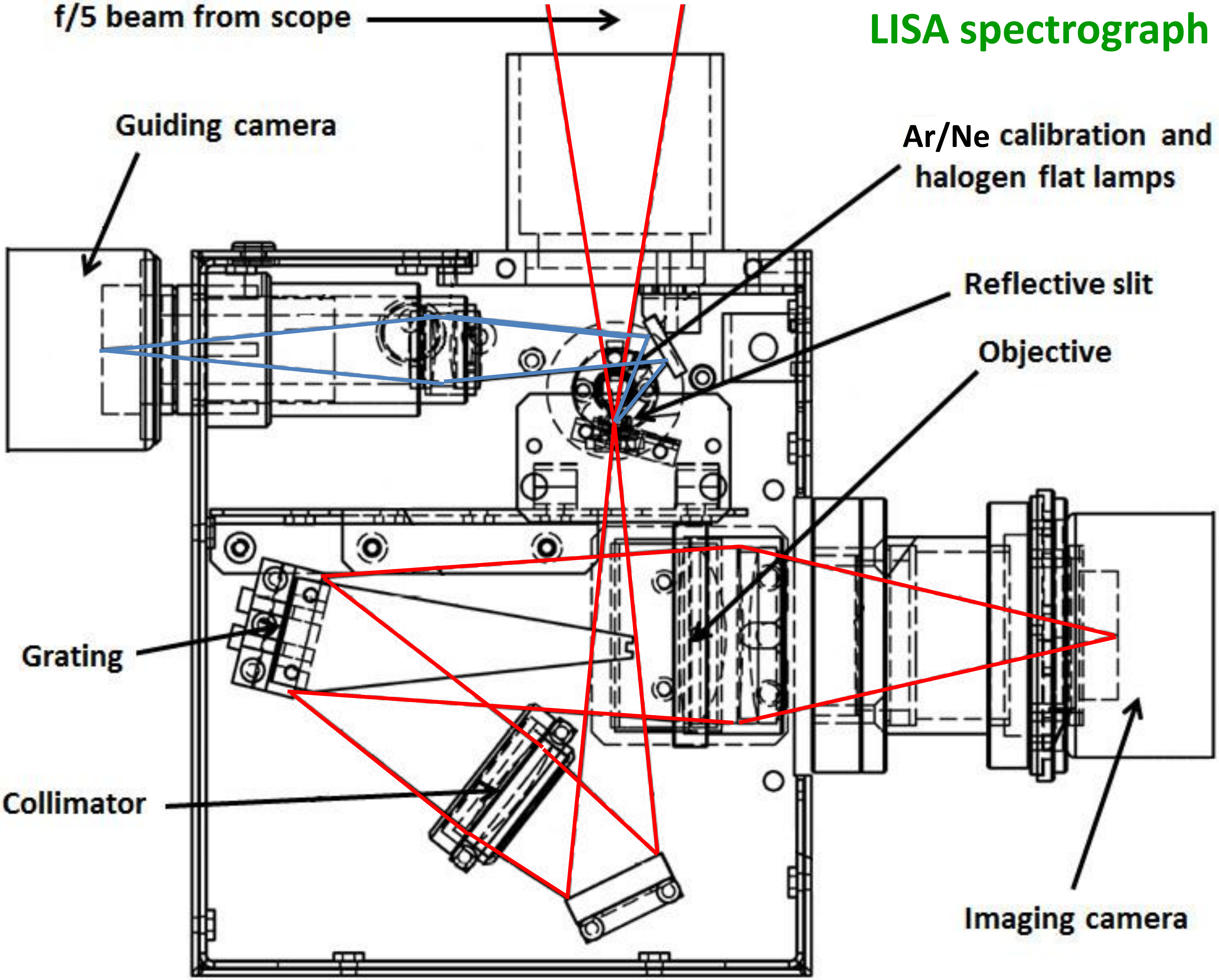
My equipment

LISA spectrograph with calibration module on a C11 scope with Starlight Xpress imaging and guiding cameras

Analysis mainly using ISIS, VSpec and PlotSpectra



LISA spectrograph



A new approach – DIY spectroscopy

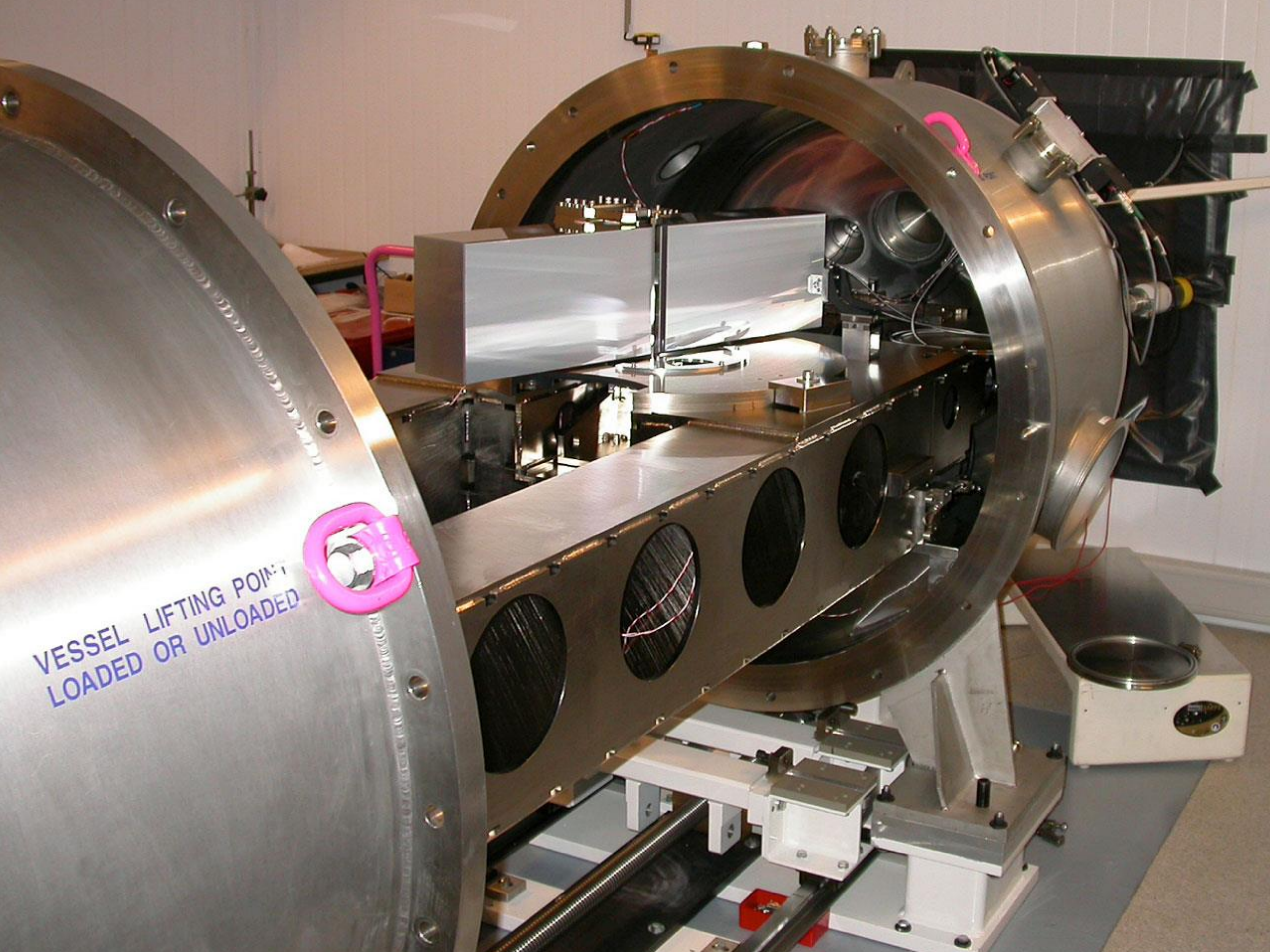
Amateurs are now starting to develop their own spectrographs using 3D printing

This is an implementation by Tony Rodda of a spectrograph design published by Paul Gerlach

For comparison – a professional spectrograph

HARPS is a high-precision echelle planet finding spectrograph on the ESO's 3.6m telescope at La Silla Observatory in Chile

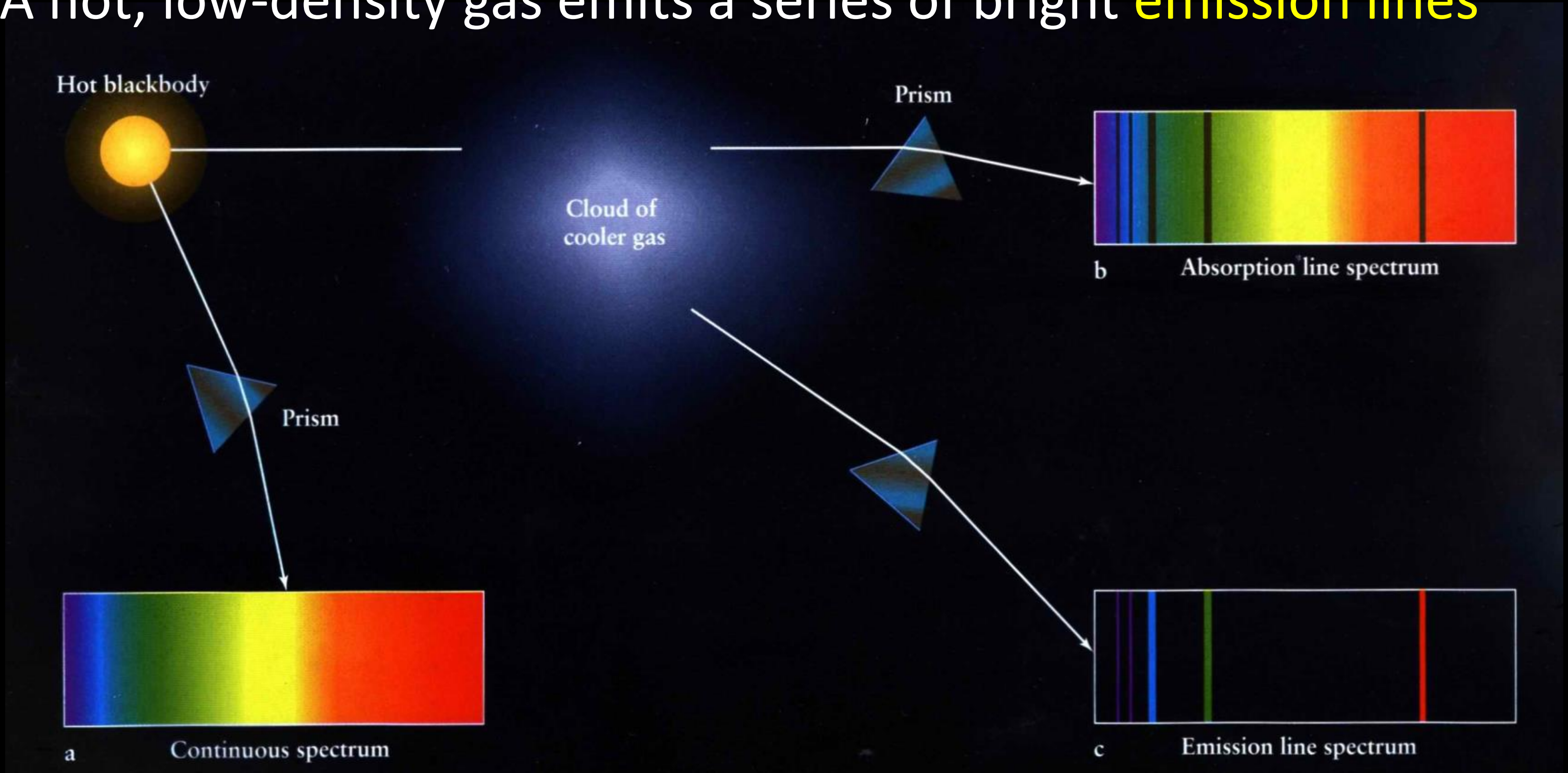
It has so far discovered over 130 exoplanets by detecting the Doppler motion of their host stars as small as 1 m/s


VESSEL LIFTING POINT
LOADED OR UNLOADED

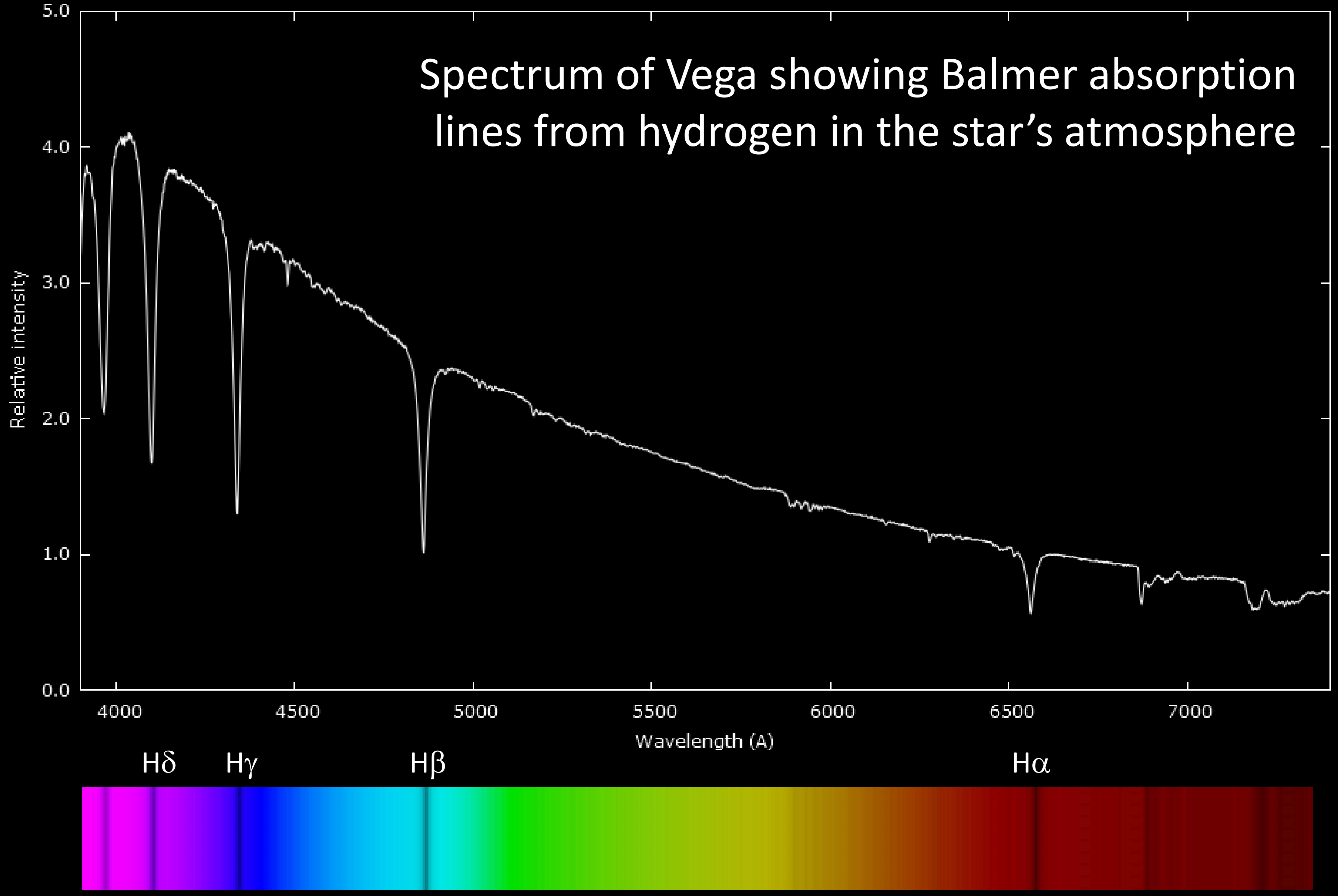
Interpreting spectra - Kirchhoff's Laws

In 1859 Kirchhoff identified three types of spectra:

- A luminous dense object produces a continuous spectrum
- A cool, thin gas absorbs certain wavelengths from a continuous spectrum producing dark absorption lines
- A hot, low-density gas emits a series of bright emission lines

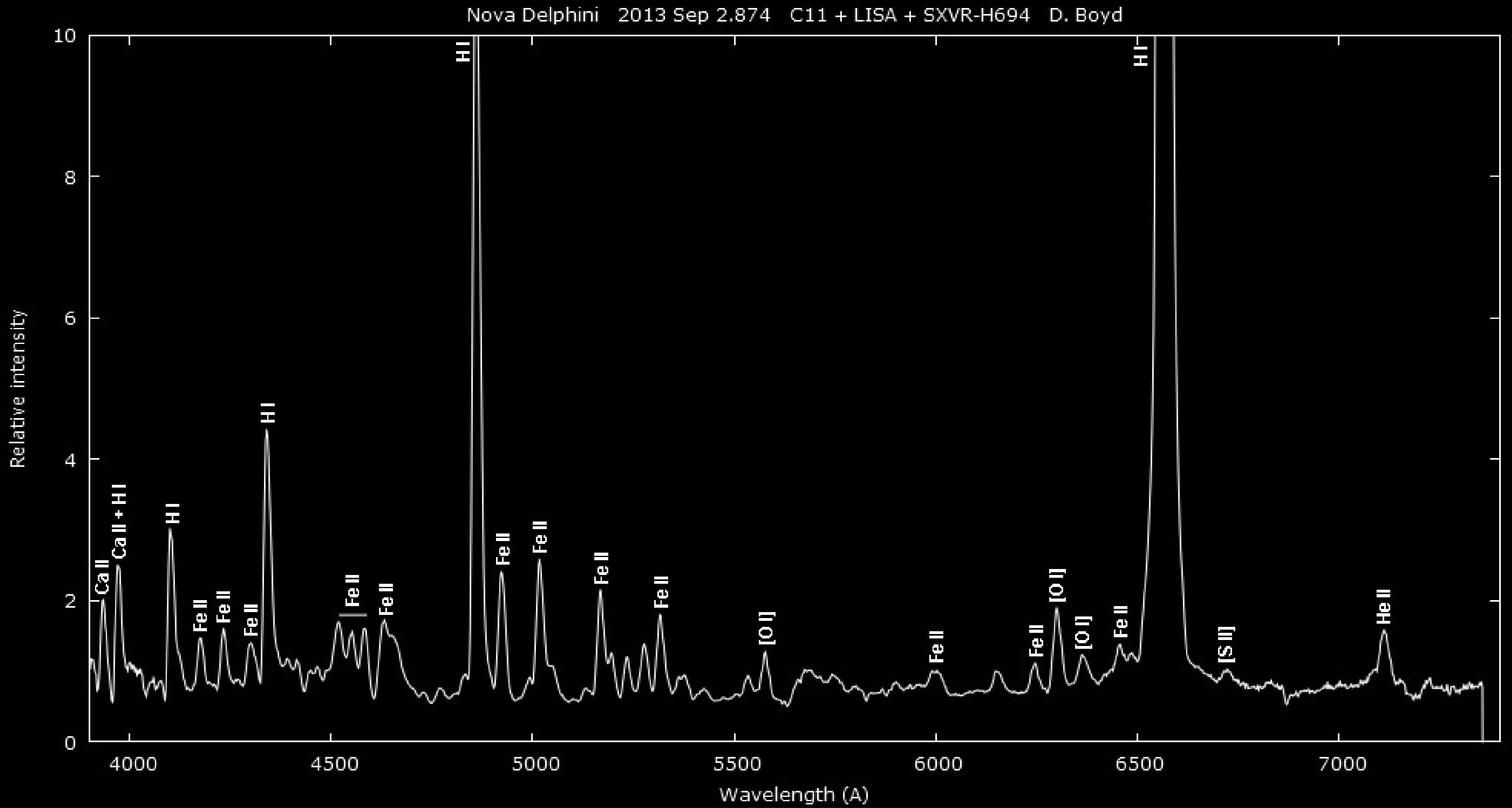


Spectra of main sequence stars show absorption lines

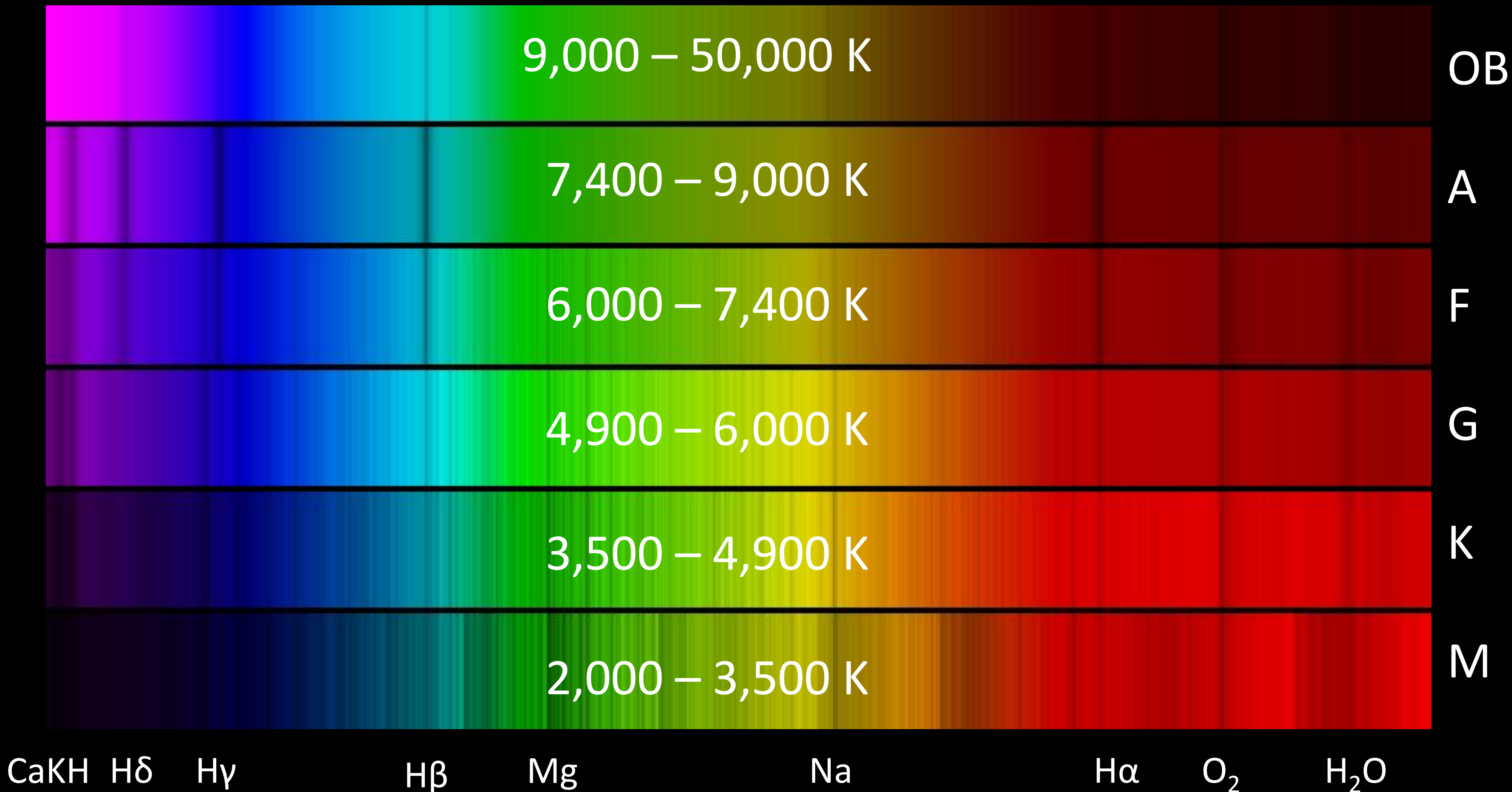


When stars get excited they tend to produce emission lines

Spectrum of Nova Delphini 2013 contains many emission lines which reveal the elements present in the expanding cloud of hot material from the nova explosion

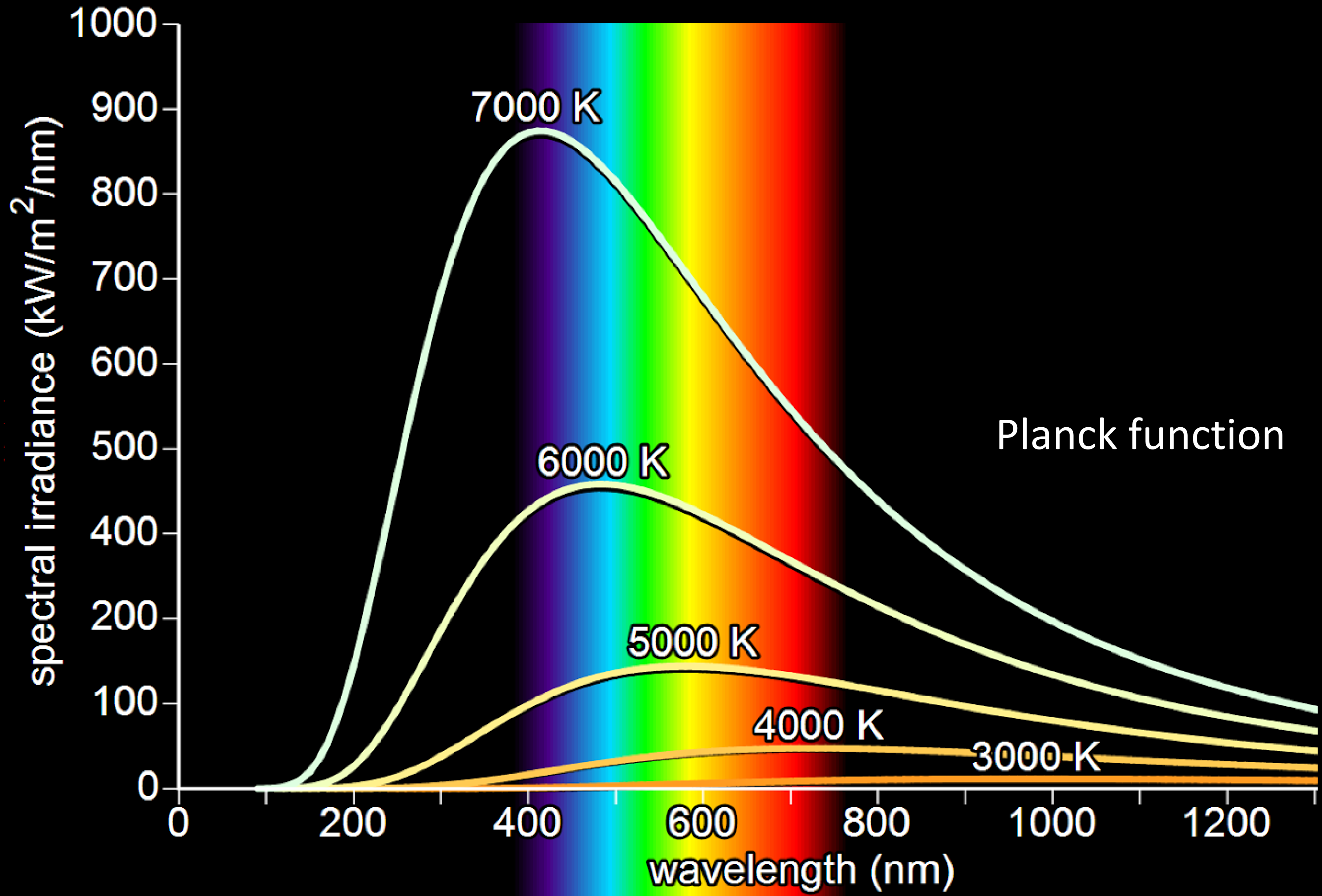


It’s all about temperature . . .



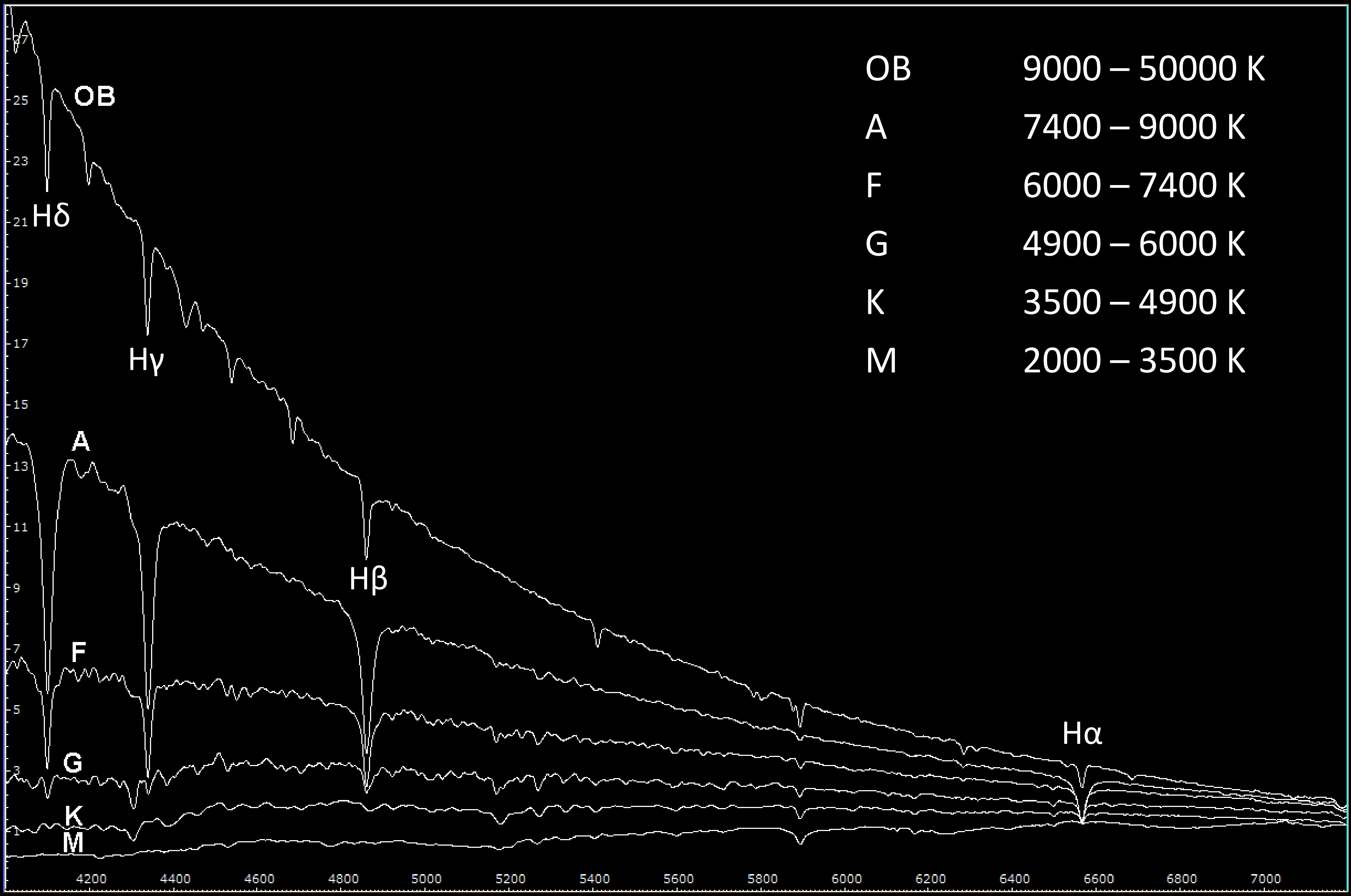
Hydrogen Balmer absorption lines are strongest in A-type stars but gradually disappear in hotter and cooler stars

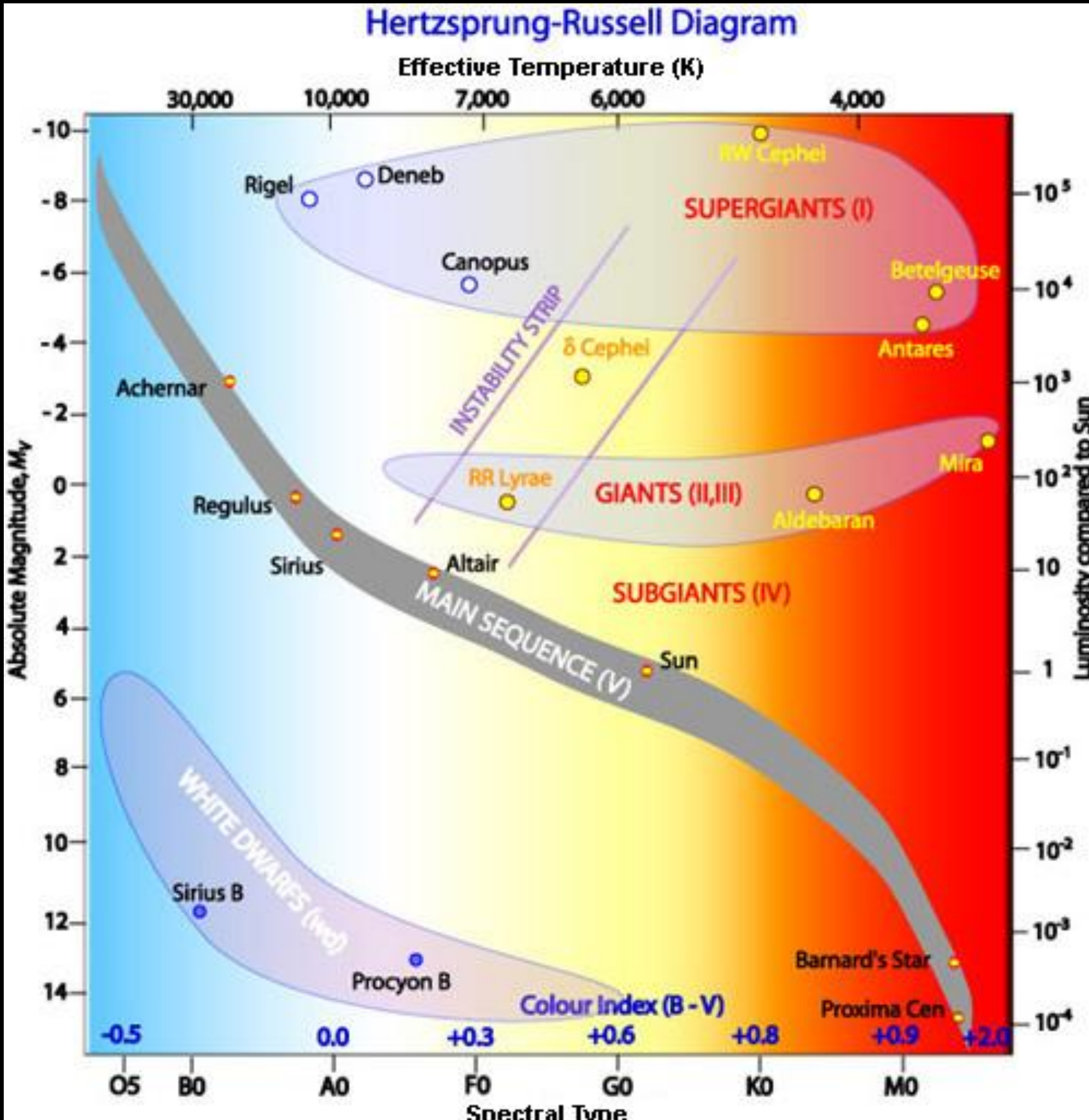
Main sequence stars radiate like black bodies



Planck function

Spectral profiles of main sequence stars





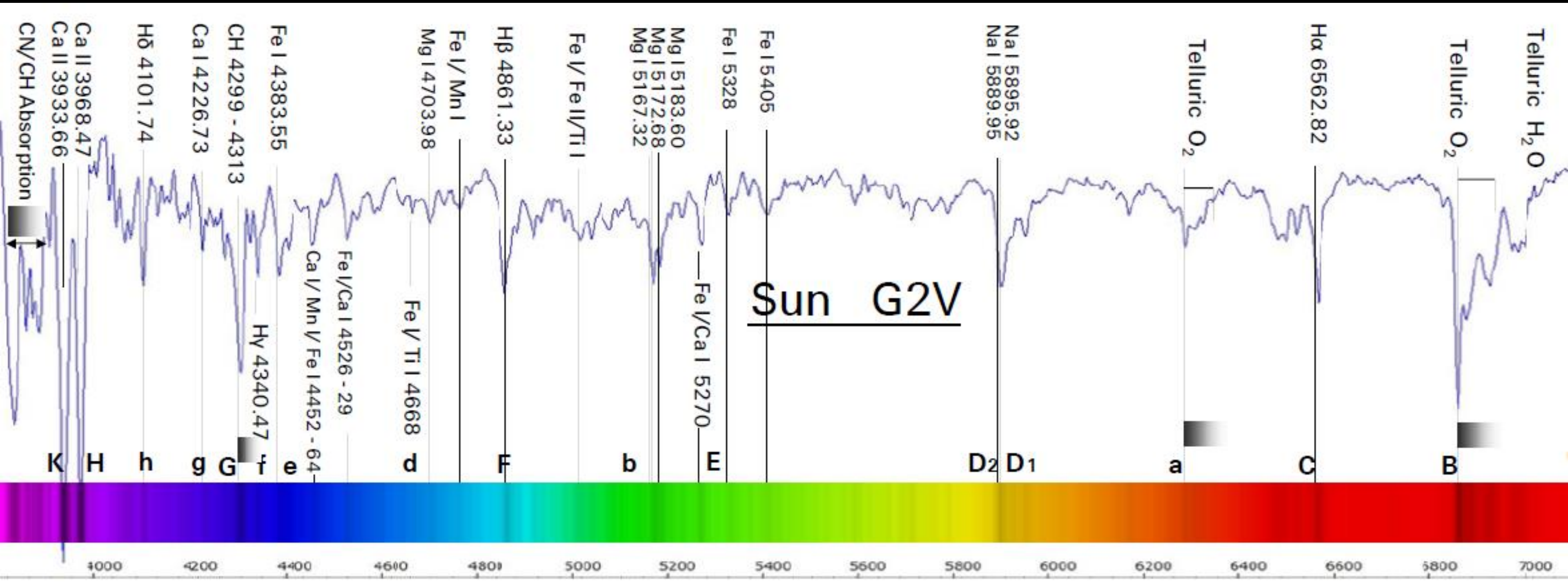
Temperature determines spectral type (as does the (B-V) colour index)

There is another dimension of the HRD not resolved by photometry

Spectral classes I - V indicate absolute luminosity and hence physical size

$$L \sim R^2 T^4$$

Spectra also reveal the chemical composition of stars



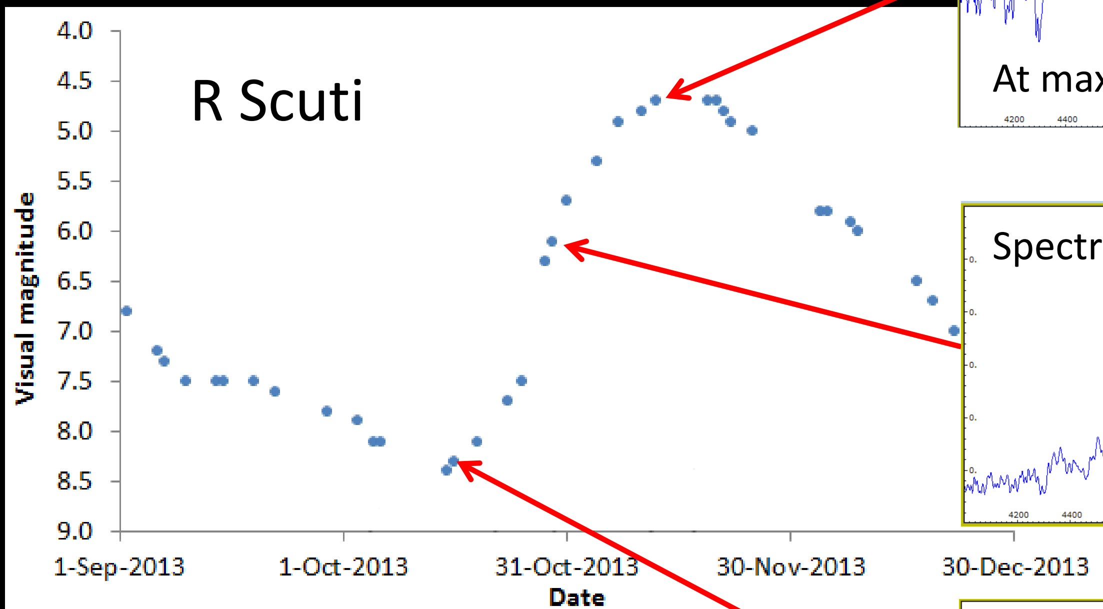
Credit: Richard Walker's Spectroscopic Atlas

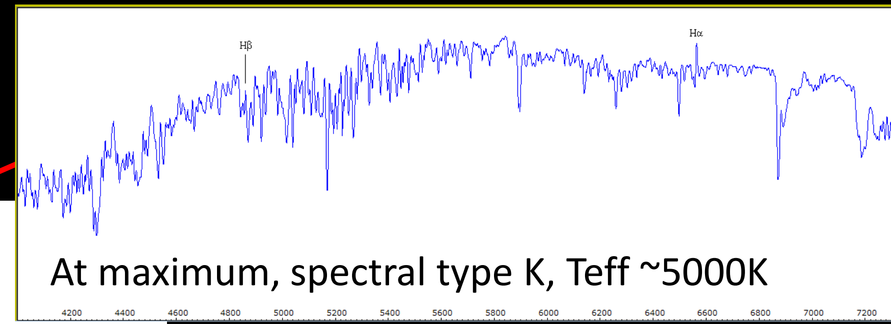
What can we learn about variable stars from spectroscopy?

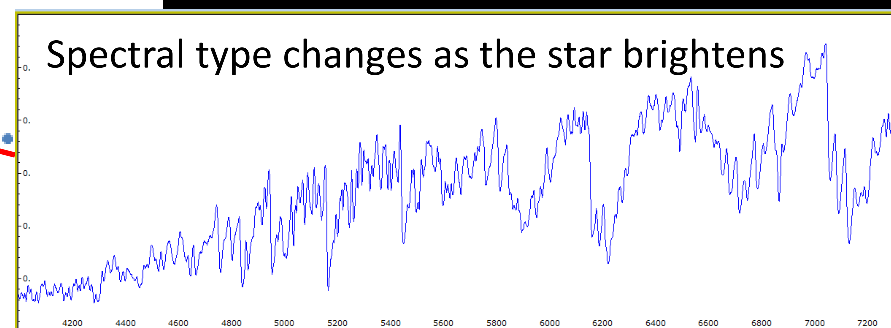
- Changes in an RV Tauri star as it pulsates
- Production of shock-induced emission lines in a Mira variable
- Identifying the nature of planetary nebulae
- Using radial velocity measurements to identify binary stars
- Dusty nature of pre-main sequence stars
- Measuring the white dwarf temperature in a symbiotic star
- Evolution of a nova as it slowly fades
- Measuring the velocity of a supernova explosion

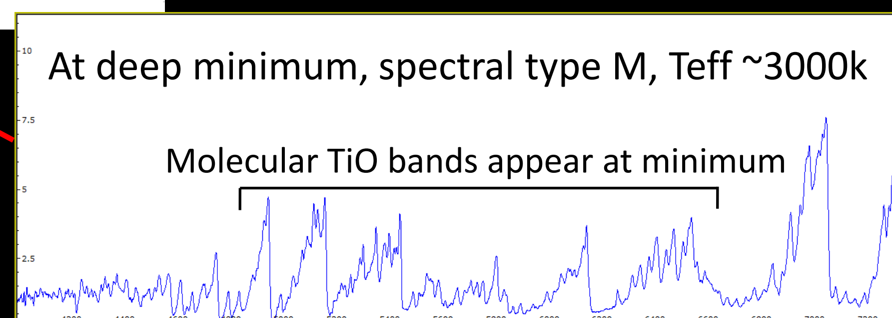
Changes in an RV Tauri star as it pulsates

Pulsating yellow post-AGB supergiants
with alternate deep and shallow minima









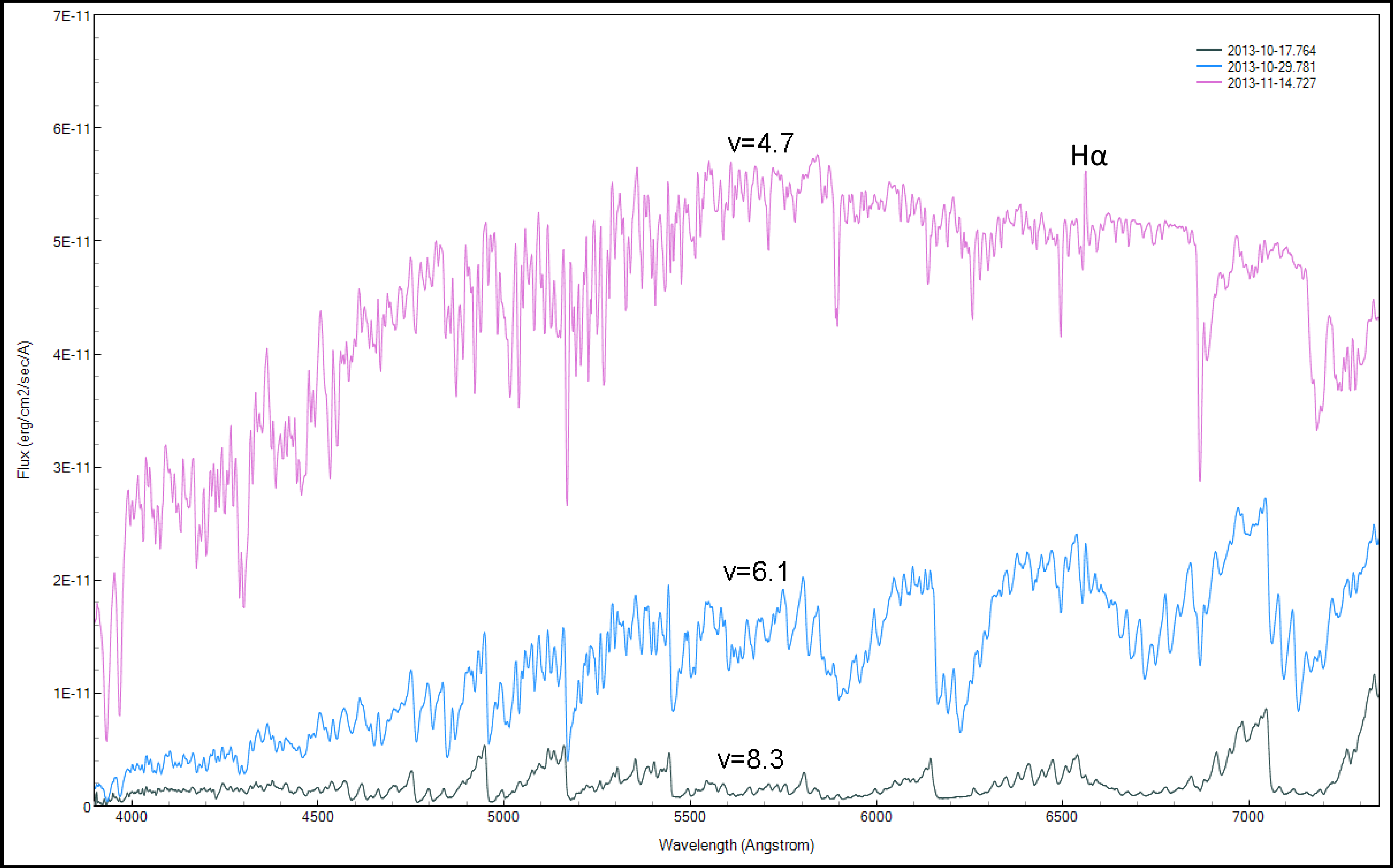
Visual magnitude range ~4.5 to 8.5

Pulsation period ~147 days

Distance ~1.27 kpc

"RV Tauri stars are heterogeneous and not well understood" (Percy)

If you know its V magnitude at the time, you can use this to calibrate the flux level of each spectrum to show the relative changes in the star's output

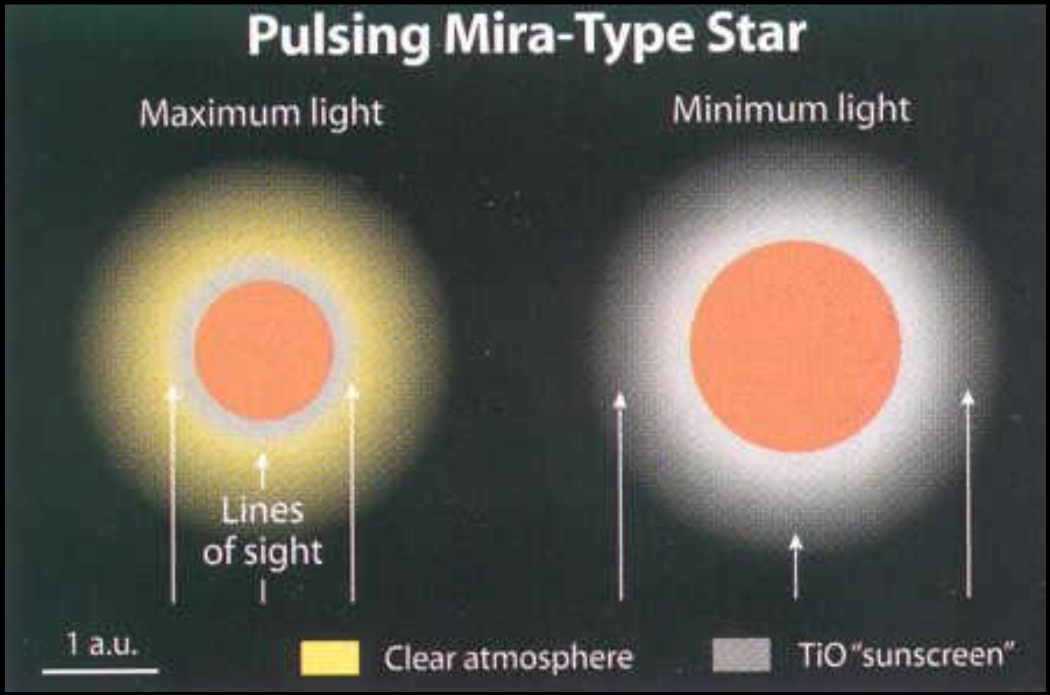


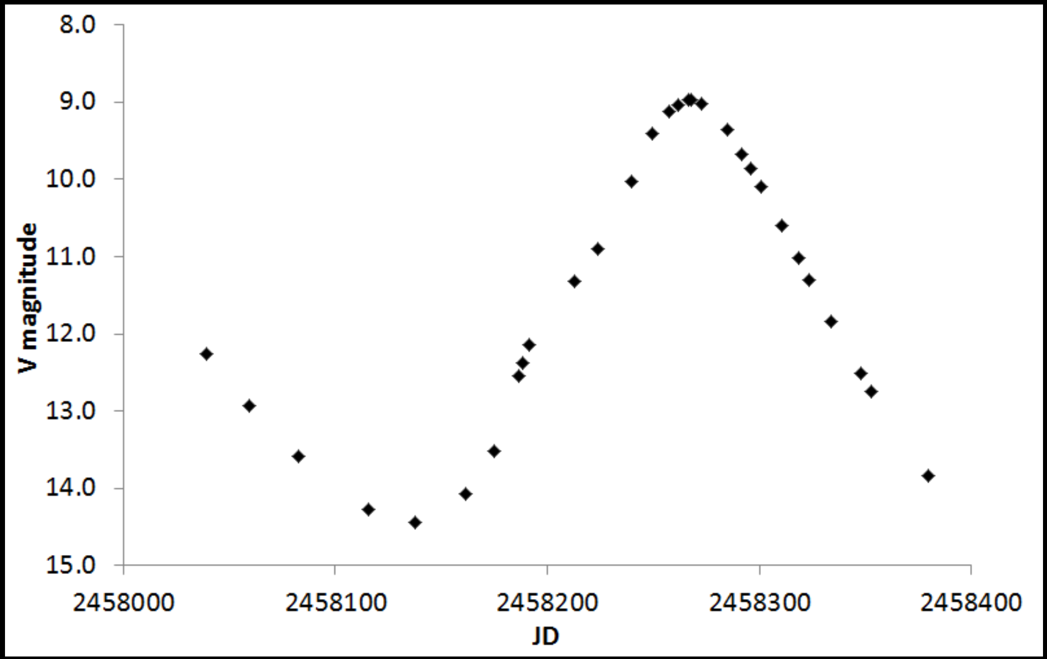
Shock-induced emission lines in a Mira variable

The pulsation cycle in Mira variables is driven by the *kappa* mechanism within the stellar photosphere which generates a shock wave in the star's atmosphere and excites the production of hydrogen Balmer emission lines

SU Cam is a relatively neglected Mira variable

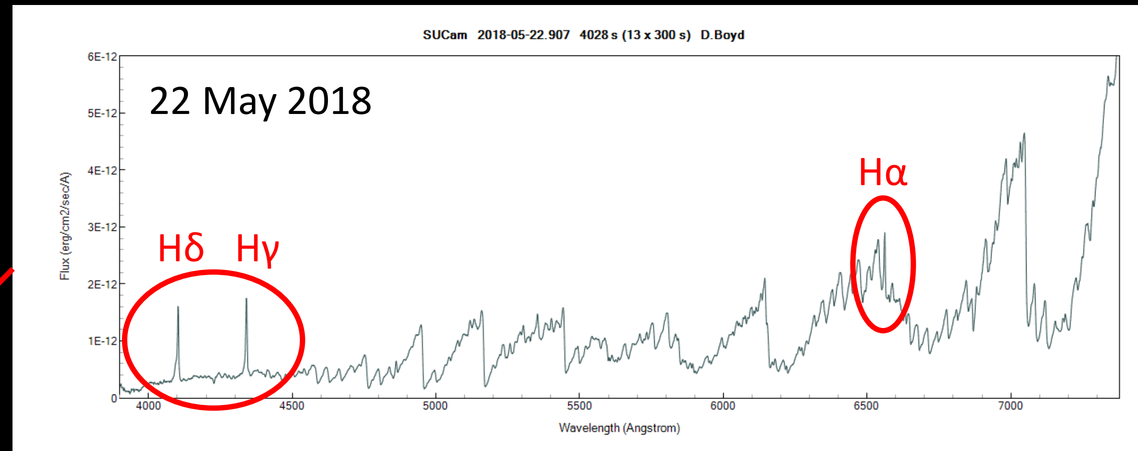
Its pulsation period changes slightly from cycle to cycle and is currently ~315 d

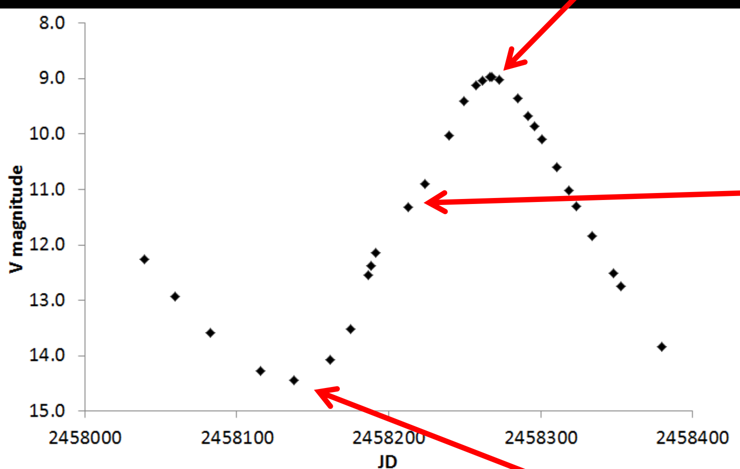


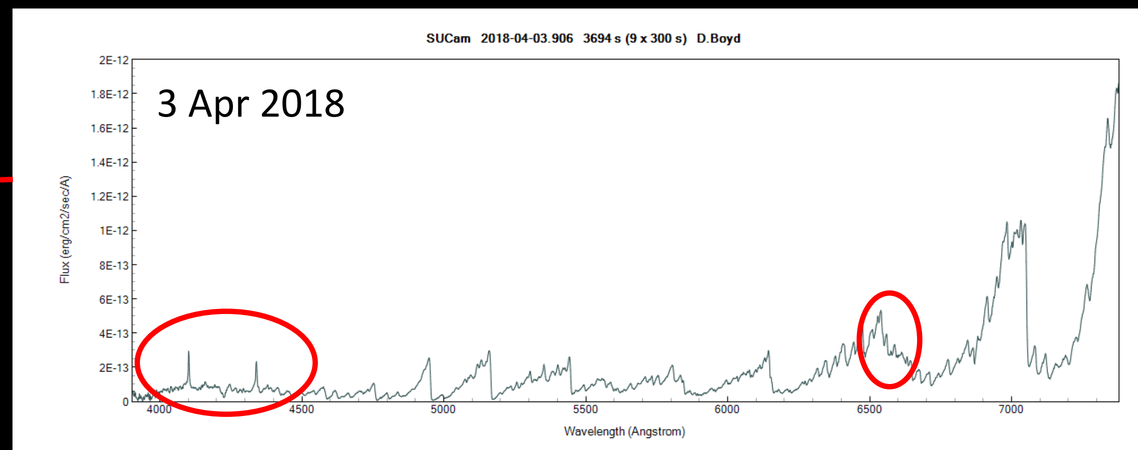


Balmer emission lines appear as the star brightens

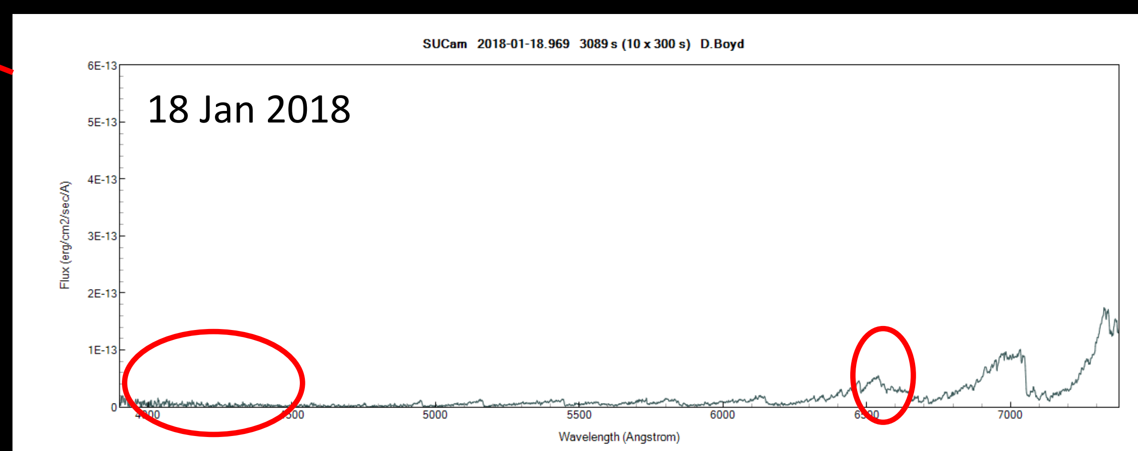
Spectral type changes from M7III to M5III







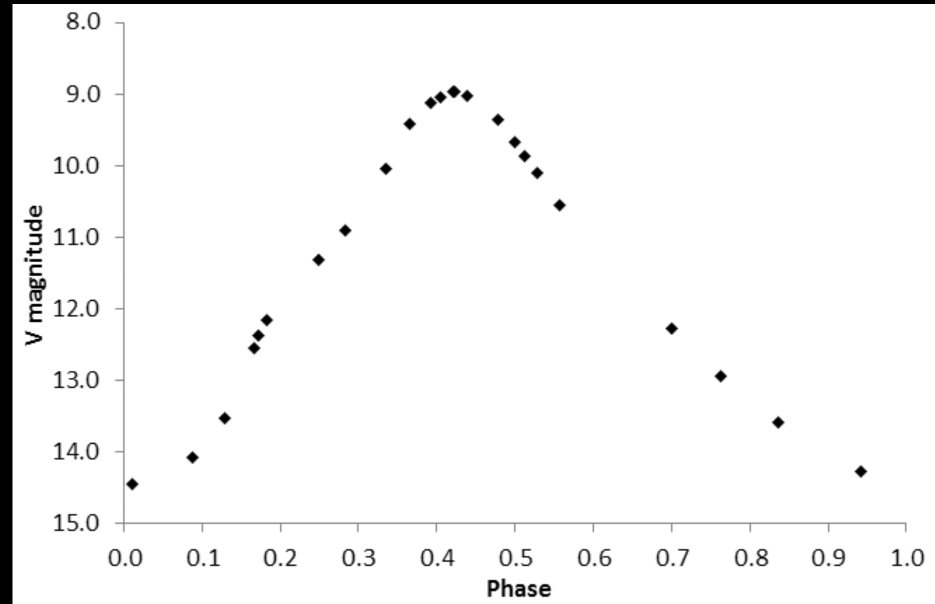
Molecular TiO bands persist throughout



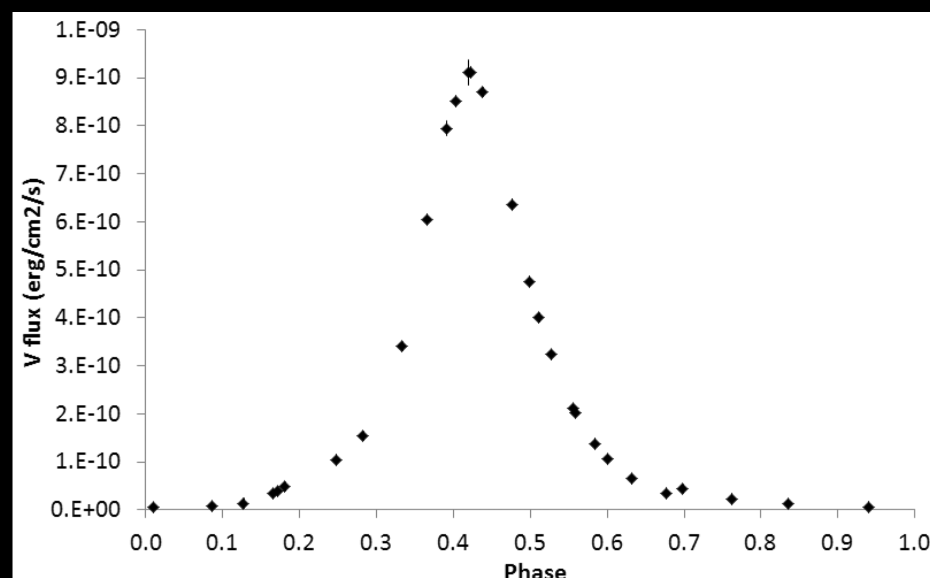
NB - flux plot scale changes by a factor of 10 from minimum to maximum

How do the emission lines behave?

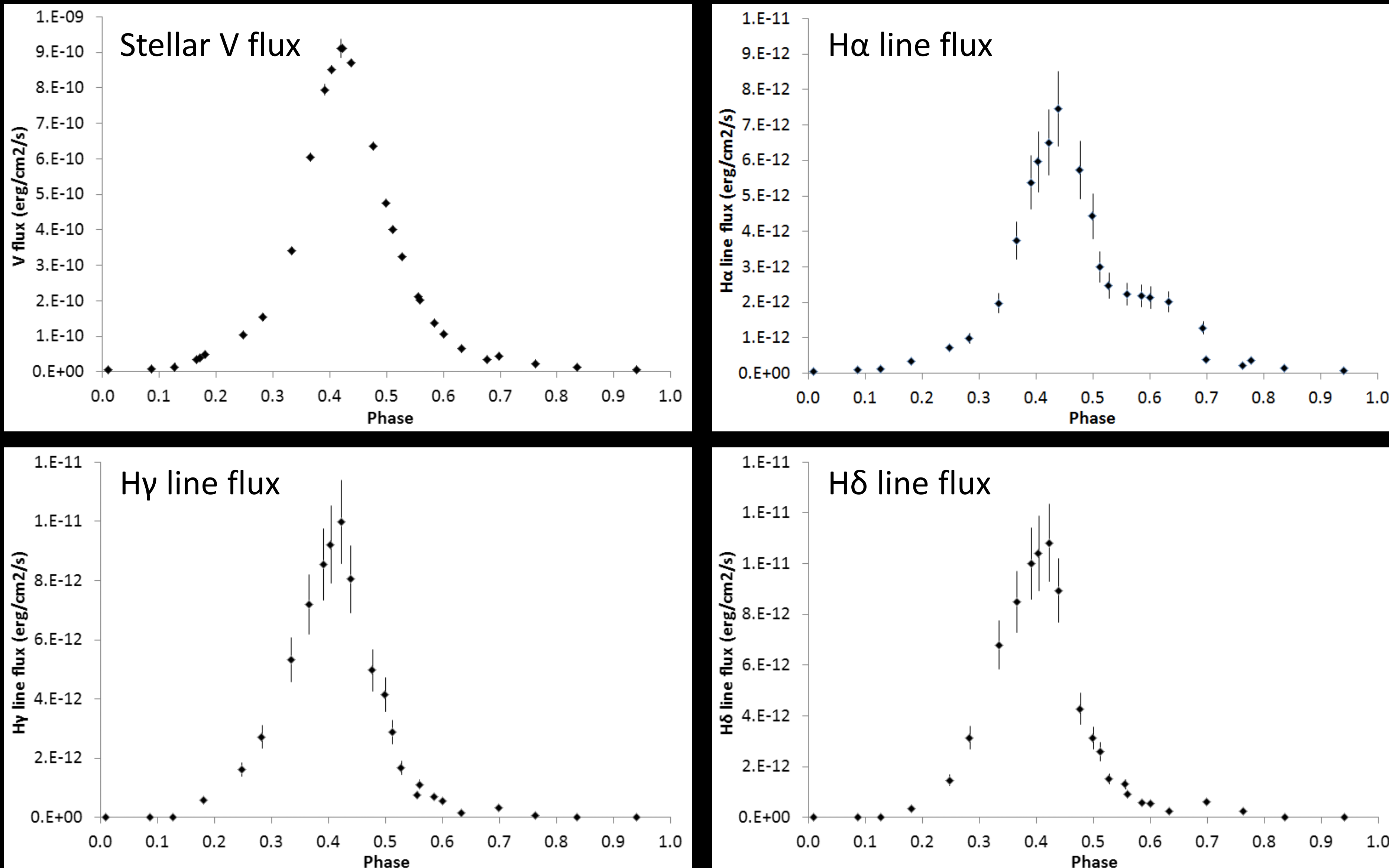
To see how these emission lines change as the star brightens, we need to convert the star's magnitude to flux (= energy output)



This involves calibrating your V filter magnitudes using the spectra of flux standard stars such as the HST CALSPEC stars



Changes in the Balmer lines follow closely changes in the star itself, except for Hα – this behaviour seems to be unreported in the literature on Mira variables

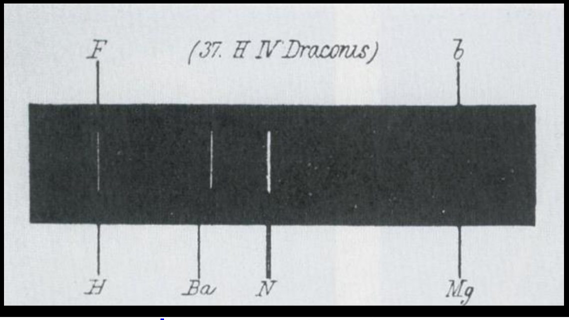


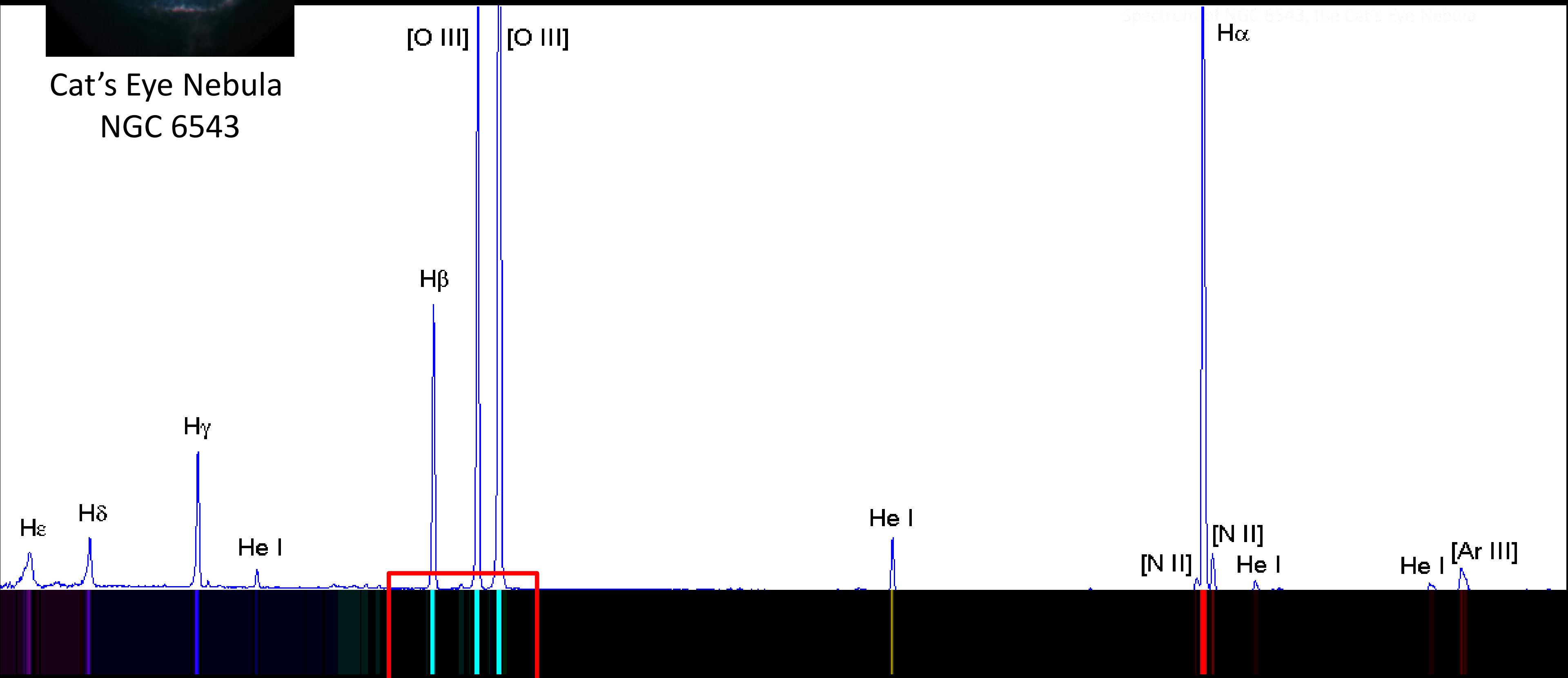
Identifying the nature of planetary nebulae

William Huggins visually recorded the spectrum of NGC 6543 in 1864

Cat's Eye Nebula
NGC 6543

He realised emission lines indicated a rarefied gas rather than stars



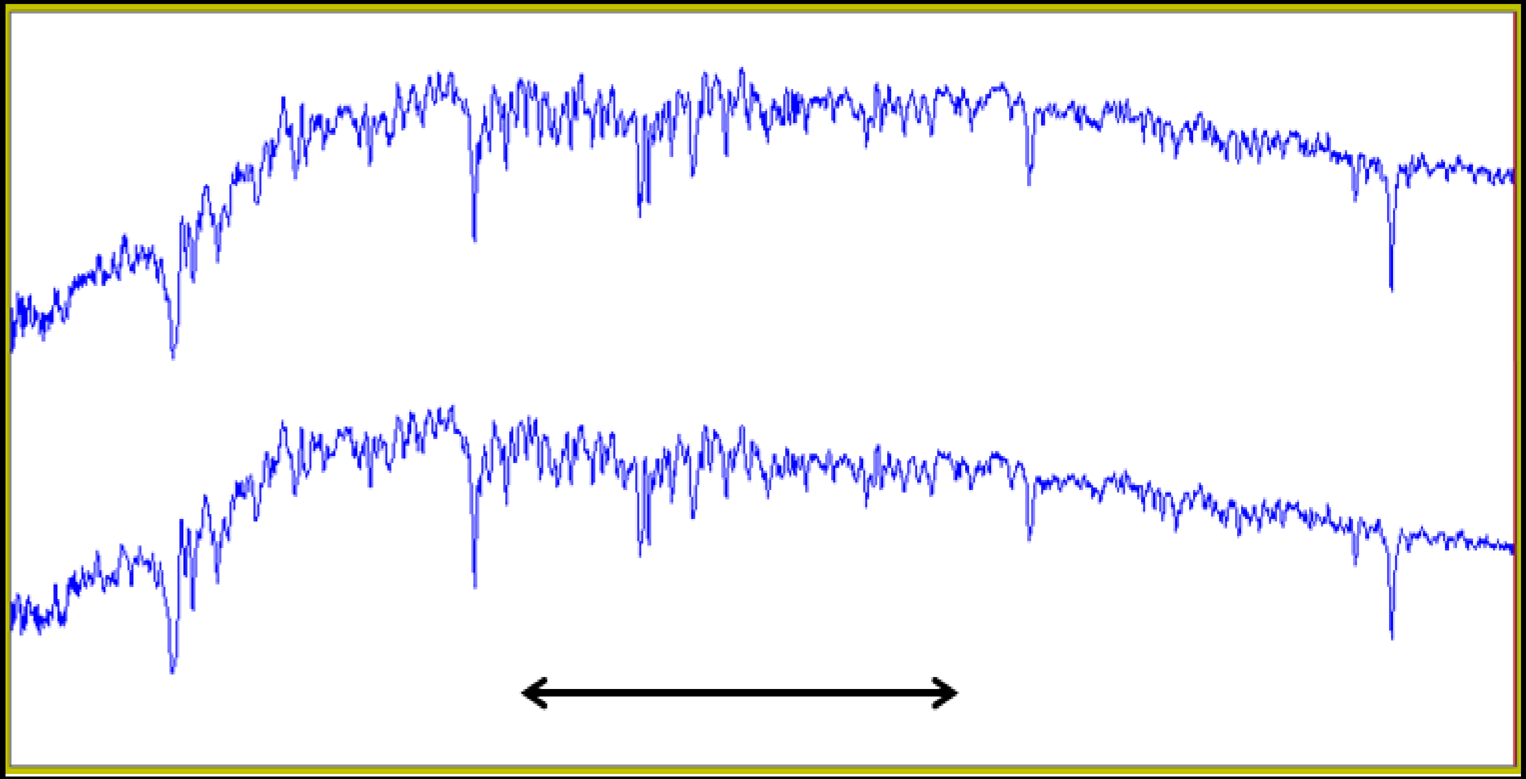


Lines seen by Huggins

We now know that two of these lines are produced by doubly ionised oxygen.

Using radial velocity measurements to identify binary stars

F, G and K type stars have sufficient metal absorption lines that even at low resolution cross-correlation can be used to measure the wavelength shift between two spectra taken at different times

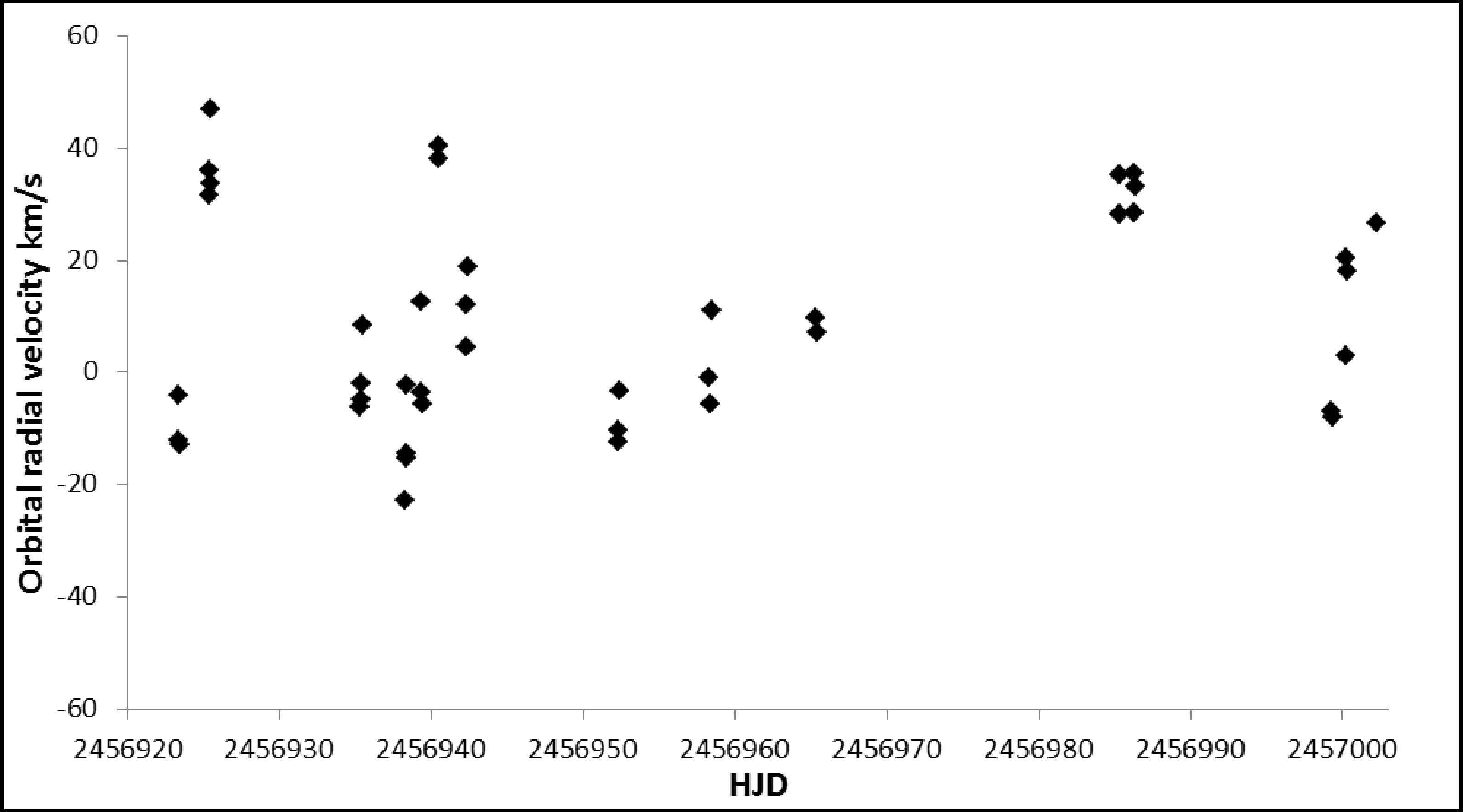


This wavelength shift gives their relative radial velocities

TYC 0555-0445

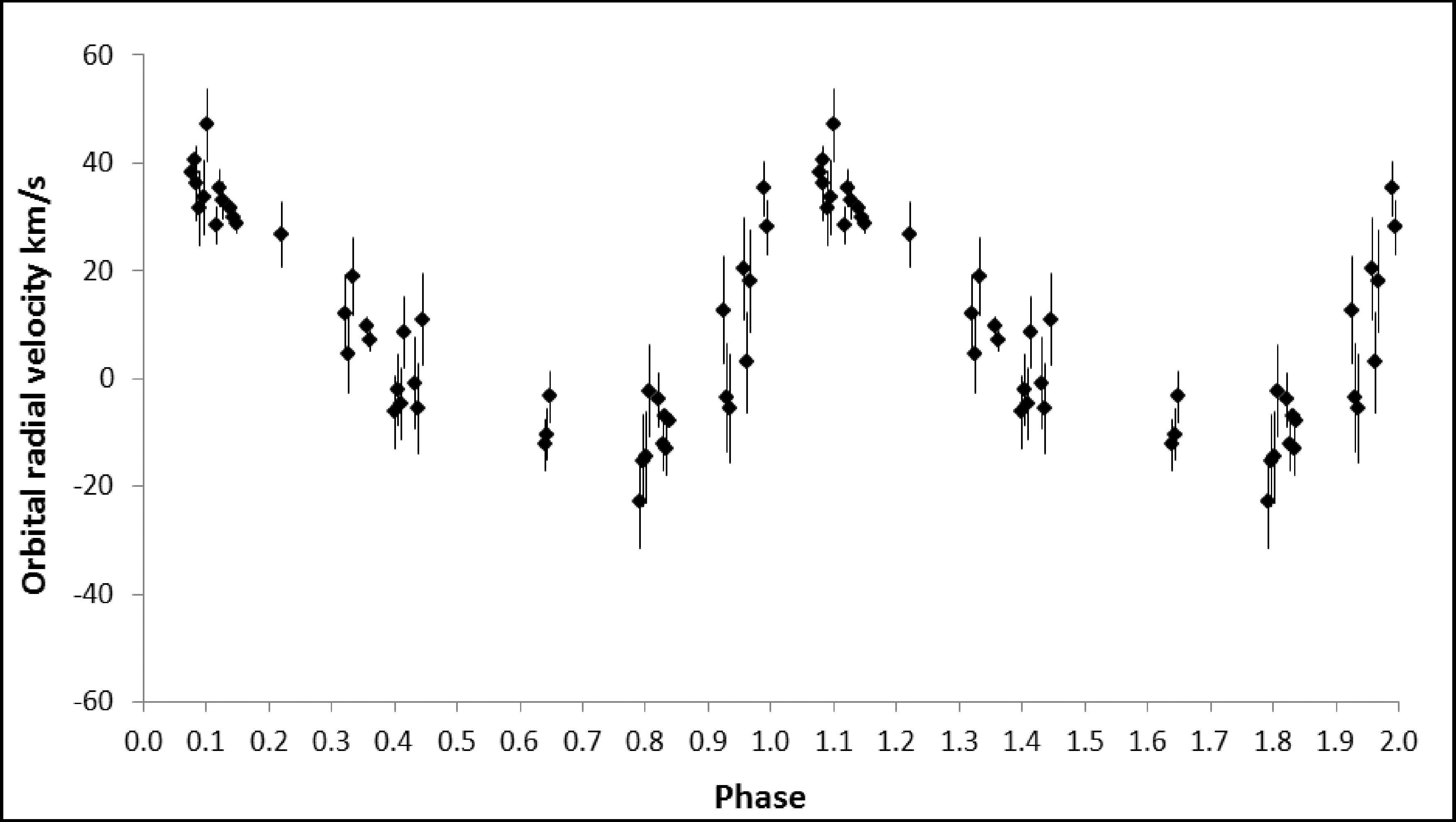
The spectrum of this non-eclipsing F-type main sequence star apparently showed a UV excess which suggested it might have a white dwarf companion

47 spectra taken on 18 nights gave these relative radial velocities



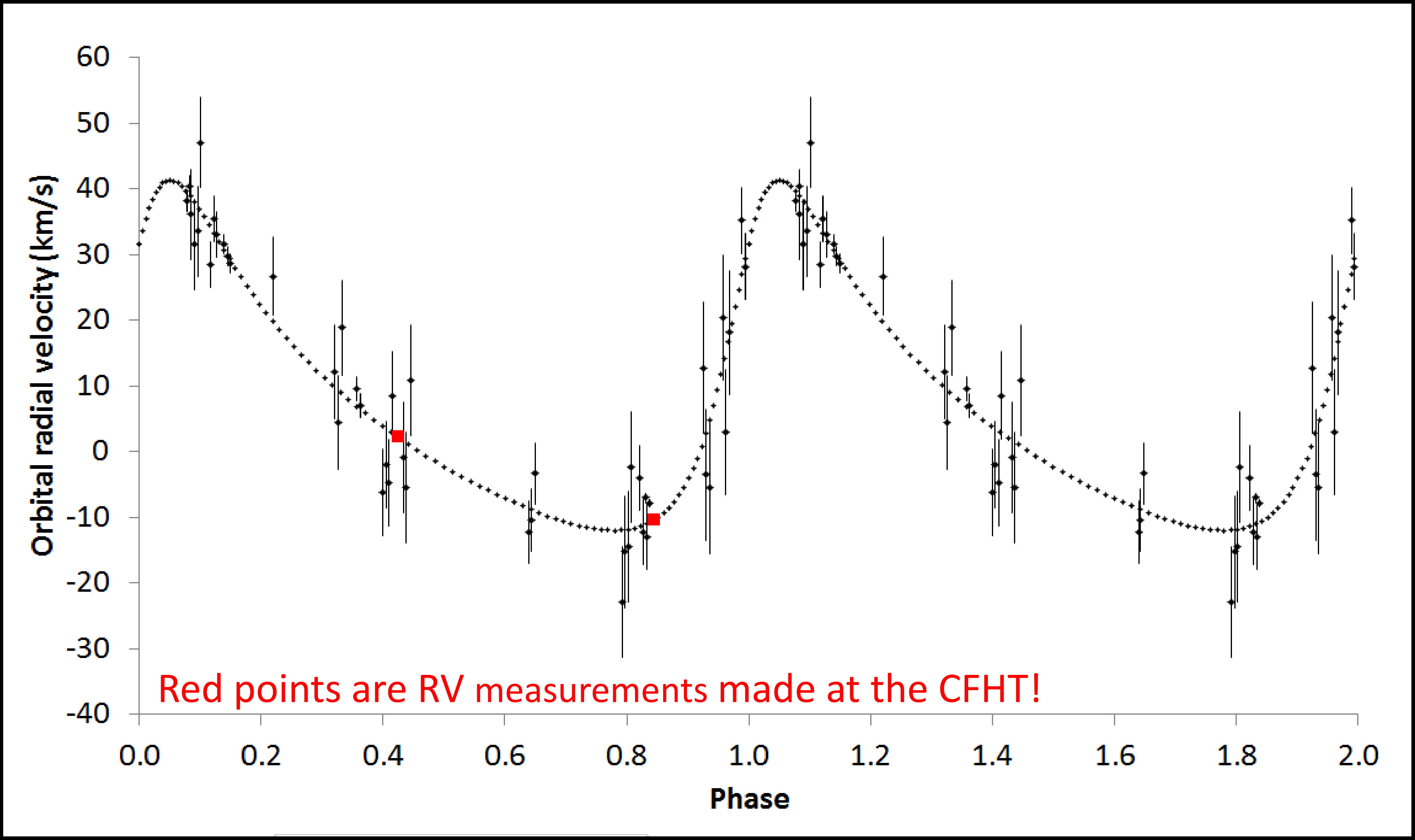
This variation confirmed that this was indeed a previously unknown binary

Period analysis of the radial velocity data gave an orbital period of 7.587 days – confirming this to be a new MS+WD single-lined spectroscopic binary



SB Solver was used to fit the data and calculate these binary parameters

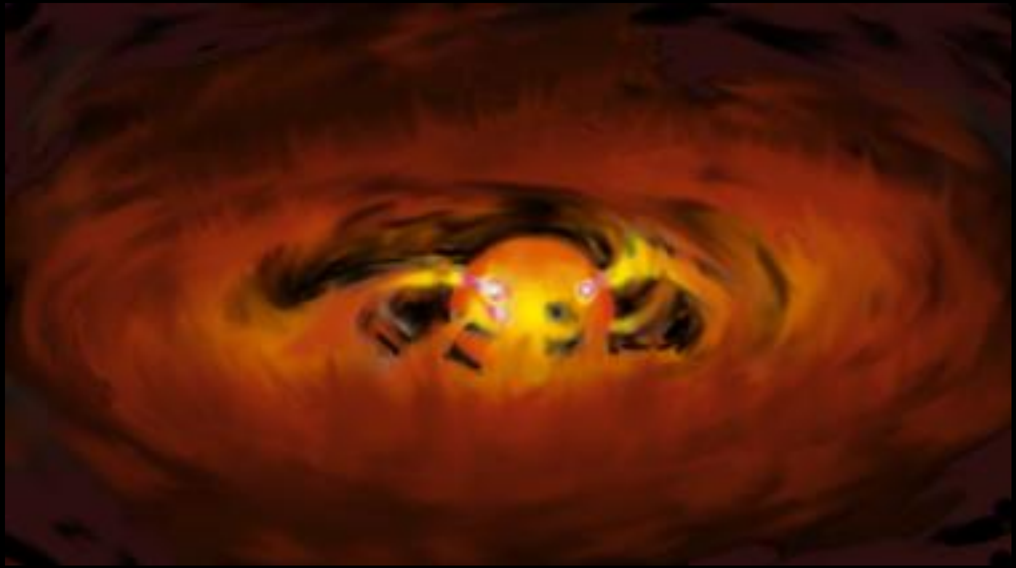
Period	7.587 d
Systemic velocity	6.92 km/s
Velocity semi-amplitude	26.65 km/s
Eccentricity	0.458
Longitude of periastron	309.41°

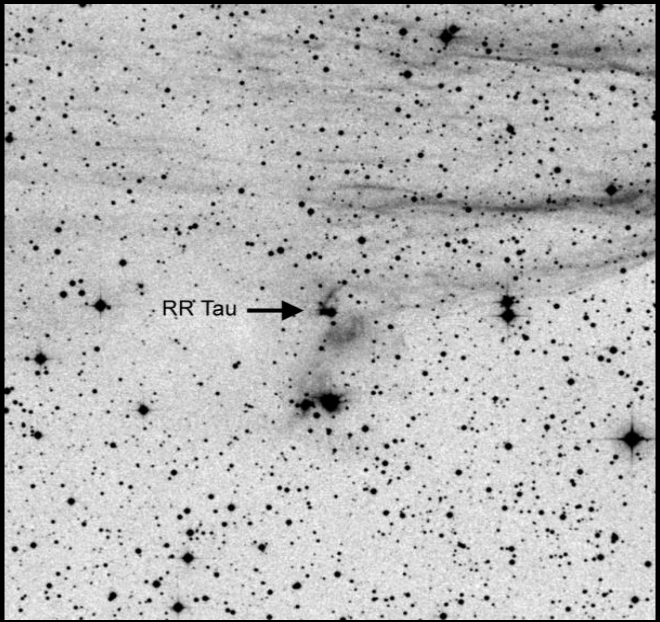


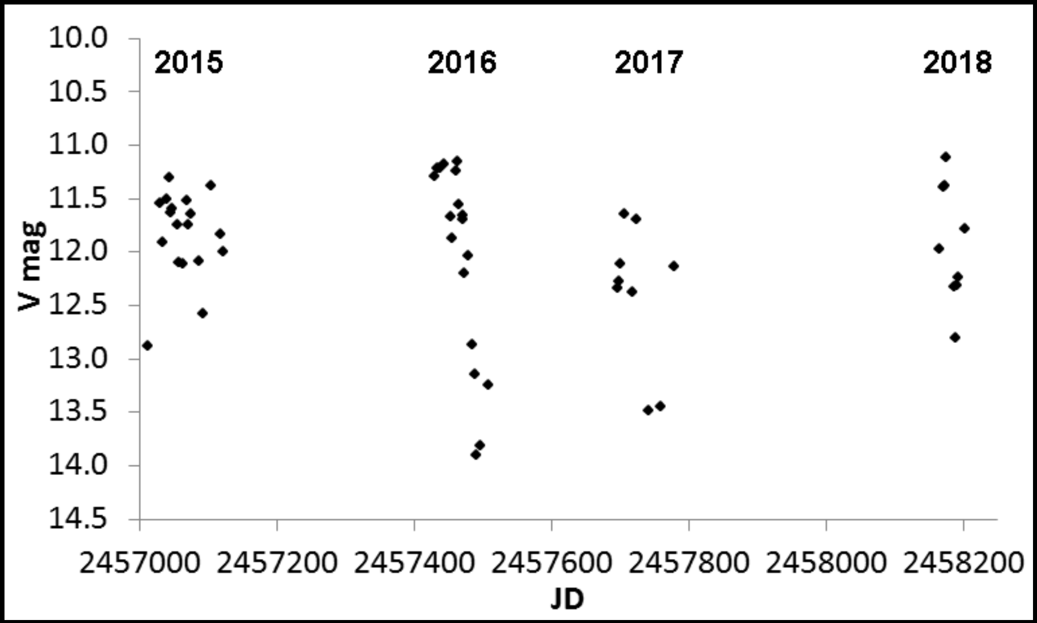
Dusty nature of pre-main sequence stars

UXORs are young stars accreting material from a circumstellar disc (also known as Herbig Ae stars)
- RR Tauri is a typical example

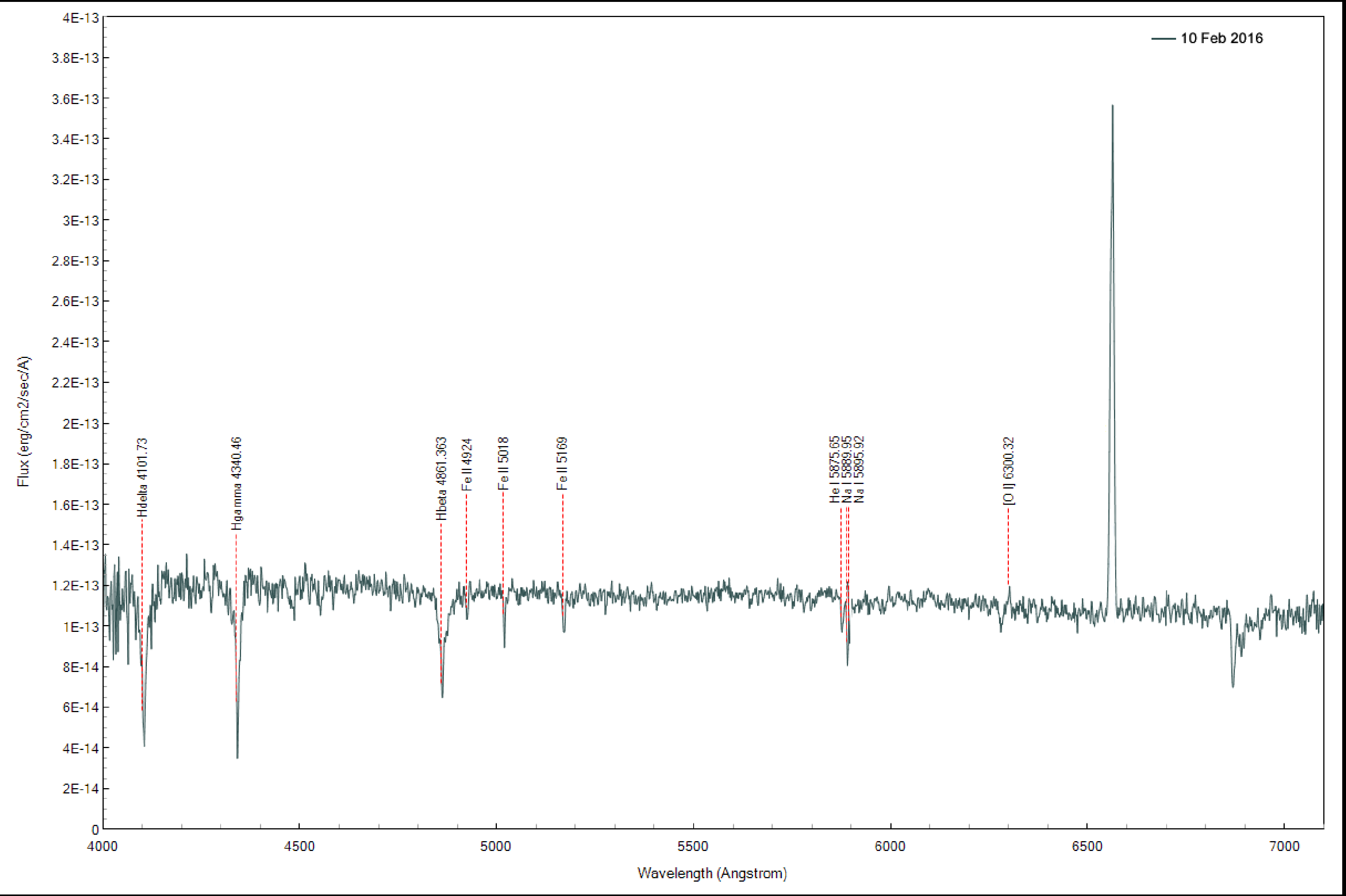
It varies continuously and my photometry shows occasional deep fades likely due to obscuration by dusty material around the star



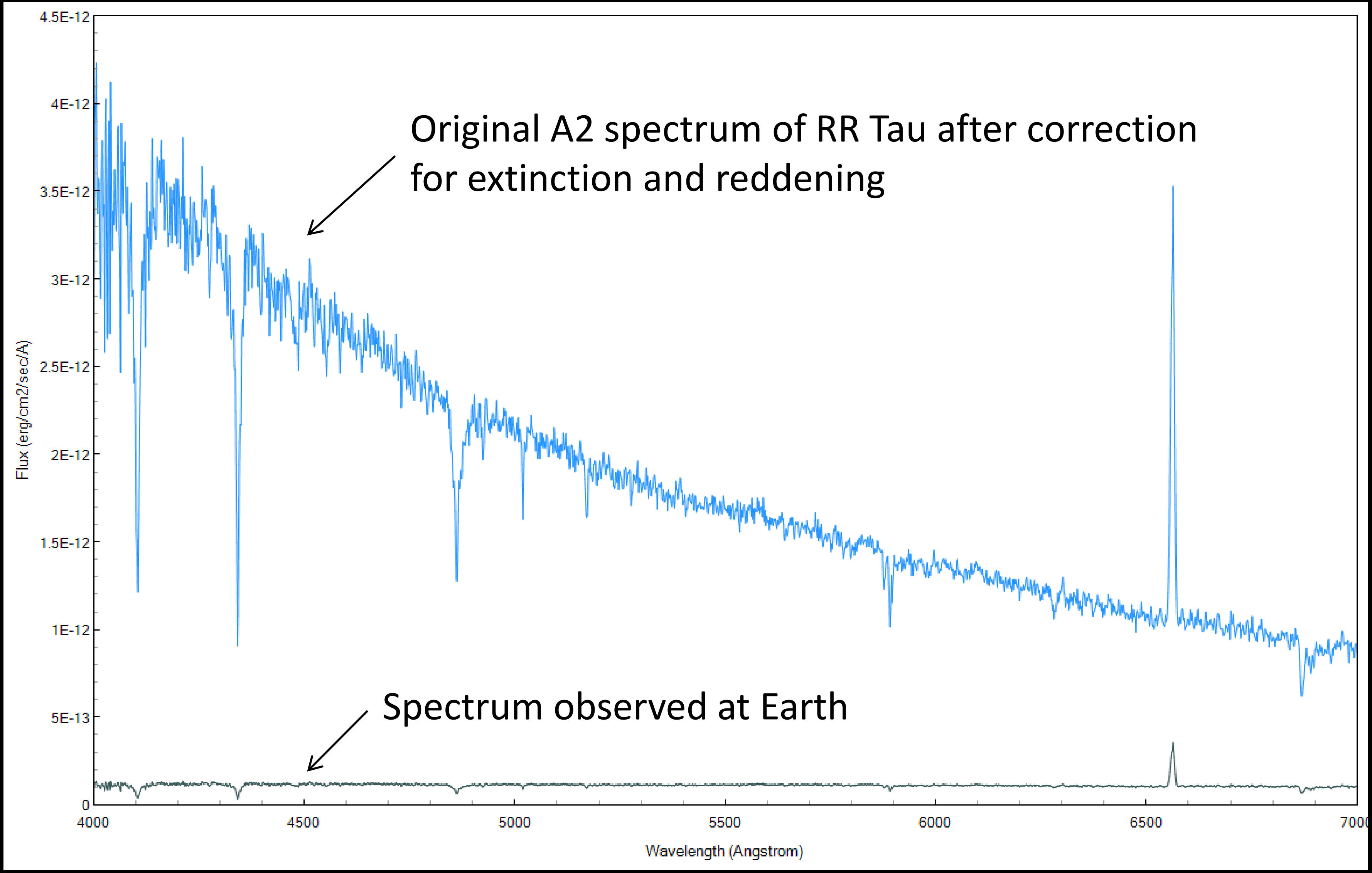




The spectrum of RR Tau shows strong Hα emission from the stellar photosphere and other hydrogen Balmer and some metal lines in absorption



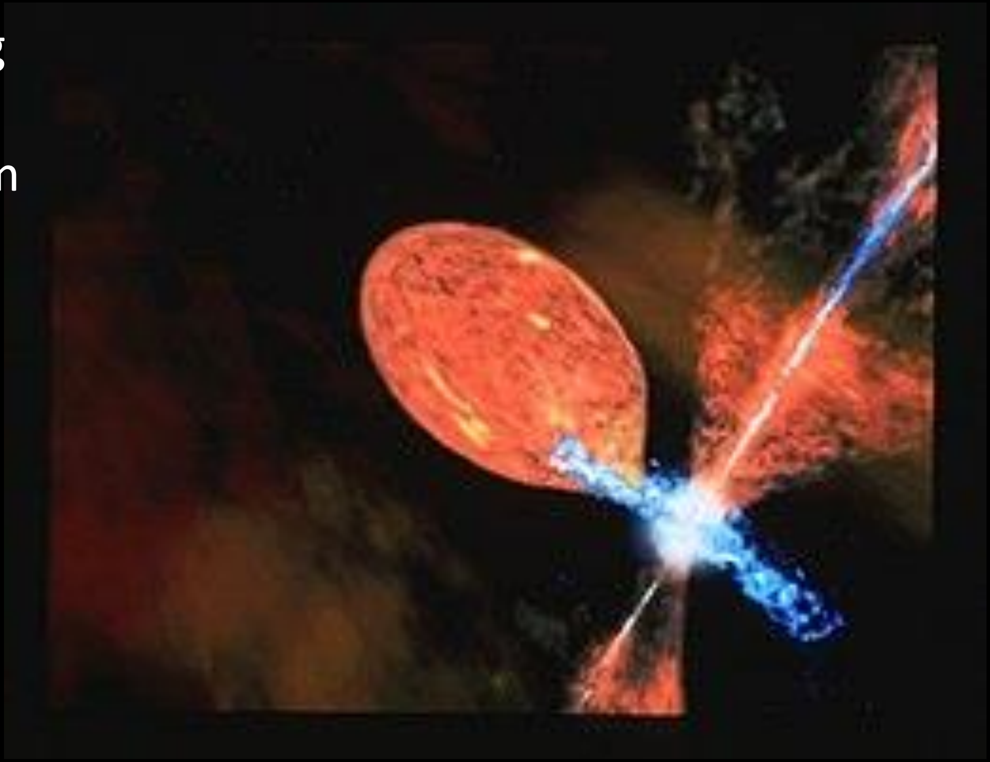
RR Tau is an A2 spectral type star but a combination of extinction (absorption) and reddening (scattering) by circumstellar material and interstellar dust means the spectrum we observe on Earth is very different



Measuring the white dwarf temperature in a symbiotic star

Symbiotic stars are binaries comprising

- a red giant emitting a wind,
- a white dwarf accreting matter from the wind,
- possibly an accretion disc around the white dwarf,
- occasionally a high velocity jet emitted orthogonal to the disc,
- a surrounding nebula which is partially ionised by UV radiation from the white dwarf

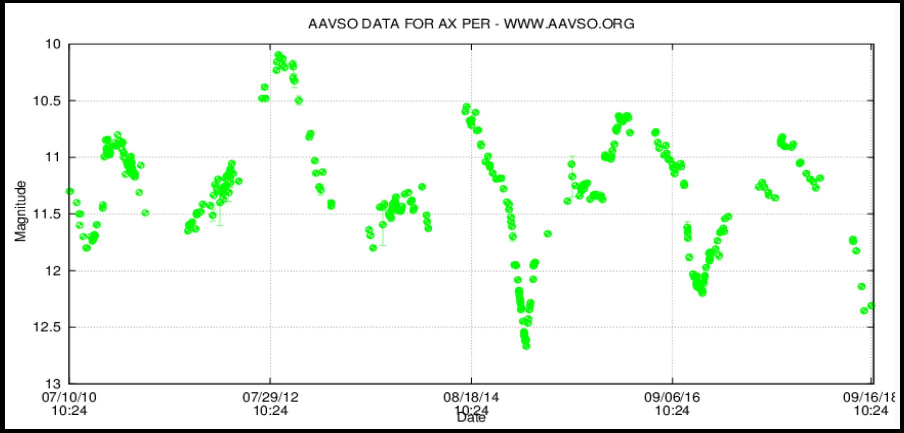


The resulting complex spectra may have contributions from all these components and can change from night to night

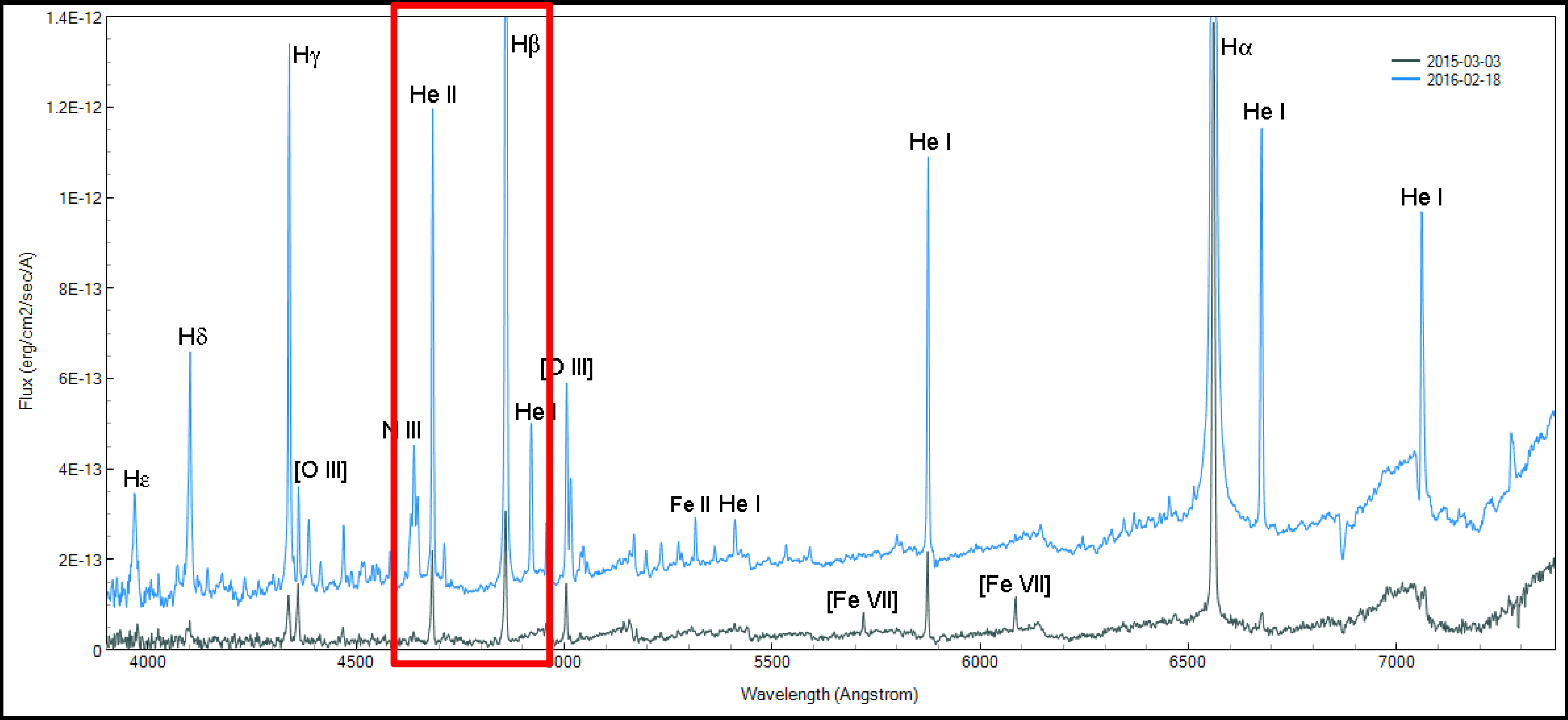
There is a pro-am campaign coordinated by the ARAS team to obtain a regular record of the spectra of all bright symbiotic stars

The light curve of the symbiotic star AX Persei shows eclipses with an orbital period of 680 days

Its spectrum varies in the course of each orbit



Out of eclipse (blue, V=10.6) there are many emission lines most of which disappear during eclipse (black, V=12.6) but lines of highly ionised iron [Fe VII] then appear



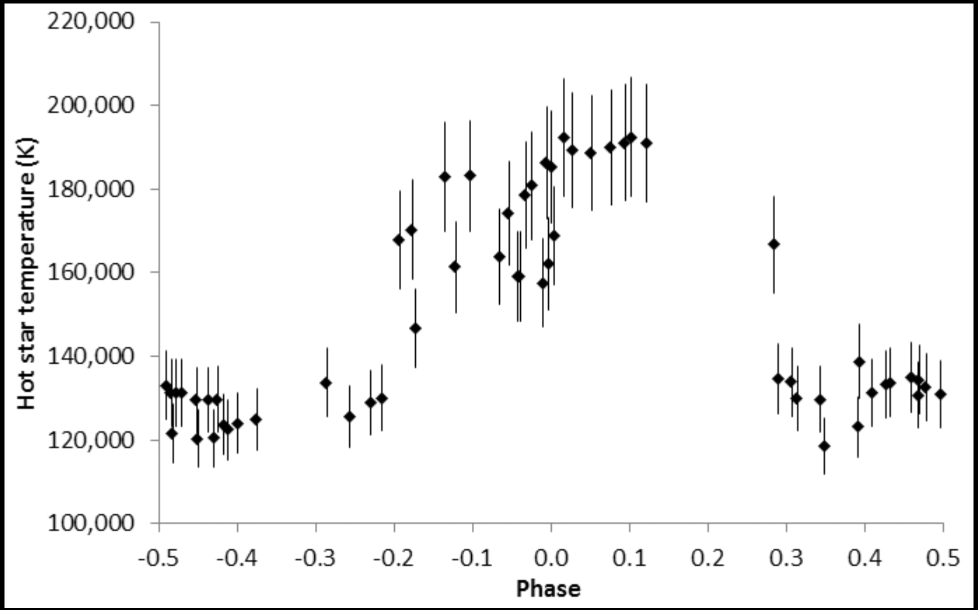
The ratio of fluxes in the He II 4686 and Hβ 4861 emission lines is a proxy for the temperature of the white dwarf

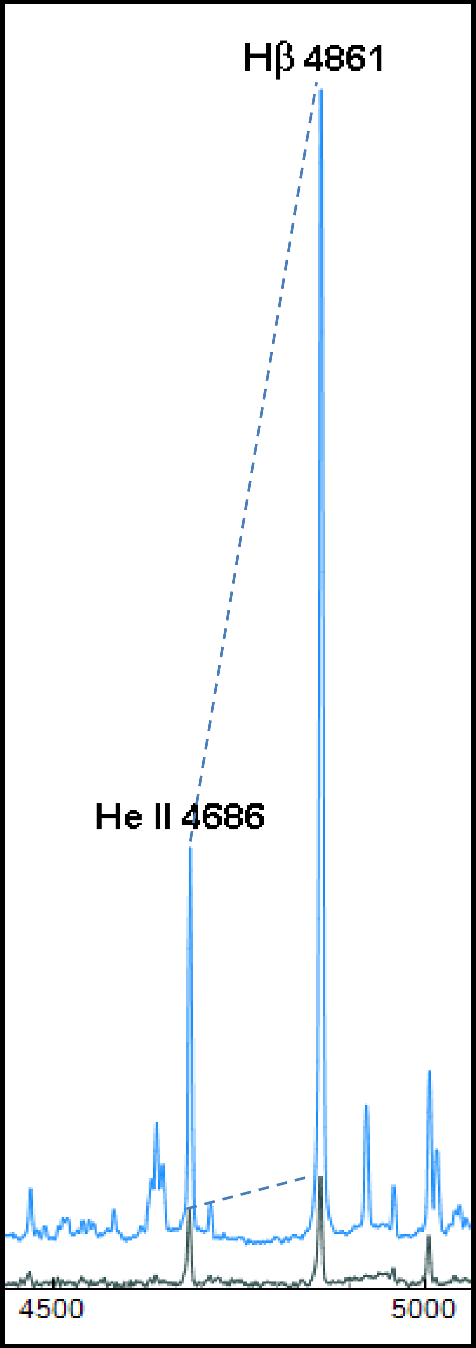
These lines are produced in the red giant wind by UV radiation from the white dwarf

Excitation energy for He II 4686 is 2.64 eV and for Hβ 4861 is 2.54 eV

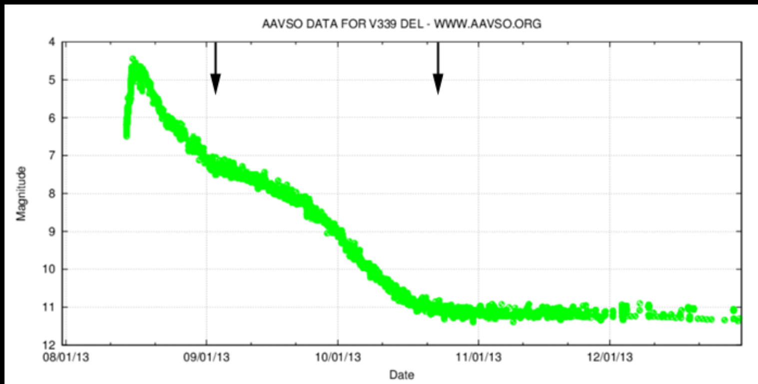
The hotter the white dwarf, the greater the production of He II 4686 compared to Hβ 4861

T_{WD} = (14.16*SQRT(He II 4686/Hβ 4861)+5.13)*10000 K



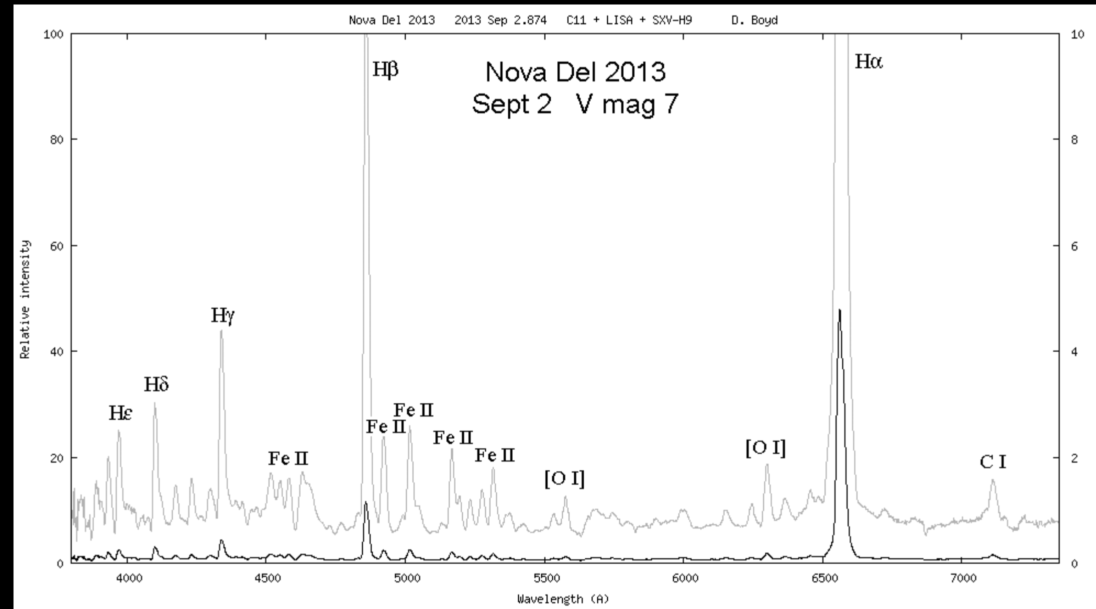


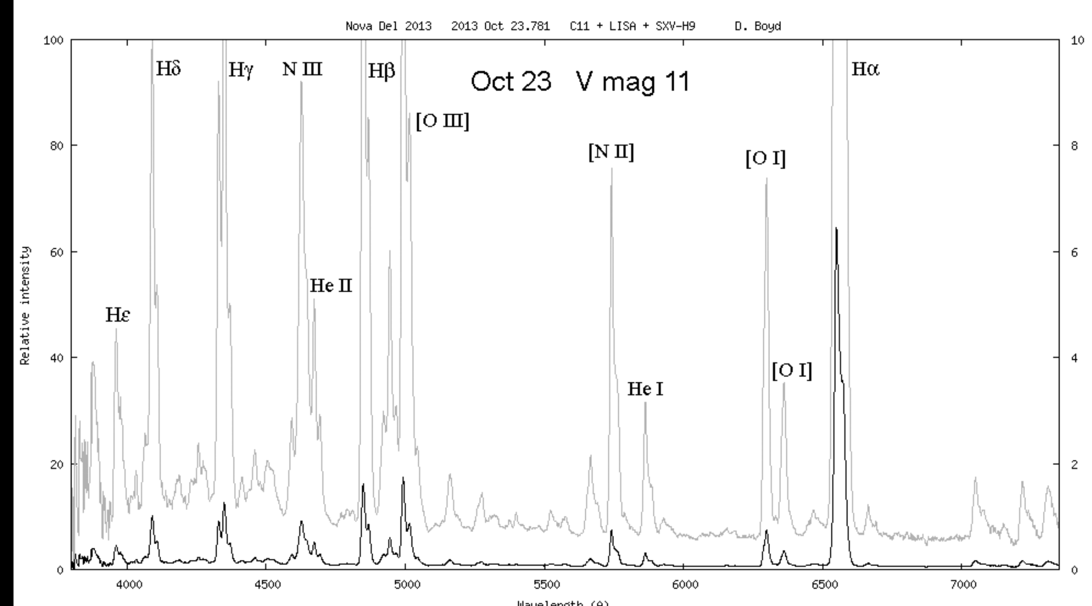
Evolution of a nova as it slowly fades – Nova Delphini 2013



Initially there are strong emission lines of singly ionised iron, Fe II, the so-called "iron curtain"

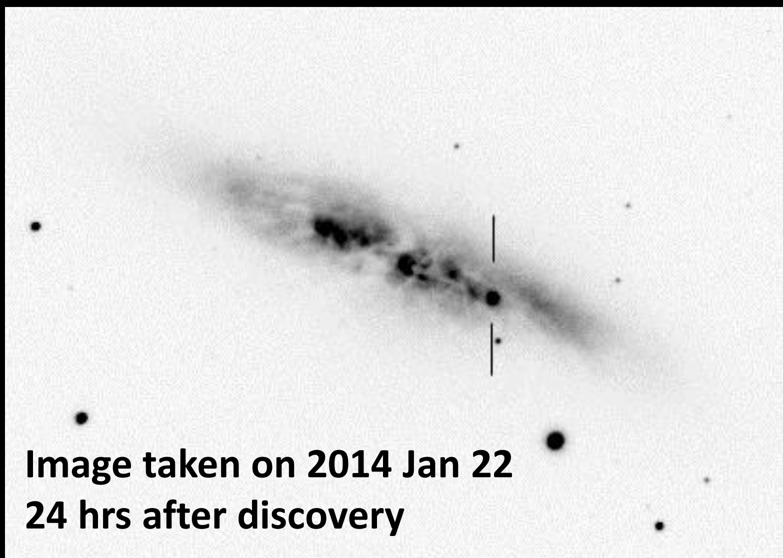
Eventually this clears and we see the expanding shell of hot gas from the explosion including forbidden lines of oxygen [O III] and nitrogen [N II]

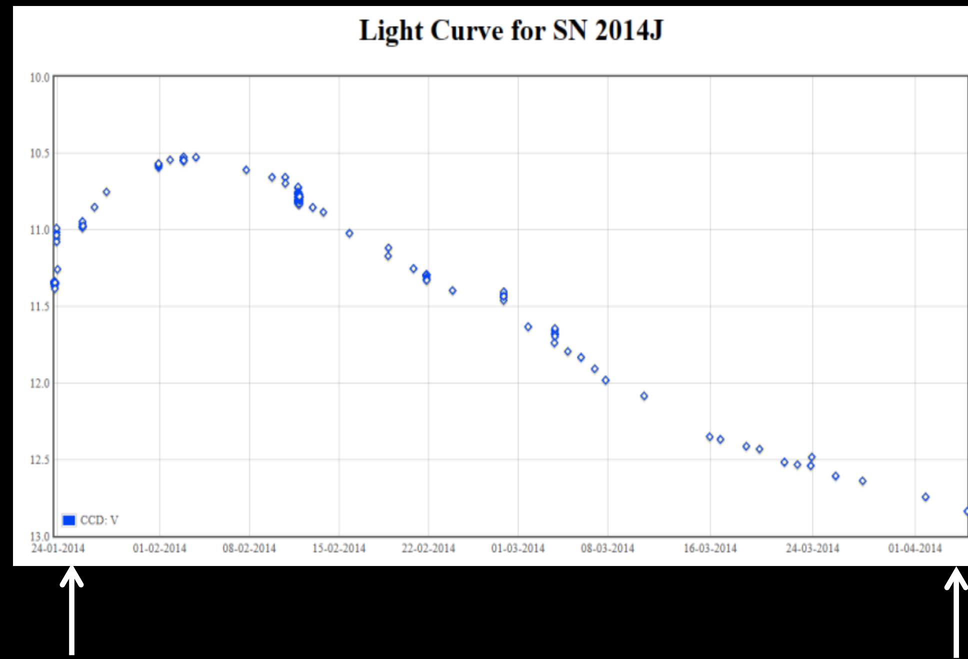




Measuring the velocity of a supernova explosion

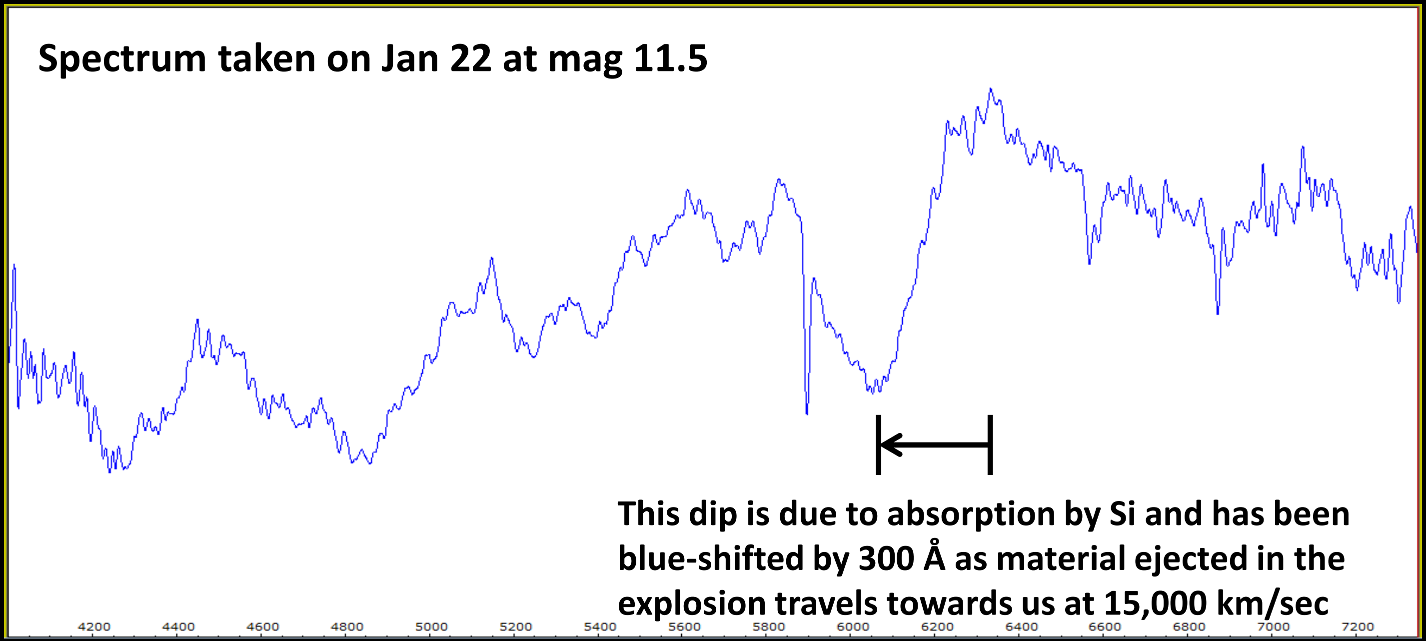
SN2014j in M82 – a bright type 1a supernova

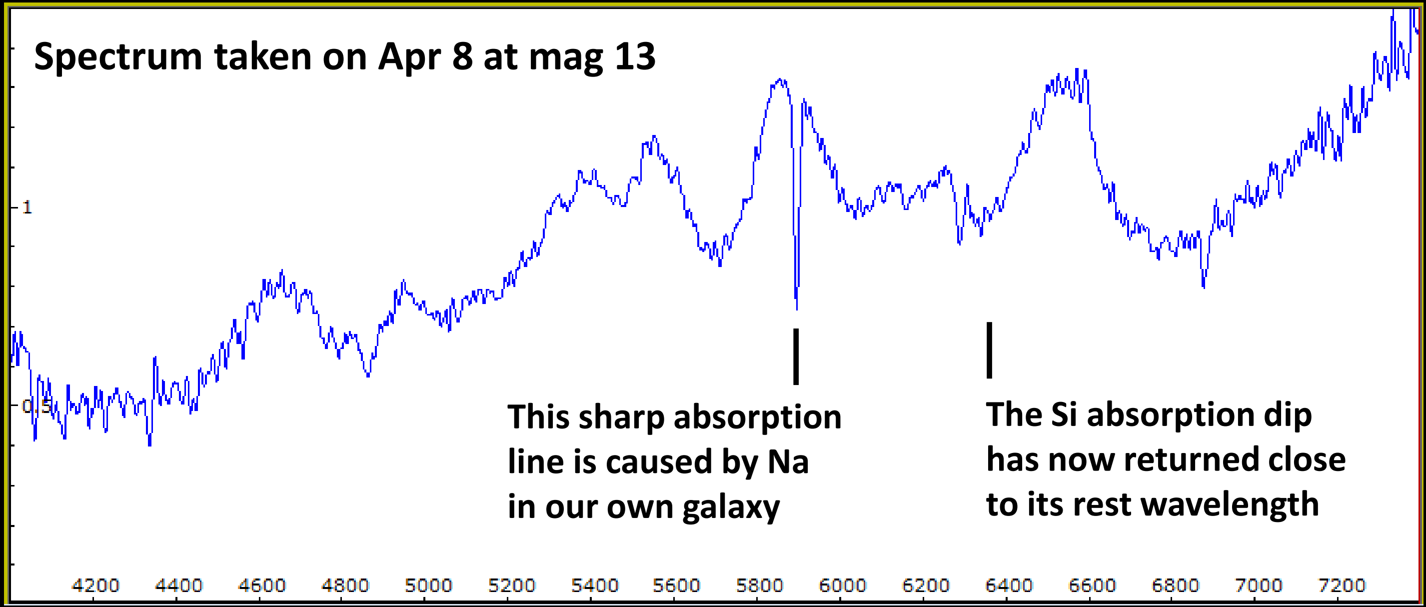




Spectra taken at the start and much later during the supernova explosion enable us to measure the changing velocity of the expanding shell of debris

Absorption lines in the spectrum are blue-shifted by the explosion





Conclusions

- Spectroscopy enables us to see many things that are not detectable using only photometry
- It provides new insight into the behaviour of variable stars of all types
- Even at amateur level it can produce scientifically useful information
- It is challenging to master but ultimately very rewarding

Thank you for listening