AGA0414 Spectroscopy

Prof. A. Ederoclite

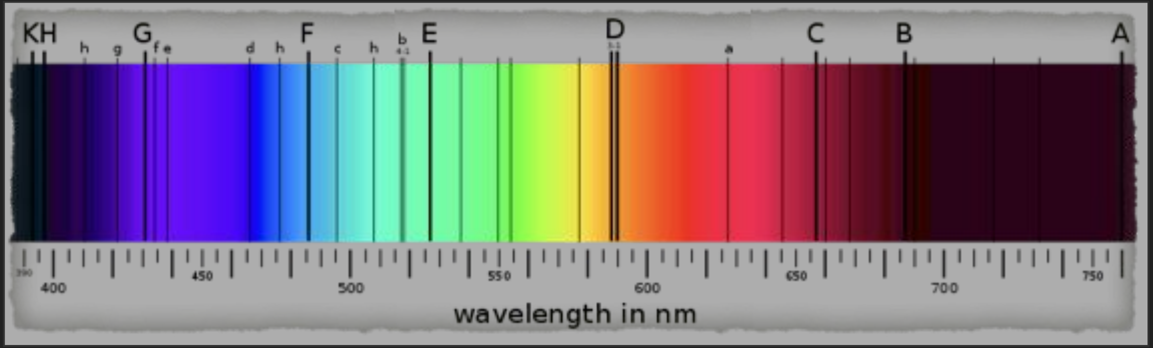
White is not a colour

If you let “white light” pass through a prism made of glass, you split it in the colours of the rainbow.

Discovered by Sir. Isaac Newton.

[Actually] White light is a superposition of light at different wavelengths, which are separated by a prism thanks to Snell’s law

Fraunhofer: the Sun has “dark lines”



1787 - 1826

Fraunhofer discovered the presence of a series of dark lines in the solar spectrum.

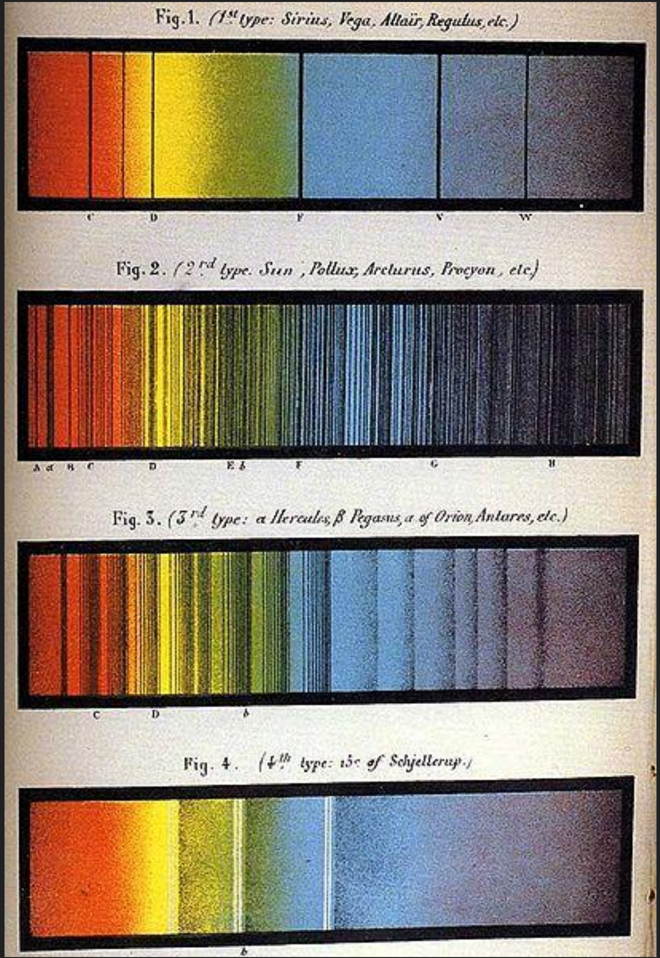
He called them with alphabet letters (capital for more intense and minuscule for less intense)

Note the wavelengths of the Na D doublet.

Secchi: stellar spectroscopy

1818 - 1878

First attempt to classify stars.

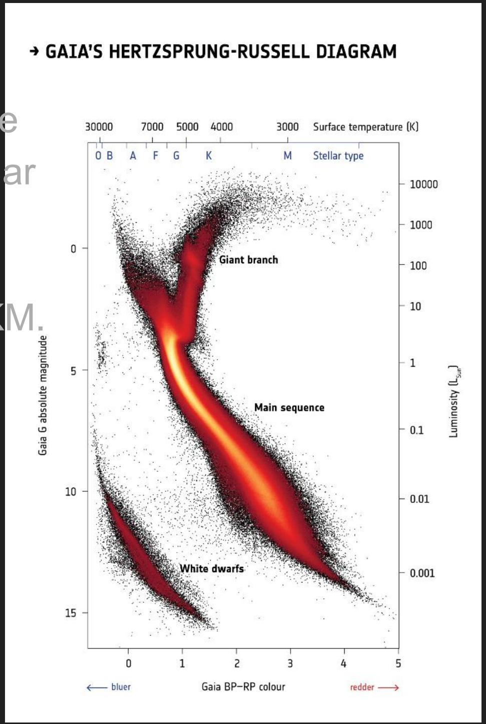


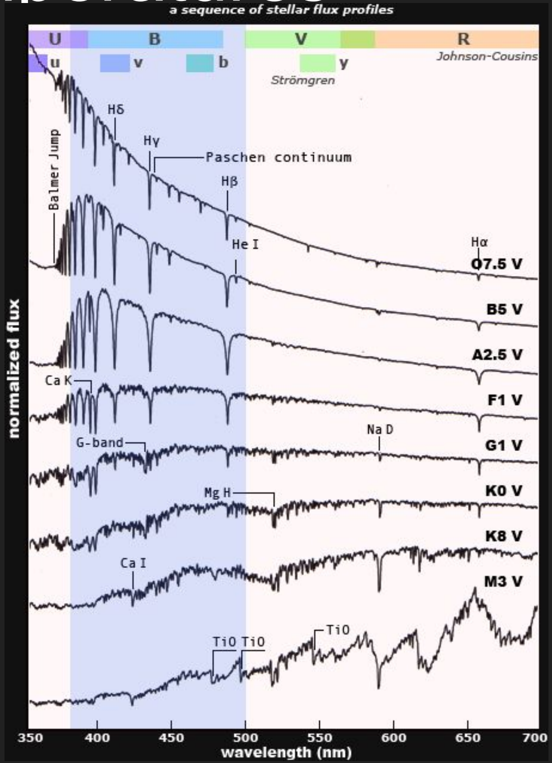
(Main Sequence) Stars of different temperatures

In the first decades of the XX century, the Harvard gorup (aka Pickering's harem) had the merit of standardising the classification of stellar spectra.

As a reminder, from hotter to cooler: OBAFGKM.

Most of that classification is what we still use today.





https://www.gaia.ac.uk/multimedia/gaia-dr2-hr-diagram

https://www.handprint.com/ASTRO/specclass.htm

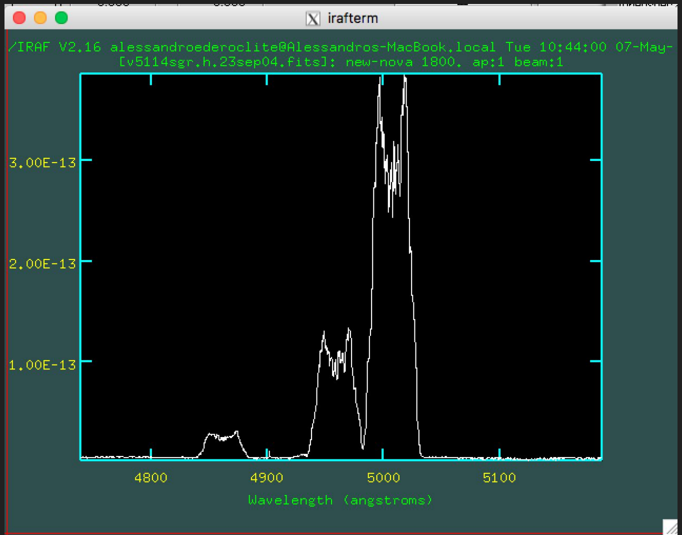
From qualitative to quantitative

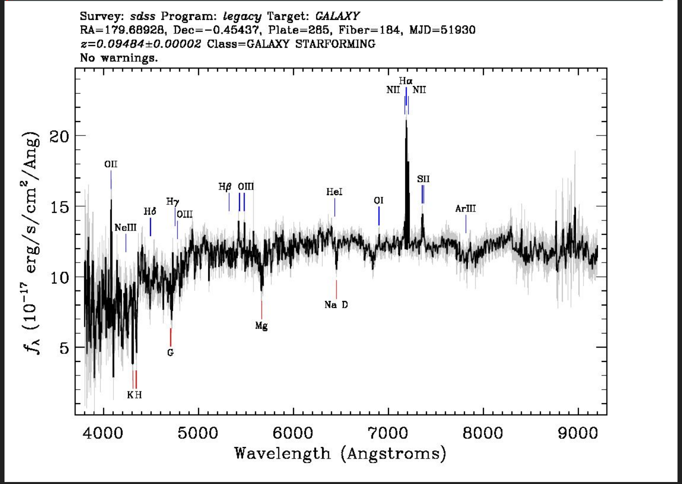
Today, we use quantum physics to derive densities and temperatures.

> You can tell temperatures with colours (e.g. the B-V colour was designed for this), but they are far less precise.

We use relativity/Doppler to derive velocities (e.g..planet finding or distant galaxies)

This is how we discovered that stars are made of (mostly) hydrogen. Btw, who discovered it?





Cecilia Payne-Gaposhkin

Possibly, the greatest astronomer of the XX century.

A couple of inspirational quotes:

Do not undertake a scientific career in quest of fame or money. There are easier and better ways to reach them. Undertake it only if nothing else will satisfy you; for nothing else is probably what you will receive. Your reward will be the widening of the horizon as you climb. And if you achieve that reward you will ask no other.

The reward of the young scientist is the emotional thrill of being the first person in the history of the world to see something or to understand something. Nothing can compare with that experience... The reward of the old scientist is the sense of having seen a vague sketch grow into a masterly landscape."

https://www.epigenesys.eu/en/science-and-society/women-in-science/808-cecilia-payne-gaposchkin

How to build a spectrograph

The heart of the spectrograph is the “dispersing element”.

Normally you have:

- A slit (to select an object)
- A collimator
- A camera

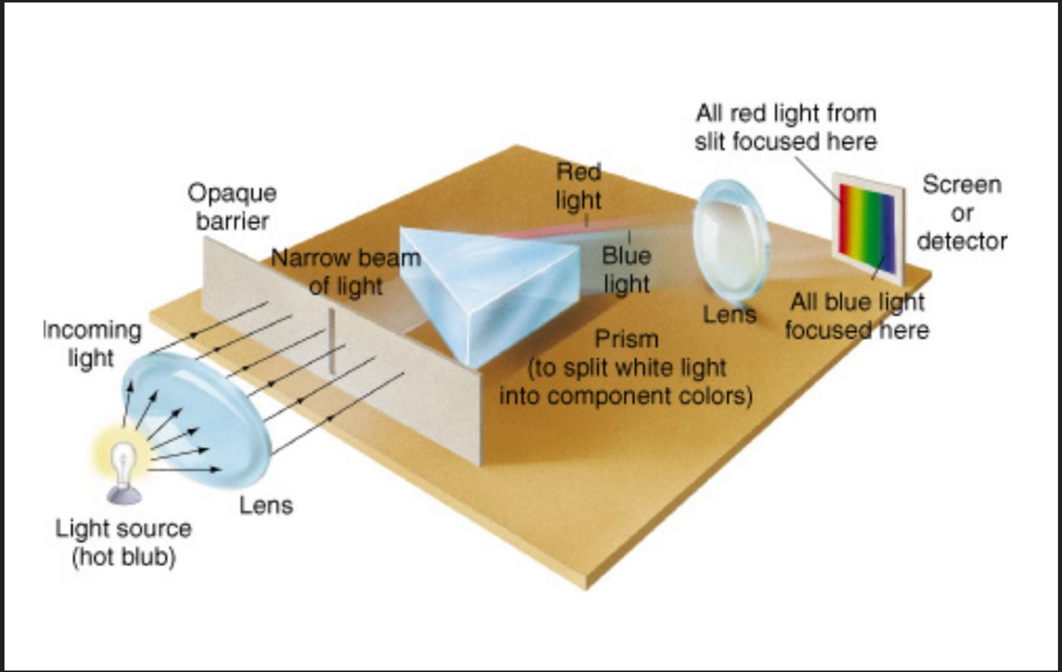
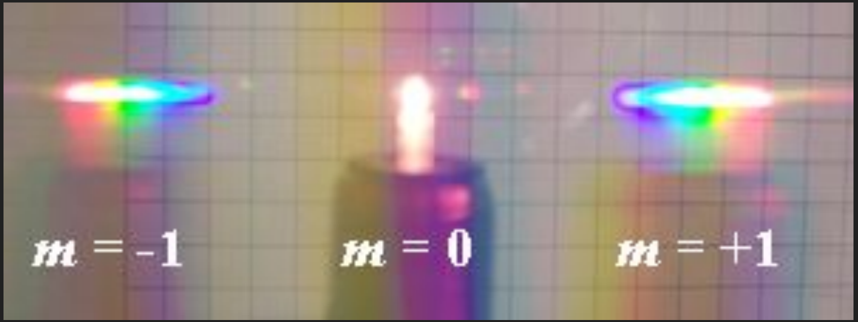


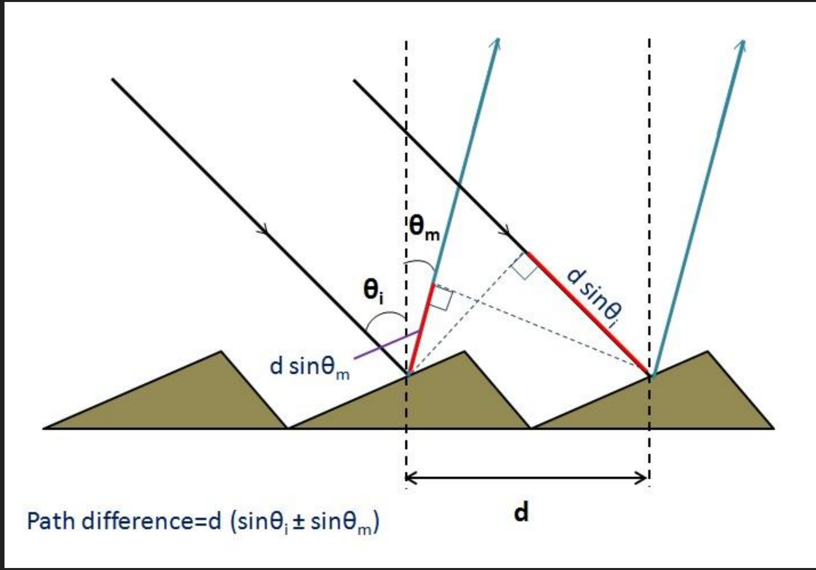
Figure stolen from R.Costa

The reflecting grating

The maximum happens when

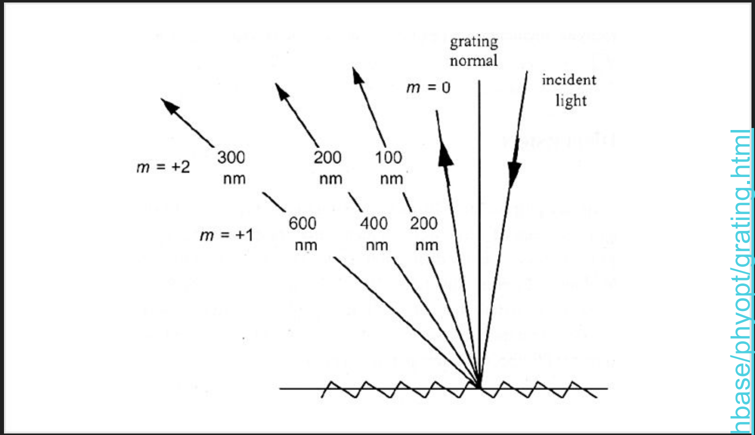
$d \sin \theta_m / \lambda = |m|$

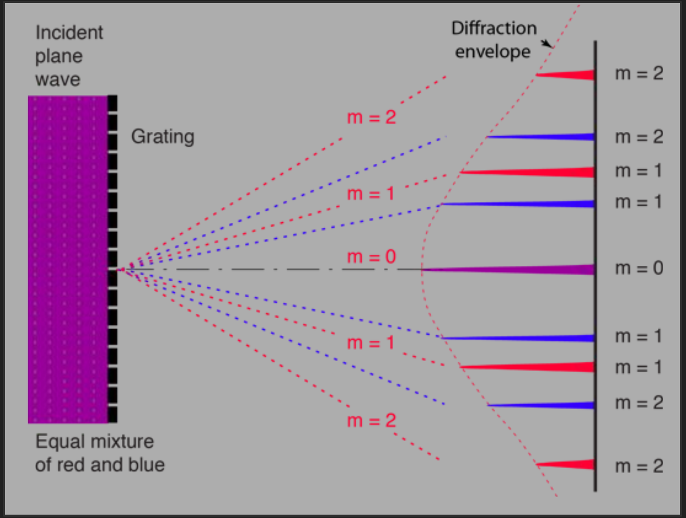




https://en.wikipedia.org/wiki/Diffraction_grating

The reflecting grating



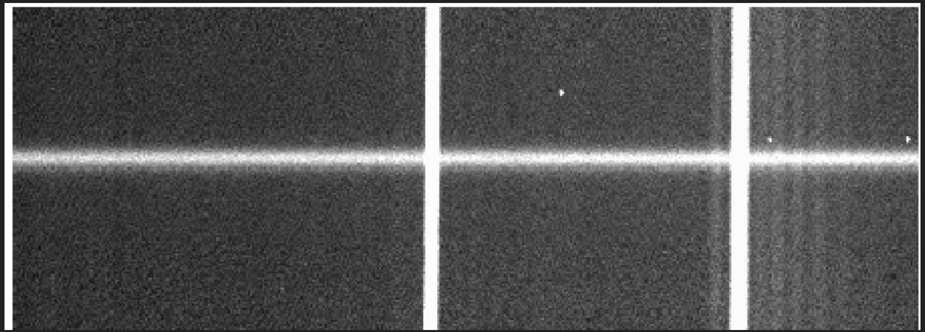


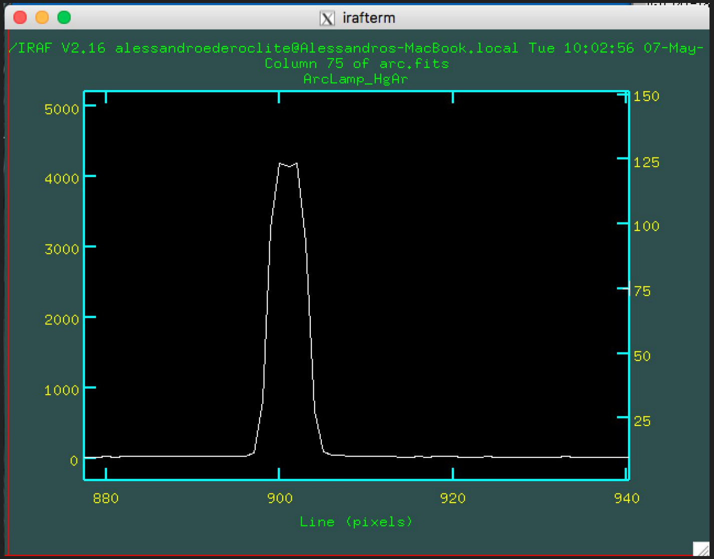
https://www.enlitechnology.com/show/diffraction-orders.htm

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html

Definition: dispersion and resolution

On a CCD, the spectrum is "dispersed": the dispersion is how many Angstrom are in a pixel.





The "resolution" R = λ / δλ (where δλ ~ 2 dispersion) is the smallest separation between two lines that I am able to measure (reminds of the Airy disc).

Examples

Dispersion: 3Å/pixels -> $\delta\lambda$ ~ 6Å -> R (@6000Å) = 1000

If CCD = 2000pixels in the dispersion direction and the first pixel has 4000Å, the maximum wavelength will be 4000Å + 2000 * 3 Å = 10,000Å

Dispersion: 0.1Å/pixels -> $\delta\lambda$ ~ 0.2Å -> R (@6000Å) = 30,000

If CCD = 2000pixels in the dispersion direction and the first pixel has 4000Å, the maximum wavelength will be 4000Å + 2000 * 0.1 Å = 4,200Å

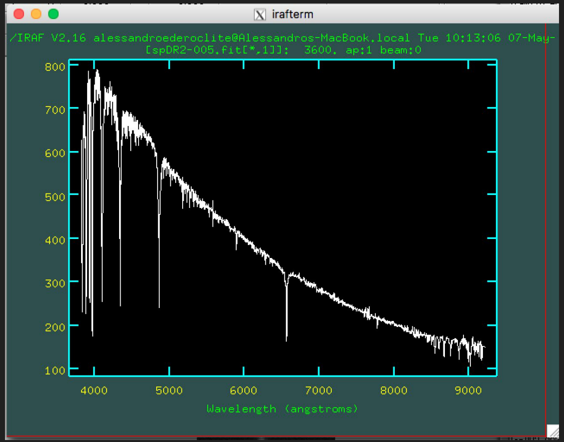
The higher the resolution, the smaller the “spectral range”

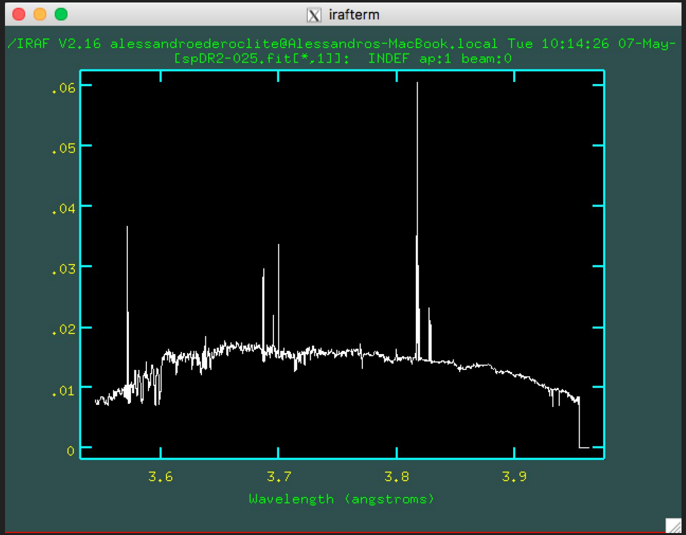
Definitions: continuum and lines

Continuum

Lines:

- Emission
- Absorption

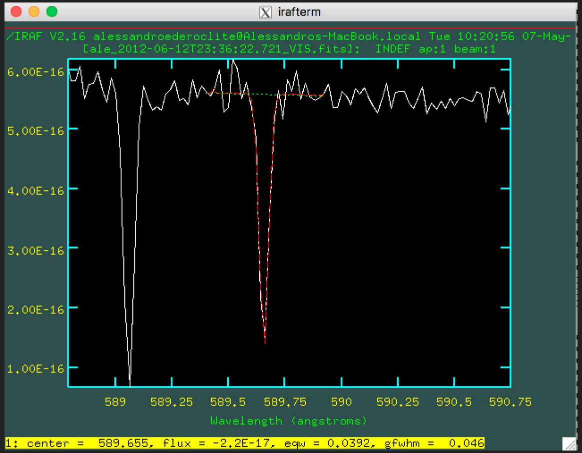


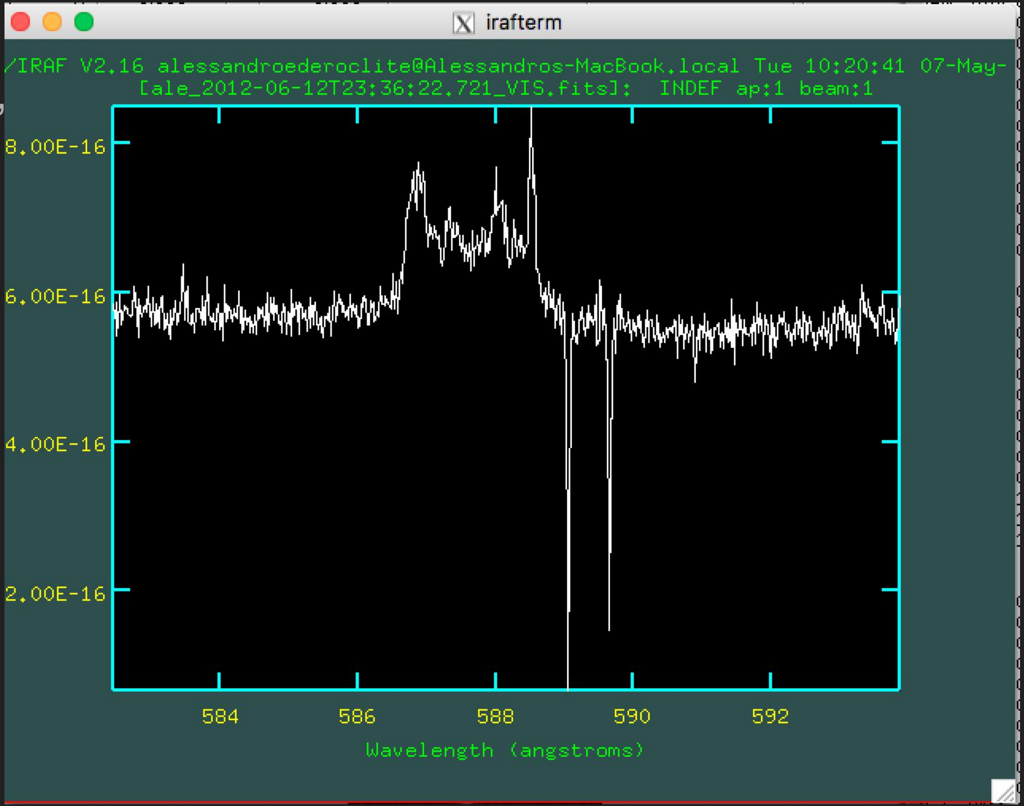


Definitions: continuum and lines

Since a line is, roughly, a Gaussian, a line is defined by:

- Centroid
- FWHM





Prism, grating or “grism” => Resolution

Element	Resolution	“Definition”
Prism	<100	Low resolution
Grism	<2,000	Low resolution
Volume Phase Holographic G.	2,000 < R < 10,000	Low / Intermediate Resolution
Gratings	> 10,000	Intermediate / High resolution

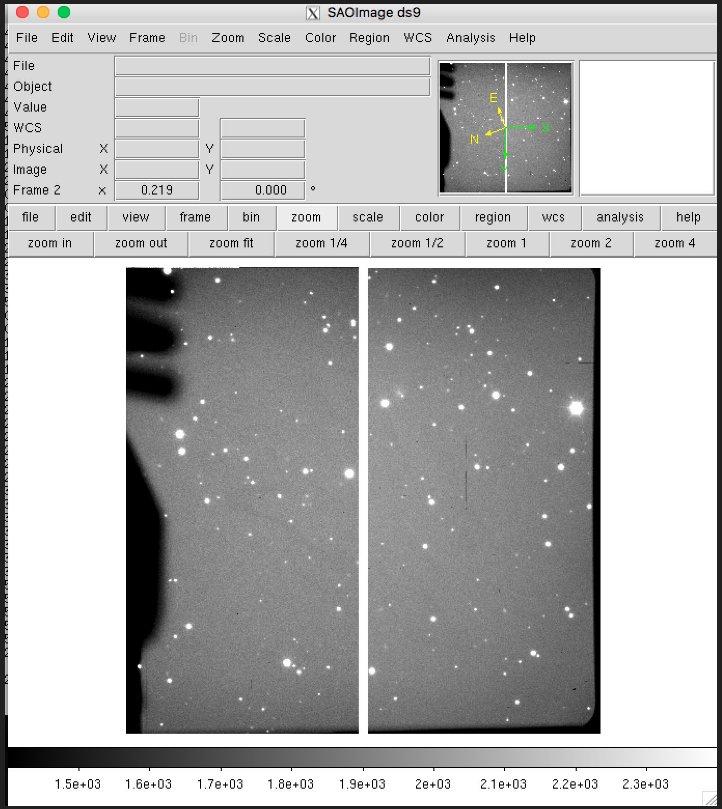
These are my definitions and they are not universal

Long slit spectroscopy

Placing a “slit” in the focal plane of the telescope to isolate the object you want to observe.

You get a spectrum of every “piece” of sky which passes through the slit.

(example with OSIRIS on GranTeCan)



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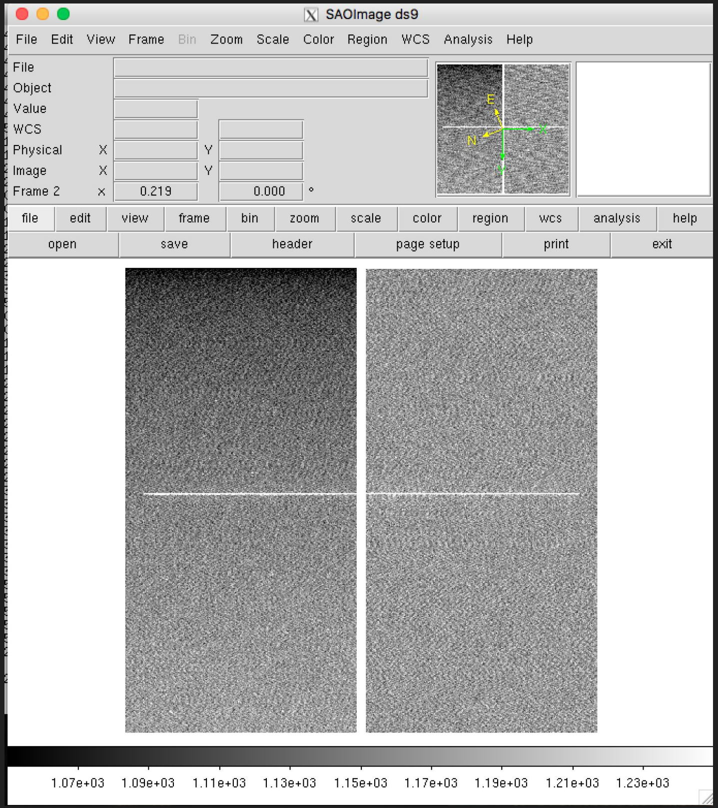

Long slit spectroscopy

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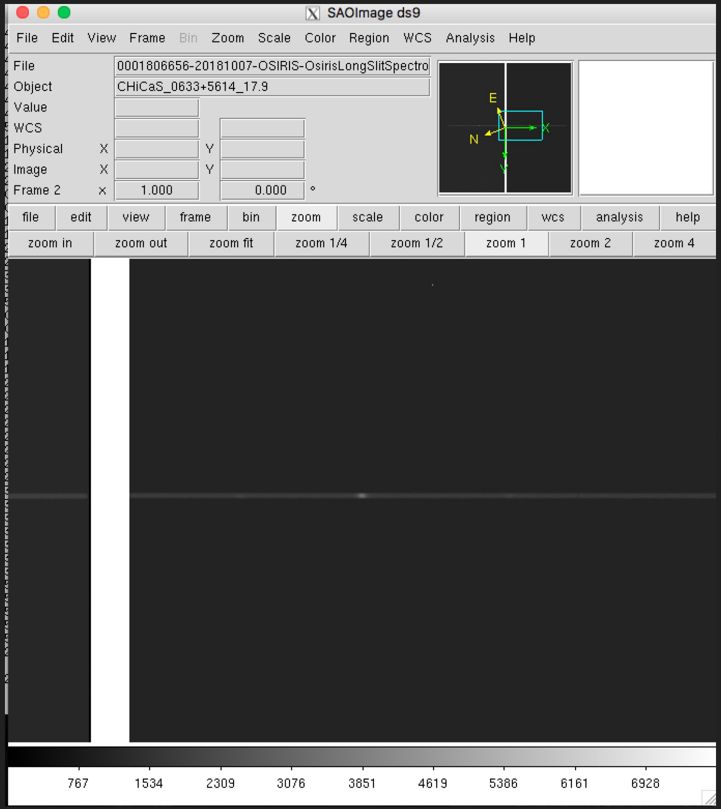
(zoom of the previous image; can you see the star through the slit?)

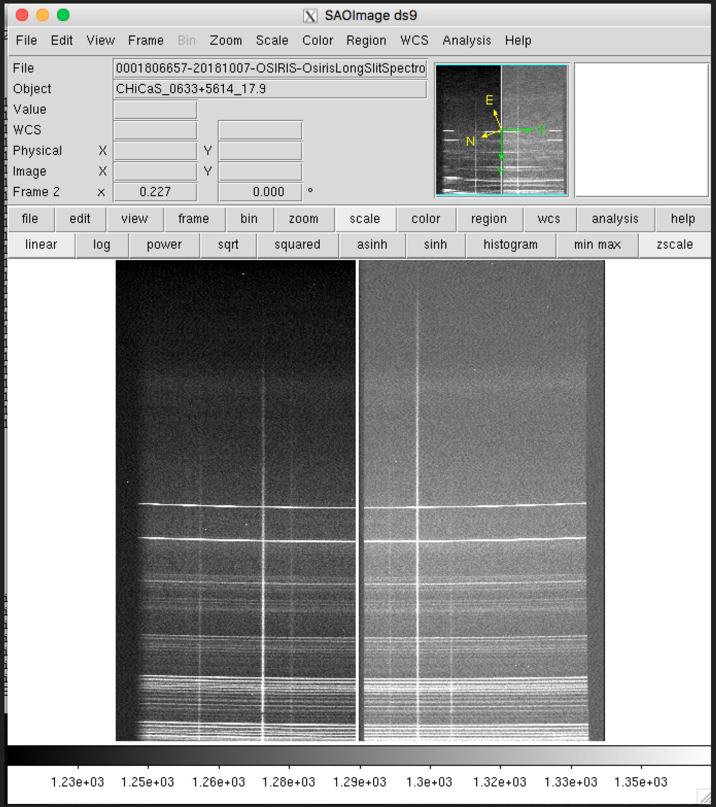


Long slit spectroscopy

Placing a “slit” in the focal plane of the telescope to isolate the object you want to observe.

You get a spectrum of every “piece” of sky which passes through the slit.

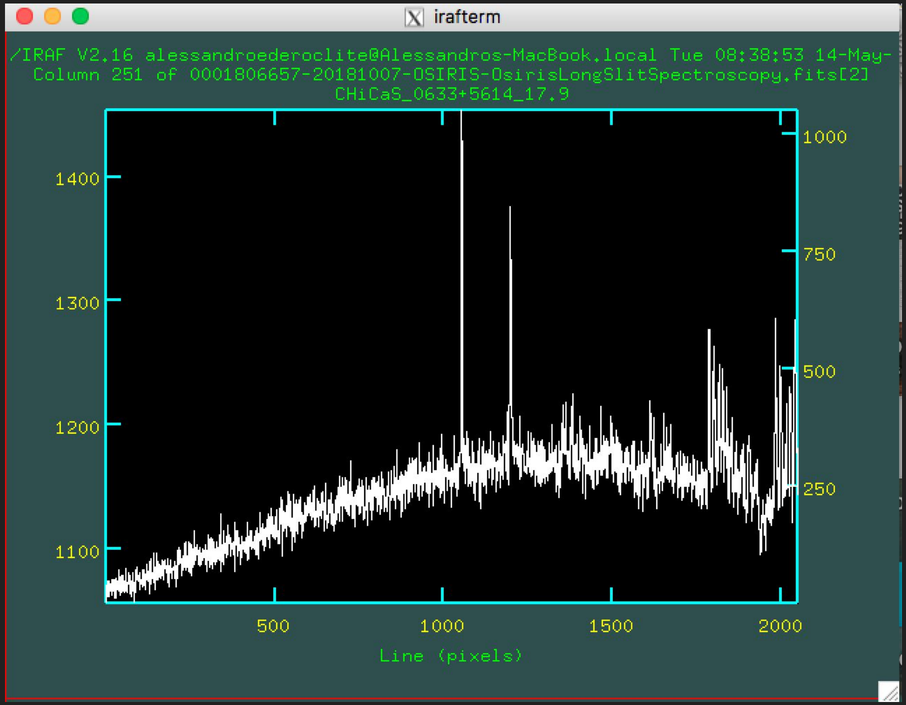
The spectrum of an object will look like a vertial line. Here we see that there are two objects in the slit (the important one is the one on the right). The horizontal lines are due to sky emission.



Long slit spectroscopy

You can integrate over the profile of the star. This is called “extracting” the spectrum.

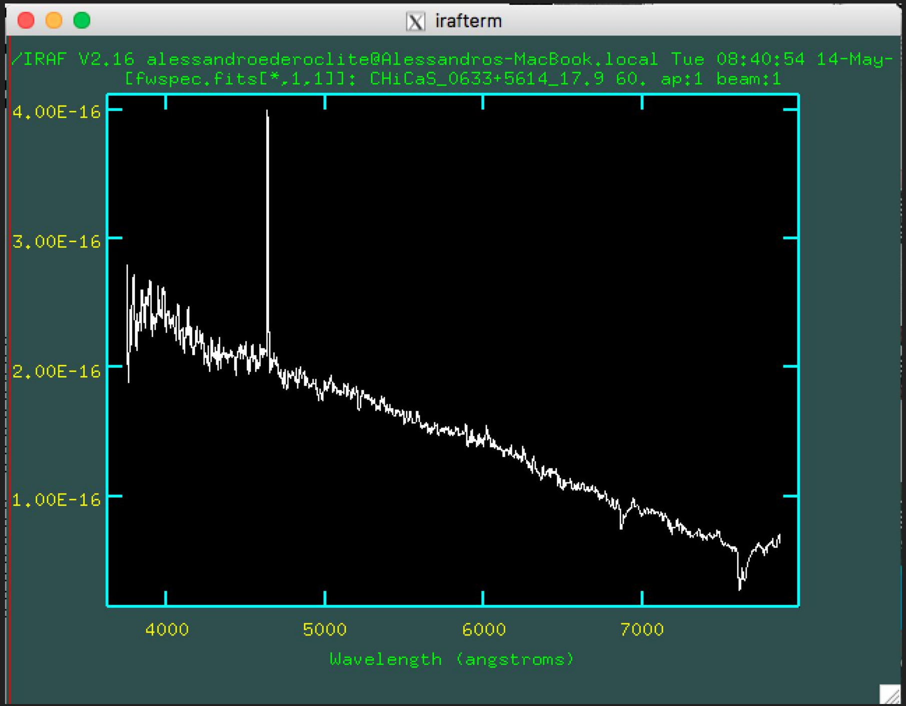
You get something like the one to the right.



Long slit spectroscopy

Spectrophotometric standard stars allow you to go from counts to physical units.

Here is the same spectrum of before once it is flux calibrated.

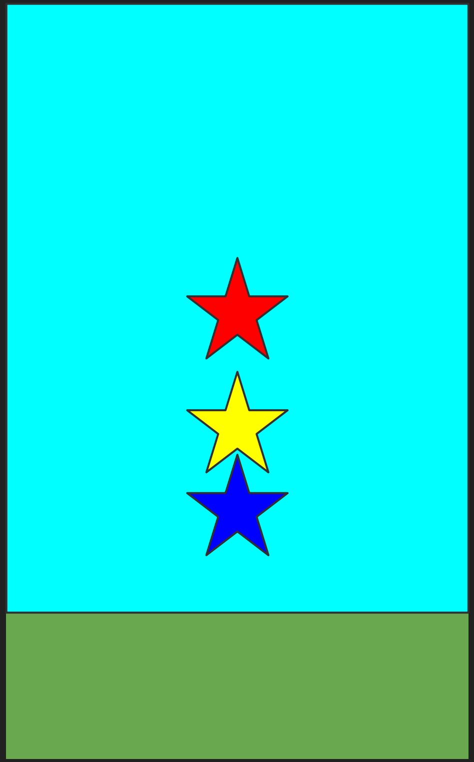


The role of the atmosphere on spectroscopy

The atmosphere acts like a prism. This is called “atmospheric dispersion”.

Many instruments have an “Atmospheric Dispersion Corrector” (ADC) to compensate.

The easy solution, though, is that you observe at “parallactic angle”. This means having the slit “vertical” wtr to the horizon.

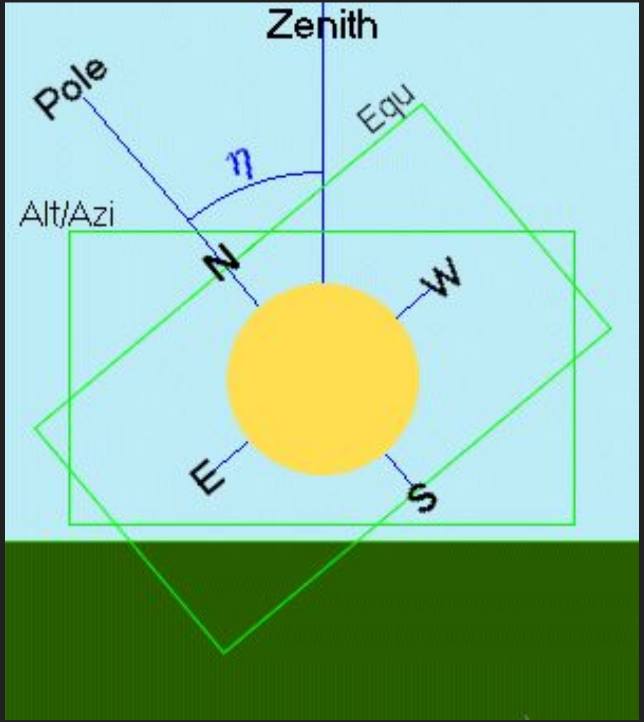


The parallactic angle

The “position angle” is the angle between the y-axis of your image and the celestial North.

The parallactic angle is the angle between the “vertical” going through your object and the North pole.

Like this, you have the “images” of the object formed along the slit and you make sure that all the flux gets to the spectrograph.



Advanced Techniques

Multi-Object: Why?

Observing objects “one-by-one” can be very time consuming.

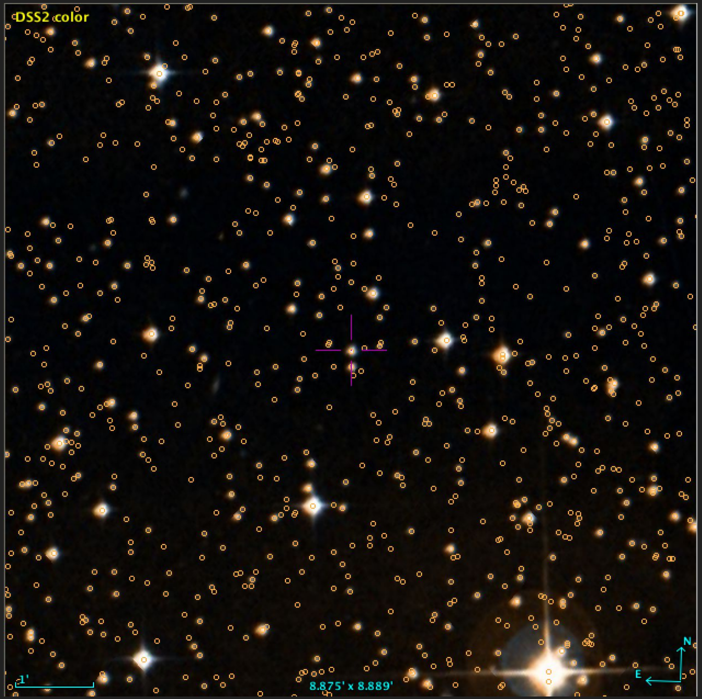
If the density of objects allows, it is a good idea to observe more than one target at a time.

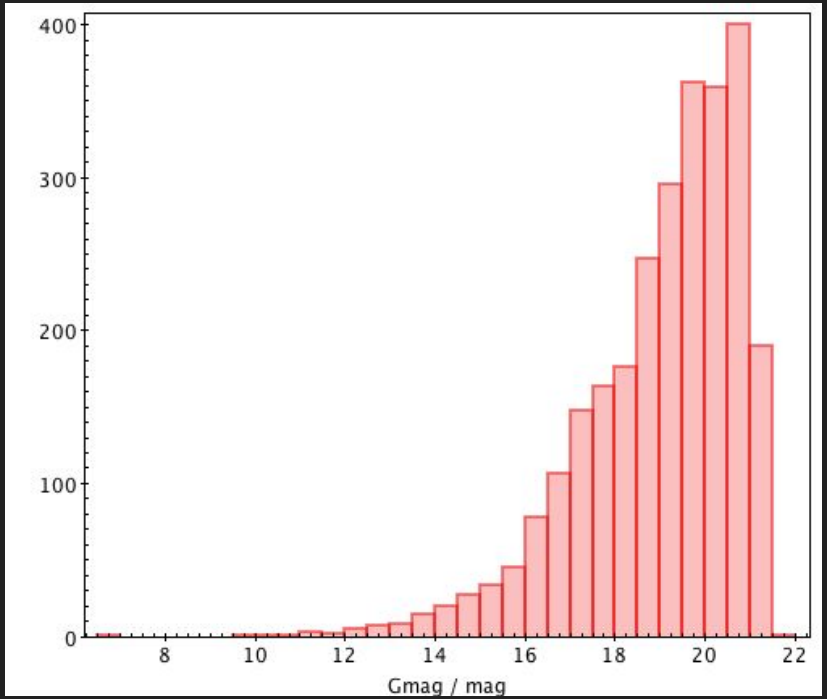
“Wide field spectroscopy” is one of the big “fashion” for large telescopes.

As usual, this does not come for free.

Every time one does MOS: there is a bias due to the selection of targets.

The T Pyx sky area and Gaia magnitudes





On the left, the filed around the star T Pyx; on the right the amount of objects detected by Gaia in this field of view. Not the increase of objects with magnitude.

MOS Masks

Metallic masks which are drilled to let light of some objects to the spectrograph.

Spectra are distributed across the field of view.

Careful: may have overlap between spectra!

Each mask only makes sense for a project.

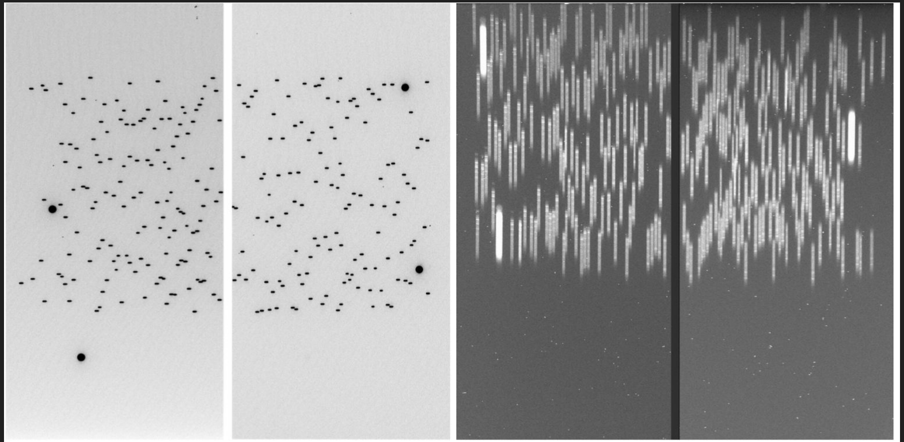


Figure 1. OSIRIS MOS spectroscopy: left) Slits as seen from the detector without adding dispersion elements in the optical path. Right) Result image of an observation showing the spectra of each object.

Vaz Cedillo et al. (2017)

Fibres

Optical fibres are an “efficient” way to carry light.

Is it better to have 25-50m of optical fibre or 2-3 mirrors?

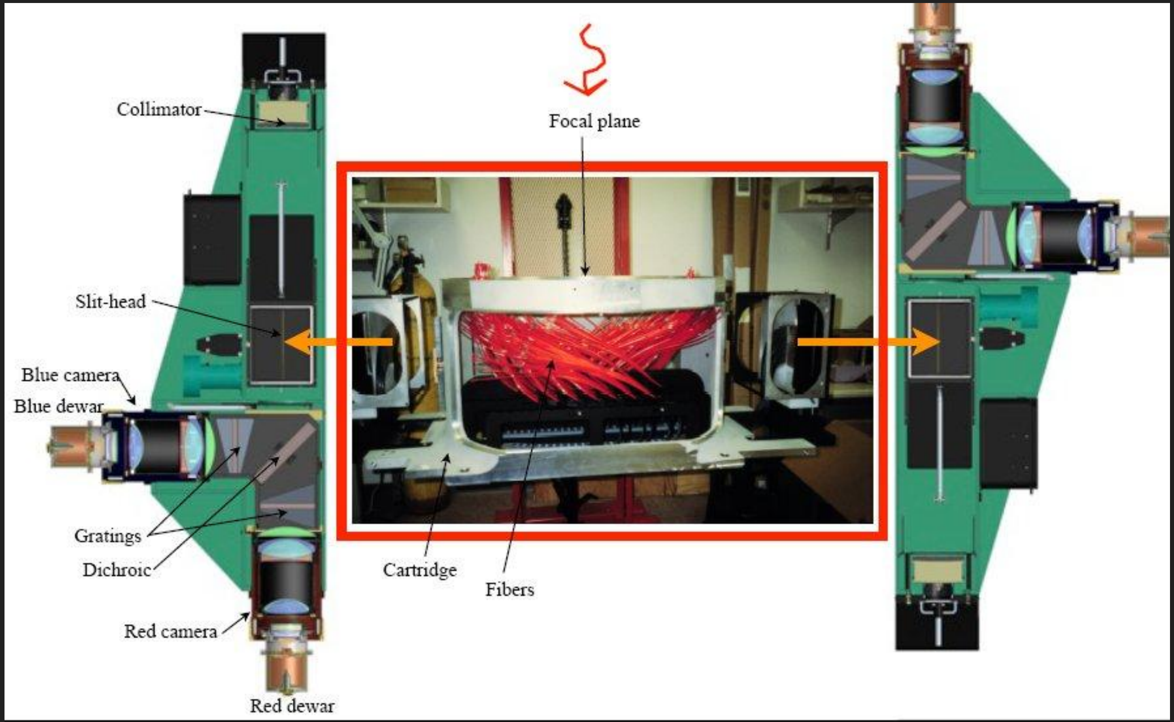
Inconvenients of optical fibres:

- Transmission depends on λ (poor in the blue)
- Change of F/# at entrance and exit (“focal ratio degradation”: at output, F/# is smaller)

Pros: high flexibility with respect to the masks

SDSS - Sloan Digital Sky Survey

SDSS is a super-famous survey which used a fiber-fed spectrograph ->



320 x 2 fibres

3” diameter

SDSS

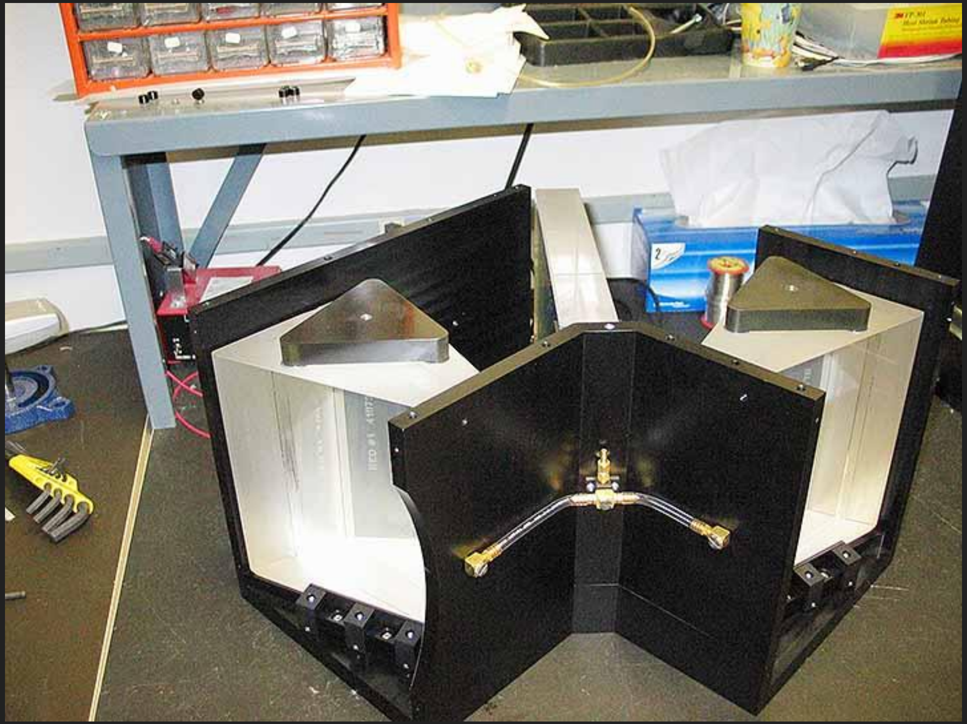
The fibres are located on a plate.

Each plate refers to a specific field.

SDSS

Two channels separated with a dichroic

R ~ 2000



Echelle spectrographs

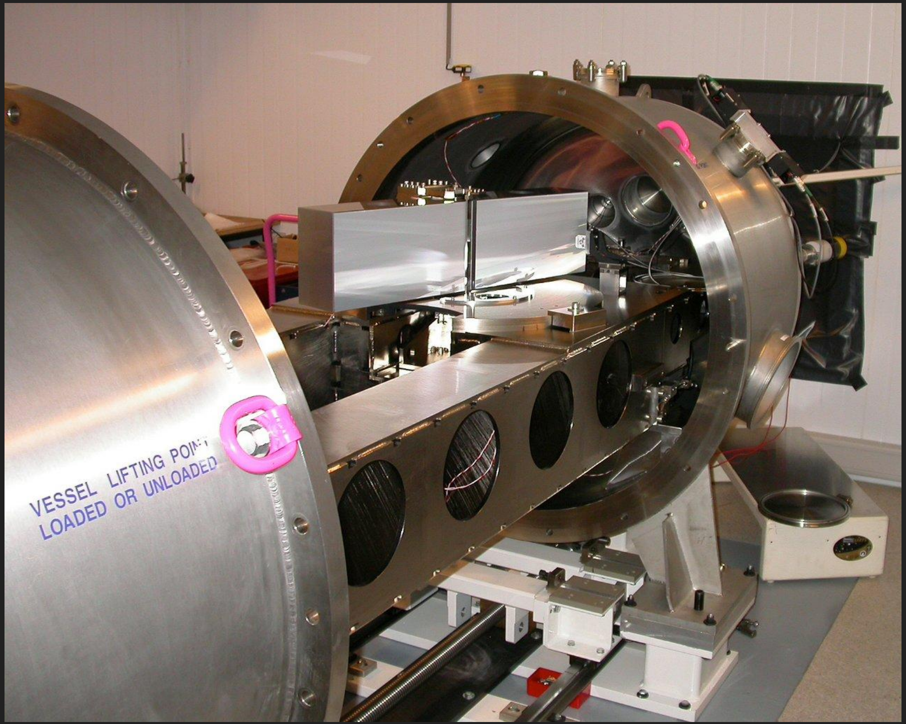
Use reflecting gratings at high orders.

Pros:

- High spectral resolution

Cons:

- “Short” long-slit
- Low efficiency
- Large gratings
- Small spectral range in the CCD
- Orders overlap… and are curved!



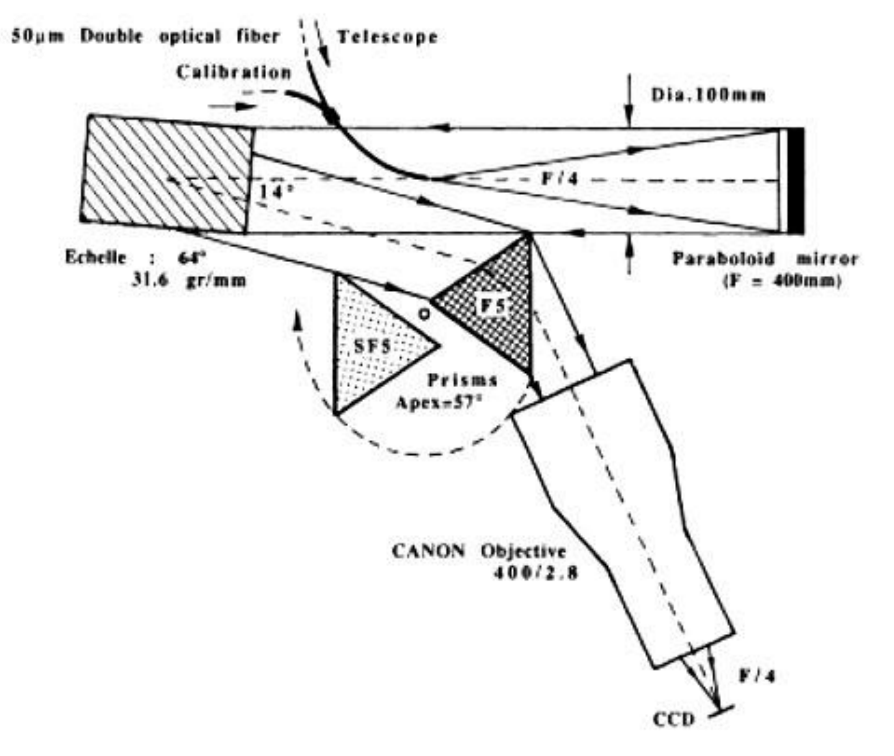
The HARPS grating
(measures 200mm x 800mm)

Cross-dispersion! :-)

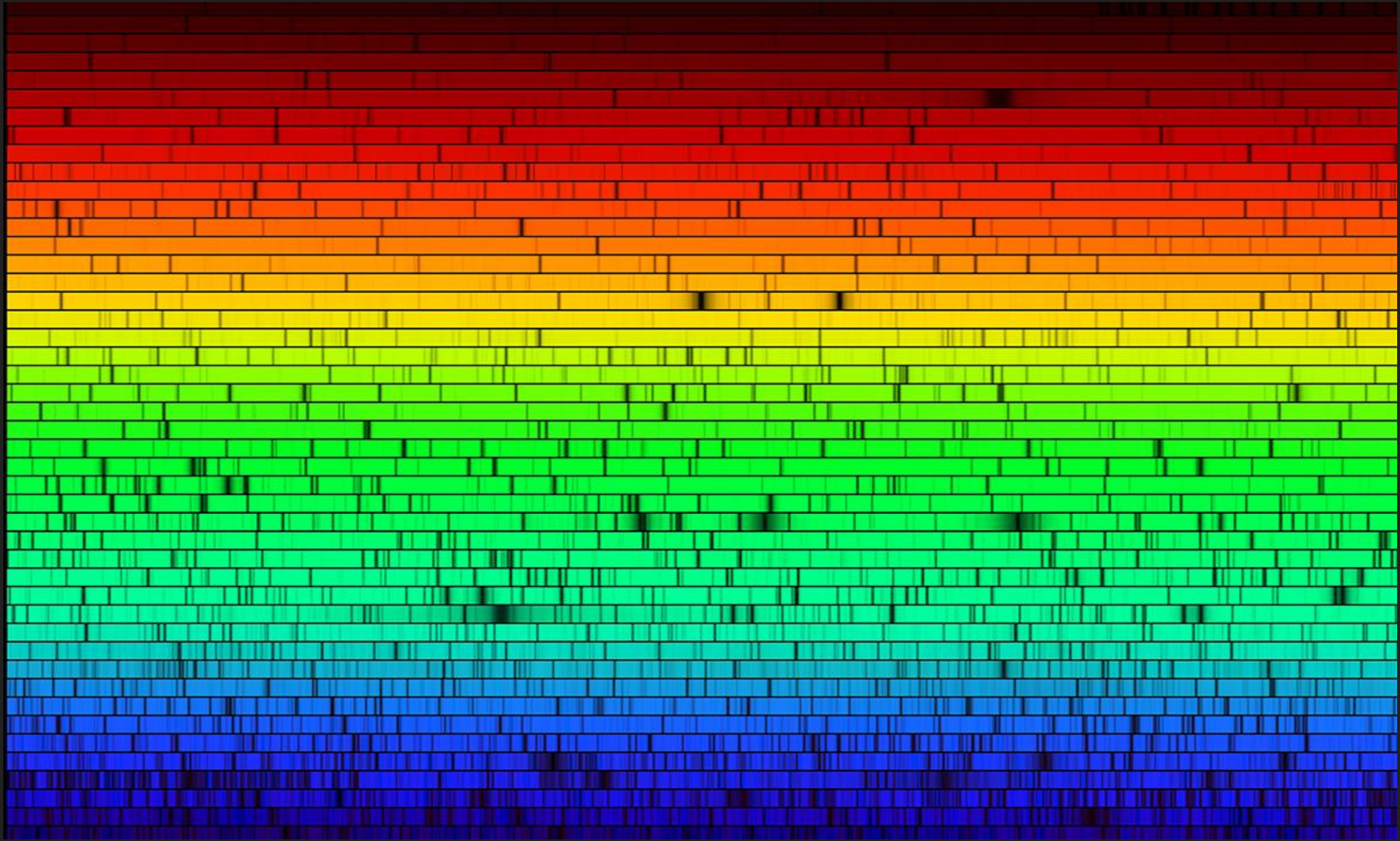
If you add another dispersing element PERPENDICULAR to the dispersion of the first one, you solve the issue.

Most (if not all) high resolution spectrographs work with this principle.

MUSICOS (@ LNA) =>



Optical layout



Fibre-fed echelle

Normally, two fibres: one for the science target and one for wavelength calibration (or sky subtraction)

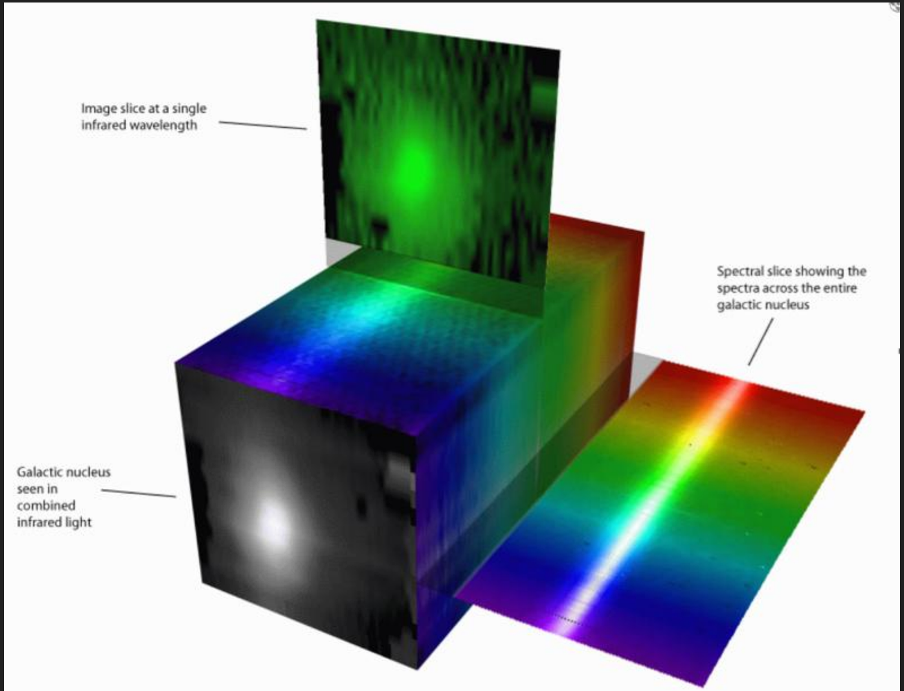
HARPS “first light” =>

Integral Field Spectroscopy (IFS)

What happens if you try to make spectra of each and every piece of sky in a small region?

This is what IFS is about.

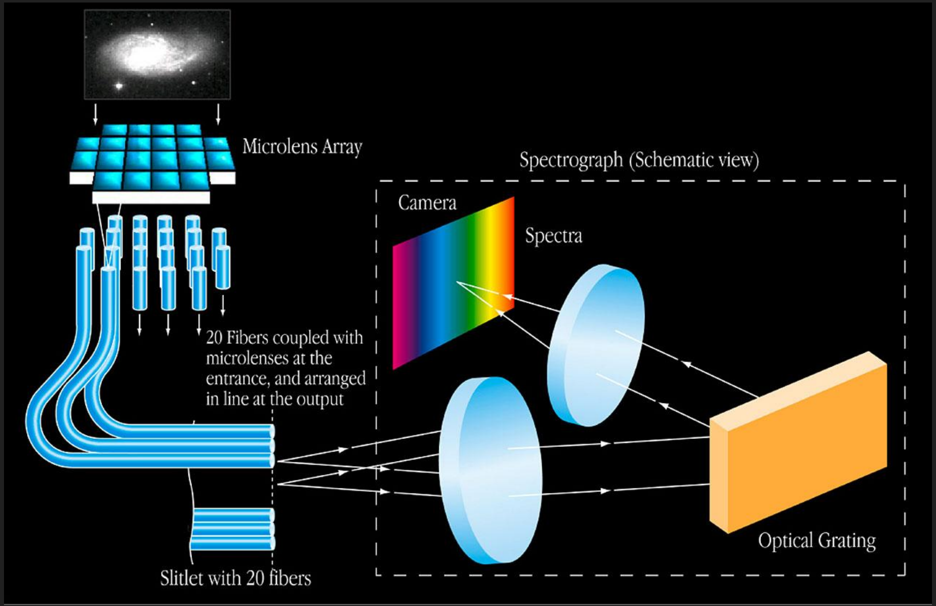
https://www.eso.org/public/teles-instr/technology/ifu/



Integral Field Spectroscopy - with fibres

You can do it putting many fibres together.

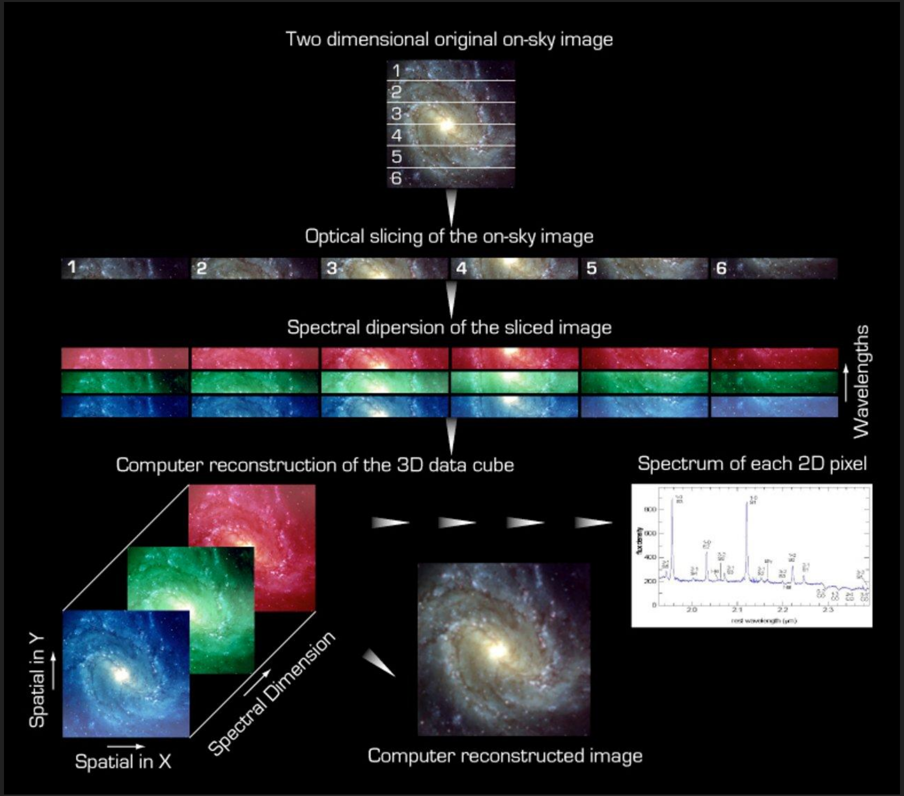
This is how many good and successful IFUs work (Gemini/GMOS, VLT/VIMOS, VLT/ARGUS, CAHA 3.6 / PMAS-PPAK, SDSS/MaNGA,...)



Integral Field Spectroscopy - with field slicer

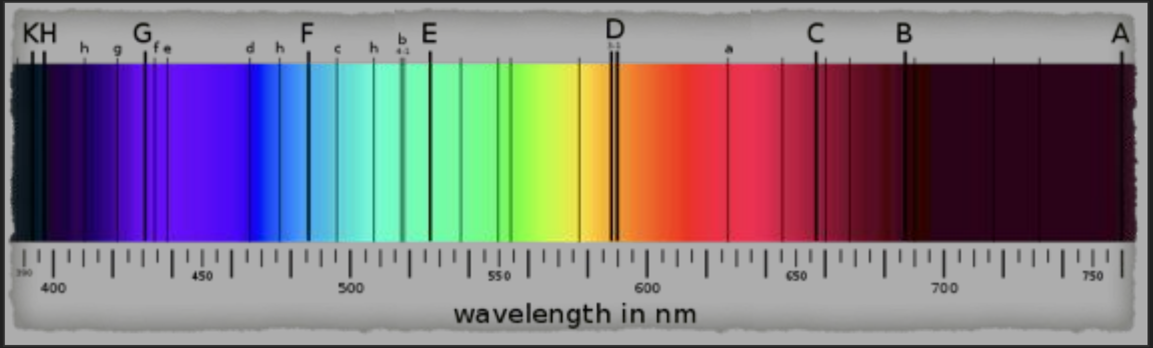
You slice up the field and send each slice to a spectrograph.

Less used (VLT/MUSE)



The Physics of Spectroscopy

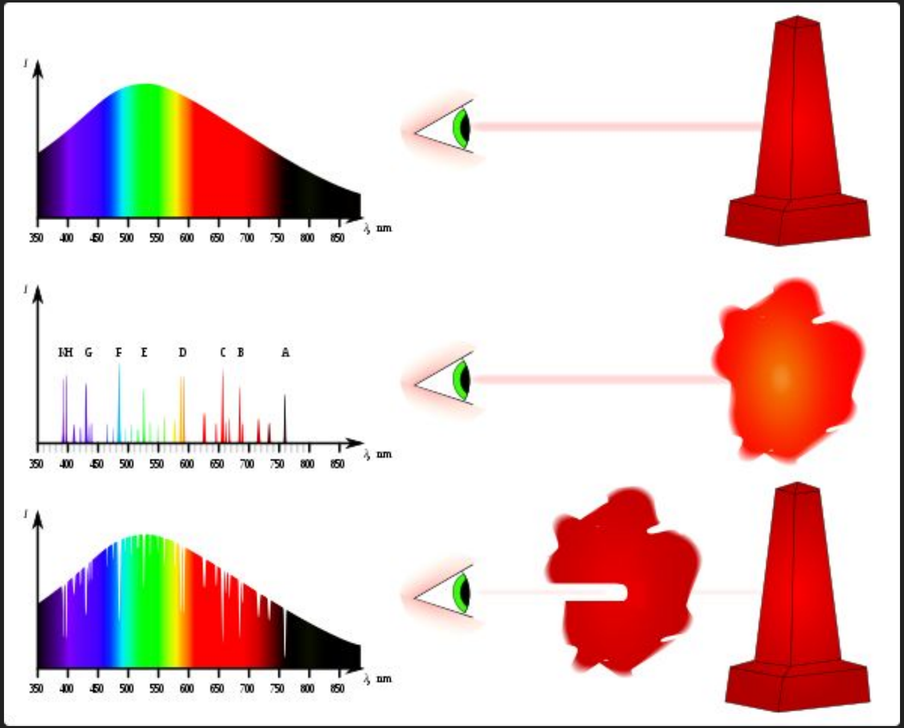
Fraunhofer: the Sun has "dark lines"



1787 - 1826

Kirkhoff Laws (Gustav Kirchhoff , 1824 - 1887)

1. A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths and thus produce a continuous spectrum.
2. A low-density gas excited to emit light will do so at specific wavelengths and this produces an emission spectrum.
3. If light composing a continuous spectrum passes through a cool, low-density gas, the result will be an absorption spectrum.



Continua

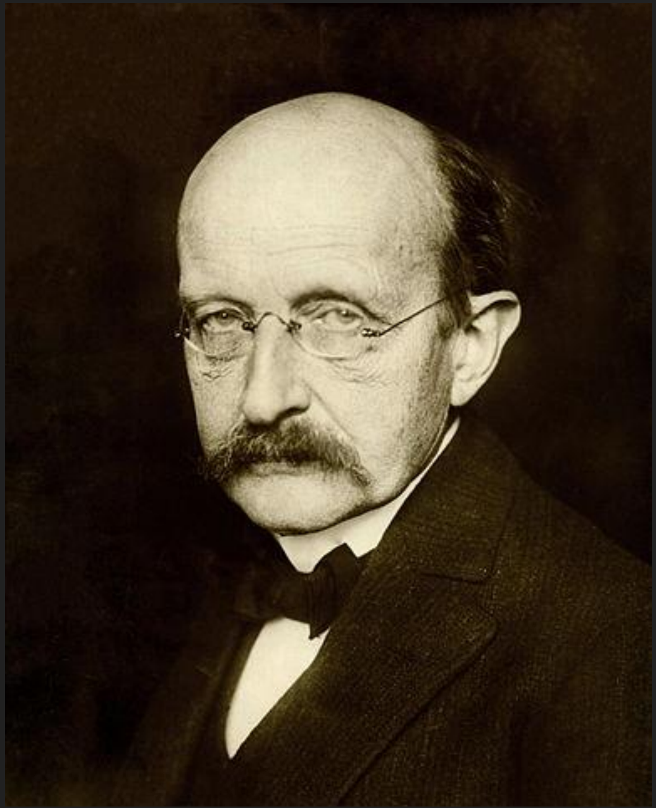
Max Karl Ernst Ludwig Plank

1858 - 1947

14 Dec 1900: Plank Postulate
“electromagnetic energy can only be emitted in quantised form” (i.e. E=hv)

Nobel Prize in Physics: 1918

https://en.wikipedia.org/wiki/Max_Planck



The Black Body

$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1},$$

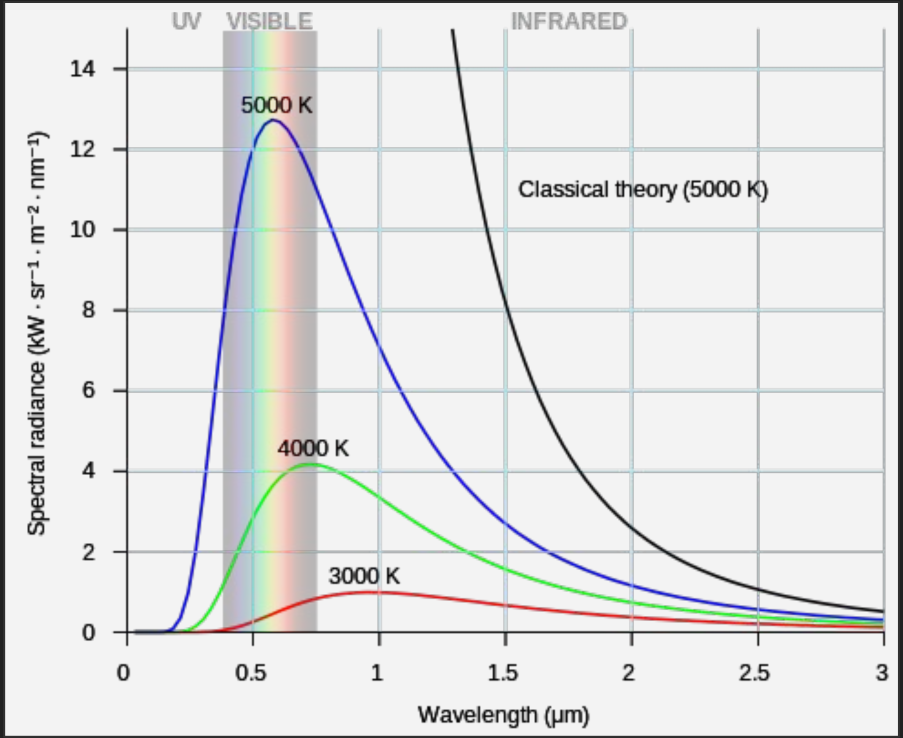
Wien's Displacement Law

$$\lambda_{\max} = \frac{b}{T},$$

Stefan-Boltzmann Law

$$L = \sigma T^4$$

https://en.wikipedia.org/wiki/Black-body_radiation



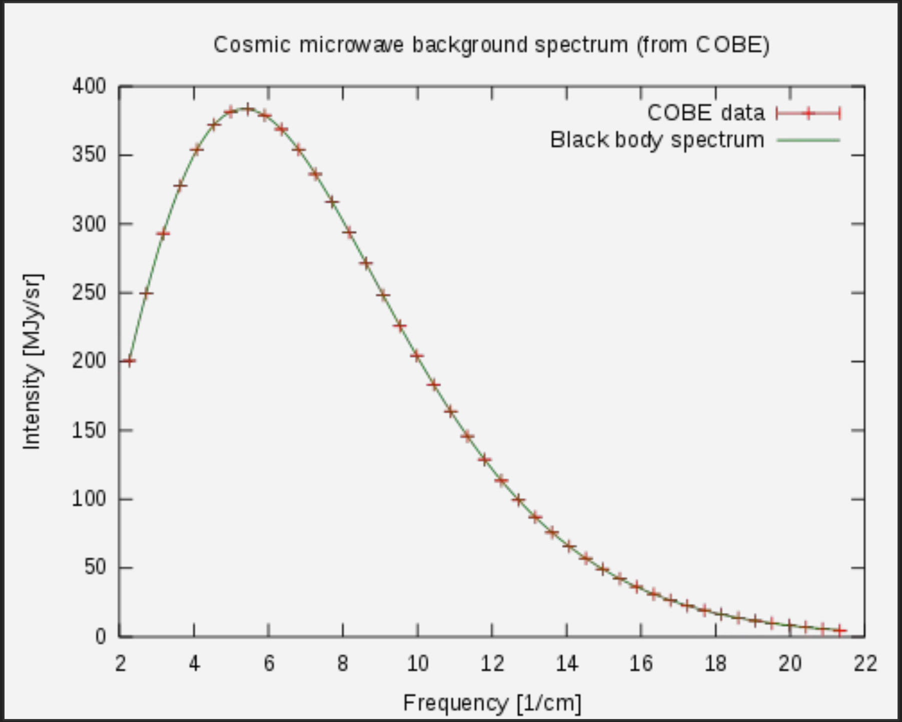
The Best Black Body Known So Far

The cosmic microwave background.

Discovered by Penzias & Wilson.

COBE measured that it is a perfect black body.

https://en.wikipedia.org/wiki/Cosmic_Background_Explorer



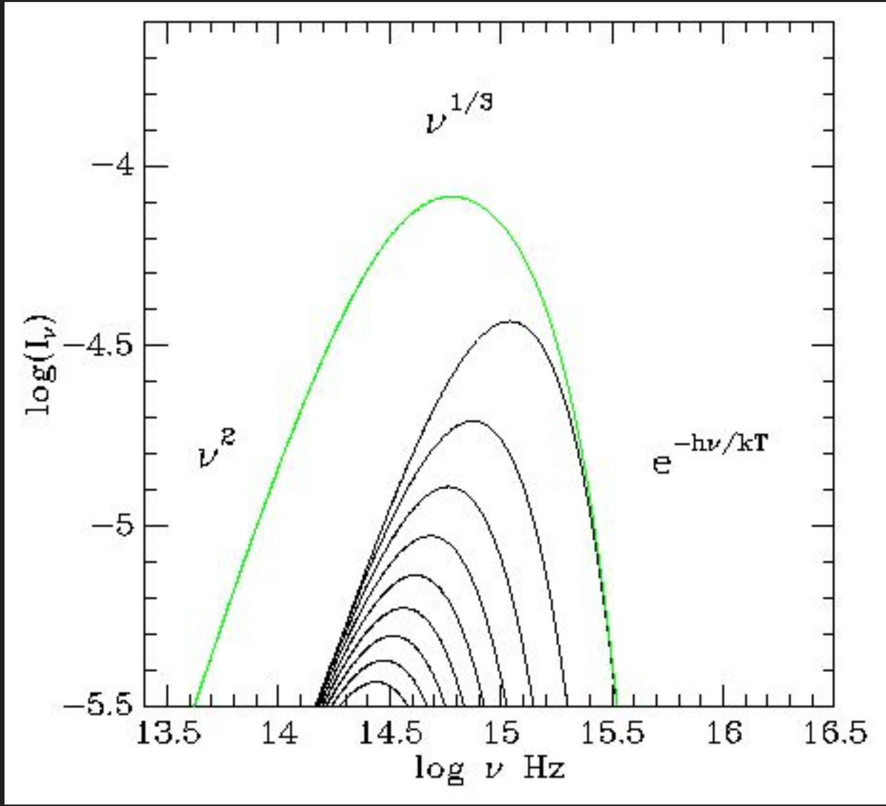
Accretion discs

Shakura & Sunyaev (1972)

$f \sim \lambda^n$

Accretion at all scales (Scaringi 2012)

http://www.astro.utu.fi/~cflynn/astroII/l6.html

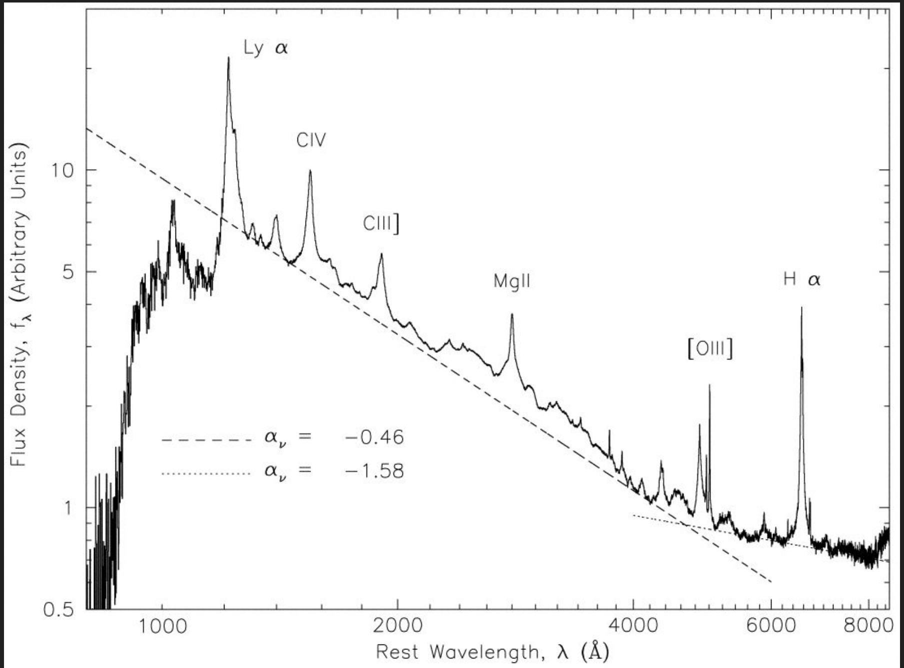


Quasars

Active Galactic Nuclei

Accretion on a supermassive black hole.

Vanden Berk et al. (2001) ->



Lines

The Hydrogen Atom

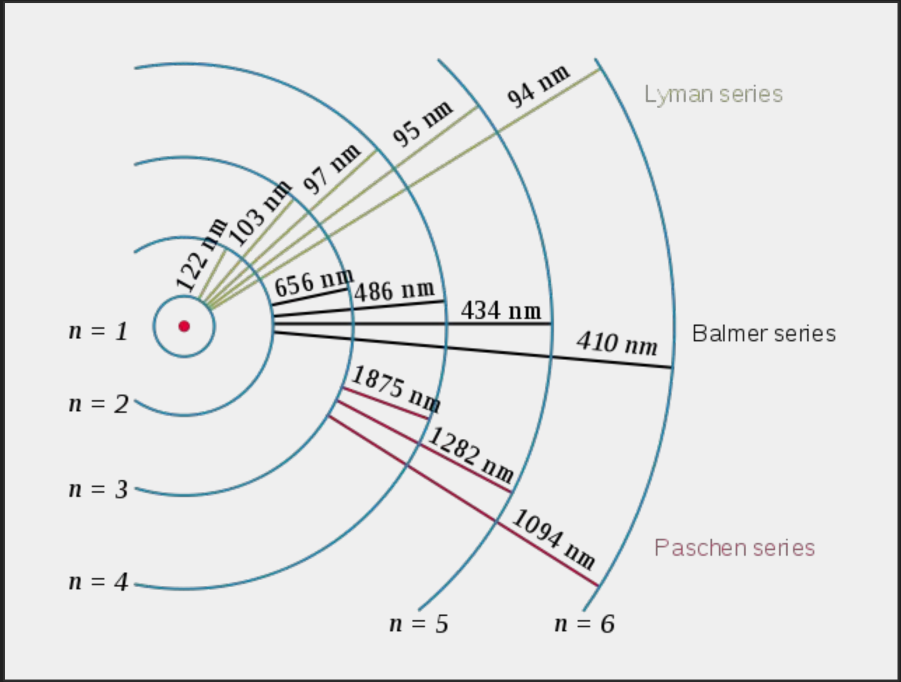
Bohr

One proton and one electron.

The electron can orbit only in given energy states (“orbitals”)

$$\frac{1}{\lambda} = Z^2 R_\infty \left(\frac{1}{{n_1}^2} - \frac{1}{{n_2}^2} \right)$$

Rydberg formula Rinf ~ 10^7 m^{-1}



Rydberg

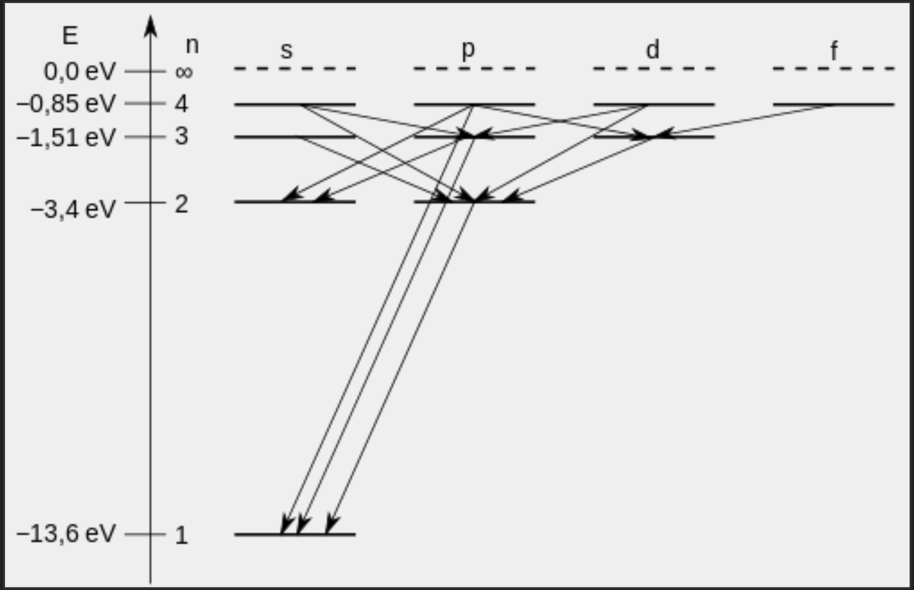
$$R_\infty = \frac{m_\mathrm{e} e^4}{8\varepsilon_0^2 h^3 c} = 10\,973\,731.568\,508\,(65)\,\mathrm{m}^{-1}$$

$$1\,\mathrm{Ry} \equiv hcR_\infty = \frac{m_\mathrm{e} e^4}{8\varepsilon_0^2 h^2} = 13.605\,693\,009(84)\,\mathrm{eV} \approx 2.179 \times 10^{-18}\,\mathrm{J}.$$

Grotrian Diagrams

Show the transitions that are possible in an atom

The best friend of a spectroscopist

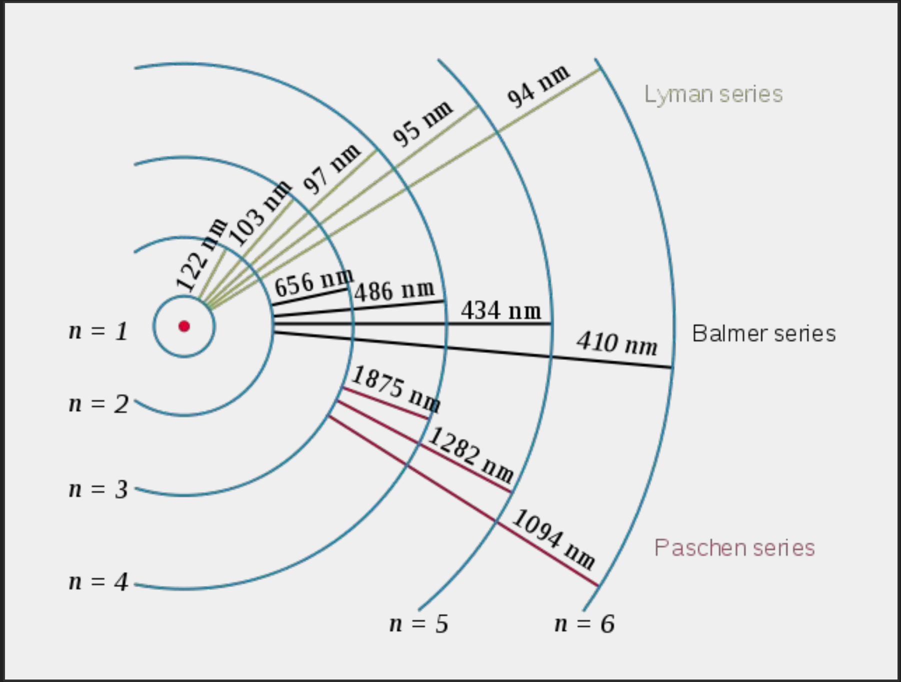


The Balmer series

It would not be such a special one if it was not that it is the one with lines in the visible.

It is the series where the electrons are “falling” to the n=2 orbital.

It is denoted by H and a greek letter.



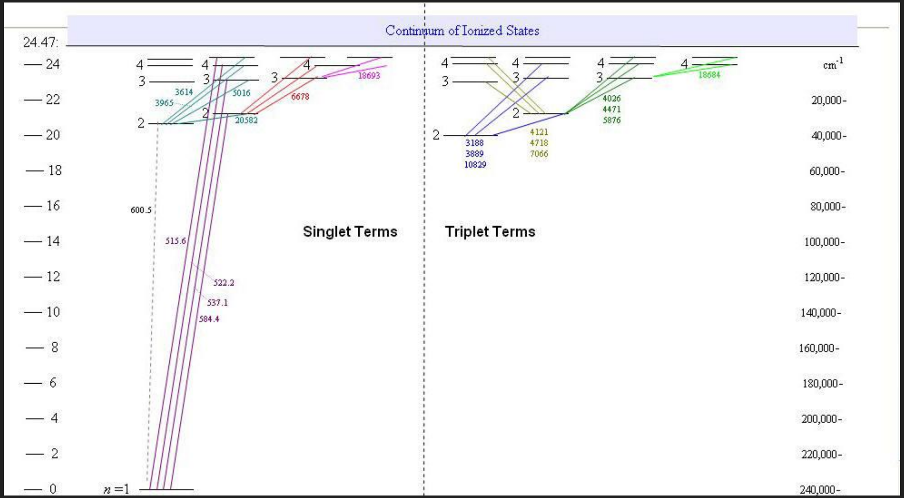
Any other atom (or molecule)

Are the energy level of He the same as H but double?

The “interaction factor” makes things more complicated.

What about molecules?

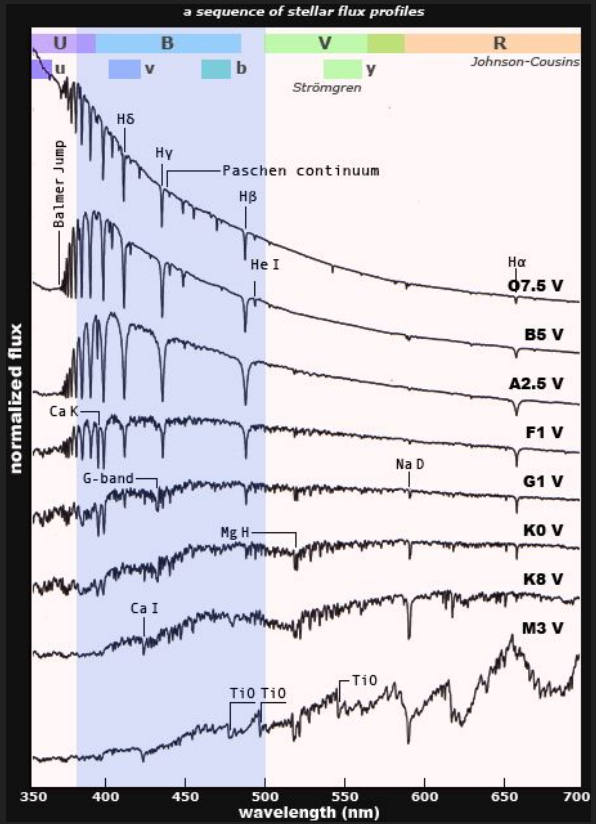
Not only they have electrons to excite but a whole structure which can rotate or oscillate!



Stellar atmospheres

Radiative transfer equation

A stellar spectrum is the result of “seeing” a blackbody through the atmosphere of a star.



https://www.handprint.com/ASTRO/specclass.htm

What makes lines large (Carrol & Ostlie, Section9.4)

- Natural broadening
  - Follows from Heisenberg's uncertainty principle: $\Delta E \sim h / \Delta t$
  - $\Delta\lambda = (\lambda^2 / 2\pi c) (1 / \Delta t_i + 1 / \Delta t_f)$
- Doppler broadening
  - In thermal equilibrium the atoms follow a Maxwell-Boltzmann distribution; the most probable speed is $v_{mp} = \mathrm{sqrt}(2kT / m)$
  - $\Delta\lambda = (2\lambda / c)\ \mathrm{sqrt}(2kT / m)$
- Pressure (and collisional) broadening
- Instrument
  - Similar to the psf for an image

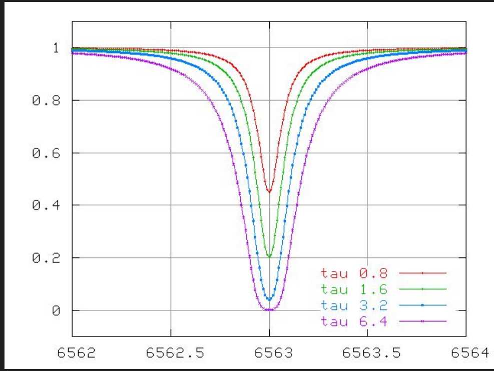
The Voigt Profile and the Curve of Growth

- Lines tend to have Gaussian cores BUT Lorenzian “wings”

https://en.wikipedia.org/wiki/Spectral_line_shape

- The equivalent width vs. the electron density is called “curve of growth”

http://spiff.rit.edu/classes/phys440/lectures/curve/curve.html



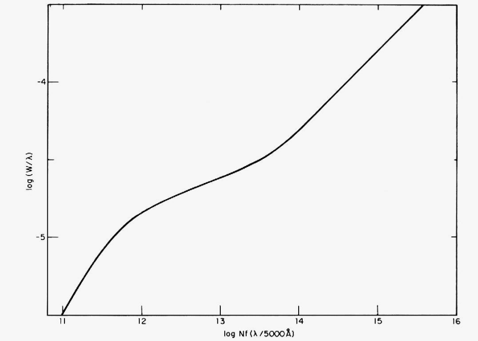
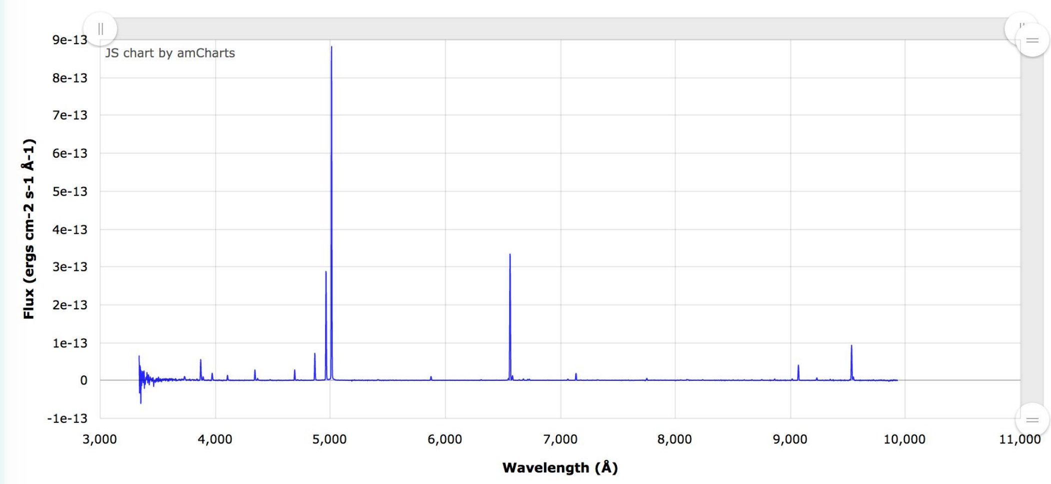
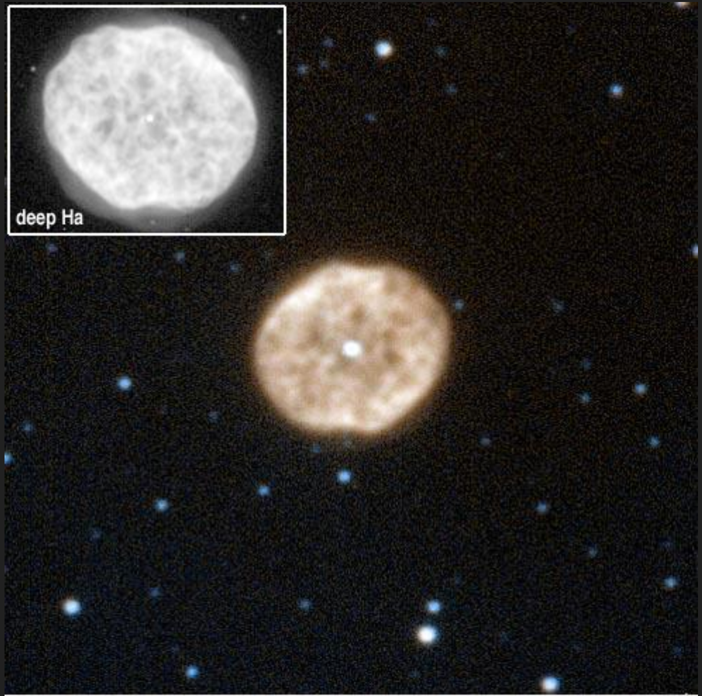


Figure 9.22 A general curve of growth for the Sun. (Figure from Aller, *Atoms, Stars, and Nebulae*, Revised Edition, Harvard University Press, Cambridge, MA, 1971.)

Emission lines (Planetary Nebulae)



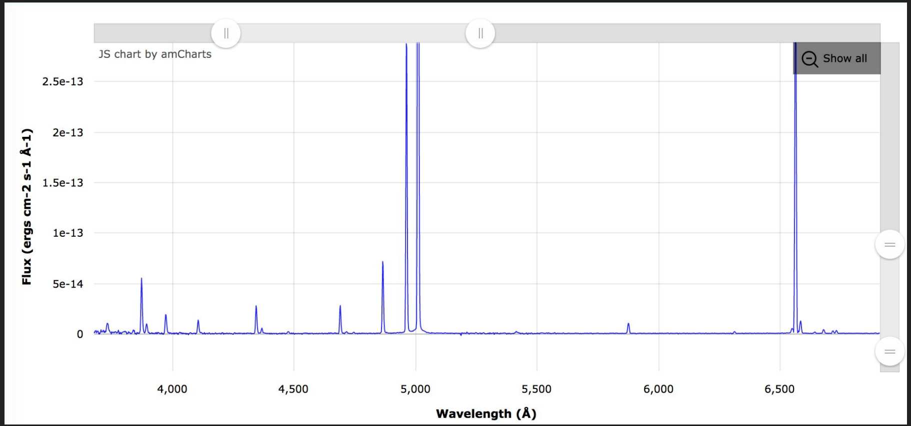


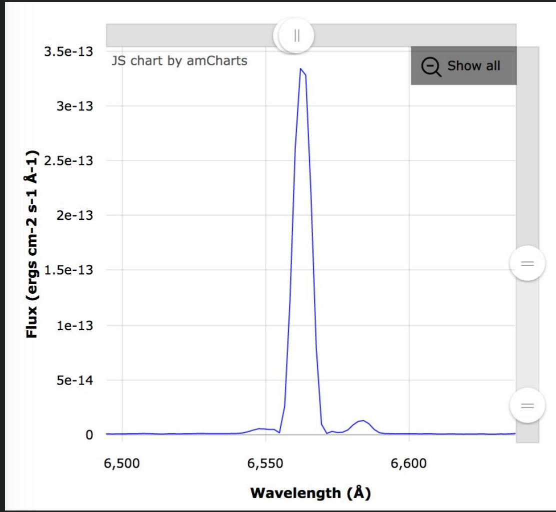
NGC 1501 G144.5+06.5 04:07.0 +60:55:00, R:G:B=log(Ha+[NII]), both, log[OIII]
"The IAC morphological catalog of northern galactic planetary nebulae"
A. Manchado, M.A. Guerrero, L. Stanghellini, M. Serra-Ricart, 1996, ed. IAC
inset: Jay Gallagher (U. Wisconsin)/WIYN/NOAO/NSF, www.noao.edu/image_gallery/html/im0034.html

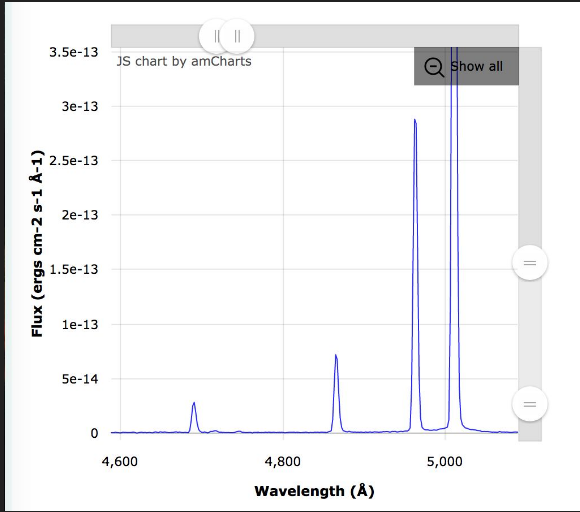
NGC 1501

https://web.williams.edu/Astronomy/research/PN/nebulae/

PNe lines


JS chart by amCharts
Show all
Flux (ergs cm-2 s-1 Å-1)
2.5e-13
2e-13
1.5e-13
1e-13
5e-14
0
4,000
4,500
5,000
5,500
6,000
6,500
Wavelength (Å)

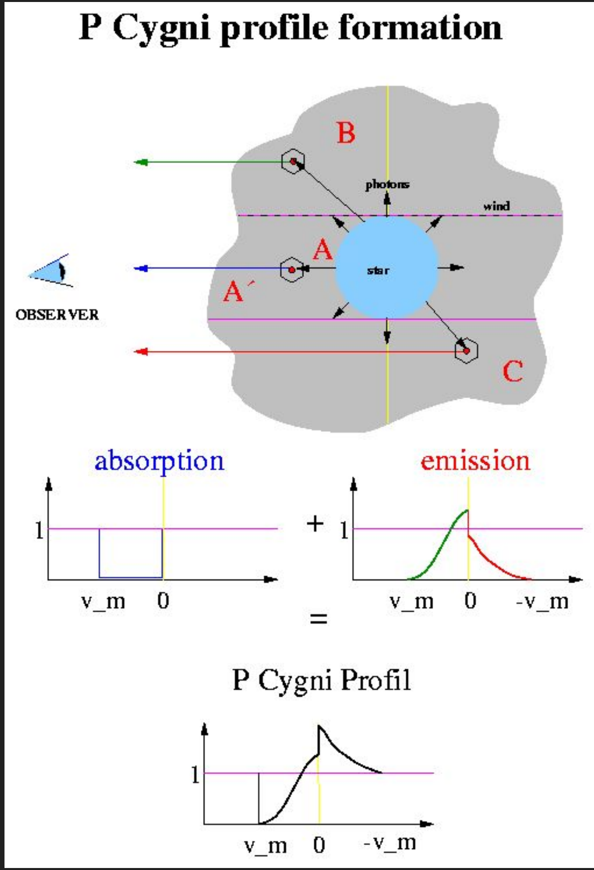

JS chart by amCharts
Show all
Flux (ergs cm-2 s-1 Å-1)
3.5e-13
3e-13
2.5e-13
2e-13
1.5e-13
1e-13
5e-14
0
6,500
6,550
6,600
Wavelength (Å)


JS chart by amCharts
Show all
Flux (ergs cm-2 s-1 Å-1)
3.5e-13
3e-13
2.5e-13
2e-13
1.5e-13
1e-13
5e-14
0
4,600
4,800
5,000
Wavelength (Å)

P Cyg

Emission and absorption playing together.

Present in all expanding atmospheres (LBVs, novae, supernovae,...)



Lyman Alpha Forest

https://youtu.be/6Bn7Ka0Tjjw

Measurables

Centroid

As easy as it may sound.

The centroid gives information on the nature of the line (well, in most cases, at least).

Series of observations may be used to see the centroid move.

Doing science with centroids

Planets (Mayor & Queloz 199?)

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

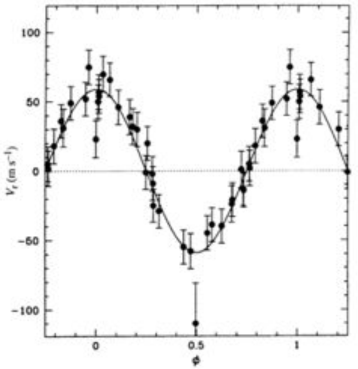


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

Quasars (Schmidt 1963)

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

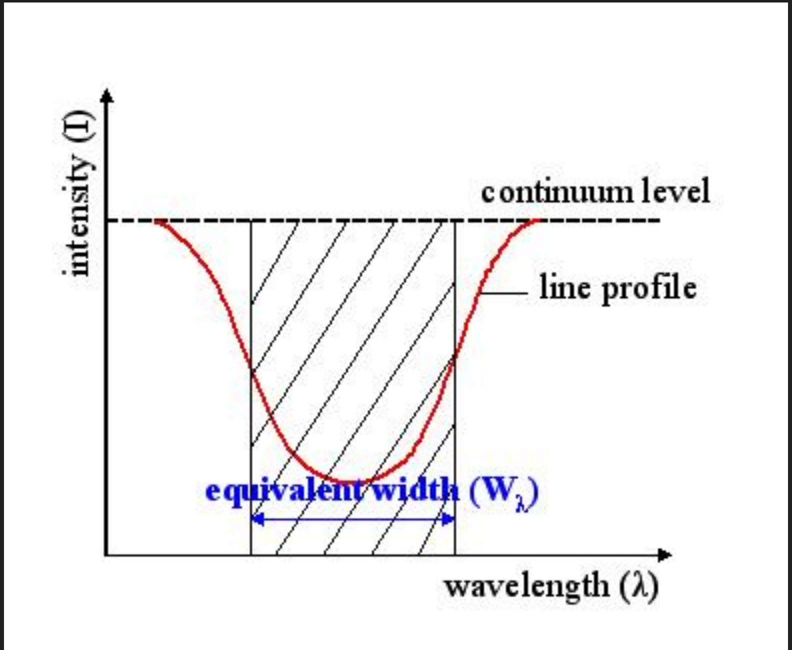
Table 1. Wave-lengths and Identifications

λ	$\lambda/1{\cdot}158$	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hε
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

Equivalent Width

The EW is the width that a line **would** have if it was rectangular and its height was the height of the continuum.

$$W_\lambda = \int (1 - F_\lambda / F_0) d\lambda.$$



https://en.wikipedia.org/wiki/Equivalent_width