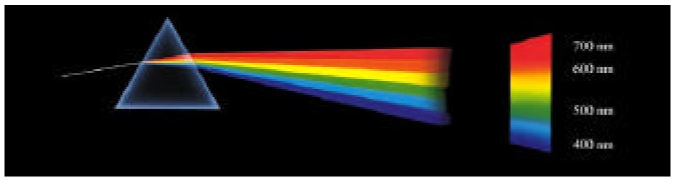
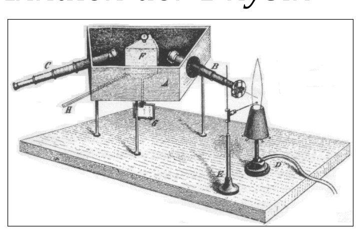
Spectroscopy in Astronomy



History

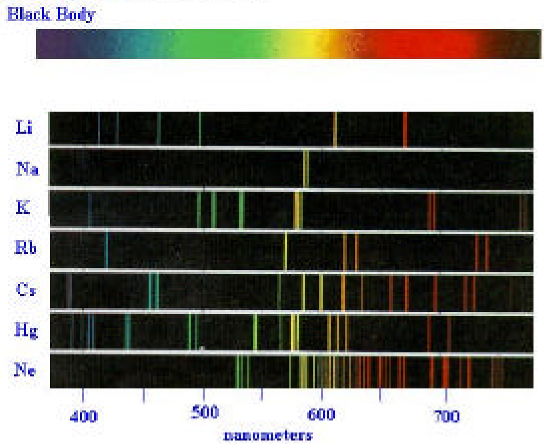
- 1814 German optician Joseph von Fraunhofer → sun with 600+ spectral lines; now we know more than 3000 lines
- 1860 German chemists Gustav Kirchhoff and Robert W. Bunsen → **Chemical Analysis by Observation of Spectra** *Annalen der Physik und der Chemie* (Poggendorff), 1860, 110, 161-189



http://dbhs.wvusd.k12.ca.us/Chem-History/Kirchhoff-Bunsen-1860.html

Black Body and Line Spectra

http://www.chem.uidaho.edu/~honors/spectra.html



- Every element has its own characteristic line pattern➔ **spectral analysis**

Solar Spectrum with absorption lines

Notice that the dark lines in the solar spectrum correspond to the emission lines of the various elements. This is because atoms can absorb or emitt at the same wavelengths.

http://www.chem.uidaho.edu/~honors/spectra.html

Application of Spectral Analysis

Combined with laboratory study, to estimate

→ composition

→ abundance of elements

→ temperature, density, pressure

→ motion (velocity and rotation) (Doppler effect)

→ magnetic field (Zeeman effect)

A picture is worth a thousand words….

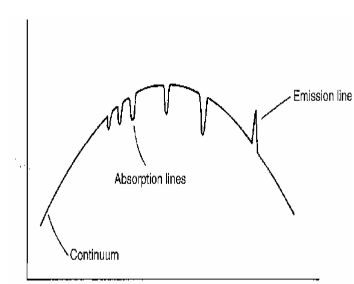
a spectrum is worth a thousand pictures!

Types of Spectra

- **Continual spectra** --- a wide range of colors (wavelengths)
- Discrete spectra --- bright or dark lines at distinct wavelengths

Emission spectra

Absorption spectra



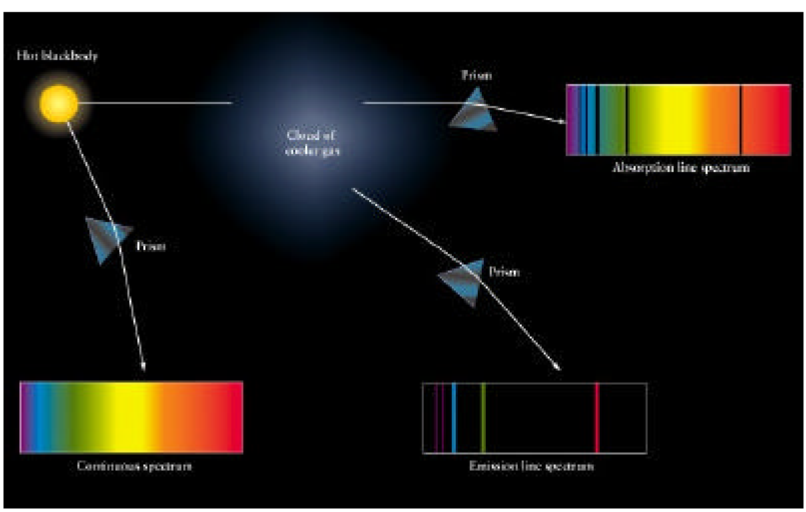
Kirchhoff's Laws

1860s by Gustav Kirchhoff

- **連續光譜**: A hot object or a hot, dense gas produces a continuous spectrum --- a complete rainbow of colors without any spectral lines, e.g., the blackbody radiation.
- **發射光譜**: A hot, rarefied gas produces an emission line spectrum --- a series of bright spectral lines against a dark background
- **吸收光譜**: A cool gas in front of a continuous source of light produces an absorption line spectrum --- a series of dark spectral lines among the colors of the rainbow

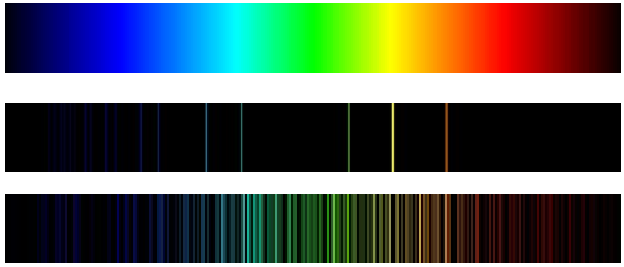
Kirchhoff's Laws

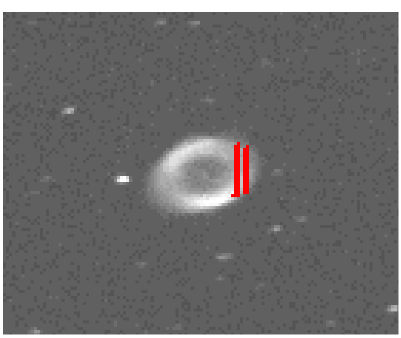
Absorption spectrum seen



Continuous spectrum seen

Emission spectrum seen

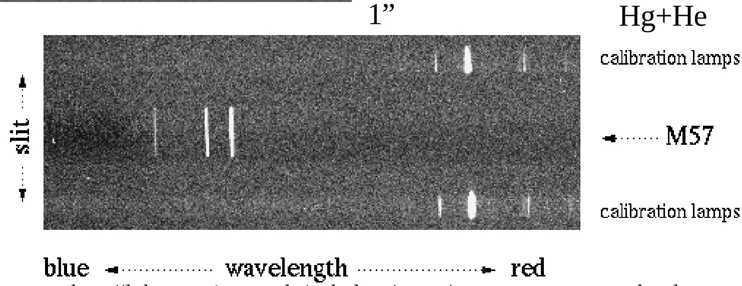




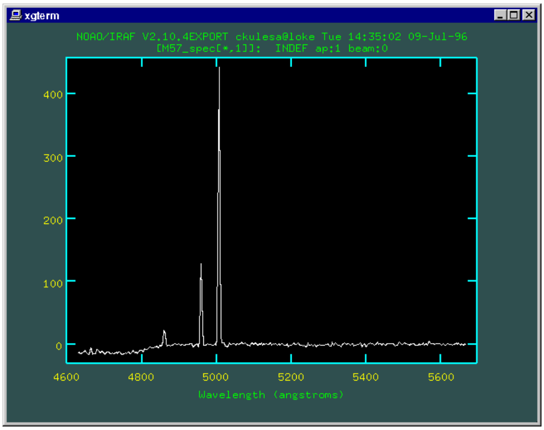
An example -----
Ring Nebula（環狀星雲， M57）：
a planetary nebula

Slit = 8’ x 1”

Hg+He

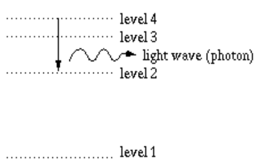


http://loke.as.arizona.edu/~ckulesa/camp/camp_spectroscopy.html



1-D spectrum shows little continuum, and a few emission lines

➔ **A line spectrum**



4861Å line from hydrogen n = 4 → 2 (called H_β line)
➔ gas is highly excited

4959Å and 5007Å doublet from twice-ionized oxygen, O++, or OIII in spectroscopic notation
➔ (oxygen) gas is ionized, with T > a few thousand K and density < $100/cm^3$

Spectroscopic Notation…

Ionization State

I ---- neutral atom, e.g., H I → H^0

II --- singly ionized atom, e.g., H II → H^+

III – doubly ionized atom, e.g., O III → O^{++}

….. and so on….e.g., Fe IIIXX

Peculiar Spectra

e (emission lines), p (peculiar, affected by magnetic fields), m (anomalous metal abundances)   e.g., B5 Ve

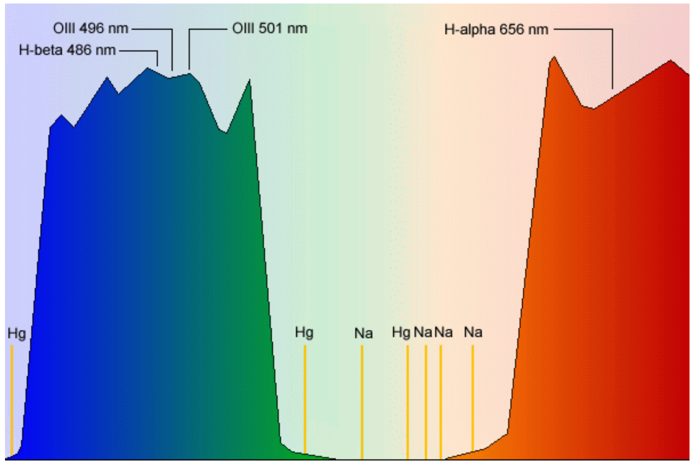
Spectroscopic Notation…(cont)

Forbidden Lines (with a pair of square brackets)
e.g., [O III], [N II]

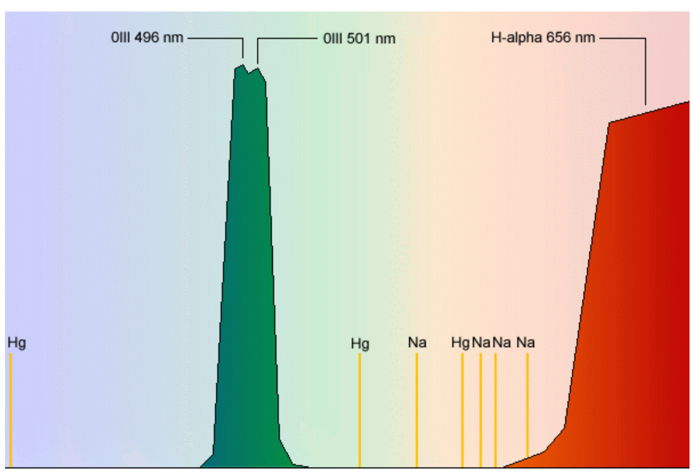
Semi-forbidden Lines (with a single bracket)
e.g., [OII

Allowed (regular) Lines (no bracket)
e.g., C IV

- Spectroscopy allows us to learn about the physical and chemical conditions, and important processes in distant celestial objects.
- Spectral AND spatial information at the same time
- One can observe nebulae like this even at a site with light pollution by using 'light-pollution filters'. How does it work?

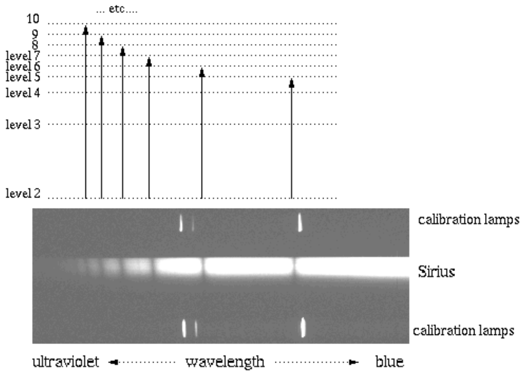


Example of the light transmission characteristics of a broadband light pollution filter. http://www.starizona.com/basics/filterl.html



Example of the light transmission characteristics of a narrowband nebula filter. http://www.starizona.com/basics/filtern.html

Another example --- Sirius （天狼星）： a hot A-type star at 10,000 K

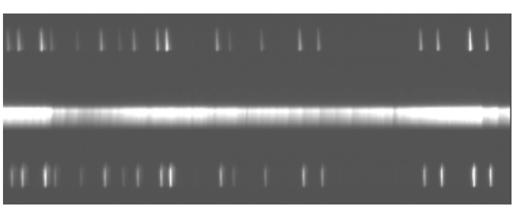


Spectral type OBAFGKML
hot → cool

Spectrum near 4000Å (blue): continuum plus a series of absorption lines → hydrogen Balmer lines

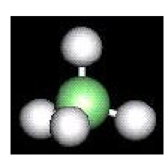
A-type stars have just the 'right' temperature to **show** prominent Balmer lines.

Yet another example ----- δ Virgo, a cool M-3 giant at 3,500 K

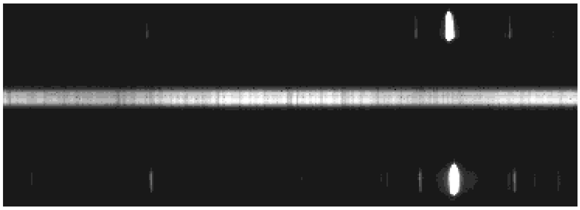


Spectrum near 6000Å (red): bright continuum at far left then drops off quickly to become a series of **bands**. These are from TiO (titanium oxide) molecules

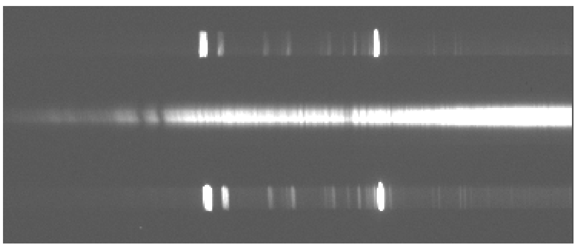
Atoms: electron energy levels
Molecules: additional rotational & vibrational levels
→ **complex spectra**



An example in between ----- Beta Bootes, a G-8 giant of 5,500K

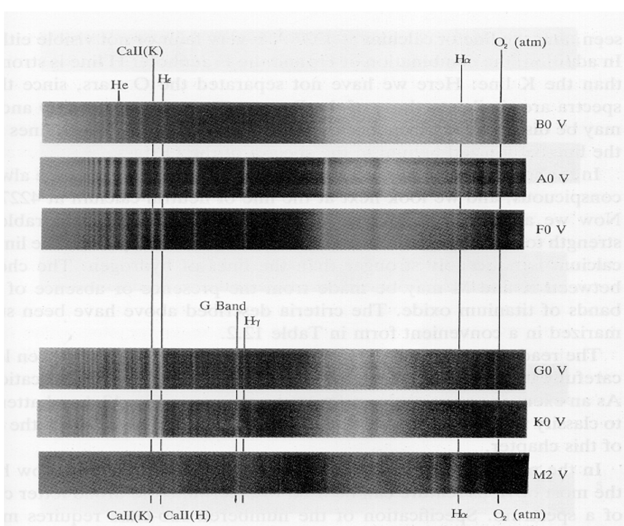


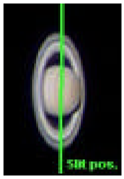
Spectrum near 5500Å (yellow): no molecules, but lots of lines (C, Fe, O, Mg, Ca, etc.)



Spectrum near 4000Å (blue): 2 dark lines at left due to CaII; H lines very weak

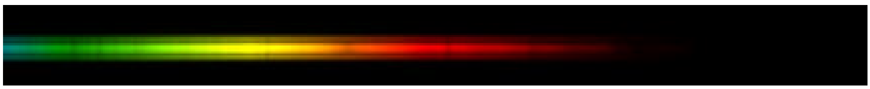
Stellar Spectral Classification





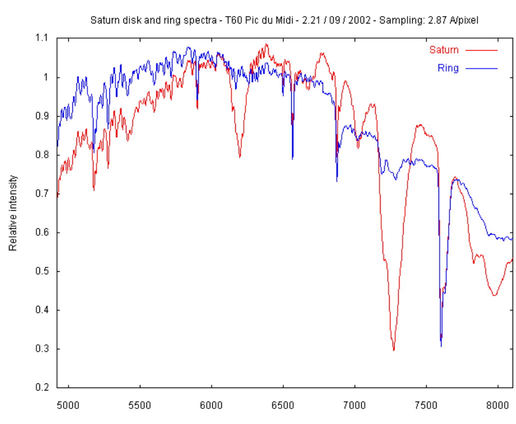
An example of spectroscopic science

simultaneous spectra of Saturn disk and rings between 4900 A and 8100Å



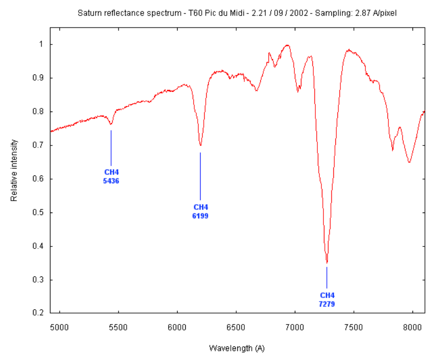
http://www.astrosurf.com/buil/us/mission2/mission2.htm#SPECTRUM%20OF%20PLANET%20SATURN

The rings spectral distribution is of a G2V stars, i.e. the Sun



Spectral and spatial information from the same spectral image

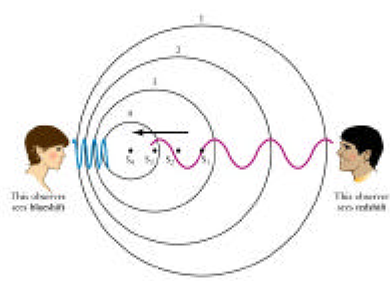
The ratio of the disk and the rings spectra
→ true spectral reflectance of Saturn



- Increased reflectance from blue to red
- Methane (CH_4) bands clearly identified

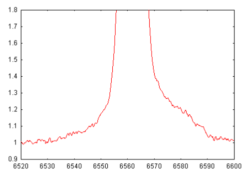
Doppler Effect --- Stellar Motions

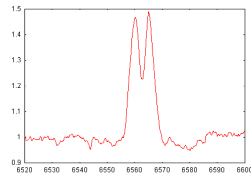
- Spin of a star
- Rotation of galaxies
- Hubble’s law on expanding universe
- ….

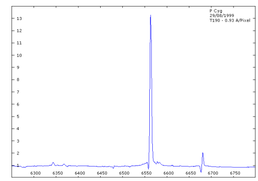


Q: *How does the spectrum of a giant star differ from that of a main-sequence star?*

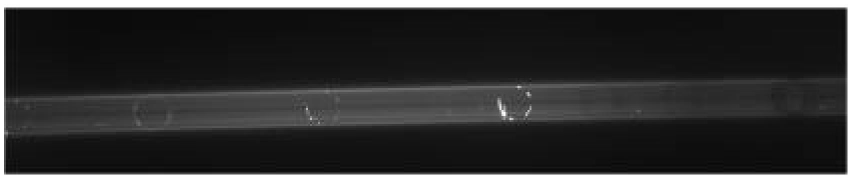
Line Profiles and Evolution



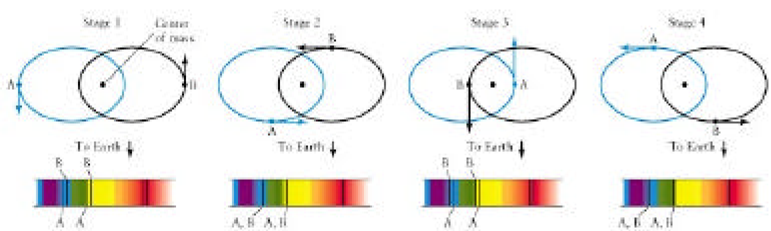


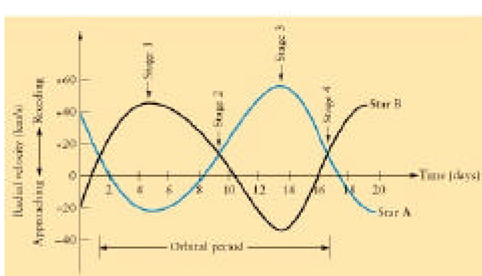


http://www.astrosurf.com/buil/us/bestar.htm



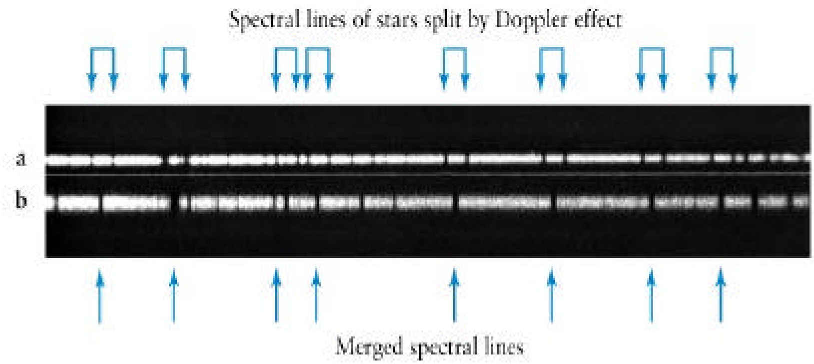
Spectral sequence during a solar eclipse http://www.astrosurf.com/buil/us/eclipse.htm





Spectroscopic binary

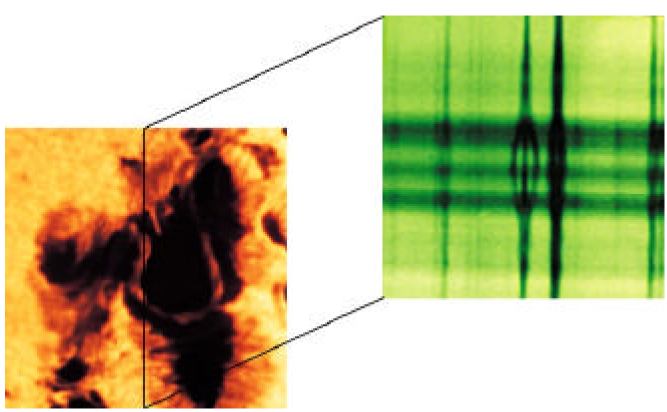
Radial-velocity curve

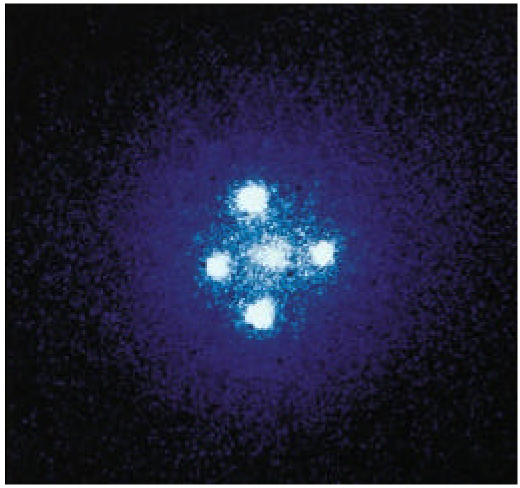


Double-lined spectroscopic binary

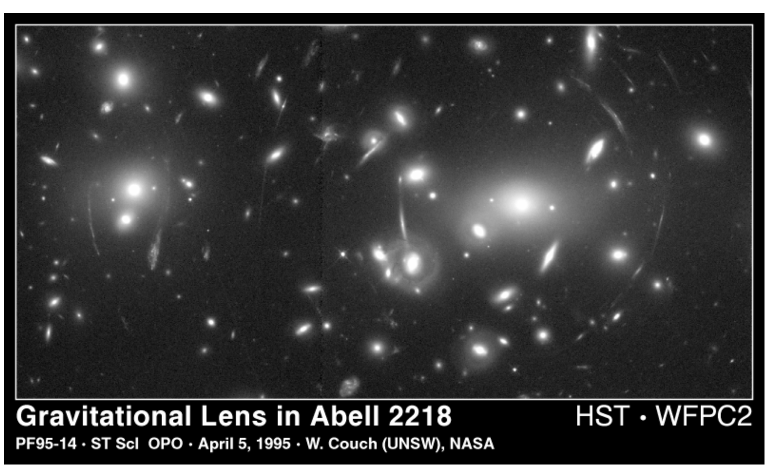
Zeeman Effect

Spectral lines split in a magnetic field

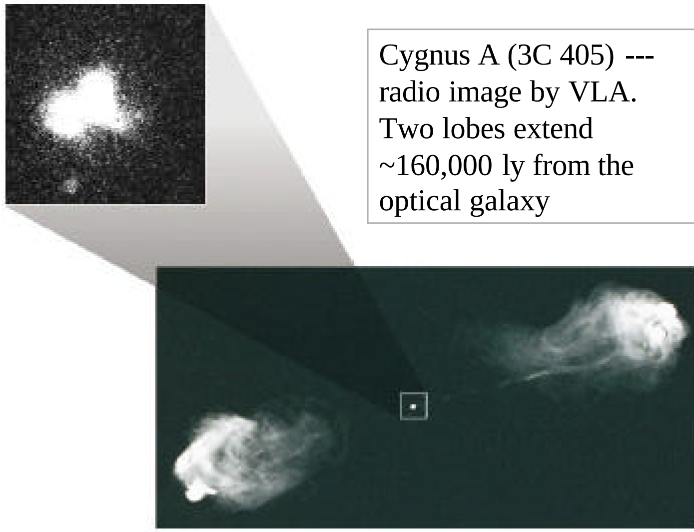




Einstein Cross by Hubble Space Telescope (HST), caused by gravitational lensing

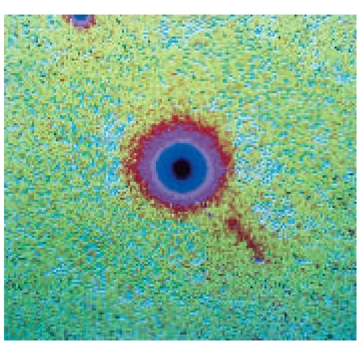


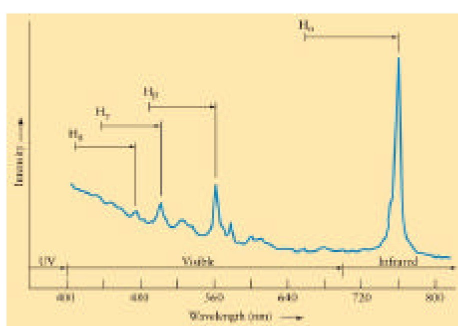
Cygnus A (3C 405) ---
radio image by VLA.
Two lobes extend
~160,000 ly from the
optical galaxy



Quasar (3C 273) ---
radio image with a jet

Spectral lines are highly redshifted
→ 15% speed of light!





Hubble expansion → 2 Gly away!

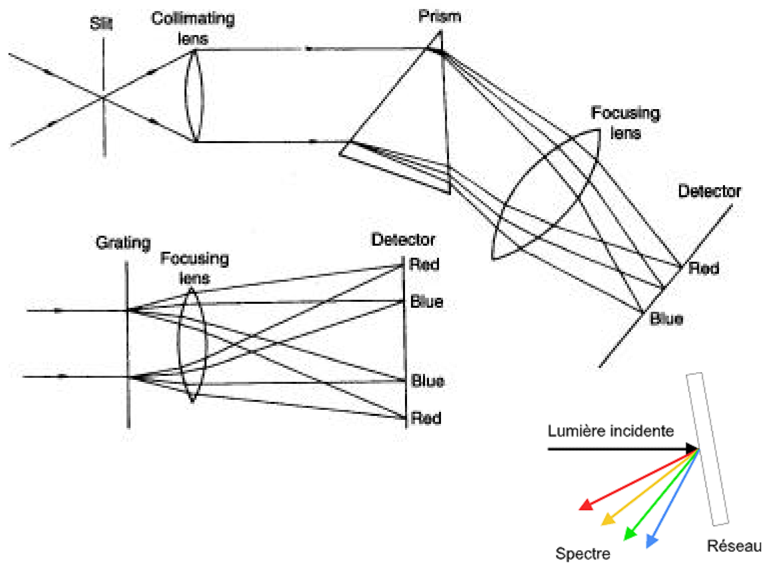
Noises

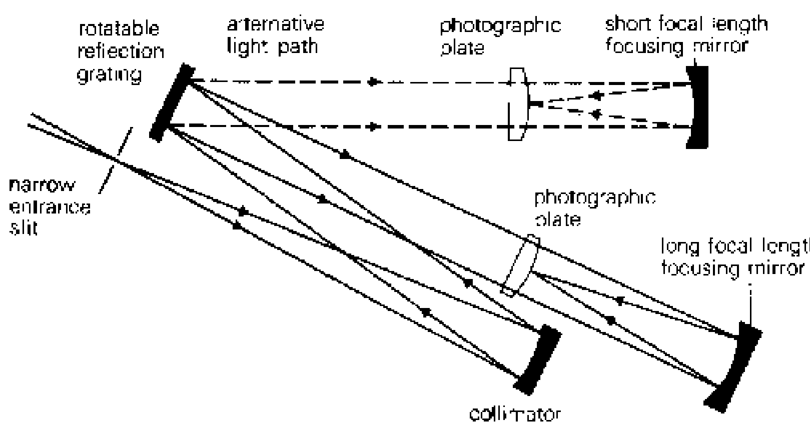
- **Photon (shot) noise** --- light arrives as discrete photon events → fluctuations in arrival rates
- **Thermal (Johnson or Nyquist) noise** --- generated in all resistors, from random nature of the motion of the charge carriers
- **Readout noise** --- errors introduced by stray capacitance in the (CCD) readout circuit

  ➔ $s^{2}_{total} = S_i\, s^{2}_{i}$

Spectrometer

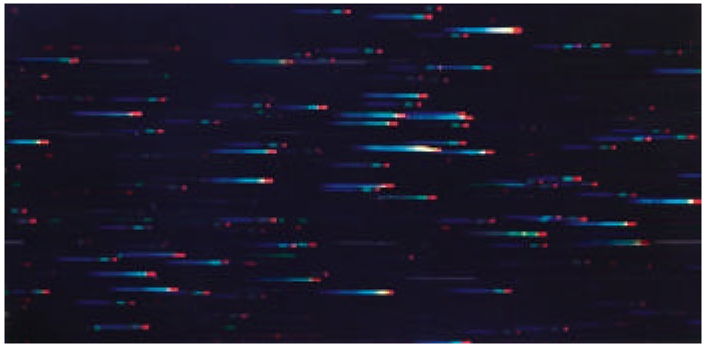
- **Entrance Aperture** --- usually smaller than seeing disk, or with a slit
- **Collimator** --- making light concentrate onto the dispersing element
- **Dispersing Element** --- prism or diffraction grating (transmitting or reflecting)
- **Spectrum Imager** --- focusing spectrum onto the recorder
- **Image Recorder** --- CCD, photographic plate, etc.





Spectrograph. Optical path in spectrograph.

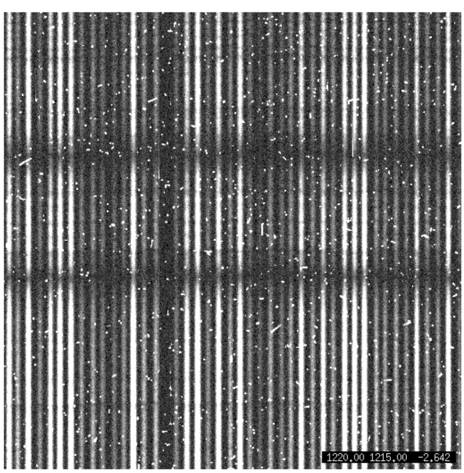
Objective Prism （物端稜鏡）



http://www.physics.curtin.edu.au/teaching/units/Ast201/Lectures/A201-9.ppt

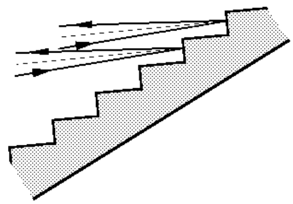
- 在物鏡前放置稜鏡 → 整個視野中的天體都被分光 → 低色散光譜

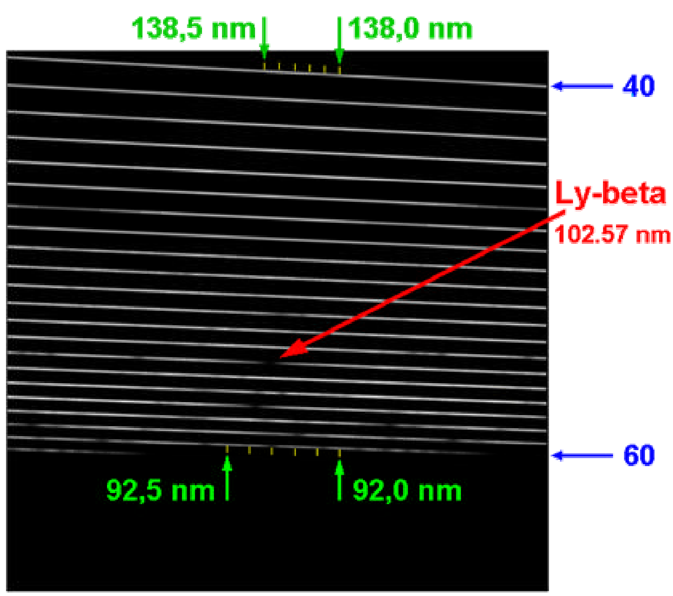
Multi-Fiber Spectroscopy



Echelle Spectrograph

- Traditional dispersing element: prism or diffraction grating
- Echelle grating blazed to concentrate into high orders (10-100) → high-dispersion spectroscopy





http://astro.uni-tuebingen.de/groups/orfeus/echelle_e.shtml