4.2.3 Medium-resolution and low-resolution spectroscopy

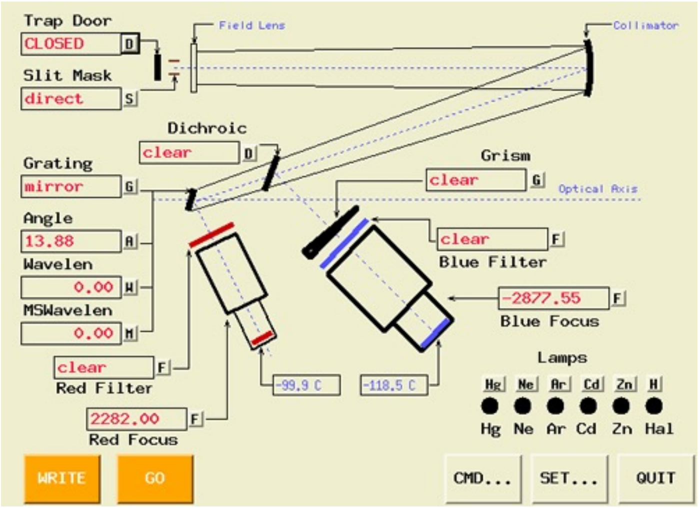
- Intermedium-resolution spectroscopy : most used

- "double" spectrograph
  - Oke(1982) pioneered for Hale telescope
  - driven by the huge spectral range of CCD (0.3-1.1um)

    ex) LRIS on Keck telescope
    - a beam-splitter

      → separate the blue and red parts of the range
    - optimized cameras and CCDs

      → record the blue and red spectra
  - most distant objects, SNe, after-glow of gamma-ray burst counterparts



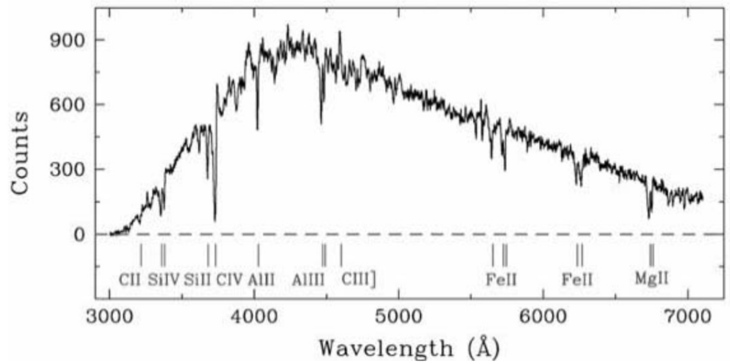
https://www2.keck.hawaii.edu/inst/lris/lrishome.html

4.2.3 Medium-resolution and low-resolution spectroscopy

- LRIS-B spectrum of Q1307-BM1163(22^{nd}-magnitude, z=1.411)
  - the observed absorption lines : 2.411 × (true wavelength)
    - CII : 133.4nm→321.6, MgII : 279.6nm→674.1nm
  - SFR : ~$30 M_{\odot}/yr$, Metallicity : ~$Z_{\odot}$

  ⇨turning gas into stars and enriching interstellar medium at a much faster rate than Milky Way

  ⇨will turn to be an elliptical galaxy lack of gas or the bulge of massive spiral galaxy



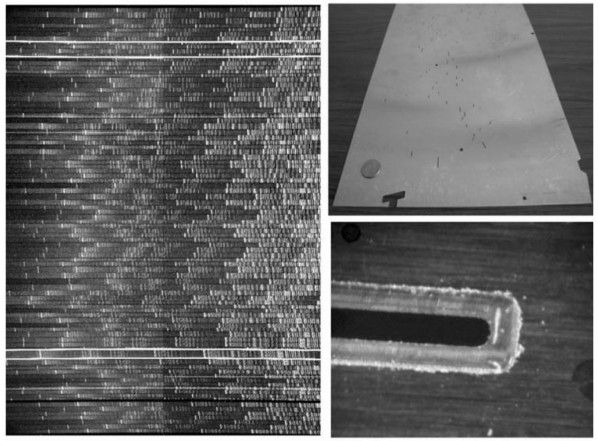
- ”faint object” class of spectrograph
  - CCD camera : image a spectrum of a faint object with low resolution
  - not to spread out the spectrum

    ⇨more light on each pixel of the CCD & detect the fainter source

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

- the possibility of recording spectra of several objects at once is attractive
- slit-less spectroscopy, objective prism spectroscopy
  - spectral resolution : determined by the seeing disk
  - works at wavelength where the sky background is dark and the field not too dense
  - method : place a thin prism at the entrance aperture of a telescope
    ⇨the star image become little spectra
  - objective prism spectroscopy
    ex) Henry Draper Catalog (225,300 sources using photographic plates)
    large Schmidt telescopes(emission-line objects)
  - slit-less spectroscopy
    ex) HST's ACS and NICMOS (grism)

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



- multi-object spectrograph
  - entrance slit composed of multiple sub-sections (“multi-slit”)
  - DEIMOS (Keck II)
    - FOV~16.7’×5.0’, R~5000-10000
    - maximum 11 masks, 400slitlets/mask

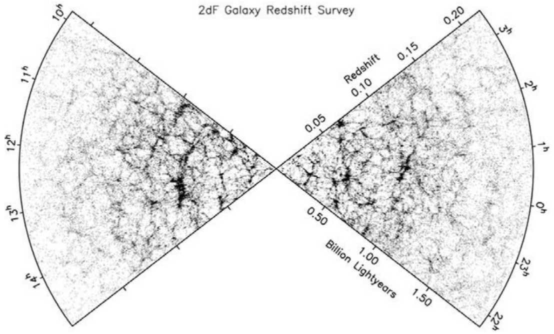
  →DEEP2 redshift survey : spectra of ~50,000 galaxies (z>0.7)
    - the evolution of galaxy properties and their tendency of cluster
- slit-mask technology for the NIR part of the spectrum
  - mask must be cold(<150K) → prevent the detectors from thermal glow

  → ・exchangeable slit-mask
    - movable opposing slit bars (quantize y-axis, allow any slit location in the x-direction)
    - micro-shutters : MEMS (micro electro-mechanical systems) technology
      - MEMS : mechanical elements, sensors, actuators, electronics on a silicon substrate

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

・optical fibers : slim and flexible glass conduits
  →“light-pipes” to transmit light over long distances with a little losses
  ・one end of fibers : the focal plane
  ・other ends : the entrance slit
ex) ・2dF(2-degree field) : 400-fiber system on the 3.9m AAT
  ・robotic arms → place the fibers in the focal plane
 ・ SDSS 2.5m telescope : 600-fiber spectrograph
  ・“plug-plates” → insert fibers into a pre-drilled mask
 ・FLAIR, FLAIR II (Anglo-Australian Schmidt Telescope) : >90fibers
  ・fibers : glued to glass plate with UV-curing optical cement (6~7h)
  ・bundle of fiber cables
   →led into the slit of a CCD grating spectrometer
 →6dF : fully automated, magnetic button fiber-positioning system
  ・r- θ positioning robot : reconfigure 150 target fibers (<1h)
   ・2 changeable plates : one in use, the other being configured

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



・SDSS and redshift surveys

→・distance of nearest galaxies (>one million)

・small faint companion galaxies to the Milky Way

・long streams of stars left behind by galaxies merging

⇔model : galaxy companions to the Milky Way should be more numerous

・200,000 quasars and 13 million galaxies

→ large-scale gravitational lensing of distant background sources

・as required by Einstein's General Relativity and the model (much of the mass is dark matter)

・3-D map (>600,000 galaxies) covering 1/10 of the sky

→galactic structures spanning a billion light years

・consistent with dark matter and dark energy models, and the idea of galactic structure imprinted by cosmic sound waves in the early Universe

4.2.5 Imaging spectroscopy; x, y, and λ

・basic approach to obtain spatial and spectral information simultaneously

→・ interference-based techniques (Fabry-Perot or imaging Michelson interferometer)

・integral field units

・Fabry-Perot (FP) etalon : two plates of high reflectivity and low absorption are held parallel

・great efficiency or throughput (> diffraction gratings)

・placed directly into the beam of an imaging system

→picture of entire field of view with the spectral purity and detail as powerful spectrometer

・limited wavelength span → an excellent image of the field

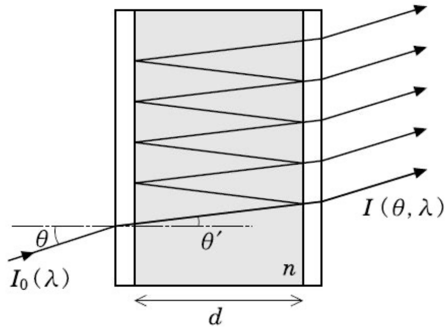
・like an ordinary wavelength selection filter

・change gap between plates → the wavelength transmitted changes

・images corresponding to different wavelengths or velocities

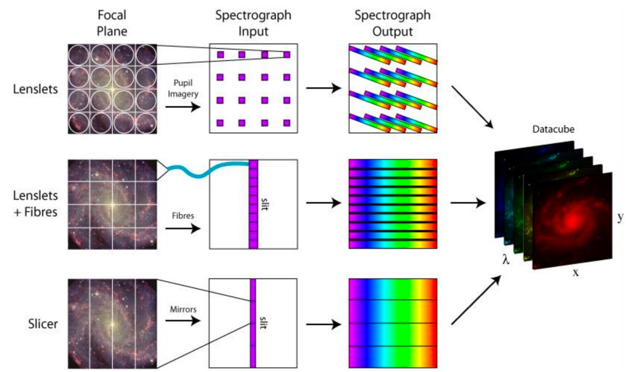
→stacked image = data cube

・3D : two spatial dimensions, one wavelength dimension



https://astro-dic.jp/fabry-perot-etalon/

4.2.5 Imaging spectroscopy; x, y, and λ

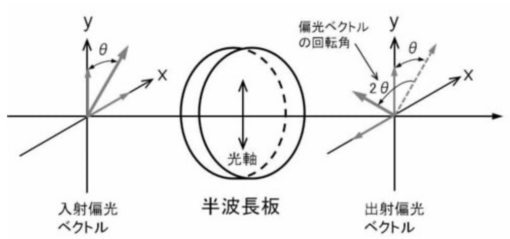


・integral field spectroscopy : most common
  ・image slicer
    ・mirror with many facets
      → subdivide the focal plane image into narrow strips
    ・another similar mirror → stack these parts along length of spectrograph slit
    ・every region of the image produces a spectrum
    ・the field of view is small
  ・an array of tiny lenses :
    ・magnified image is fed to “microlens” array
    ・microlens array → subdivide the image into numerous small segments
    ・ every segments on the detector represent spatial and spectral information
  ・optical fiber
    ・subdivide the focal plane with numerous, packed fibers into a 2D pattern
    ・collect all the fibers into a 1D stack
    ・feed to the long slit of a spectrograph
  →deployable IFUs : small, could be positioned anywhere over a large field of view

4.3 POLARIZATION; TRANSVERSE WAVES
4.3.1 Introduction

- polarization : vibration of the electromagnetic waves in the same plane
  - unpolarized : no preferred orientation, random vibration in all planes
  - linearly polarized : preferred plane of vibration which doesn't change
  - circularly polarized : plane of vibration rotates by 360° through a wave cycle
- phenomena produces polarization
  - interaction of unpolarized light with matter
    - reflection from solid surfaces
    - scattering of photons by electrons, molecules, and small grains
    - absorption by certain materials in the interstellar medium
  - generation of polarized light by atoms
    - the radiation emitted by atoms suffered Zeeman effect in a magnetic field
    - synchrotron radiation emitted by high energy electrons spiraling in a magnetic field around a neutron star
- polarization spectra and images contain information about physical processes and source geometry

4.3.1 Introduction



https://astro-dic.jp/wave-plate/

・to determine the polarization state

・relative brightness measurements at different settings of a polarization modulator

・simple modulator : retardation plate made from a crystal showing birefringence (double refraction)

・the material has different refractive indices $(n_0,\ n_e)$ for polarization perpendicular (ordinary) and parallel (extraordinary) to the axis of anisotropy

・birefringence : $\Delta n = n_0 - n_e$

→relative phase shift between orthogonally polarized waves : $\gamma = \frac{2\pi \Delta n L}{\lambda}$ (L : thickness of the crystal)

・$L = \lambda/4$(quarter-wave plate) : linearly polarized light→circular polarization

・$L = \lambda/2$(half-wave plate) : rotate the direction of the polarization of the emergent light relative to the incoming light

・to avoid the systematic intensity variations in the light

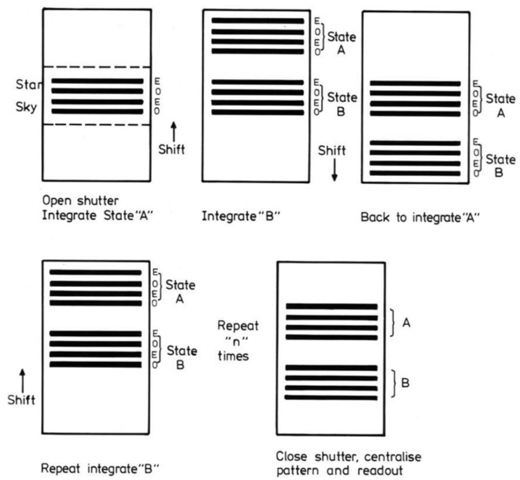
・the rate of changing the setting of the modulator should be rapid

・measure two polarization positions simultaneously → both are affected in the same way by systematic errors

4.3.2 Polarization maps and spectra

・use the charge-coupling attributes of the CCD
　・build up the polarization signals until enough counts accumulated (≫electronic read-out noise)

→ISP(Imaging SpectroPolarimeter, McLean 1981) : based on three-phase CCD, basically CCD camera
　・grism in the filter positions → convert ISP to a spectrometer
　・polarization modulator in front of the optical system→convert ISP to a polarimeter
　　・spectropolarimetry mode
　　　・a polarizer was placed under the slit of the spectrograph
　　　→two oppositely polarized spectra(E and O rays) on CCD
　　　(two slits for star and sky→four spectra in total)
　　　・bi-directional charge transfer
　　　　・images (or spectra) corresponding to orthogonal polarization state of the modulator
　　　　→stored in the top and bottom thirds of the CCD array
　　　　・the central part → light collection



Sequence of CCD frames for shift image polarimetry

4.3.2 Polarization maps and spectra

・scientific result

・the first high resolution images of the synchrotron polarization from the Crab Nebula (M1)

→divide nebular and pulsar polarizations

・polarization measurements are important in revealing the nature of AGN powered by the accretion disk around SMBH

・AGN are obscured by gas and dust clouds

・scattered light include the information from core is polarized

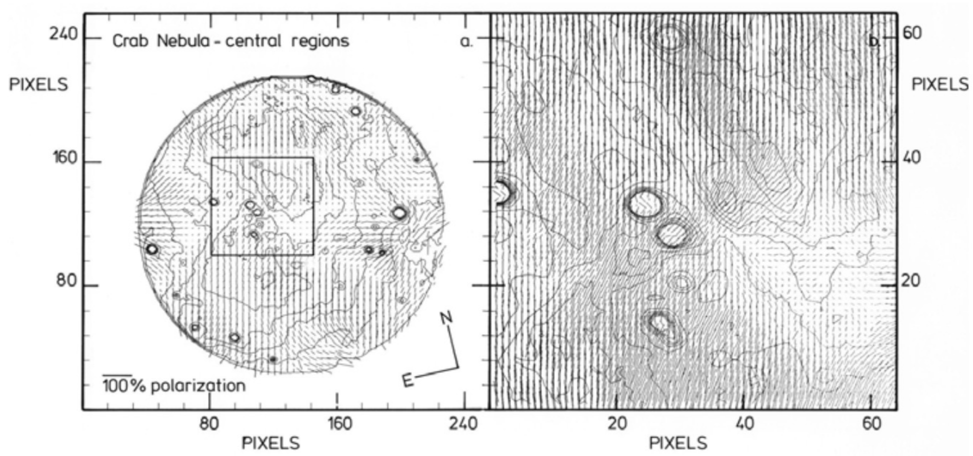


Figure 4.20. A contour map obtained by the author of the bright emission associated with the Crab Nebula supernova remnant overlaid with tiny line segments which represent the amount of polarization and the orientation of the magnetic field in the nebula. Credit: McLean *et al.* (1983).

4.3.2 Polarization maps and spectra

・spectroscopy with other variation of charge-shifting concept

・nod and shuffle method : remove sky background

・move the telescope between the object position and the sky reference position (nodding)

・shifting the charge on the CCD pixels between illuminated and storage regions (shuffling)

→use the same pixels for both object and sky

・polarization can be detected across the electromagnetic spectrum from X-rays to radio waves

・polarization of CMB (cosmic microwave background)

・contain information on the formation of the early Universe

・comes from the "surface of last scattering" when the Universe has expanded enough to become neutral (~380,000 years old)

→ CMB can become partially polarized, if there are free electrons around the photons to interact with via scattering

⇨the Universe have been re-ionized by the first generation of stars

・WMAP (Wilkinson Microwave Anisotropy Probe)

→~10% of the CMD photons have scattered in this way

⇨reionization event happened about 400 million years after the Big Bang

4.4 SUMMARY

・many technologies (lasers, fiber optics, micromachining, diamond-polishing, and advanced technology)

→contributed to astronomical instruments

・discoveries that are enabled by technologies

・Pluto-sized objects in the outer solar system

・hundreds of other planetary systems

・brown dwarfs (the missing link between small stars and gas-giant planets)

・evidence for a black hole at the center of the Milky Way

・conclusive evidence for dark matter throughout the Universe

・ implication from SNe studies that expansion of the Universe seems to be accelerating