Overview

Mankind has watched and studied the heavens for thousands of years, with the help of just one 'detector' – the human eye. Our eyes respond to radiation over a very restricted range of **wavelengths** from violet to red:

$$400 \text{ nm} - 700 \text{ nm} \quad (400\text{Å} - 7000\text{Å})$$

Our eyes are **logarithmic detectors**, leading to the definition of the magnitude:

$$\boxed{m = -2.5 \log_{10} \text{flux} + \text{constant.}}$$

The constant is set so that the brightest stars are about zero magnitude; the faintest stars we can see are about 6th magnitude, or a factor about 250 fainter.

The **telescope**, invented in the 17th century, let us see much fainter stars, on account of its bigger light-collecting area; but the detector was still the limited human eye, which only adds up light over a short **integration time** (about 1/30 second). The invention of **photography** in the mid-19th century helped astronomers to see much fainter by using long time exposures, but even these detectors failed to register most of the light they received. The ultimate limit to sensitivity comes from the quantum nature of light: energy is transmitted in discrete packets of energy called **photons**, with energy

$$\boxed{E = h\nu}$$

at frequency ν, where h is Planck's constant. Today we often use **photoelectric detectors**, in which an electron is produced by the passage of a photon. The most common device is the kind of solid-state technology found in video cameras (the **CCD**, or charge-coupled device). The best of these devices will produce an electron on more than 80% of the occasions that they are struck by a photon. The equivalent rate for photographic plates is more like 1%.

However, much of the revolutionary expansion of astronomical knowledge during the past 40 years came through the development of **new technologies**. Astronomers can now survey the Universe not only in the limited optical range of 400 – 700 nm, but over the entire range of the electromagnetic spectrum from 10^{-6} nm to 10 m. This range spans a great variety of physical processes and new kinds of astronomical sources. Some information, too, comes from other observations besides electromagnetic radiation.

In this module we shall look in turn at various phases of this astronomical revolution: the observational techniques, the physical processes involved, and the new astronomical discoveries that resulted. The recommended textbook is ZELIK: 'Astronomy – The Evolving Universe' (8th edition; Wiley 1997). More detailed suggestions for optional background reading will given at relevant places in the notes, and at the end of the module.

TEMPERATURE AND WAVEBAND

Prof Lawrence (The Scientific Style) introduced the properties of thermal (or **blackbody**) radiation at temperature T, for which the energy distribution with frequency ν is given by the **Planck Formula**:

$$B(\nu, T) = \frac{2h}{c^2}\,\nu^3 \left(e^{h\nu/kT} - 1\right)^{-1} \to \frac{2kT}{c^2}\,\nu^2 \quad \text{for small } \nu,$$

where $B(\nu, T)$ gives the amount of energy being emitted in unit range of frequency, and k is called Boltzmann's constant. *You do not need to memorise or use this formula.* You should however know that thermal radiation peaks at wavelength $\lambda_{\rm peak}/\mu{\rm m} = 2900\,{\rm K}/T$ [Wien's Law] and that the total energy is proportional to T^4 [Stefan-Boltzmann Law]. The expansion of Planck's law shows that $B \propto \nu^2$ is characteristic of the low-frequency (long-wavelength) 'tail' of thermal radiation, which cuts off abruptly at high frequencies, where the photon energy exceeds the typical thermal energy kT.

The energy distribution of astronomical objects like **stars** is only *approximately* a blackbody curve. Nevertheless, it is a good rule of thumb to say that there is a close relation between the temperature of a body and the waveband where it emits most of its energy. Thus, stars have surface temperatures of a few thousand K and all emit most of their energy in the **visible spectrum** ($0.4 - 1\mu$m). However, sources at very high or very low temperatures would not be picked out from observations in the visible region. Examples of this set of sources are:

- Very hot matter such as gas streams in a close binary star: $T \sim 10^7$ K, peaking at $\lambda \sim 0.3$ nm (X-rays).
- Very cold matter such as interstellar grains (solid particles): $T \sim 30$ K, peaking at $\lambda \sim 100\mu$m (far infrared).

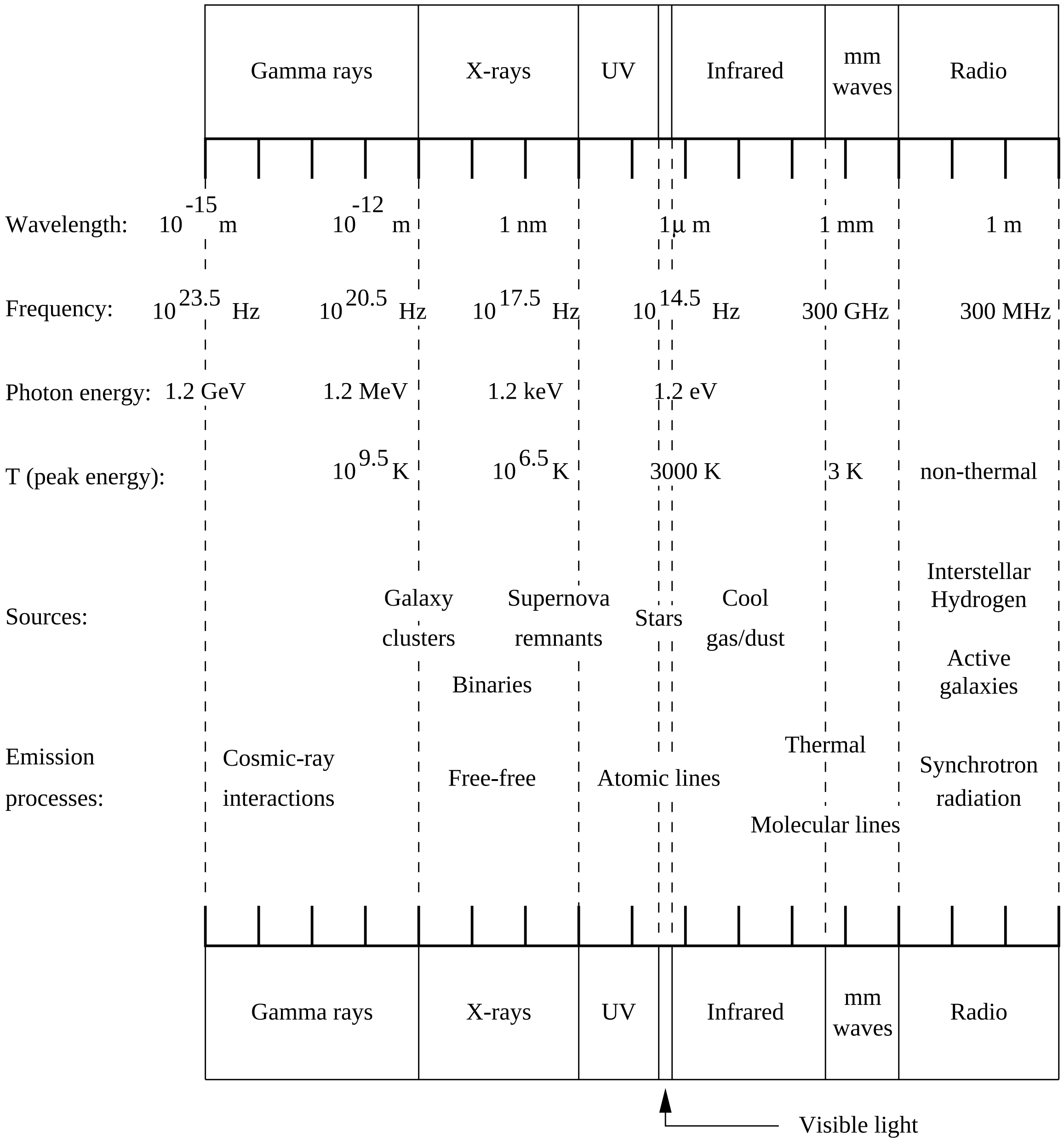
The existence of such sources, and even more exotic ones, was not revealed until the development of The New Astronomies.

SPECTRAL LINE RADIATION

The most important correction to the basic idea of smooth thermal emission is given by the narrow features that arise from transitions between discrete energy levels in atoms and molecules. These can be **emission lines**, if the dominant source of emission is a cloud of diffuse gas, or **absorption lines** if we have something like thermal emission shining through a cloud of gas. For example, the emission of the Sun contains many absorption lines owing to the thermal light from its main surface passing through its outer atmosphere.

Spectral lines are arguably the most important pieces of information in astronomy. They give important information about chemical composition, temperature, pressure, velocity (from the **Doppler shift** $\delta\lambda/\lambda = v/c$).

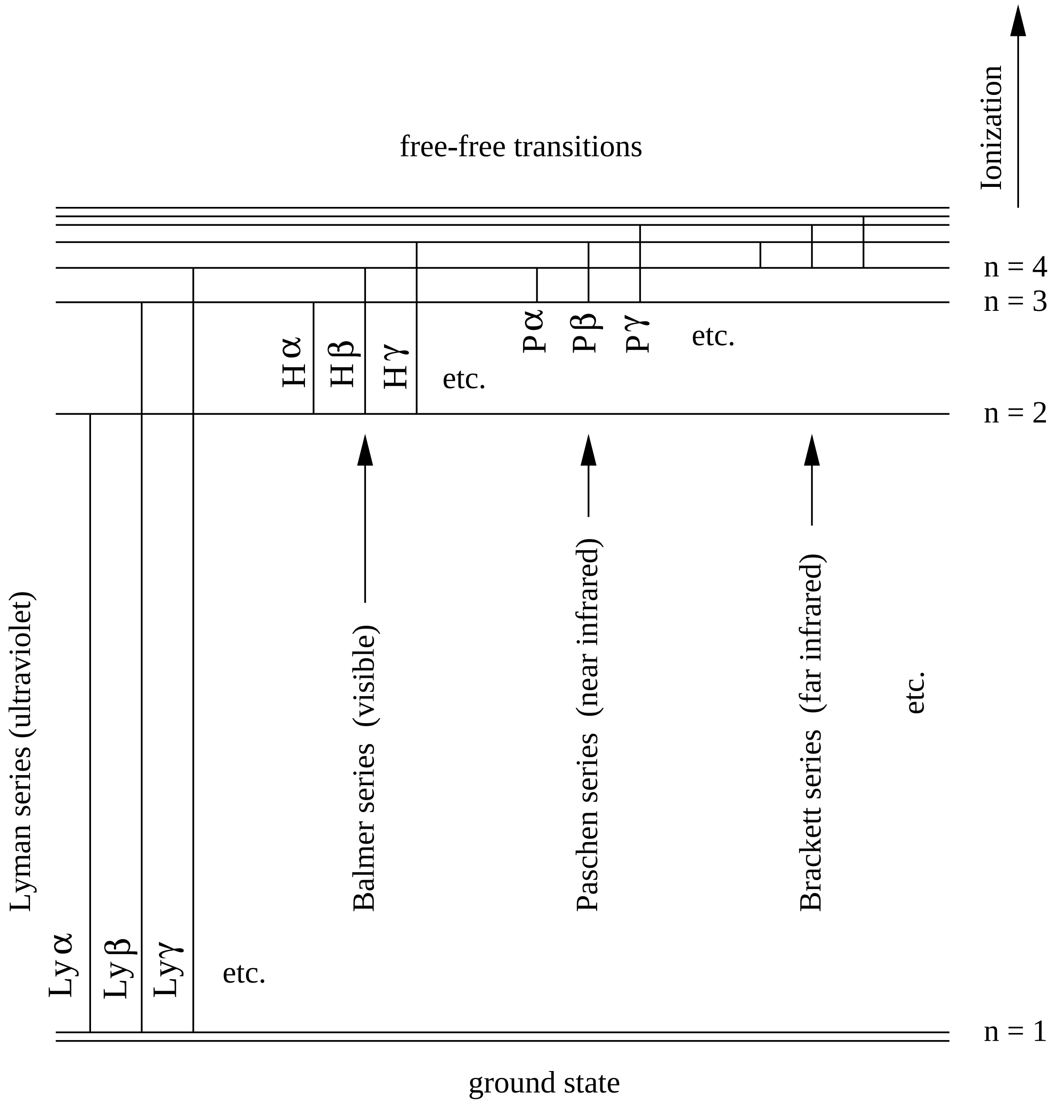
The Electromagnetic Spectrum



This diagram summarizes the range of wavelengths accessible to today's astronomers, together with some of the sources and processes that may produce the radiation we observe.

- Wavelength λ and frequency ν are related by $\lambda\nu = c$ (approximately $3 \times 10^8\,\mathrm{m\,s^{-1}}$).
- Photon energy $h\nu$ is approximately 1.25 electron volts (eV) at $\lambda = 1\mu$m.
- Planck distribution ('black body'): $T_{\mathrm{peak}} \simeq 2900/\lambda$, where T is in K and λ is in μm (WIEN displacement law).

Energy levels for the Hydrogen atom



For transition between two energy levels, $h\nu = E_m - E_n = 13.6(1/m^2 - 1/n^2)$ eV. Other atoms, and especially molecules, have more complicated energy levels.

- Cooler gas surrounding hotter star $\rightarrow$ absorption lines ($\uparrow$ transitions)
- Free-space excited or ionized gas $\rightarrow$ emission lines ($\downarrow$ transitions)
- In a cool gas most atoms are in ground state, $n = 1$. (N.B. 21-cm radio line of H; see below). H $\rightarrow$ H_2 in cool molecular clouds (giving more complex spectrum)