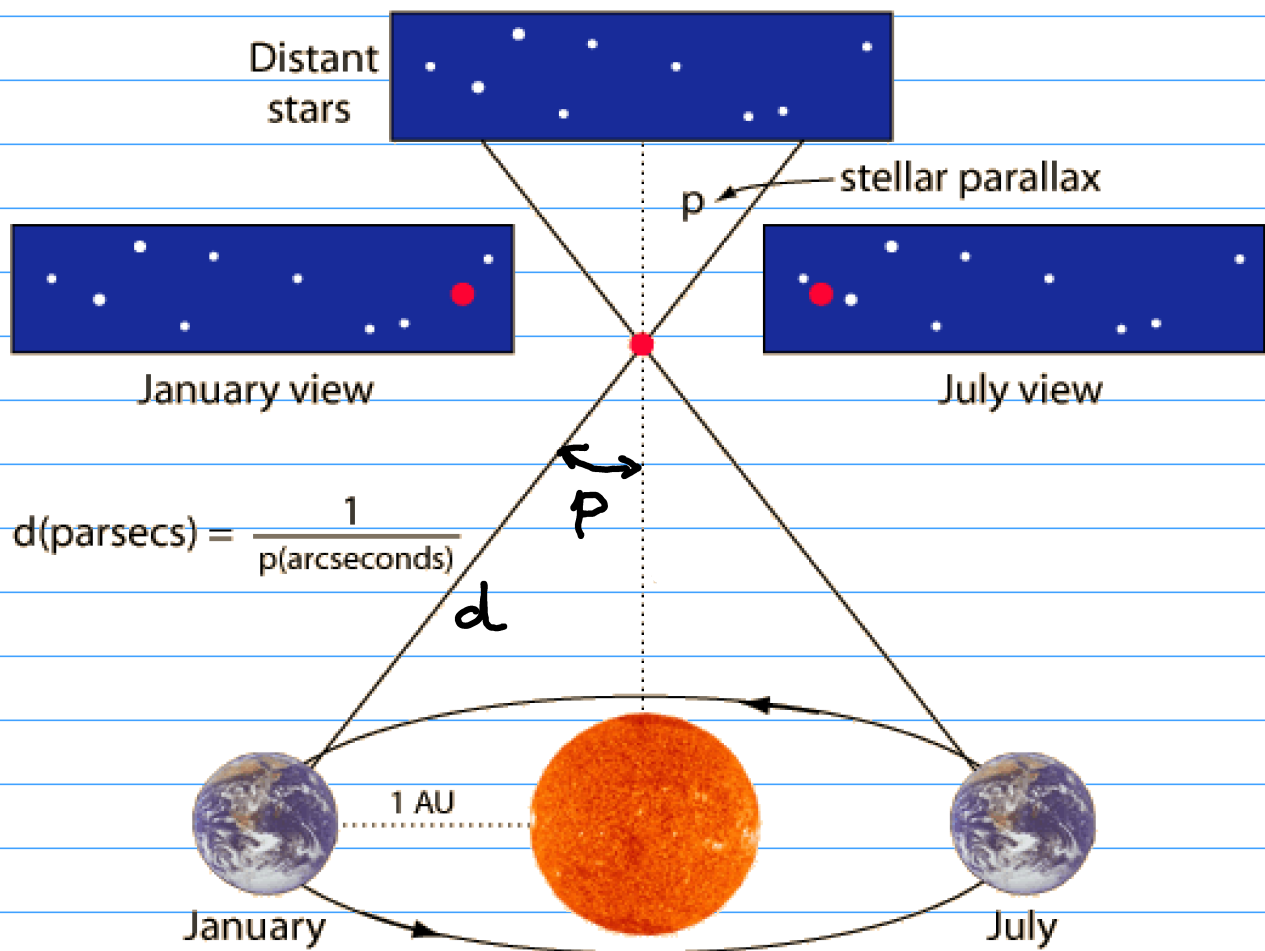


MEASURING THE PROPERTIES OF STARS

1) MEASURING THE DISTANCES OF STARS

FOR NOT TOO DISTANT STARS THE DISTANCE CAN BE FOUND FROM STELLAR PARALLAX



MEASURED IN RADIANS

TRIGONOMETRY: $\frac{1 \text{ AU}}{d} = \sin p \approx p = \frac{2\pi}{360} p$

↑

MEASURED IN DEGREES

Thus, $d \propto \frac{1}{p}$.

CHANGE THE UNIT FOR DISTANCE SO THAT

$$\boxed{d = \frac{1}{p}} \quad \text{OR} \quad p = \frac{1}{d}$$

IN PARSECS (pc)

IN SECONDS OF ARC
(OR ARCSECONDS)

$$1 \text{ ARCMINUTE} = \frac{1^\circ}{60}$$

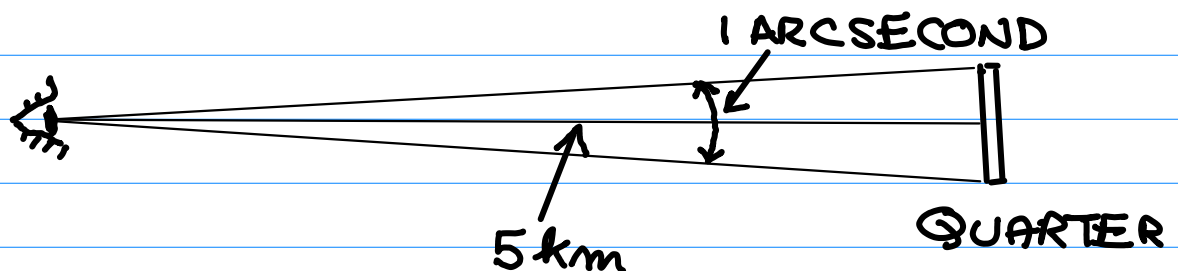
$$1 \text{ ARCSECOND} = \frac{1 \text{ ARCMINUTE}}{60} = \frac{1^\circ}{3,600}$$

IT TURNS OUT THAT

$$\boxed{1 \text{ pc} = 3.26 (\approx 3.3) \text{ ly} = 206,265 \text{ AU}}$$

NOTE THAT THE LARGER THE DISTANCE (d),
THE SMALLER THE PARALLAX ANGLE (p), AND
VICE VERSA.

EVEN FOR THE CLOSEST STAR (PROXIMA CENTAURI) THE PARALLAX ANGLE IS LESS THAN 1 ARCSECOND ($p = 0.769 \text{ ARCSECOND}$)



THE STELLAR PARALLAX WAS FIRST MEASURED IN 1838 BY F. BESSEL.

BECAUSE OF THE ATMOSPHERIC BLURRING THE GROUND BASED MEASUREMENTS OF PARALLAX HAVE AN UNCERTAINTY OF 0.002 ARCSECONDS (FOR $p = 0.02$ ARCSECONDS THE ERROR IS 10%). HENCE, WE CANNOT USE PARALLAX MEASUREMENTS FROM THE GROUND BASED OBSERVATORIES FOR STARS WHOSE DISTANCE IS GREATER THAN

$$\frac{1}{0.02} \text{ pc} = 50 \text{ pc} \approx 160 \text{ ly}.$$

THE DISTANCES TO ABOUT 10,000 STARS WERE DETERMINED USING THE PARALLAX METHOD FROM THE GROUND BASED OBSERVATORIES.

IN 1989 SATELITE HIPPARCOS (HIGH PRECISION PARALLAX COLLECTING SATELLITE) WAS PUT INTO ORBIT, AND IT COLLECTED THE DATA FOR 4 YEARS. PARALLAX DATA 20 TIMES MORE ACCURATE THAN THOSE OBTAINED FROM THE GROUND BASED OBSERVATORIES WERE

COLLECTED FOR 120,000 STARS, AND AS ACCURATE AS THE GROUND-BASED MEASUREMENTS FOR OVER 1 MILLION STARS.

2) MEASURING THE ENERGY OUTPUT OF STARS, I.E. THEIR LUMINOSITY L

ONCE THE STAR DISTANCE (d) IS KNOWN, ITS LUMINOSITY (L), I.E. THE ENERGY OUTPUT PER UNIT TIME (MEASURED IN WATTS), CAN BE DETERMINED FROM ITS MEASURED BRIGHTNESS (B) USING

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

↑ MEASURE ↑ DEDUCE

IN THIS WAY IT WAS DETERMINED THAT THE LUMINOSITY OF THE SUN IS

$$L_{\odot} = 4 \times 10^{26} \text{ W} = 100 \text{ BILLION 1 MEGATON H-BOMBS PER SECOND}$$

↑
DENOTES SOLAR PROPERTY

400 TRILLION TRILLION

FOR THE PURPOSE OF SOLVING PROBLEMS ON TESTS AND EXAMS IT IS SUFFICIENT TO USE

$$\boxed{B = \frac{L}{d^2}} \text{ OR } \boxed{L = Bd^2}$$

WHICH CAN BE OBTAINED BY CHANGING THE UNIT FOR, SAY, L FROM W TO $W/4\pi$.

EXAMPLE:

STARS X AND Y HAVE THE SAME BRIGHTNESS AND THE DISTANCE OF X IS 5 TIMES THAT OF Y . THE LUMINOSITY OF X IS _____ THAT OF Y .

(a) 25 TIMES (b) $1/25$ (c) 5 TIMES (d) $1/5$

SOLUTION:

	B	d	$L = Bd^2$
X	1	5	$L = 1 \times 5^2 = 25$
Y	1	1	$L = 1 \times 1^2 = 1$

THE ANSWER IS (a).

3) MEASURING THE SURFACE TEMPERATURE OF STARS

THE COLOR OF A LIGHT SOURCE DEPENDS ON ITS TEMPERATURE:

LOW (RED)



HIGH (ORANGE-YELLOW)

WIEN'S LAW:

SURFACE TEMPERATURE
(in K)

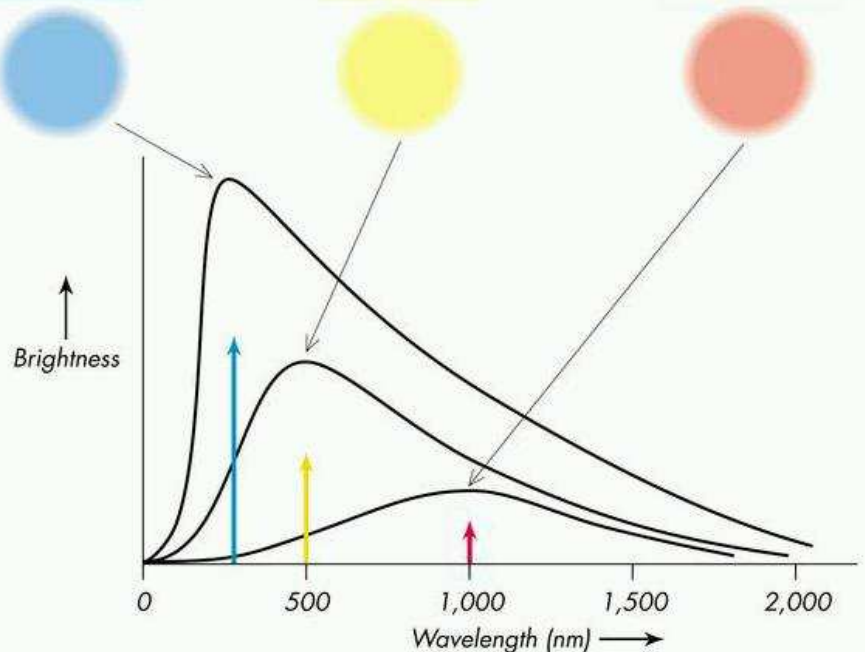
$$T = \frac{3 \times 10^6}{\lambda_m}$$

THE WAVELENGTH
AT WHICH THE SOURCE
EMITS MOST ENERGY
(in nm)

$T = 12,000 \text{ K}$
 $\lambda_m \approx 250 \text{ nm}$

$T = 6000 \text{ K}$
 $\lambda_m \approx 500 \text{ nm}$

$T = 3000 \text{ K}$
 $\lambda_m \approx 1000 \text{ nm}$

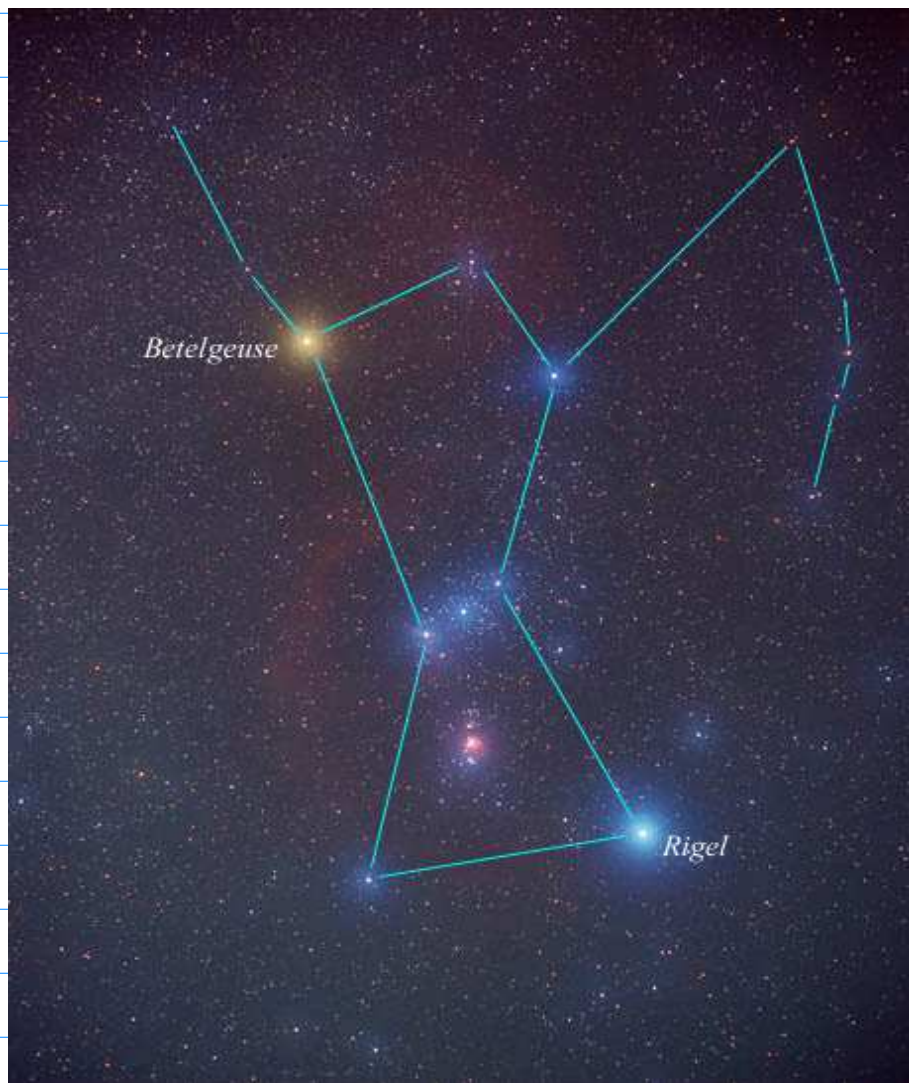


TEMPERATURE IN DEGREES CELSIUS

$$T(K) = T(^{\circ}C) + 273.16$$

TEMPERATURE IN DEGREES KELVIN

THEREFORE, VERY HOT STARS LOOK BLUISH (RIGEL IN ORION) AND COLDER STARS LOOK REDDISH (BETELGEUSE IN ORION):



CONSTELLATION ORION

NOTE: TO DETERMINE THE SURFACE TEMPERATURE OF A STAR ITS DISTANCE IS NOT REQUIRED.

4) MEASURING THE RADIUS OF A STAR

THE RADIUS (R) OF A STAR CAN BE DETERMINED FROM ITS LUMINOSITY (L) AND SURFACE TEMPERATURE (T) USING THE STEFAN-BOLTZMANN LAW:

A UNIVERSAL CONSTANT ($5.7 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4}$)

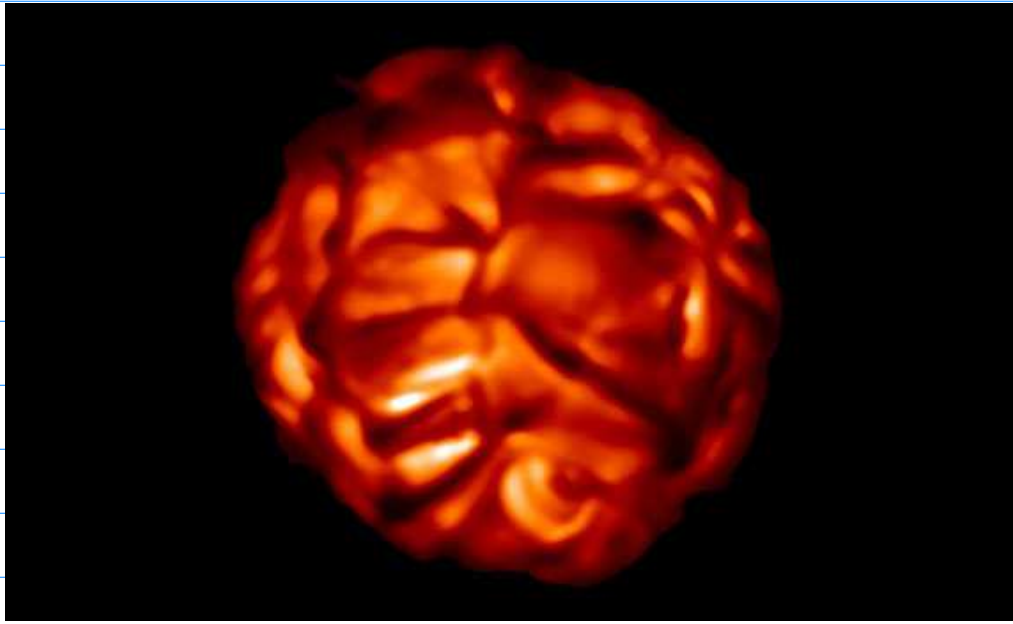
$$L = 64\pi R^2 T^4$$

SURFACE AREA OF A SPHERE OF RADIUS R

NOTE: IF THE TEMPERATURE IS DOUBLED, THE LUMINOSITY INCREASES BY A FACTOR OF $2^4 = 16$. IF THE RADIUS IS DOUBLED THE LUMINOSITY IS INCREASED BY A FACTOR OF $2^2 = 4$.

THUS THE STARS WHICH ARE VERY LUMINOUS, BUT COOL (RED) MUST HAVE VERY LARGE RADII.

EXAMPLE: BETELGEUSE in ORION



$$L = 120,000 L_{\odot}, T = 3,000 \text{ K} = \frac{T_{\odot}}{2}$$

THUS

$$\frac{L}{L_{\odot}} = 120,000$$

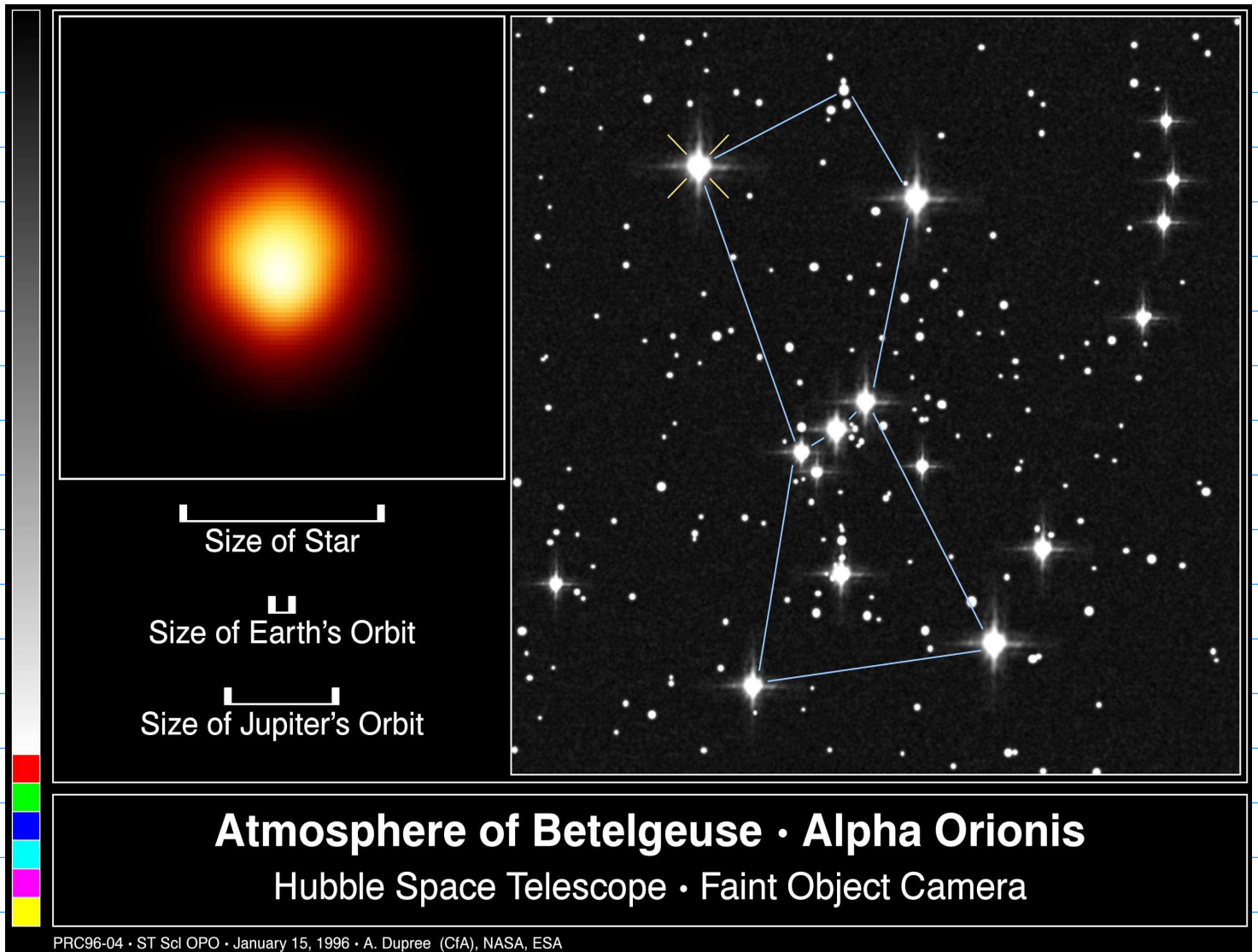
AND SINCE

$$\frac{L}{L_{\odot}} = \frac{34\pi R^2 T^4}{34\pi R_{\odot}^2 T_{\odot}^4} = \left(\frac{R}{R_{\odot}}\right)^2 \left(\frac{1}{2}\right)^4$$

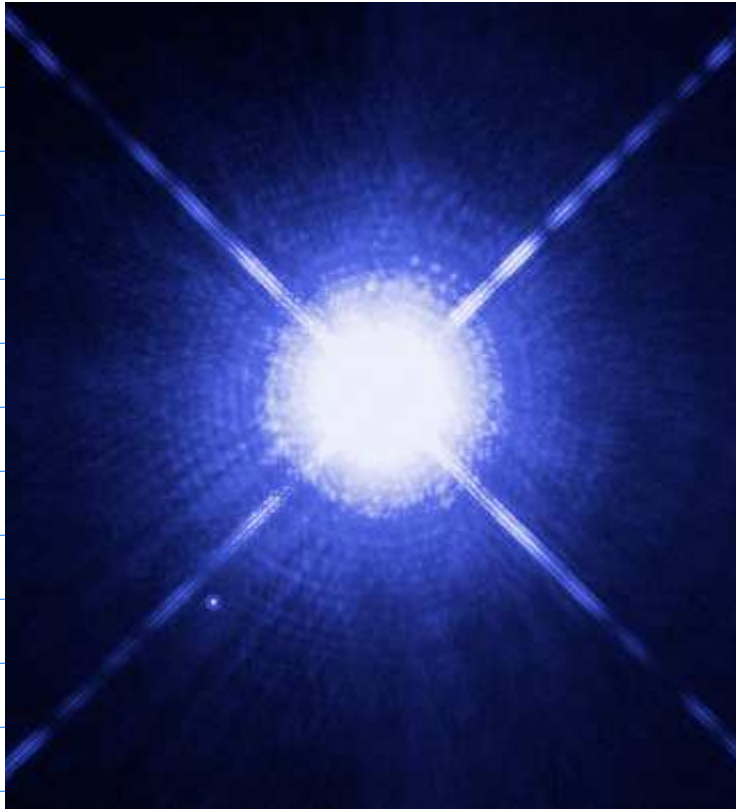
ONE FINDS

$$\frac{R}{R_{\odot}} = 2^2 \sqrt{120,000} \simeq 1,400$$

BETELGEUSE IS A RED SUPERGIANT!



ON THE OTHER HAND, STARS THAT ARE DIM (LOW L) BUT ARE VERY HOT (HIGH T) MUST HAVE VERY SMALL RADII (WHITE DWARFS). A TYPICAL WHITE DWARF HAS A RADIUS COMPARABLE TO THE RADIUS OF THE EARTH



WHITE DWARF SIRIUS B

5) CHEMICAL COMPOSITION OF STARS

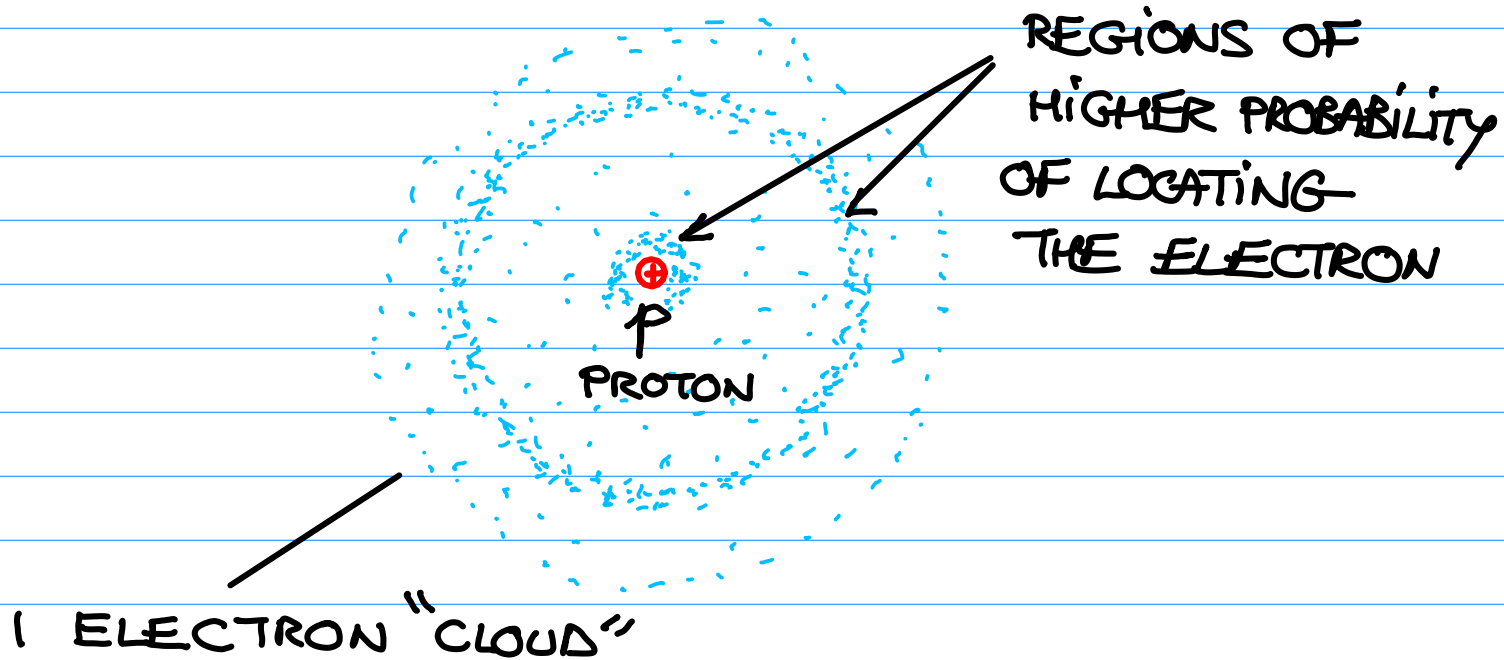
THE ORDINARY MATTER IS MADE OUT OF ATOMS OF CHEMICAL ELEMENTS AND MOLECULES, WHICH ARE THE AGREGATES OF SEVERAL OR MANY ATOMS HELD TOGETHER BY ELECTRICAL FORCES.

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⁵⁸ Ce	⁵⁹ Pr	⁶⁰ Nd	⁶¹ Pm	⁶² Sm	⁶³ Eu	⁶⁴ Gd	⁶⁵ Tb	⁶⁶ Dy	⁶⁷ Ho	⁶⁸ Er	⁶⁹ Tm	⁷⁰ Yb	⁷¹ Lu
⁹⁰ Th	⁹¹ Pa	⁹² U	⁹³ Np	⁹⁴ Pu	⁹⁵ Am	⁹⁶ Cm	⁹⁷ Bk	⁹⁸ Cf	⁹⁹ Es	¹⁰⁰ Fm	¹⁰¹ Md	¹⁰² No	¹⁰³ Lr

TO DESCRIBE THE ATOMS AND THE SUBATOMIC PARTICLES ONE NEEDS QUANTUM MECHANICS, WHICH WAS DEVELOPED IN 1920s.

THE SIMPLEST, AND THE LIGHTEST, ATOM IS THE HYDROGEN (H) ATOM



THE HEISENBERG UNCERTAINTY RELATION:

$$\Delta x (m\Delta v) \geq \frac{h}{4\pi}$$

↑
UNCERTAINTY
IN POSITION

↑
UNCERTAINTY IN VELOCITY

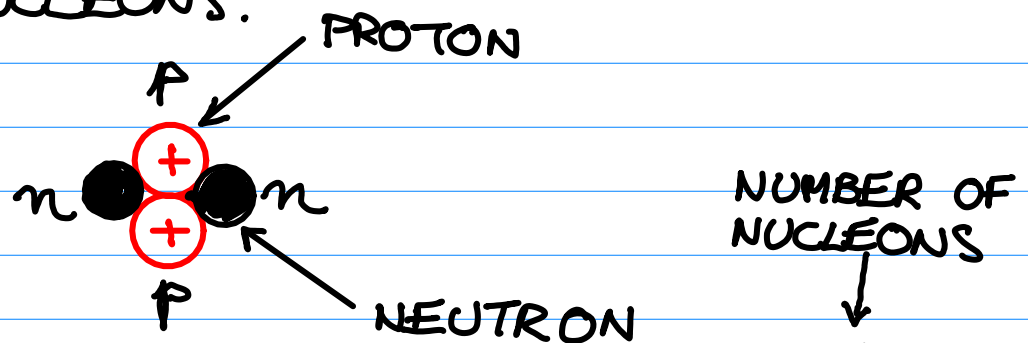


THIS MEANS THAT ELECTRONS AND OTHER SUBATOMIC PARTICLES DO NOT HAVE TRAJECTORIES, UNLIKE THE PLANETS, BASEBALLS AND OTHER MACROSCOPIC OBJECTS.

THE QUANTUM MECHANICS CAN ONLY GIVE A PROBABILITY OF LOCATING ELECTRON AT A GIVEN SPOT.

ELECTRON AND PROTON CARRY EQUAL AMOUNTS OF OPPOSITE ELECTRIC CHARGE. PROTON IS ABOUT 2,000 TIMES MORE MASSIVE THAN THE ELECTRON.

IN GENERAL, ATOMIC NUCLEUS CONSISTS OF SEVERAL PROTONS (POSITIVE ELECTRIC CHARGE) AND NEUTRONS (NO ELECTRIC CHARGE) - SO-CALLED NUCLEONS.



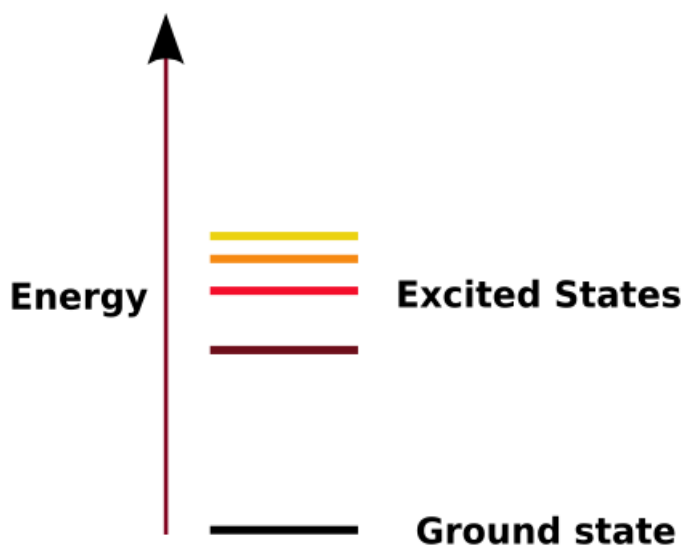
THE NUCLEUS OF HELIUM-4 (${}^4\text{He}$)

NEUTRAL He ATOM HAS TWO ELECTRONS BOUND TO THE NUCLEUS BY ELECTRICAL FORCES (10^{36} TIMES STRONGER THAN THE FORCE OF GRAVITY AND LIKE GRAVITY IT VARIES WITH DISTANCE AS $1/\text{DISTANCE}^2$ - IT'S A LONG RANGED FORCE).

IF THE LIKE CHARGES REPEL (THE OPPOSITE CHARGES ATTRACT), WHY DOESN'T THE NUCLEUS FLY APART?

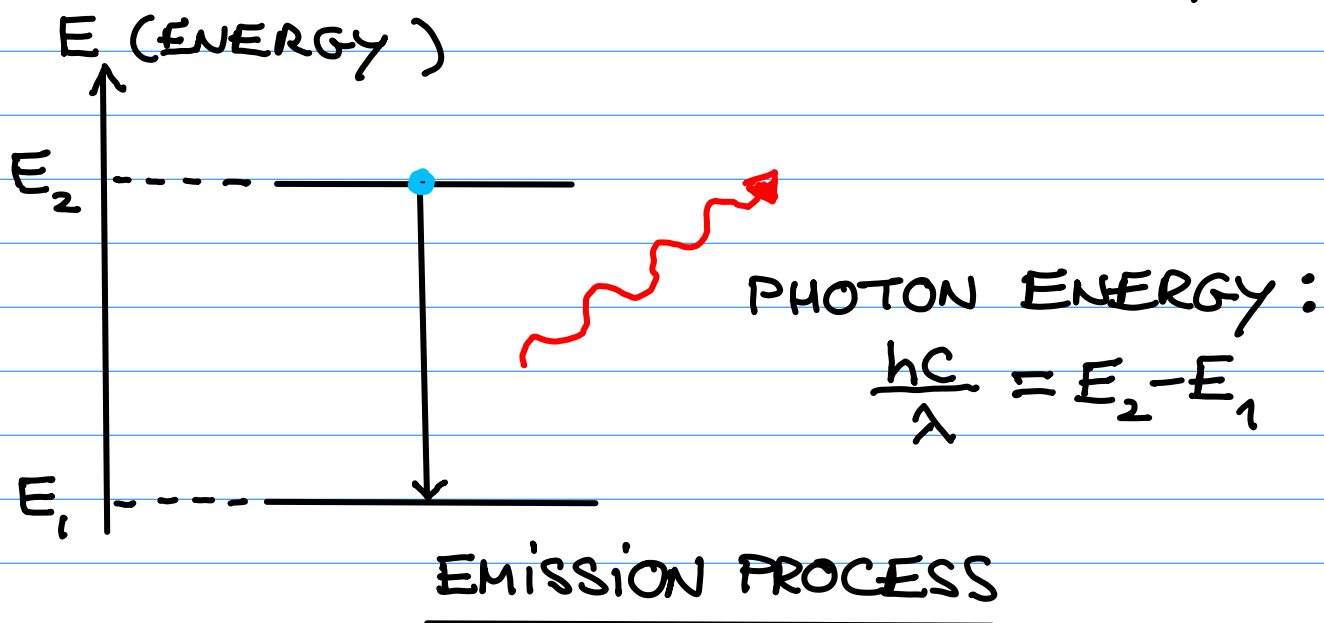
THE NUCLEUS IS HELD TOGETHER BY THE STRONG NUCLEAR FORCE (100 TIMES STRONGER THAN THE ELECTRICAL FORCE BUT VERY SHORT RANGED - IT ACTS OVER A DISTANCE EQUAL TO THE SIZE OF THE PROTON - ABOUT 10^{-15} m).

THE QUANTUM MECHANICS PREDICTS THAT AN ELECTRON BOUND TO ATOMIC NUCLEUS CAN HAVE ONLY CERTAIN DISCRETE VALUES OF ENERGY - THE ENERGY LEVELS:

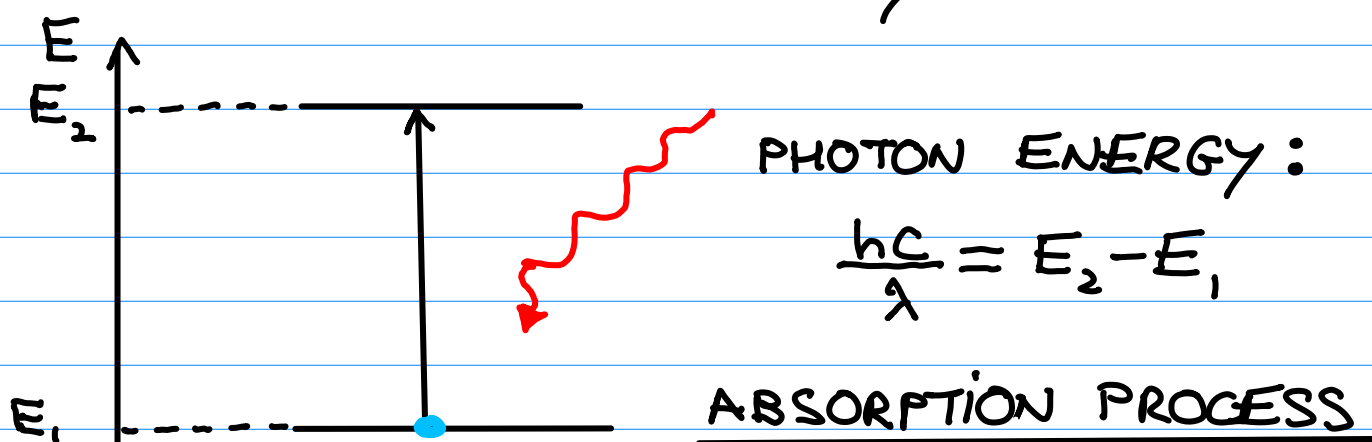


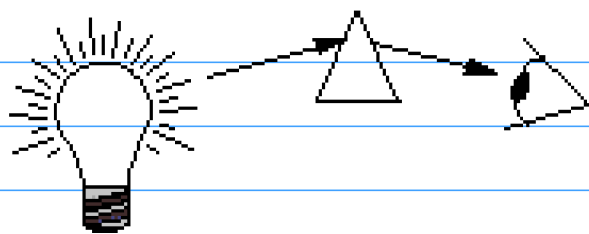
THE ATOMS OF DIFFERENT CHEMICAL ELEMENTS HAVE DIFFERENT SETS OF ENERGY LEVELS. THUS, A SET OF ATOMIC ENERGY LEVELS CHARACTERIZES A PARTICULAR CHEMICAL ELEMENT.

A PHOTON OF ELECTROMAGNETIC RADIATION IS EMITTED WHEN AN ELECTRON IN THE ATOM MAKES A TRANSITION FROM A HIGHER ENERGY LEVEL TO A LOWER ENERGY LEVEL:

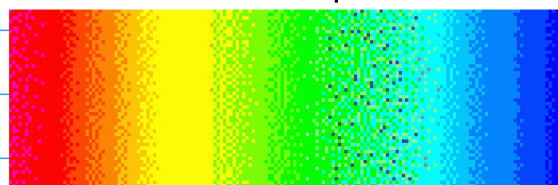


A PHOTON CAN BE ABSORBED BY AN ATOM IF ITS ENERGY IS EQUAL TO THE DIFFERENCE OF TWO ATOMIC ENERGY LEVELS. THE ABSORPTION IS ACCOMPANIED BY ELECTRON MAKING A TRANSITION FROM THE LOWER TO THE HIGHER ENERGY LEVEL:

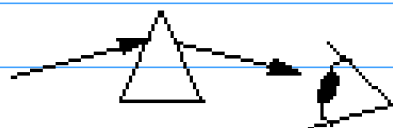
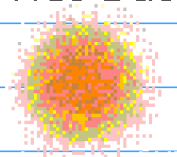




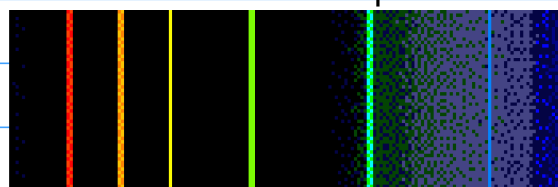
Continuum Spectrum



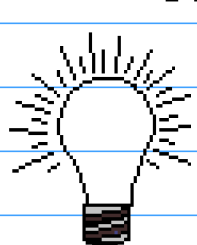
Hot Gas



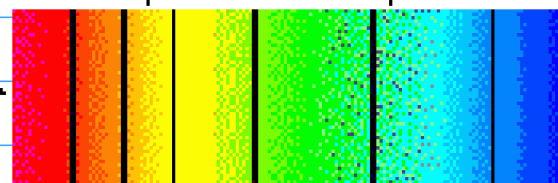
Emission Line Spectrum



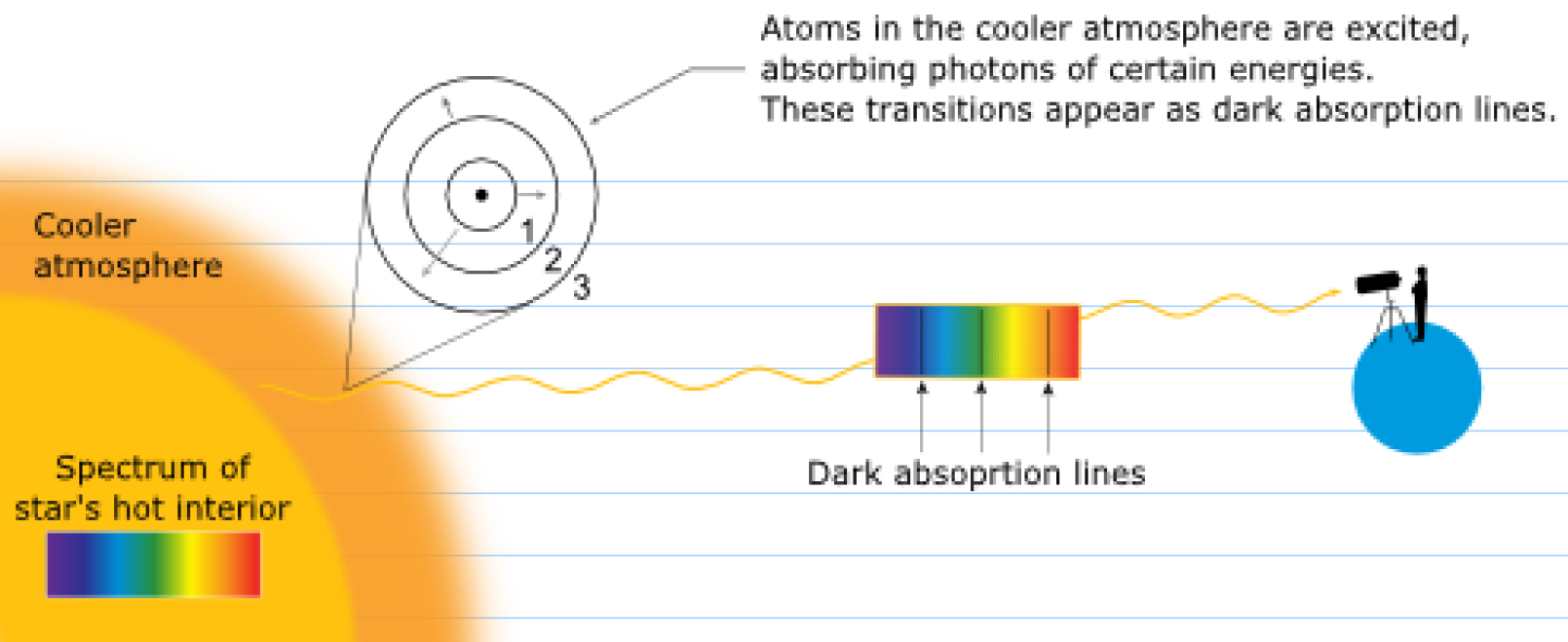
Cold Gas



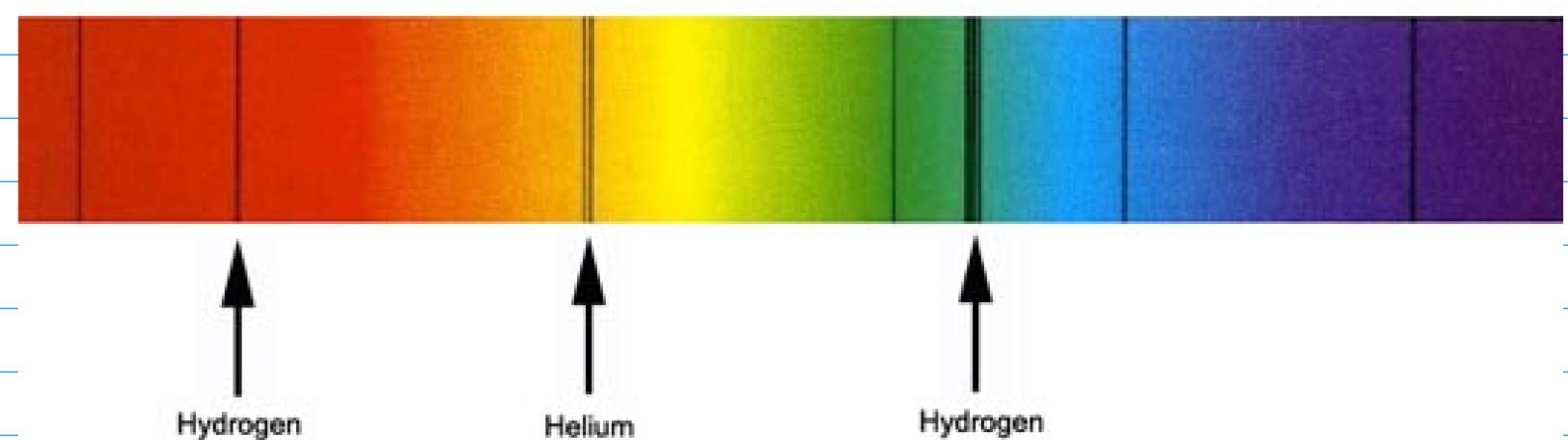
Absorption Line Spectrum



THE WAVELENGTHS OF THE EMISSION OR ABSORPTION LINES ARE DETERMINED BY THE ENERGY DIFFERENCES BETWEEN THE ATOMIC ENERGY LEVELS OF THE CHEMICAL ELEMENTS PRESENT IN THE GAS. THEREFORE THE EMISSION/ABSORPTION SPECTRUM COULD BE USED TO IDENTIFY THE CHEMICAL ELEMENTS PRESENT IN THE GAS. THE INTENSITY OF THE SPECTRAL LINES DEPENDS ON THE CONCENTRATION OF THE CHEMICAL ELEMENT AND TEMPERATURE:

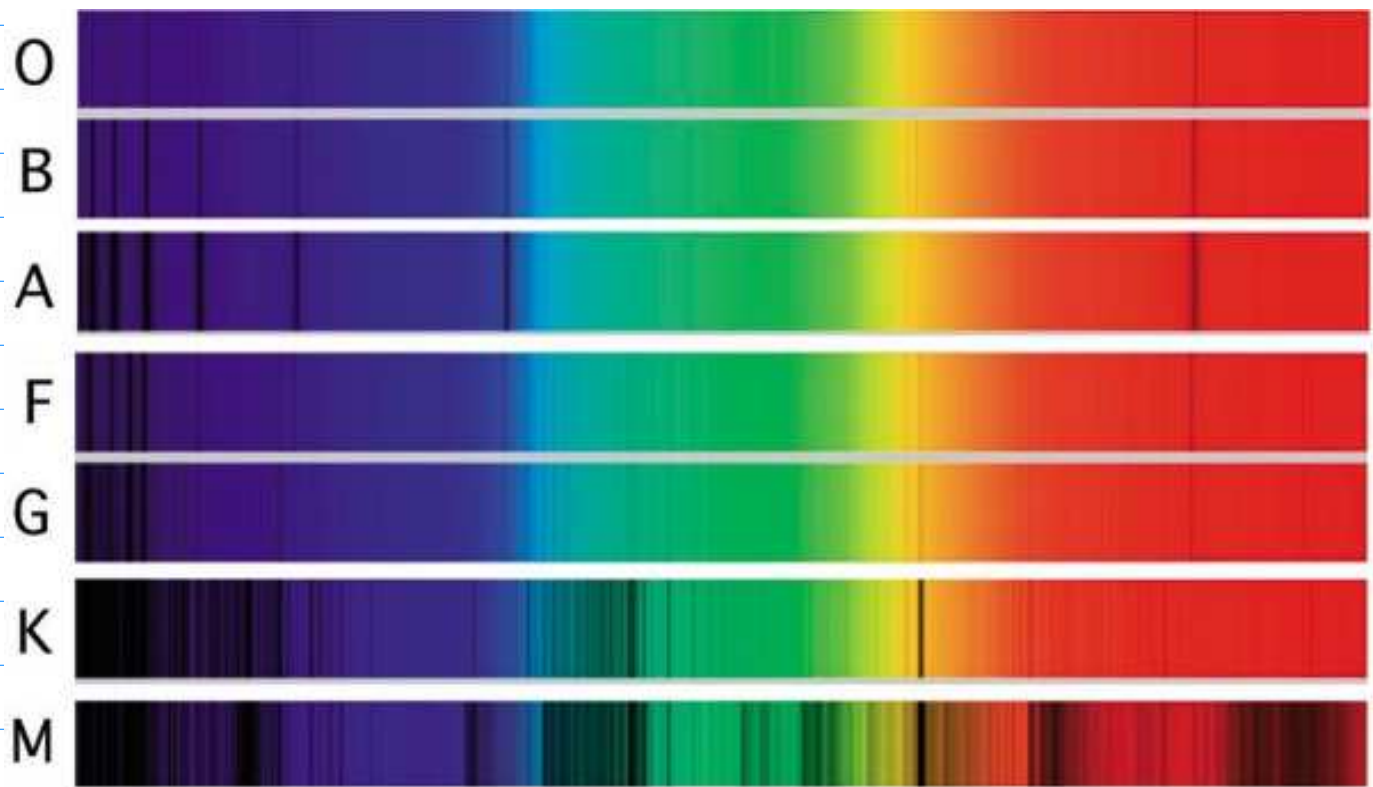


THE ABSORPTION SPECTRUM OF THE SUN:



IN THIS WAY ONE FINDS THAT VIRTUALLY ALL STARS ARE COMPOSED MAINLY OF HYDROGEN (ABOUT 75% BY MASS) AND HELIUM (ABOUT 25% BY MASS), WHILE ALL OTHER CHEMICAL ELEMENTS AMOUNT TO 1-2% OF THE MASS OF THE STAR.

SPECTRAL CLASSES:



THE SPECTRA HAVE DIFFERENT NUMBER AND INTENSITY OF THE ABSORPTION LINES. SPECTRAL CLASSES ARE DETERMINED BY THE SURFACE TEMPERATURE OF THE STAR: AT VERY HIGH TEMPERATURES MOST ATOMS IN THE ATMOSPHERE OF A STAR ARE IONIZED - THE ELECTRONS ARE NOT BOUND TO THE NUCLEI - AND THUS THERE ARE A FEW ELECTRONS IN THE BOUND STATE ENERGY LEVELS THAT COULD

PARTICIPATE IN THE ABSORPTION PROCESS.

<u>SPECTRAL CLASS</u>	<u>EXAMPLE</u>	<u>TEMPERATURE</u>
O	STARS IN ORION'S BELT	$> 30,000 \text{ K}$
B	RIGEL	$30,000 - 10,000 \text{ K}$
A	SIRIUS	$10,000 - 7,500 \text{ K}$
F	POLARIS	$7,500 - 6,000 \text{ K}$
G	SUN	$6,000 - 5,000 \text{ K}$
K	ARCTURUS	$5,000 - 3,500 \text{ K}$
M	BETELGEUSE, PROXIMA CENTAURI	$< 3,500 \text{ K}$