McLean 輪読 第 2 回 p.138-152

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4.2.2 High resolution, from cosmic abundances to planet hunting

- classical spectrograph
  - single, long and narrow slit
  - ideal for studies of nebulae and galaxies
  - good sky subtraction for single objects
- High-resolution spectrograph
  - very large
  - located at a stationary focus of the telescope
  - HIRES(High Resolution Spectrograph) on Keck I telescope

subtle spectral differences between H and D

- distant galaxies
- determine primordial D/H abundance ratio
- estimate ratio of baryons to photons
  - use CMB to derive the density of photons
  - derive the density of baryonic matter
- distant QSO
- Lymna-alpha line of normal hydrogen is the strongest
- a weak line of deuterium 82km/s to the blue
- $z > 2.5$ Lyman series moves from the UV to the visible

first observation using Keck telescope

- by Michele Mayor and Didier Queloz
- October 5th, 1995
- ELODIE high-resolution echelle spectrograph at the Genea Observatory
- 5.5-mag G5V star 51 Pegasi (15.4pc away from Earth)

one week later

- by Geoff Marcy and Paul Butler
- high-resolution(Hamilton) echelle spectrometer at Lick Observatory
- confirmed the object is about $0.5 M_{\text{Jupiter}}$

after findings

- other extrasolar planets to 51 Peg found
- other groups developed similar instruments
- Swiss team began a southern hemisphere program using CORALIE
- similar study was initiated at Anglo-Australian Telescope
- Geoff Marcy and Paul Butler moved to the 10m Keck telescope and HIRES echelle spectrometer
- by 2007, over 200 extrasolar planetary systems found
- California and Carnegie Planet Search(CCPS)

basis of extrasolar planets probe

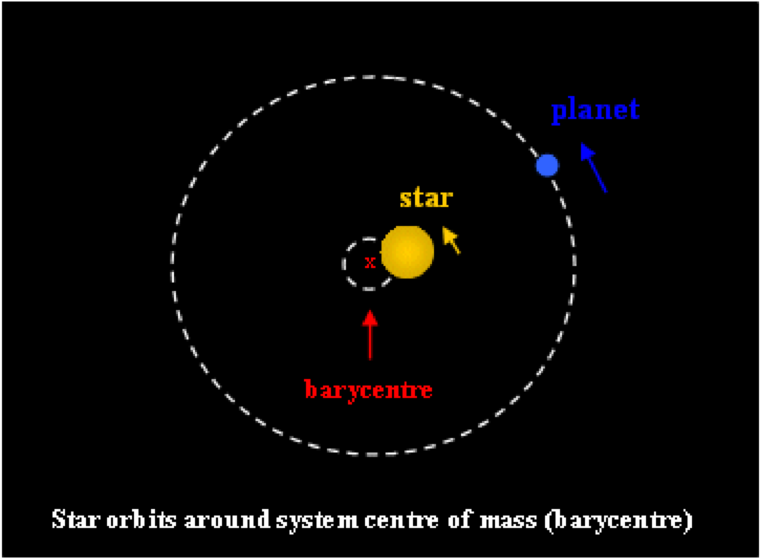

Figure: http://www.superwasp.org/exoplanets.htm

Kepler's Third Law

$$a^3 = \left(\frac{GM_{\text{star}}}{4\pi^2}\right) P^2$$

- $a = 1[\text{AU}]$, $P = 1[\text{yr}]$, $M_{\text{star}} = M_{\odot}$,then $G/4\pi^2 = 1$
- Doppler Shift of the spectral lines in the star $\rightarrow P$
- type of the star $\rightarrow M_{\text{star}}$
- Thus, the size of the orbit(a) found

Kinetic Equation

$$\frac{M_{\text{pl}} V_{\text{pl}}^2}{a} = \frac{GM_{\text{star}} M_{\text{pl}}}{a^2}$$

- $V_{\text{pl}} = \sqrt{\frac{GM_{\text{star}}}{a}}$

conservation of angular momentum

$$M_{\rm pl} V_{\rm pl} = M_{\rm star} V_{\rm star}$$

- Doppler shift $\frac{\Delta\lambda}{\lambda} = \frac{K}{c}$
- $K = V_{\rm star} \sin i$

therefore...

$$M_{\rm pl} \sin i = \frac{M_{\rm star} K}{V_{\rm pl}} = 11.2 M_{\oplus} \left(\frac{M_{\rm star}}{M_{\odot}} \right) \left(\frac{K}{1[{\rm m/s}]} \right) \left(\frac{30[{\rm km/s}]}{V_{\rm pl}} \right)$$

if $M_{\text{star}} = M_{\odot}\ldots$

- limiting velocity precision 1[m/s]
- $V_{\text{pl}} = 30$[km/s]
- to detect the analog of Earth requires about 0.1[m/s]

observe small effect

- Sun orbits its center in common with Jupiter with 14.7[m/s]
- $R \sim 100,000$ then $\Delta V = 3$[km/s] is required to detect a Jupiter-mass planet at 5[AU]

observe small effect

- allow incoming starlight to pass through a chamber containing an trunslucent gas
- gas absorbs a small amount of light at a few very specific places in the spectrum
- positional accuracies $\leftarrow$ spectral resolution $\sim 0.1\Delta\lambda$
- cross-correlation technique
- HIRES instrument on Keck : residual error ± 1[m/s]

‘double’ spectrograph

- John Beverley Oke(1982)
- for 5m Hale Telescope at Palomar
- many Cassegrain spectrographs are now double system
- LRIS(Low Resolution Imaging Spectrograph) on the Keck telescope
- CCD's spectral range: $0.3[\mu m] - 1.1[\mu m] \rightarrow$ spilt(blue/red)
- beam-spilitter is used to study distant objects

Q1307-BM1163

- LRIS-B specrum of Q1307-BM1163 (22-mag at $z = 1.411$) (Fig4.13)
- UV-sensitive CCD, a pair of 2K×4K devices from e2v technologies
- $z = 1.411 \rightarrow \lambda$is observed at 2.411 times

ex

- CII(133.4[nm]) is observed at 321.6[nm]
- MgII(279.6[nm]) is observed at 674.1[nm]

- this galaxy's SFR $\sim 30 M_\odot$
- the abundance of hevier elements is close to that of Sun
- star forming and ISM enriching much faster than the Milky Way
- likely to be an elliptical galaxy devoid of gas/bulge of a massive spiral galaxy

low-resolution spectrograph

- image spectrum of faint object with low spectral resolution
- not to spread out the available light too much
- more light will be on pixel of the CCD
- fainter source can be detected

4.2.4 Multiobject spectroscopic surveys; 3-D maps of the Universe

- spectroscopic measurements are very slow
- the possibility of recording spectra from several objects at once?

slit-less spectroscopy

- remove the slit
- OK for point sources
- spectral resolution is determined by the seeing disk(not slit width)
- only works at wavelength where sky background is very dark and the field not too dense to avoid overlapping
- place a thin prism over the entrance aperture
- all the star images become little spectra

slit-less spectroscopy

- 1893-1924:Henry Draper(HD) Catalog of 225,300 sources
- modern: objective prism surveys with Schmidt telescopes
- The Hubble Space Telescope's Advanced camera for Surveys(ACS) and Near-Infrared Camera and Multi-Object Spectrometer(NICMOS) : in space, grism(grating + prism)

multi-object spectroscopy

- entrance slit composed of multiple sub-sections
- positioned by computer to pick up many different object
- Fig4.14 DEIMOS muli-object spectrograph on the Keck II telescope
- 'slit-mask'
- slit are cut at different angles and in different locations on the mask
- 11 masks in a cassette
- each mask can have about 400 slitlets (16.7 $\times$ 5.0[arcmin])
- $R \sim 5000 - 1000$
- 8 CCDs / 64 megapixels fed by f/1.29 optics

multi-object spectroscopy

- DEEP2 redshift survey
- ~ 50000 faint galaxies with $z > 0.7$
- galaxy properties and tendency to cluster compared to lower z
- complementary to SDSS, 2dF, VLT/VIRMOS Deep Survey

near-infrared spectrum

- slit masks loaded through a vacuum-crygenic air lock system
- movable opposing slit bars
  - quantize y-axis
  - allow any location in x
- micro-shutters
  - outgrowth of micro-electro-mechanical systems(MEMS) technology

MEMS

- the integration of mechanical elements, sensors, actuators, and electronics on a silicon substrate
- micromachining
  - selectively etch away parts of the silicon wafer
  - add new structural layers
- ex. deformable mirrors(DMs) for wavefront control in AO system

- Boston Micromachines Corporation
  - only 10.5[mm] in size
  - actuator array of 1,024 elements
  - each capable of delivering a stroke of 1.5[μm]
- Planet Imager for the gemini South 8m telescope(future)
  - 4,000 actuators

microshutter

- $100 \times 200[\mu m]$ tiny cell
- 250×250grid
- slightly magnetized and opened by scanning a magnet
- selected apertures are held open by control voltage difference between the shutter and an electrode on the wall

transparent optical fiber

- transmit light over very long distances with slight losses
- one end: points corresponding to interesting objects
- the other end: entrance slit of the spectrograph
- spetrum recorded simultaneously

example of fiber ptic coupled system

- MEDUSA (1979)
- now such systems are common: 2dF(2-degree field), Anglo-Australian Telescope(AAT)
- Fig4.15

photographic Schmidt telescope

- Anglo-Australian Schmidt Telescope, in the early 1980s
- FLAIR(and FLAIR II): fiber optic system (over 90 fibers)
- $6.5° \times 6.5°$ field of view
- FLAIR has been replaced by 6dF(6-degree field)

6dF

- fully automated, pick-place, magnetic button fiber-positioning system
- 150 target fibers in less than 1 hour
- two interchangeble plates
- light-collecting prism attached to fiber
  - 0.1[nm/pixel] – 0.4[nm/pixel] resolution
  - limiting mag 18

Mapping the Universe

- Hubble's Law and SDSS $\rightarrow$ three-dimensional picture of the Universe
- about 100 times larger than before
- a complete redshift limited survery(QSO or faint galaxies) become viable

SDSS found faint companion galaxies to the Milky Way

- SDSS found
  - small faint companion galaxies
  - long streams of stars left behind by satellite
- leading model for galaxy formation that dwarf galaxy companions to the Milky Way should be more numerous

other findings

- use 200,000 QSO and 13 million galaxies
- large-scale gravitational lensing of distant background sources(QSO) by foreground matter
  - Einstein's General Relativity
  - standard model as to dark mater

structure of the universe

- large-scale structure
- enormous clusters of galaxies spread out in filaments
- use three-dimensional map with 600,000 galaxies
- SDSS-II found galatic structures sppaning a billion light years
    - consistent with dark mater/dark energy model
    - idea of galactic structure imprinted by cosmic sound waves in the early Universe

4.2.5 Imaging spectroscopy; $x, y, and \lambda$

- the remainder of the field must be hidden from the spectrometer by the slit-mask
- measureaments are repeated many times with the telescope motion control
- how to spatial and spectral information simultaeously?
- Fabry-Perot interferometer
- integral field units

Fabry-Perot interferometer

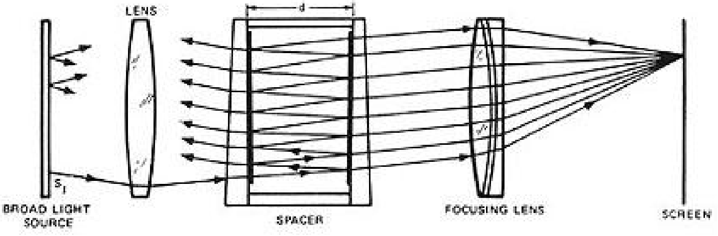

Figure:
https://www.astro.cf.ac.uk/observatory/solarobservatory/equipment

Fabry-Perot interferometer

- two face-to-face circular platex
- high reflectivity
- low absorption
- flat to a tiny fractin of the wavelength of light

ex.

4.5[nm] in the mid-visible

- much greater efficiency than diffracion grating
- spectral purity and detail
- as the spacing between two surfaces is changed, so the wavelength
- controled by computer
- result $\longrightarrow$ date cube(x, y, λ)

Fabry-Perot interferometer

- very small range of wavelength
- excellent image of the field

integral field spectroscopy

- image slicer
- example: '3-D' integral field spectrometer
- mirror with many tilted facets
- subdivide the image in the focal plane into narrow strips then another mirror
- stack these parts along the length of a spectrograph slit
- field of view is relatively small ($8'' \times 8''$)

different approach

- TIGER instrument at the CFHT
- subdivide into numerous very small segments using array of tiny lenses
- image is greatly magnified and fed to a microlens array
- image is sliced up and emited to the spectrograph

ARGUS instrument at CFHT

- subdivide the focal plane with numerous,closely packed optical fibers
- collect all the fibers into a one-dimentional stack($\rightarrow$ spectrograph)
- by IFU...small integral field units can be positioned anywhere and to the infrared