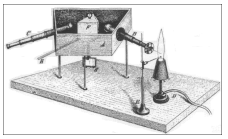
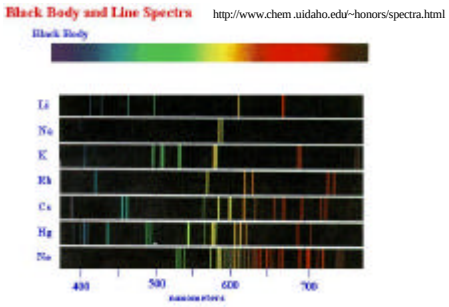
Spectroscopy in Astronomy

History

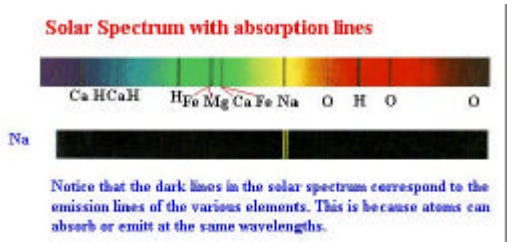
- 1814 German optician Joseph von Fraunhofer → sun with 600+ spectral lines; now we know more than 3000 lines
- 1860 German chemists Gustav Kirchhoff and Robert W. Bunsen → **Chemical Analysis by Observation of Spectra** *Annalen der Physik und der Chemie* (Poggendorff), 1860, 110, 161-189



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



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



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

Application of Spectral Analysis

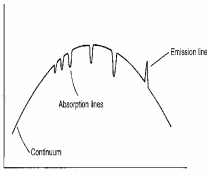
Combined with laboratory study, to estimate
→ composition
→ abundance of elements
→ temperature, density, pressure
→ motion (velocity and rotation) (Doppler effect)
→ magnetic field (Zeeman effect)

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



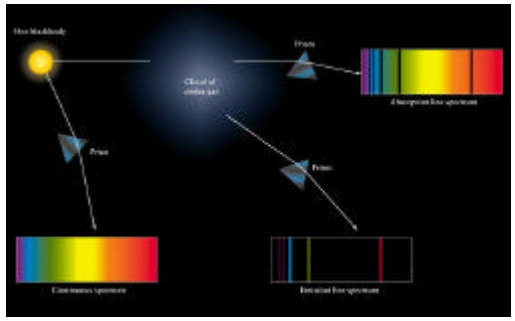
Kirchhoff's Laws

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

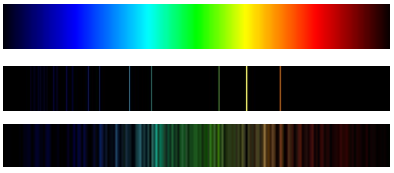
Kirchhoff's Laws

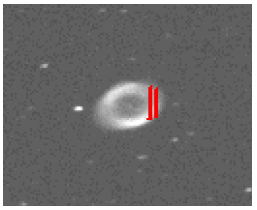
Absorption spectrum seen



Continuous spectrum seen

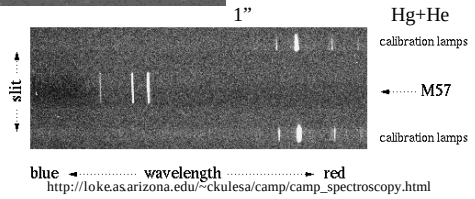
Emission spectrum seen



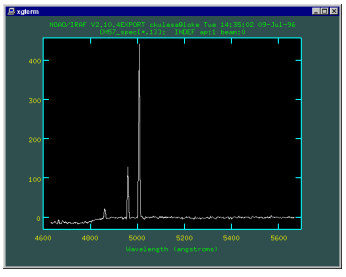


An example -----
Ring Nebula（環狀星雲， M57）:
a planetary nebula

Slit = 8' x 1"

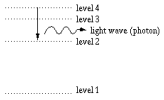


http://loke.as.arizona.edu/~ckulesa/camp/camp_spectroscopy.html



1-D spectrum shows little continuum, and a few emission lines
→ **A line spectrum**

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



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

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

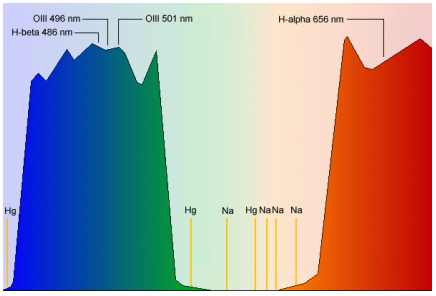
Peculiar Spectra

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

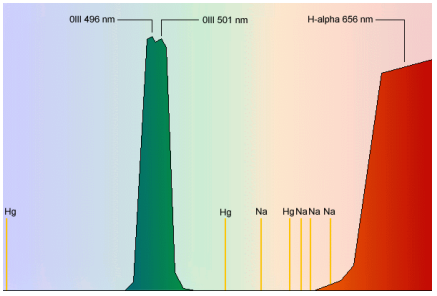
Spectroscopic Notation…(cont)

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?

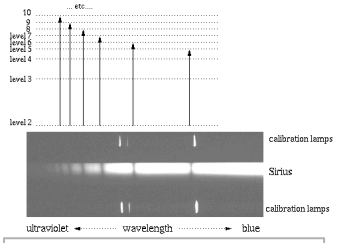


Example of the light transmission characteristics of a broadband light pollution filter. http://www.starizona.com/basics/filter1.html



Example of the light transmission characteristics of a narrowband nebula filter. http://www.starizona.com/basics/filter4.html

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

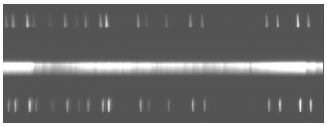


Spectrum near 4000Å (blue): continuum plus a series of absorption lines → hydrogen Balmer lines

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

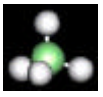
Spectral type OBAFGKML
hot → cool

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

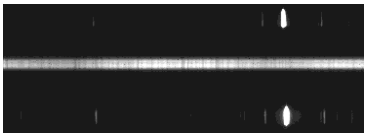


Spectrum near 6000Å (red): bright continuum at far left then drops off quickly to become a series of **bands**. These are from TiO (titanium oxide) molecules

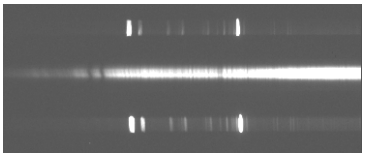
Atoms: electron energy levels
Molecules: additional rotational & vibrational levels
→ **complex spectra**



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

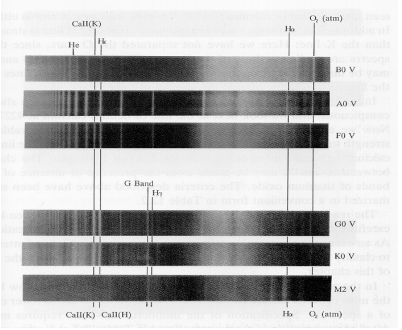


Spectrum near 5500Å (yellow): no molecules, but lots of lines (C, Fe, O, Mg, Ca, etc.)



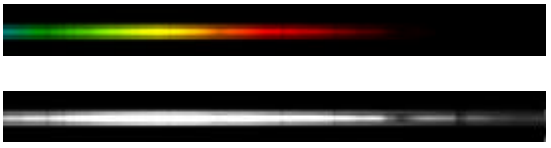
Spectrum near 4000Å (blue): 2 dark lines at left due to CaII; H lines very weak

Stellar Spectral Classification



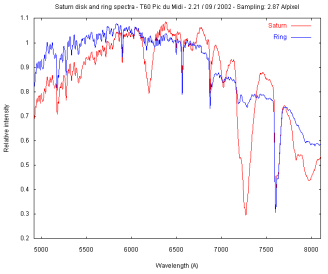
An example of spectroscopic science

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



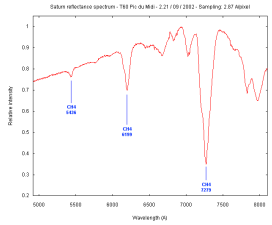
http://www.astrosurf.com/buil/us/mission2/mission2.htm#SPECTRUM%20OF%20PLANET%20SATURN

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



Spectral and spatial information from the same spectral image

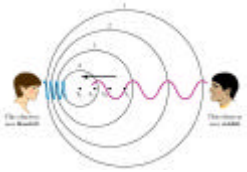
The ratio of the disk and the rings spectra
→ true spectral reflectance of Saturn



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

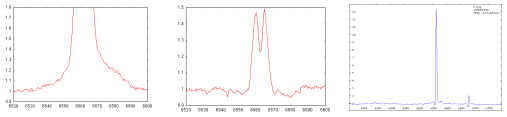
Doppler Effect --- Stellar Motions

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

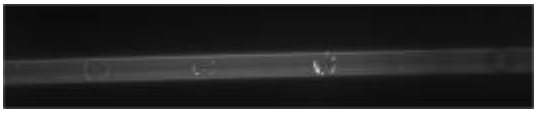


***Q**: How does the spectrum of a giant star differ from that of a main-sequence star?*

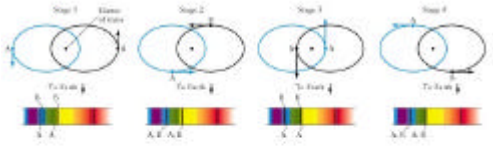
Line Profiles and Evolution

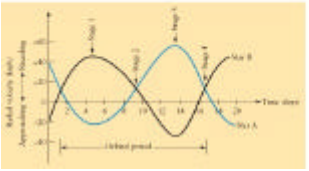


http://www.astrosurf.com /buil /us/bestar.htm



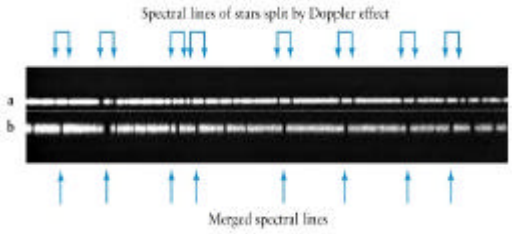
Spectral sequence during a solar eclipse http://www.astrosurf.com /buil /us/eclipse .htm





Spectroscopic binary

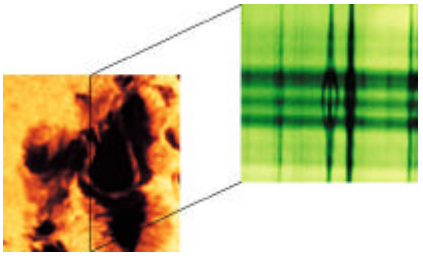
Radial-velocity curve

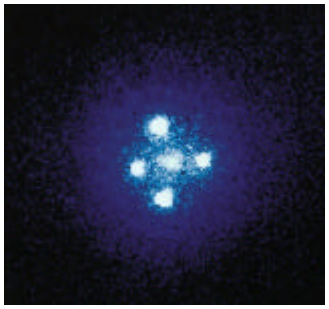


Double-lined spectroscopic binary

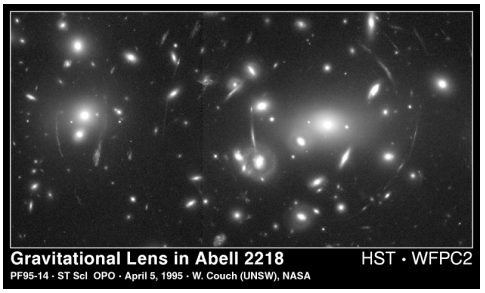
Zeeman Effect

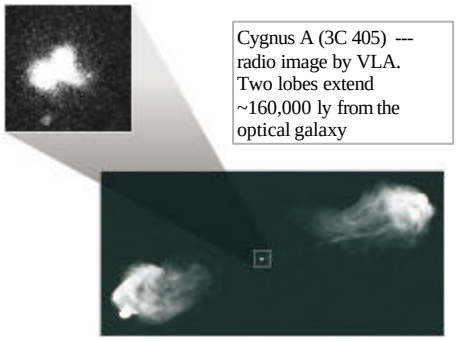
Spectral lines split in a magnetic field





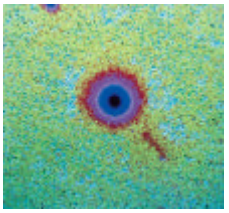
Einstein Cross by Hubble Space Telescope (HST), caused by gravitational lensing



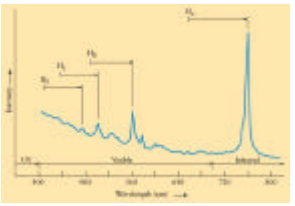


Cygnus A (3C 405) --- radio image by VLA. Two lobes extend ~160,000 ly from the optical galaxy

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

→ $s^2_{total} = S_i \; s^2_i$

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Midterm Exam 2002 Fall

The 1-meter telescope at Lulin Observatory has a focal length of 8000 mm. The telescope is equipped with a CCD camera, with 2048 x 2048 pixels, each pixel of physical dimension of 13 micron x 13 micron. (1) What is the theoretical diffraction limit of the telescope optic, in unit of arc-second? (2) Calculate the field of view of the camera. (15 points)

The probability that an electron is at a distance r from the center of the nucleus of a hydrogen atom is given by

$$P(r) = Cr^2 e^{-r/R}$$

(1) Evaluate the constant C. (2) Find the mean radius $\langle r \rangle$ and its standard deviation. (10 points)

Describe the advantages and disadvantages, optically and mechanically, of a reflecting telescope (using mirrors) versus a refracting telescope (using lenses). Why are all large, modern telescopes reflectors? (15 points)

Compare the performance among the three kinds of detectors, an eye, a photographic plate, and a charge-coupled device, in terms of quantum efficiency, linearity, dynamical range, ease of storage, cost, etc. (20 points)

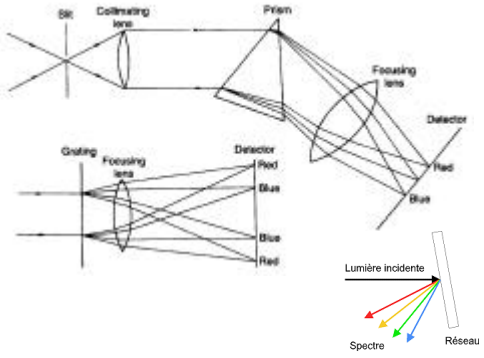
What kind of effects does the Earth's atmosphere have on astronomical observations? Be as elaborative as possible. (20 points)

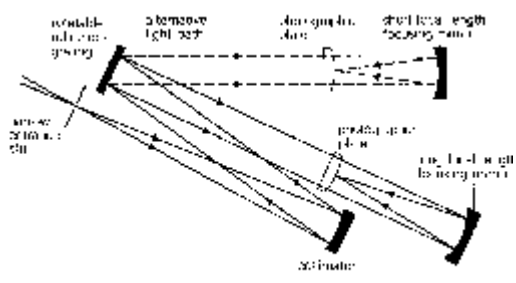
The Sun moves to the vernal equinox around March 21 every year. The Galactic center has equatorial coordinates of Right Ascension 17h, and Declination −30 degrees. What is the best time of the year (i.e., highest up in the sky at midnight) to observe the Galactic center from Taiwan? From the United States? What is its maximum elevation of the Galactic center above the horizon seen in Taiwan? (10 points)

In a dark, clear night sky, how does one distinguish a planet from a regular 'fixed' star? Why? (10 points)

Spectrometer

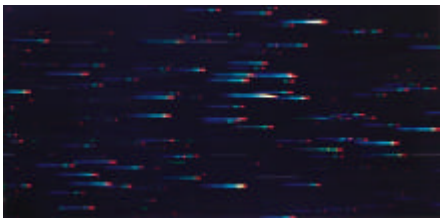
- **Entrance Aperture** --- usually smaller than seeing disk, or with a slit
- **Collimator** --- making light concentrate onto the dispersing element
- **Dispersing Element** --- prism or diffraction grating (transmitting or reflecting)
- **Spectrum Imager** --- focusing spectrum onto the recorder
-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





Spectrograph. Optical path in spectrograph.

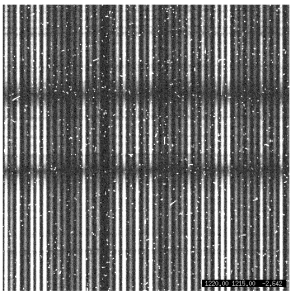
Objective Prism （物端稜鏡）



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

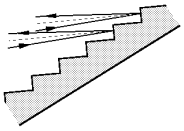
- 在物鏡前放置稜鏡 → 整個視野中的天體都被分光 → 低色散光譜

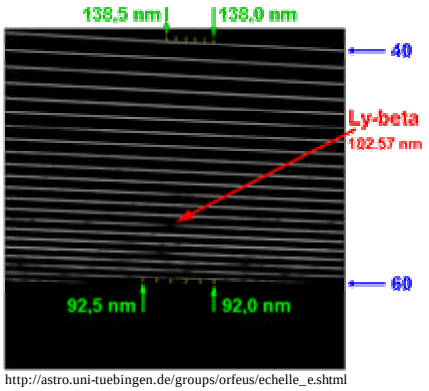
Multi-Fiber Spectroscopy



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