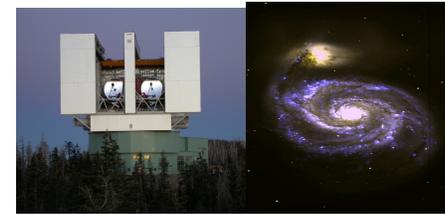




THE OHIO STATE UNIVERSITY



”STARS”

SULTANA N. NAHAR

Astronomy, Ohio State University, Columbus, Ohio, USA
- Adjunct Professor, Aligarh Muslim University, India
- Adjunct Professor, Cairo University, Egypt

”BIBHA ALL-GIRLS ASTRONOMY WORKSHOP 2021”



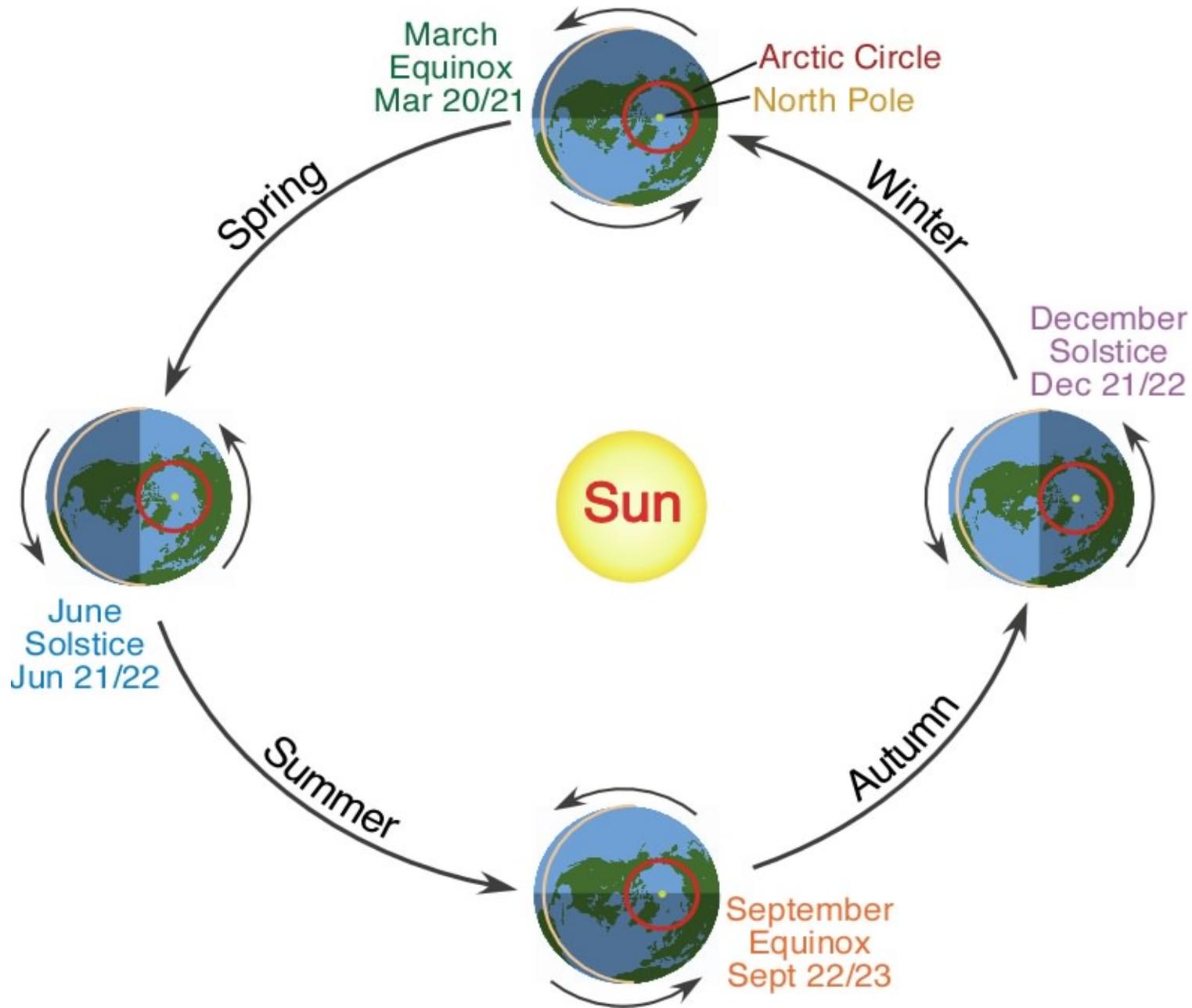
International Astronomical Union (IAU)
National Outreach Coordinator (NOC)
BANGLADESH



Bangladesh Astronomical Society

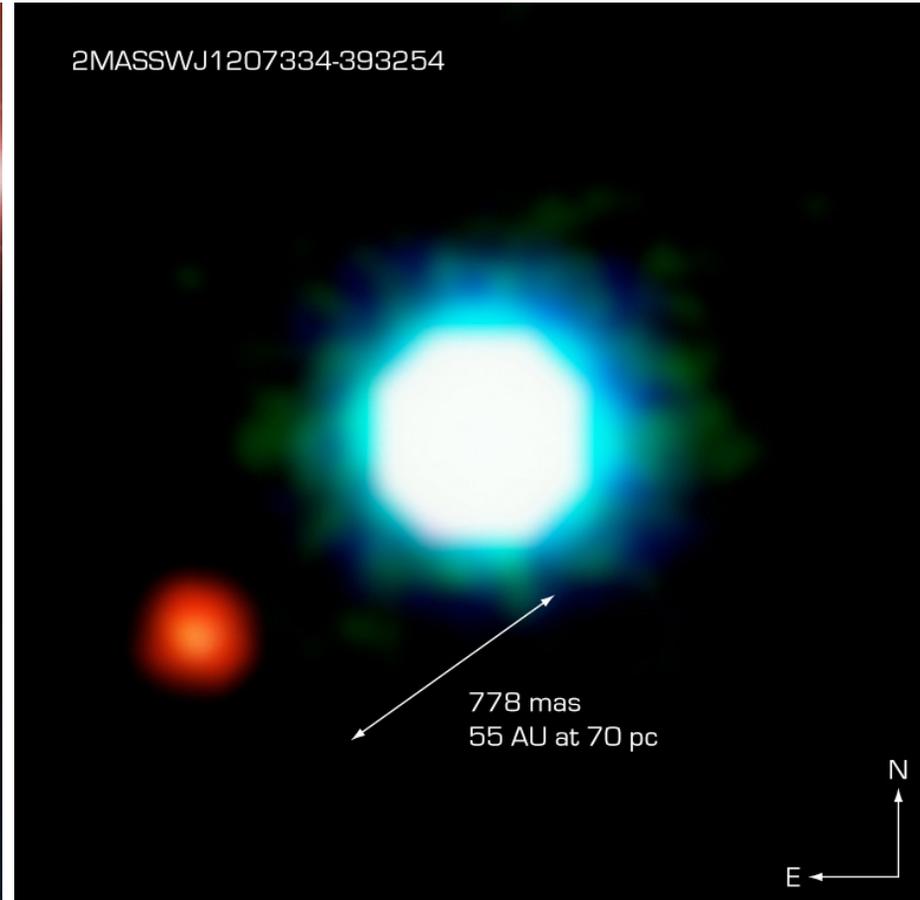
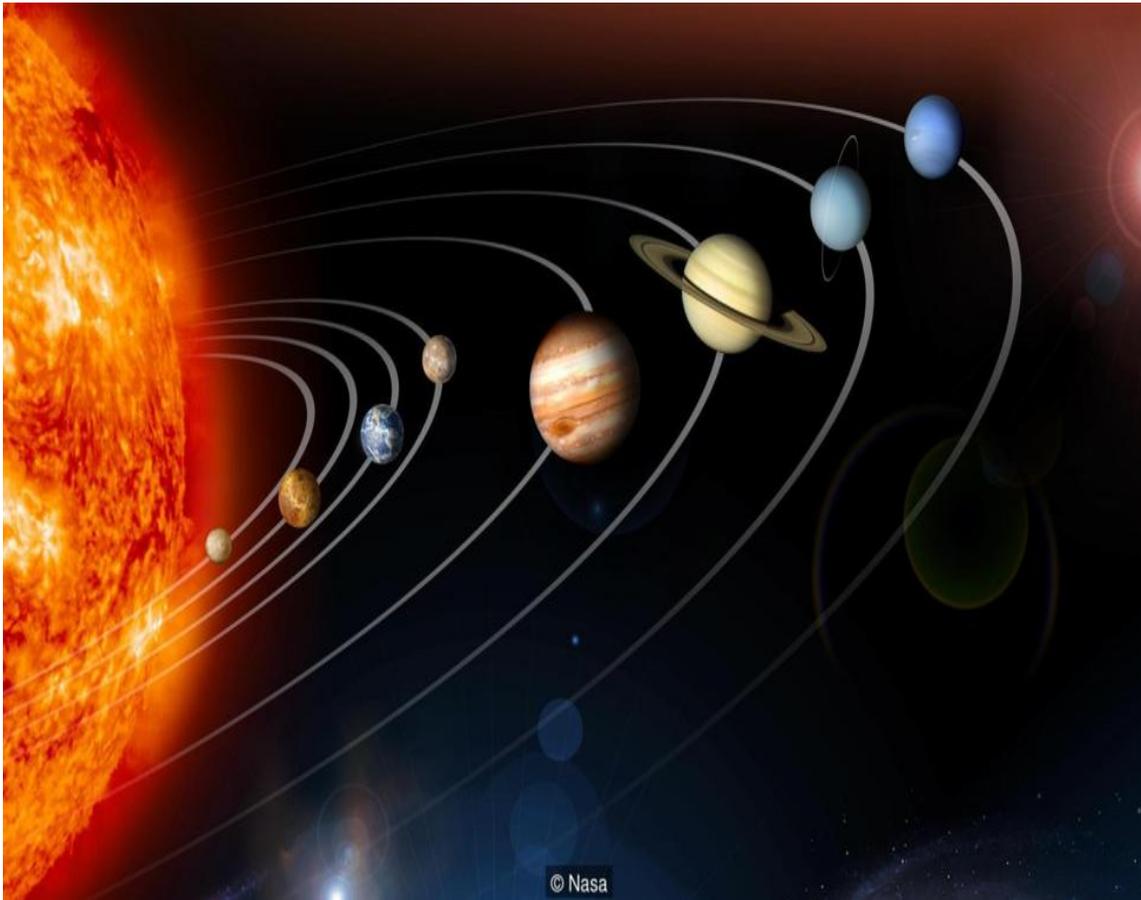
Dhaka, Bangladesh
Feb 11-13, 2021

The SUN, Our STAR



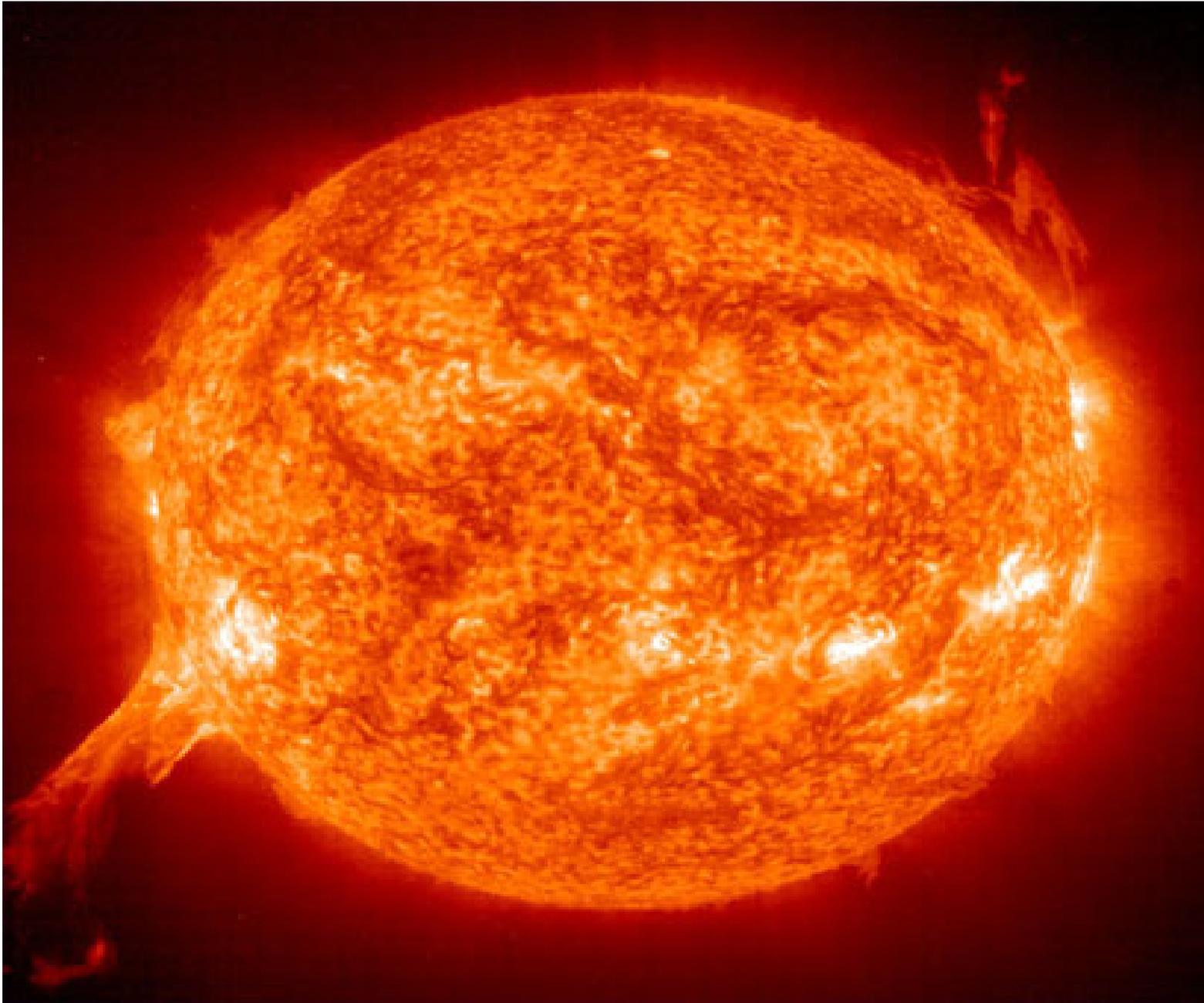
- Sun is the source of energy for our Earth, its planet
 - It is the standard for studying other stars

SUN: 110 x Diameter of the Earth



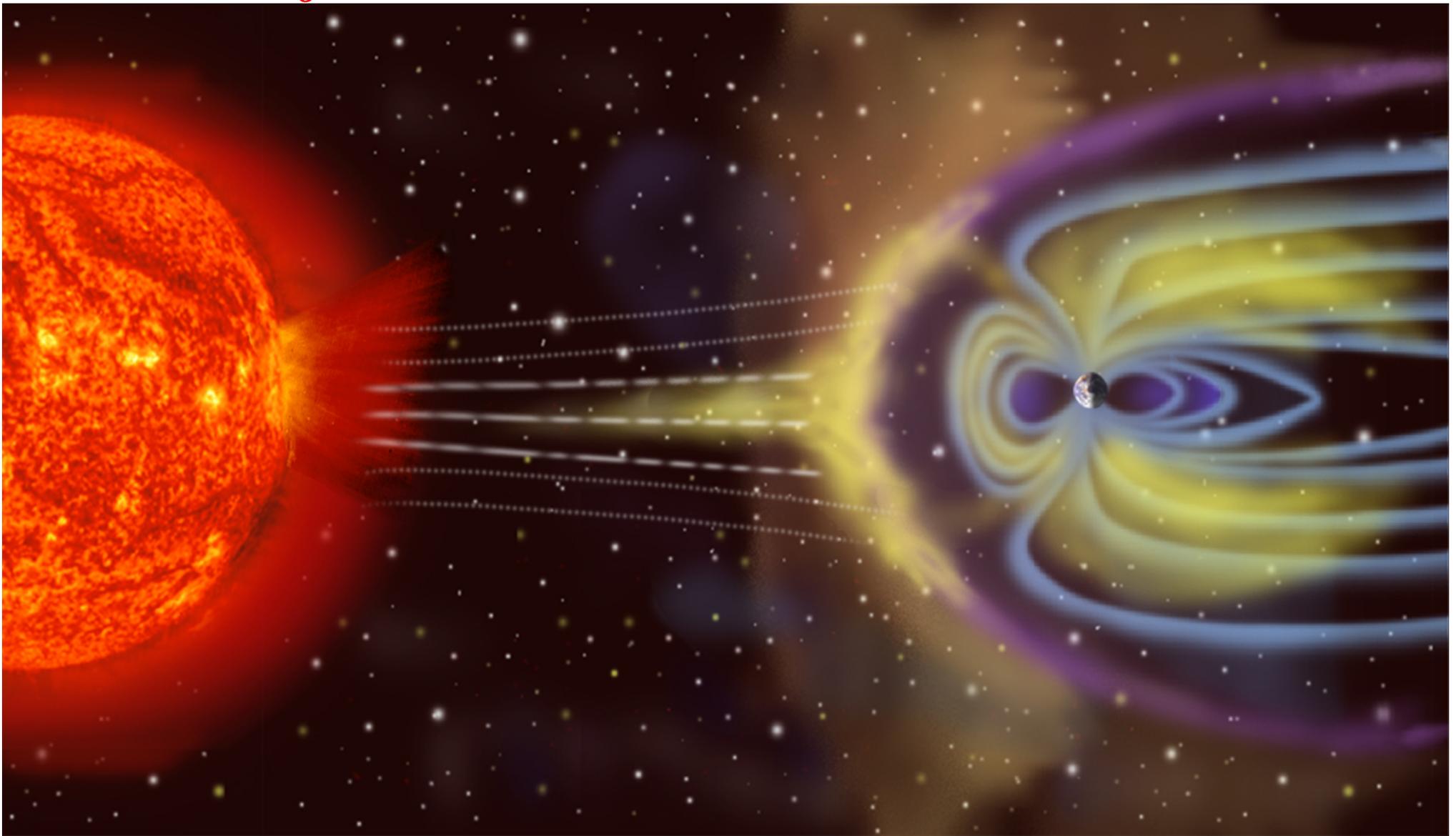
- **L: Solar planets:** Planets around our sun
- **R: Exoplanets:** Planets around a star except the sun - typically around cool red dwarfs
- The 1st exoplanet 2M120b-ESO2004, by HARPS in 2004
- Sun: 8 planets and a number of dwarf planets around it

SUN - The "unQuiet" Star (Observed by space observatory SOHO)



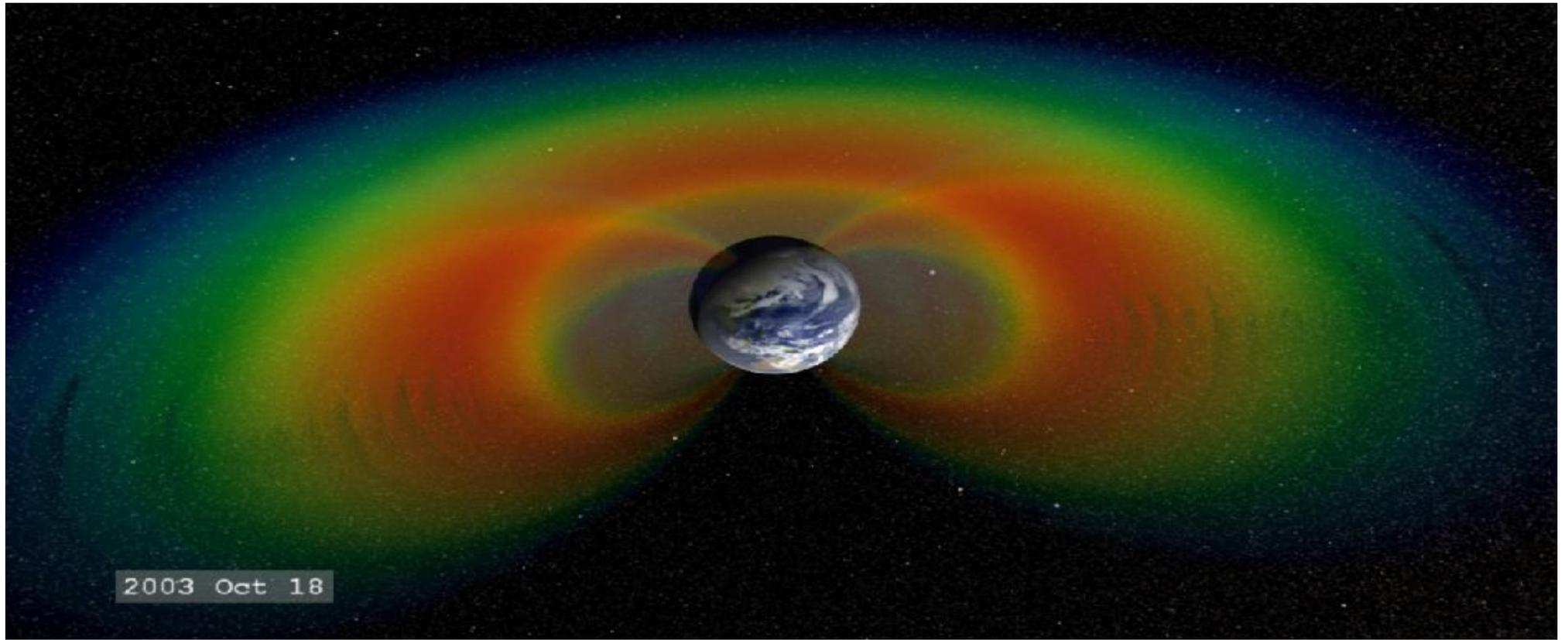
- Sun has a 11 years cycle of minimum to maximum ACTIVITY, when its magnetic field flips between North and South
- Eruptions with explosions ejecting large amount of particles & radiation

Solar Ejections - Radiation & Particles

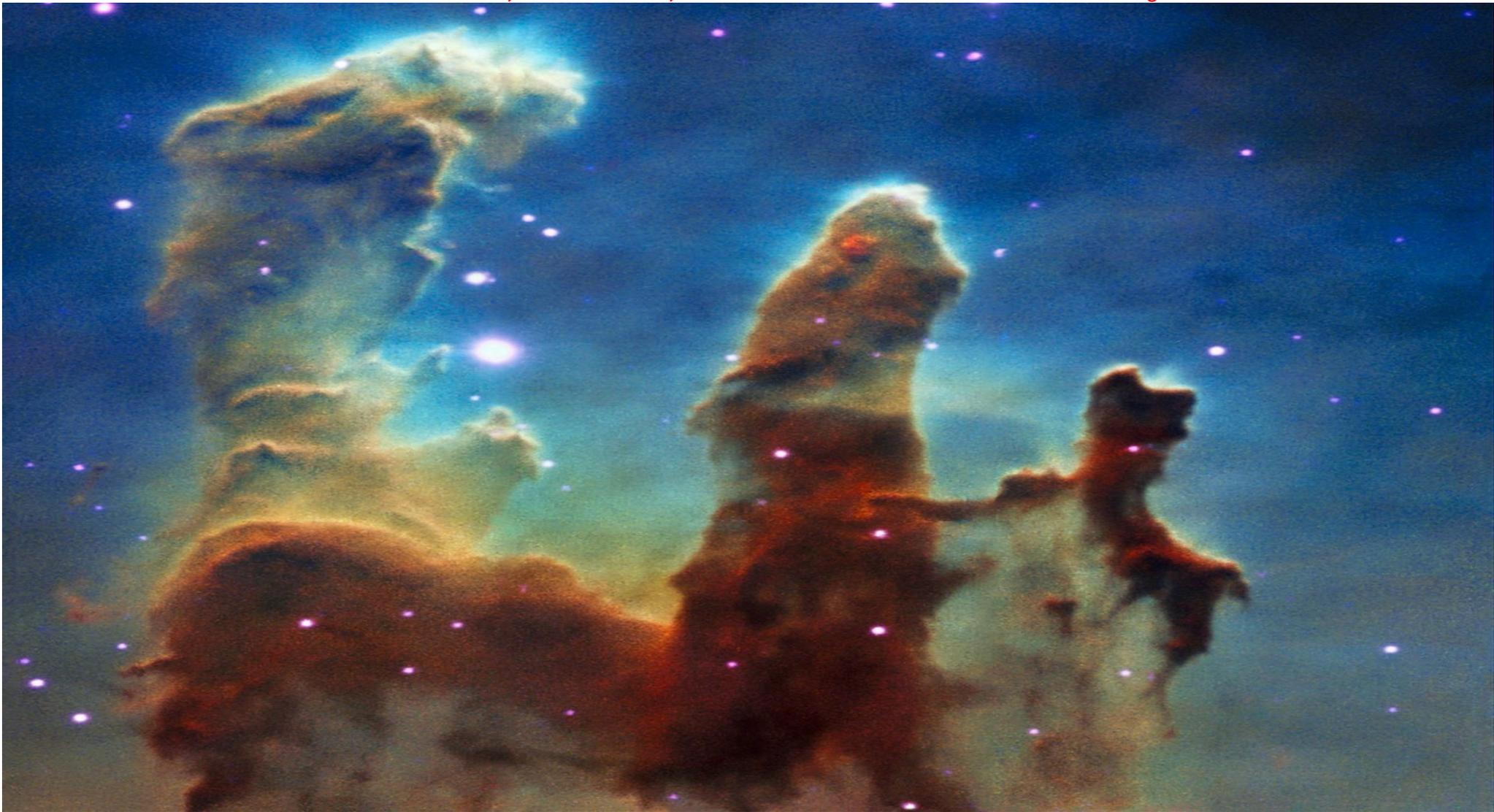


- Solar storms ejects bursts of electrons, protons, & heavy ions accelerated by massive explosions inside
- Our Earth's atmosphere and magnetic field protects us from these massive bursts of particles and radiation by reflections, absorption, and captures
- For example, magnetic field capture charged particles, ozone layer blocks most ultraviolet, X-rays and Gamma rays
- Most dangerous particles are ions which can

VAN ALLEN BELT FROM HALLOWEEN SOLAR STORM, AURORA



STARS: BORN, LIVE, DIE - Has a Life Cycle



- Atoms, molecules, dust traveling in space slowly accumulate due to gravity - form gaseous nebula
- Concentrated gas and dust collapse due to gravity. A star starts to form and then starts to shine. They usually form in groups
- It takes about a million years to form a star
- Pillars of Creation in Eagle Nebula, stellar birth place

FORMATION OF ELEMENTS VIA NUCLEAR FUSION AT CENTER -

generates radiation that travels out - makes the star shine

PERIODIC TABLE
Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum	<i>c</i>	299 792 458 m s ⁻¹	(exact)
Planck constant	<i>h</i>	6.626 07 × 10 ⁻³⁴ J s	(<i>h</i> = <i>h</i> /2π)
elementary charge	<i>e</i>	1.602 177 × 10 ⁻¹⁹ C	
electron mass	<i>m_e</i>	9.109 38 × 10 ⁻³¹ kg	
proton mass	<i>m_p</i>	0.510 999 MeV	
fine-structure constant	<i>α</i>	1.672 622 × 10 ⁻²⁷ kg	
Rydberg constant	<i>R_∞</i>	1/137.035 999	
	<i>R_∞hc</i>	3.289 841 960 × 10 ¹⁵ Hz	
	<i>R_∞hc</i>	13.605 69 eV	
Boltzmann constant	<i>k</i>	1.380 6 × 10 ⁻²³ J K ⁻¹	

Physical Measurement Laboratory
www.nist.gov/pml

Standard Reference Data
www.nist.gov/srd

■ Solids

■ Liquids

■ Gases

■ Artificially Prepared

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA	IIA	IIIB	IVB	VB	VIB	VII	VIII	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	H Hydrogen 1.008* 1s 13.5984																	He Helium 4.002602 1s ² 24.5874
2	Li Lithium 6.94* 1s ² 2s 5.3917	Be Beryllium 9.0121831 1s ² 2s ² 9.3227											B Boron 10.81* 1s ² 2s ² 2p 11.2603	C Carbon 12.011* 1s ² 2s ² 2p ² 14.5341	N Nitrogen 14.007* 1s ² 2s ² 2p ³ 14.5341	O Oxygen 15.999* 1s ² 2s ² 2p ⁴ 13.6181	F Fluorine 18.99840316 1s ² 2s ² 2p ⁵ 17.4228	Ne Neon 20.1797 1s ² 2s ² 2p ⁶ 21.5645
3	Na Sodium 22.98976928 [Ne]3s 5.1391	Mg Magnesium 24.305* [Ne]3s ² 7.6462											Al Aluminum 26.9815385 [Ne]3s ² 3p 5.9858	Si Silicon 28.085* [Ne]3s ² 3p ² 8.1517	P Phosphorus 30.97376200 [Ne]3s ² 3p ³ 10.4867	S Sulfur 32.06* [Ne]3s ² 3p ⁴ 10.3600	Cl Chlorine 35.45* [Ne]3s ² 3p ⁵ 12.9676	Ar Argon 39.948 [Ne]3s ² 3p ⁶ 15.7596
4	K Potassium 39.0983 [Ar]4s 4.3407	Ca Calcium 40.078 [Ar]4s 6.1132	Sc Scandium 44.955908 [Ar]3d ¹ 4s ² 6.5615	Ti Titanium 47.867 [Ar]3d ² 4s ² 6.8281	V Vanadium 50.9415 [Ar]3d ³ 4s ² 6.7462	Cr Chromium 51.9961 [Ar]3d ⁵ 4s 6.7665	Mn Manganese 54.938044 [Ar]3d ⁵ 4s ² 7.4340	Fe Iron 55.845 [Ar]3d ⁶ 4s ² 7.9025	Co Cobalt 58.933194 [Ar]3d ⁷ 4s ² 7.8810	Ni Nickel 58.6934 [Ar]3d ⁸ 4s 7.6399	Cu Copper 63.546 [Ar]3d ¹⁰ 4s 7.7264	Zn Zinc 65.38 [Ar]3d ¹⁰ 4s ² 9.3942	Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p 5.9993	Ge Germanium 72.630 [Ar]3d ¹⁰ 4s ² 4p ² 7.8994	As Arsenic 74.921595 [Ar]3d ¹⁰ 4s ² 4p ³ 9.7886	Se Selenium 78.971 [Ar]3d ¹⁰ 4s ² 4p ⁴ 9.7524	Br Bromine 79.904* [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138	Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶ 13.9996
5	Rb Rubidium 85.4678 [Kr]5s 4.1771	Sr Strontium 87.62 [Kr]5s ² 6.6949	Y Yttrium 88.90584 [Kr]4d ⁵ 5s 6.2173	Zr Zirconium 91.224 [Kr]4d ⁵ 5s 6.6339	Nb Niobium 92.90637 [Kr]4d ⁴ 5s 6.7589	Mo Molybdenum 95.95 [Kr]4d ⁵ 5s 7.0924	Tc Technetium (98) [Kr]4d ⁵ 5s ² 7.1194	Ru Ruthenium 101.07 [Kr]4d ⁷ 5s 7.3605	Rh Rhodium 102.90550 [Kr]4d ⁸ 5s 7.4589	Pd Palladium 106.42 [Kr]4d ¹⁰ 8.3369	Ag Silver 107.8682 [Kr]4d ¹⁰ 5s 7.5762	Cd Cadmium 112.414 [Kr]4d ¹⁰ 5s ² 8.9938	In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p 5.7864	Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 5p ² 7.3439	Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³ 8.6084	Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴ 9.0097	I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 5p ⁵ 10.4513	Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶ 12.1298
6	Cs Cesium 132.9054520 [Xe]6s 3.8939	Ba Barium 137.327 [Xe]6s ² 5.2117		Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ² 6.8251	Ta Tantalum 180.94788 [Xe]4f ¹⁴ 5d ³ 6s ² 7.5496	W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ² 7.8640	Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ² 7.8335	Os Osmium 192.223 [Xe]4f ¹⁴ 5d ⁶ 6s ² 8.4382	Ir Iridium 192.223 [Xe]4f ¹⁴ 5d ⁷ 6s ² 8.9588	Pt Platinum 195.084 [Xe]4f ¹⁴ 5d ⁹ 6s 8.9588	Au Gold 196.966569 [Xe]4f ¹⁴ 5d ¹⁰ 6s 9.2256	Hg Mercury 200.592 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	Tl Thallium 204.38* [Hg]6p 6.1083	Pb Lead 207.2 [Hg]6p ² 7.2855	Bi Bismuth 208.98040 [Hg]6p ³ 8.414	Po Polonium (209) [Hg]6p ⁴ 8.414	At Astatine (210) [Hg]6p ⁵ 9.31751	Rn Radon (222) [Hg]6p ⁶ 10.7485
7	Fr Francium (223) [Rn]7s 4.0727	Ra Radium (226) [Rn]7s ² 5.2764		Rf Rutherfordium (267) [Rn]5f ¹⁴ 6d ² 7s ² 6.01	Db Dubnium (268) [Rn]5f ¹⁴ 6d ³ 7s ² 6.8	Sg Seaborgium (271) [Rn]5f ¹⁴ 6d ⁴ 7s ² 7.8	Bh Bohrium (272) [Rn]5f ¹⁴ 6d ⁵ 7s ² 7.7	Hs Hassium (270) [Rn]5f ¹⁴ 6d ⁶ 7s ² 7.6	Mt Meitnerium (276) [Rn]5f ¹⁴ 6d ⁷ 7s ² 7.6	Ds Darmstadtium (281) [Rn]5f ¹⁴ 6d ⁸ 7s ² 7.6	Rg Roentgenium (280) [Rn]5f ¹⁴ 6d ⁹ 7s ² 7.6	Cn Copernicium (285) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7.6	Uut Ununtrium (284) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7.6	Fl Flerovium (289) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7.6	Uup Ununpentium (288) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7.6	Lv Livermorium (293) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7.6	Uus Ununseptium (294) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7.6	Uuo Ununoctium (294) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7.6
			La Lanthanum 138.90547 [Xe]5d ¹ 6s ² 5.5769	Ce Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ² 5.5386	Pr Praseodymium 140.907 [Xe]4f ³ 6s ² 5.473	Nd Neodymium 144.242 [Xe]4f ⁴ 6s ² 5.5250	Pm Promethium (145) [Xe]4f ⁵ 6s ² 5.582	Sm Samarium 150.36 [Xe]4f ⁶ 6s ² 5.6437	Eu Europium 151.964 [Xe]4f ⁷ 6s ² 5.6704	Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ² 6.1498	Tb Terbium 158.92535 [Xe]4f ⁹ 6s ² 5.8638	Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ² 5.9391	Ho Holmium 164.93033 [Xe]4f ¹¹ 6s ² 6.0215	Er Erbium 167.259 [Xe]4f ¹² 6s ² 6.1077	Tm Thulium 168.93422 [Xe]4f ¹³ 6s ² 6.1843	Yb Ytterbium 173.054 [Xe]4f ¹⁴ 6s ² 6.2542	Lu Lutetium 174.9668 [Xe]4f ¹⁴ 5d ¹ 6s ² 5.4259	
			Ac Actinium (227) [Rn]6d ¹ 7s ² 5.3802	Th Thorium 232.0377 [Rn]6d ² 7s ² 6.3067	Pa Protactinium 231.03588 [Rn]5f ¹ 6d ¹ 7s ² 5.89	U Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ² 6.1941	Np Neptunium (237) [Rn]5f ⁴ 6d ¹ 7s ² 6.2655	Pu Plutonium (244) [Rn]5f ⁶ 7s ² 6.0258	Am Americium (243) [Rn]5f ⁷ 7s ² 5.9738	Cm Curium (247) [Rn]5f ⁸ 7s ² 5.9914	Bk Berkelium (247) [Rn]5f ⁹ 7s ² 6.1978	Cf Californium (251) [Rn]5f ¹⁰ 7s ² 6.2817	Es Einsteinium (252) [Rn]5f ¹¹ 7s ² 6.3676	Fm Fermium (257) [Rn]5f ¹² 7s ² 6.50	Md Mendelevium (258) [Rn]5f ¹³ 7s ² 6.58	No Nobelium (259) [Rn]5f ¹⁴ 7s ² 6.65	Lr Lawrencium (262) [Rn]5f ¹⁴ 7s ² 7p 4.90	

Atomic Properties of Cerium (Ce):

- Atomic Number: 58
- Ground-state Level: 1G₄
- Symbol: Ce
- Name: Cerium
- Standard Atomic Weight: 140.116
- Ground-state Configuration: [Xe]4f¹5d¹6s²
- Ionization Energy (eV): 5.5386

*Based upon ¹²C. () indicates the mass number of the longest-lived isotope. [†]IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see iupac.org for an explanation and values. For a description of the data, visit physics.nist.gov/data NIST SP 966 (September 2014)

- 118 Elements: Gases (pink), Solids (white), Liquids (blue) A lab generated yellow element is replaced with astrophysical observation
- Elements are created through nuclear fusion. It starts with creating He from 2 H atoms. As plasma density and T increase in the stellar core, Li, C, N, O etc are created, and the process continues up to Fe

”OUR COSMIC SELVES”: (NY Times, April 13, 2015)



Astronomer Prof. Carl Segan promoted: ”We are made of star dusts”

- Science continues to show that life on Earth is intimately

Mysterious galaxy 3521 Our galaxy: MILKY WAY



The spiral galaxy NGC 3521 is located around 26 million light years away in the constellation Leo, with enormous amounts of surrounding dust and stray stars glowing far out from its disk.

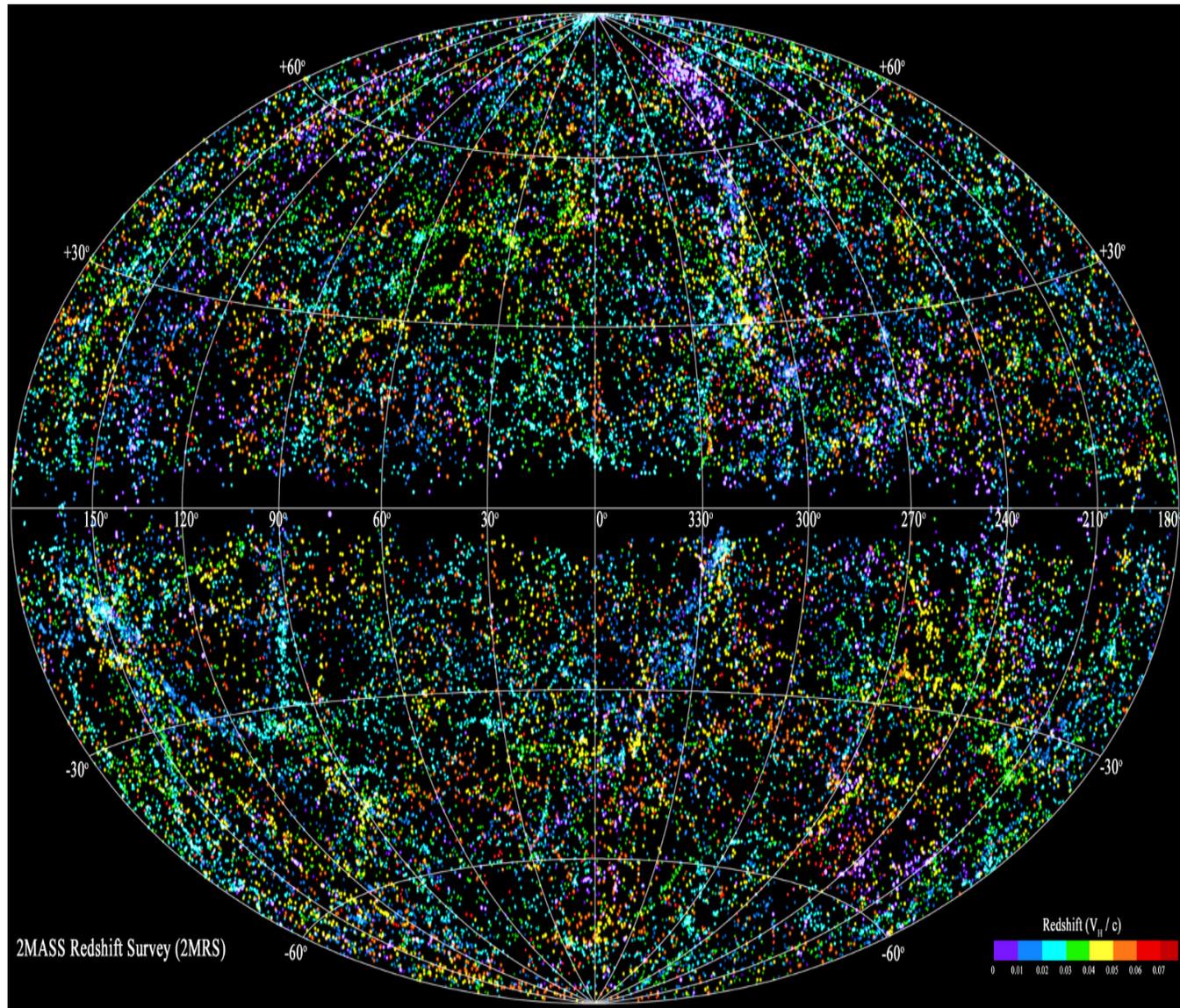
Gas + stars form Galaxy, MILKY WAY, Our Galaxy!



- Milky Way: 200-400 billion stars, including the Sun
- Milky way - spherical . The Sun is near the edge of it

UNIVERSE through RADIATION:

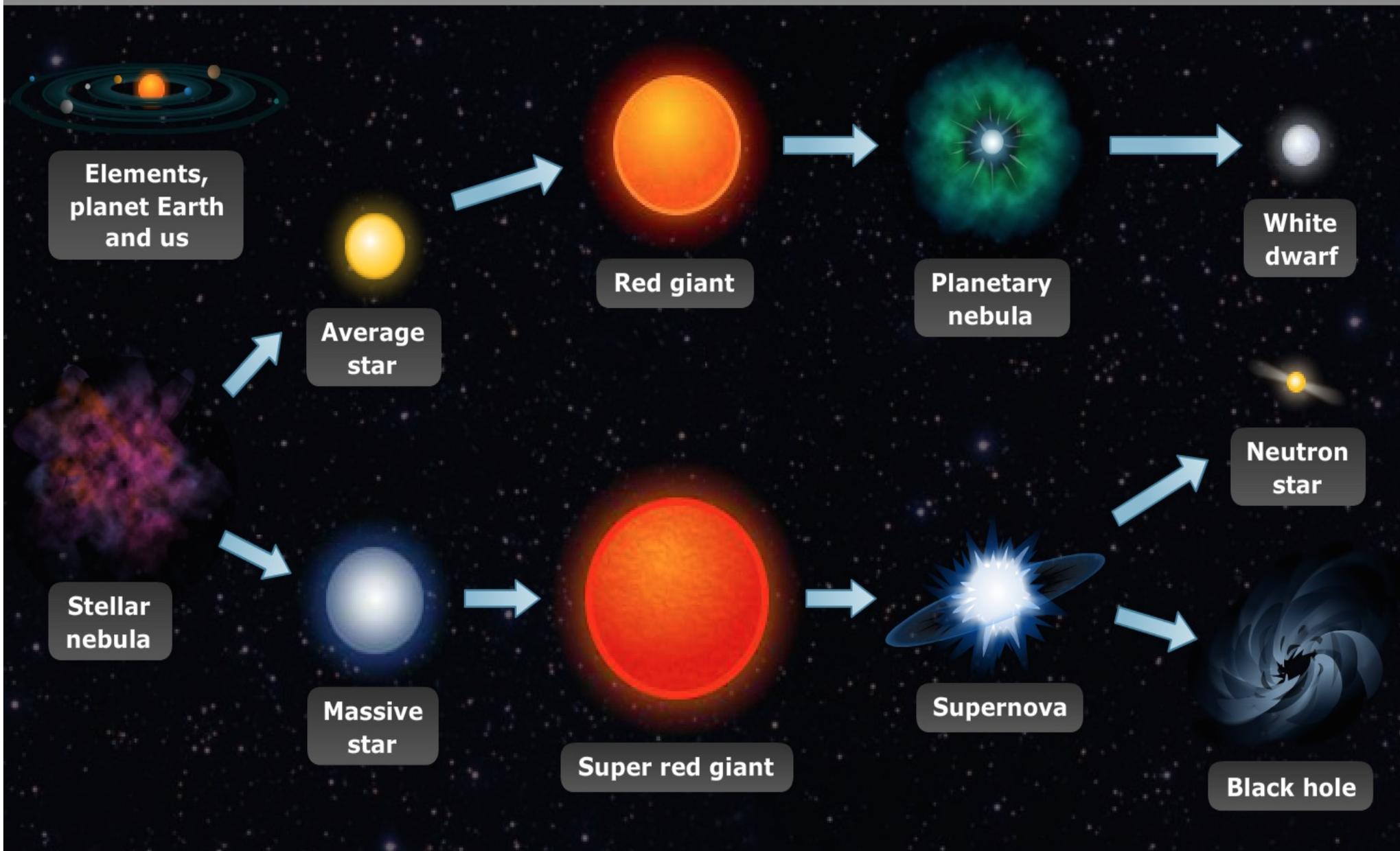
Most Complete 3D Map of the universe (Created: By 2MASS - 2-Micron All Sky Survey over 3 decades)



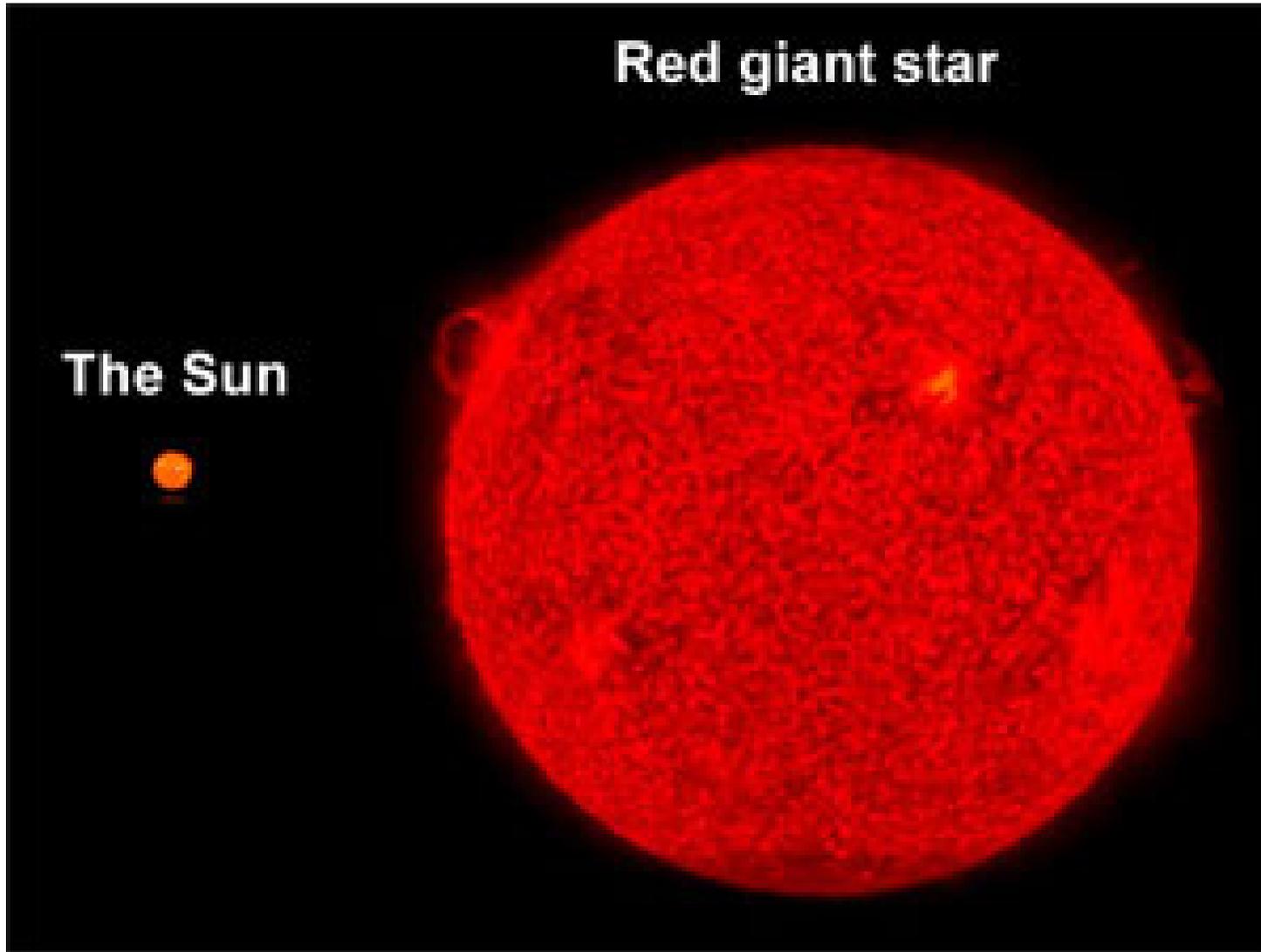
- Includes 43,000 galaxies extended over 380 million light years
- Redshifts, or measurements of galaxy distances, were added
- Missing black band in the middle because of invisibility behind our Milky Way

LIFE CYCLES OF AVERAGE AND MASSIVE STARS

UNIVERSAL ELEMENT FORMATION



FATE OF OUR SUN IN 6-7 BYR: RED GIANT



- Red Giant is a dying expanded star with H fuel gone.
- The heat and radiation will put materials out to form a red giant. The outer atmosphere is inflated and tenuous, making the radius immense. Our earth will be engulfed by the Sun.

PLANETARY NEBULA - Endpoint of a Star [PNe K 4-55 below]



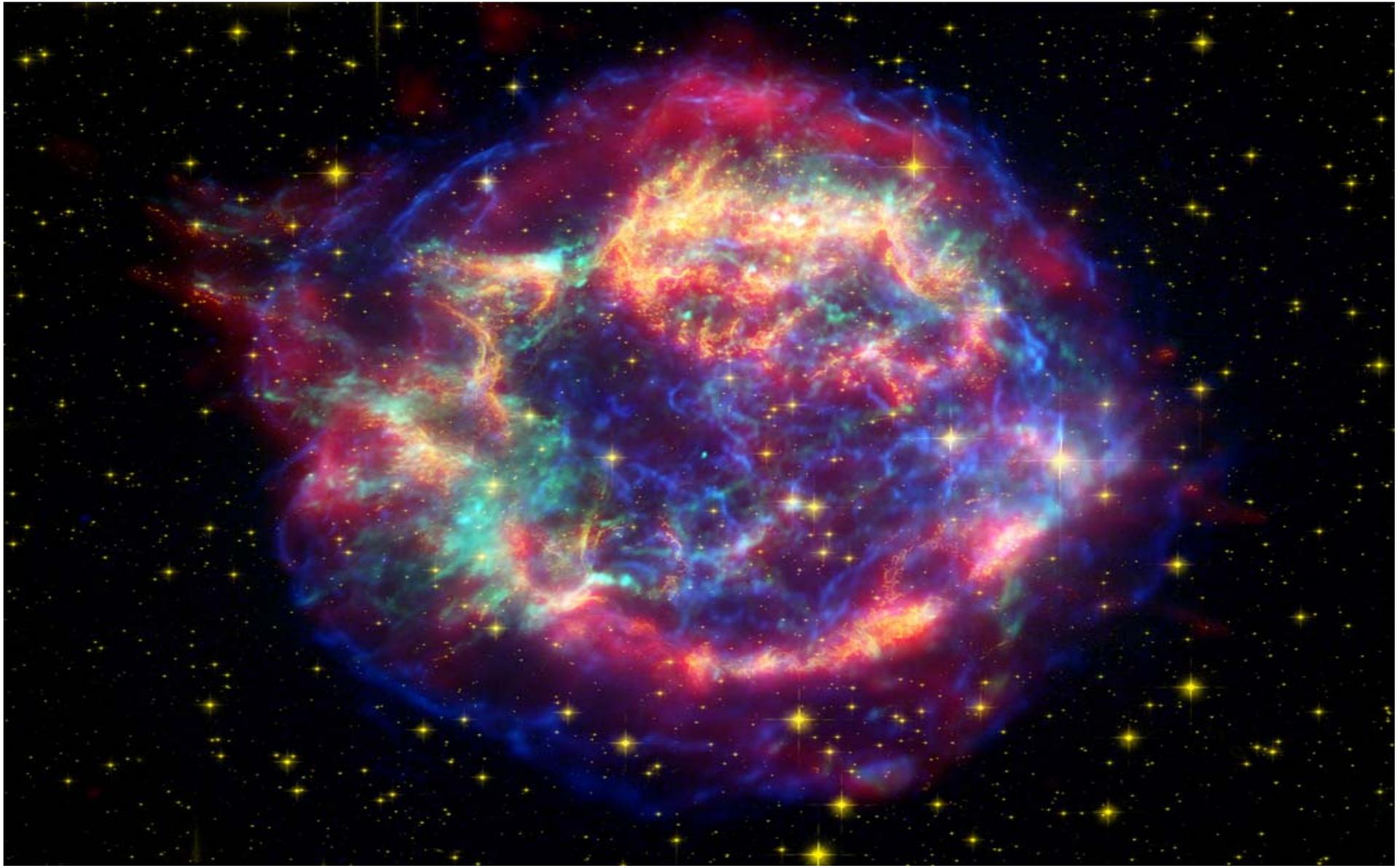
- Red giant will slowly become planetary nebulae
- Condensed central star: very high $T \sim 100,000$ K ($\gg T \leq 40,000$ K - typical star). Envelope: thin gas radiatively ejected & illuminated by central star radiation: red (N), blue (O). Lines of low ionization states - low ρ & low T

End of life: WHITE DWARF - Ex: Diamond white dwarf 2014



- "Astronomers discover Earth-sized diamond-encrusted white dwarf" 2014. Its so old that it has crystallized into a Earth-sized diamond
- A white dwarf is very dense: its mass is comparable to that of the Sun, while its volume is comparable to that of Earth.
- About 98% stars will end up as white dwarfs
- Ultimately they will be black dwarfs after losing all energies

Creation of Heavy Elements: Supernova explosion, r-process



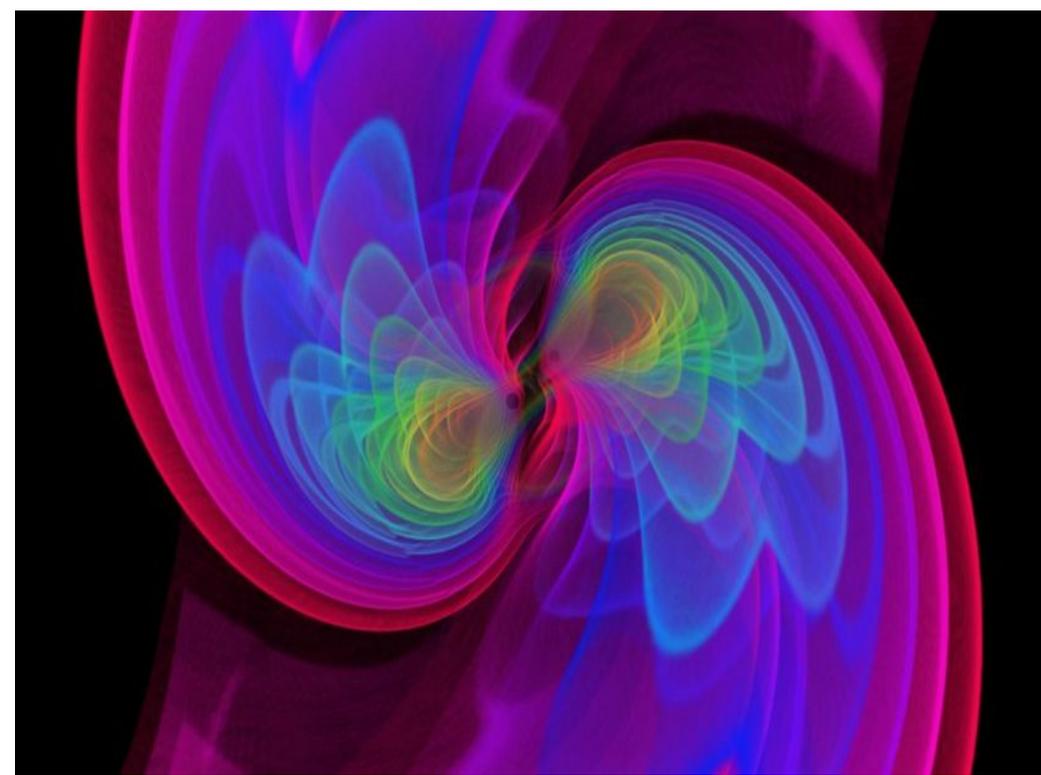
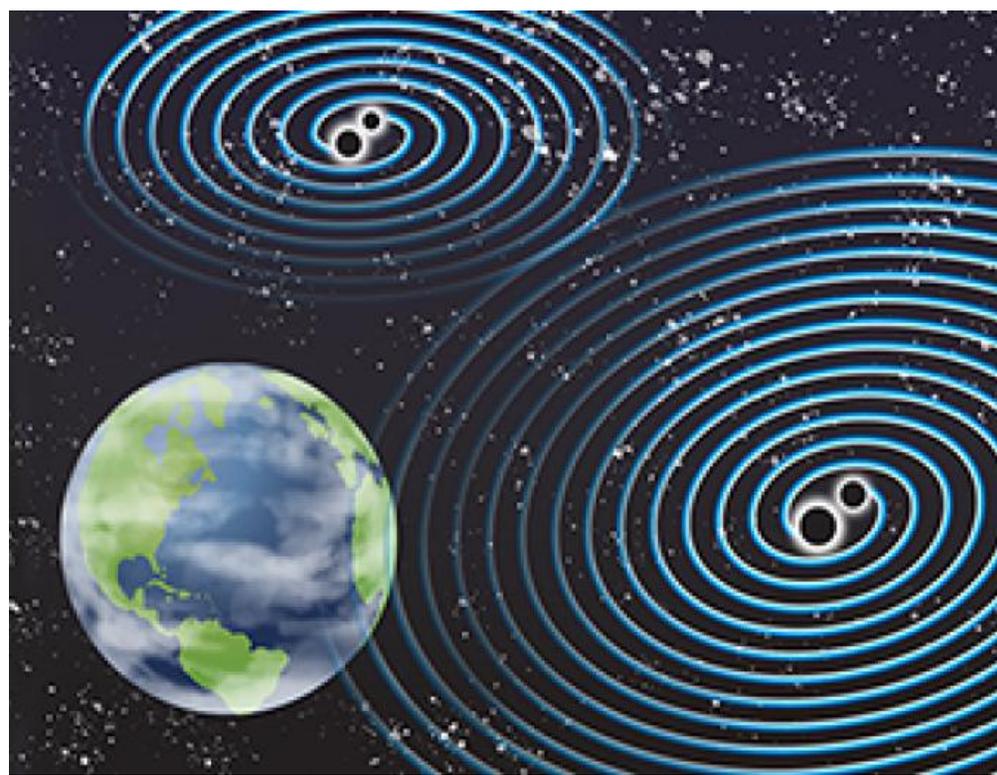
Supernova remnant Cassiopeia A: • Observation: Spitzer (Infrared - red), Hubble (Visible - yellow), Chandra (X-ray - green & blue)
• As a massive star collapses & expand, Heavier elements are created by r-process. **New source of r-process: mergers of black holes, neutron stars - a kilonova event**

NEUTRON STAR - At center of Crab Nebula



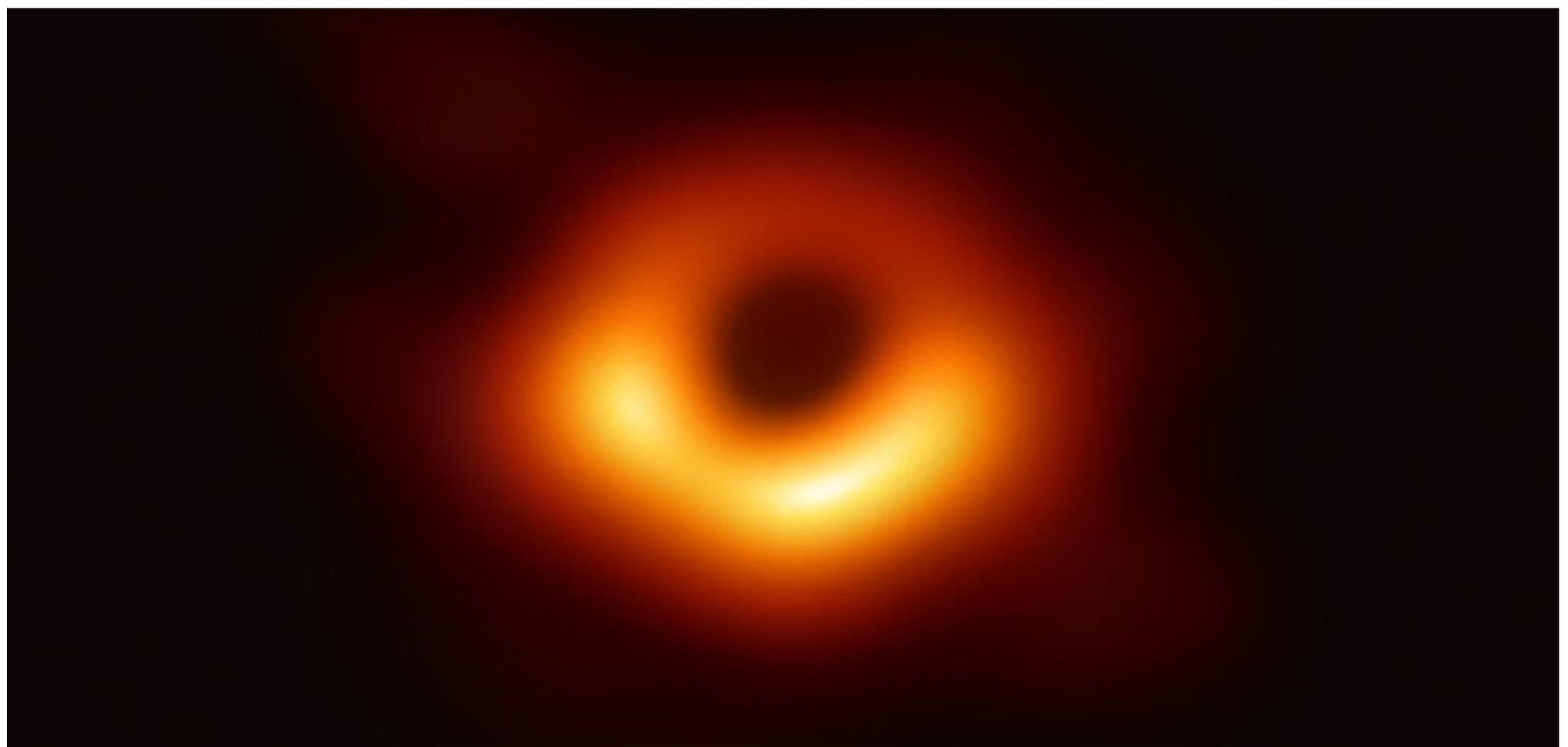
- After supernova explosion strong gravity due to stellar mass, can cause electrons to combine with protons to form neutrons.
- The Crab Nebula, the result of a bright supernova explosion At its center is a super-dense neutron star, rotating once every 33 milliseconds, shooting out rotating lighthouse-like beams from radio waves to

GRAVITATIONAL WAVES (GW) AND 3 LIGO SET-UPS



- Einstein predicted that an accelerating or decelerating mass will generate gravitational waves which will travel at the speed of light. It is similar to that of a charged particle which gives out electromagnetic waves. However, the GWs are extremely weak to detect - very large radio waves. They will expand and contact the earth if they pass.
- Russian idea of using laser interference to detect small change by the GWs in 1960s - was implemented by Rainer Weiss in the LIGO set-up - first detection in 2015 after over 20 years - Nobel prize in 2017
- 3 far-apart set-ups: Hanford in Washington State, Livingston in Louisiana, Pisa in Italy help to detect the direction of GWs.

First ever black hole image released, Apr 10, 2019



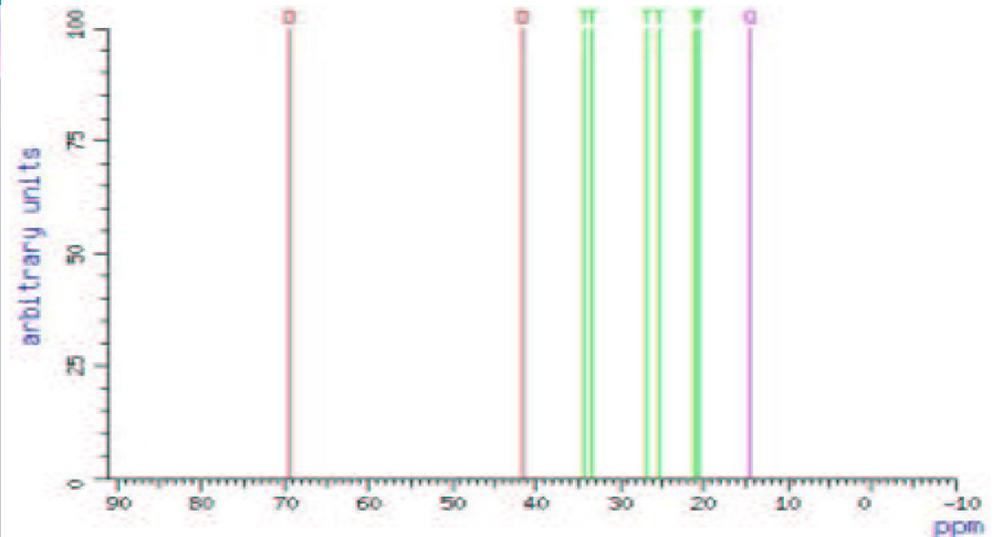
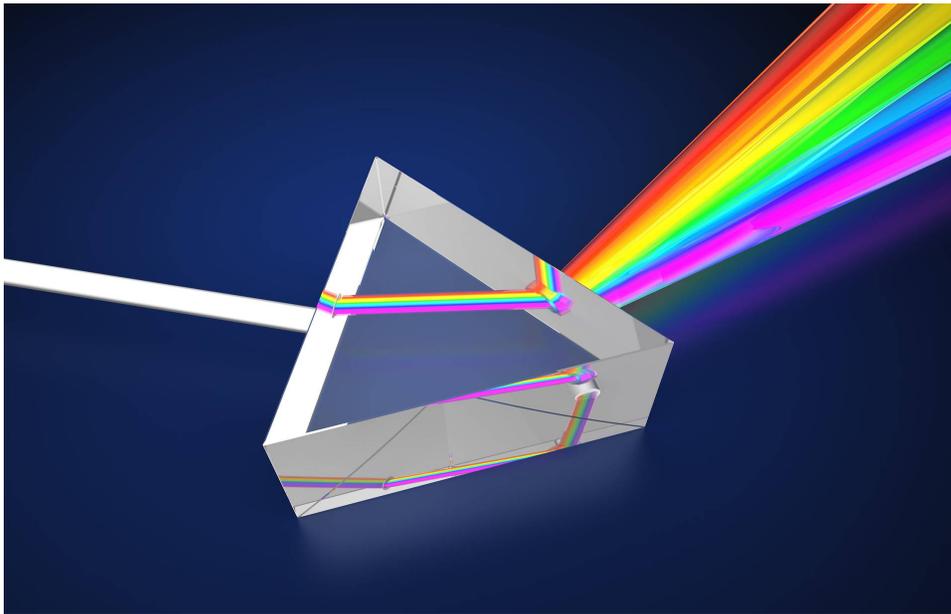
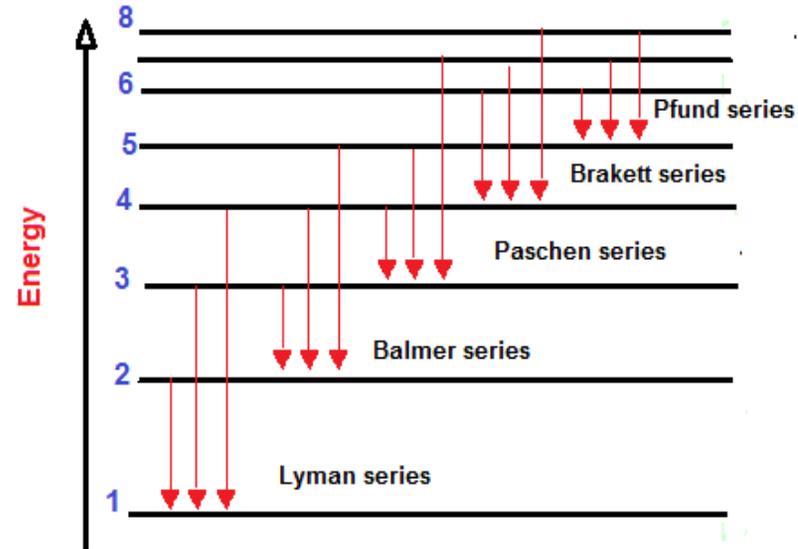
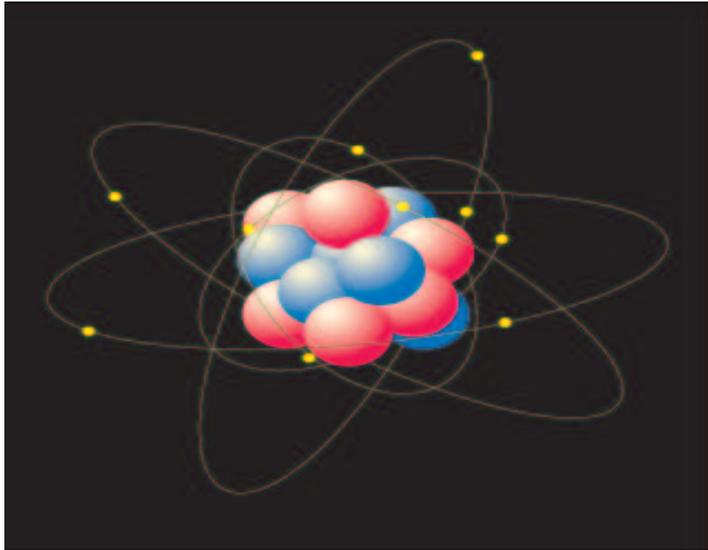
- The first ever image of a black hole, located in a distant galaxy, measures 40 Bkm across - 3M times the size of the Earth - and has been described as "a monster". It was composed from photographs by a network of eight "Event Horizon" telescopes across the world.
- **The monster black hole in the center of our Milky Way galaxy: 4M** time heavier than our Sun, tracked by the movement of 28 stars circling around it - Nobel prize in 2020

”STAR EATING BLACK HOLE”, ”Scientists watch a black hole shredding a star” (NASA, OSU 2019)



- Detected by TESS of NASA, AASA-GN led by OSU
- Tidal disruption event (TDE) - when a star gets too close to a black hole
- Depending on a number of factors, the black hole can either absorb the star or tear it apart into a long, spaghetti-like strand

RADIATION FROM ATOMS & SPECTRUM



- Energy levels are quantized
- An electron can be excited to higher levels. While dropping down, it gives out a photon. Radiation contains photons of many energies
- SPECTURM: Splitting the radiation in to its colors: Rainbow, C

THE 1ST OBSERVATORY, SAMARKAND, 1420, BY MUSLIM RULER ULUGH BEG (Iran has an older model)



- Ulugh Beg built the madrasa in 1420 in Samarkand and extended it to an observatory
- Beg himself recorded many astronomical objects.

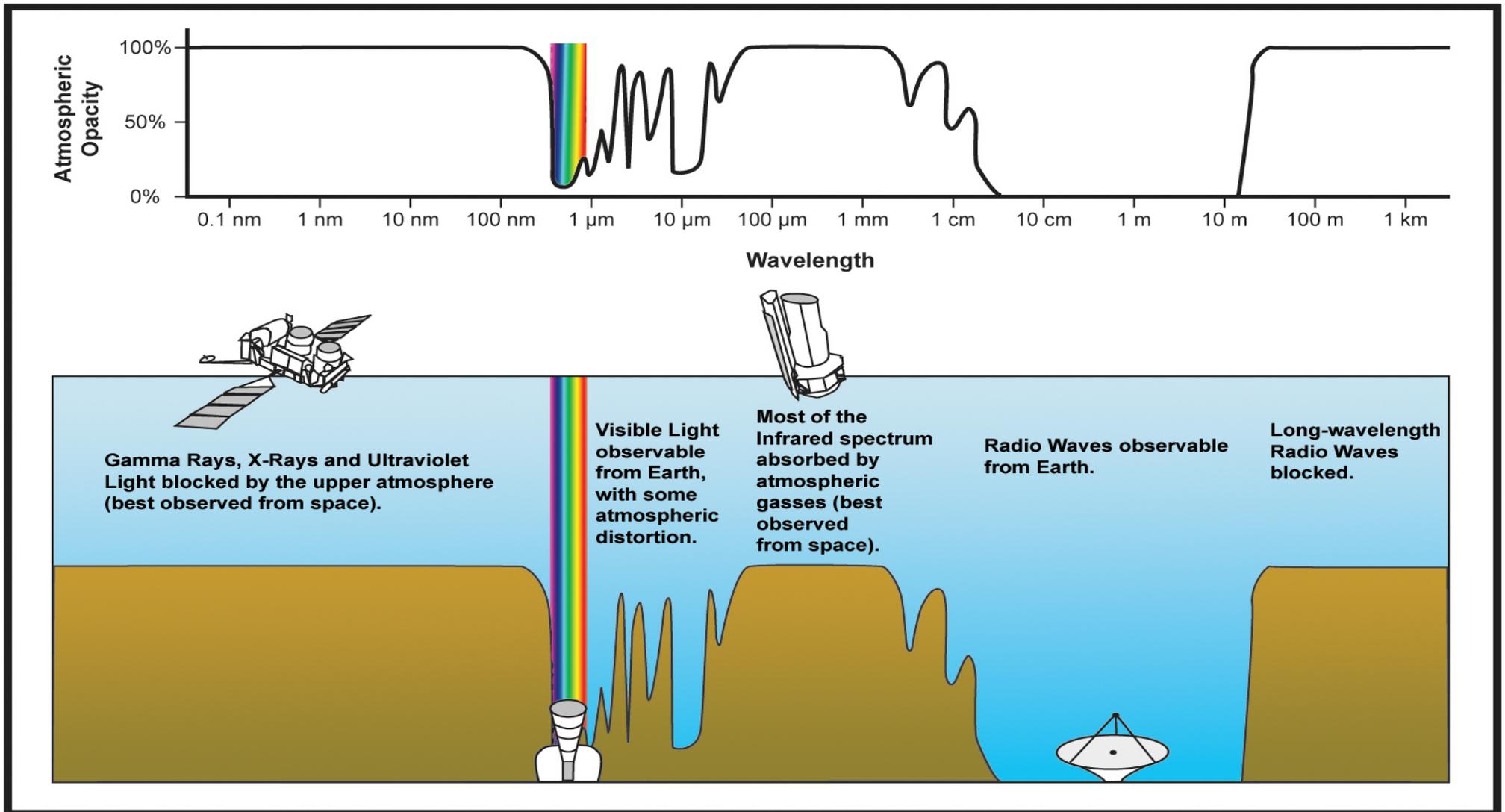


Large Binocular Telescope in Arizona (8.4m Mirrors, NIR-optical)



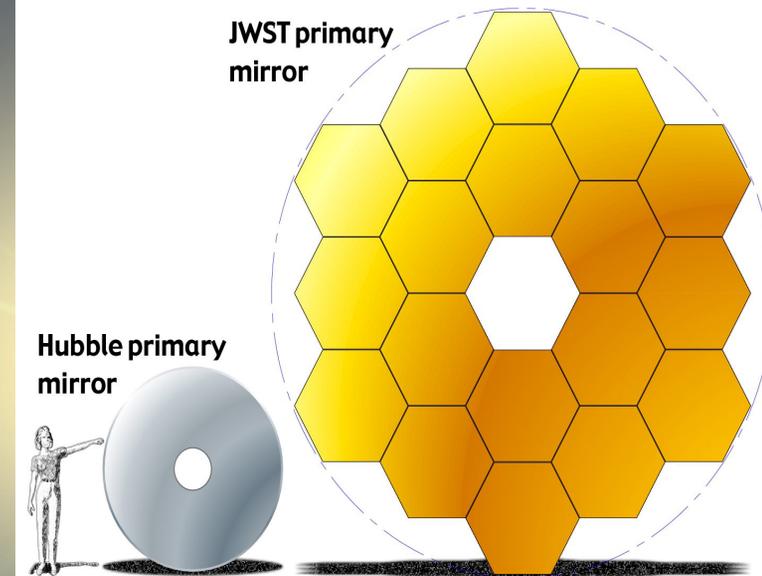
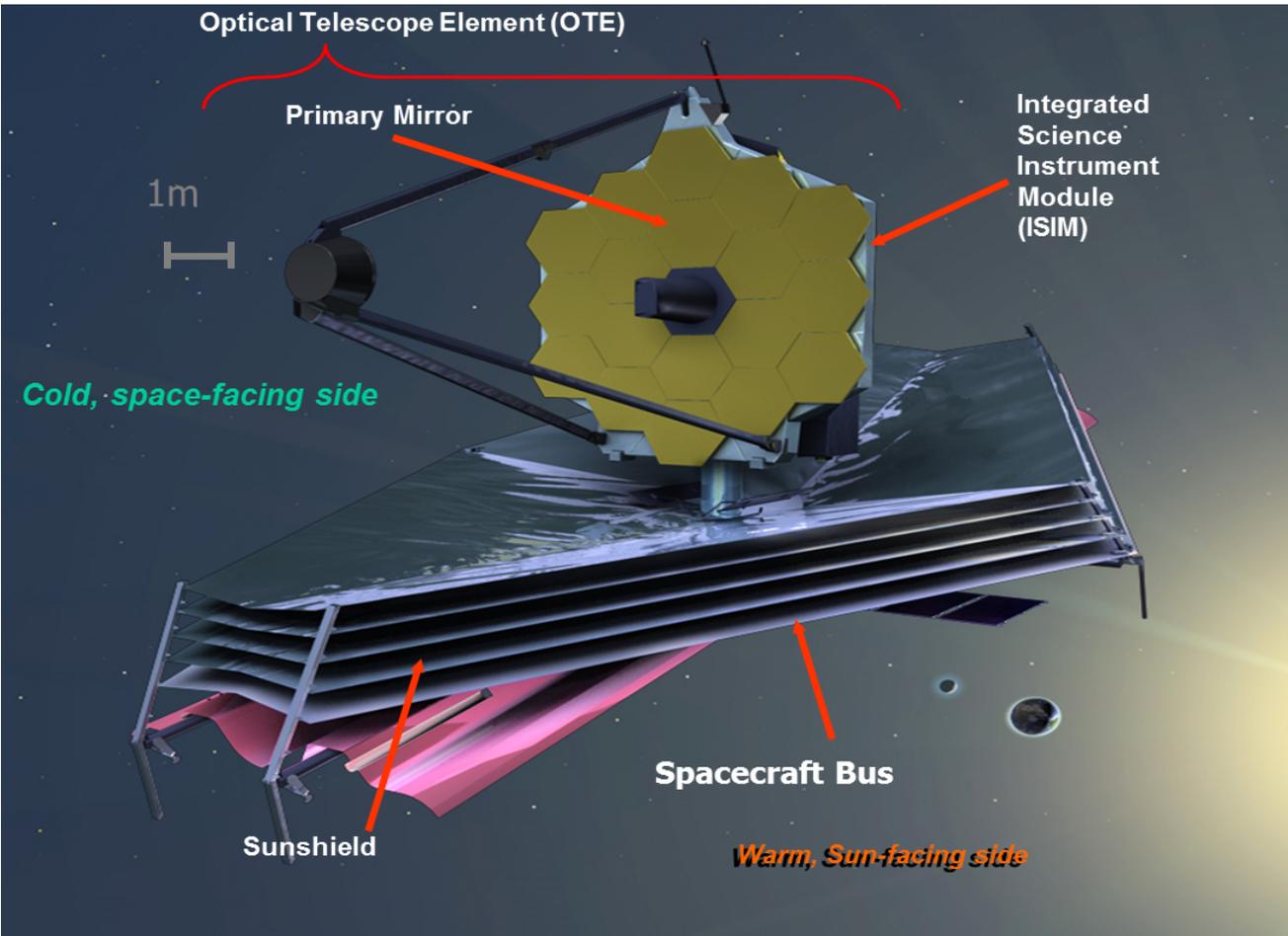
L: Hubble space telescope, R: International Space station of NASA

ATMOSPHERIC OPACITY - ABSORPTION OF RADIATION



- Higher opacity -less radiation reaching earth's surface
- Opacity determines types of telescopes - earth based or space based
- Gamma, X-ray, UV are blocked while visible light passes through
- CO₂, H₂O vapor, other gases absorb most of the infrared frequencies
- Part of radio frequencies is absorbed by H₂O and O₂, and part passes through

James Webb Space Telescope (JWST): Infrared 0.6 - 28.5 μm



- 18 mirrors combine to create 6.5m - Hubble: 2.4m diameter lens
- Mass: 6500 kg - Launch: March 2021
- Expected to detect lines of kilonova events

Determination of OPACITY: RADIATIVE ATOMIC PROCESSES

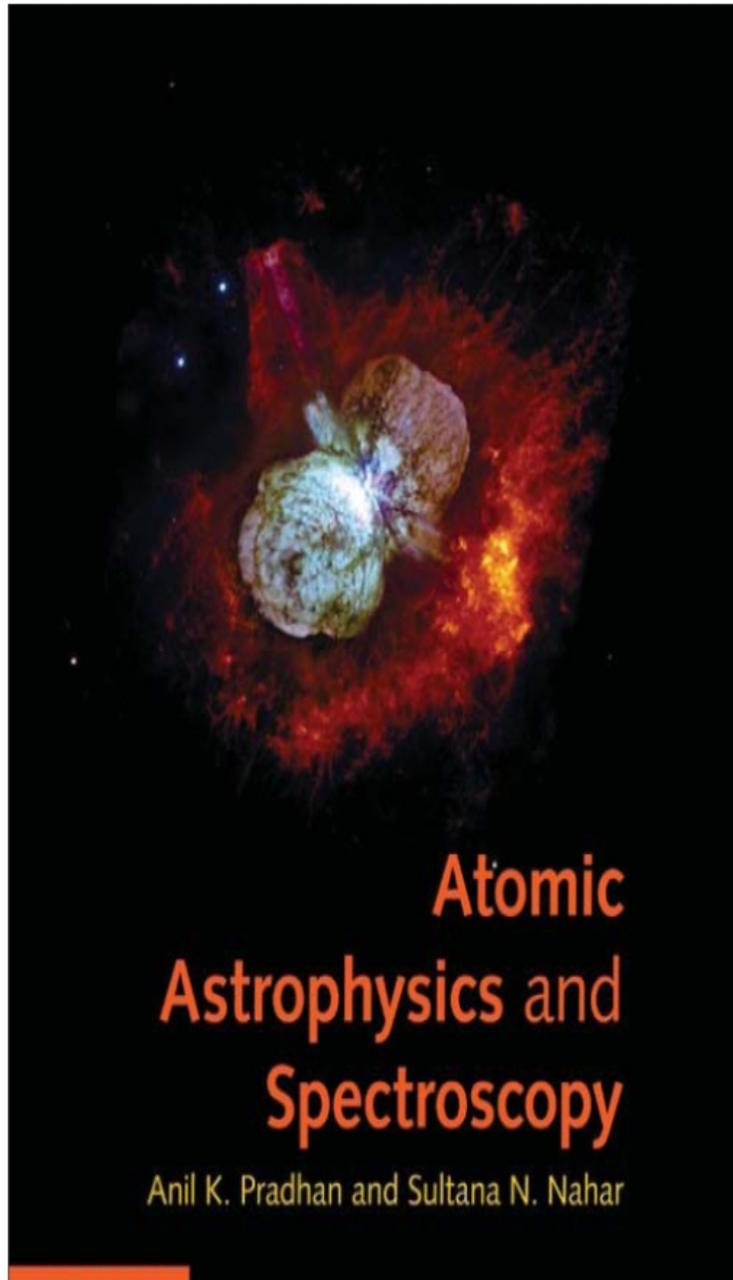


Table of Contents

1. Introduction
2. Atomic structure
3. Atomic processes
4. Radiative transitions
5. Electron-ion collisions
6. Photoionization
7. Electron-ion recombination
8. Multi-wavelength emission spectra
9. Absorption lines and radiative transfer
10. Stellar properties and spectra
11. Stellar opacity and radiative forces
12. Gaseous nebulae and HII regions
13. Active galactic nuclei and quasars



and Arizona, Germany, Italy



Large Binocular Telescope (LBT)

Largest Telescope: 8.4m Mirrors (11.8m), NIR-Optical

