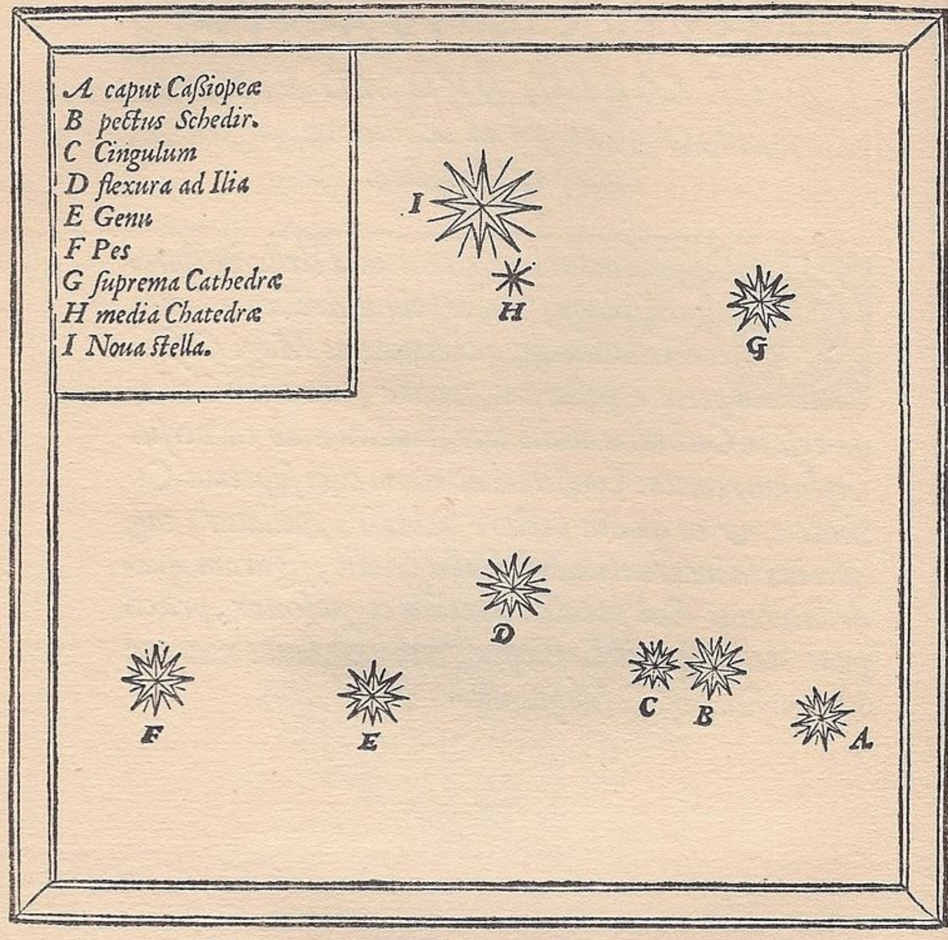
"When according to habit I was contemplating the stars I noticed a new star surpassing the others in brilliancy"

Tycho Brahe

Alex Sinclair – Workshop 2



Diſtantiam verò huius ſtellæ à fixis aliquibus in hac Caßiopeiæ conſtellatione, exquiſito inſtrumento, & omnium minutorum capacj, aliquoties obſeruaui. Inueni autem eam diſtare ab ea, quæ eſt in pectore, Schedir appellata B, 7. partibus & 55. minutis: à ſuperiori verò

Hertzsprung Russell

- Making Sense from Chaos

Key characteristics of stars include:

Mass,
Temperature,
Luminosity,
Physical size,
Spectral Classification.

Vast bodies of measured star data have been accumulated.

Temperature[8] (Kelvin)	Conventional color	Apparent color [9][10][11]	Mass[8] (solar masses)	Radius[8] (solar radii)	Luminosity[8] (bolometric)
≥ 30,000 K	blue	blue	$\geq 16\ M_{sun}$	$\geq 6.6\ R_{sun}$	$\geq 30{,}000\ L_{sun}$
10,000 - 30,000 K	blue to blue white	blue white	$2.1 - 16\ M_{sun}$	$1.8 - 6.6\ R_{sun}$	$25 - 30{,}000\ L_{sun}$
7,500 - 10,000 K	white	white to blue white	$1.4 - 2.1\ M_{sun}$	$1.4 - 1.8\ R_{sun}$	$5 - 25\ L_{sun}$
6,000 - 7,500 K	yellowish white	white	$1.04 - 1.4\ M_{sun}$	$1.15 - 1.4\ R_{sun}$	$1.5 - 5\ L_{sun}$
5,200 - 6,000 K	yellow	yellowish white	$0.8 - 1.04\ M_{sun}$	$0.96 - 1.15\ R_{sun}$	$0.6 - 1.5\ L_{sun}$
3,700 - 5,200 K	orange	yellow orange	$0.45 - 0.8\ M_{sun}$	$0.7 - 0.96\ R_{sun}$	$0.08 - 0.6\ L_{sun}$
≤ 3,700 K	red	orange red	$\leq 0.45\ M_{sun}$	$\leq 0.7\ R_{sun}$	$\leq 0.08\ L_{sun}$

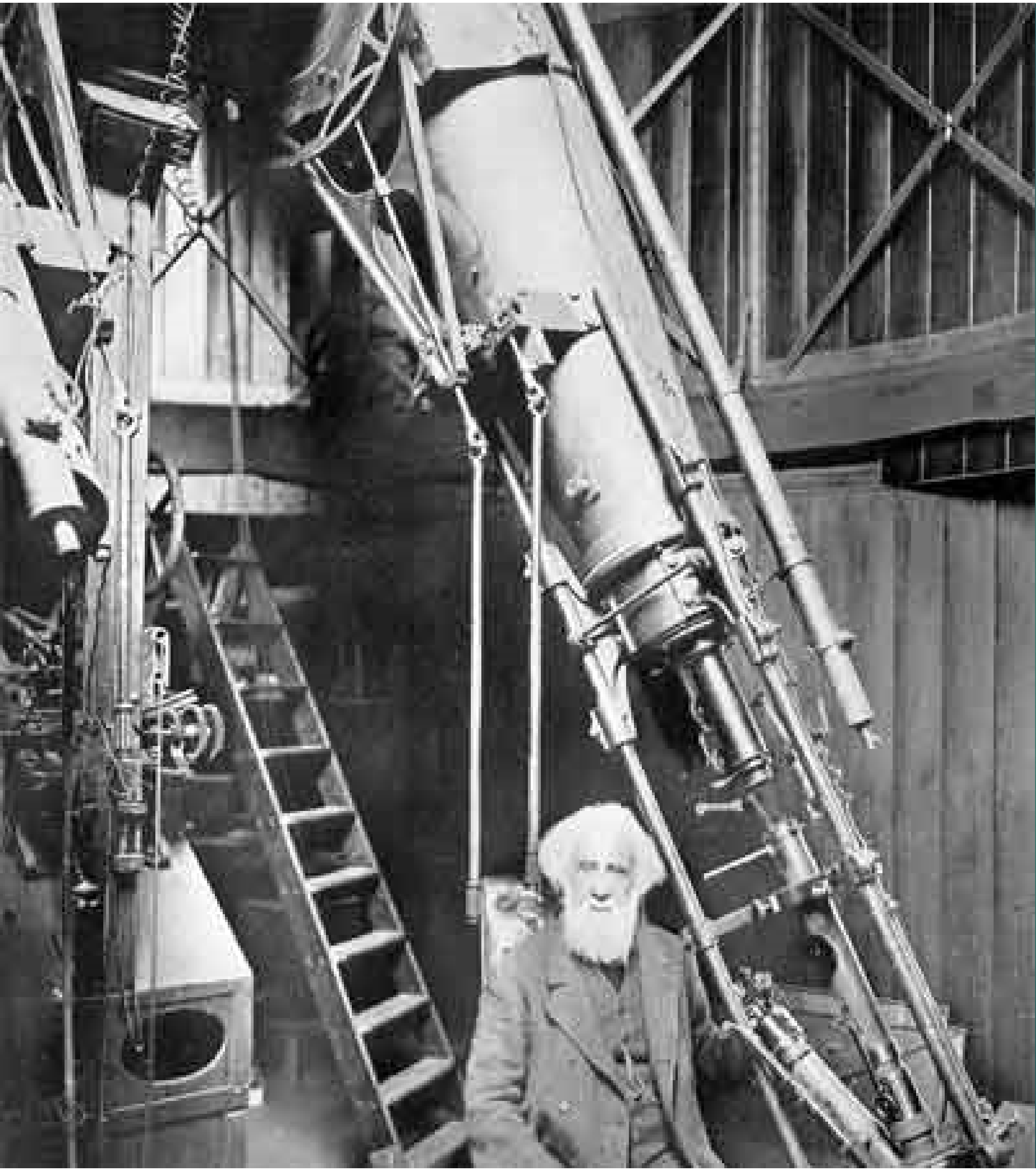
http://en.wikipedia.org/wiki/Stellar_classification

Table of main-sequence stellar parameters[24]

Stellar Class	Radius	Mass	Luminosity	Temperature	Examples[25]
	$R/R_\odot$	$M/M_\odot$	$L/L_\odot$	K	
O6	18	40	500,000	38,000	Theta1 Orionis C
B0	7.4	18	20,000	30,000	Phi[1] Orionis
B5	3.8	6.5	800	16,400	Pi Andromedae A
A0	2.5	3.2	80	10,800	Alpha Coronae Borealis A
A5	1.7	2.1	20	8,620	Beta Pictoris
F0	1.3	1.7	6	7,240	Gamma Virginis
F5	1.2	1.3	2.5	6,540	Eta Arietis
G0	1.05	1.10	1.26	5,920	Beta Comae Berenices
G2	1.00	1.00	1.00	5,780	Sun[note 2]
G5	0.93	0.93	0.79	5,610	Alpha Mensae
K0	0.85	0.78	0.40	5,240	70 Ophiuchi A
K5	0.74	0.69	0.16	4,410	61 Cygni A[26]
M0	0.63	0.47	0.063	3,920	Gliese 185[27]
M5	0.32	0.21	0.0079	3,120	EZ Aquarii A
M8	0.13	0.10	0.0008	2,660	Van Biesbroeck's star[28]

But tabulated and catalogued records do not allow ready appreciation of what these data imply.

Ready understanding of the ‘big picture’ necessitates something more:

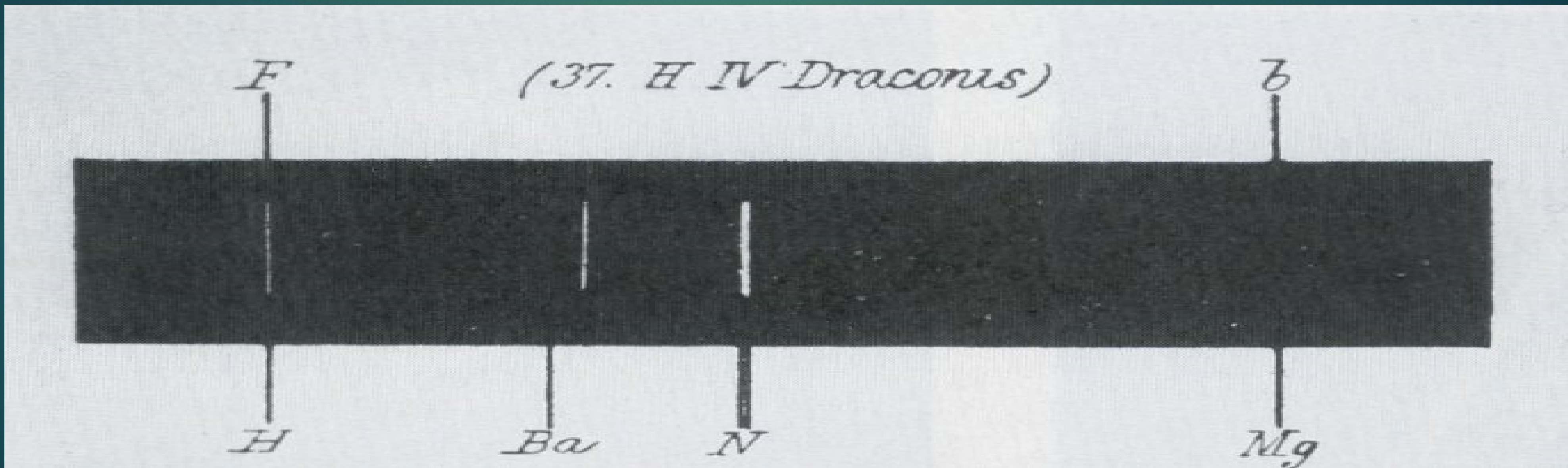


The second half of the 19th century saw pioneering work in stellar spectroscopy.

By 1875 English astronomer William Huggins, working in his own observatory at Tulse Hill, London, was able to photograph stellar spectra.

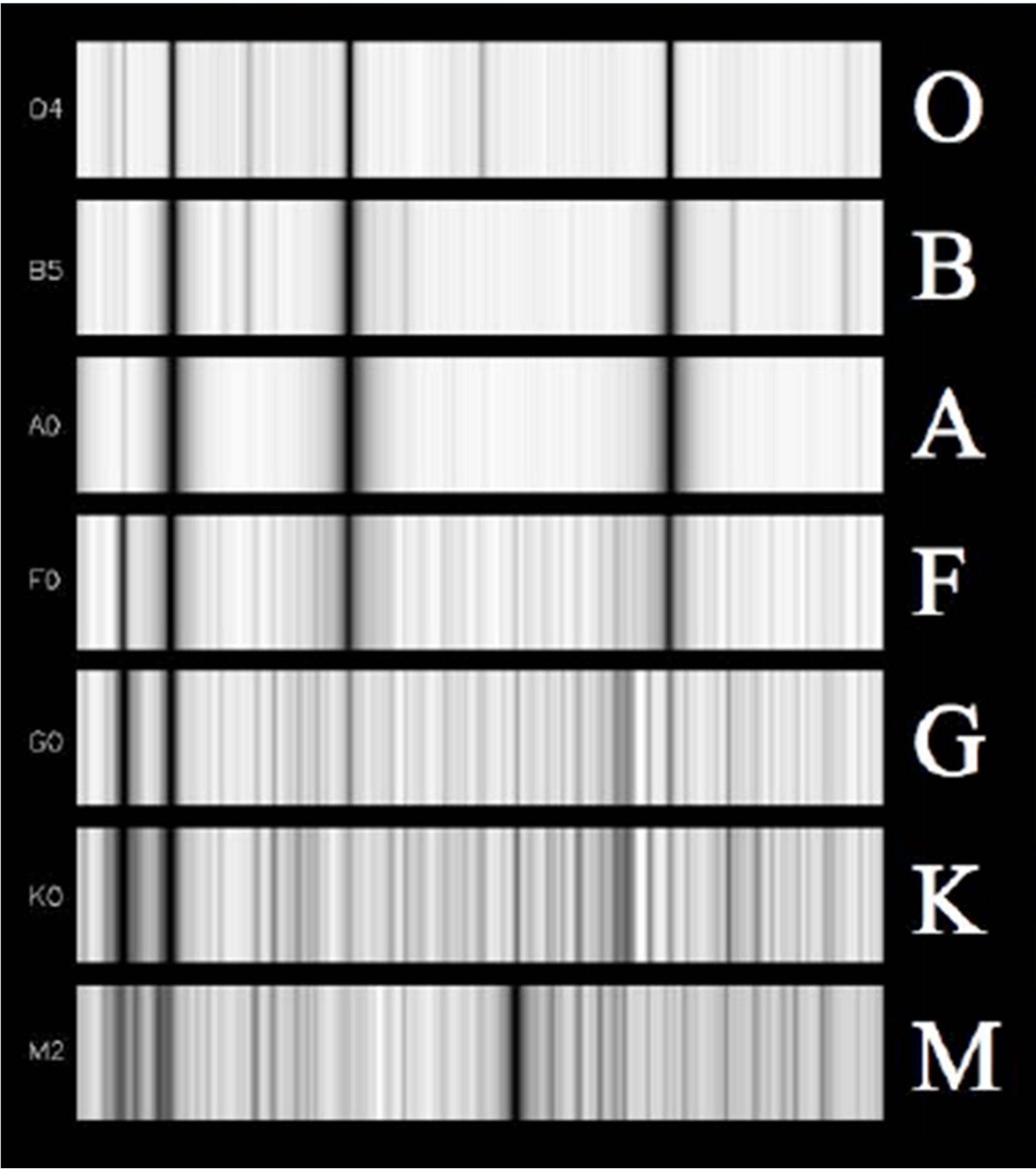
Soon many others followed in Huggin's footsteps.

Early photo-spectrograph (Huggins)



In 1881 Edward Pickering, director of Harvard College observatory, hired Williamina Fleming (his then housemaid) as a ‘computer’ to undertake calculations regarding preparation of a star catalogue. But she was soon promoted to supervise a team of other women to examine and classify stellar spectral photographs.

Williamina Fleming (standing) with members of the ‘computers’ group including Antonia Maury and Annie Jump Cannon.

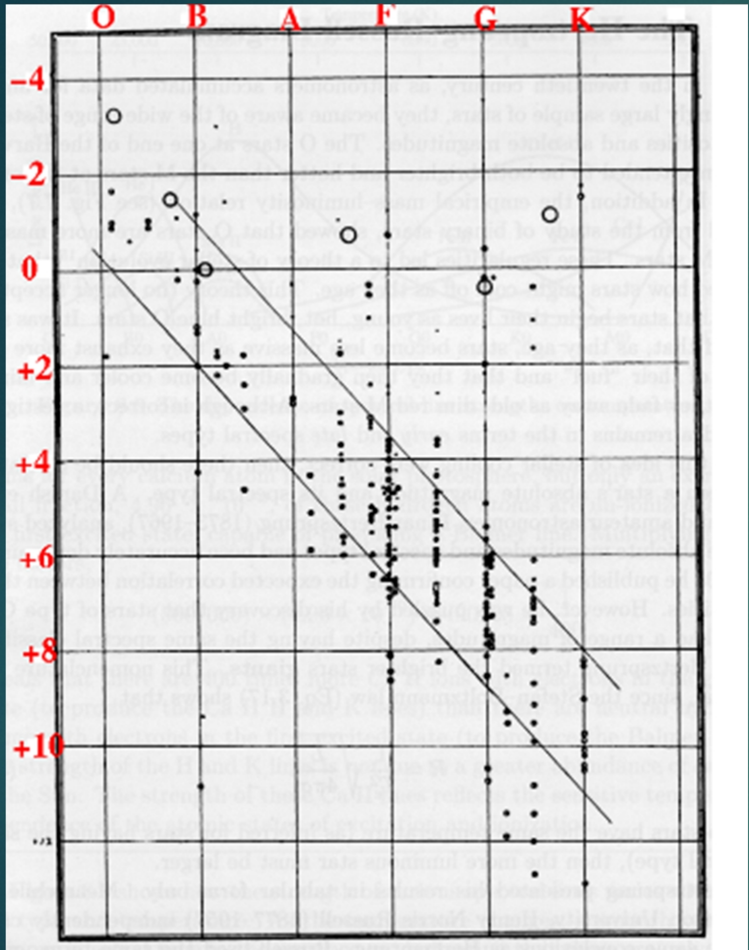


After much analysis and simplification of early schemes the group settled on the present day ‘O - M’ classification of spectral types.

This was based on the width and prominence of the spectral lines.

In 1908 Danish amateur astronomer Ejnar Hertzsprung (later turned professional) visited Karl Schwarzschild at Göttingen University to discuss an early diagram developed by Hertzsprung to illustrate photographic magnitudes plotted against effective stellar light wavelength.

A year or so after Hertzsprung conceived his initial ideas American astronomer Henry Norris Russell independently produced a similar diagram based on spectral type as conceived by Williamina Fleming.



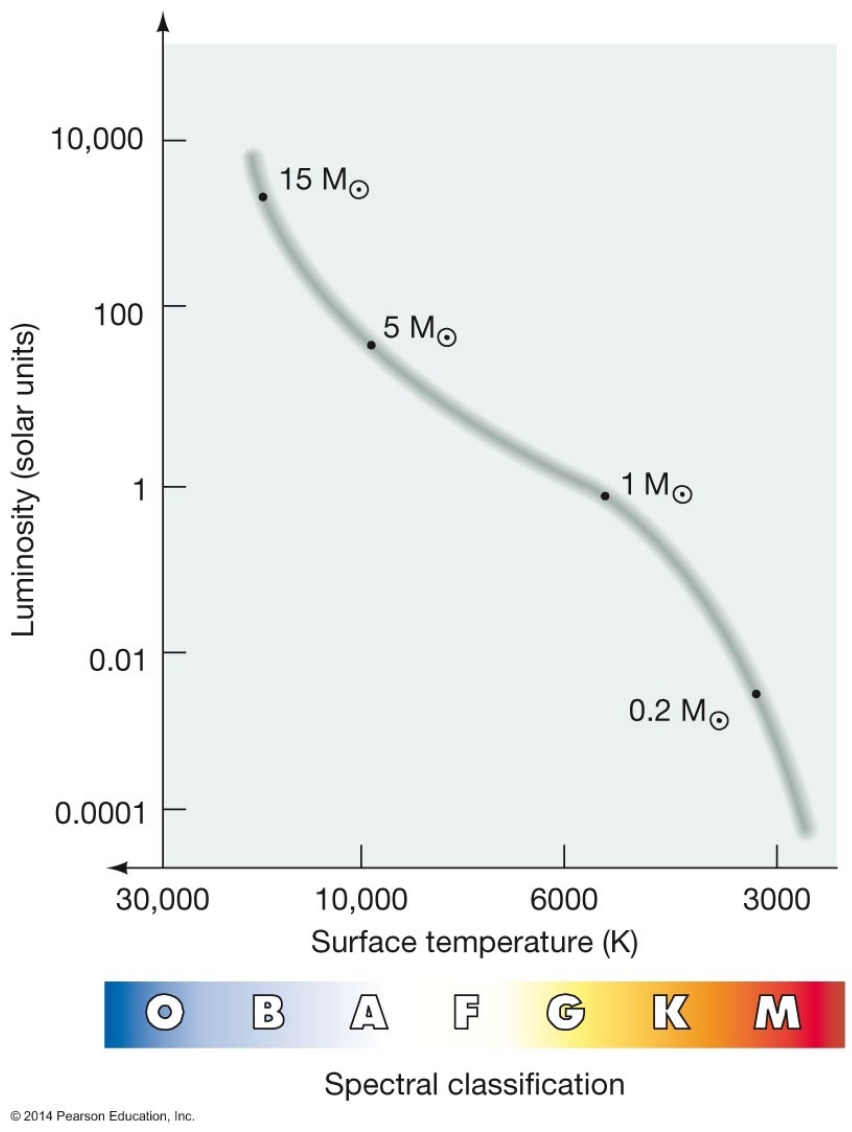
ure 8.10 Henry Norris Russell's first diagram, with spectral types
d along the top and absolute magnitudes on the left-hand side. (Figure
Russell, *Nature*, *93*, 252, 1914.)

1913 - Henry Norris Russell's 1st HR diagram. A scatter graph of absolute magnitude against spectral type.

Future development of this diagram went under the name of Hertzsprung-Russell (HR).

The HR diagram eventually became one of the most important tools in astronomy.

In the 1920s astronomer Celia Payne Gaposhkin and physicist Meghnad Saha demonstrated that the classification sequence O B A F G K M actually represented a sequence of reducing stellar surface temperature.



This work led to the modern form of HR diagram – **Temperature** against **Luminosity**.

The most prominent feature of the HR-Diagram is the diagonal running from upper left (hot & bright) to lower right (cool & dim). This is the **Main Sequence**.

NB: The main sequence is NOT a sequence of stellar evolution.

The HR diagram is a scatter graph:

It is based on two specific stellar properties: temperature/spectral type and luminosity.

Data represent practical observations not mathematical or theoretical relationships.

However, the HR diagram may be annotated with theoretically derived curves concerning star radius, mass and lifetime.

The HR diagram is NOT a graph of star population size or spatial distribution – but it happens that ≈90% of all stars lie on the Main Sequence.

Stars have a range of luminosities of over 10 billion - from 50,000 times fainter to 1,000,000 brighter than the Sun.

A range of surface temperature of about 15,000.

Range of radii about 100,000.

Range of mass of about 1,000

An HR diagram can accommodate these vast orders of magnitude.

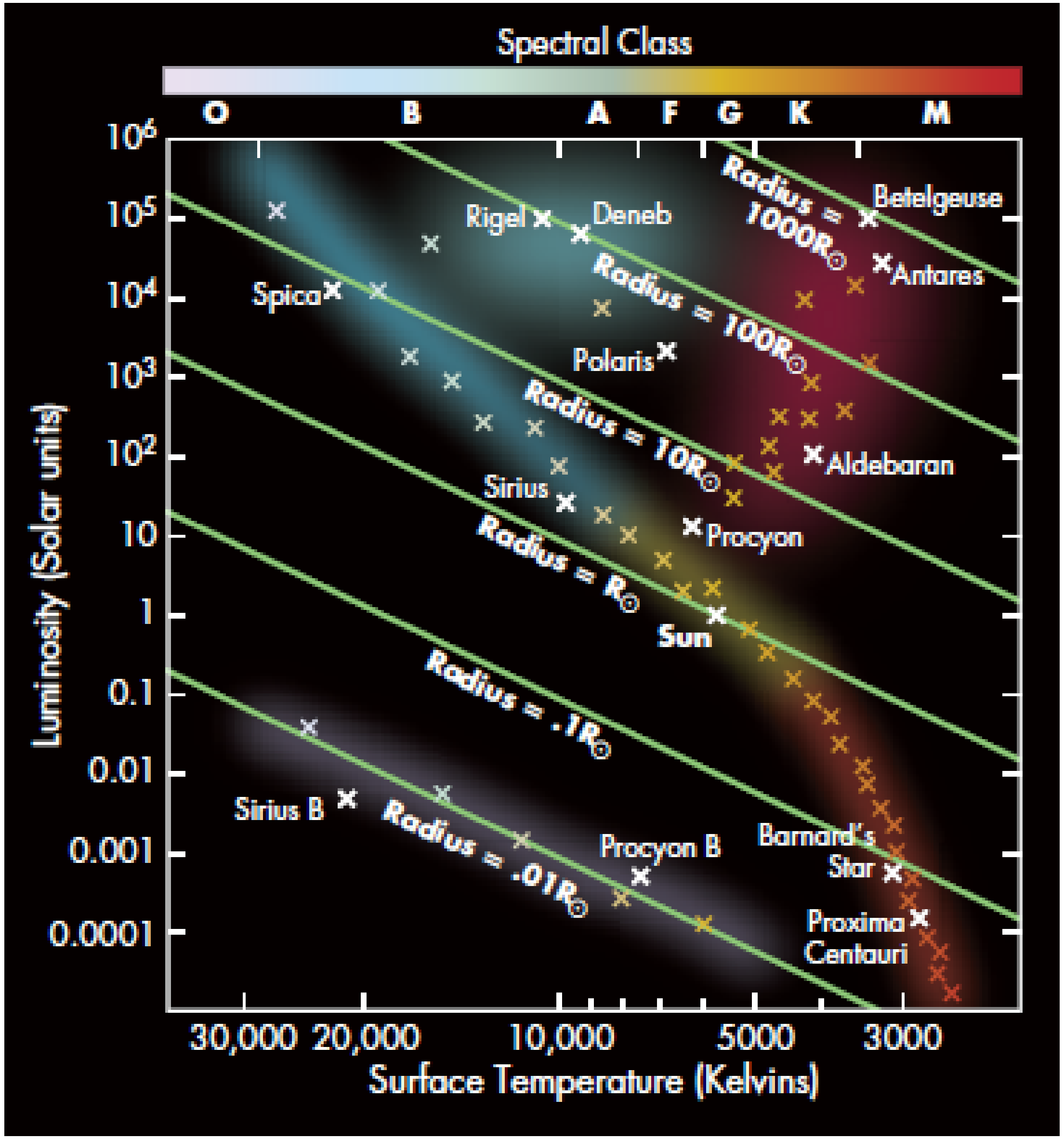
A star's radius is mathematically related to its luminosity and temperature by the Stefan-Boltzmann Law.

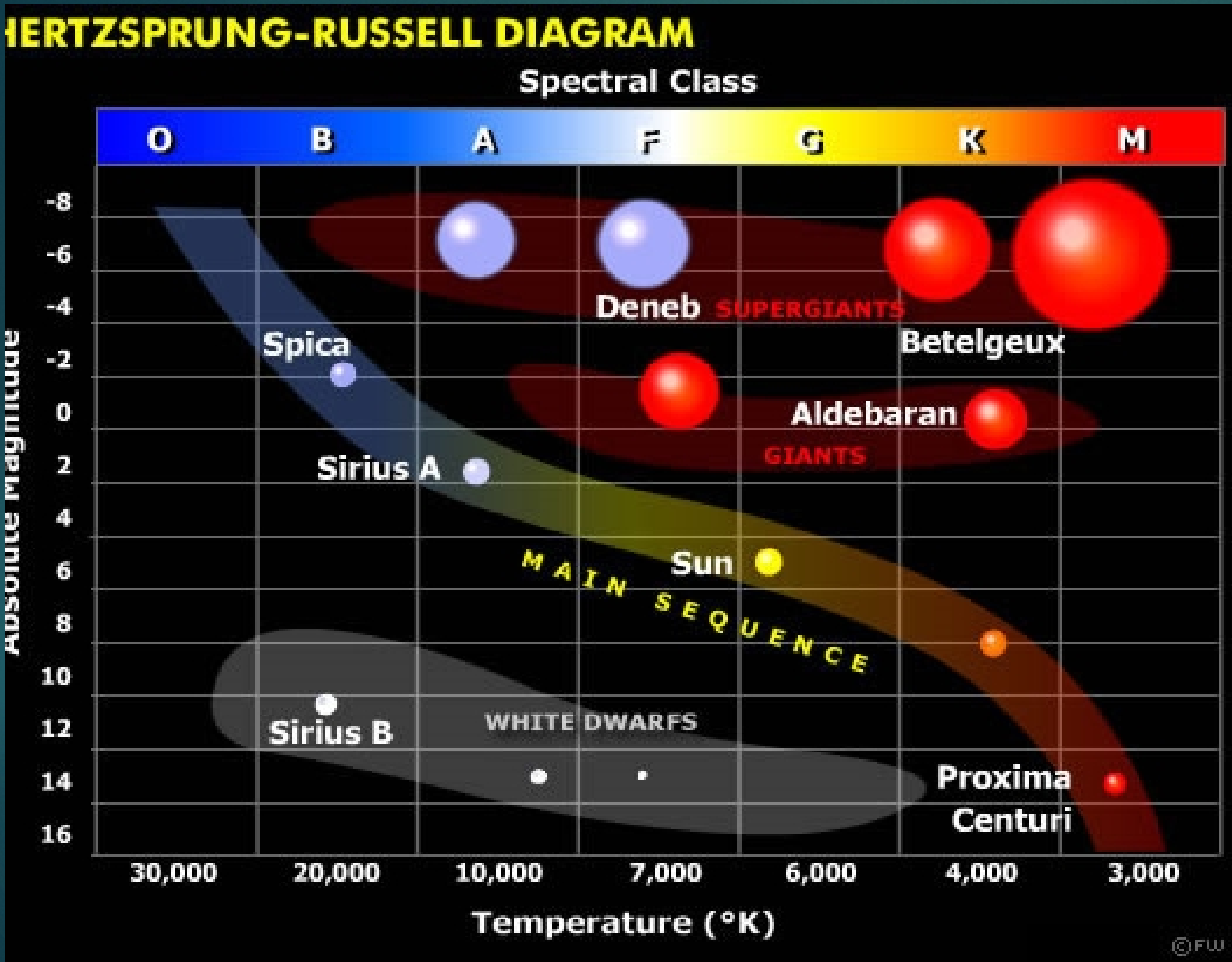
$$\sigma = 5.67 \bullet 10^{-8} W / m^2 K^4$$

$$L = 4\pi R^2 \sigma T^4$$

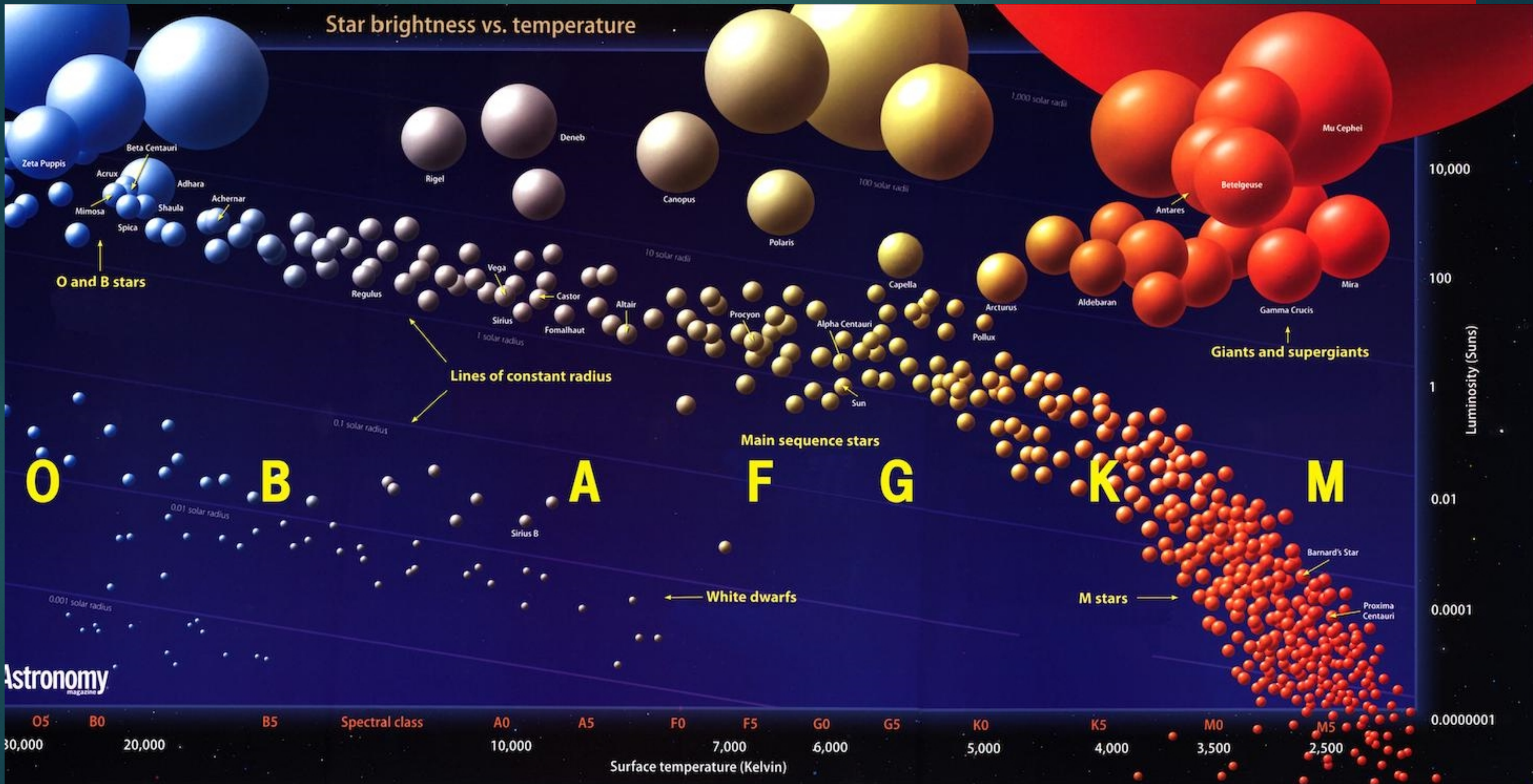
$$R^2 \propto \frac{L}{T^4}$$

This relationship allows calculated lines of constant radius to be added to the HR diagram.

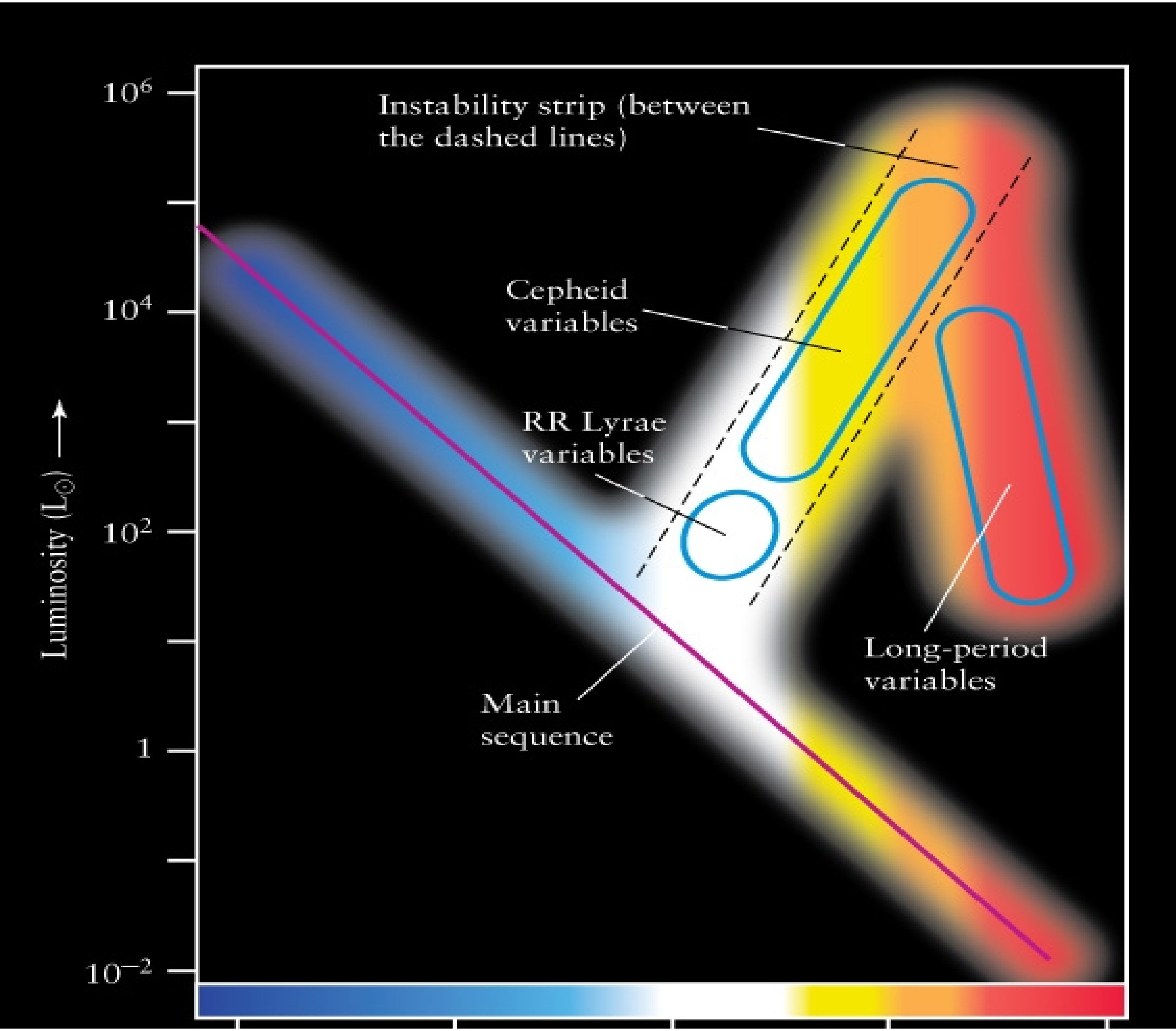

Spectral Class
O
B
A
F
G
K
M
Luminosity (Solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
0.01
0.001
0.0001
Surface Temperature (Kelvins)
30,000
20,000
10,000
5000
3000
Rigel
Deneb
Betelgeuse
Antares
Spica
Polaris
Aldebaran
Sirius
Procyon
Sun
Sirius B
Procyon B
Barnard's Star
Proxima Centauri
Radius ≈ 1000R☉
Radius ≈ 100R☉
Radius ≈ 10R☉
Radius ≈ R☉
Radius ≈ .1R☉
Radius ≈ .01R☉



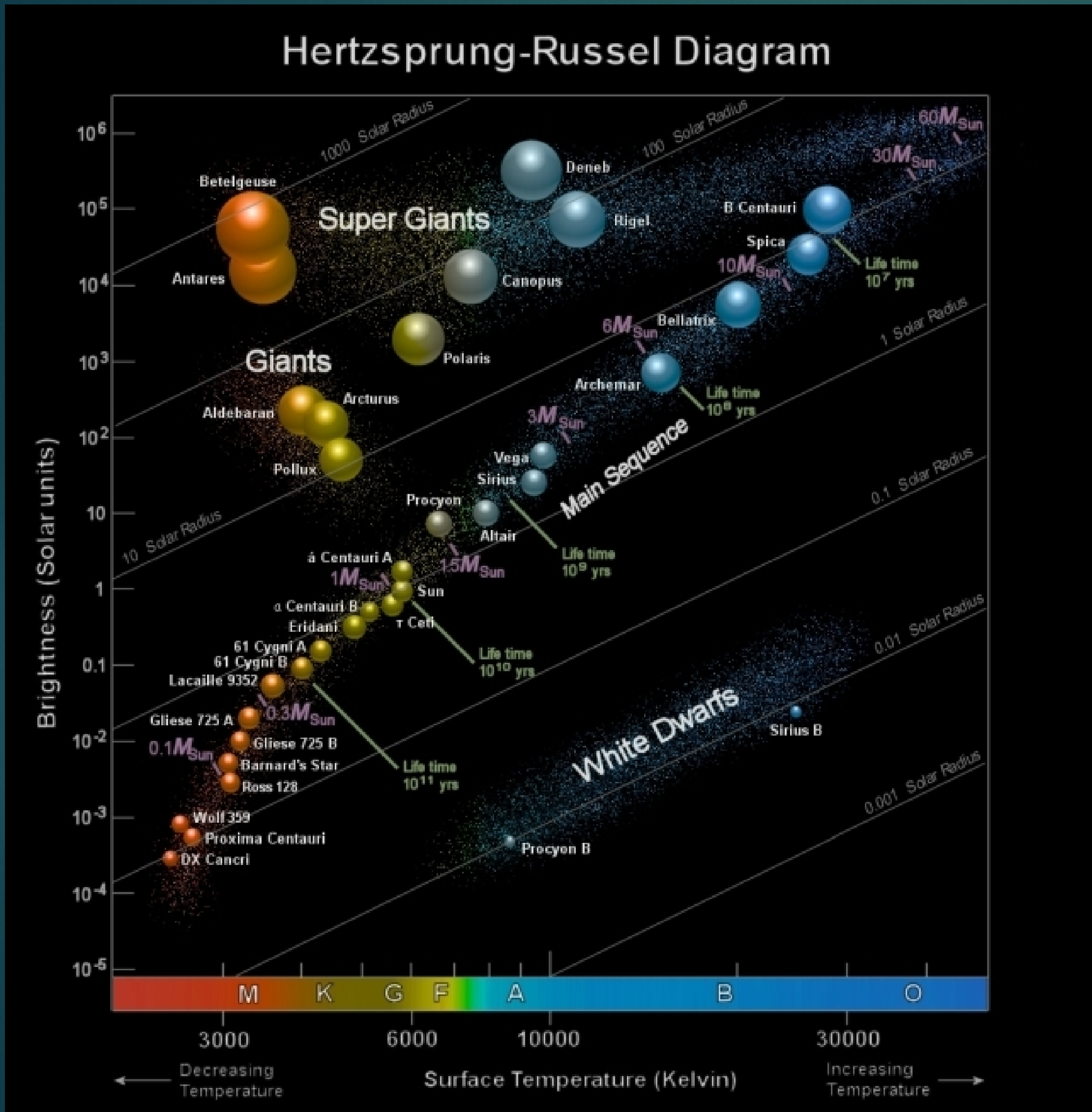
Other important concepts to arise from HR are the relative locations of giant, super-giant and white dwarf stars.



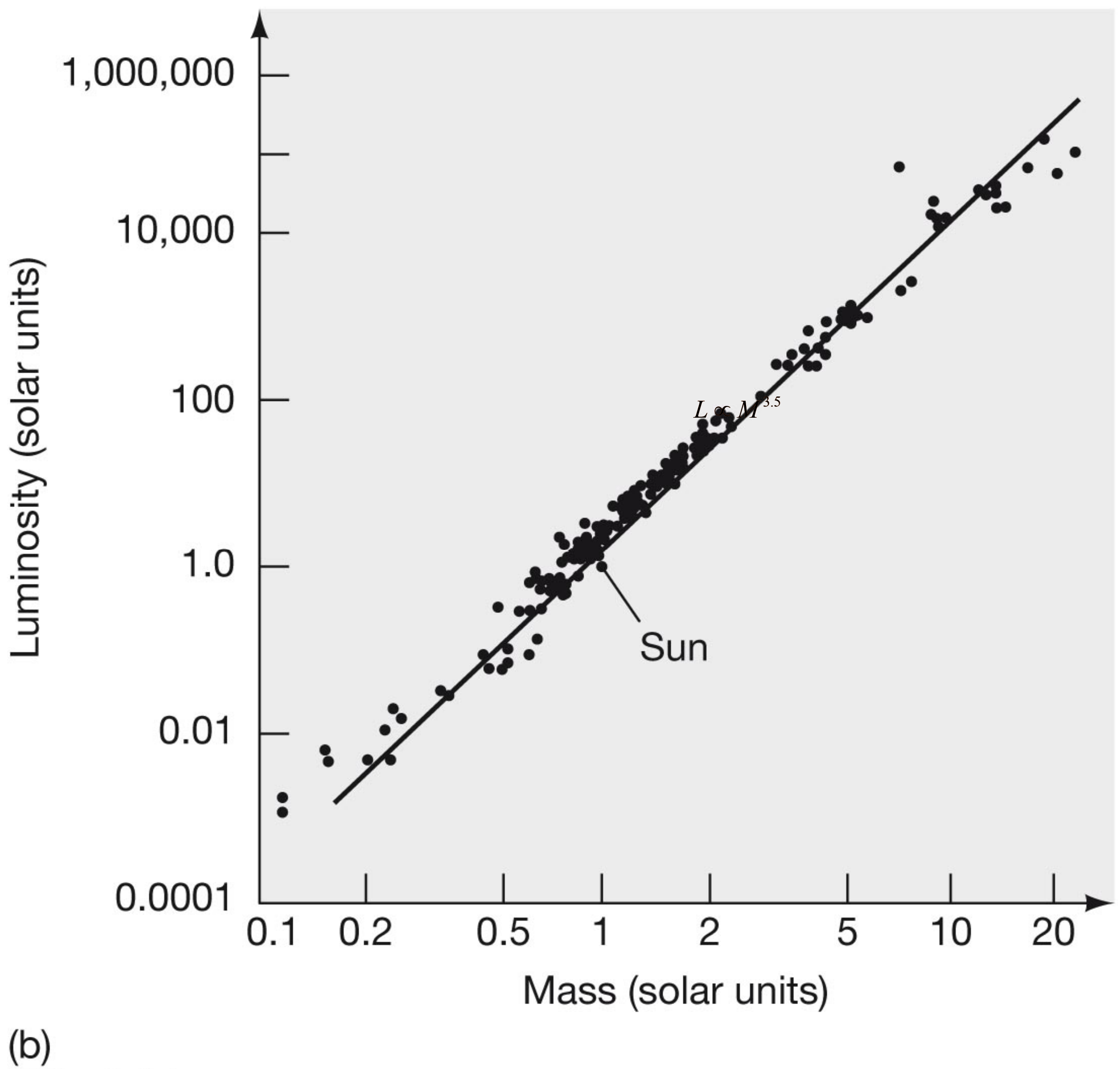
Star brightness vs. temperature
Zeta Puppis
Beta Centauri
Acrux
Adhara
Mimosa
Shaula
Achernar
Spica
O and B stars
Rigel
Deneb
Canopus
Polaris
Regulus
Vega
Castor
Sirius
Fomalhaut
Altair
Procyon
Alpha Centauri
Sun
Capella
Arcturus
Pollux
Aldebaran
Antares
Betelgeuse
Mu Cephei
Mira
Gamma Crucis
Giants and supergiants
1,000 solar radii
100 solar radii
10 solar radii
1 solar radius
0.1 solar radius
0.01 solar radius
0.001 solar radius
Lines of constant radius
Main sequence stars
O
B
A
F
G
K
M
Sirius B
White dwarfs
M stars
Barnard's Star
Proxima Centauri
10,000
100
1
0.01
0.0001
0.0000001
Luminosity (Suns)
O5
B0
B5
Spectral class
A0
A5
F0
F5
G0
G5
K0
K5
M0
M5
30,000
20,000
10,000
7,000
6,000
5,000
4,000
3,500
2,500
Surface temperature (Kelvin)
Astronomy magazine



The instability strip.



The tradition of HR temperature scale increasing right to left can be reversed.



There is no **overall** stellar mass-luminosity relation – the brightness of a star changes over its lifetime.

But for **main sequence** stars an approximate relationship is:

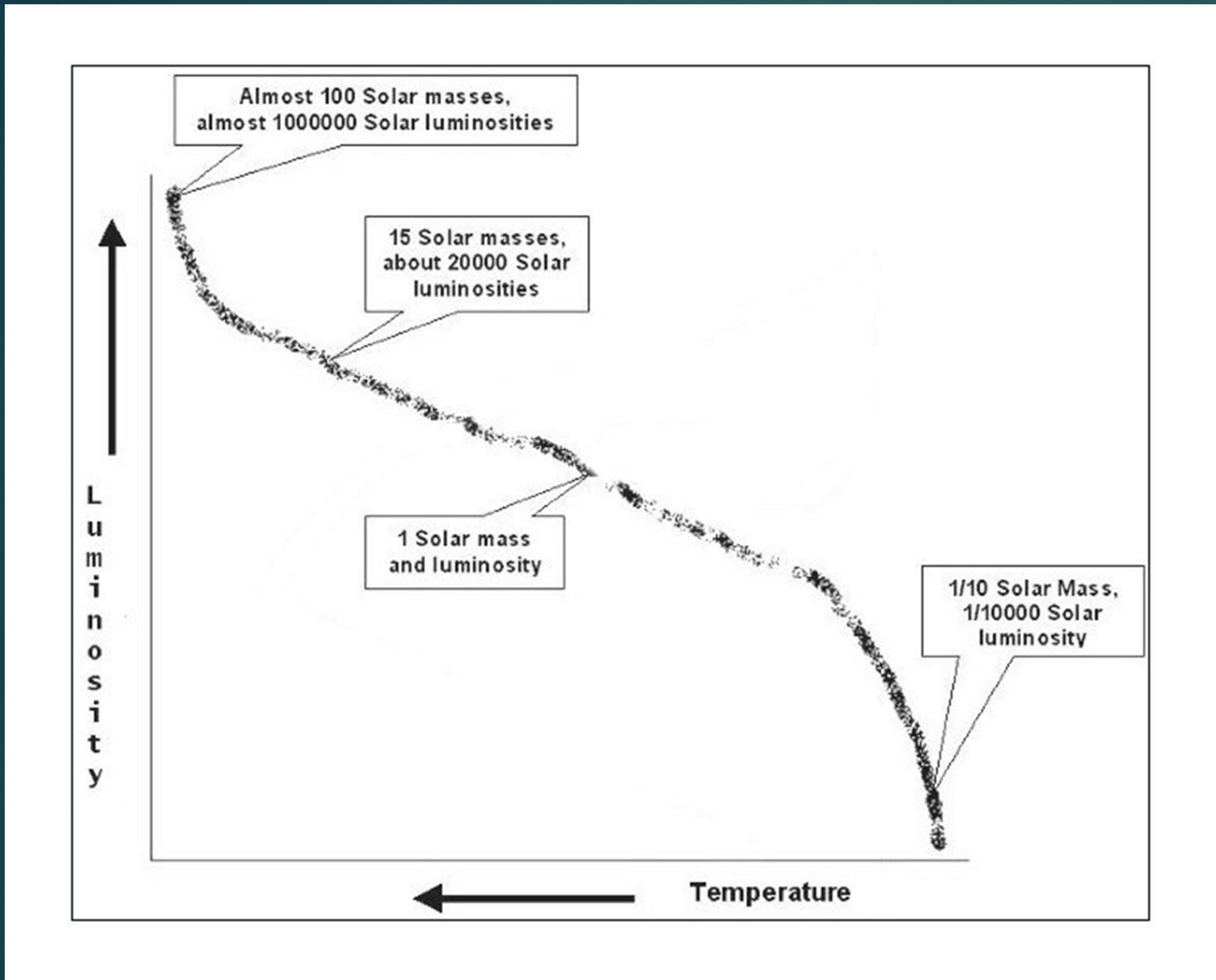
$$L \propto M^{3.5}$$

Slopes of possible straight lines on a logarithmic plot vary from about 3.0 to 4.0.

More massive stars would collapse. Less massive stars would be exploded by radiation pressure.

It follows that the temperature, spectral type and location of a given star on the **main sequence** is determined by its **mass.**

Therefore the mass of a main **sequence star** can be approximated (in solar units of 2x10^30kg) from the luminosity (in solar units) as apparent from the HR diagram.



Main Sequence mass v luminosity

The relationship between luminosity and mass has important implications for main sequence stellar lifetime:

Luminosity is proportional to the rate at which hydrogen is consumed in the stellar core.

Main Sequence stars twice as bright as the Sun consume hydrogen 10 times more quickly than the Sun.

The approximate mass to luminosity relationship persists for all **main sequence** stars of greater and smaller mass than the Sun.

Main Sequence Stellar lifetime v Solar Mass Equivalent

1	Solar mass	≈	10	billion	yrs.
2	.. ..	≈	2	billion	yrs.
4	.. ..	≈	400	million	yrs.
8	.. ..	≈	80	million	yrs.
16	.. ..	≈	15	million	yrs.
32	.. ..	≈	3	million	yrs.
64	.. ..	≈	1	million	yrs.
0.50	.. ..	≈	50	billion	yrs.
0.25	.. ..	≈	250	billion	yrs.
0.13	.. ..	>	1	trillion	yrs.

Source: cseligman.com

It is to be expected that this vast difference in stellar lifespan will be reflected in the numeric distribution of existing stars.

Massive hot blue giant stars will be few in number because they die young. Small and cool red dwarfs with lifetimes comparable to the age of the Universe! – well they will hang around forever because the Universe is not yet old enough for them to die…

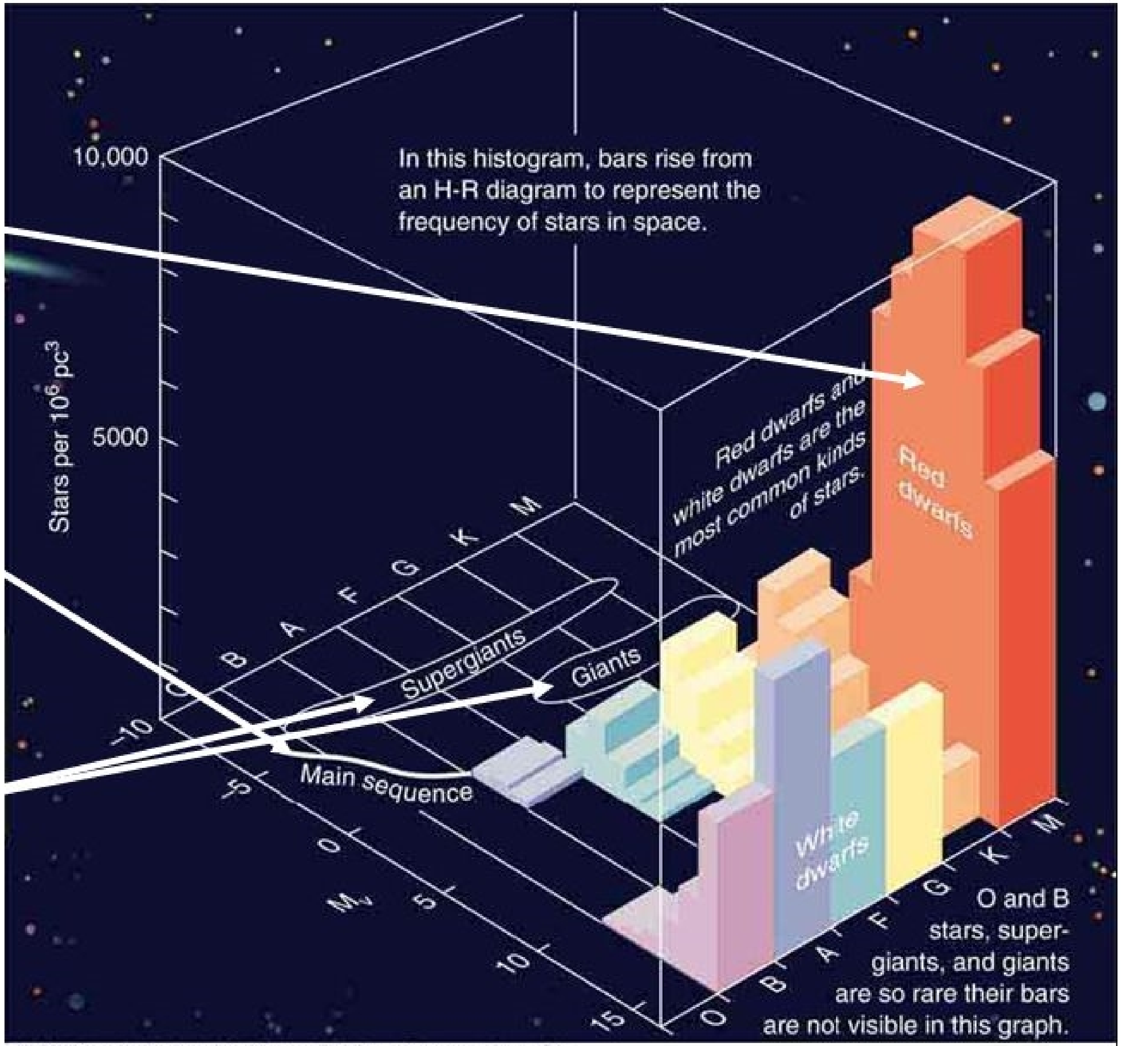
Stellar Population Distribution Explained

Faint, red dwarfs (low mass) are the most common stars. Long lived

Bright, hot, blue main-sequence stars (high-mass) are very rare. Short lived

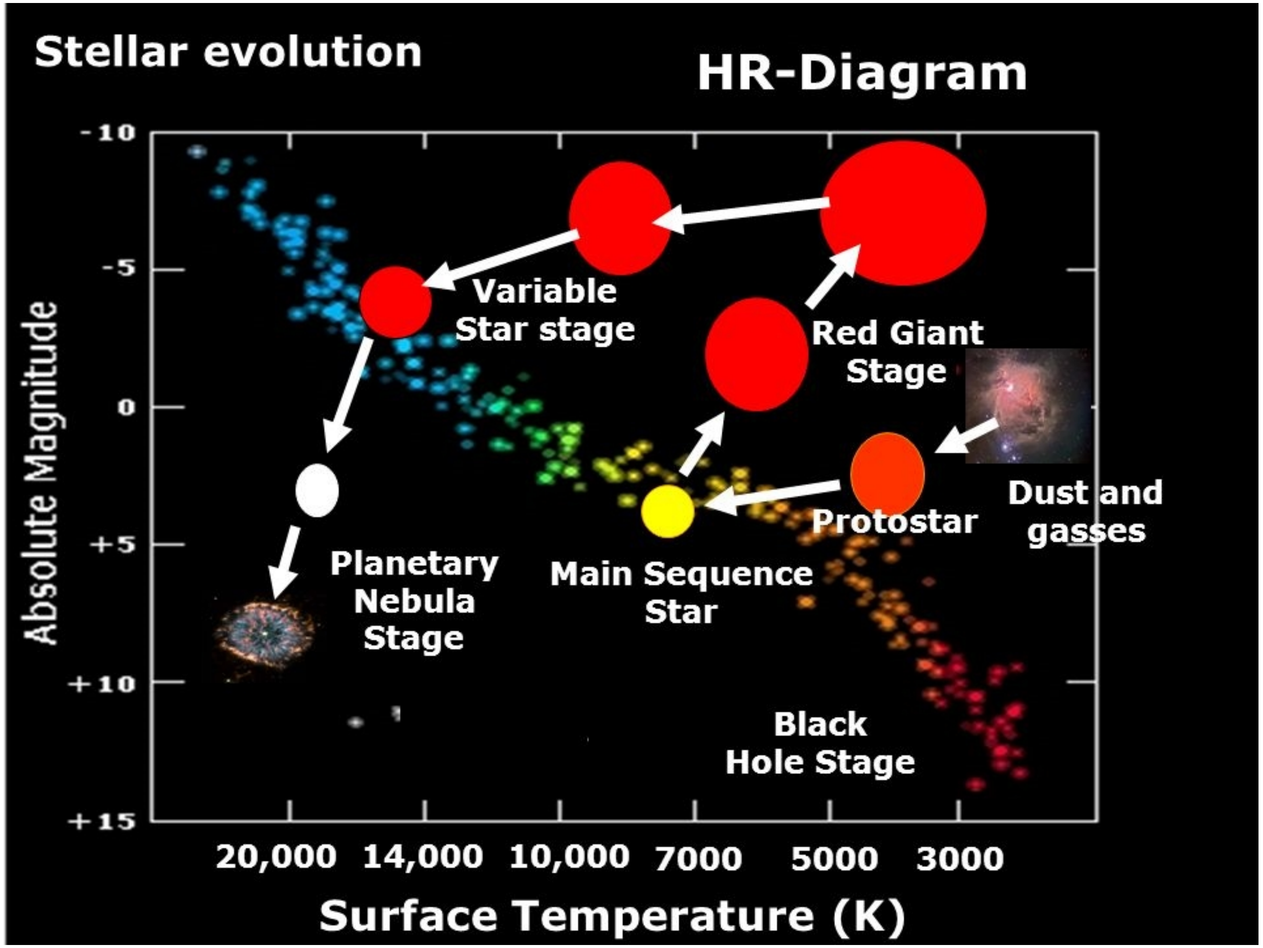
Giants and supergiants are extremely rare.

Passing through a stage.



Stellar evolution does NOT consist of moving linearly up or down the main sequence.

On the HR diagram evolution over time occurs by a star moving diagonally.



Evolution of sun-like stars.

The HR diagram can depict the degree of radical change experienced by a star during evolution from birth to demise.

Summary:

The HR diagram is one of the most important tools in astronomy.

It depicts observation of absolute luminosity against surface temperature.

A star’s size, internal structure and evolutionary stage can be determined simply from its position on the HR diagram.

By exploiting the instability strip the HR diagram can be used to estimate the distance of stars and star clusters.