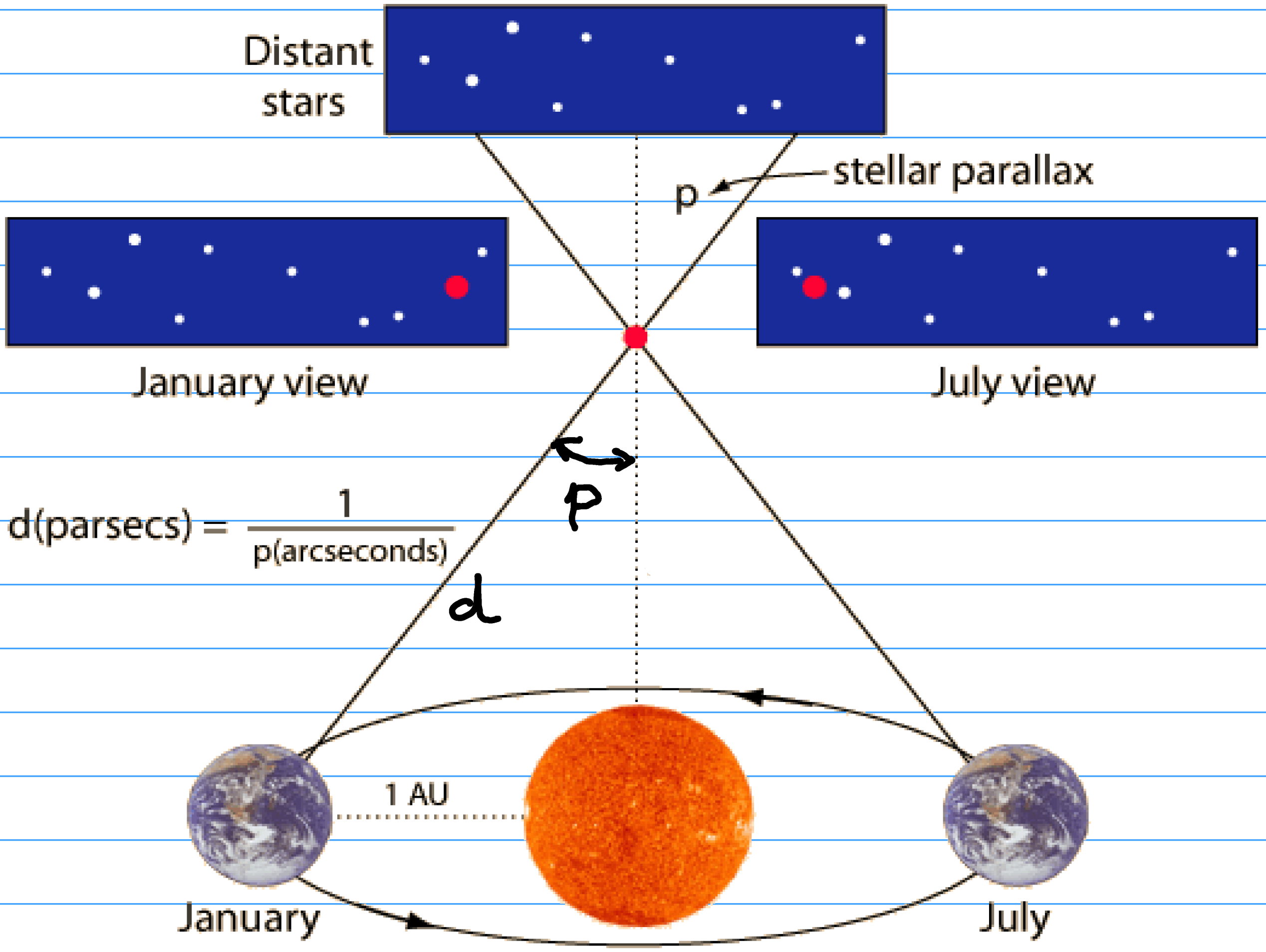
MEASURING THE PROPERTIES OF STARS

1) MEASURING THE DISTANCES OF STARS

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



TRIGONOMETRY: $\frac{1\,AU}{d} = \sin p \simeq \overset{\text{MEASURED IN RADIANS}}{\overset{\downarrow}{p}} = \frac{2\pi}{360} \underset{\text{MEASURED IN DEGREES}}{\underset{\uparrow}{p}}$

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)

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

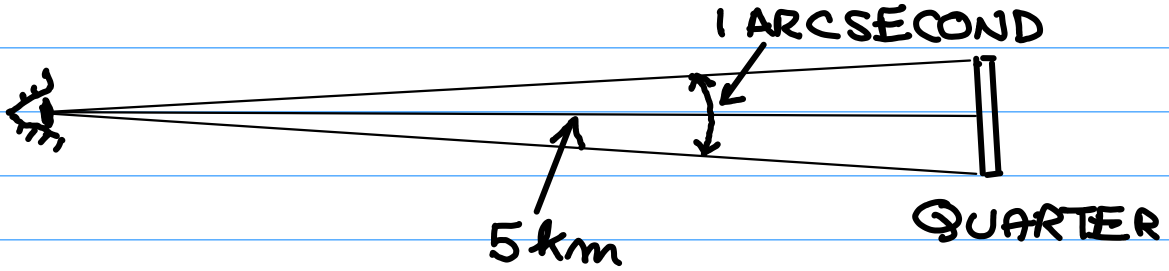
$$1 \text{ ARCSECOND} = \frac{1 \text{ ARCMINUTE}}{60} = \frac{1^\circ}{3{,}600}$$

IT TURNS OUT THAT

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

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

EVEN FOR THE CLOSEST STAR (PROXIMA CENTAURI) THE PARALLAS ANGLE IS LESS THAN 1 ARCSECOND ($p = 0.769$ ARCSECOND)



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

BECAUSE OF THE ATMOSPHERIC BLURRING THE GROUND BASED MEASURMENTS 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

$$\frac{1}{0.02}\,pc = 50\,pc \simeq 160\,ly.$$

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. THER 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

DEDUCE

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

MEASURE

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

$$L_\odot = \underbrace{4\times 10^{26}}_{\text{400 TRILLION TRILLION}}\ \text{W} = \text{100 BILLION 1 MEGATON H-BOMBS PER SECOND}$$

DENOTES SOLAR PROPERTY

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

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

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)

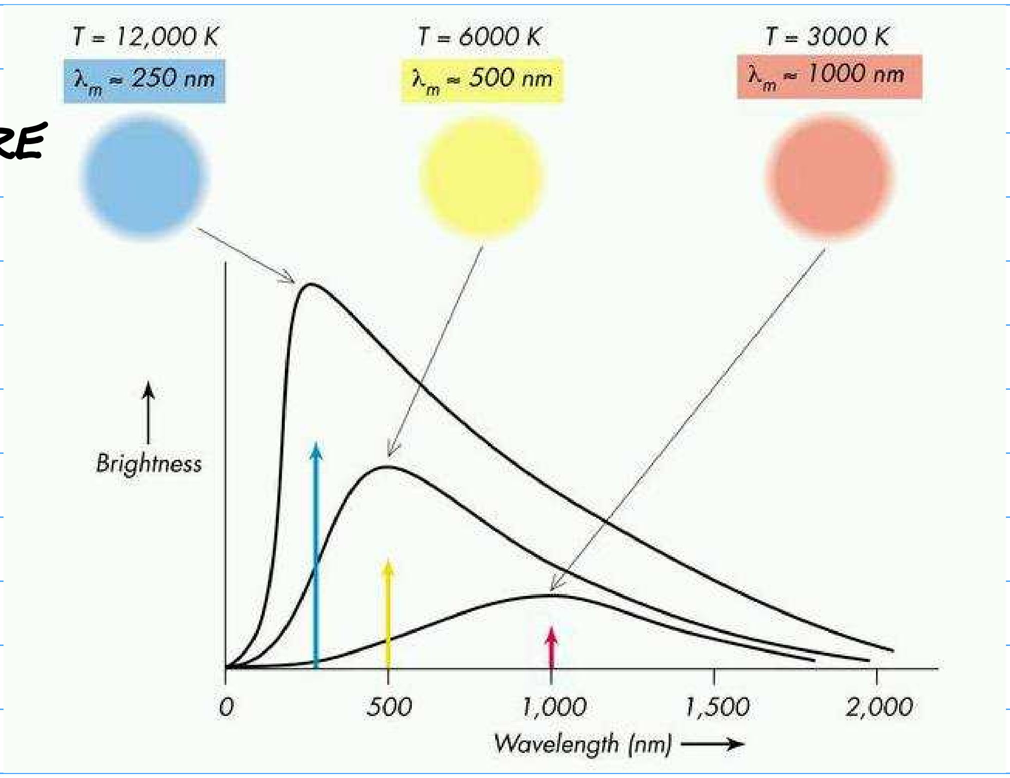
HIGH (ORANGE-YELLOW)

WIEN'S LAW:

SURFACE TEMPERATURE (IN K)

$$\boxed{T = \frac{3\times10^{6}}{\lambda_m}}$$

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

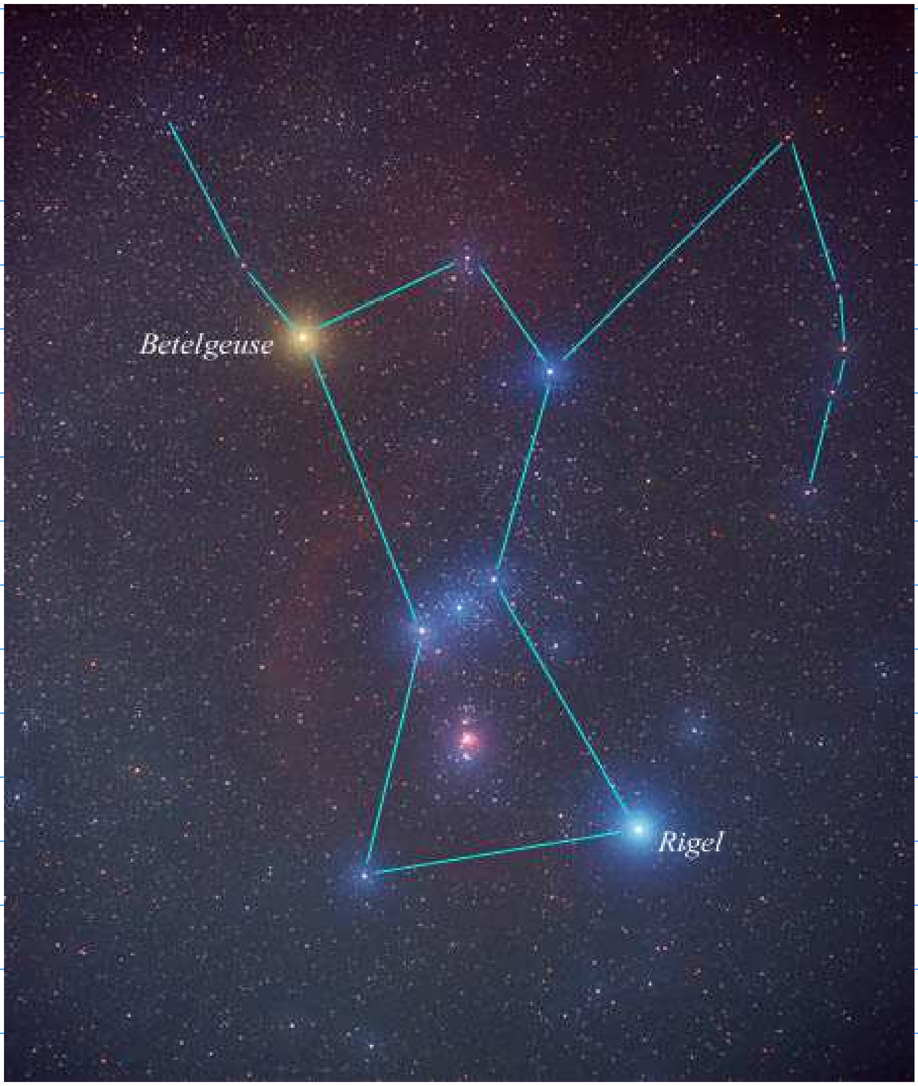


TEMPERATURE IN DEGREES CELSIUS

$$T(K) = T(°C) + 273.16$$

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

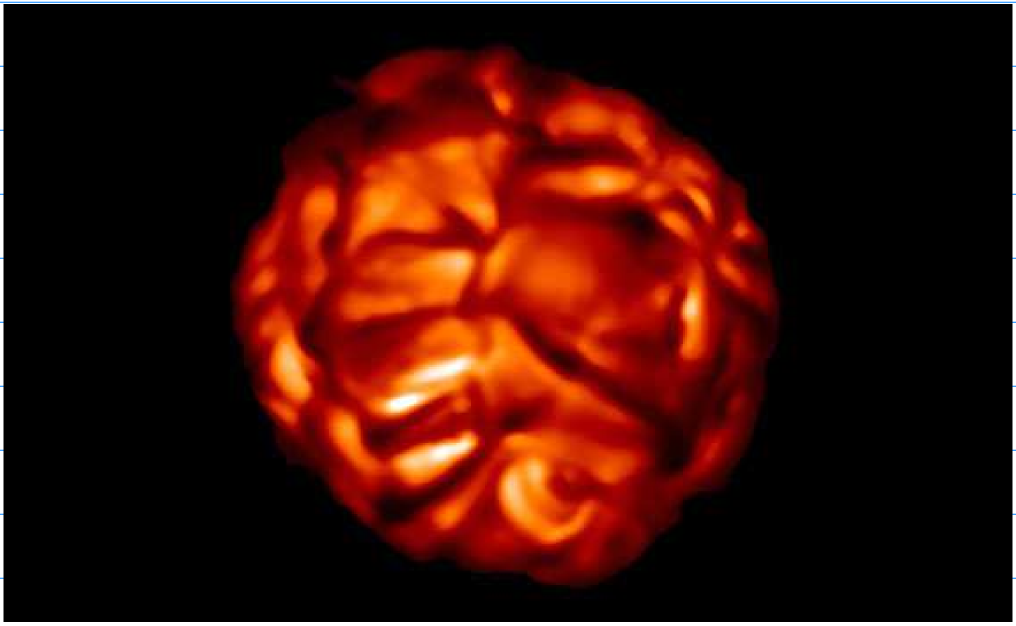
THE RADIUS (R) OF A STAR CAN BE DETERMINED FROM ITS LUMINOSITY (L) AND SURFACE TEMPERATURE (T) USING THE STEFAN-BOLTZMANN LAW:

$$\boxed{L = \overset{\text{A UNIVERSAL CONSTANT } \left(5.7\times10^{-8}\,\frac{W}{m^2K^4}\right)}{\downarrow \atop \sigma}\;\underbrace{4\pi R^2}_{\text{SURFACE AREA OF A SPHERE OF RADIUS R}}\;T^4}$$

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



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

THUS

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

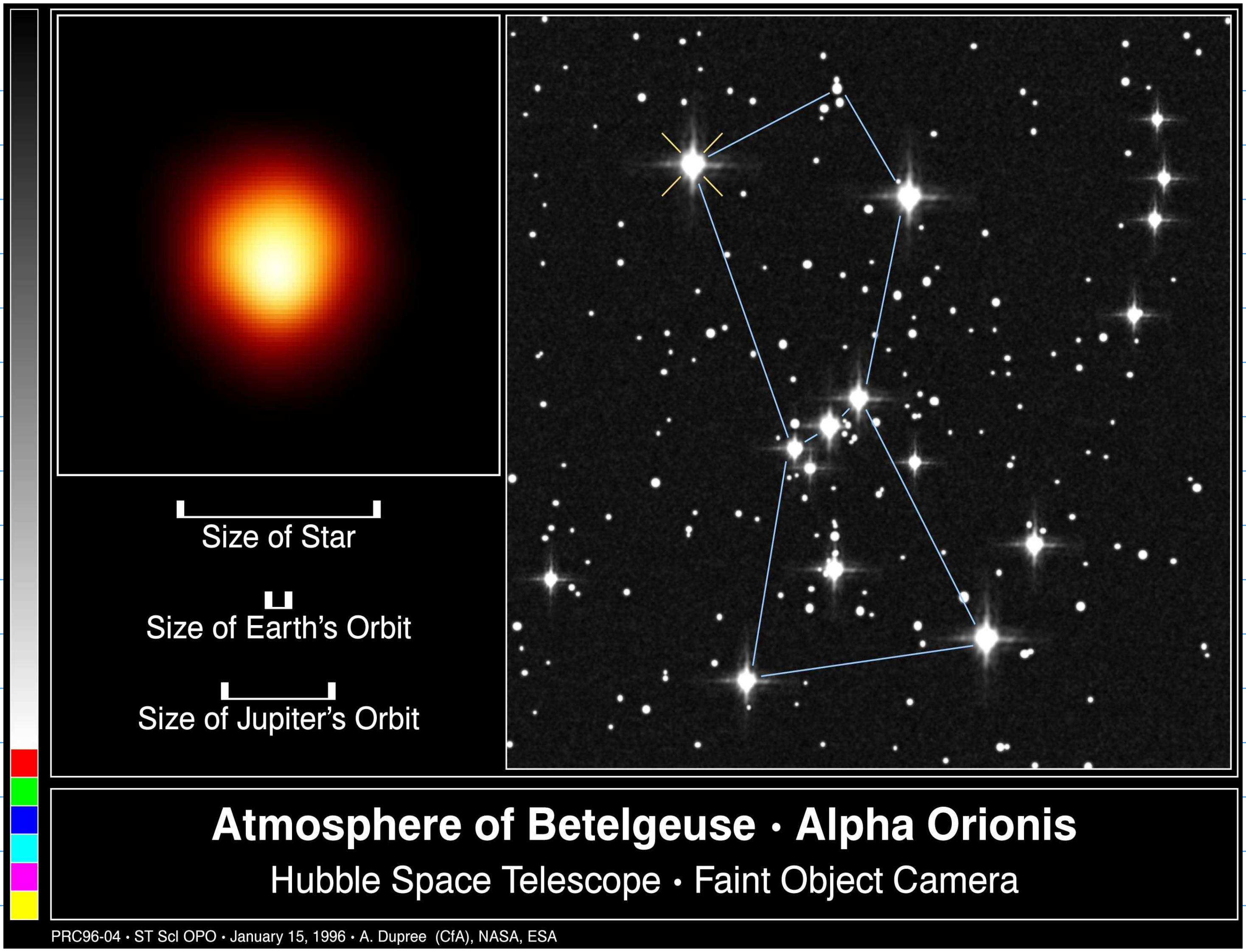
AND SINCE

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

ONE FINDS

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

BETELGEUSE IS A <u>RED SUPERGIANT!</u>

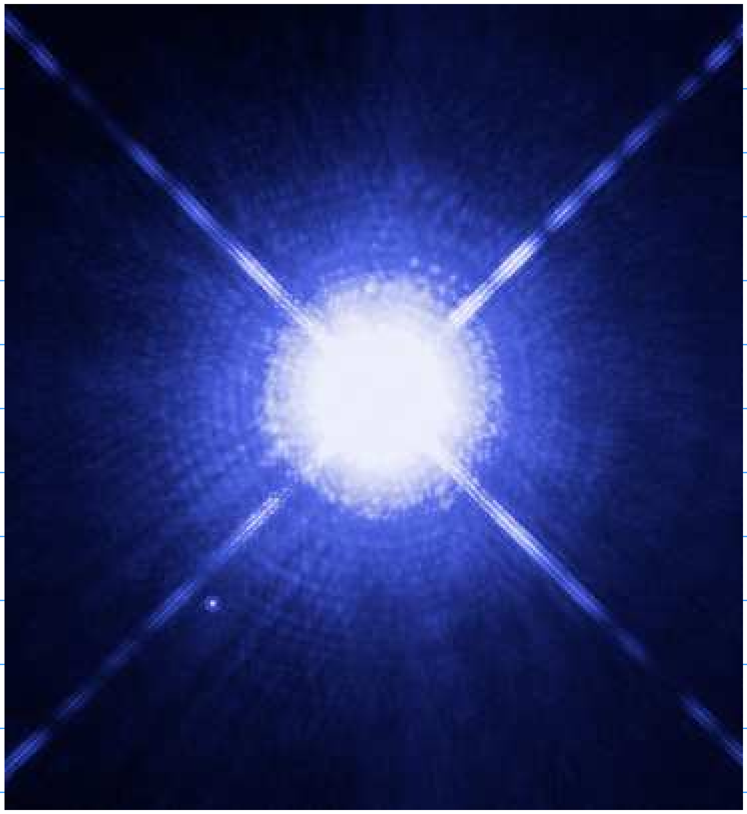


Atmosphere of Betelgeuse • Alpha Orionis

Hubble Space Telescope • Faint Object Camera

PRC96-04 • ST ScI OPO • January 15, 1996 • A. Dupree (CfA), NASA, ESA

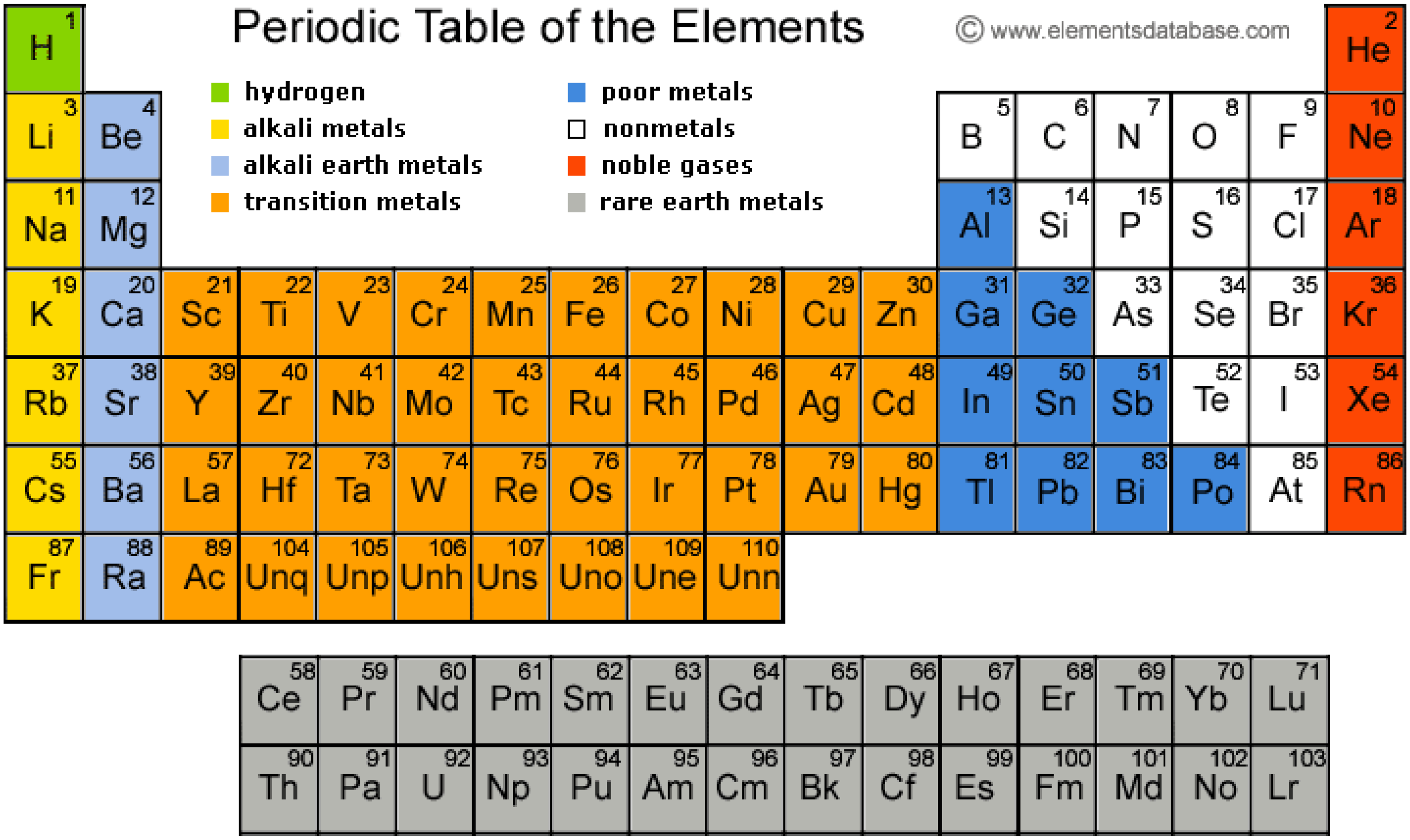
ON THE OTHER HAND, STARS THAT ARE DIM (LOW L) BUT ARE VERY HOT (HIGH T) MUST HAVE VERY SMALL RADII (WHITE DWARFS). A TYPICAL WHITE DWARF HAS A RADIUS COMPARABLE TO THE RADIUS OF THE EARTH



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.



Periodic Table of the Elements

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- 🟩 hydrogen
- 🟨 alkali metals
- ▦ alkali earth metals
- 🟧 transition metals
- 🟦 poor metals
- ☐ nonmetals
- 🟥 noble gases
- ▩ rare earth metals

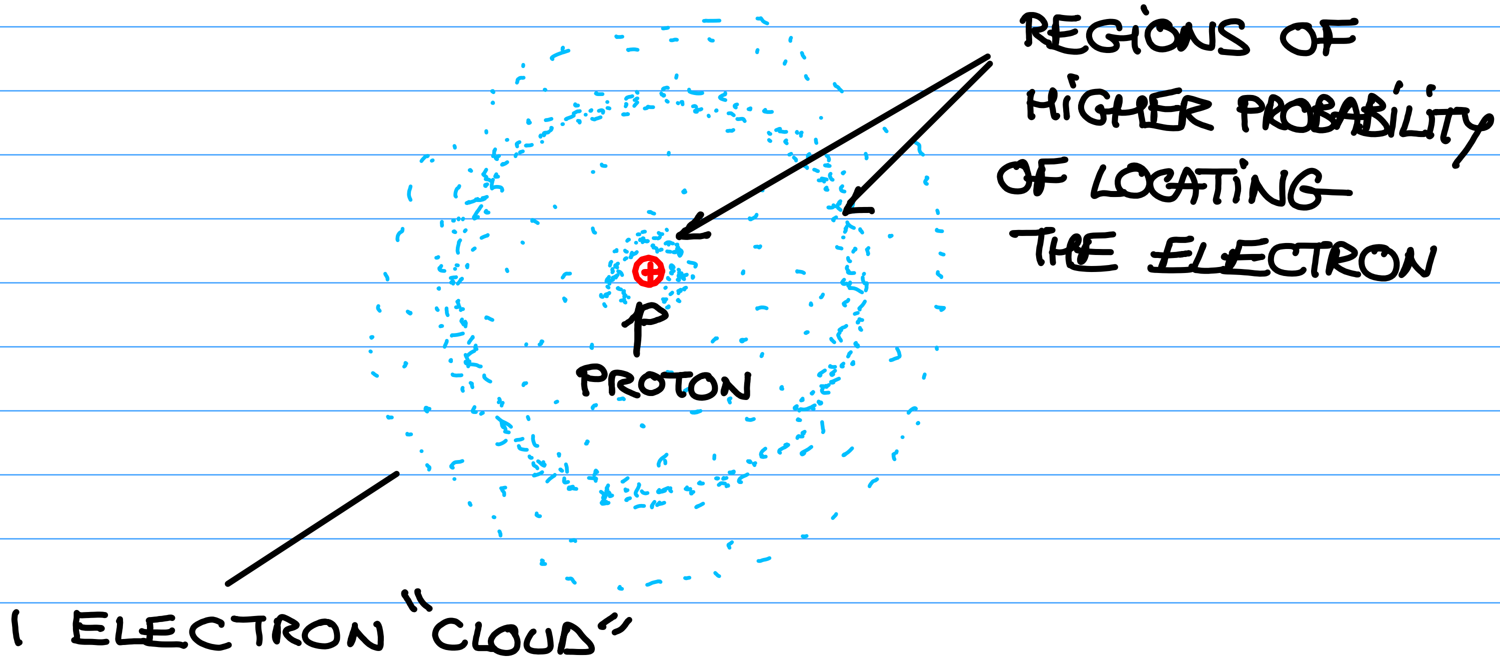
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

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

ATOMS (A TYPICAL SIZE IS 10^{-10} m = 0.1 nm) CONSIST OF A NUCLEUS (A TYPICAL SIZE IS 10^{-15} m = SIZE OF THE ATOM / 100,000), WHICH CARRIES A POSITIVE ELECTRIC CHARGE, AND NEGATIVELY CHARGED ELECTRONS, WHICH ARE BOUND TO THE NUCLEUS BY ATTRACTIVE ELECTRICAL FORCE.

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

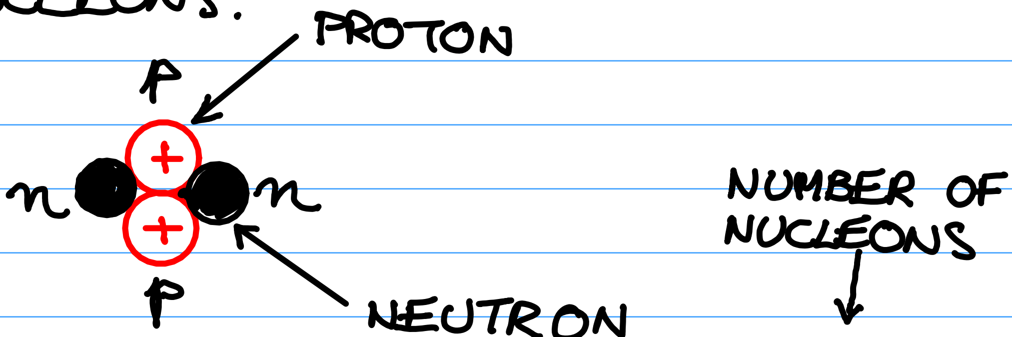
UNCERTAINTY IN VELOCITY

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.



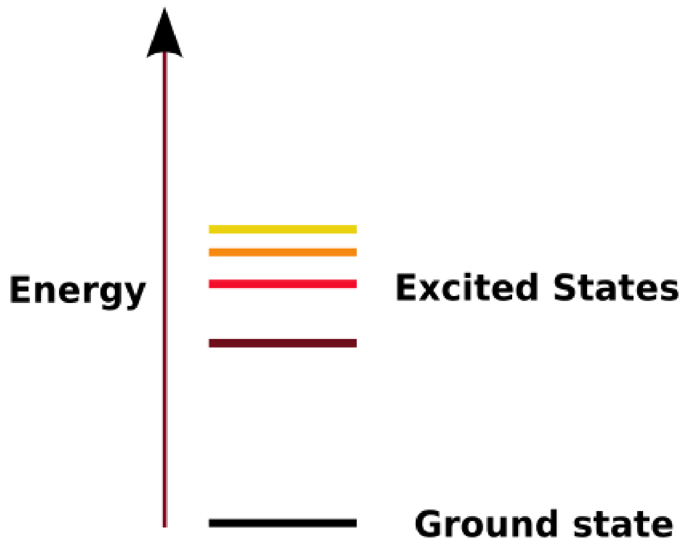
THE NUCLEUS OF HELIUM-4 (^{4}He)

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 IS A LONG RANGED FORCE).

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

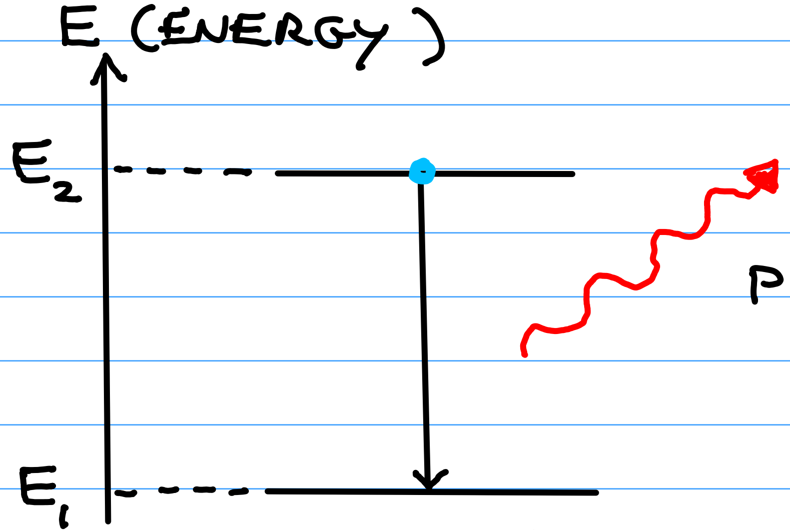
THE NUCLEUS IS HELD TOGETHER BY THE STRONG NUCLEAR FORCE (100 TIMES STRONGER THAN THE ELECTRICAL FORCE BUT VERY SHORT RANGED - IT ACTS OVER A DISTANCE EQUAL TO THE SIZE OF THE PROTON - ABOUT 10^{-15} m).

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:

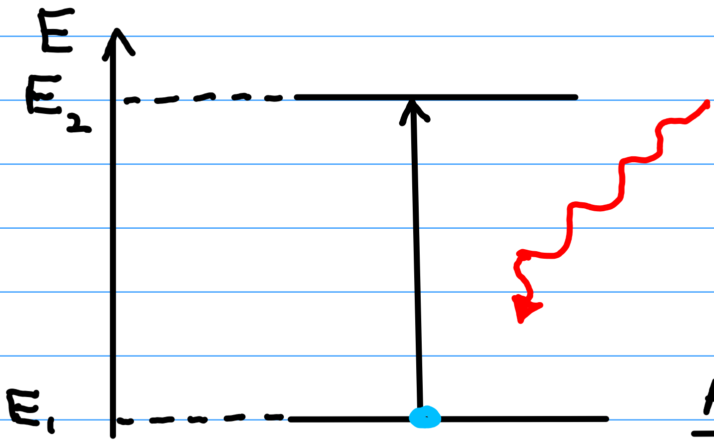


PHOTON ENERGY:

$$\frac{hc}{\lambda} = E_2 - E_1$$

EMISSION PROCESS

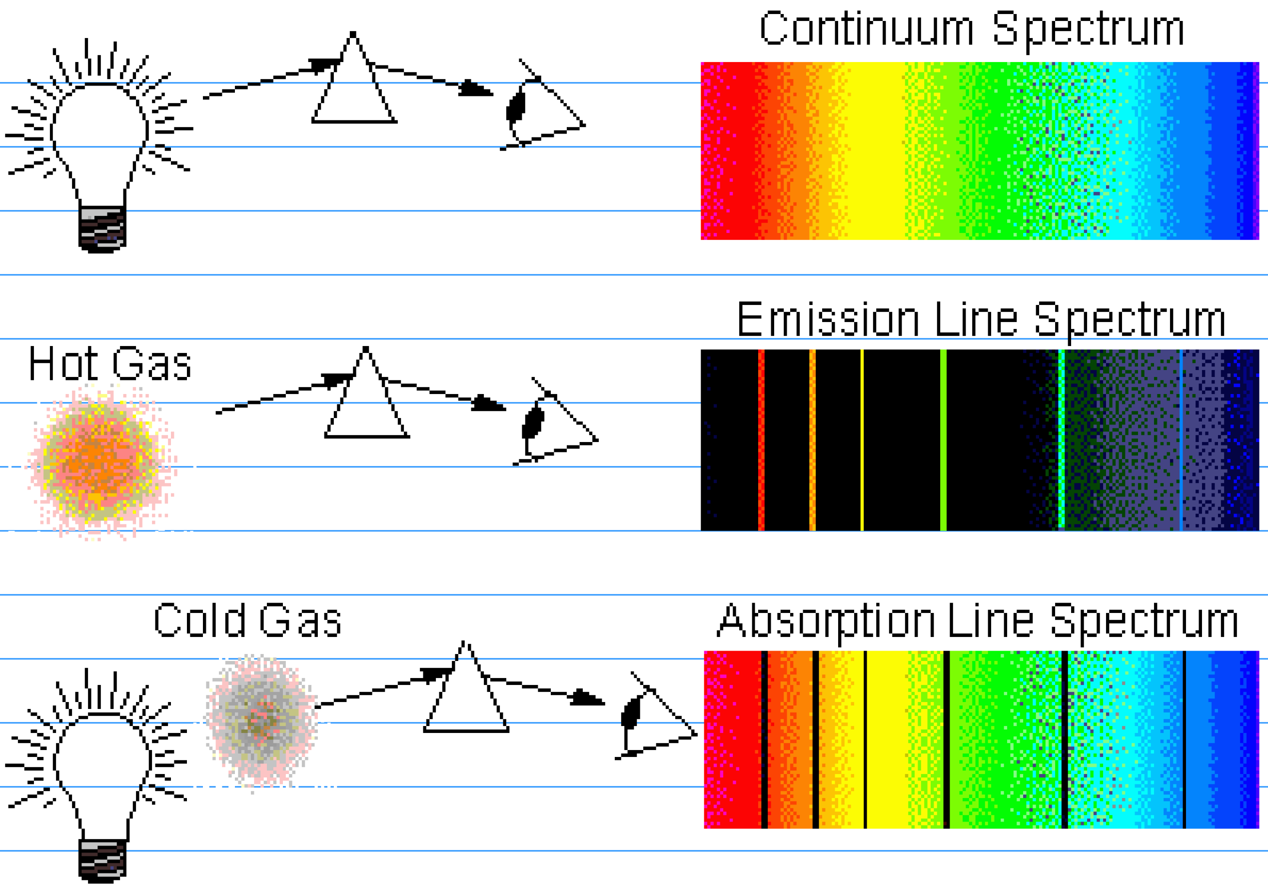
A PHOTON CAN BE ABSORBED BY AN ATOM IF ITS ENERGY IS EQUAL TO THE DIFFERENCE OF TWO ATOMIC ENERGY LEVELS. THE ABSORPTION IS ACCOMPANIED BY ELECTRON MAKING A TRANSITION FROM THE LOWER TO THE HIGHER ENERGY LEVEL:



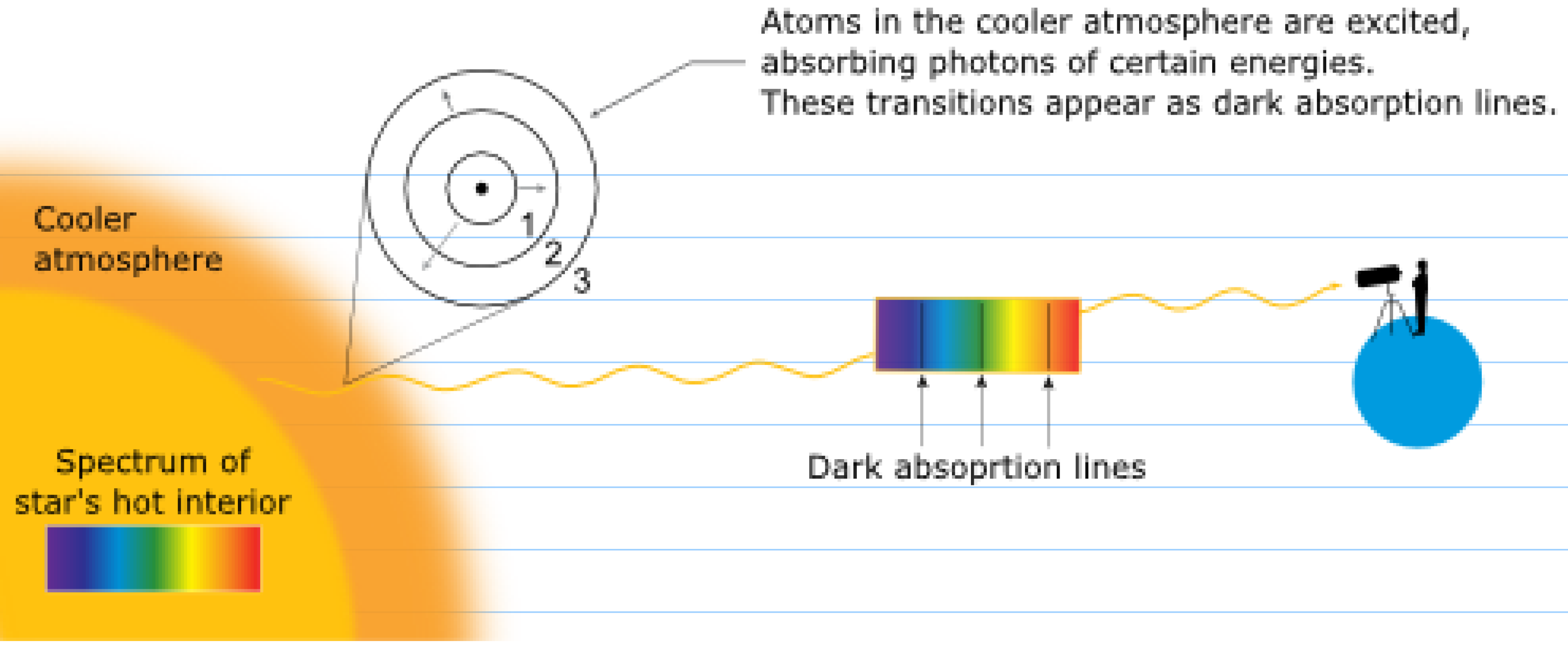
PHOTON ENERGY:

$$\frac{hc}{\lambda} = E_2 - E_1$$

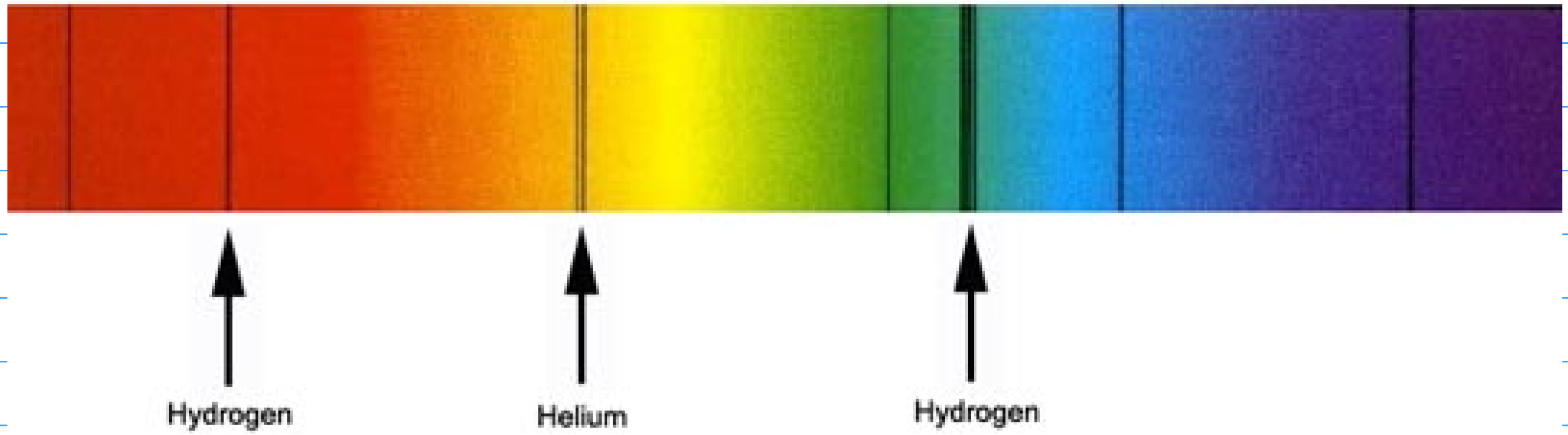
ABSORPTION PROCESS



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. THERFORE 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:

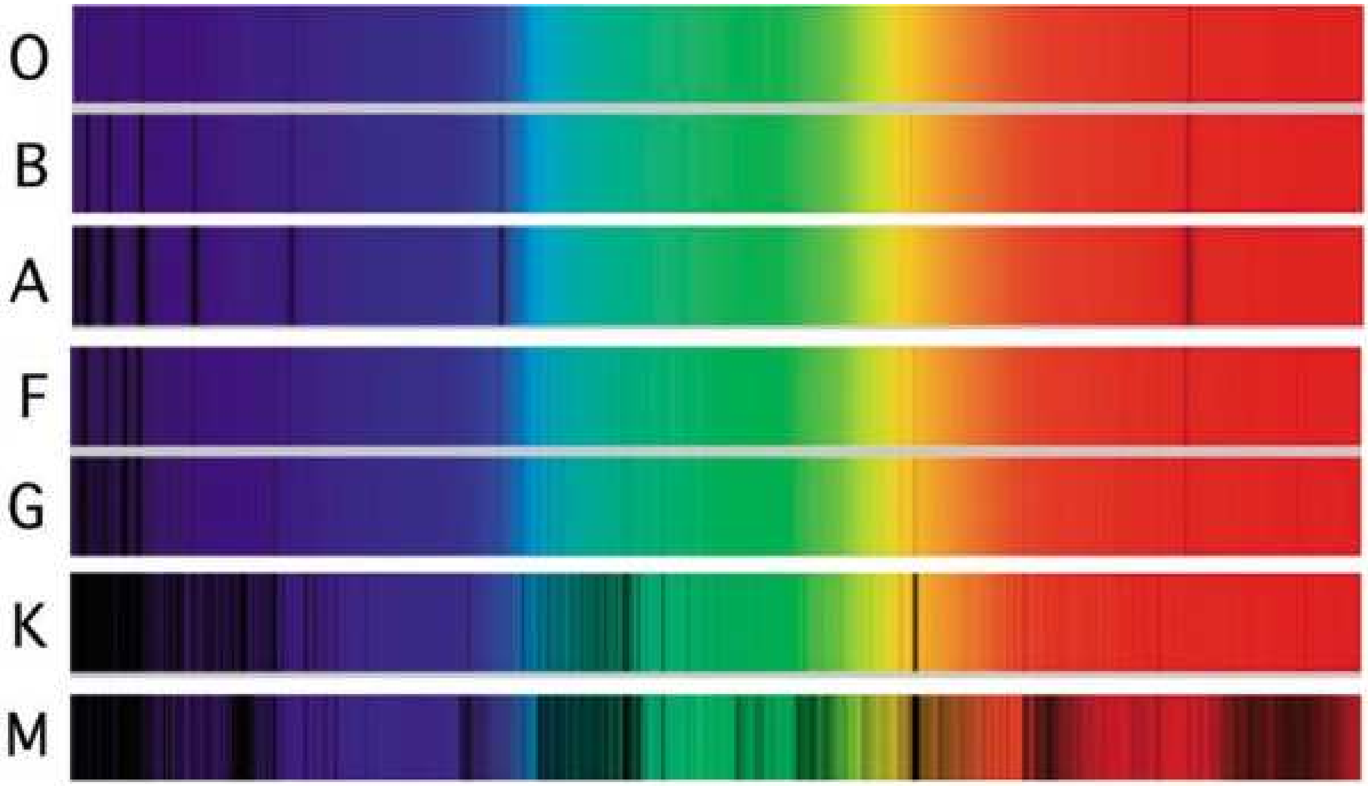


THE ABSORPTION SPECTRUM OF THE SUN:



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 CLASSED 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.

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