ASTROPHYSICAL INFORMATION DERIVED FROM THE EM SPECTRUM

Position

Radial Velocity

Transverse Velocity

Distance

Luminosity

Temperature(s)

Chemical Composition

Mass

Size

Pressure

Density

Magnetic Fields

Rotation

Turbulence

Variability

....etc

THE ELECTROMAGNETIC SPECTRUM

- **References: LLM: 1, 2.2, 3.2.1, 3.3**

- **Regions of the EM spectrum: see chart, next page**

  o **Nomenclature**

  o **Wavelength, frequency, energy units**

  Convenient working units in any band typically yield numerical values in the range 1–10000 → heterogenous!

  Radio: cm, GHz, or MHz
  Far-IR/Sub-mm: μ or mm
  IR: μ
  UVOIR: Å, μ, or nm
  EUV: eV or Å
  X-Ray: keV
  Gamma Ray: MeV

  o **Windows in Earth's atmosphere**

  o **History of astronomical coverage: see Lecture 1**

  o **Modern detection limits: see chart**

  o **Major discoveries: see 2.A**

  o **Important observatories: see 2.B**

EM SPECTRUM (continued)

Here is a convenient summary of the EM spectrum from Menzel, Whipple & de Vaucouleurs (1970). (Detector listing out of date.)

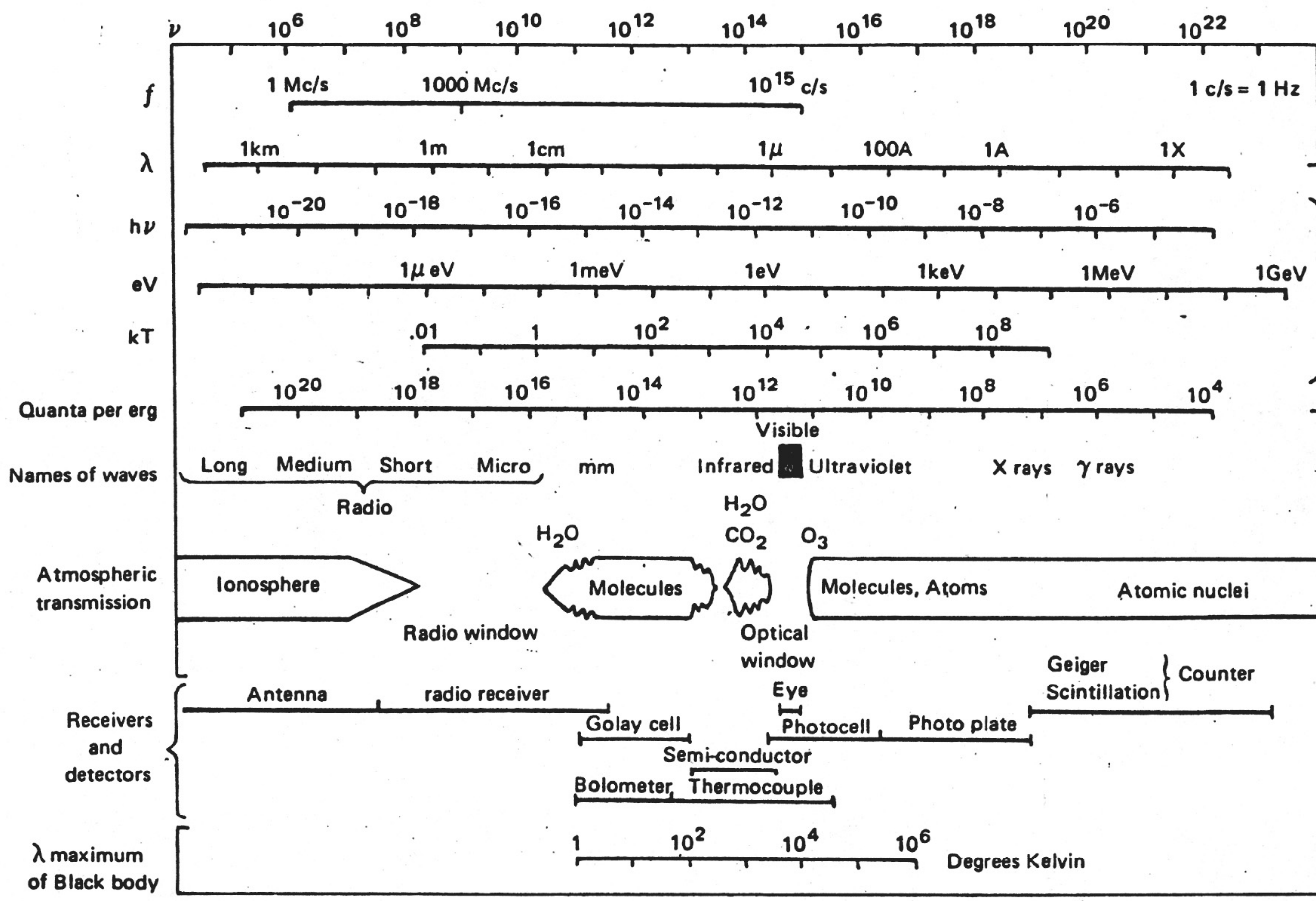
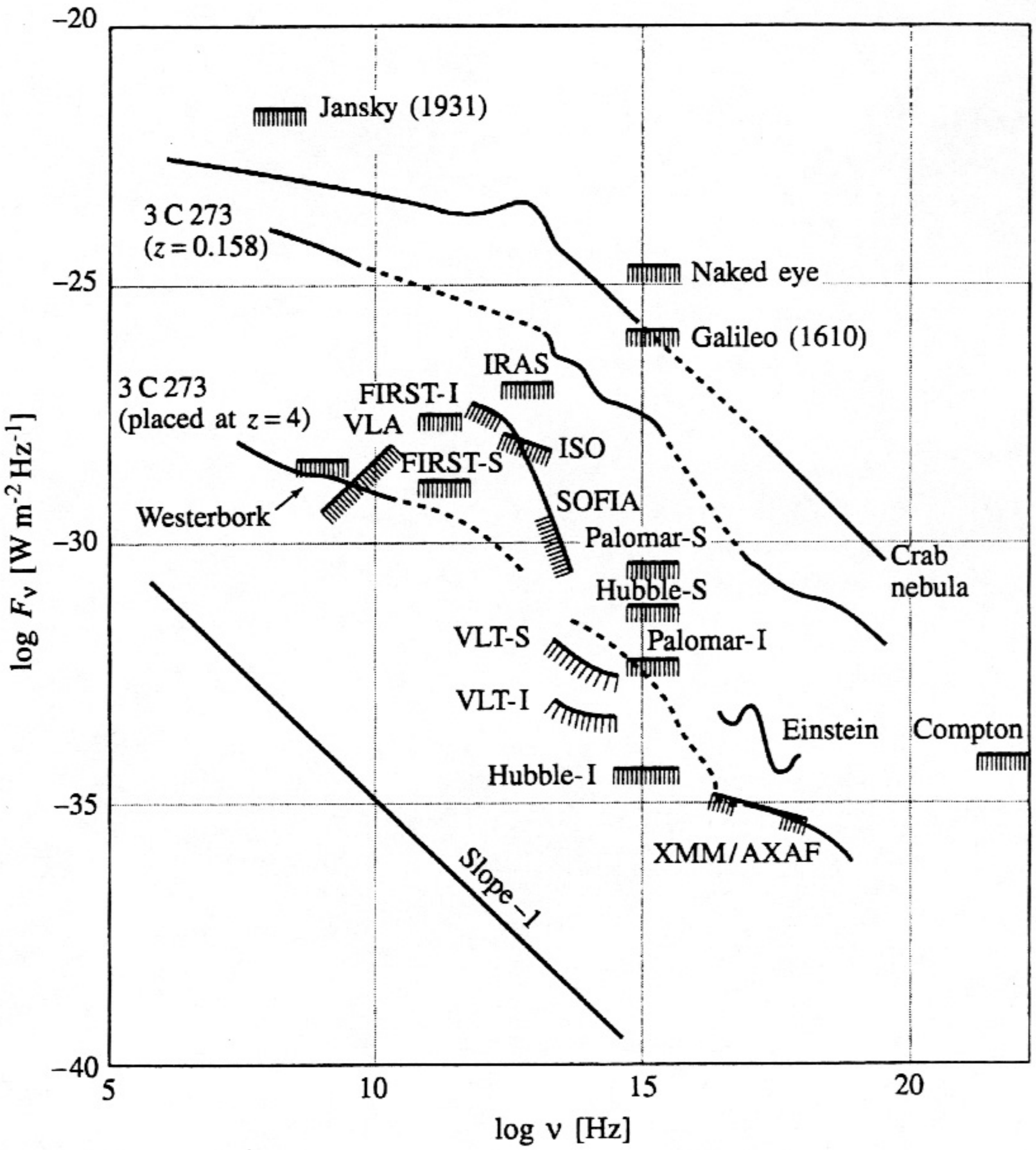


FIGURE 8-1 *The electromagnetic spectrum and detectors. Symbols: ν, frequency in cycles/sec or Hertz, Hz; f, frequency in 10^6 Hz or Mc/s; λ, wavelength; hν, energy of a quantum in ergs; eV, energy of a quantum in electron volts (1 eV $= 1.59 \times 10^{-12}$ erg); kT, thermal energy in °K.*

EM SPECTRUM (continued)

<u>Modern detection limits</u>. The envelope with a slope of -1 corresponds to $\nu F_\nu = const$ and implies constant energy per decade in EM spectrum.



EM DETECTOR TYPES

Bolometers

- Most basic detector type: a simple absorber
- Temperature responds to total EM energy deposited by all mechanisms during thermal time-scale
- Electrical properties change with temperature
- Broad-band (unselective); slow response
- Primarily far infrared, sub-millimeter (but also high energy thermal pulse detectors)

Coherent Detectors

- Multiparticle detection of electric field amplitude of incident EM wave
- Phase information preserved
- Frequency band generally narrow but tunable
- Heterodyne technique mixes incident wave with local oscillator
- Response proportional to instantaneous power collected in band
- Primarily radio, millimeter wave, but some IR systems with laser LO's

EM DETECTORS (continued)

Photon Detectors

- **Respond to individual photon interaction with electron(s)**
- **Phase not preserved**
- **Broad-band above threshold frequency**
- **Instantaneous response proportional to collected photon rate (not energy deposition)**
- **Many devices are integrating (store photoelectrons prior to readout stage)**
- **UVOIR, X-ray, Gamma-ray**
  - **Photoexcitation devices: photon absorption changes distribution of electrons over states. E.g.: CCD's, photography**
  - **Photoemission devices: photon absorption causes ejection of photoelectron. E.g.: photocathodes and dynodes in photomultiplier tubes.**
  - **High energy cascade devices: X- or gamma-ray ionization, Compton scattering, pair-production produces multiparticle pulse. E.g. gas proportional counters, scintillators**

USEFUL EM SPECTRUM CONVERSIONS

21 cm = 1420 MHz [Hyperfine line, HI]

1 cm = 30 GHz

1 mm = 300 GHz = 1000μ

1 $\mu = 10^4$ **Å = 1000 nm**

5500 Å $= 5.5 \times 10^{14}$ **Hz [V band center]**

1 nm = 10 Å

1 Å $= 10^{-8}$ **cm**

1 eV $= 1.60 \times 10^{-12}\,\mathrm{erg} =$ **12400 Å**

13.6 eV = 912 Å [Lyman limit = IP of HI]

1 keV = 12.4 Å $= 2.4 \times 10^{17}$ **Hz**

$m_e c^2$ **= 511 keV**

EM SPECTRUM MEASUREMENTS

Basic observed quantity: FLUX

Flux is the energy incident per unit time per unit area within a defined EM band:

$$f \equiv E_{in\,band}/A\,t$$

(**or power per unit area**)

Usually quoted at top of Earth's atmosphere

Band definitions for flux:

- o **"Bolometric": all frequencies**
- o **Finite bands (typically 1-20%) defined by, e.g., filters such as U,B,V,K**
- o **"Monochromatic": infinitesimal band,** $\nu \rightarrow \nu + d\nu$

Also called "spectral flux density"

Denoted: f_ν **or** f_λ

Note conversion: since $f_\nu d\nu = f_\lambda d\lambda$ **and** $\nu = c/\lambda$,

$$\rightarrow \nu f_\nu = \lambda f_\lambda$$

Not observed directly. Rather, inferred from observations made with finite bands:

$$< f_\lambda >= \int T(\lambda) f_\lambda d\lambda \,/ \int T(\lambda) d\lambda,$$

...where T **is the system response function.**

EM MEASUREMENTS (continued)

Units for astronomical fluxes: Note <u>not MKS</u>

- **Standard UVOIR Units:**

$$[f_\nu] = \text{erg s}^{-1}\ \text{cm}^{-2}\,\text{Hz}^{-1}$$
$$[f_\lambda] = \text{erg s}^{-1}\ \text{cm}^{-2}\,\text{Å}^{-1}$$

- **All-band unit (from radio "flux unit"): Jansky**

$$\mathbf{1\ Jy} = 10^{-26}\,\text{w m}^{-2}\,\text{Hz}^{-1}$$
$$= 10^{-23}\,\text{erg s}^{-1}\ \text{cm}^{-2}\,\text{Hz}^{-1}$$

THE UVOIR MAGNITUDE SYSTEM, BRIEFLY

An ancient and arcane, but compact and by now unchangeable, way of expressing brightnesses of astronomical sources.

Magnitudes are a logarithmic measure of spectral flux density (not flux!)

- **Monochromatic Apparent Magnitudes**

  o $m_\lambda \equiv -2.5 \log_{10} f_\lambda - 21.1$,

  where f_λ is in units of $\mathrm{erg\ s^{-1}\ cm^{-2}\ \AA^{-1}}$

  o This system of "monochromatic magnitudes per unit wavelength" is also known as the "STMAG" system, because it is widely used by HST observers.

  o Normalization is chosen to coincide with the zero point of the widely-used "visual" or standard "broad-band" V magnitude system:

  i.e. $m_\lambda(5500\,\text{Å}) = V$

  o Zero Point: fluxes at 5500 Å corresponding to $m_\lambda(5500\text{Å}) = 0$, are (Bessell 1998)

  $f^0_\lambda = 3.63 \times 10^{-9}\,\mathrm{erg\ s^{-1}\ cm^{-2}\ \AA^{-1}}$, or

  $f^0_\nu = 3.63 \times 10^{-20}\,\mathrm{erg\ s^{-1}\ cm^{-2}\ Hz^{-1}}$, or

  $f^0_\nu = 3630$ Janskys

  $\phi^0_\lambda = f^0_\lambda/\mathrm{h}\nu = 1005$ photons $\mathrm{cm^{-2}\,s^{-1}\,\AA^{-1}}$
  is the corresponding photon rate per unit wavelength

THE MAGNITUDE SYSTEM (continued)

- **Surface Brightnesses (extended objects):**

  - o $\mu_\lambda \equiv m_\lambda + 2.5 \log_{10} \Omega$

    where m_λ is the integrated magnitude of the source and Ω is the angular area of the source in units of arcsec^2. 1 arcsec$^2 = 2.35 \times 10^{-11}$ steradians.

  - o **μ is the magnitude corresponding to the mean flux in one arcsec^2 of the source. Units of μ are quoted, misleadingly, as "magnitudes per square arcsecond."**

- **Absolute Magnitudes**

  - o **$M \equiv m - 5 \log_{10}(D/10)$, where D is the distance to the source in parsecs**
  - o **M is the apparent magnitude the source would have if it were placed at a distance of 10 pc.**
  - o **M is an <u>intrinsic</u> property of a source**
  - o **For the Sun, M_V = 4.83**

[A more complete discussion of magnitudes & colors will be given later.]

SPECTRAL ENERGY DISTRIBUTIONS

The spectral energy distribution (SED) is $f_\nu(\nu)$ or $f_\lambda(\lambda)$ — i.e. the distribution of spectral flux density over wavelength or frequency.

- o For a given SED, the total flux in a finite band is then:

$$F_b = \int_{\nu_1}^{\nu_2} f_\nu \, d\nu$$

$$= \ln 10 \int_{\nu_1}^{\nu_2} \nu f_\nu \, d \log_{10}(\nu)$$

  This implies that $\nu f_\nu = \lambda f_\lambda \sim$ the power per unit area per decade in the SED.

Most astronomical sources are broad-band emitters, over at least several decades. Multiband observations of the SED permit dissection of source physics.

- o It is tempting to approximate multiband SED data with simple functions, like power laws or Planck functions. But this is almost always misleading. See "3C 273 and the Power Law Myth," Perry et al. MNRAS, 228, 623, 1987 and the plots on the next page.

- o Lesson: coordinates used for representation of an SED can influence one's impression of source energetics, emission mechanism, source structure, importance of given EM domain, etc. Plotting style chosen often depends on funding agency!

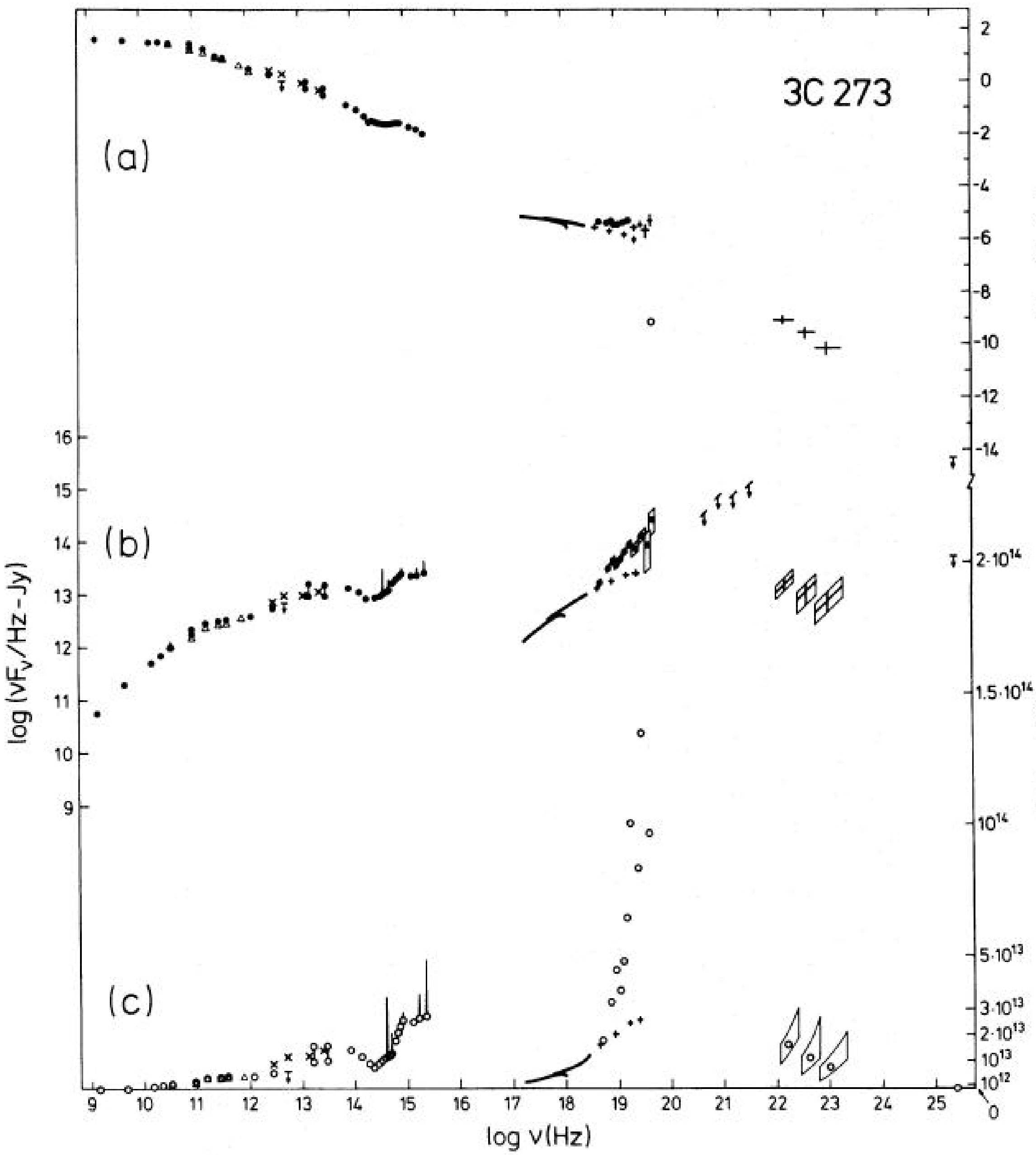


Figure 1. The spectrum of 3C 273: (a) the log of the observed flux density plotted against the log of the frequency; (b) log ($\nu\times$flux density) plotted against log frequency; this represented peaks where the emitted energy peaks; (c) linear representation of frequency$\times$flux density plotted against log frequency; the area under the curve is proportional to the emitted energy per frequency bandwidth at the frequency shown. It is clear from (c) that the energy is not emitted uniformly over all frequencies.

CHARACTERIZATION OF EM SOURCES

- **Luminosity (L)**

  o <u>Power</u> (energy/sec) radiated by source into 4π sterad

  o Units: $\mathrm{egs\ s^{-1}}$

- **Flux (f)**

  o Power from source crossing normal to <u>unit area</u> at specified location a distance D from source

  o $f = L/4\pi D^2$ if source isotropic, no absorption

  o Units: $\mathrm{egs\ s^{-1}\,cm^{-2}}$

- **Specific Intensity (or "surface brightness") (I)**

  o Power from source crossing unit area at specified location and moving into <u>unit solid angle</u> about a specified direction

  o Units: $\mathrm{egs\ s^{-1}\,cm^{-2}\,sterad^{-1}}$

  o Relation to flux: if $\hat{r}$ is a unit direction vector at the surface, which has a normal vector $\hat{z}$, then:

  $$f = \int_{4\pi} I(\hat{r})\ \hat{z}\cdot\hat{r}\ d\Omega$$

  where the element of solid angle in spherical coordinates is $d\Omega = \sin\theta\, d\theta d\phi$.

  o So: $f \sim \langle I \rangle\, \Delta\Omega$

  o I is <u>independent of distance</u> if there is no absorption or emission along path <u>and</u> source remains resolved

EM CHARACTERIZATION (continued)

- **As for flux, symbols like L_ν, I_ν, I_λ denote monochromatic versions of these quantities.**

- **Warning: this nomenclature is ubiquitous among astronomers but is not widely used outside of astronomy. In radiometry, for instance, "irradiance" is used for flux, "radiance" is used for specific intensity, "flux" is used for luminosity, and so forth. Symbols are also different. Beware!**

THE PLANCK FUNCTION

The Planck function is both a useful fiducial energy distribution <u>and</u> an important diagnostic of source astrophysics. It describes the EM energy distribution of a source in thermal equilibrium (= a "black body"). Assumptions about source:

- **Strictly homogeneous: T constant, unchanging everywhere.**
- **Strong coupling between radiation field and matter; optically thick**
- **All microscopic processes in balance; number in states given by Boltzman distribution**

Under these conditions, the specific intensity (I) is independent of the source's density, chemical composition, shape, etc., and is given by:

$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/kT\lambda}-1}$$

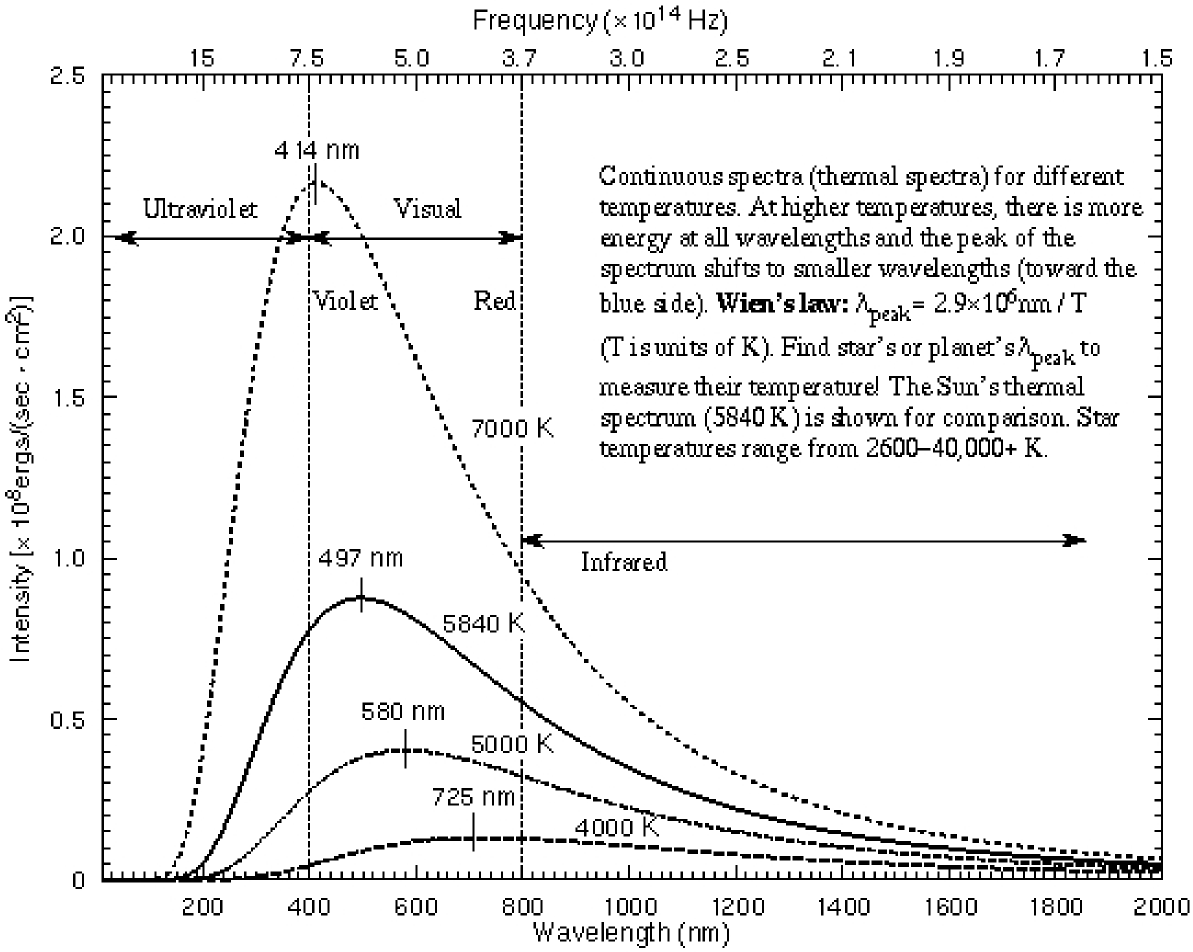
Units: erg s^{-1} cm^{-2} [Hz or cm]$^{-1}$ sterad^{-1}

Bolometric integral:

$$\int_0^\infty B_\nu(\nu, T)d\nu = \int_0^\infty B_\lambda(\lambda, T)d\lambda = \sigma_0 T^4/\pi,$$

where σ_0 is the Stefan-Boltzmann constant (5.67×10^{-5} erg s^{-1} cm^{-2} deg^{-4})

THE PLANCK FUNCTION (continued)



Planck Function Spectra (©Nick Strobel)

Plotted is πB_λ in units of $10^8\,\mathrm{erg\ s^{-1}\ cm^{-2}\,nm^{-1}}$

THE PLANCK FUNCTION (continued)

Limiting forms:

$$h\nu/kT << 1 \rightarrow B_\nu(T) = 2kT/\lambda^2 \quad \text{(“Rayleigh-Jeans”)}$$

$$B_\lambda(T) = 2ckT/\lambda^4 \quad \text{(See next page)}$$

$$h\nu/kT >> 1 \rightarrow B_\nu(T) = 2h\nu^3\, e^{-h\nu/kT}/c^2 \quad \text{(“Wien”)}$$

Limit on SED Slope:

**Note that $d\log B_\nu/d\log\nu \leq 2$ for all ν and T.
A steeper continuum slope might occur in the case of nonthermal sources, etc., but is a warning to do a reality check.**

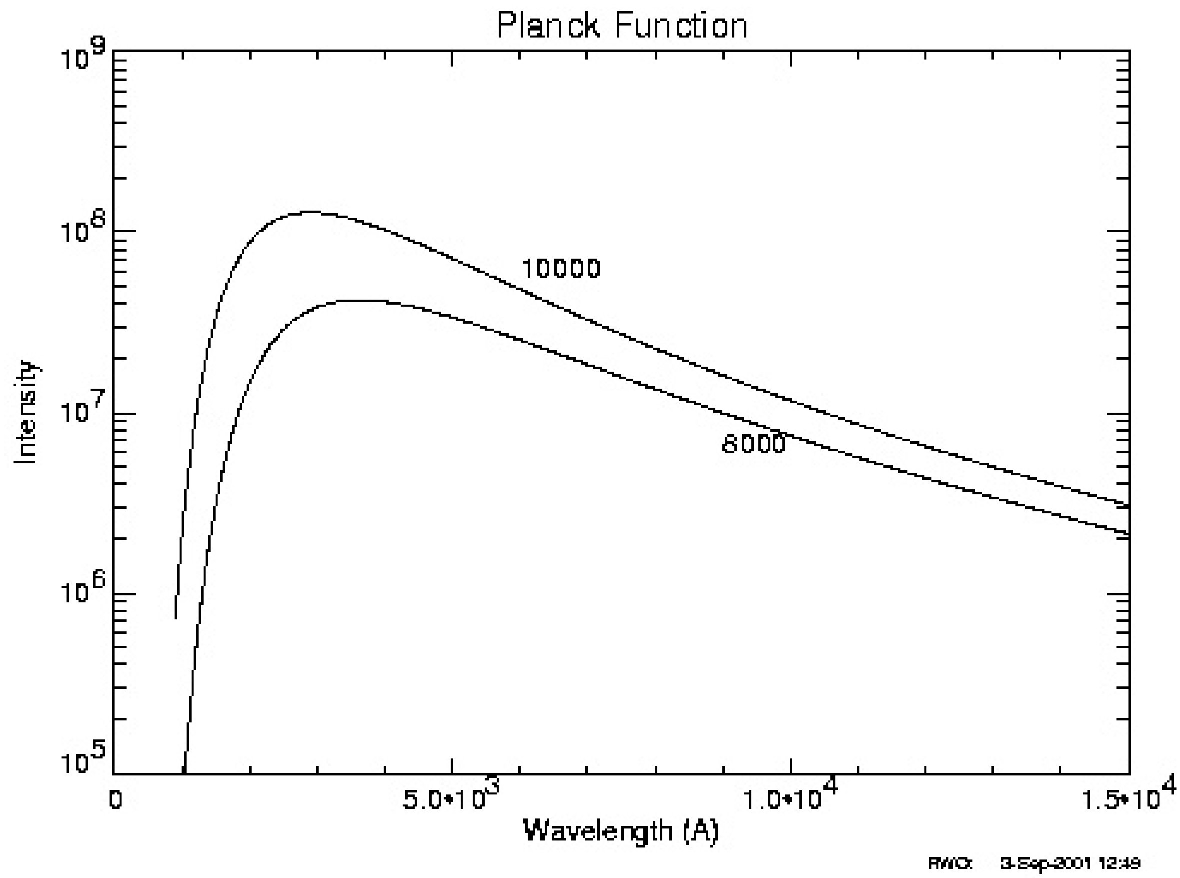
Wien's Displacement Law: maximum in Planck function occurs at

$$\lambda_{max} = 0.51T^{-1} \text{ cm for } B_\nu$$

$$\lambda_{max} = 0.29T^{-1} \text{ cm for } B_\lambda$$

Cf. plot on previous page. Useful for defining the “characteristic temperature” of a given EM domain

THE PLANCK FUNCTION (continued)



Planck function plotted in log (flux) to show Rayleigh-Jeans asymptote ($B_\lambda \sim \lambda^{-4}$) at long wavelengths.
Plotted is πB_λ in units of $\mathrm{erg\ s^{-1}\ cm^{-2}\ \AA^{-1}}$.
Curves labeled with temperature.