**Reading: Chapters 1 of Binney & Tremaine, Chapters 1-2 of Binny & Merrifield**

**Light:**

Stars make up most of the objects in the **visible** Universe. The only information we can obtain about stars comes from the light they emit.

What are the four basic properties of a **photon** that one can measure?

Answer:

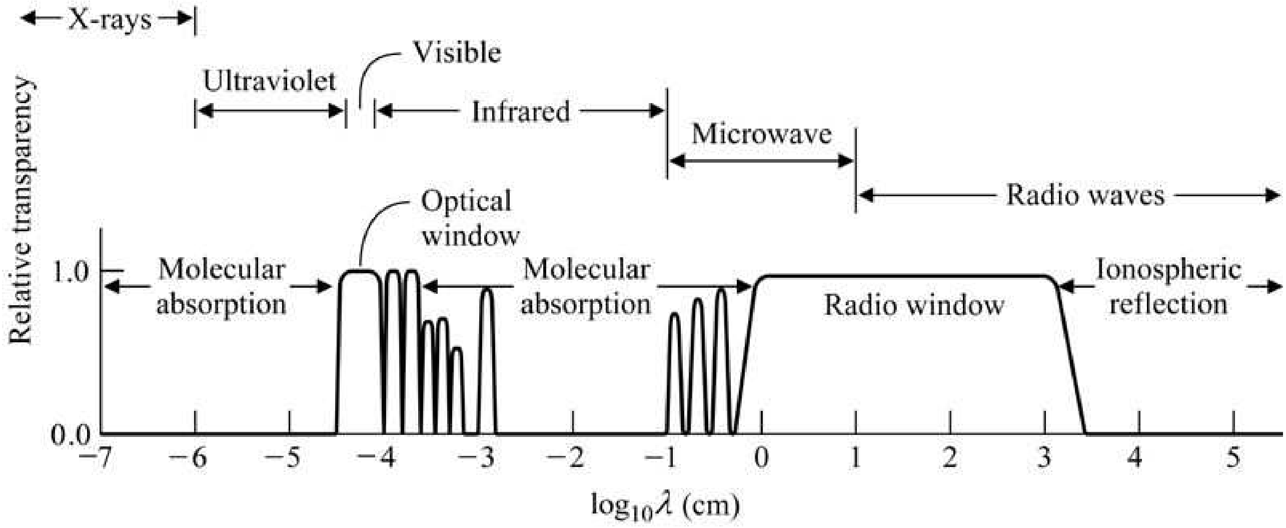
- Wavelength, frequency or energy (all are the same thing via $E = h\nu$);
- Direction;
- Polarization;
- Arrival time.

Nearly all of observational astronomy boils down to determining one or more of the four properties of the photon!

The name of the game is to collect and detect photons.

**“Familes” of photons”**

- visible: 3000-10,000 Å, ground-based observations
- near infrared: 1-10 $\mu$m, ground-based observations
- far infrared: 10-100 $\mu$m, space-based observations
- microwave: 10 $\mu$m-1 mm, ground-based observations
- millimeter: 1 mm - several cm, ground-based observations
- radio: several cm - $\approx$ 1 km, ground-based observations
- ultraviolet: 900-3000 Å, space-based observations
- extreme ultraviolet: a few hundred Å, space-based observations




The transparency of Earth's atmosphere as a function of wavelength (from Carroll & Ostlie).

Most of the observations for stellar astronomy are done in the relatively small optical window from the ground, although space-based UV, X-ray, and IR observations are becoming more frequent.

**Telescopes and light detection:**

In general, one uses a **telescope** to collect light and focus it on a **detector**. The total amount of light collected depends on the **collecting area** of the telescope and the **efficiency** of the detector in detecting photons.

The largest optical telescopes in use today have primary mirrors with diameters of up to 8.2m for single mirrors and 10m for segmented mirrors. Serious plans are underway to build telescopes with segmented mirrors in the 30m to 100m range.

Historically, there have been four types of detectors used in stellar astronomy:

(1) the human eye;

- first observations carried out in antiquity
- advantages: relatively sensitive over a broad wavelength range
- disadvantages: cannot integrate or record

(2) photographic plates (or film);

- first observations date back to the 1850s
- advantages: large area on the sky, fairly permanent record
- disadvantages: only about 4% efficient, response not linear, difficult to manulipulate on a computer

(3) photomultiplier tubes;

- first observations date back to the 1920s
- advantages: relatively efficient, high time resolution possible, can record electronically for use on a computer
- disadvantages: no image

(4) charge-coupled devices (CCDs).

- first observations date back to the 1970s
- advantages: very efficient, approaching 100% at some wavelengths, digital image
- disadvantages: relatively small size on the sky

Food for thought: the magnitude limit for stellar images achieved by the Palomar 200 inch (5m) telescope and a photographic plate is **roughly the same** as that achieved by the 40 inch (1m) telescope at Mount Laguna using a CCD camera!

The differences in the collecting area is a factor of 25, but a CCD can be about 25 times more efficient (at its peak wavelength) than photographic emulsion.

**Flux densities, magnitudes, and color indices:**

Terms like "luminosity" and "intensity" have been often used in vauge ways.

The **luminosity** of a source is defined to be the total amount of energy radiated over all wavelengths per unit time in all directions. Units are watts (W) or erg $\mathrm{s}^{-1}$, or scaled in terms of the Solar luminosity:

$$\begin{aligned} L_\odot &= (3.846 \pm 0.008) \times 10^{26}\,\mathrm{W} \\ &= (3.846 \pm 0.008) \times 10^{33}\,\mathrm{erg\ s}^{-1}. \end{aligned}$$

How **bright** an object **appears** to us depends on its luminosity and **distance** $d$. A proper term for brightness is **flux density**, denoted $F$. The units are W m$^{-2}$ or erg s$^{-1}$ cm$^{-2}$.

The **inverse square law** sets the relationship between luminosity, flux density, and distance:

$$F = \frac{L}{4\pi d^2}$$

The human eye has a **logarithmic perception of brightness**, so historically the scale of relative brightnesses of stars has been the **magnitude** scale.

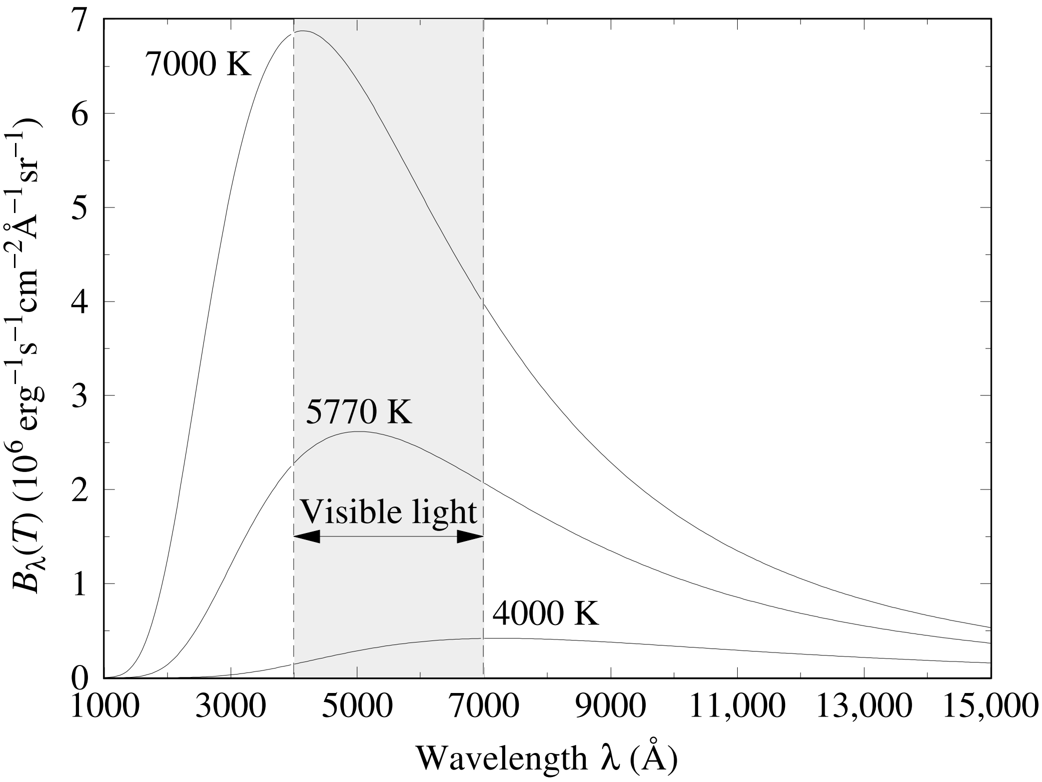
A difference in 5 magnitudes corresponds to a ratio of 100 in flux density, so that

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{F_1}{F_2}\right).$$

Note: the log function will be taken to be base 10 unless otherwise stated.

One can define the **absolute magnitude** $M$ of a source as the apparent magnitude the source **would have if it were located at a distance of 10 pc**:

$$m - M = 5 \log d - 5$$




**Black bodies:**

Any object with a temperature above absolute zero emits radiation of **all** wavelengths with different efficiencies.

An **ideal** emitter absorbs **all** of the light incident upon it, and reradiates the energy with the characteristic **black body** spectrum.

The black body spectrum is **continuous** with some energy at all wavelengths.

**Planck's Law** gives the functional form:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}[\exp(hc/\lambda kT) - 1]^{-1}$$

The peak is at $\lambda_{\mathrm{max}}$, whose value depends on the temperature $T$:

$$\lambda_{\mathrm{max}} T = 0.290\,\mathrm{cm\ K}$$

(This equations is **Wien's Law**). As a consequence of Wien's law, hotter objects are **bluer**.

The luminosity of a black body with a surface area $A$ is given by the **Stefan-Boltzmann** equation:

$$L = A\sigma T^4$$

where $\sigma = 5.670 \times 10^{-5}$ erg s$^{-1}$ cm$^{-2}$ K$^{-4}$.

For stars, one can **define** an **effective temperature** from the star's luminosity and radius via the Stefan-Boltzmann equation:

$$T_{\mathrm{eff}} = \left(\frac{L}{4\pi R^2 \sigma}\right)^{1/4}$$

**Stellar Energy Distributions:**

Bye eye, it is obvious that stars have different colors. Betelgeuse appears red to the eye, where as Rigel is blue/white.

From Wien's Law, the color differences are related to the temperature differences.

One way to observationally characterize the color differences is through the use of **color indices.**

We can define a star's observed **magnitude** in a **filter bandpass** (i.e. not just at a single wavelength) as follows:

Let the spectral energy distribution of the star as a function of wavelength be denoted by $E(\lambda)$.

Denote the transmission of the filter + telescope + detector combination by $S(\lambda)$.

Let $\lambda_1$ and $\lambda_2$ be the lower and upper wavelength regions for the filter.

The observed magnitude $m_j$ is

$$m_j = -2.5 \log \left[ \int_{\lambda_1}^{\lambda_2} E(\lambda) S_j(\lambda) d\lambda \right] + C_j$$

where $C_j$ is the zero point agreed upon by convention.

The well-defined photometric system, with $n$ filters, has all of its response curves defined solely by the filter (and not by the detector and/or telescope).

One can define the **effective wavelength** of the filter to be

$$\lambda_e = \frac{\int_{\lambda_1}^{\lambda_2} \lambda E(\lambda) S_j(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E(\lambda) S_j(\lambda) d\lambda}$$

The effective wavelength of a filter then depends on the star that is observed.

One can define a **color index** as simply the **difference** between the magnitudes in two filters:

$$c_{1,2} = m_{\lambda_1} - m_{\lambda_2} = -2.5 \log \left( \frac{f_{\lambda_1}}{f_{\lambda_2}} \right) + z_{\lambda_1} - z_{\lambda_2}$$

where the $z$s are the zero points.

The color index simply gives a measure of the flux **ratio** at two wavelengths (or effective wavelengths in the case of filters).

One wants to observe the spectral energy distribution of a star to learn more about its physics.

Intermediate or broadband filters allow one to efficiently observe large numbers of stars on modest sized telescopes.

Historically, there have been a number of **photometric systems** developed.

$UBV$

The first $UBV$ system was developed by Johnson & Morgan (1953, ApJ, 117, 313).

It was origionally developed for blue-sensitive photomultipliers, and extended to the $R$ and $I$ passbands when red sensitive phototubes became available. They gave a set of standard stars.

Recently Kron & Cousins modified the $R$ and $I$ bandpasses:

$$(V-R)_C = 0.715(V-R)_J - 0.02$$
$$(V-I)_C = 0.770(V-I)_J + 0.01$$

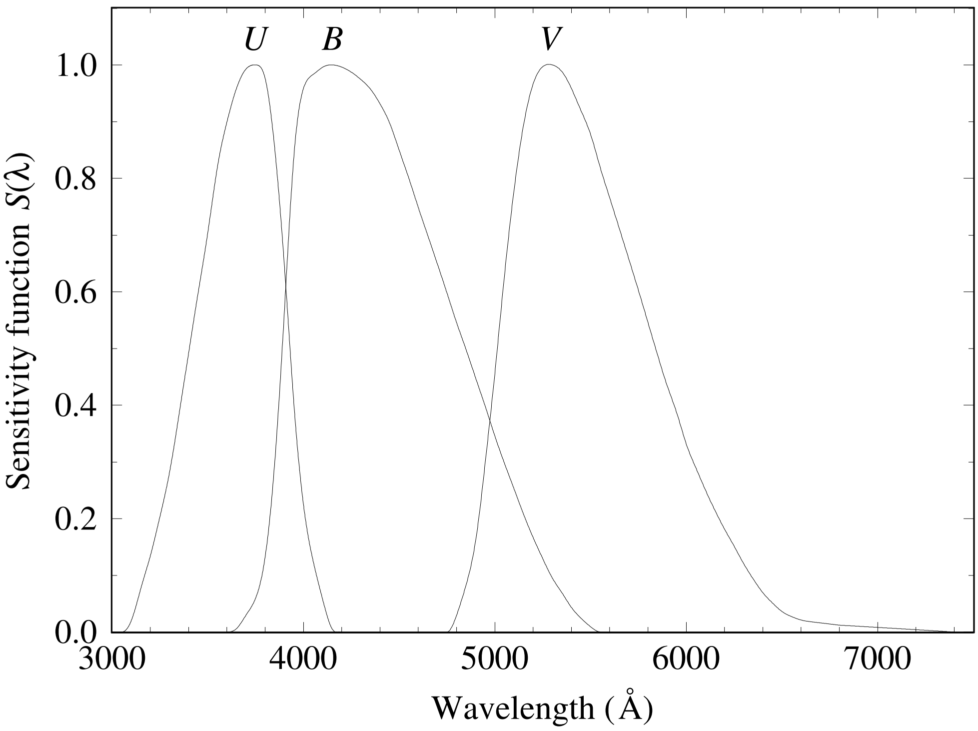
for stars hotter than spectral type M, and

$$(V-R)_C = 0.600(V-R)_J - 0.12$$
$$(R-I)_C = 1.045(R-I)_J - 0.094$$

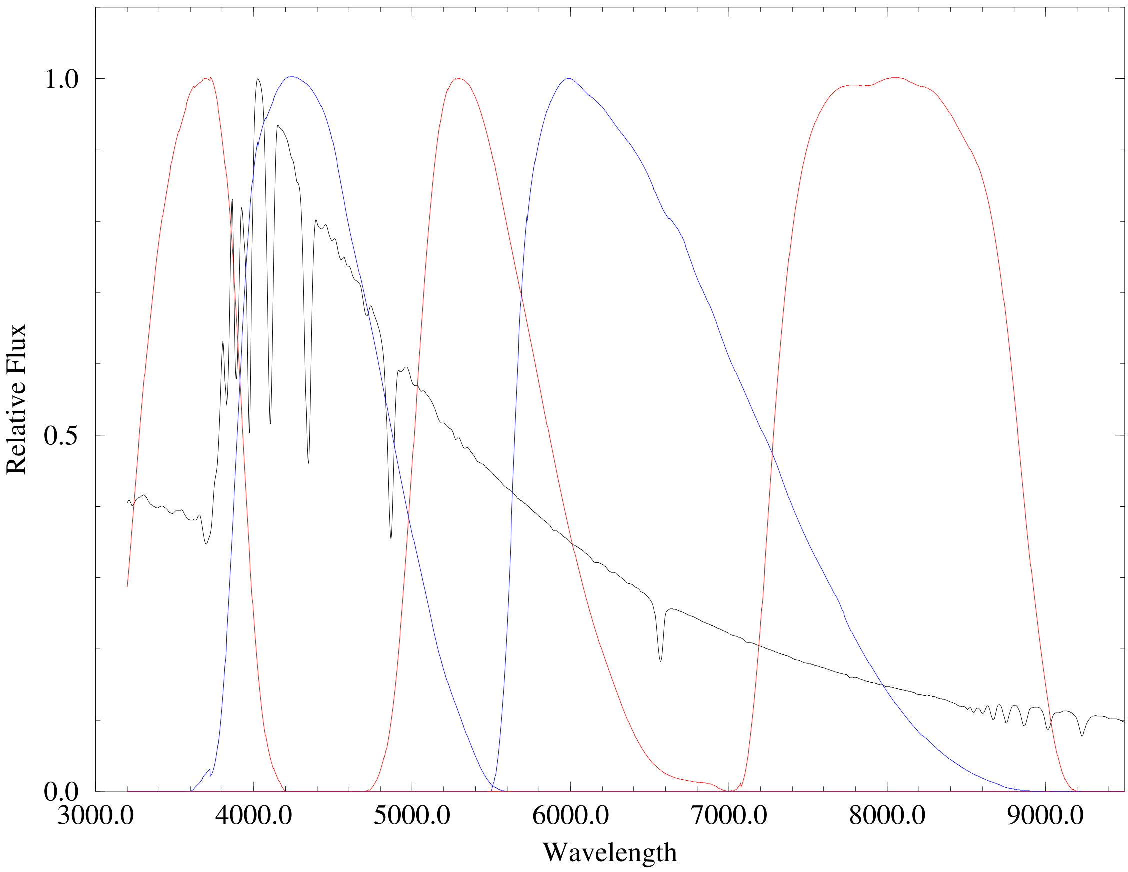
for M stars.

The most used definition of the $UBVRI$ Johnson-Cousins system is given in Bessel (1990, PASP, 102, 1181).

Landolt (1992, AJ, 104, 340) gives a list of faint standard stars for use on large telescopes.

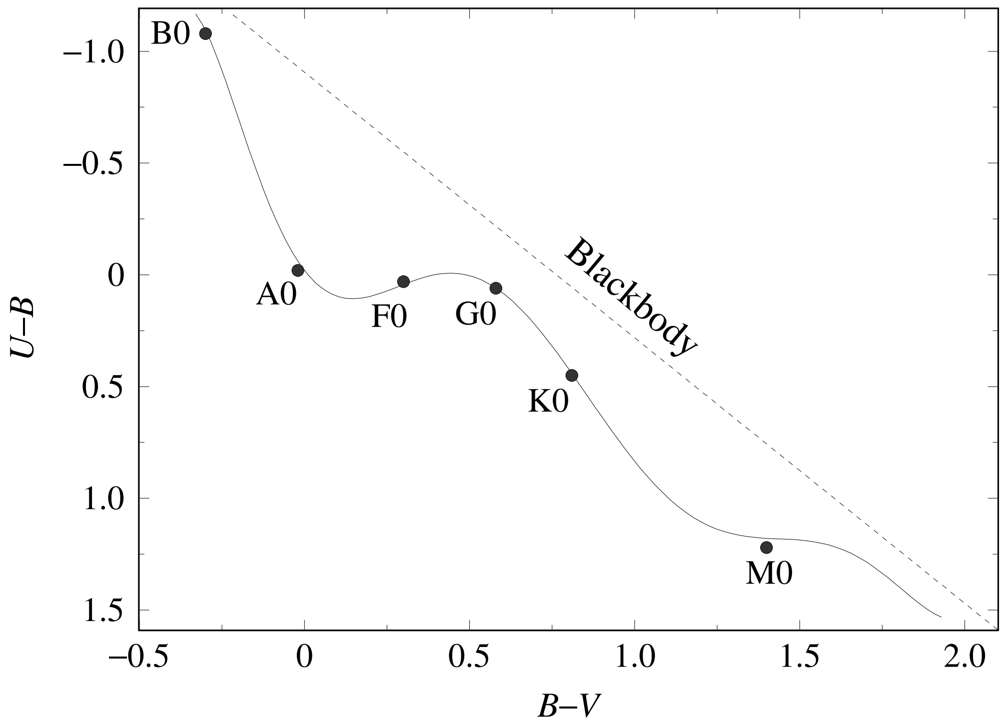



Here are the $UBV$ response curves.




The $UBVRI$ system is useful because its **color indices** are useful indicators of stellar temperatures (from B to K), and provides a measure of the interstellar extinction.

The $B-V$ color index measures the slope of the spectrum in the visible, and is sensitive to temperarure, while the $U-B$ color index measures the height of the **Balmer jump** and is sensitive to both temperature and luminosity.




Main sequence stars have a well-defined track in the $U - B$-$B - V$ **color-color** diagram. The curve near spectral type A0 is related to the Balmer jump.

The effects of interstellar dust were determined observationally by observing O-stars.

Interstellar dust removes more blue light than red light (the amount of scattering) depends on $\lambda^{-1}$). Thus extinction due to dust **increases** $B$ more than it does $V$, so that $B-V$ always **increases** with extinction.

The **color excess** in a color index is defined by

$$E(B-V) = (B-V) - (B-V)_0$$

or

$$E(U-B) = (U-B) - (U-B)_0$$

The **ratio** of the color excesses is found to be

$$X = \frac{E(U-B)}{E(B-V)} = 0.72+0.05E(B-V)$$

for B stars. For other spectral types a slightly more cmplex formula applies.

The **extinction due to dust** can be (on average) found from the color excess:

$$A_V = R\mathrm{ext}E(B-V)$$

where $R_{\mathrm{ext}} \approx 3.1$ for most directions on the sky.

Interstellar extinction will make stars appear **fainter**, and hence will change the apparent distance modulus:

$$(V - A_V) - M_V = 5\log d - 5$$

**Stellar Spectra:**

The ability of a prism to disperse light has been known for a long time (e.g. Newton in *Opticks*.

Wollaston was the first to observe *spectral lines* in the Sun in 1992.

**Spectral Lines** were mapped in the Sun by the early 1800s (e.g. Fraunhofer). Fraunhofer determined that one dark line in the solar spectrum had the same wavelength as the yellow light emitted by burning soduim.

Fraunhofer observed the moon and Venus in his spectroscope and found identical spectral lines, indicating that they shone by reflecting sunlight.

By 1817 Fraunhofer had found that different stars had different spectra (he used visual observations).

In 1860 Kirchhoff & Bunsen published *Chemical Analysis and Spectral Observations*. They showed that each element has its own spectral signature.

Helium is discovered on the Sun in 1869, and found on Earth in 1895.

In 1872 Henry Draper took the first photograph of a stellar spectrum.

At Harvard, Pickering, Fleming, & Cannon developed a general classification scheme, based on the appearance of the hydrogen absorption lines, with type A the first (H strongest) B the second, etc.

Final adopted sequence: O B A F G K M, with decimal subdivisions

**type O** hottest stars, few lines, strong He II

**type B** hot blue-white stars, He I lines strongest at B2, hydrogen lines starting to appear

**type A** white stars, Balmer lines strongest at A0, calcium lines getting stronger.

**type F** yellow-white stars, calcium lines get stronger, hydrogen lines get weaker. Metal lines start to appear.

**type G** yellow stars, iron getting stronger.

**type K** cool orange stars, dominated by metallic lines

**type M** cool red stars, dominated by molecules, especially TiO.

Spectral type sequence.

Recently, the sequence has been extended to **type L** and **type T** for stars at the coolest end.

Also, there are classifications for peculiar stars, and for evolved stars as well (e.g. white dwarfs).

The spectral type sequence is an **empirical** sequence defined by a grid of 55 stars in the 1943 publication *Atlas of Stellar Spectra* by Morgan, Keenan, & Kellman.

The atlas published **photographic spectra** at moderate dispersion in the blue region.

Observers classified their spectra by **visual** comparison with the standard stars.

More qualitative criterion can be found in several sources, e.g. Jaschek & Jaschek, 1987, *The Classification of Stars*, Cambridge University Press.

More recently, clever numerical techniques (e.g. neural networks) have been used to automatically classify spectra:

Snider, et al. 2001, ApJ, 562, 528

Singh, et al. 1998, MNRAS, 295, 312

Bailer-Jones, et al. 1998, MNRAS, 298, 361

The **physical** basis of the Harvard system was not worked out until the 1920s. It was not obvious what caused the differences in line strengths between certain elements in certain types of stars (e.g. the change of the Balmer lines between type A0 and G2).

Cecilia Payne showed that the Harvard sequence was a **temperature sequence**. The balance of certain atoms in certain ionized states depends on the temperature (among other things), so to first order radical change in the strength of the hydrogen lines between A0 and G0 is simply a temperature effect.

Figure from Ostlie & Carroll.

There is a neat JAVA tool on the web where you can plot the spectra of different spectra types and compare it to a black body:

http://www.jb.man.ac.uk/distance/life/sample/java/spectype/specplot.htm

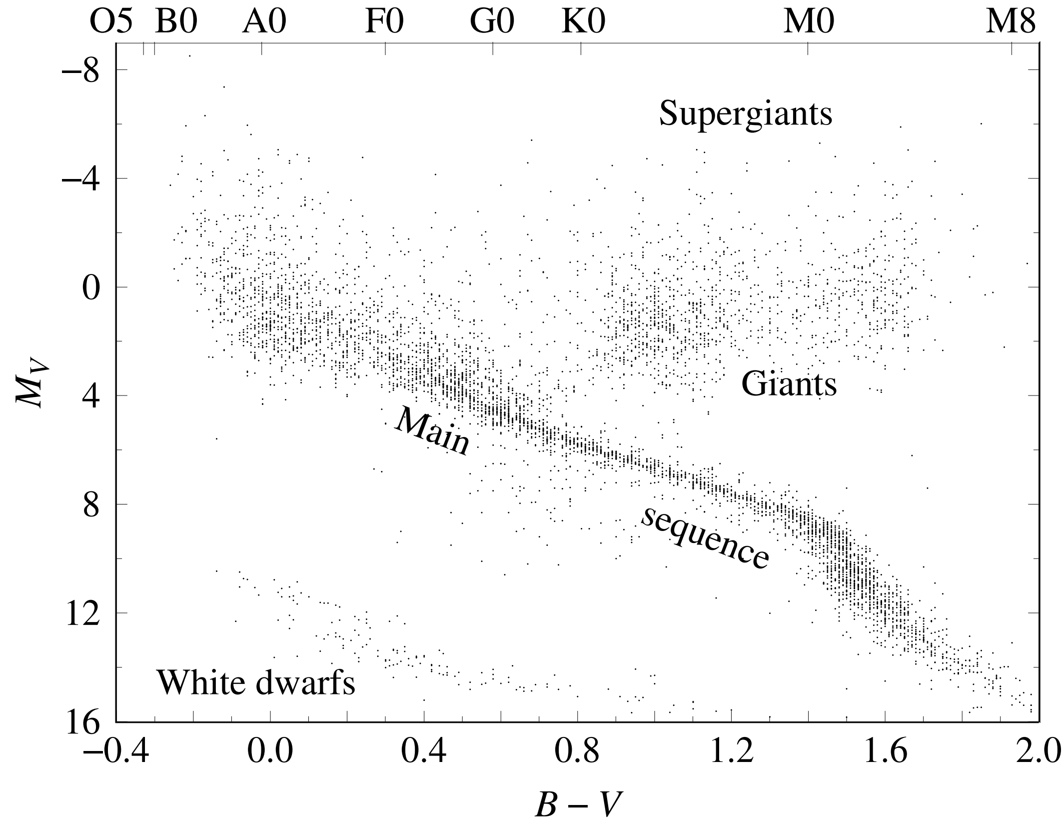
| Spectral type | Temperature (K) | Color |
|---|---|---|
| O | $> 20,000$ | hottest blue |
| B | $20,000 - 10,000$ | blue |
| A | $10,000 - 7,000$ | white to blue-white |
| F | $7,000 - 6,000$ | white |
| G | $6,000 - 5,000$ | yellow |
| K | $5,000 - 3,000$ | orange-red |
| M | $3,500 - 2,000$ | red |

By the 1900s, observers had begun to build up good observational data on stellar properties, including observed magnitudes, absolute magnitudes for some stars (determined by using parallaxes), colors, and spectral types. Also, for a few stars in binaries crude estimates were available for the masses.

In 1905 Hertzsprung published tables showing a correlation between the absolute magnitude and spectral type. He also found some G and K stars had a large range in absolute magitudes.

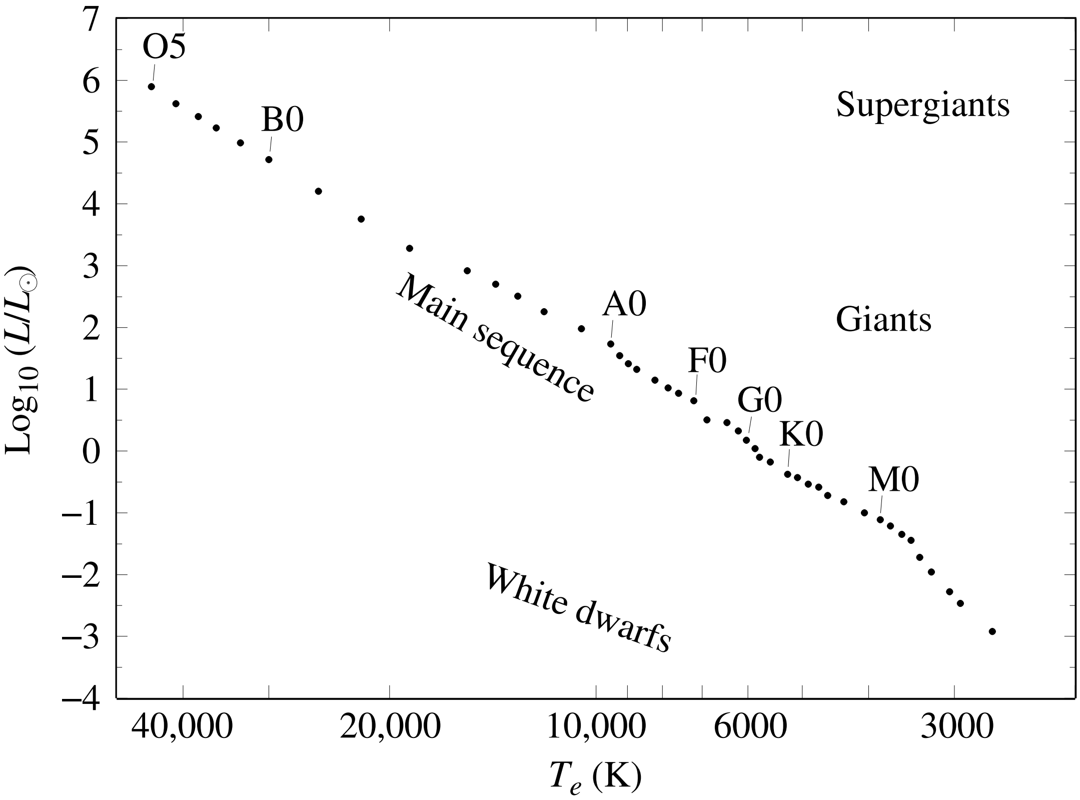
Henry Norris Russell **plotted** stellar temperatures, with spectral types on the $x$-axis and absolute magnitudes on the $y$-axis.

Hertzsprung's and Russell's work showed that **stars do not occupy all of the parameter space in the magnitude-spectral type plane**. This implies that the structure of stars is governed by a few relatively simple physical laws.




(from Ostlie & Carroll)

Today, one often uses a **color index**, rather than a temperature on the $x$-axis. Such a diagram is often called a **color magnitude diagram**.




(from Ostlie & Carroll)

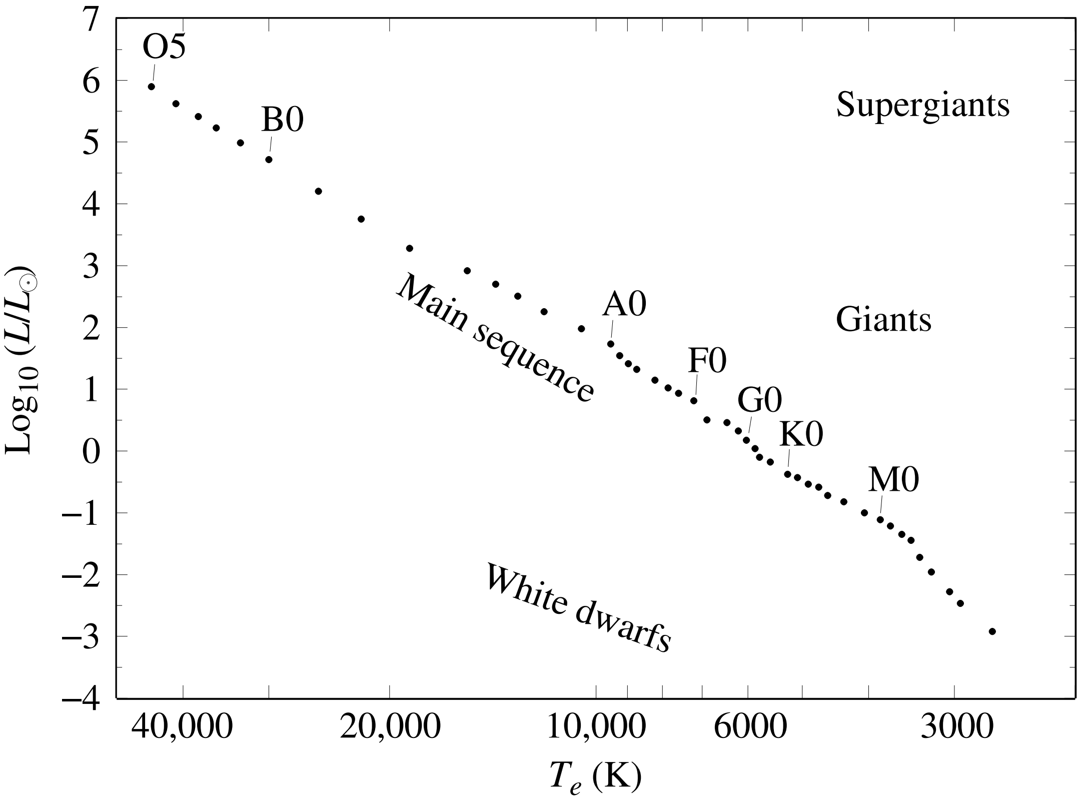
From a theorist's point of view, the useful quantities are the **effective temperature** and **luminosity**.

Hertzsprung noticed that some stars of the same spectral type had rather different absolute magnitudes.

He called the brighter stars **giants** since

$$\frac{R_1}{R_2} = \left(\frac{L_1}{L_2}\right)^{1/2} \left(\frac{T_2}{T_1}\right)^2$$

by the Stefan-Boltzmann law. For the G stars, the temperatures are roughly the same, so brighter stars must have larger radii.




(from Ostlie & Carroll)

As one can see from the HRD, **main sequence** stars have a relatively small range in radii.

**giant and supergiant** stars can have radii as large as 1000 $R_\odot$ or more.

Stellar **masses** span (in round numbers) the range from $0.08\,M_\odot$ to $100\,M_\odot$.

From before, the stellar radii range from $0.01\,R_\odot$ (the white dwarfs) to over $1000\,M_\odot$ for the super giants.

The **surface gravity** is related to the mass and radius of the star:

$$g \propto \frac{GM}{R^2}$$

or, by using logarithms,

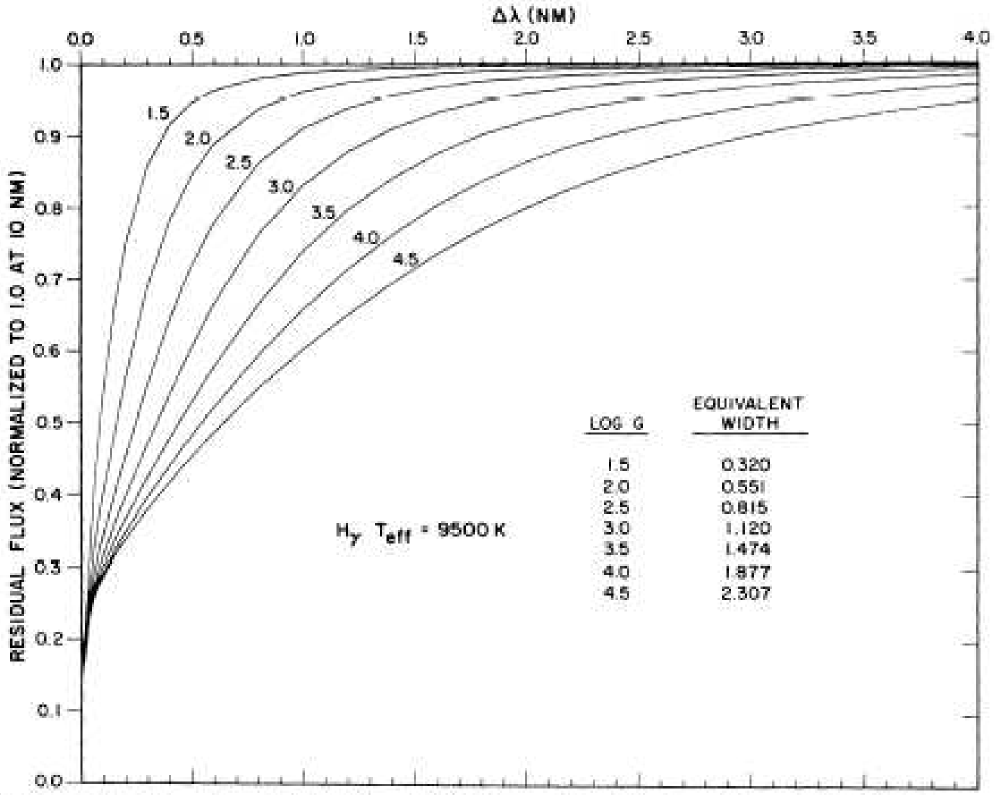
$$\log g \propto \log M - 2\log R$$

Given the dynamic range in $M$ ane $R$ as noted above, the range in surface gravities can span 8 decades!

As the science and art of spectroscopy advanced, it was realized that there were subtle differences in the spectra between main sequence stars (the dwarfs) and the giants and supergiants.

In general, stars with lower surface gravities (the giants and supergiants) have **sharper or narrower** spectral lines, owing to fewer collisions of ions in the atmosphere, and hence less broadening.

Figure from *An Atlas of Representative Stellar Spectra*, by Yamashita et al., 1978.



-H$\gamma$ profiles as a function of gravity for $T_{eff}$ = 9500 K, roughly A0, where the profile is ideal for gravity determination

For A stars, the effect of the surface gravity on the Balmer line profiles is quite dramatic.

From Kurucz, 1979, ApJS, 40, 1 (the most cited paper in all of astronomy).

A **luminosity class** was added to the spectral classification scheme.

| Class | Type of Star |
|---|---|
| Ia-O | Extreme supergiants |
| Ia | luminous supergiants |
| Ib | Less luminous supergiants |
| II | bright giants |
| III | Normal giants |
| IV | Subgiants |
| V | main sequence (dwarfs) |
| VI, sd | subdwarfs |
| D | white dwarfs |

A complete spectral type includes a letter (temperature) and a Roman numerial (luminosity).

**Narrow-band photometry**

Once the classification scheme became established and the physical understanding behind the HR diagram grew, observers sought an efficient **photometric** system to study effective temperature, surface gravity, and reddening.

The most successful system of **narrow-band** filters is the Strómgren (1966, ARA&A, 4 433).

The bandpasses are narrow, and as a result the response curves are specified by the filters themselves, i.e. the properties of the detector do not matter.

| name | symbol | central $\lambda$ | $\Delta\lambda$ |
|---|---|---|---|
| ultraviolet | $u$ | 3500Å | 380Å |
| violet | $v$ | 4100Å | 200Å |
| blue | $b$ | 4700Å | 200Å |
| yellow | $y$ | 5500Å | 200Å |
| narrow $\beta$ | | 4681Å | 30Å |
| wide $\beta$ | | 4861Å | 100Å |