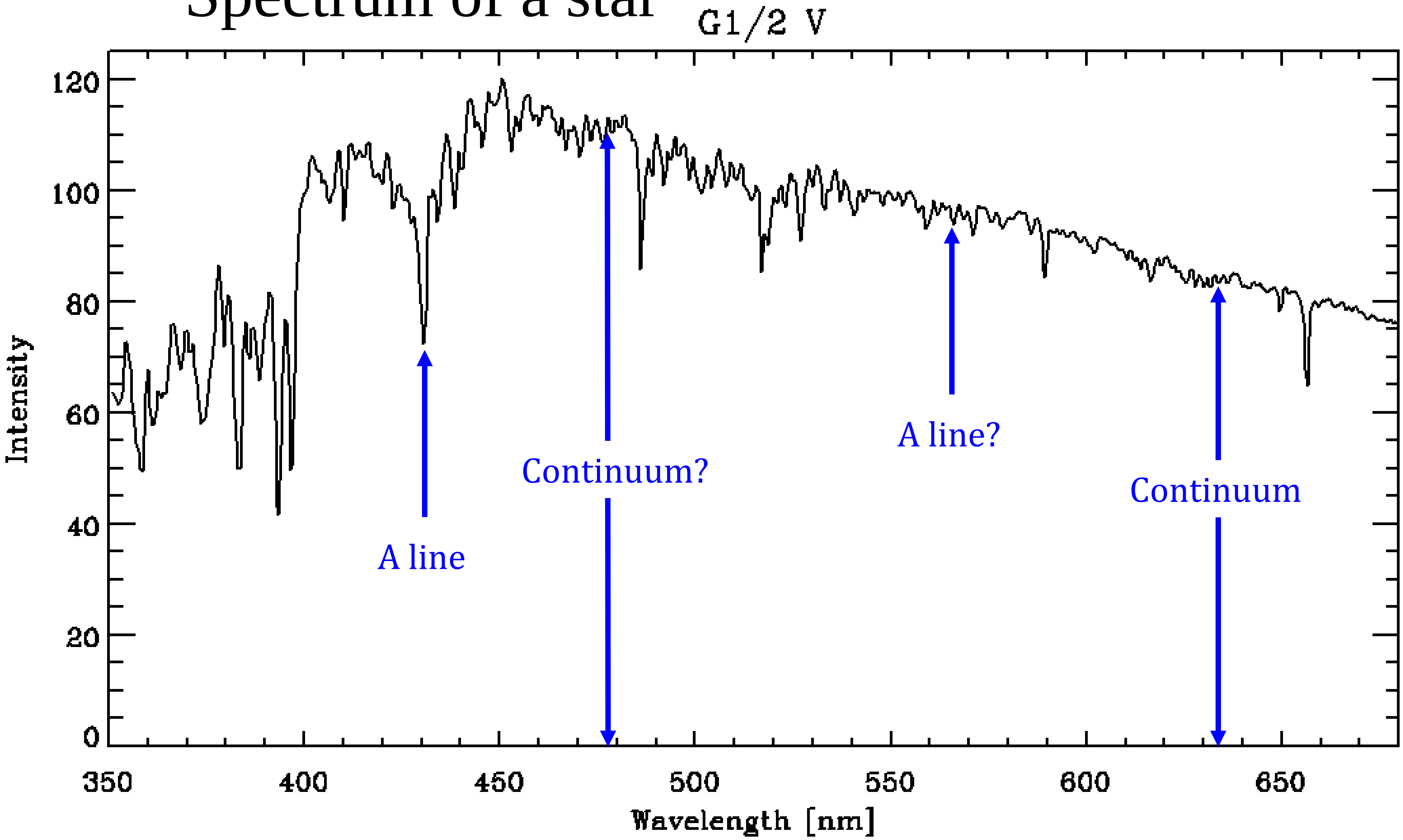
Astronomical Observations

- Electromagnetic (EM) radiation (from gamma rays to radio waves) + cosmic rays + neutrinos + gravitational waves …

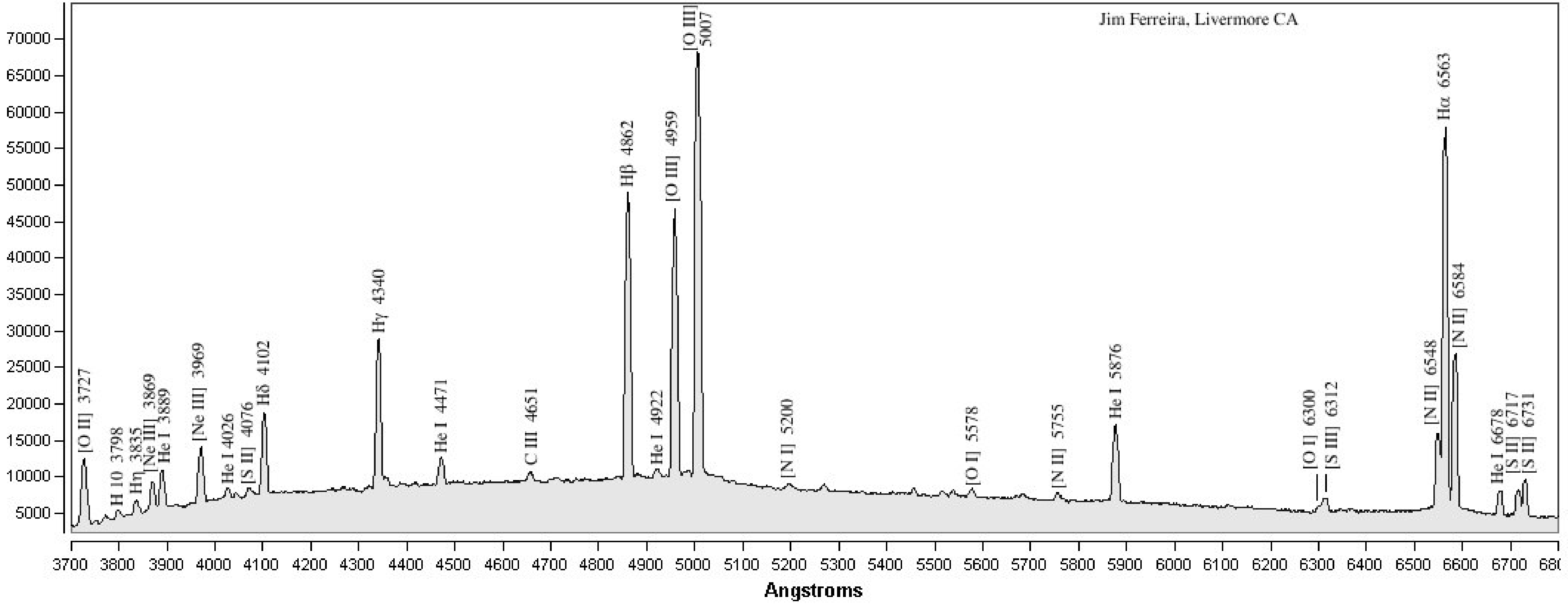
Interactions between matter, between matter and energies/photons. We detect photons.

- Diagnosed by photometry, spectroscopy, polarization, etc.
  - **line** (absorption, emission) in a narrow range of frequency
    e.g., $h\nu$ + H(^{1}S) → H(^{2}P) ($h\nu$ =10.2 eV or λ=121.6 nm)
  - **continuum** (absorption, emission) over a wide range of ν
    e.g., $h\nu$+ H(^{1}S) → $H^+ + e^-$ ($h\nu \geq$ 13.6 eV or $\lambda \leq$91.2 nm)

Spectrum of a star



Orion Nebula - M42 20141110UT Alpy 600 / C9@f/6.3



- **Photometry**

  measurement of brightness of radiation (of a source, or a position in sky)

  Astronomers use “magnitude” ↔ flux density

  At the V band ($\lambda_{\rm eff}$ =550 nm; $\Delta\lambda$ =86 nm), $F_\nu^{\rm v=0} = 3.64 \times 10^{-23}$ [W m^{-2} Hz^{-1}]

  $F_\lambda^{\rm v=0} = 3.61 \times 10^{-11}$ [W m^{-2} nm^{-1}]; $N_\lambda = 1000$ [photons s^{-1} cm^{-2} Å^{-1}]

- **Spectroscopy**

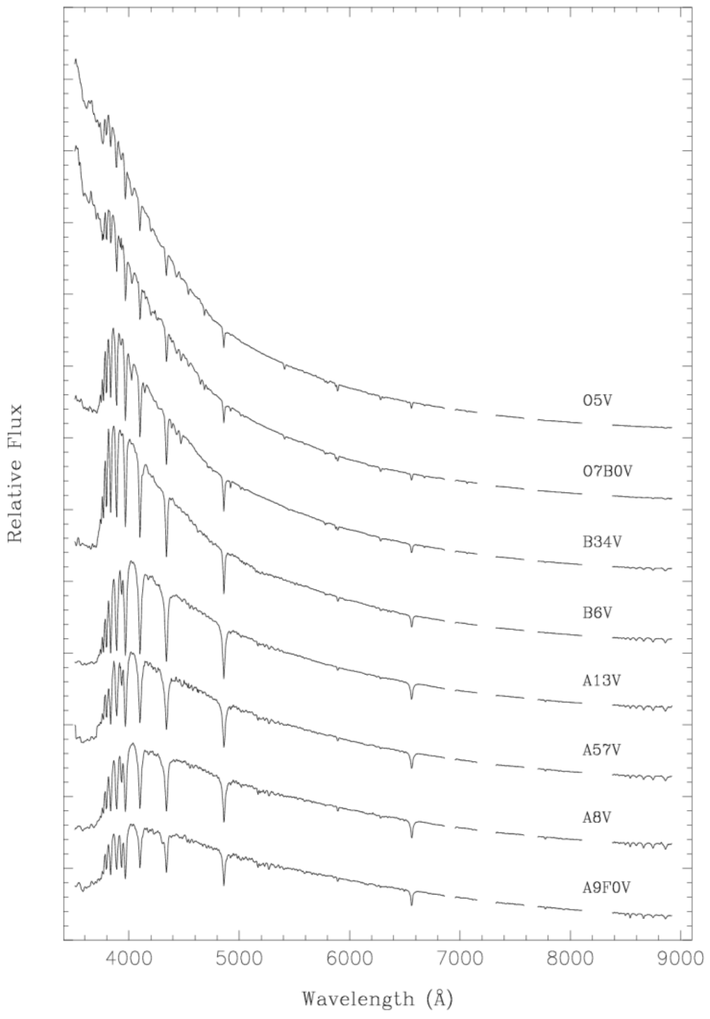
  measurements of brightness distribution with wavelength or frequency

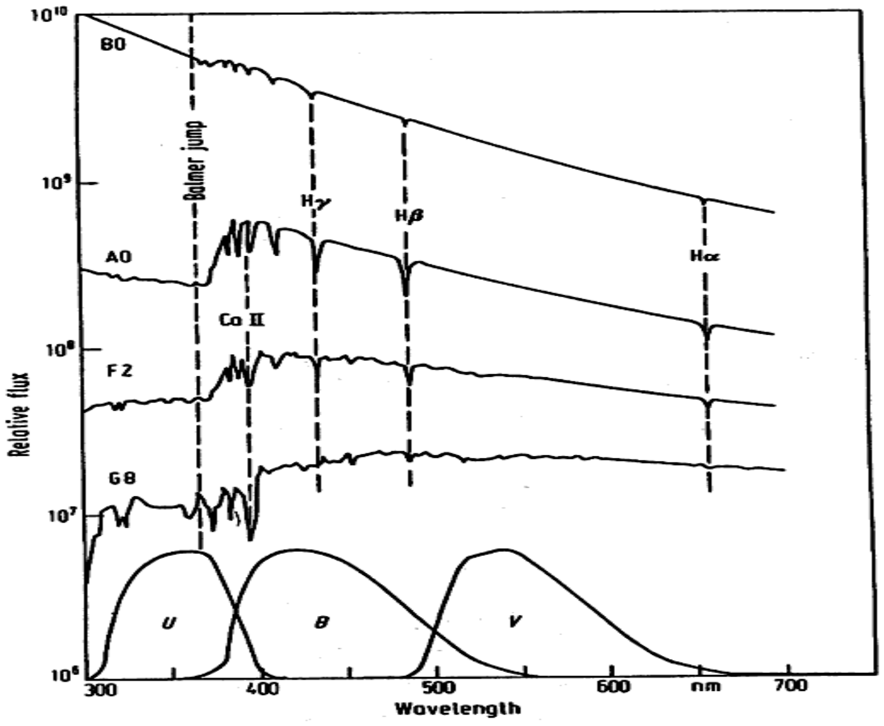
Spectrophotometry; Integral Field Unit (IFU); IF Spectrograph

- **Polarimetry**

  measurements of the polarization level (polarized intensity/total intensity) and position angle

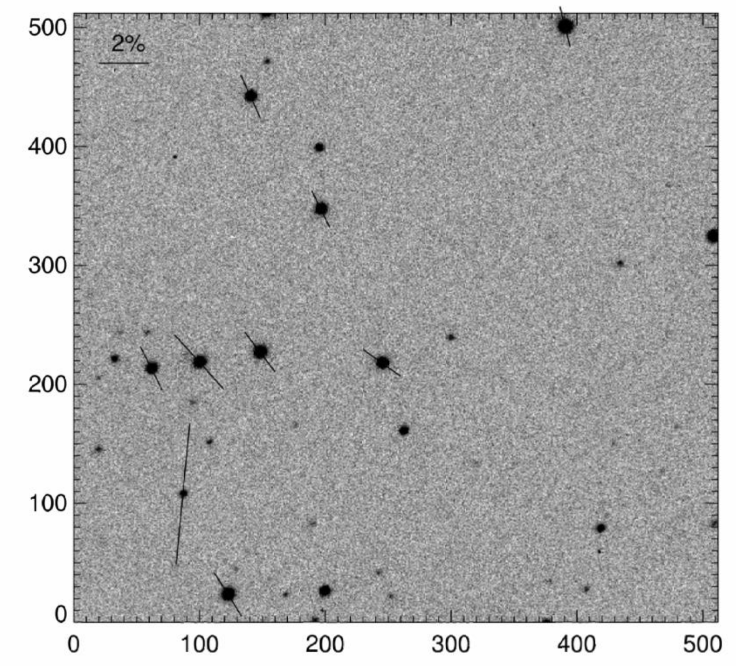
Spectra of hot stars

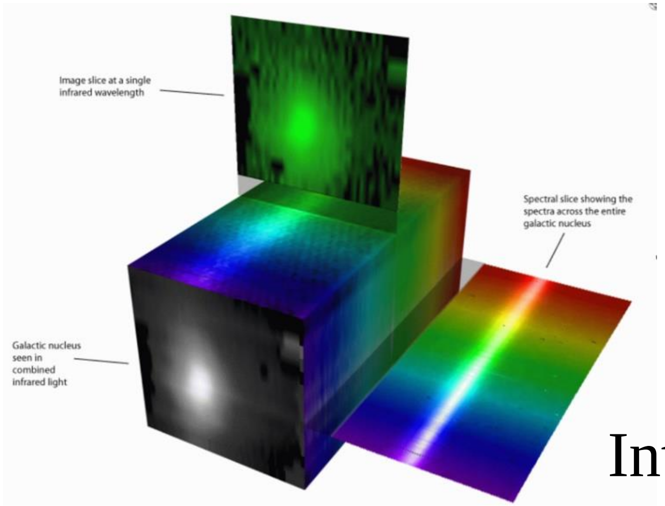




Imaging photometry

Photometry and polarization of background stars of a globule





Integral field spectroscopy

- candela (cd; = candle in Latin; luminous intensity; power per solid angle)
- lumen (lm; luminous flux; $= 1\ \mathrm{cd} \cdot \mathrm{sr}$

  LED bulb ~ 500 lm; classroom projector ~5000 lm

- illuminance (lux; $= \mathrm{lm/m^2}$)

  clear day ~10,000 lux; office ~200 lux; a dark day ~100 lux;
  twilight ~10 lux; moonless clear night 0.001 lux; full moon ~0.1 lux;
  $m_\mathrm{V} = 0 \rightarrow 2.08\ \mu lux$; $m_\mathrm{V} = 6 \rightarrow 8\ nlux$;
  iPhone 11 ~10 lux

Observations of the ISM

- Difficult: typical temperature either too **low** or too **high**, so observable usually only outside visible wavelengths.

Planck function (1901)

$$B_\nu \, d\nu = \frac{2h\nu^3}{c^2} \frac{n_\nu^2}{e^{h\nu/k_B T} - 1} d\nu \;[\mathrm{erg\ s^{-1}\ cm^{-2} sr^{-1}\ Hz^{-1}}]$$

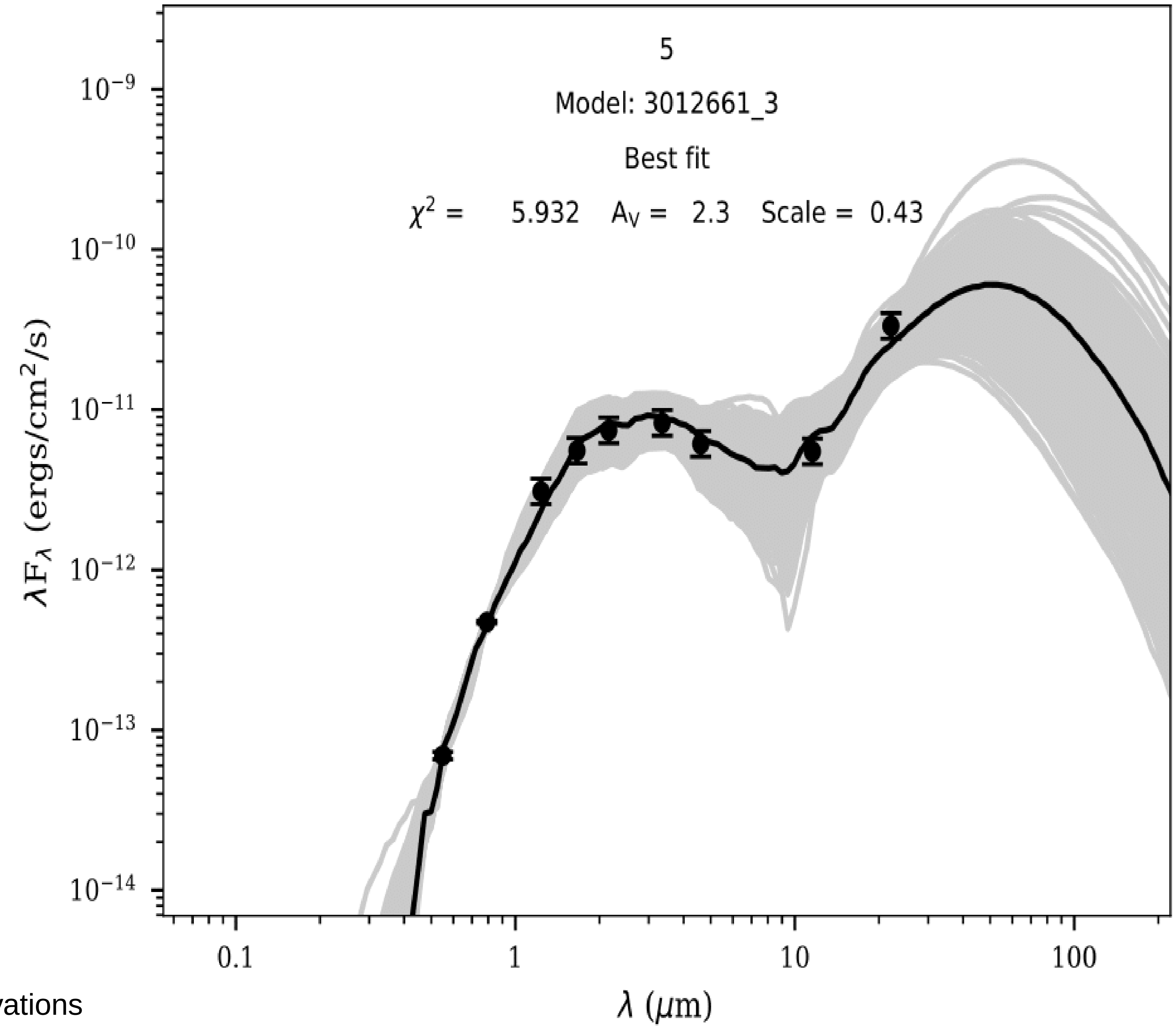
$$B_\lambda \, d\lambda = \frac{2hc^2}{\lambda^5} \frac{n_\nu^2}{e^{hc/\lambda k_B T} - 1} d\lambda \;[\mathrm{erg\ s^{-1}\ cm^{-2} sr^{-1}\ \text{Å}^{-1}}]$$

$\lambda_{\mathrm{max}} T \approx 2900\ [\mu\mathrm{m} \cdot \mathrm{K}]$ … Wien's displacement law

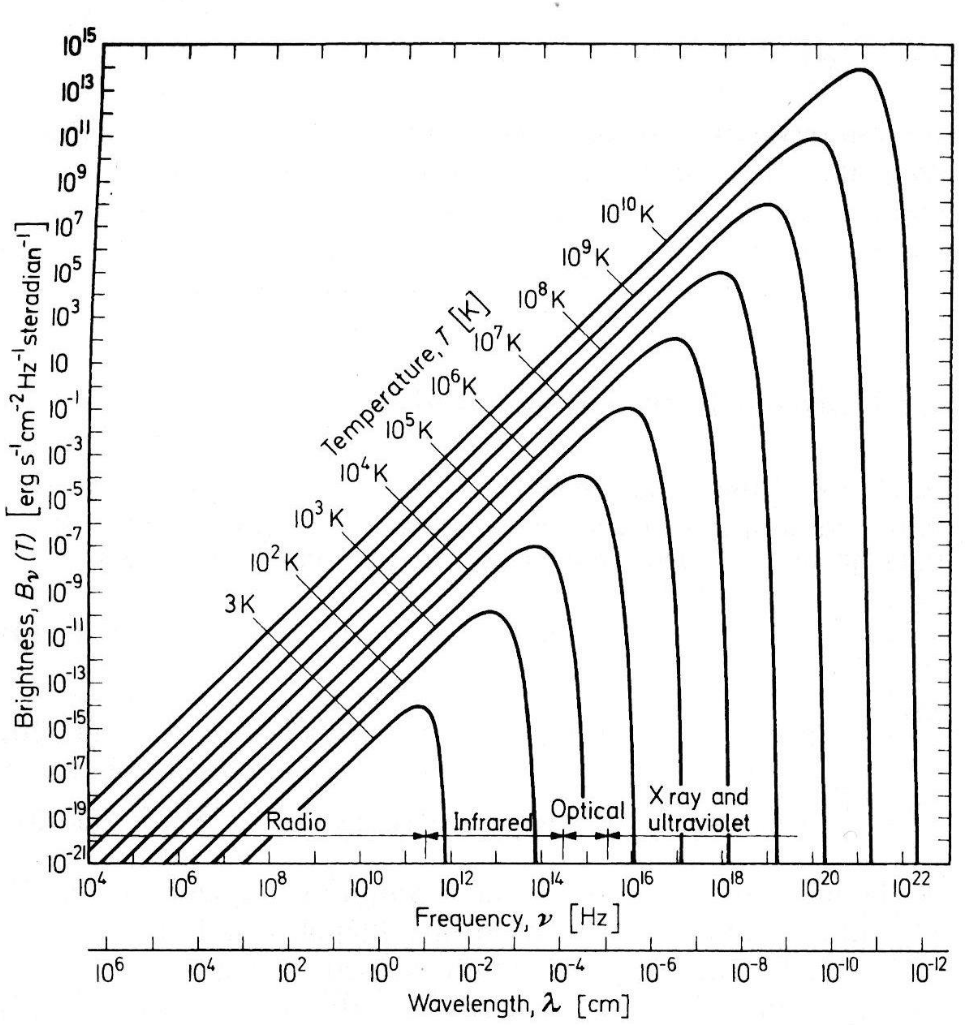
Not possible until the second half of the 20^{th} century (detector technology, from space, etc.)

Exercise

Calculate the brightness of a blackbody radiator with a temperature of 6000 K at wavelength 500 nm.


5
Model: 3012661_3
Best fit
χ^2 = 5.932 A_V = 2.3 Scale = 0.43
λF_λ (ergs/cm^2/s)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0.1
1
10
100
λ (μm)

Blackbody radiation (Planck function) is continuum radiation.



Lang

Fig. 1.1. The brightness, $B_\nu(T)$, of a black-body radiator at frequency, ν, and temperature, T. The Planck function $B_\nu(T)$, is given by Eq. (1.119)

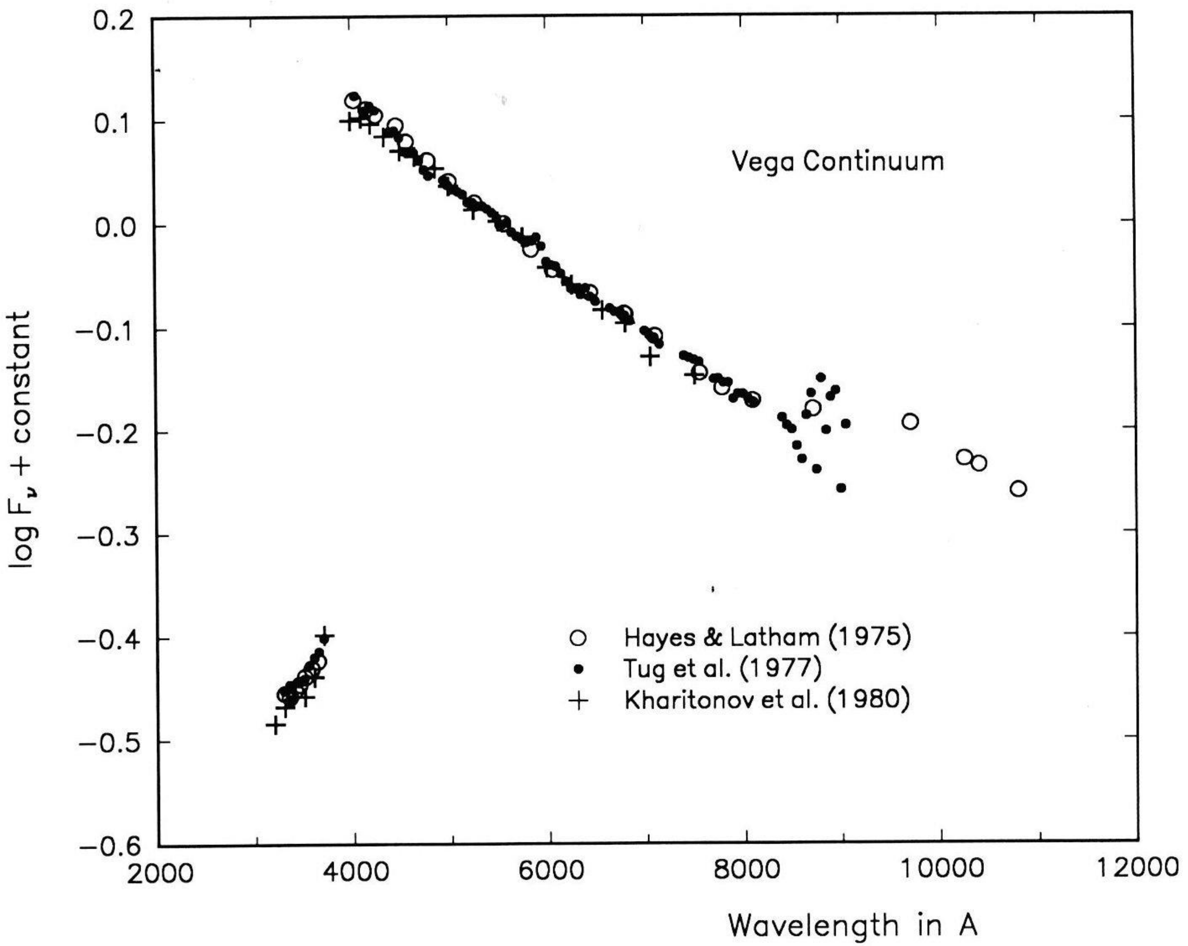


Fig. 10.3. Measurements of the energy distribution of Vega (A0 V) are compared. The large apparent scatter between 8500 Å and 9000 Å arises from the confluence of the Paschen lines.

Gray

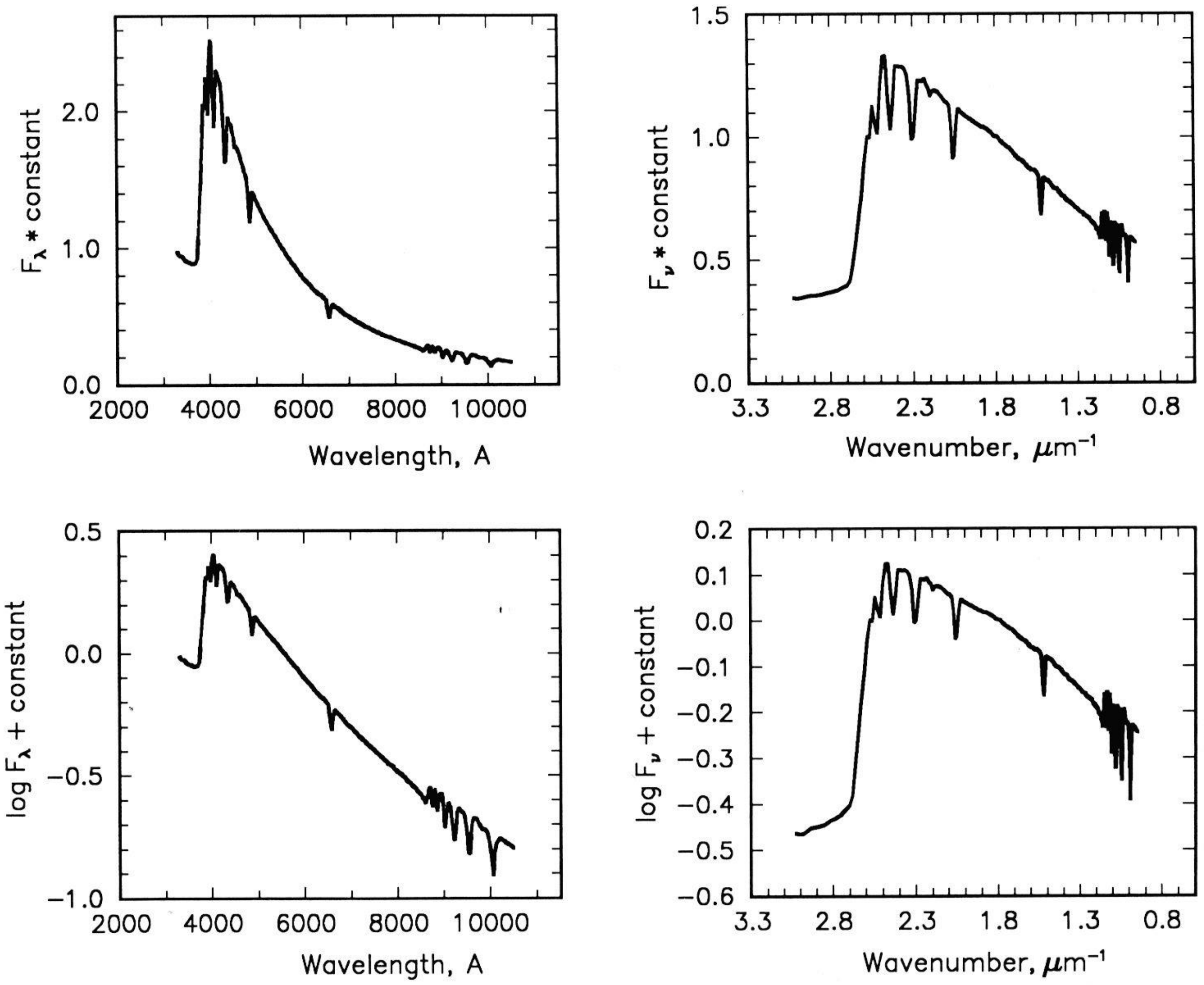


Fig. 10.4. The shape of a stellar energy distribution can look very different according to which coordinates are used. Those in Fig. 10.3 and the four shown here are the most common.

Possible ways to exhibit the energy distribution, wavelength versus frequency, logarithmic versus linear …

Gray

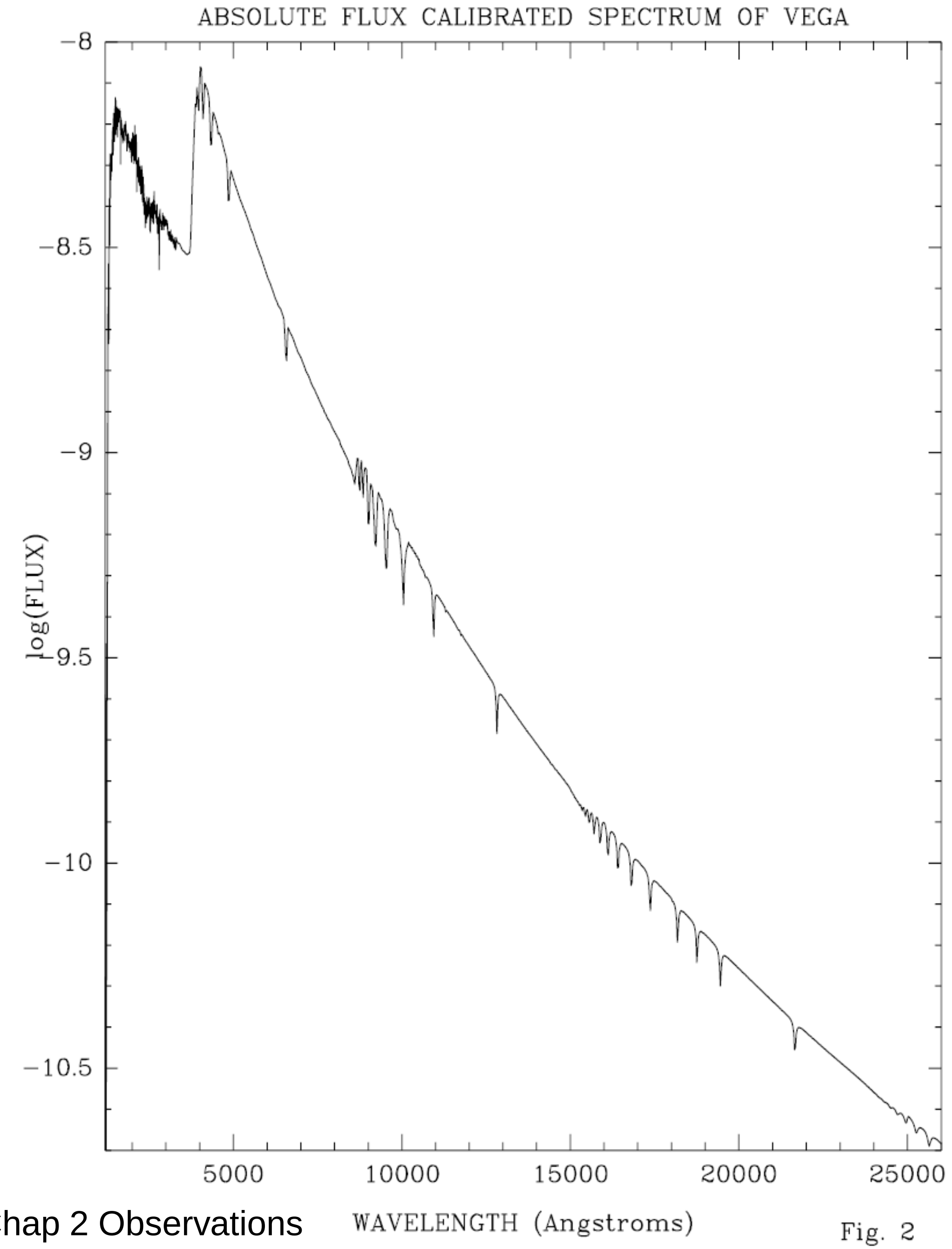
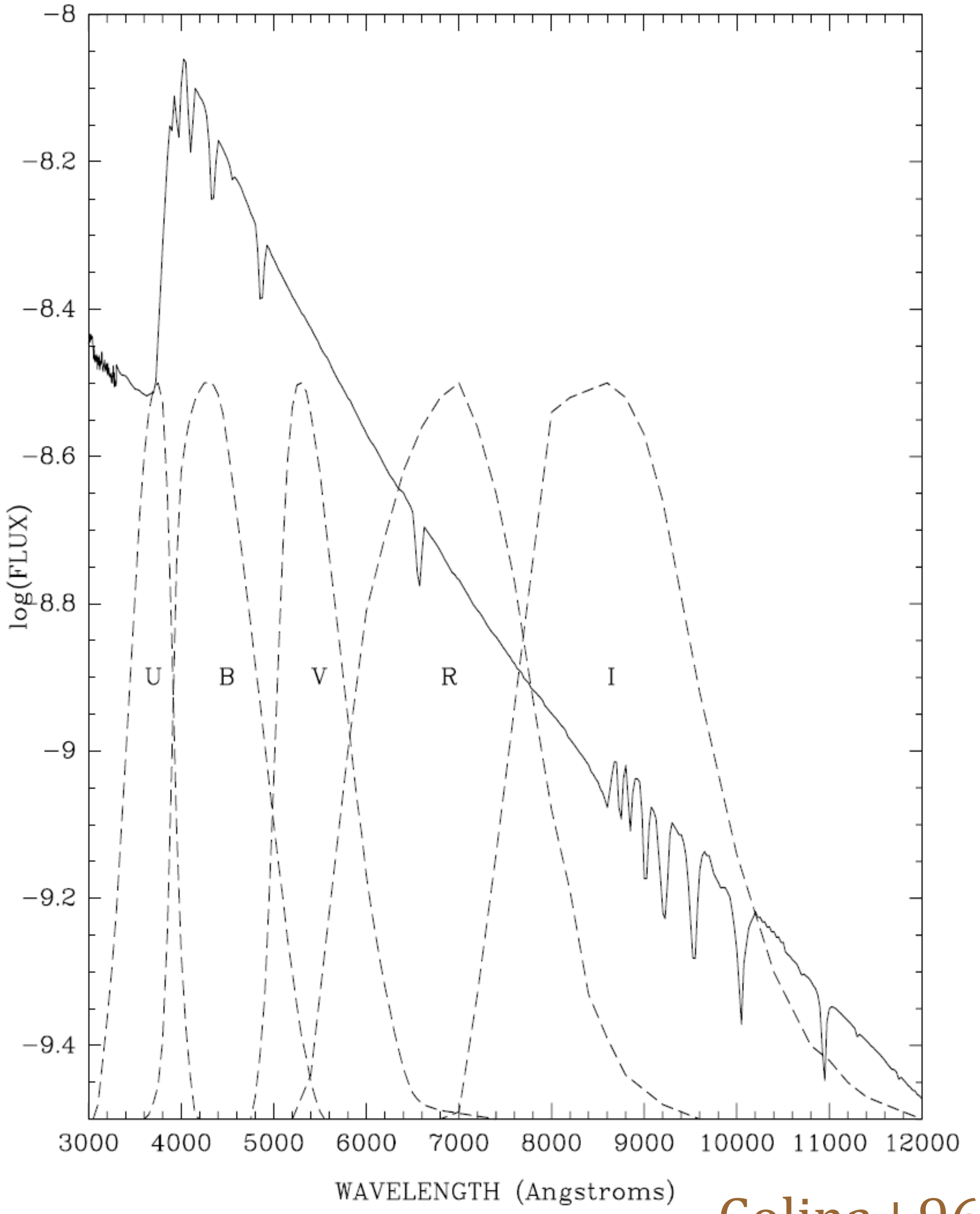


Fig. 2



Colina+96

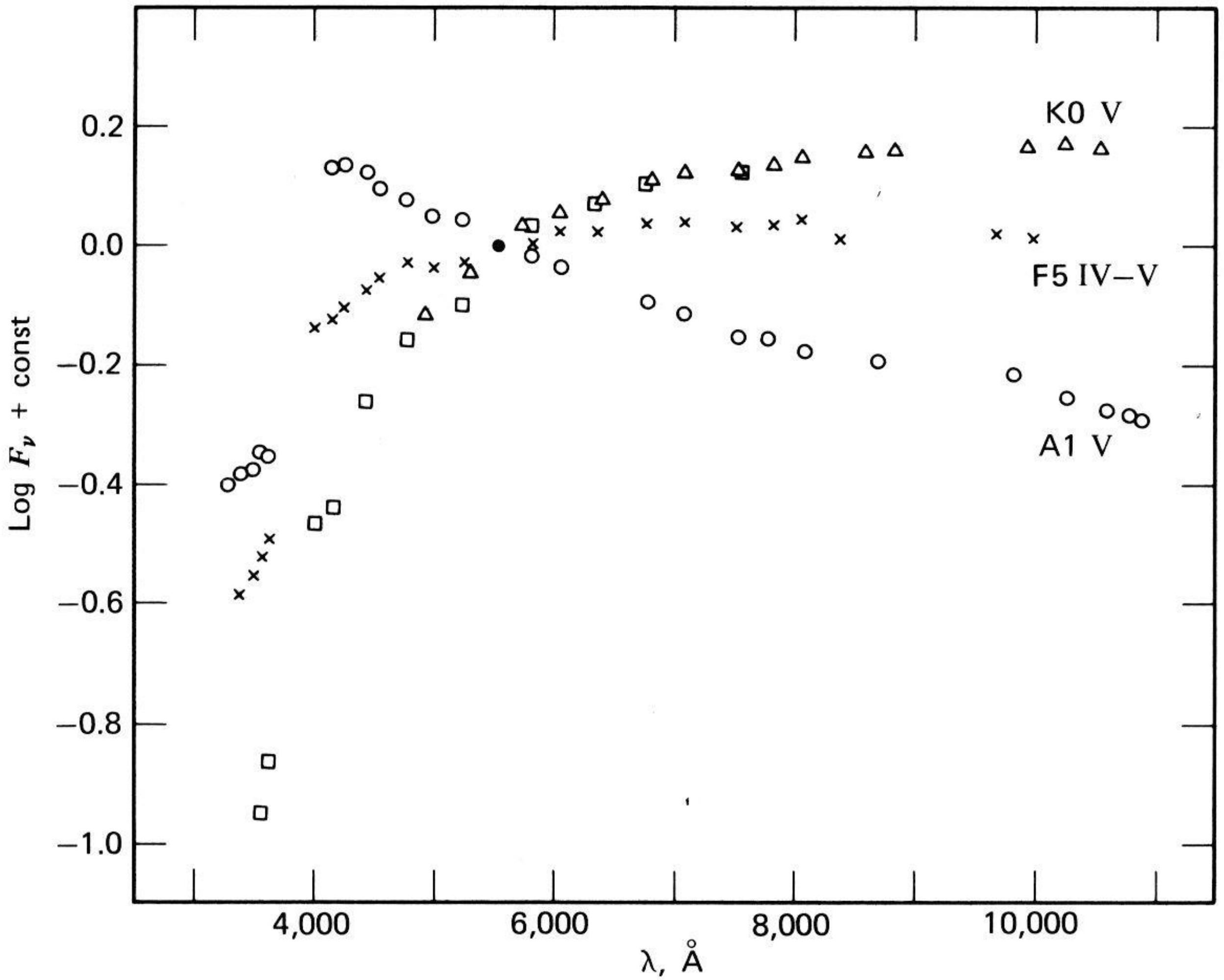


Fig. 10.6. The slope of these continua show a large change with spectral type. All three are normalized to the flux at λ5556. Some of the irregularities in the Paschen continua arise from the absorption of lines. Data from Bessell (1967), Whiteoak (1967), Gray (1967), and Hayes (1968, private communication).

Behavior of the stellar photospheres of various temperatures …

Gray

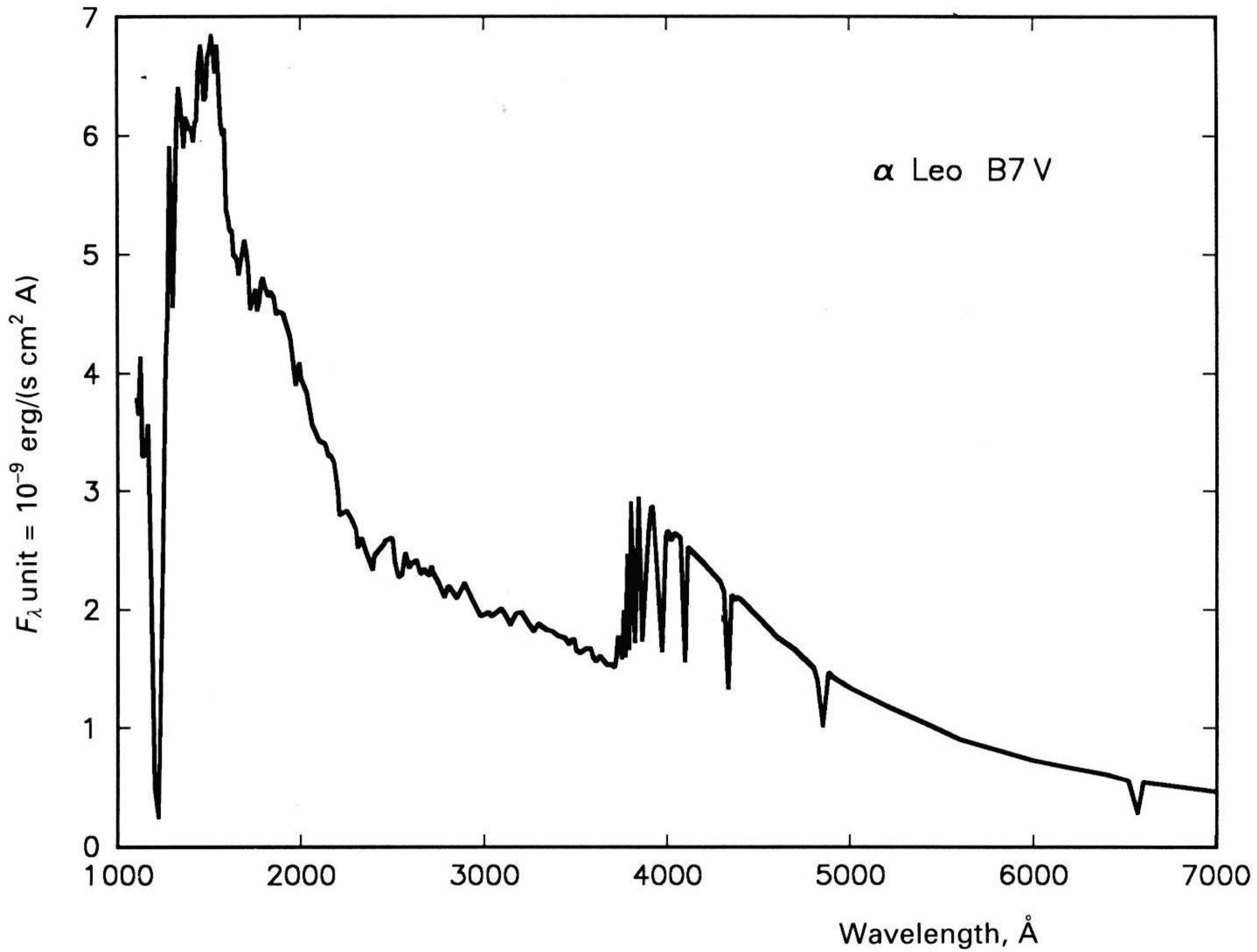


Fig. 10.7. The ultraviolet portion of the energy distribution for α Leo is strong and should be used to model the star. Data from Code *et al.* (1976).

... but there is more than the photosphere

... in UV

Code+76, Gray

… or in IR

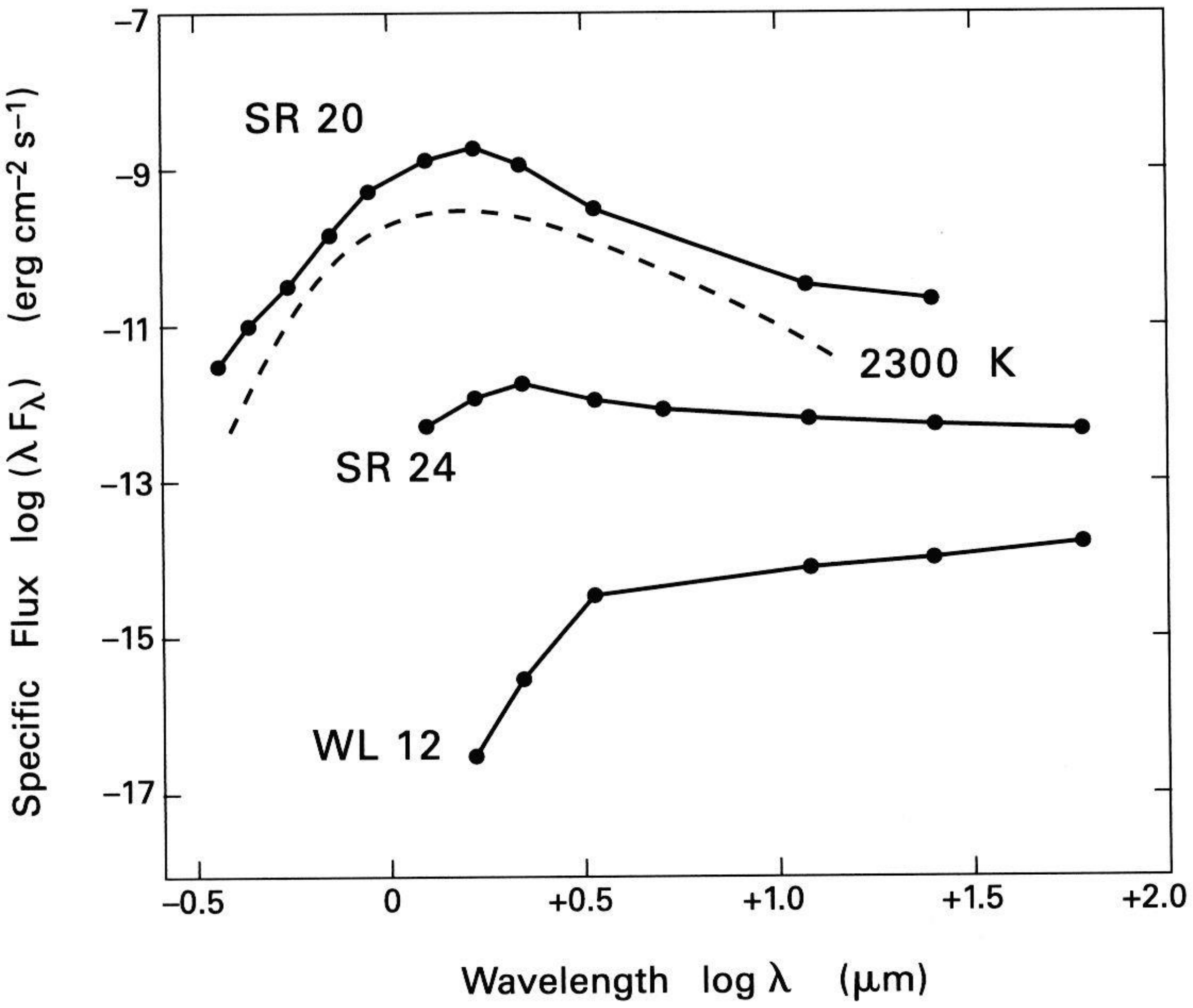


Figure 4.3 Spectral energy distribution of three stars in the ρ Ophiuchi dark cloud complex. The dashed curve corresponds to a blackbody at 2300 K. From bottom to top, these broadband spectra exemplify Class I, II, and III sources, respectively.

Stahler & Pallas

The Interstellar Medium --- HW20220303

due in two weeks

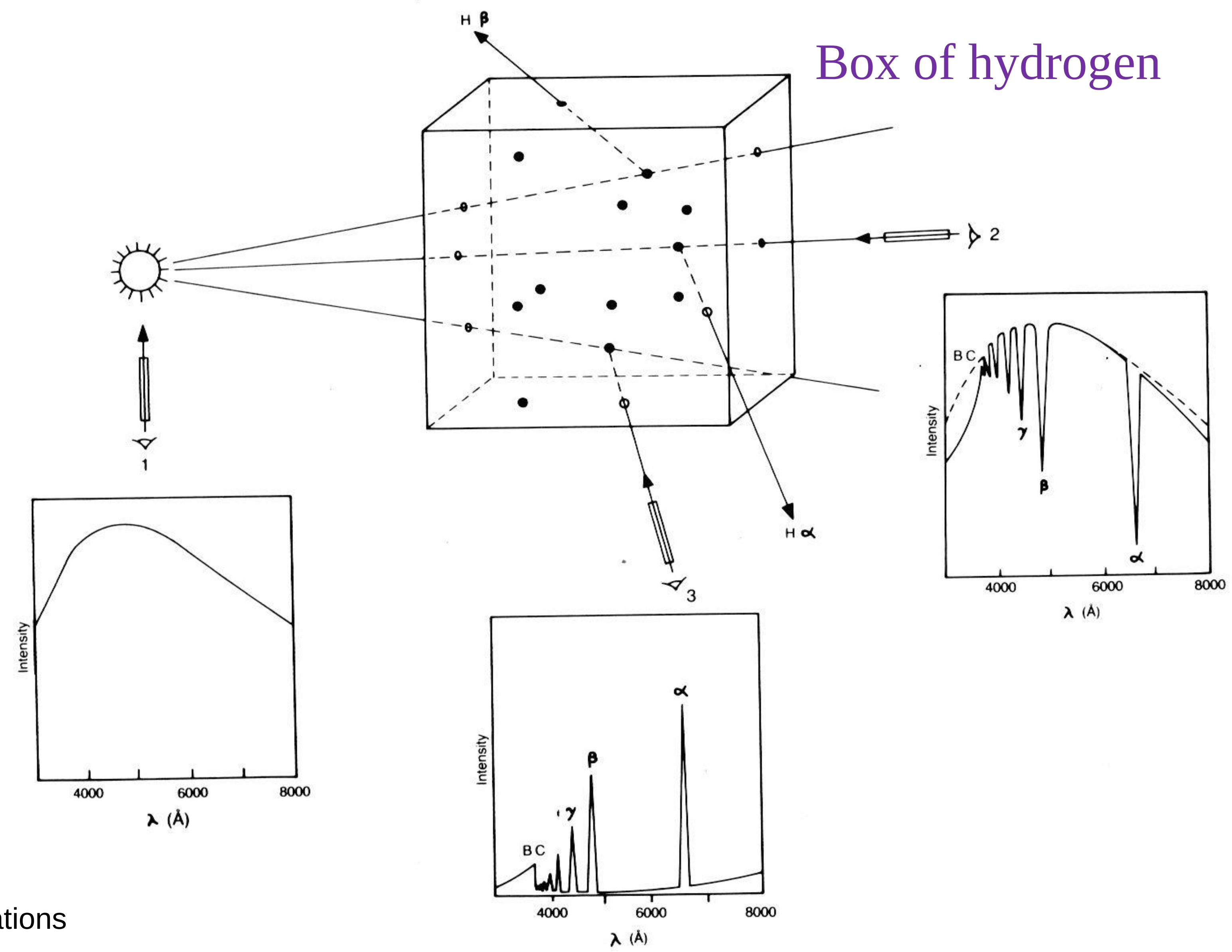
1. Given the surface temperature and radius of the Sun, compute (a) the solar luminosity, (b) the energy flux received above the Earth atmosphere (the "solar constant"), (c) the flux received at Proxima Centauri.

2. The gas in molecular clouds has a typical temperature of 20 K, whereas the gas in intergalactic space of a galaxy cluster has a typical temperature of 10 million K. Estimate in each case the wavelength range around which blackbody radiation has the strongest intensity.

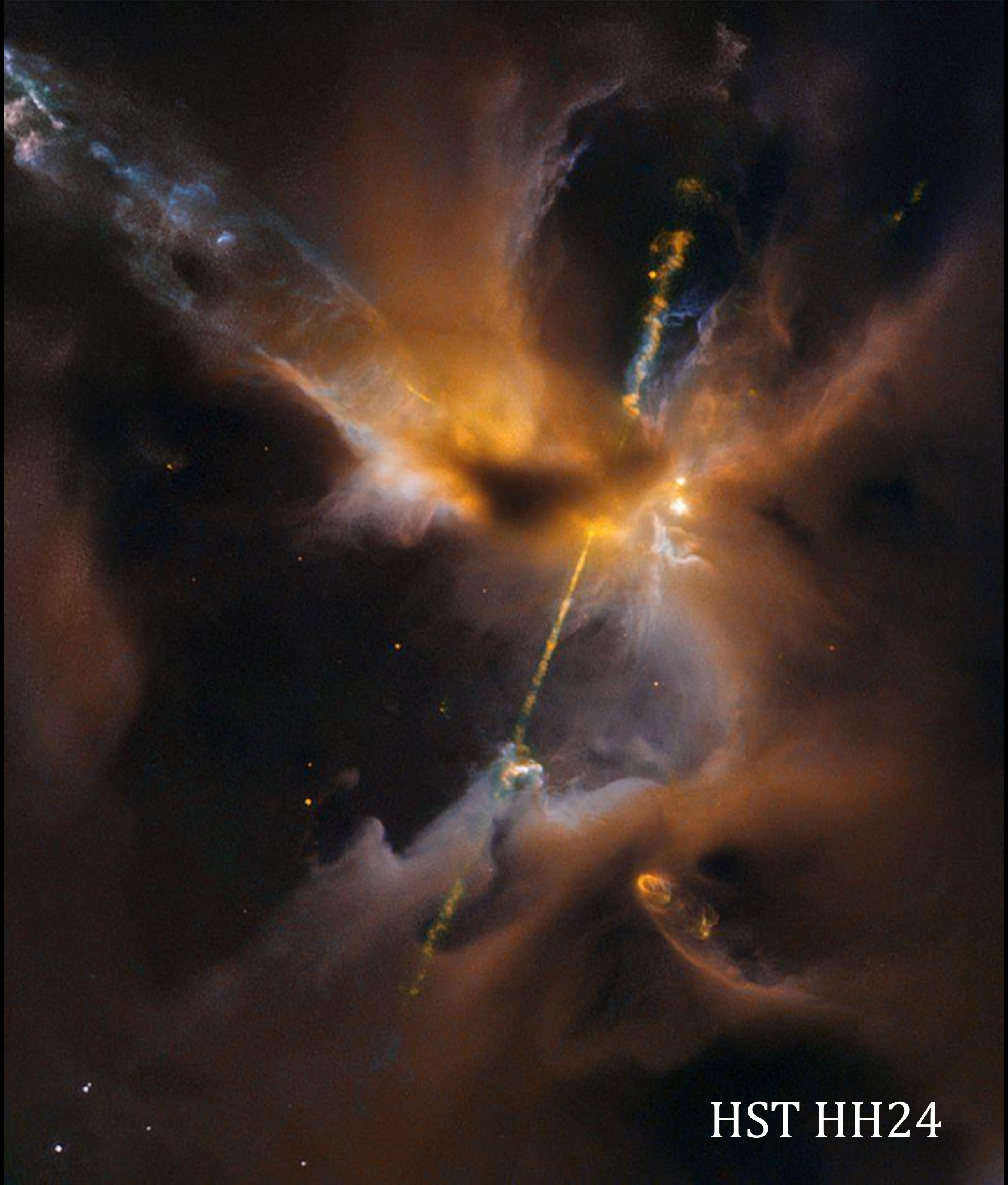
3. From simple Bohr model or dimensional analysis, estimate the typical frequency ranges of electronic, vibrational, and rotational transitions of molecules. For each of these transitions, what kind of observational instrumentation (e.g., UV, optical/IR, FIR, millimeter) is required?

4. Calculate the Doppler FWHM for a gas of H atoms radiating at 100 nm with a temperature of 300 K. Show that the collisional broadening in such a gas will not be important until the number density is approximately 10^{21} cm^{-3}. Assume a geometric cross-section for hydrogen-atom collisions.

Formation of Spectral Lines (Kirchhoff's law)

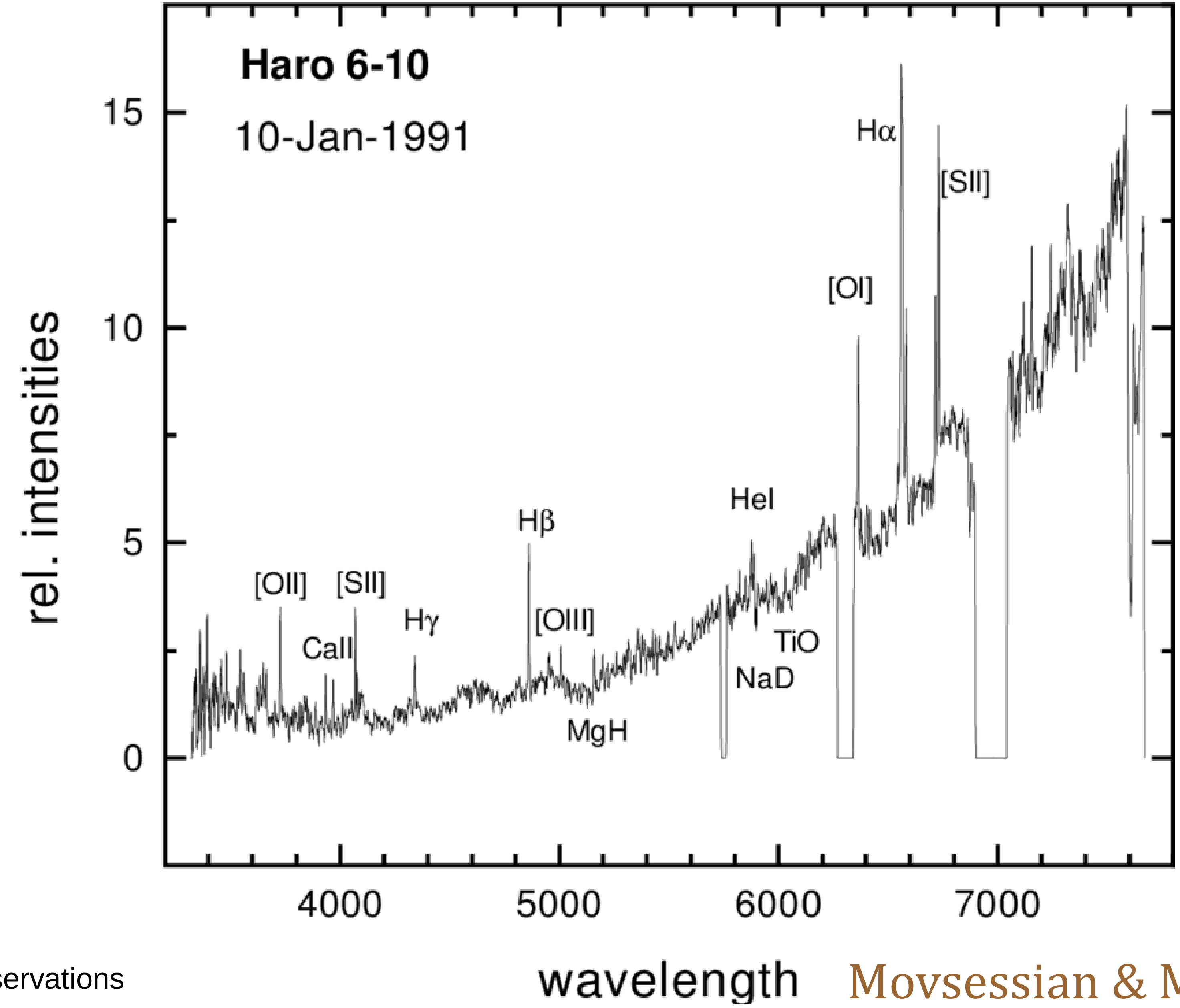


Kaler

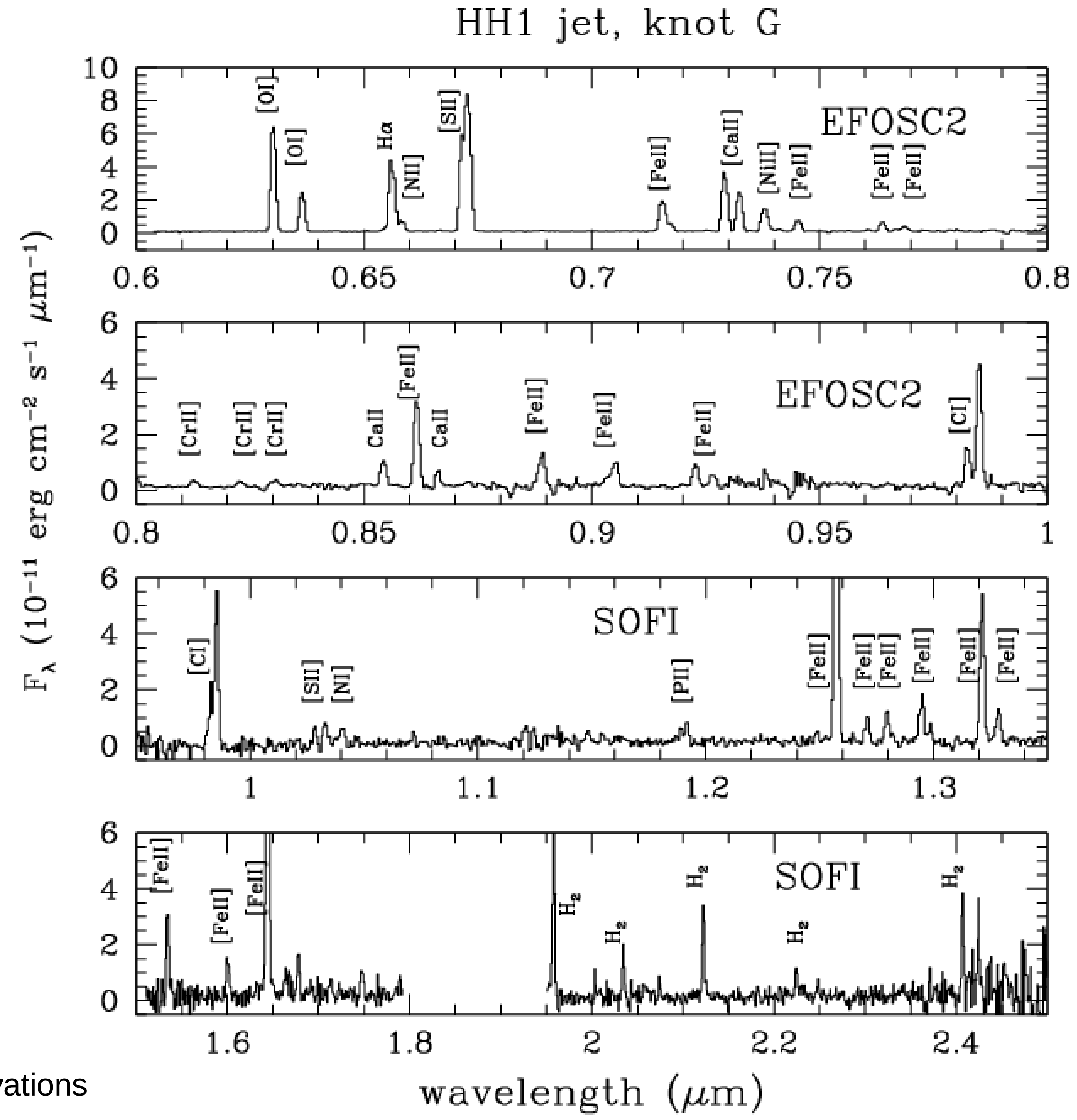


HST HH24

HST HH46/47



Movsessian & Magakian (1999)



HH1 jet, knot G
EFOSC2
EFOSC2
SOFI
SOFI
[OI]
[OI]
Hα
[NII]
[SII]
[FeII]
[CaII]
[NiII]
[CrII]
CaII
[CI]
[PII]
[NI]
H_2
F_λ (10^{-11} erg cm^{-2} s^{-1} μm^{-1})
wavelength (μm)

Nisini+05

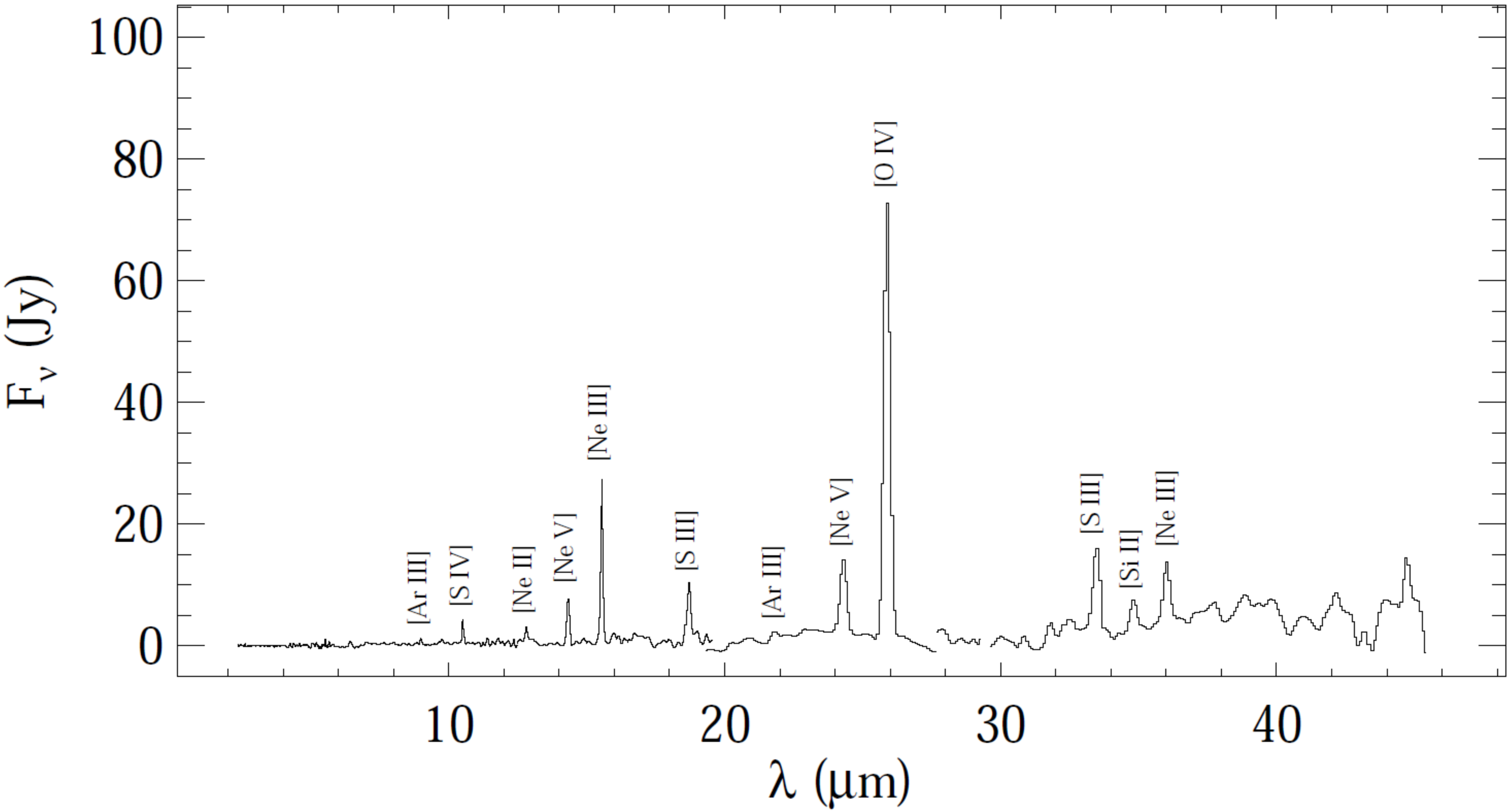


FIG. 2.—*ISO*-SWS spectrum of the planetary nebula NGC 6445

van Hoof +99

Continuum

Absorption --- bound-free (ionization); free-free
Emission --- (thermal) blackbody; bremsstrahlung
(non-thermal) synchrotron; Cherenkov

Matter ←→ energy ➔ what we observe

Thermodynamics (ISM cooling, heating, chemical reactions …)

Line

- Emission --- atom/ion/molecule already excited (by collisions or absorption of a photon, stellar or else)
- Absorption --- atom initially in a lower state and absorbs a background photon

Transition between 2 quantum levels
(electronic, rotational, vibrational, stretching…)

- Collision ($u \rightarrow l$) or ($l \rightarrow u$) (upwards or downwards)
  spontaneous emission ($u \rightarrow l$) (only downwards)
  absorption ($l \rightarrow u$) (only upwards)
- Diagnosis: line strength, central wavelength, shape, ...

About hydrogen …