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., $h\nu + \mathrm{H}(\,^1\mathrm{S}) \rightarrow \mathrm{H}(\,^2\mathrm{P})$ ($h\nu$ =10.2 eV or λ=121.6 nm)
  - **continuum** (absorption, emission) over a wide range of ν
    e.g., $h\nu + \mathrm{H}(^1\mathrm{S}) \rightarrow \mathrm{H}^+ + \mathrm{e}^-$ ($h\nu \geq 13.6$ eV or $\lambda \leq 91.2$ nm)

- **Photometry**

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

Astronomers use "magnitude" ↔ flux density

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

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

- **Spectroscopy**

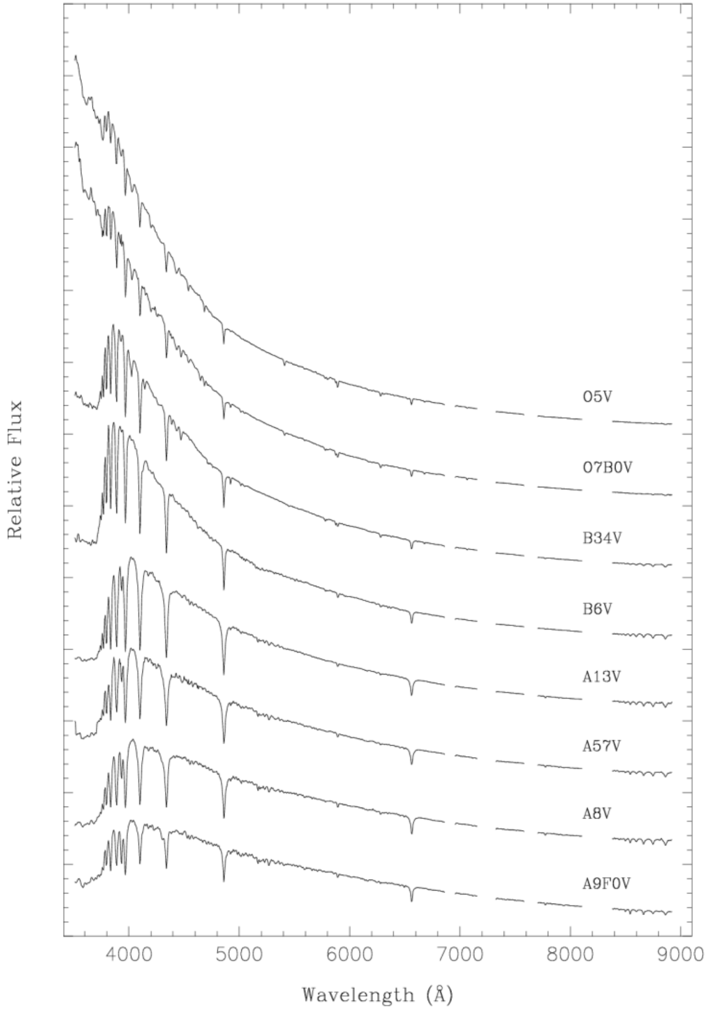
measurements of brightness distribution with wavelength or frequency

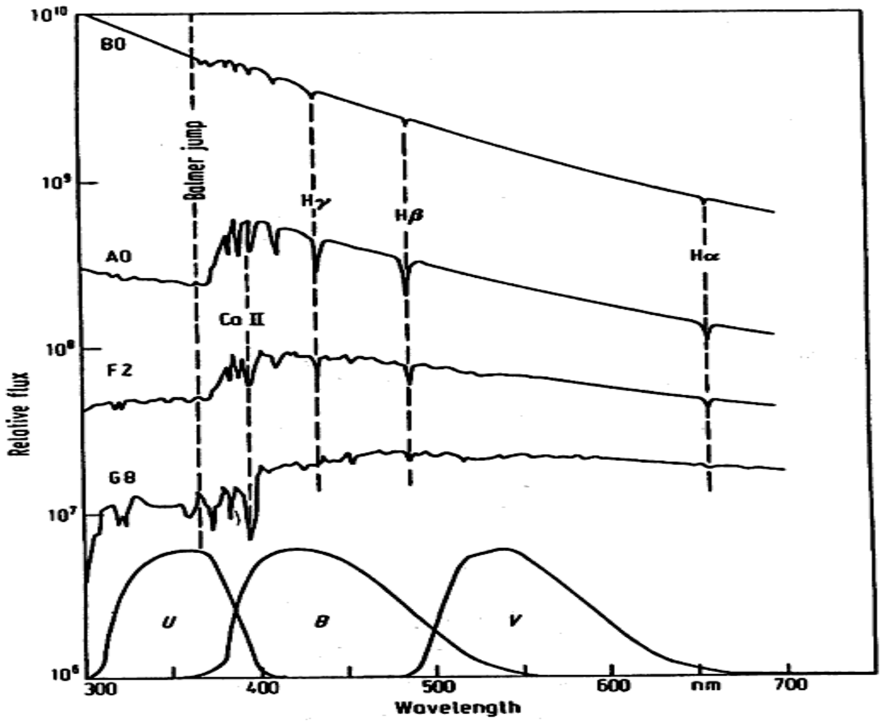
Spectrophotometry; Integral Field Unit (IFU); IF Spectrograph

- **Polarimetry**

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

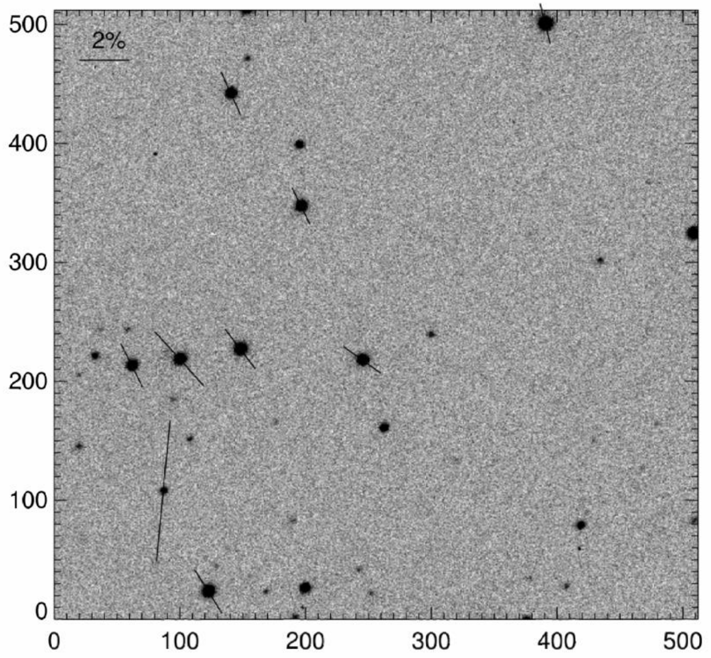
Spectroscopy of hot stars

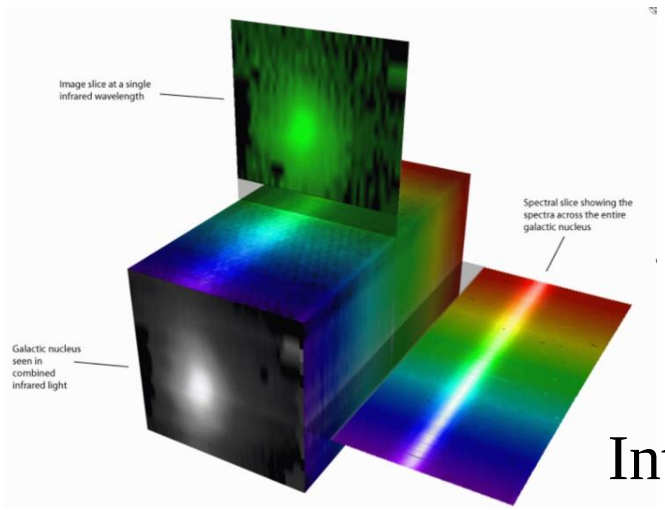




Imaging photometry

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;
  $m_\mathrm{V} = 0\ \rightarrow 2.08$ *μlux;* $m_\mathrm{V} = 6\ \rightarrow 8$ *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

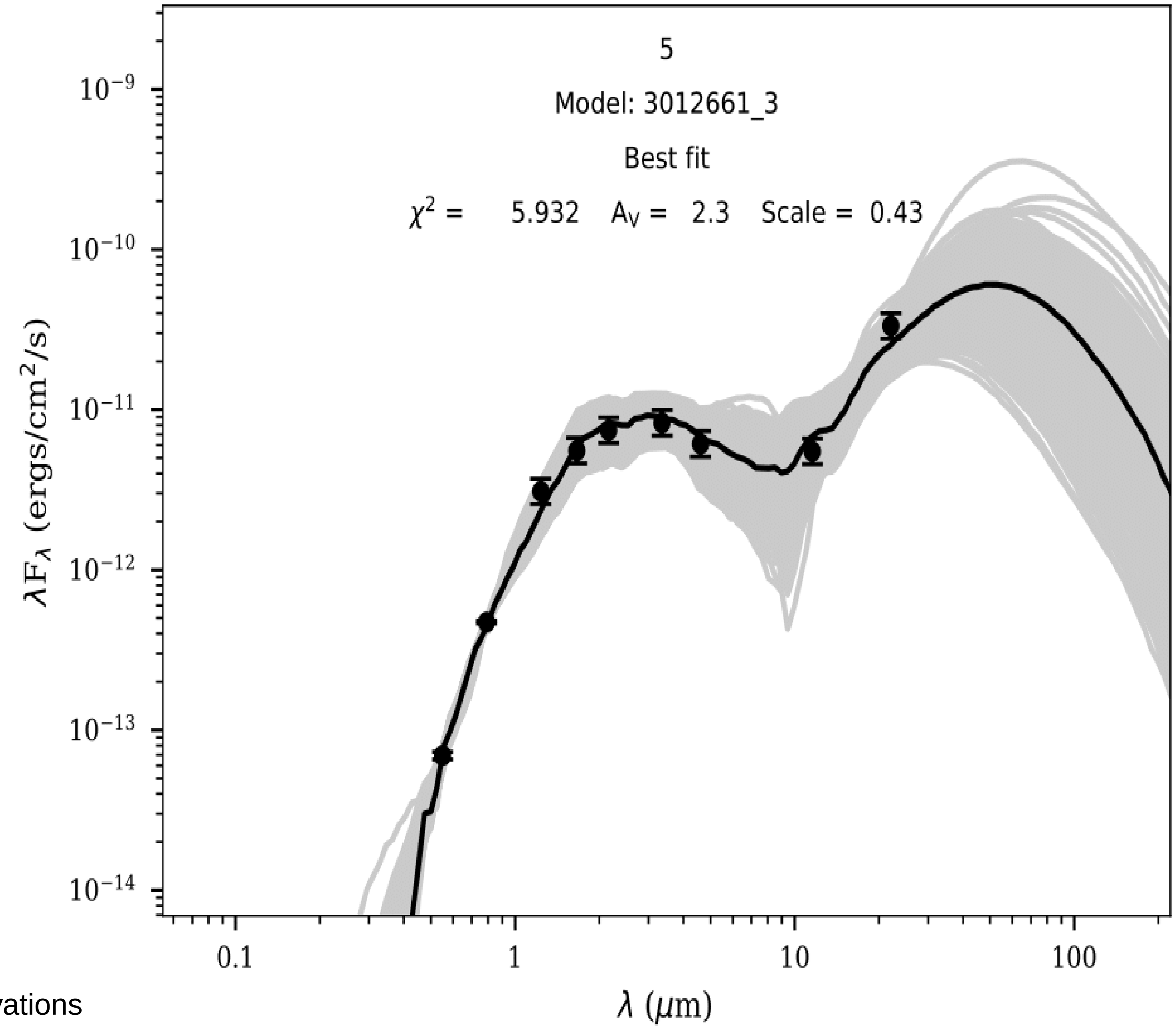
Not possible until the second half of the 20th century (detector technology, from space, etc.)

Exercise

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

A: $2.6\times 10^{-8}\ \mathrm{W\ m^{-2}\ rad^{-2}\ Hz^{-1}}$

Kraus p.3-19


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)

Exercise

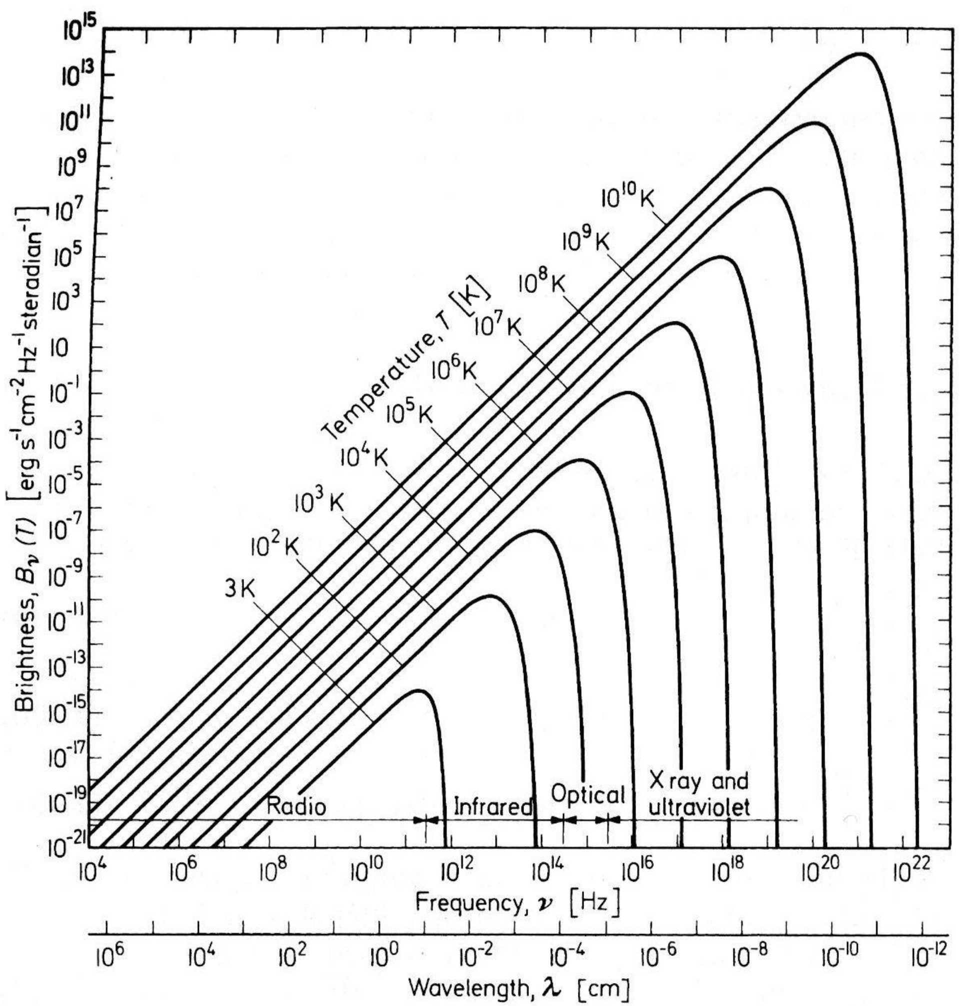
The solar photosphere has a temperature of 6000 K.

The gas in molecular clouds has a typical temperature of 15 K.

The gas in intergalactic space of a galaxy cluster has a typical temperature of 10 million K.

Estimate the wavelength range around which blackbody radiation has the strongest intensity in the above cases.

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)

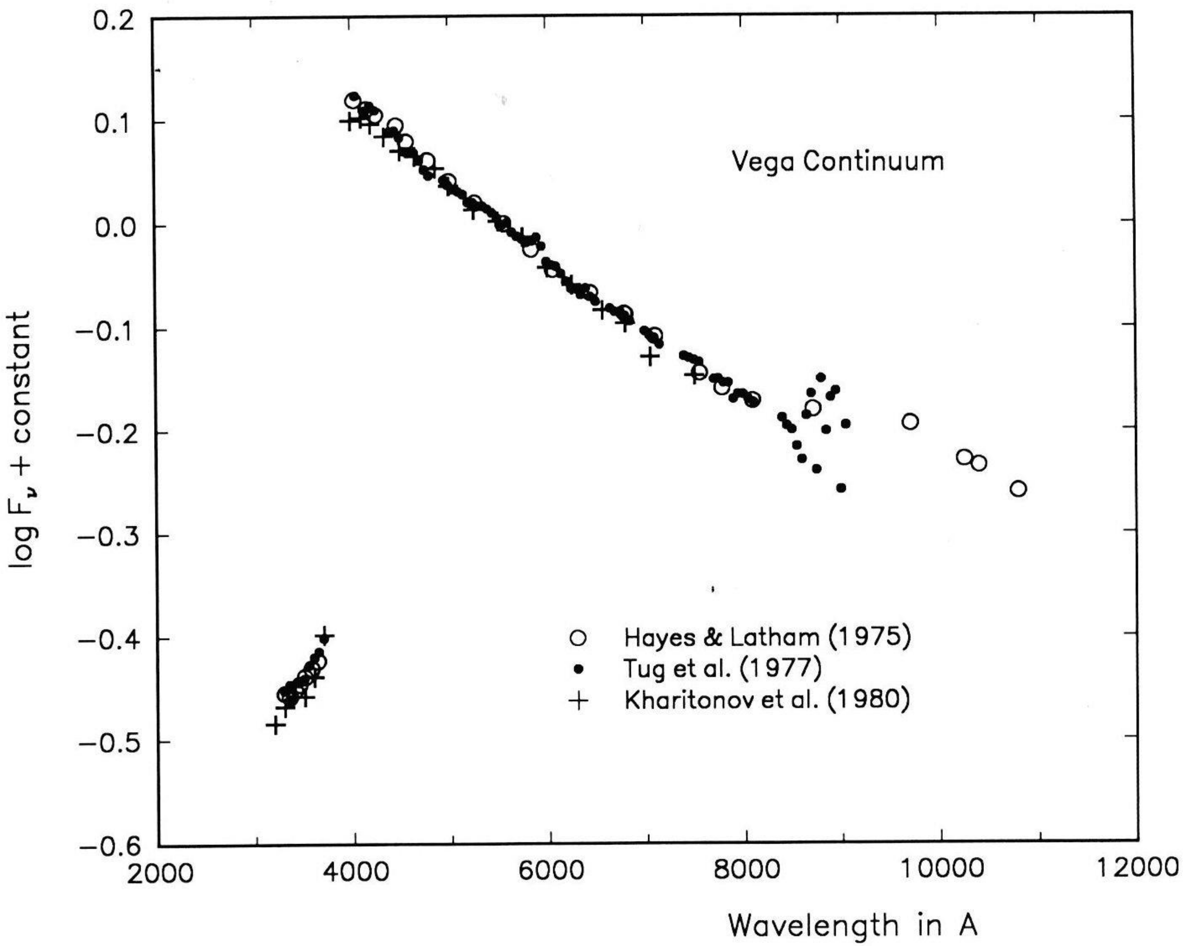


Fig. 10.3. Measurements of the energy distribution of Vega (A0 V) are compared. The large apparent scatter between 8500 Å and 9000 Å arises from the confluence of the Paschen lines.

Gray

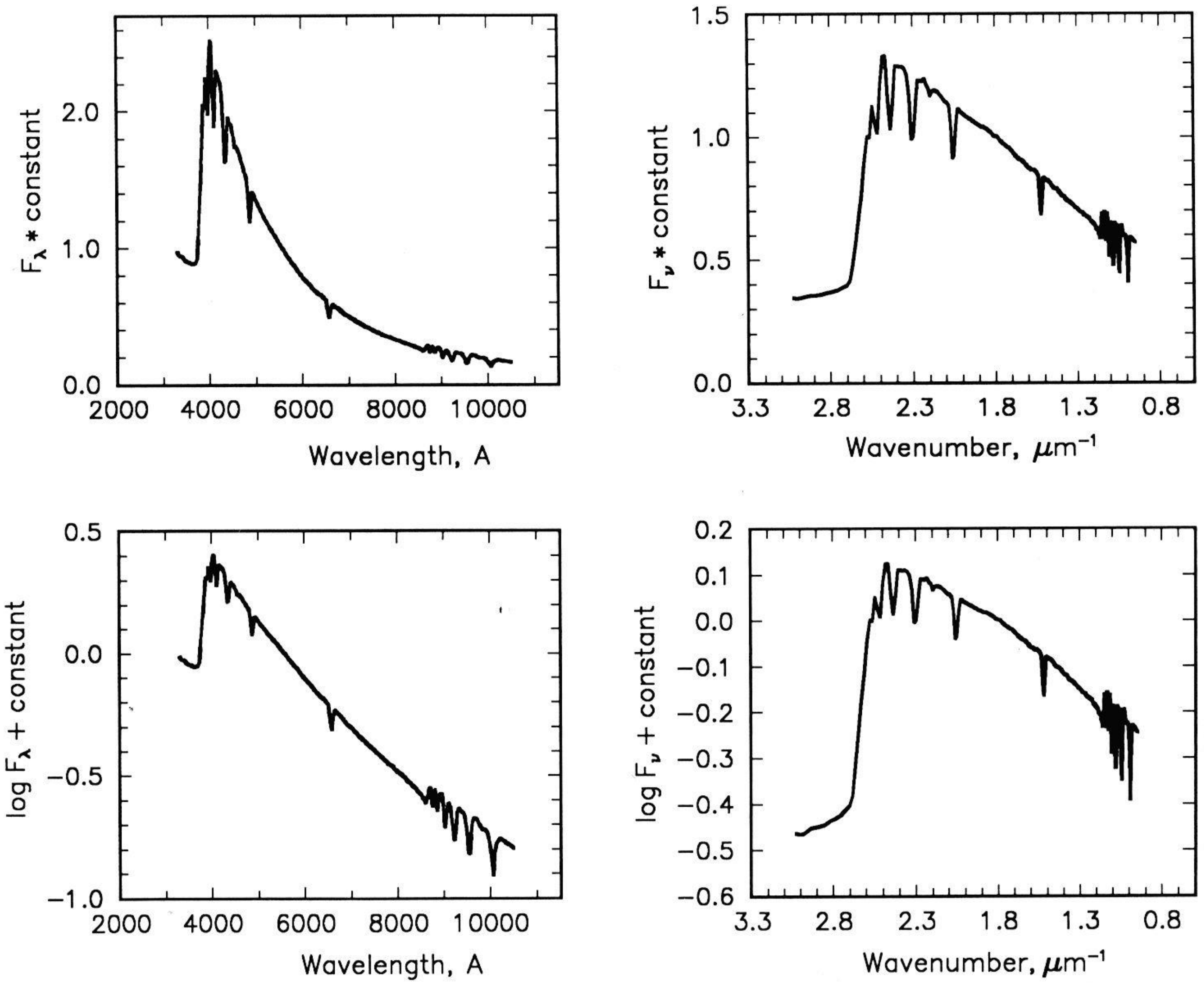


Fig. 10.4. The shape of a stellar energy distribution can look very different according to which coordinates are used. Those in Fig. 10.3 and the four shown here are the most common.

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

Gray

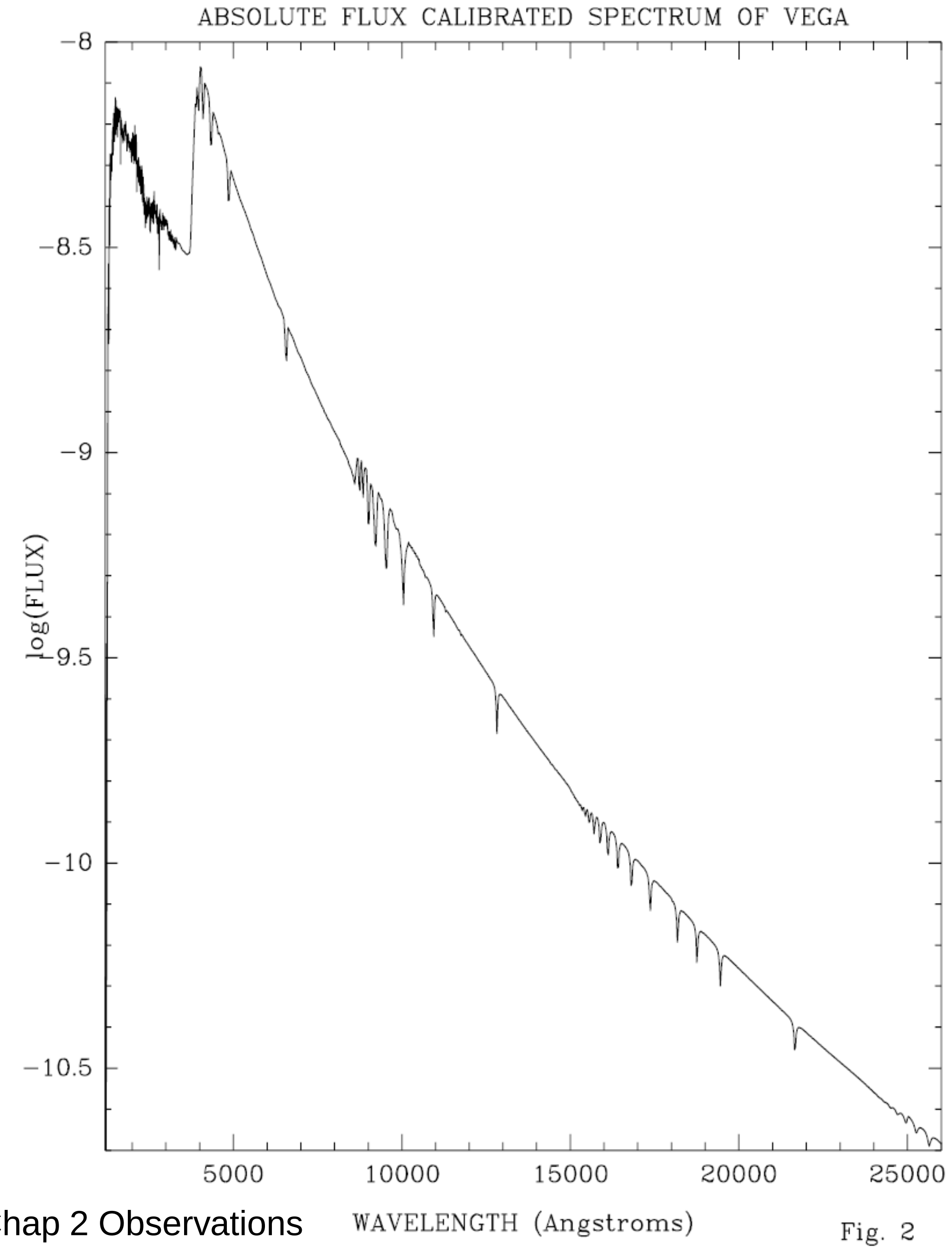
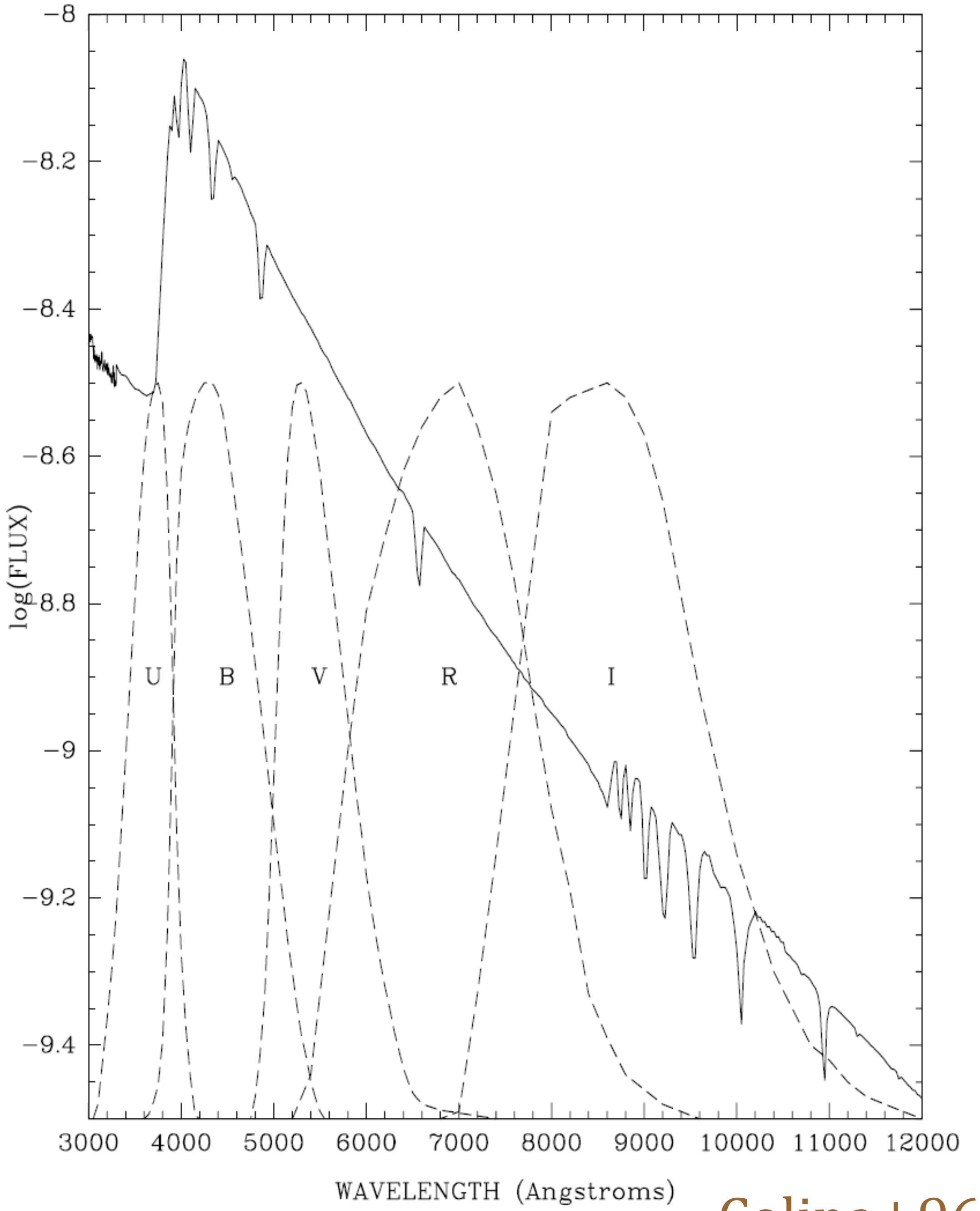


Fig. 2



Colina+96

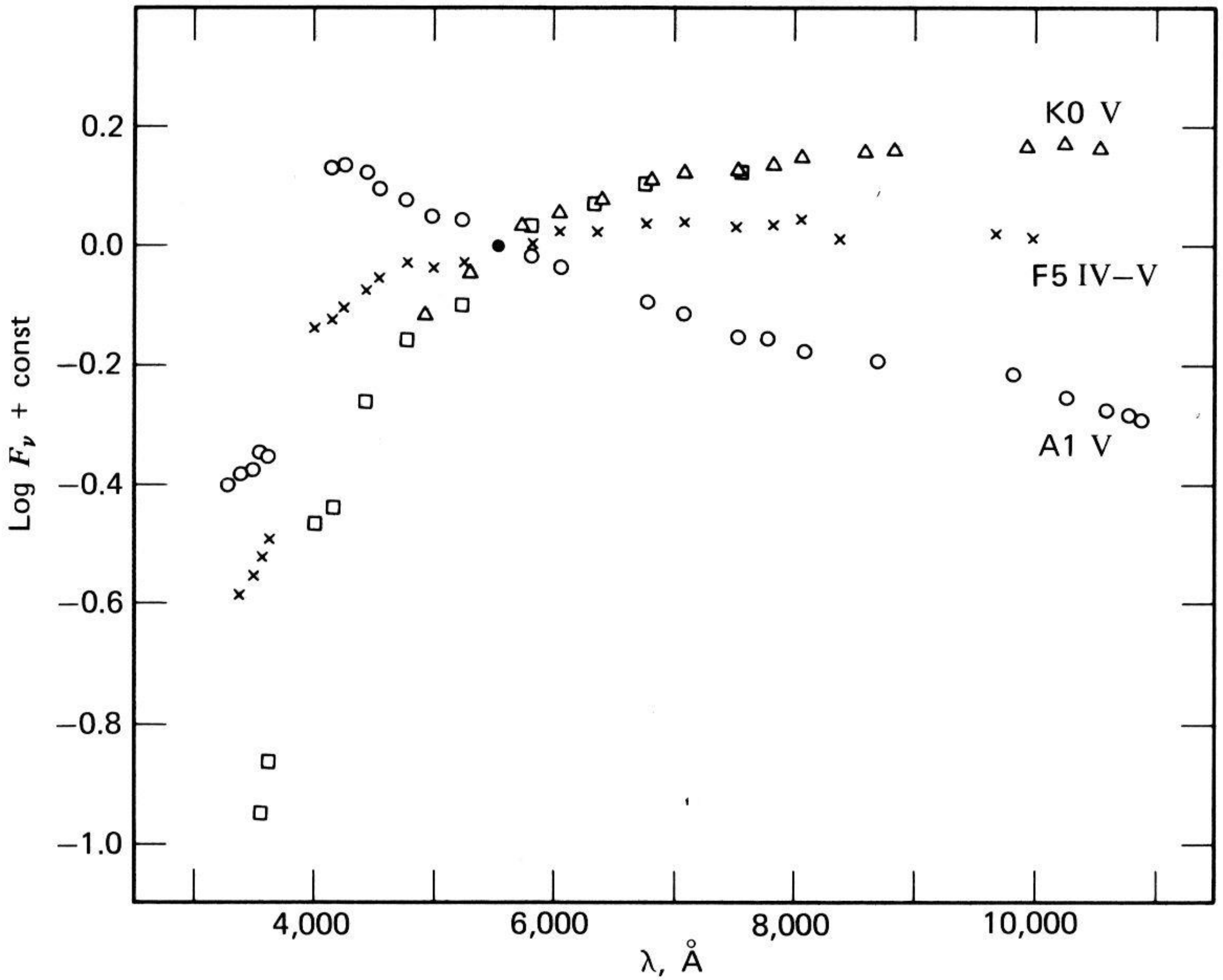


Fig. 10.6. The slope of these continua show a large change with spectral type. All three are normalized to the flux at λ5556. Some of the irregularities in the Paschen continua arise from the absorption of lines. Data from Bessell (1967), Whiteoak (1967), Gray (1967), and Hayes (1968, private communication).

Behavior of the stellar photospheres of various temperatures …

Gray

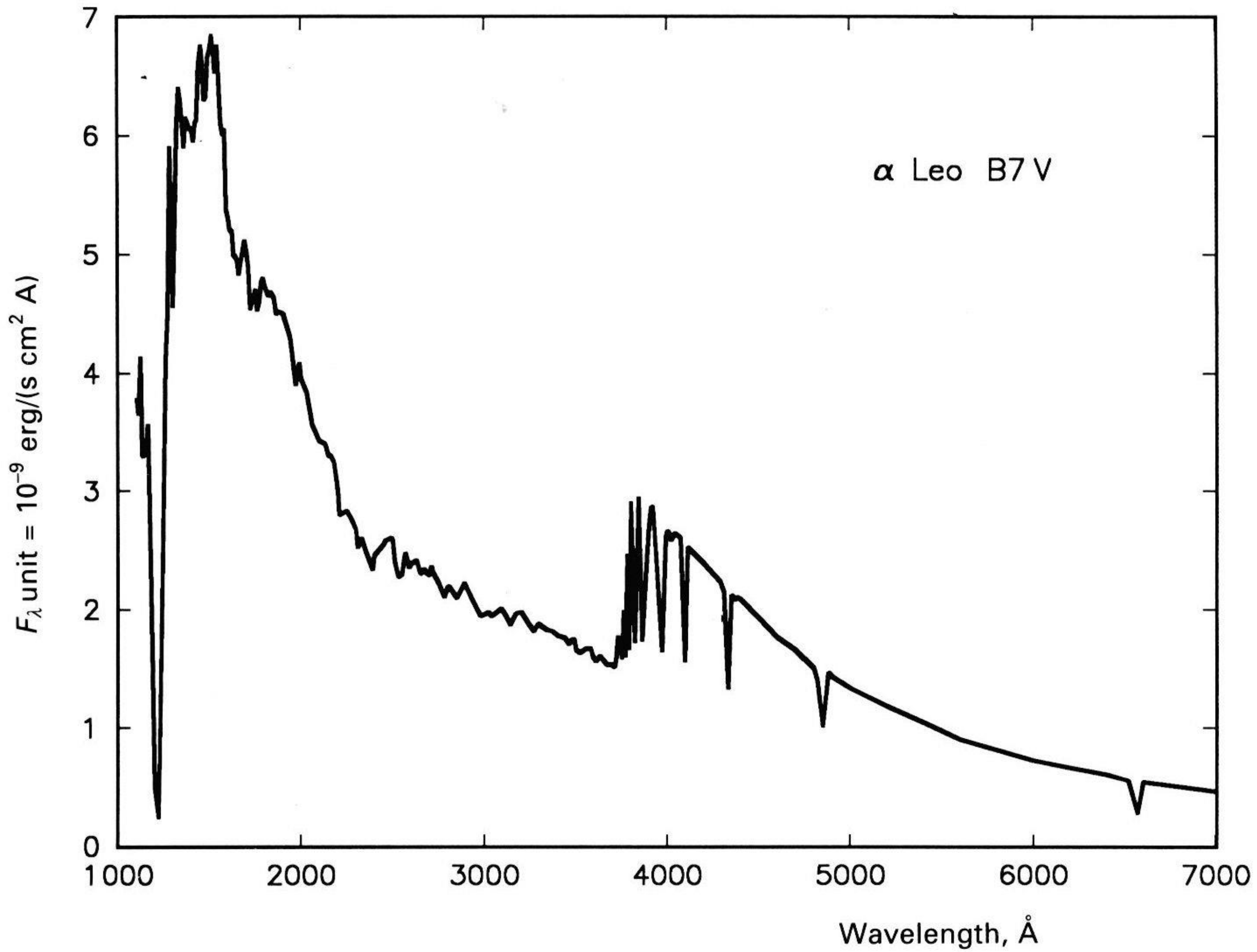


Fig. 10.7. The ultraviolet portion of the energy distribution for α Leo is strong and should be used to model the star. Data from Code *et al.* (1976).

… but there is more than the photosphere

… in UV

Code+76, Gray

… or in IR

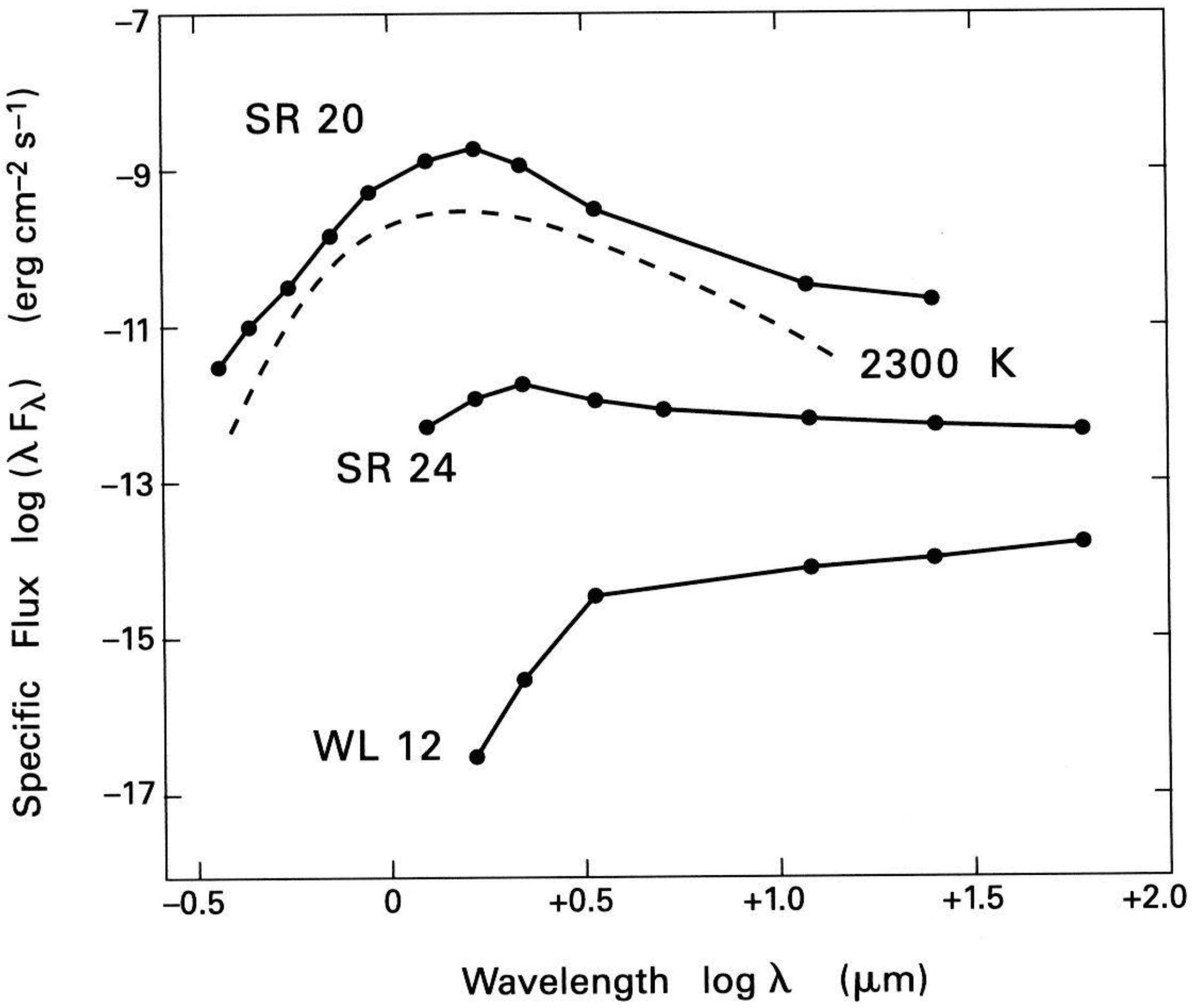
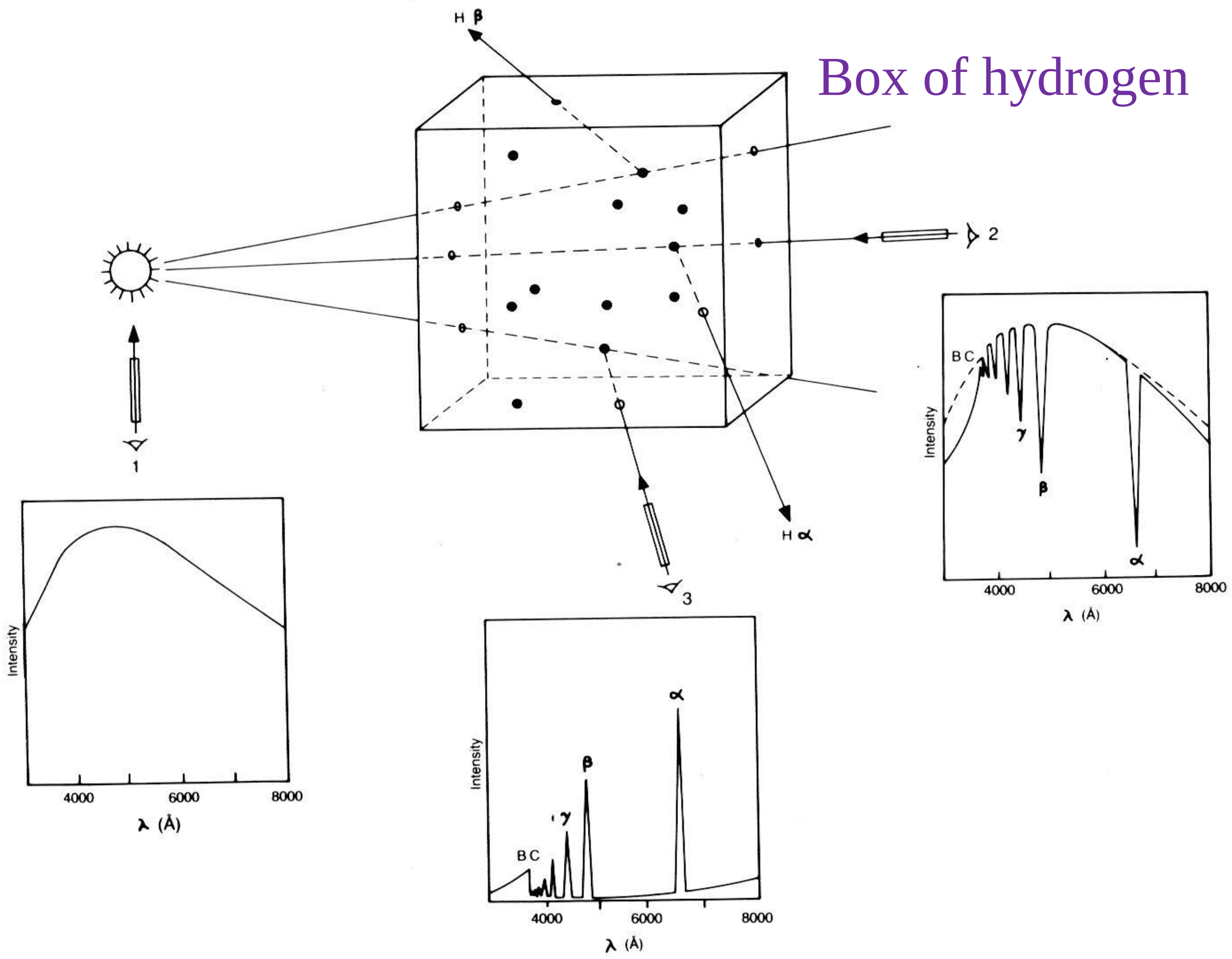


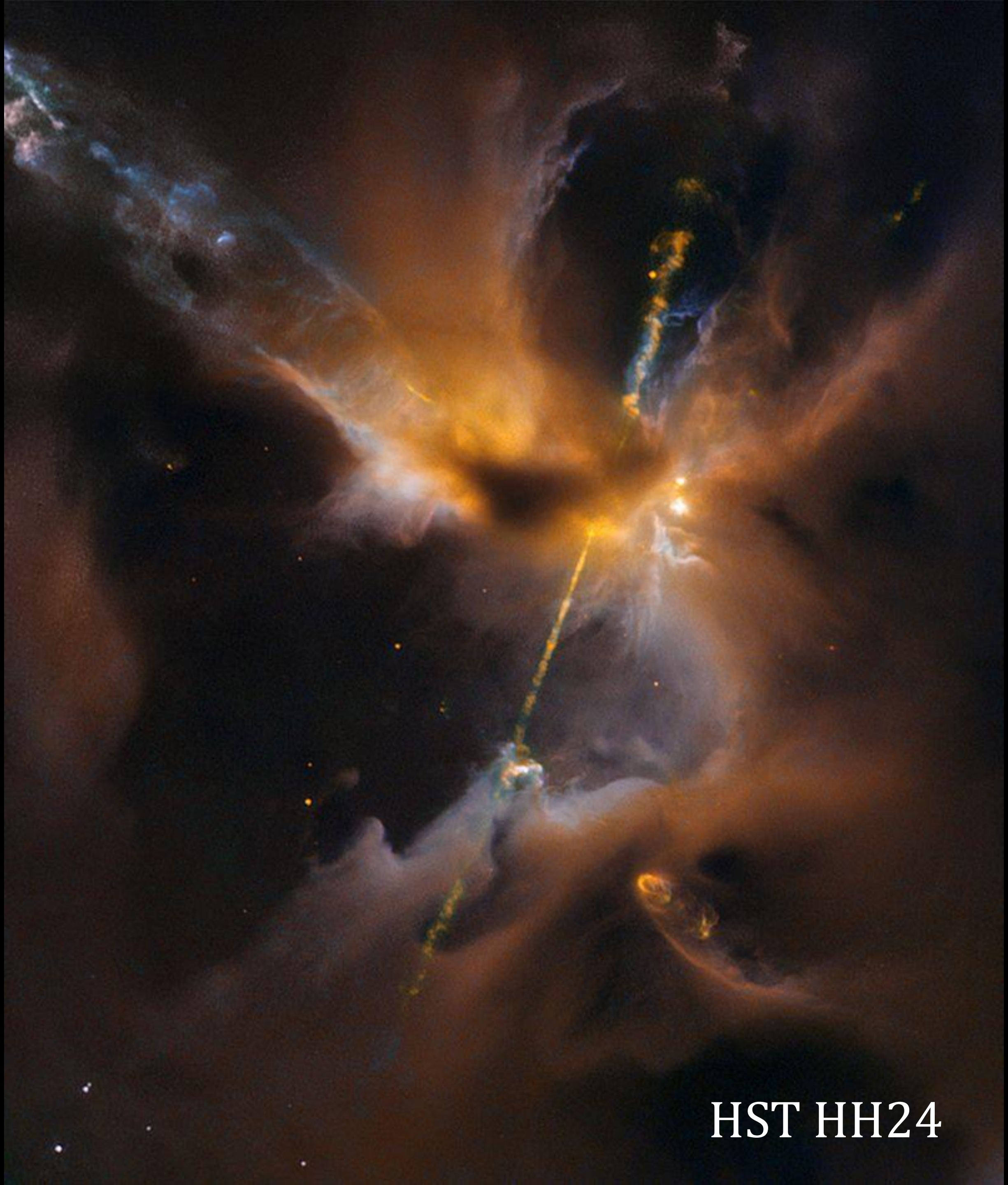
Figure 4.3 Spectral energy distribution of three stars in the ρ Ophiuchi dark cloud complex. The dashed curve corresponds to a blackbody at 2300 K. From bottom to top, these broadband spectra exemplify Class I, II, and III sources, respectively.

Stahler & Pallas

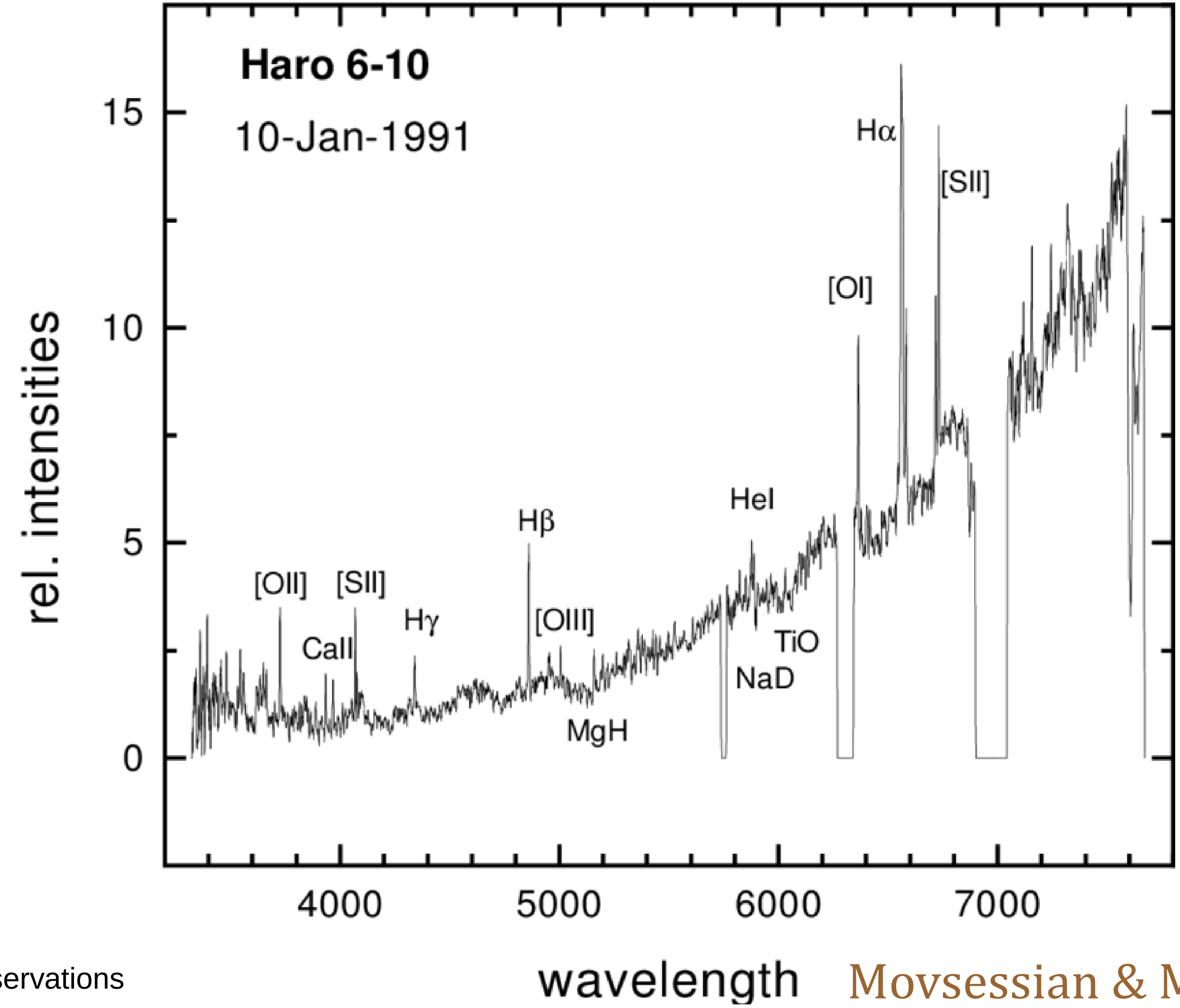
Formation of Spectra (Kirchhoff's law)



Kaler



HST HH24


HST HH46/47



Movsessian & Magakian (1999)

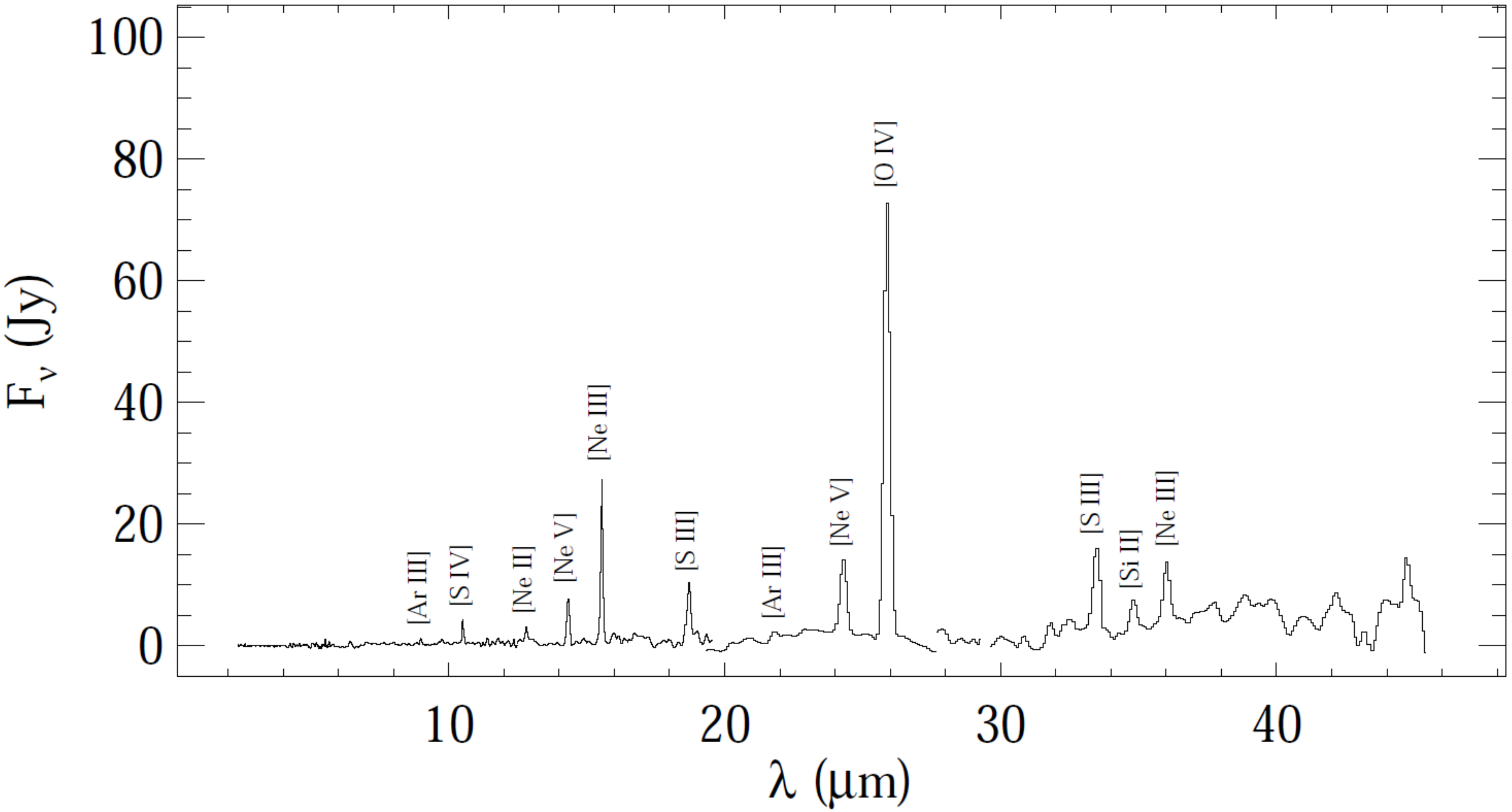
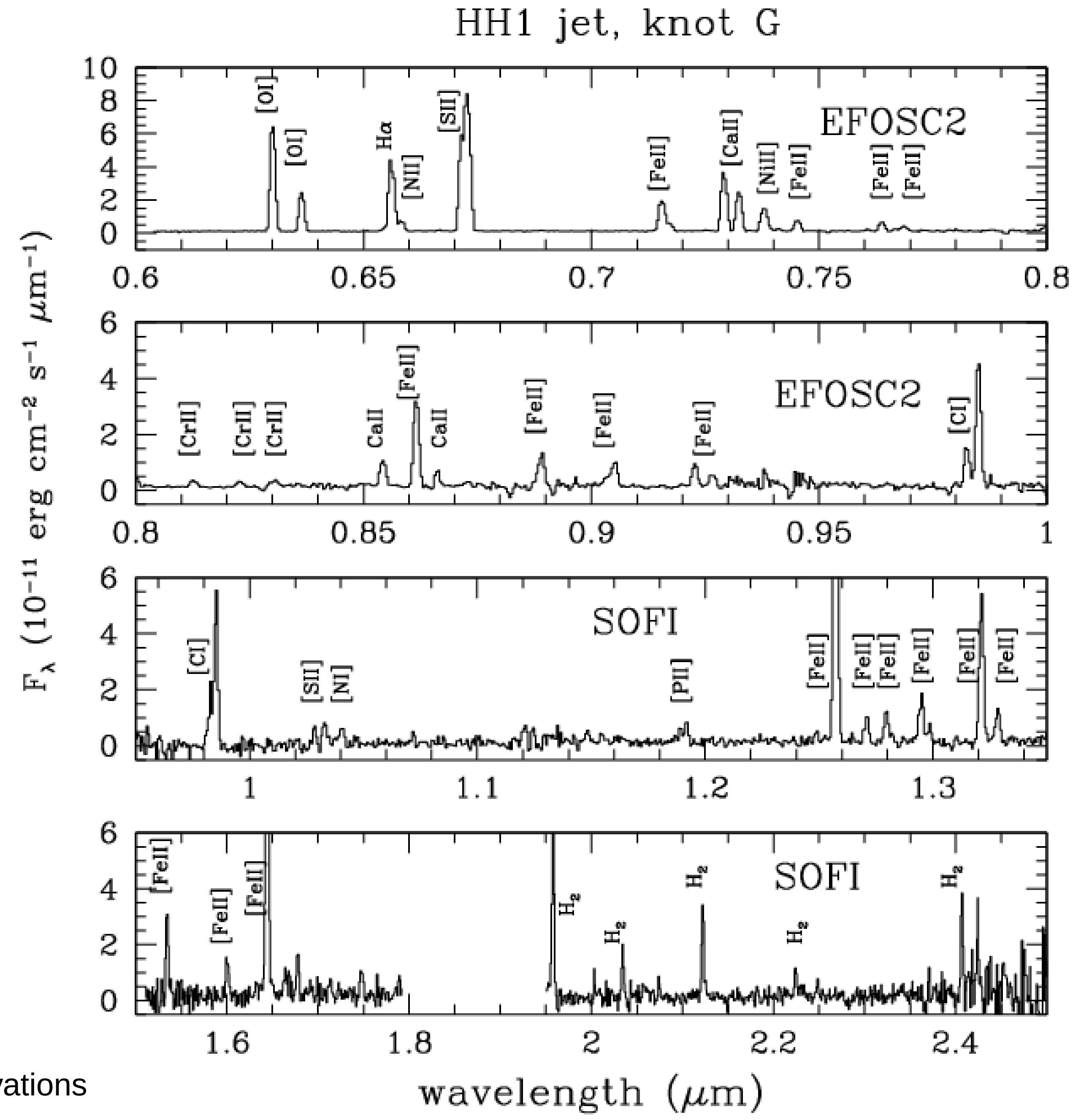


FIG. 2.—*ISO*-SWS spectrum of the planetary nebula NGC 6445

van Hoof +99


HH1 jet, knot G
EFOSC2
EFOSC2
SOFI
SOFI
[OI]
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Hα
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[SII]
[FeII]
[CaII]
[NiII]
[FeII]
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[FeII]
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[FeII]
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[FeII]
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[FeII]
[FeII]
[FeII]
H2
H2
H2
H2
H2
F_λ (10^{-11} erg cm^{-2} s^{-1} μm^{-1})
wavelength (μm)

Nisini+05

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 …