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Appendices

”THE SUN”

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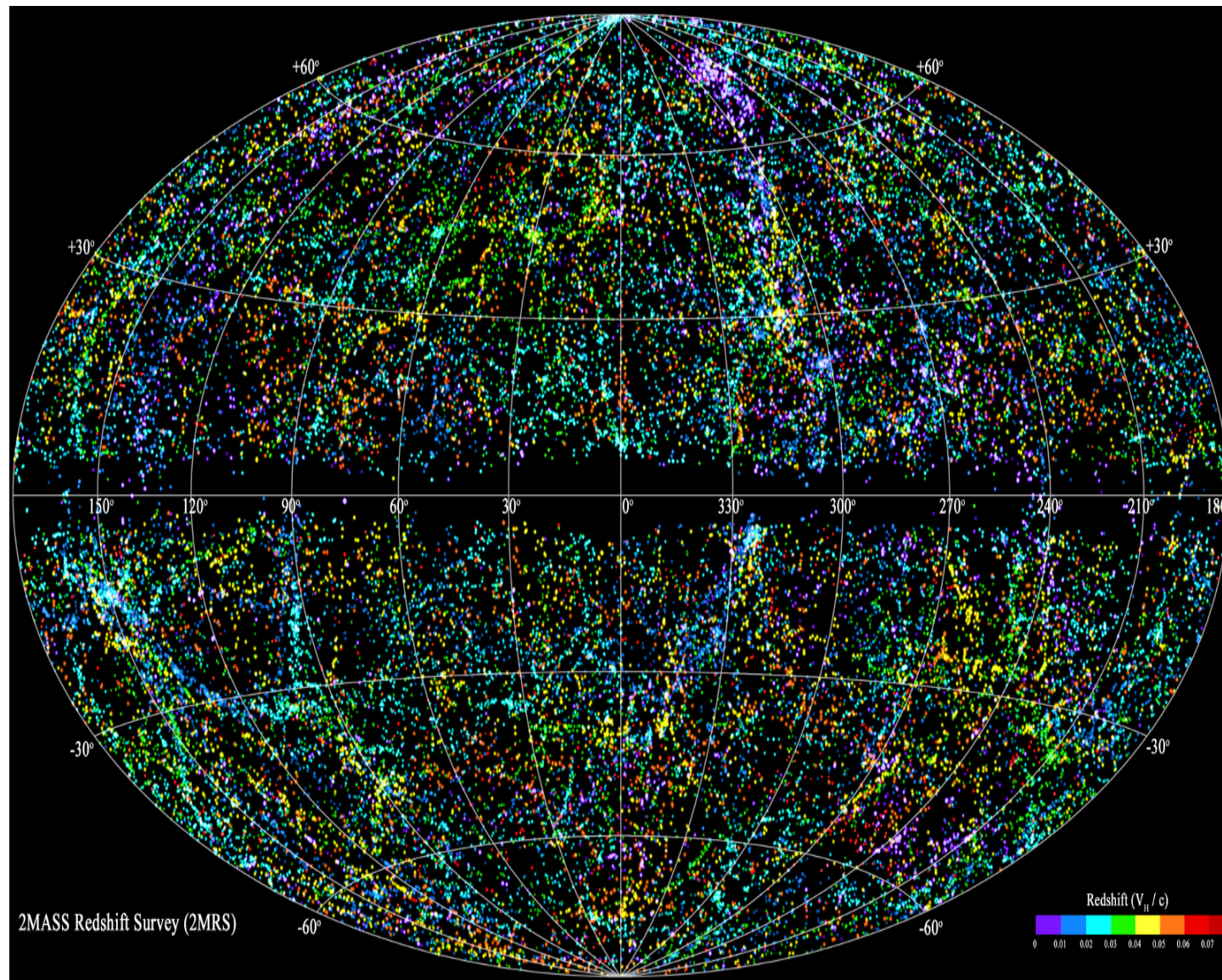


Delaware, Ohio, March 9, 2024

SUPPORT:  (DOE),  ,  Supercomputer Center

UNIVERSE through RADIATION: Most Complete 3D Map

Created by 2MASS (2-Micron All Sky Survey over 2 decades)



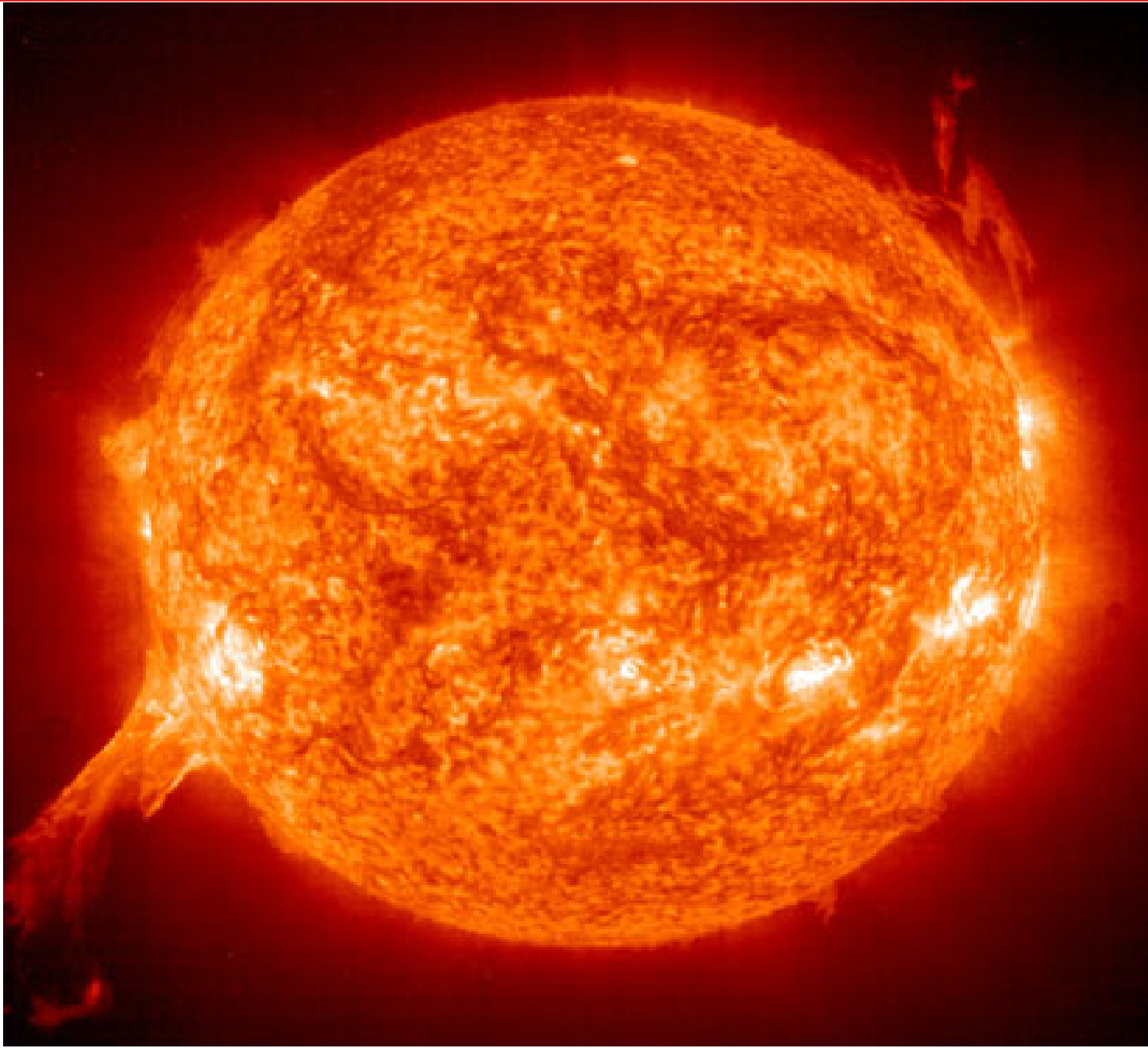
- The 2-Micron All-Sky Survey includes 43,000 galaxies within 380 million Ly
- There are at least 2 trillion galaxies in the observable universe
- Universe size: about 93 billion light years
- Signals can not travel faster than light, any object farther away from the age of the universe, 13.8 Byrs cannot reach us

Our galaxy: MILKY WAY



- Has 200-400 billion stars. Our Sun is a typical, standard star is one of them, located near the edge. How do we study them? - Analyzing the light coming from them.
- Milky way is spherical. Crossing over will take (diameter) over 100,000 LY. **The Sun is near the edge of it**

MOTIVATION: STUDY OF OUR STAR, THE SUN



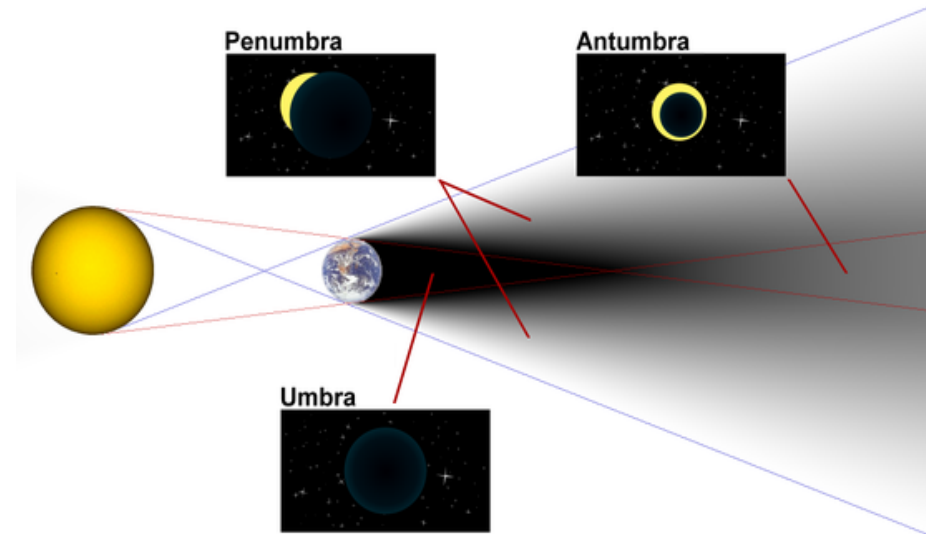
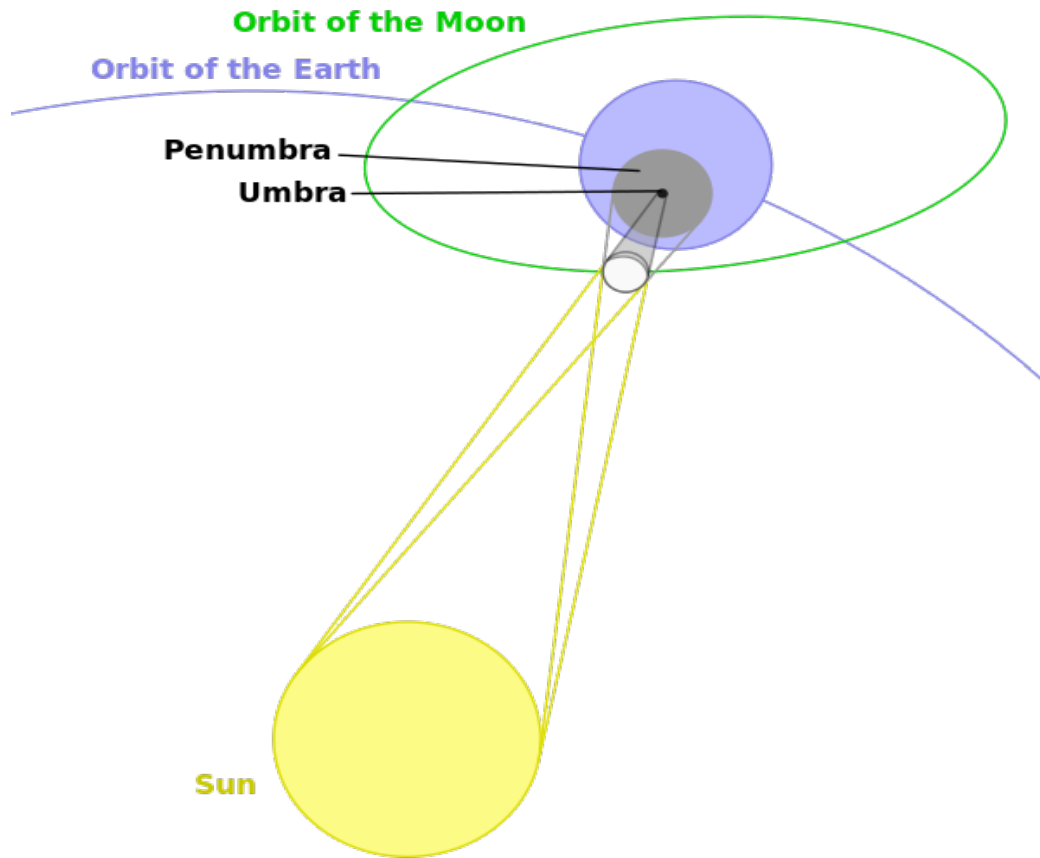
- Source of our energy,
- Standard to study other stars
- Crucial to have accurate information
- Has number of dedicated observatories

The SUN, our STAR (diameter: 110 x Diameter-earth)



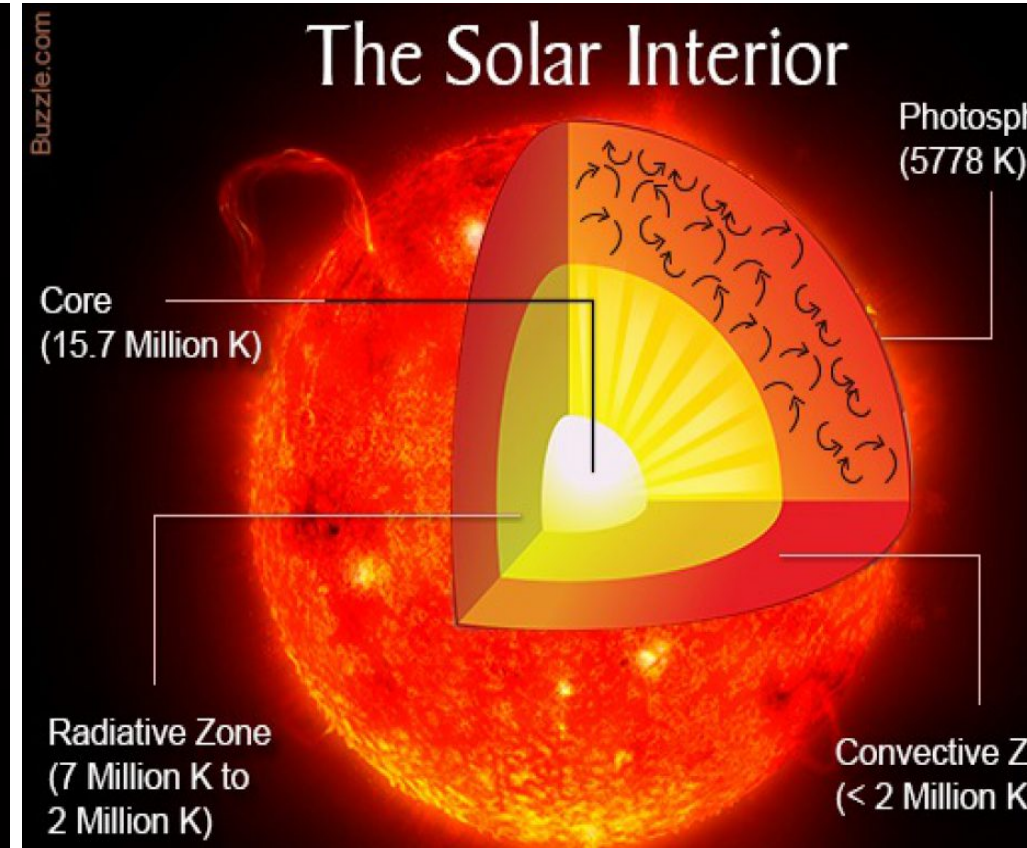
- The Sun has 8 planets (M-V-E-M terrestrial, J-S-U-N gaseous)
- It is an extremely dense and hot ball of plasma, gives out huge amount of radiation, Only small fraction of sun's radiation reaches the earth. The Sun is the source of energy for us

SOLAR ECLIPSE (April 8, 2024)



- Alignment of the Sun, Moon, and Earth during a solar eclipse.
- **Umbra:** The dark gray region between the Moon and Earth where the Sun is completely obscured by the Moon. The small area where the umbra touches Earth's surface is where a total eclipse can be seen.
- **Penumbra:** The larger light gray area is the penumbra, in which a partial eclipse can be seen.
- **Antumbra:** An observer in the antumbra, the area of shadow beyond the umbra, will see an annular eclipse.

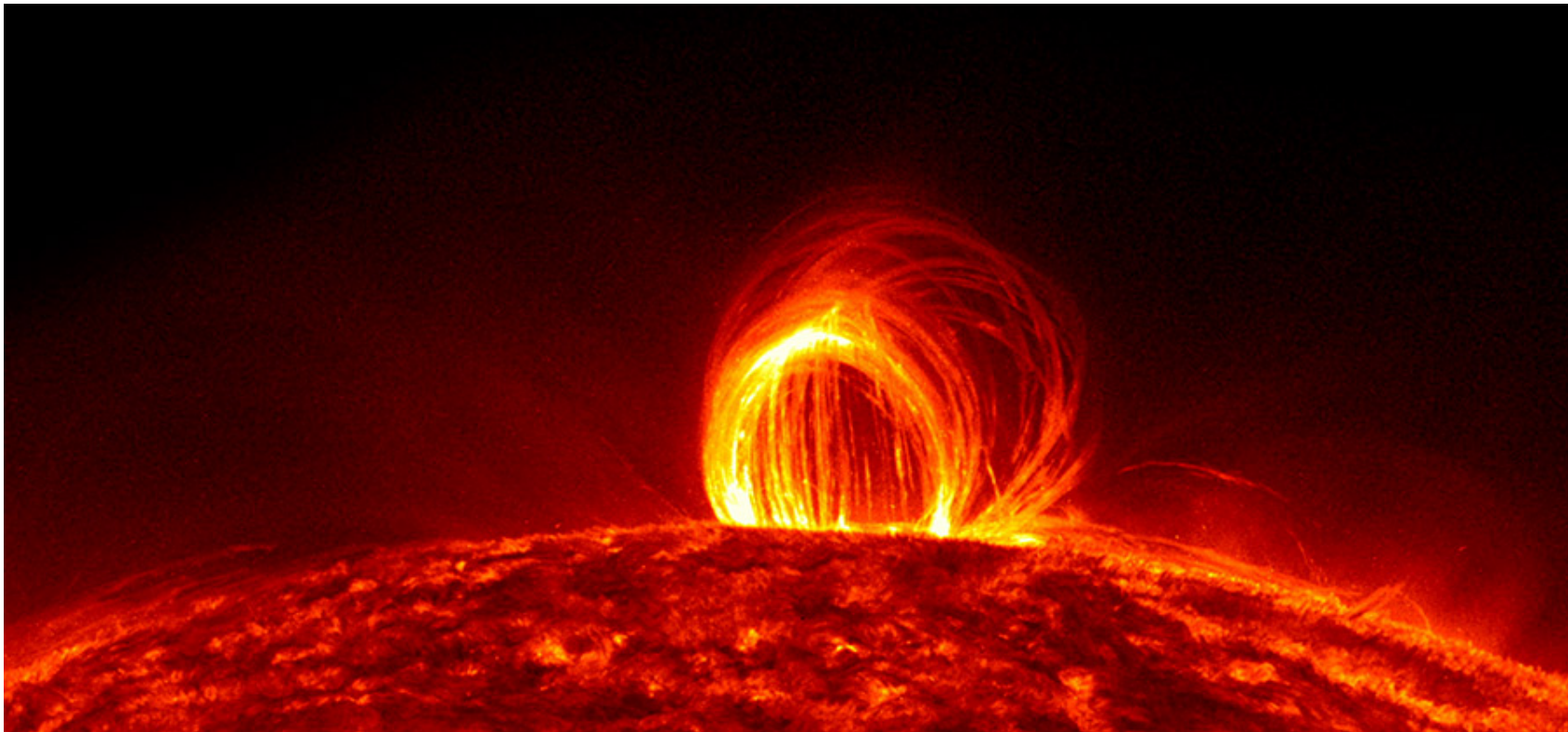
ECLIPSE MAKES SOLAR OUTER LAYERS VISIBLE



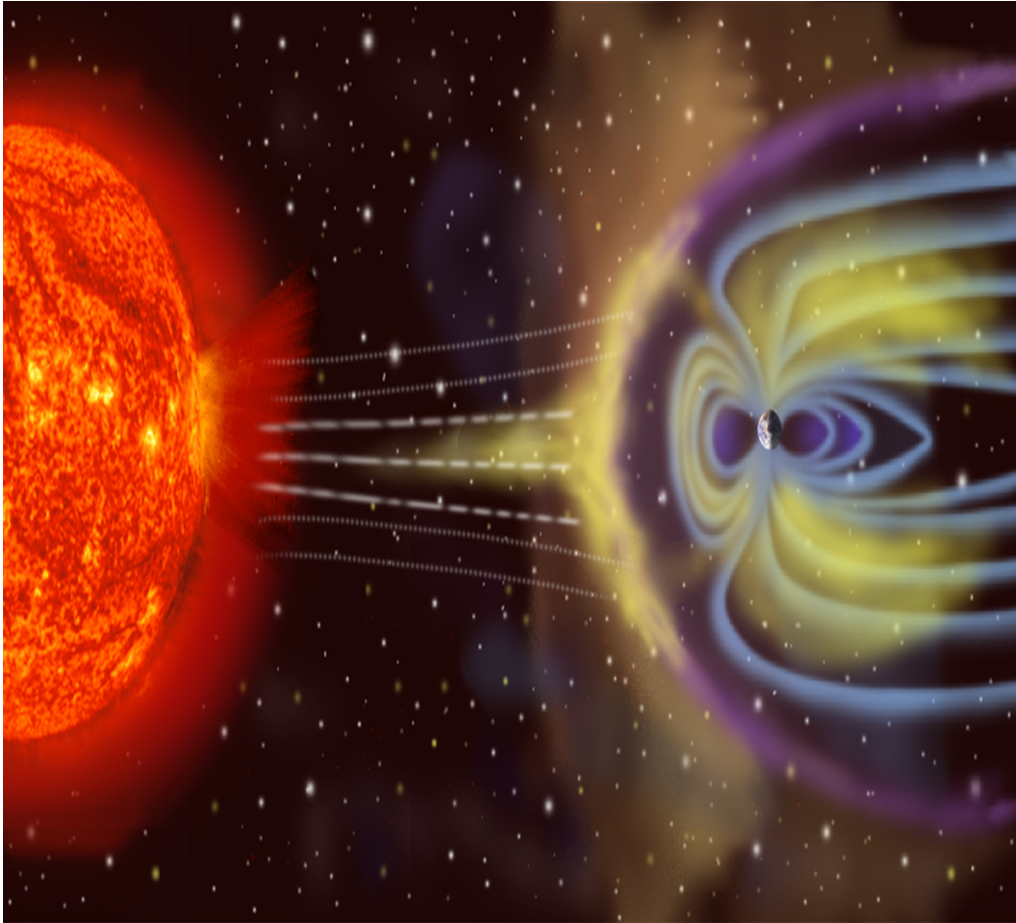
- Full solar eclipse, a cosmological event of interest, occurs at occasional alignments of the Sun, Earth and Moon.
- Total eclipse gives the scope to see the surrounding of the Sun blocked by Sunlight
- The Sun is surrounded by three outer thin plasma regions: Photosphere (surface to 250 mi, 6500 - 400 K), Chromosphere (250-1300 mi, 4000 - 8000 K), Transition Region (60 mi, 8000 - 500,000 K) and the Corona (1300 - , 500,000 - a few Million K)
- Sun's inner layers: Core (15 MK), Radiative Zone and Convection Zone (2 MK) BCZ

CORONAL TEMPERATURE & Fe XIII FORBIDDEN TRANSITIONS

- High temperature in corona was a mysterious finding of Edlen. The forbidden transitions within the ground 3P state of highly charged Fe XIII was strong to be observed in solar flare by Edlen who then calculated the flare temperature over million degrees compared to the assumed value of a few thousand degrees. **Sudden rise in temperature in Corona, which is much further away from the surface of the Sun, has remained a puzzle**
- Physics Today (jul 2023): A new instrument reveals not only the size of plasma rain in the Sun's corona but also the atmospheric response, which provides more clues about the coronal-heating phenomenon.

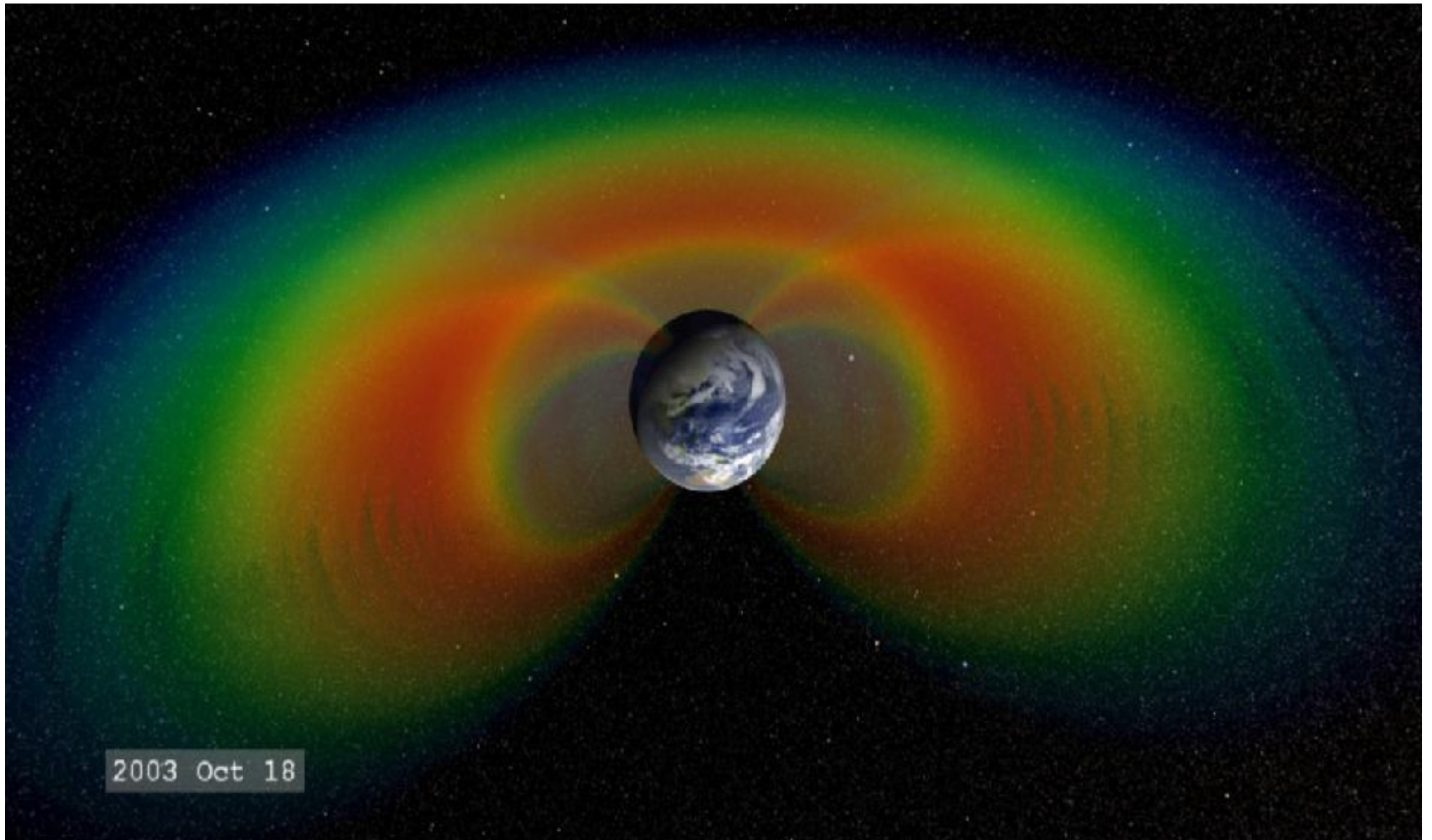


THE SOLAR STORM



- The active sun with solar spots blasts huge amount of radiation Gamma ray, x-ray, UV, and charged particles in space which are harmful to us
- Fortunately, we have protections i) the atmosphere deflects and burns the particles, ii) ozone blocks high energy radiation, and iii) our earth's magnetic field captures the charged particles seen as aurora or the northern lights. solar storm, i.e., violent eruptions and ejection of huge amount of radiation,

VAN ALLEN BELT AURORA: HALLOWEEN SOLAR STORM



Earth's magnetic dipole field lines rotating with the Earth have accumulation of charged particles on four different days in 2003; Oct 17, Oct 30, Nov 5, Dec 11

NORTHERN LIGHTS (AURORA BOREALIS): Birkeland

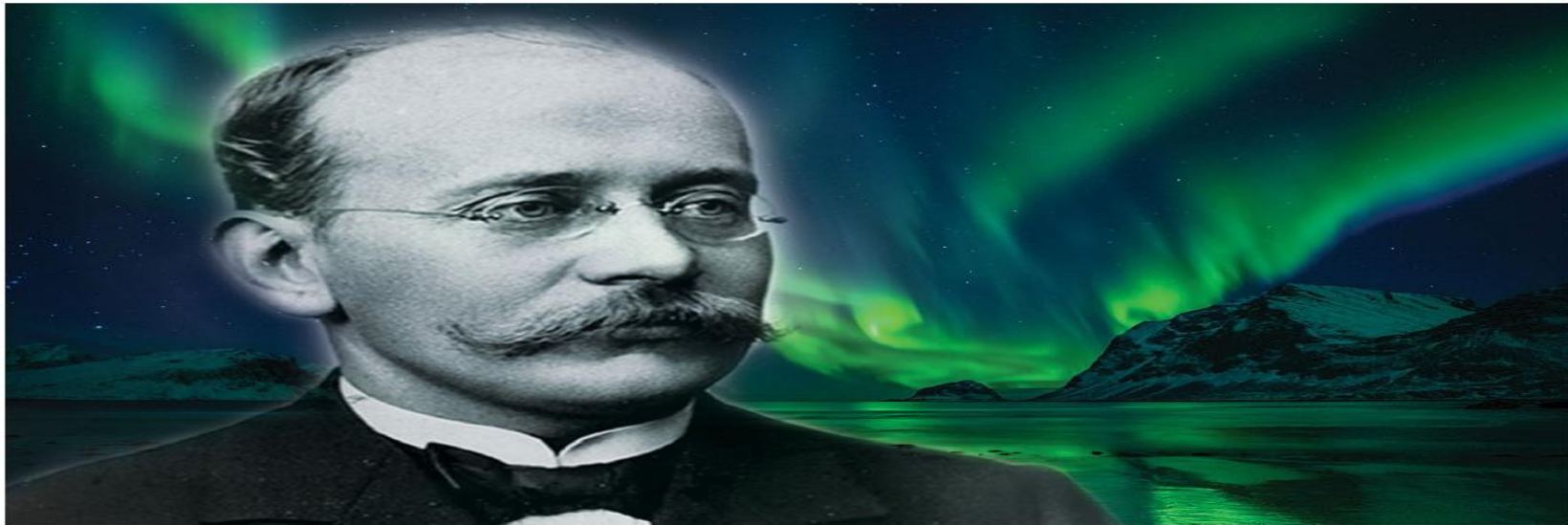
Birkeland dedicated and risked his life and fund to study Northern lights, that was associated with superstitious, and found the relation with solar spots

THIS MONTH IN

Physics History

June 15, 1917: Death of Kristian Birkeland, King of the Northern Lights

BY ABIGAIL EISENSTADT



Kristian Birkeland. His face now adorns the Norwegian 200-kroner banknote, but he died decades before he was recognized for his work.

Physicist Kristian Birkeland was the first man to describe how charged particles from the Sun interact with Earth's magnetism to create dazzling phenomena like the aurora borealis. But he did so at a cost, sacrificing money, community, and health in fervent pursuit of his goal: understanding the northern lights.

Born in 1867 in present-day Oslo, Norway, Birkeland's passion for electromagnetism grew serious in his teens under the mentorship of a math teacher. At age 18, he published his first research paper. A few years later, he became the youngest faculty member in sciences and mathematics at what was then Norway's only university—today's University of Oslo.

But his academic career was just the start of his story. Birkeland had always been interested

After a flurry of analysis, Birkeland established a connection between polar electromagnetic currents and the aurora borealis. He published his theory, seeking international scientific recognition—especially from England's most prestigious scientific institution, the Royal Society, whose validation could rocket his career to new heights. But the Society vehemently opposed his theory. One of their past presidents, the revered thermodynamics expert Lord Kelvin, had declared in 1892 that there was no relationship between sunspots and geomagnetism. The Royal Society took Lord Kelvin's word as doctrine. Birkeland would fight for the rest of his career to gain British recognition for his auroral theories.

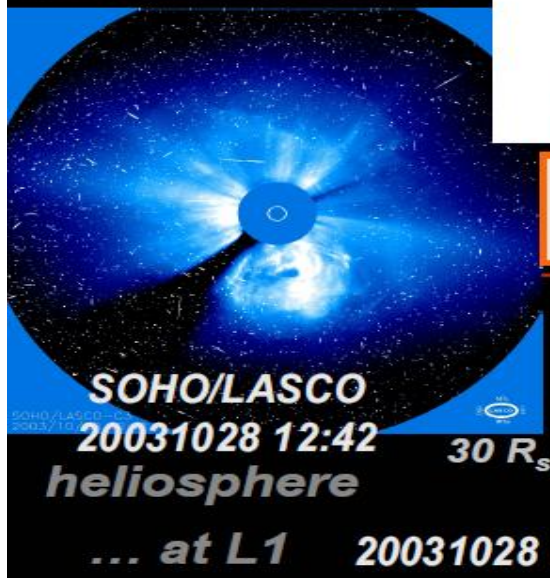
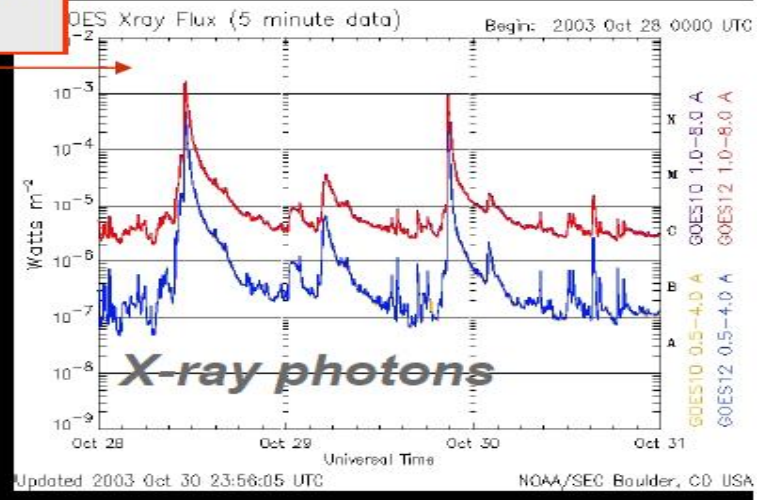
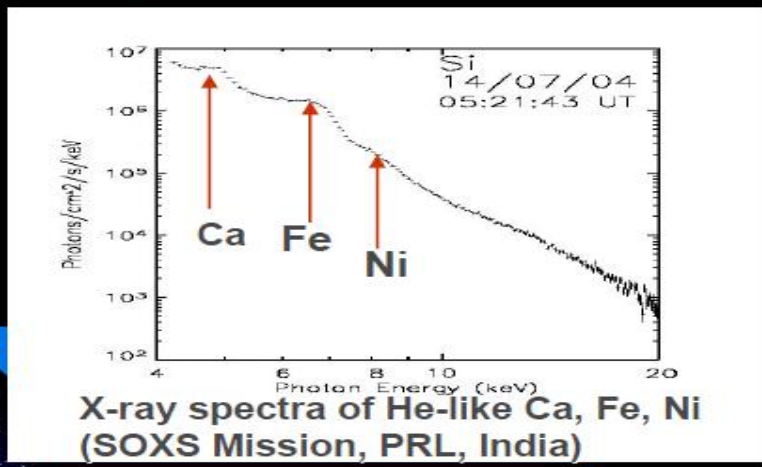
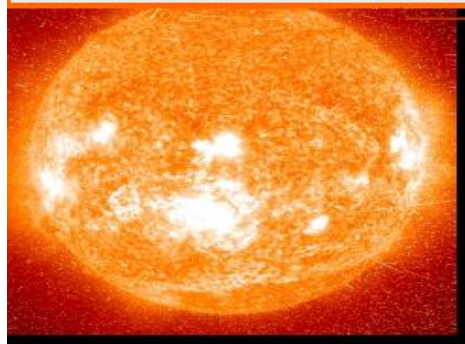
After his first expedition, Birkeland began

"Halloween" Solar Storm (Oct 28, 2003) (Chandra, SOHO, SOXS)

X-Ray Modeling of Solar Corona and Flares: "Halloween" Solar Storm (Oct 28, 2003)

active region with big sunspot erupts

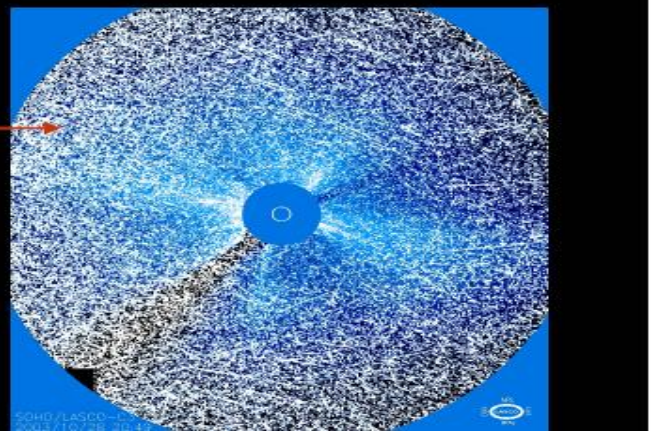
8 minutes later ... X-class Flare observed on the Earth



coronal mass ejection leaves the Sun

8 hours later... particles saturate SOHO/LASCO detector and reach the Earth ("proton shower")

NOAA National Weather Service



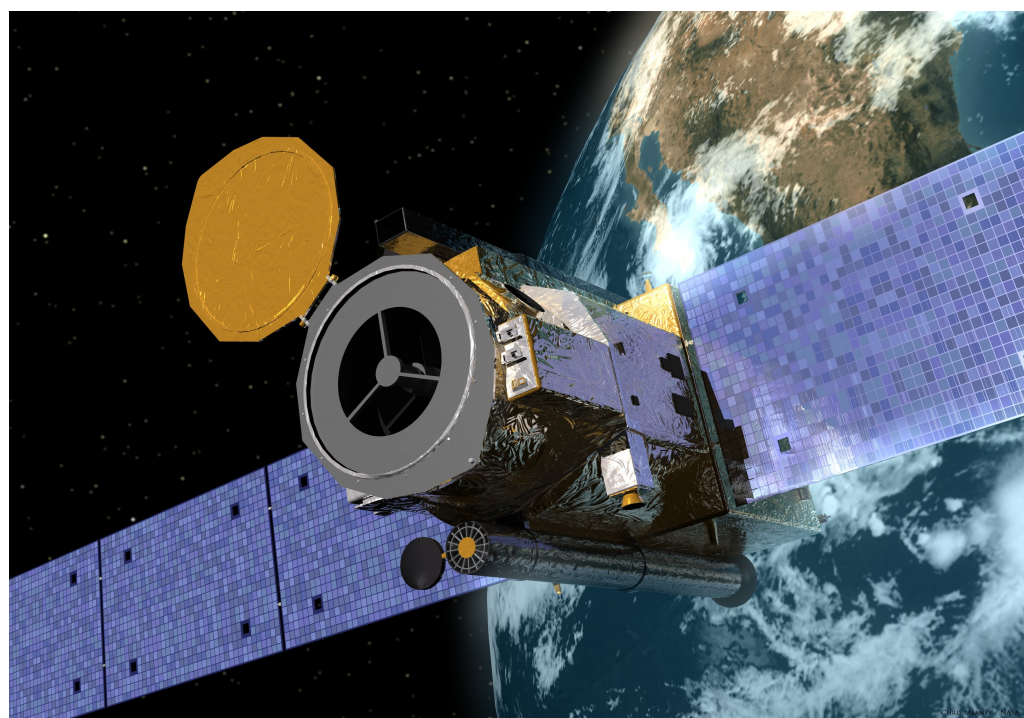
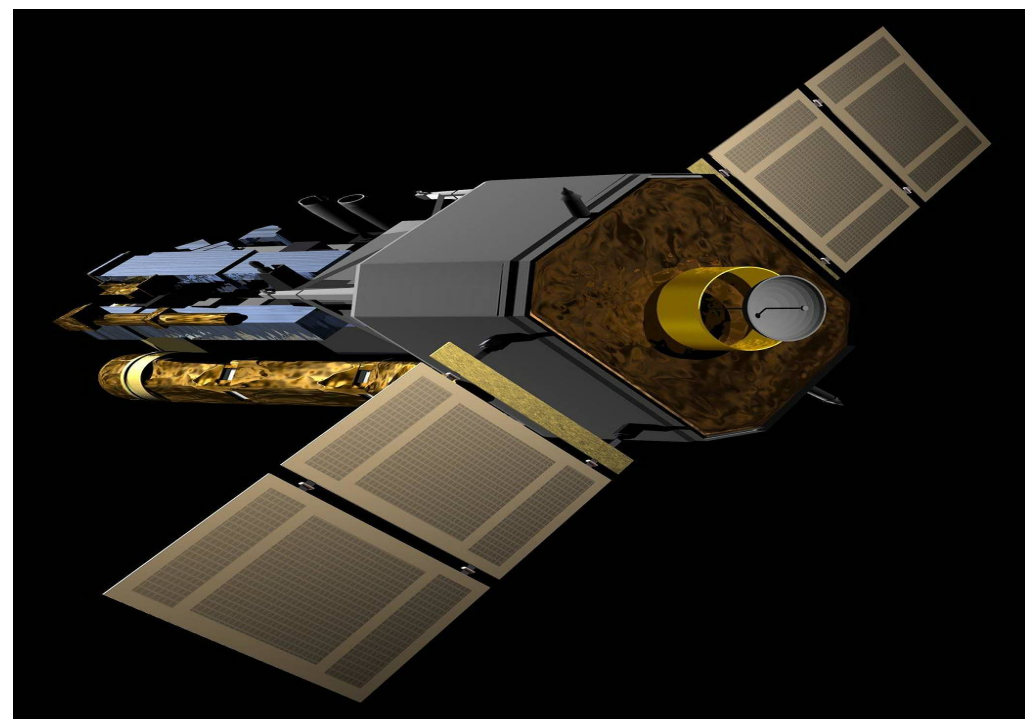
- Top Left: Sun spots are detected, - Lower Left: SOHO mass detector, LASCO, detects large coronal mass ejection. - Lower Right: 8 hours later it is swarmed by the particles, proton shower - Spectra of Solar Flares: X-ray emission peaks from He-like Ca, Fe, Ni

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



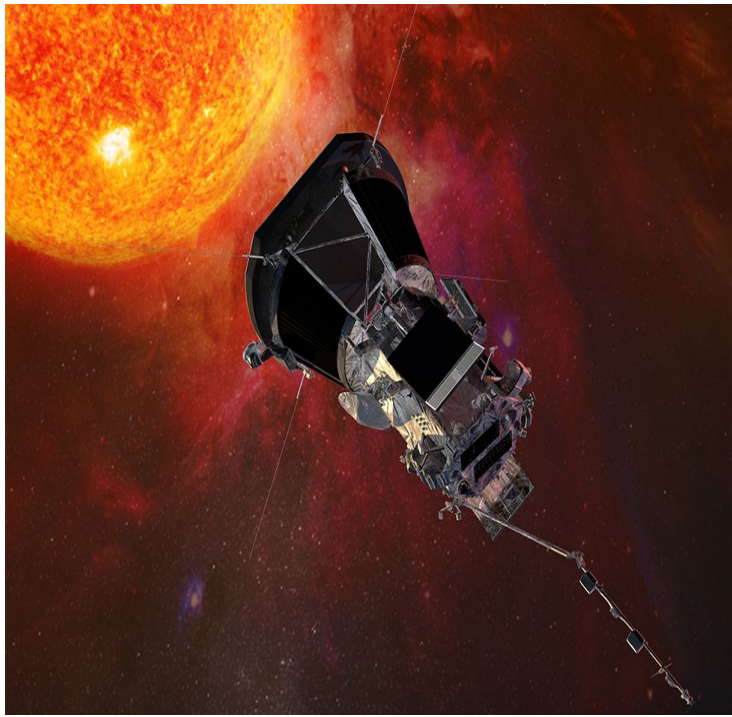
- Ulugh Beg built the madrasa in 1420 in Samarkand and extended it to an observatory
- Beg himself cataloged over 1000 stars.

DEDICATED OBSERVATORIES FOR THE SUN
LT: SDO, RT: SODO, LB: HINODE, RB: STEREO



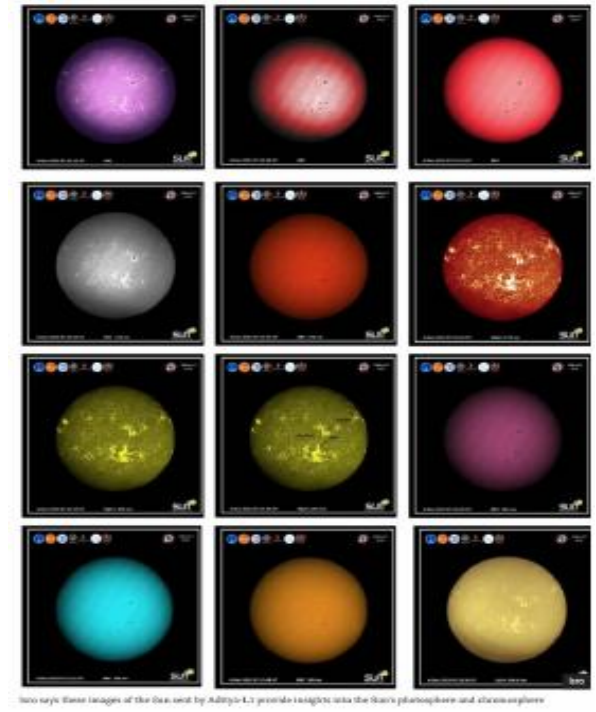
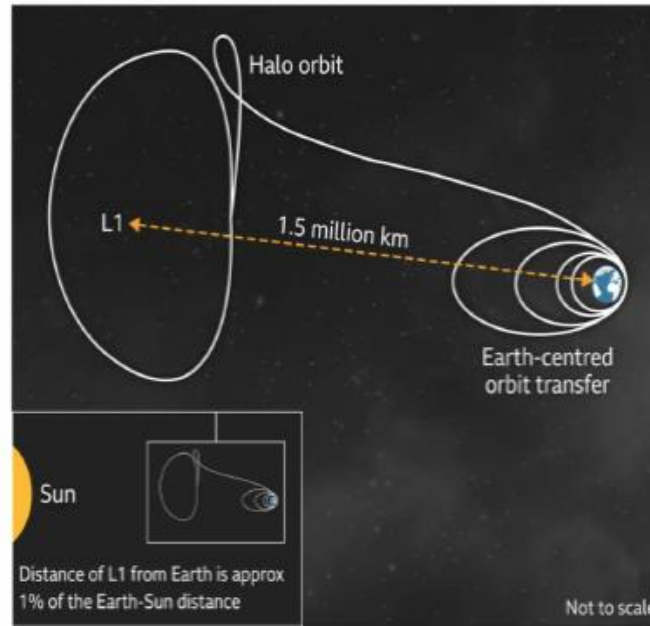
DEDICATED OBSERVATORIES FOR THE SUN

PARKER SOLAR PROBE & ADITYA L1



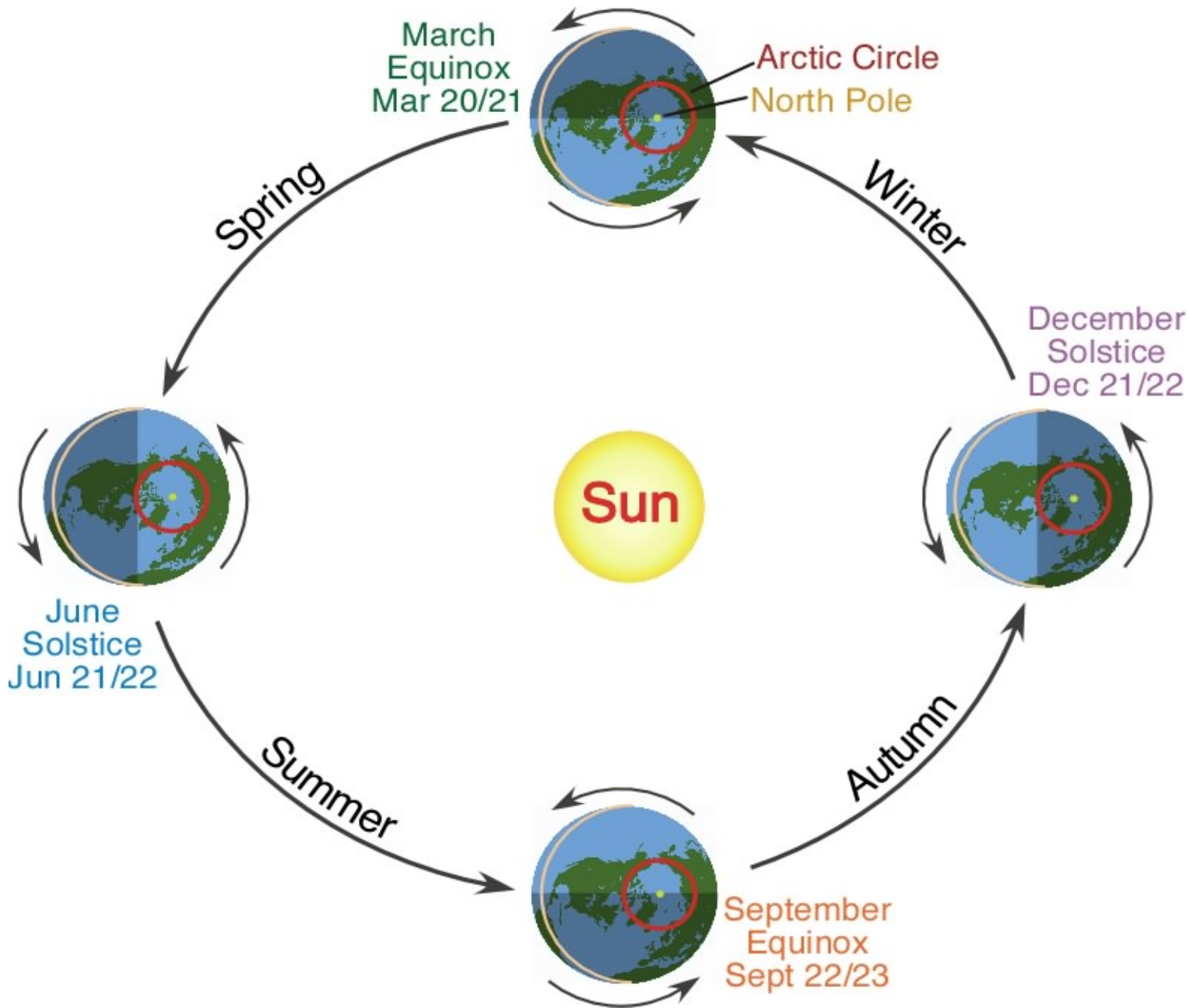
Aditya-L1 mission trajectory

The first Indian solar mission to study the Sun



- **L:** Parker Solar Probe makes historic pass through Sun's atmosphere withstanding intense heat.
 - A satellite/ spacecraft goes around the earth several times, each time making a longer elliptical loop by the gravitational push, until going straight toward the object - path of Indian spacecraft Aditya L1 (Lagrange point 1) to study the Sun.
 - It sent various images of the Sun in corona and chromosphere.

The SUN, Our STAR



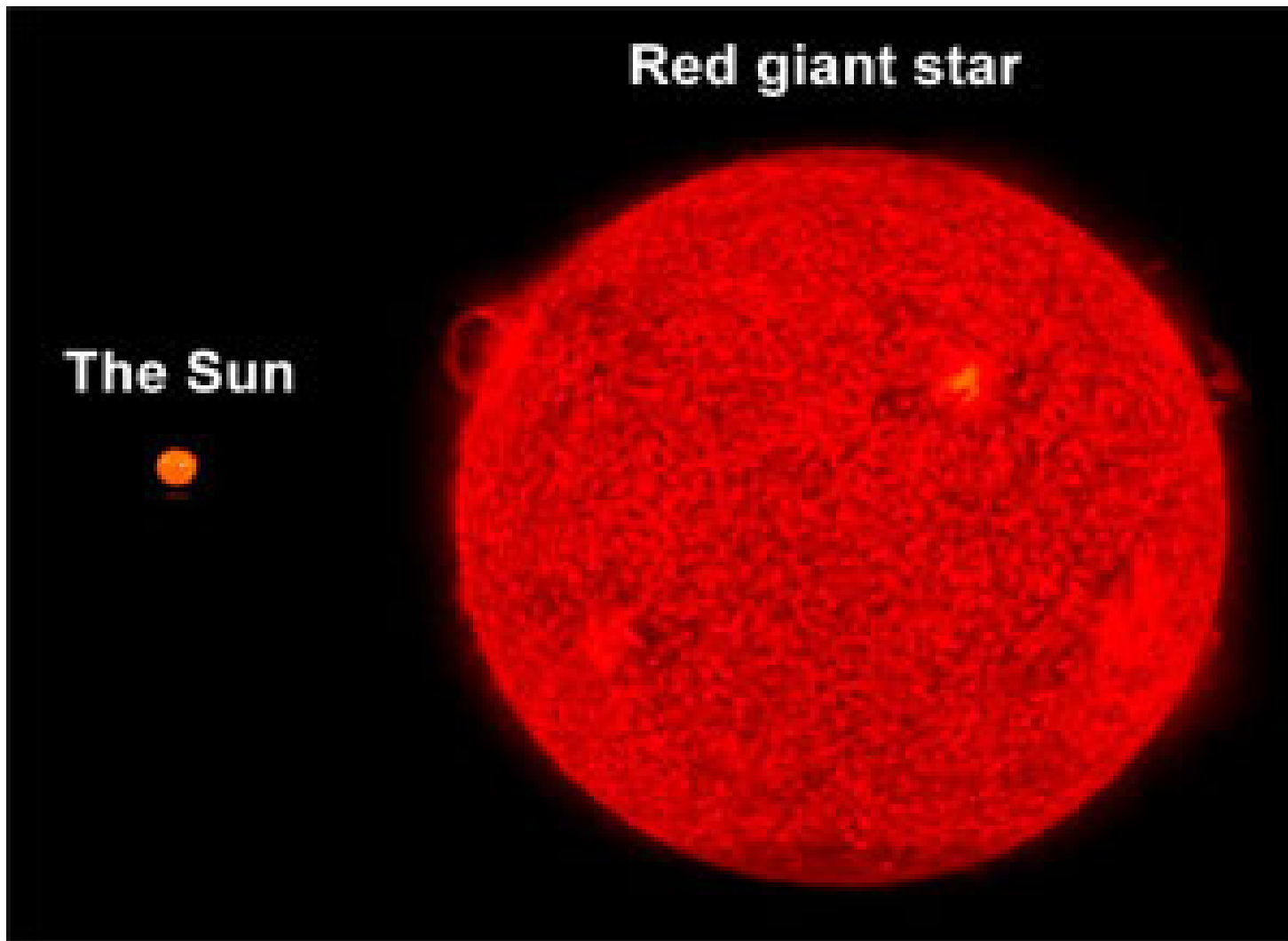
- Because of earth's tilt, we have very rich seasons

The EARTH: Our beautiful home



- Sky is blue at high Sun because atmospheric molecules scatter the blue photons to the earth. Blue sky is reflected on the water.
- Sunrise or sunset brings red photons as they travel through layers of atmosphere and bend to reach earth's surface. This also causes Sun to be seen when it may be below the horizon

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



- SUN: 4.5 BYr old, live for another 6-7 BYr. The current age of the universe ~ 13.8 BYr
- It will become a Red Giant, a dying expanded star with H fuel gone
- The heat, radiation, electrons will push materials out to form a red giant.
- Red giant will slowly become planetary nebulae and ultimately white dwarf. Over 90% stars will end up to white dwarf and lot of diamond in them \rightarrow earth will be engulfed, we will need another home

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



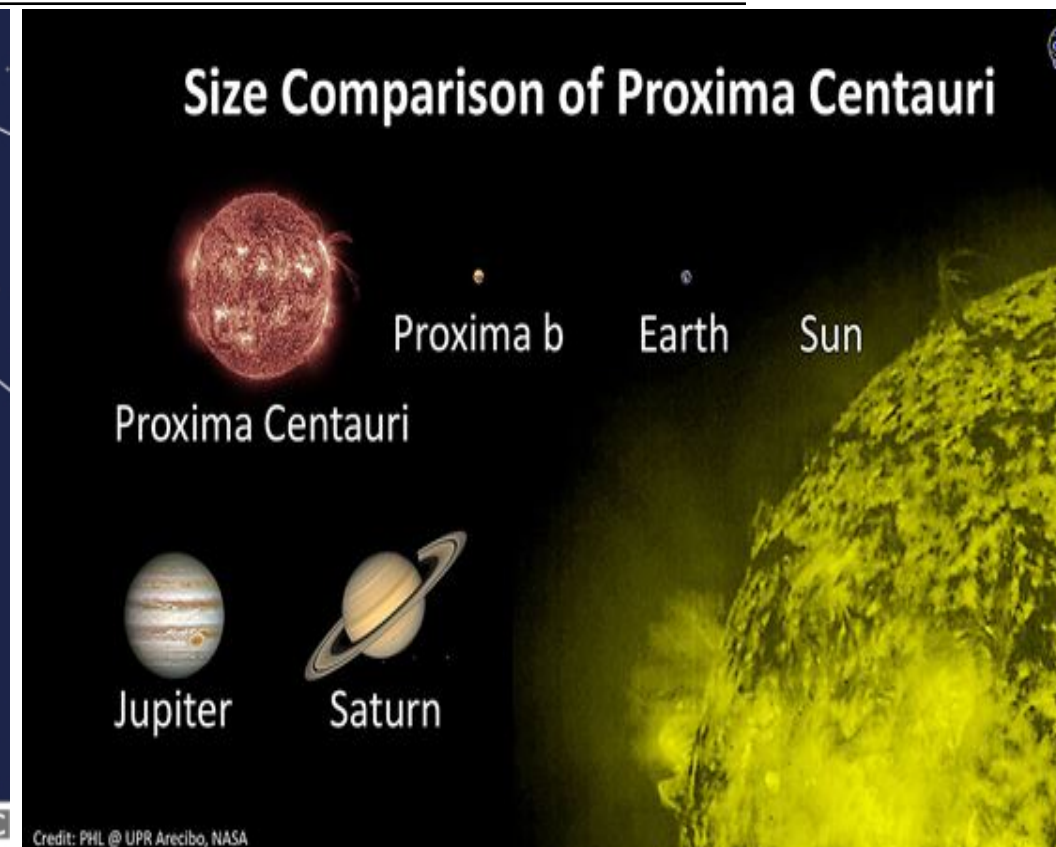
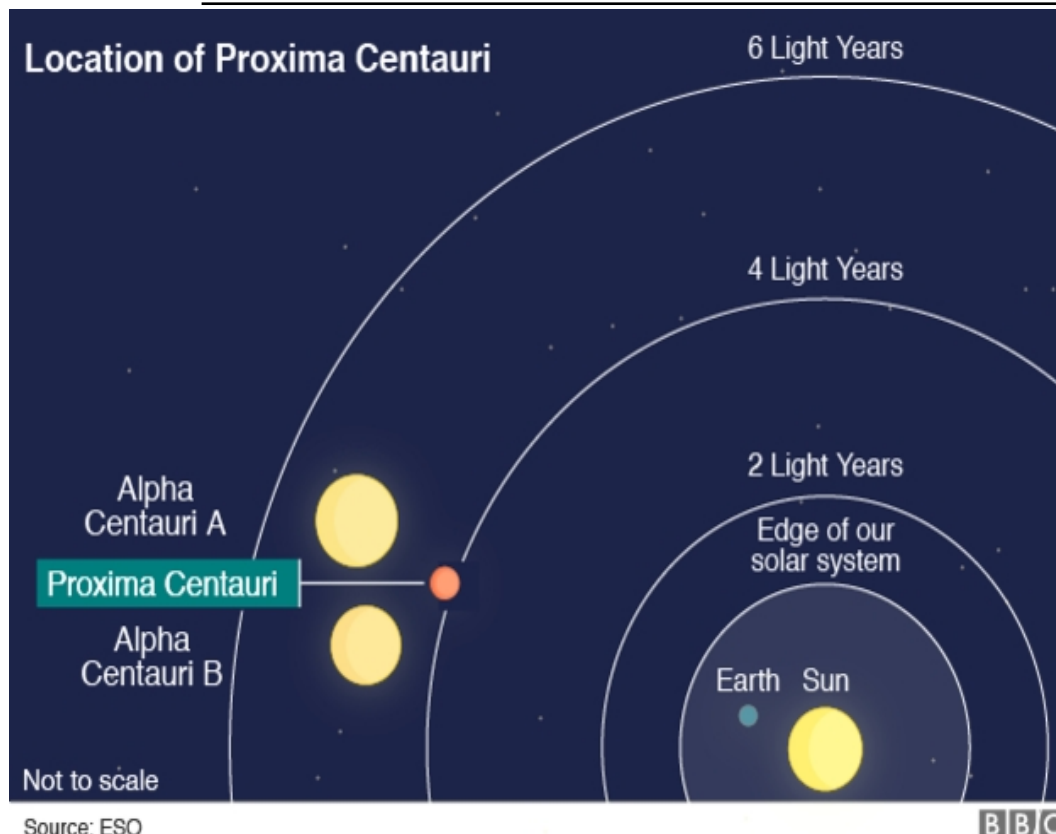
- Condensed central star: very high $T \sim 100,000$ K ($\gg T \leq 40,000$ K - typical star). Envelope: thin gas radiatively ejected & illuminated by central star radiation: red (N), blue (O). Lines of low ionization states - low ρ & low T
- Ionized gaseous nebulae: associated with birth & endpoint of stellar evolution \rightarrow chemical enrichment is a chronometer of life of the universe itself

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



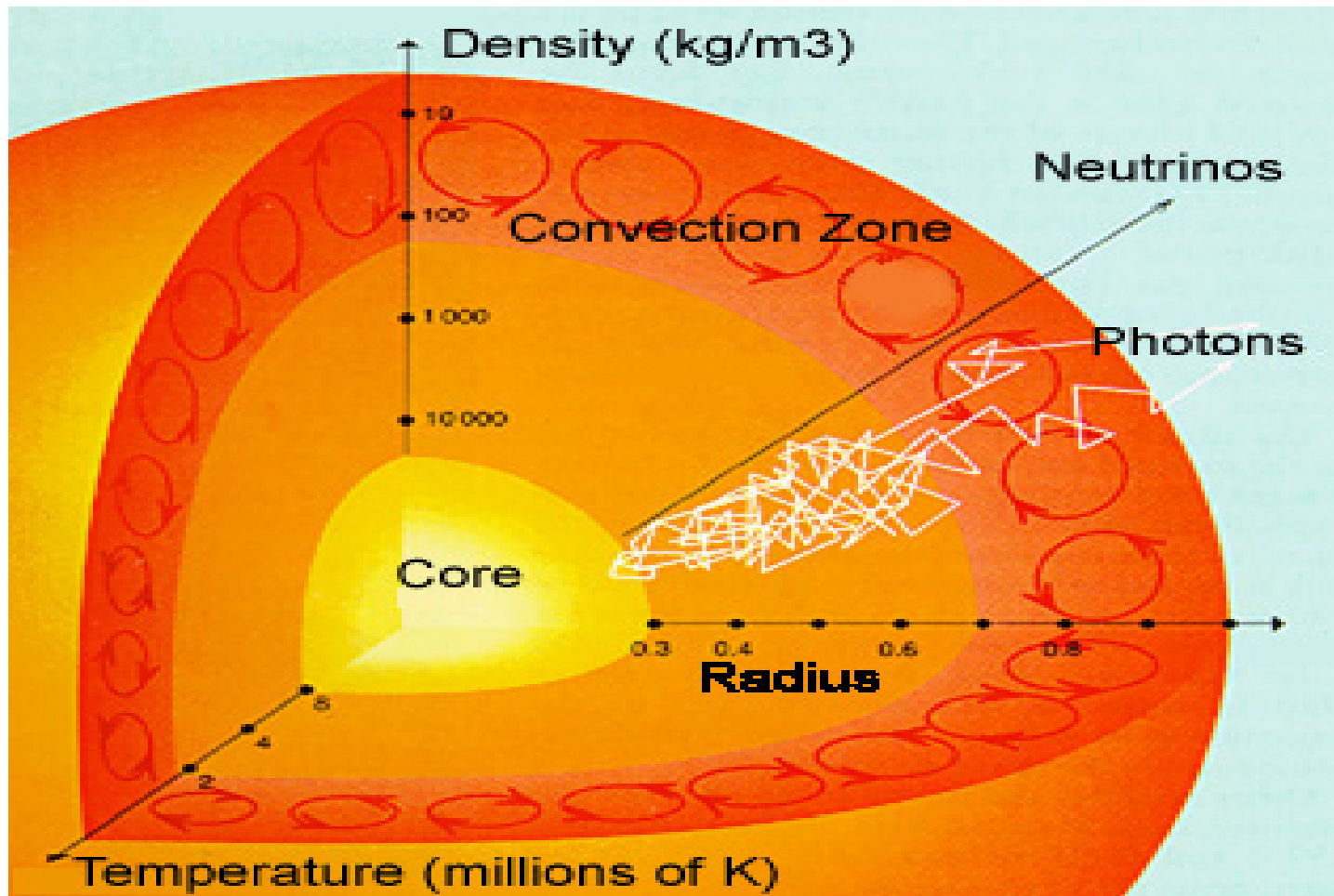
- "Astronomers discover Earth-sized diamond-encrusted white dwarf" 2014. It is so old that it has crystallized into a Earth-sized diamond
- A white dwarf is very dense: its mass is comparable to that of the Sun, while its volume is comparable to that of Earth.
- About 98% stars will end up as white dwarfs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

OUR INTEREST: HABITABLE EXOPLANETS



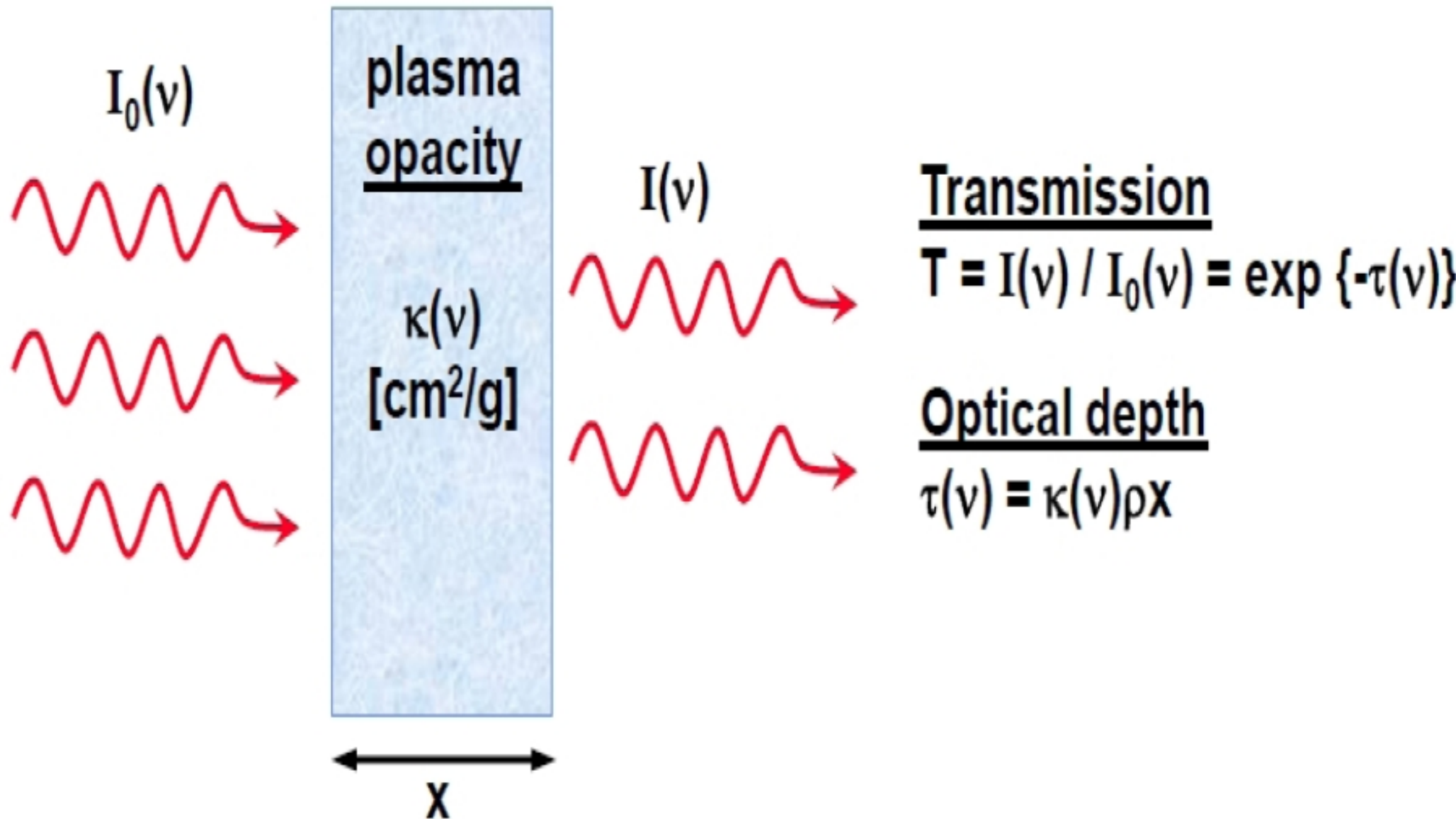
- Habitable planets where liquid water may exist
 - Proxima b, exoplanet to our closest star Alpha Centauri (4 ly away: Earth-like in size, hard & rocky surface, possibility of liquid water & temperature similar to us
- But a spacecraft using current technology will take 18 thousands of years to reach it → New idea for 20 years
- It was calculated that Proxima Centauri was moving around 3 to 5 mph toward • 1 in 5 sun-like stars have an earth-sized planet in the habitable zone → potentially 11B planets exist in Milky Way

SOLAR PLASMA OPACITY & ELEMENTAL ABUNDANCES



- **3 regions of the Sun:** 1) Core: 15 mK, 150 g/cm³ - nuclear fusion center - H fuses to He & produces gamma rays, 2) Radiative zone - highly dense and hot plasma - energy transfer through diffusion, 3) Convection zone - boiling plasma. **The change in phase between radiative and convection zones is distinct. The boundary distance R_{RC} is known.**
- Absorption of radiation by the constituent elements cause solar plasma opacity and slow down the escape of the radiation. R_{RC} can be predicted from opacity

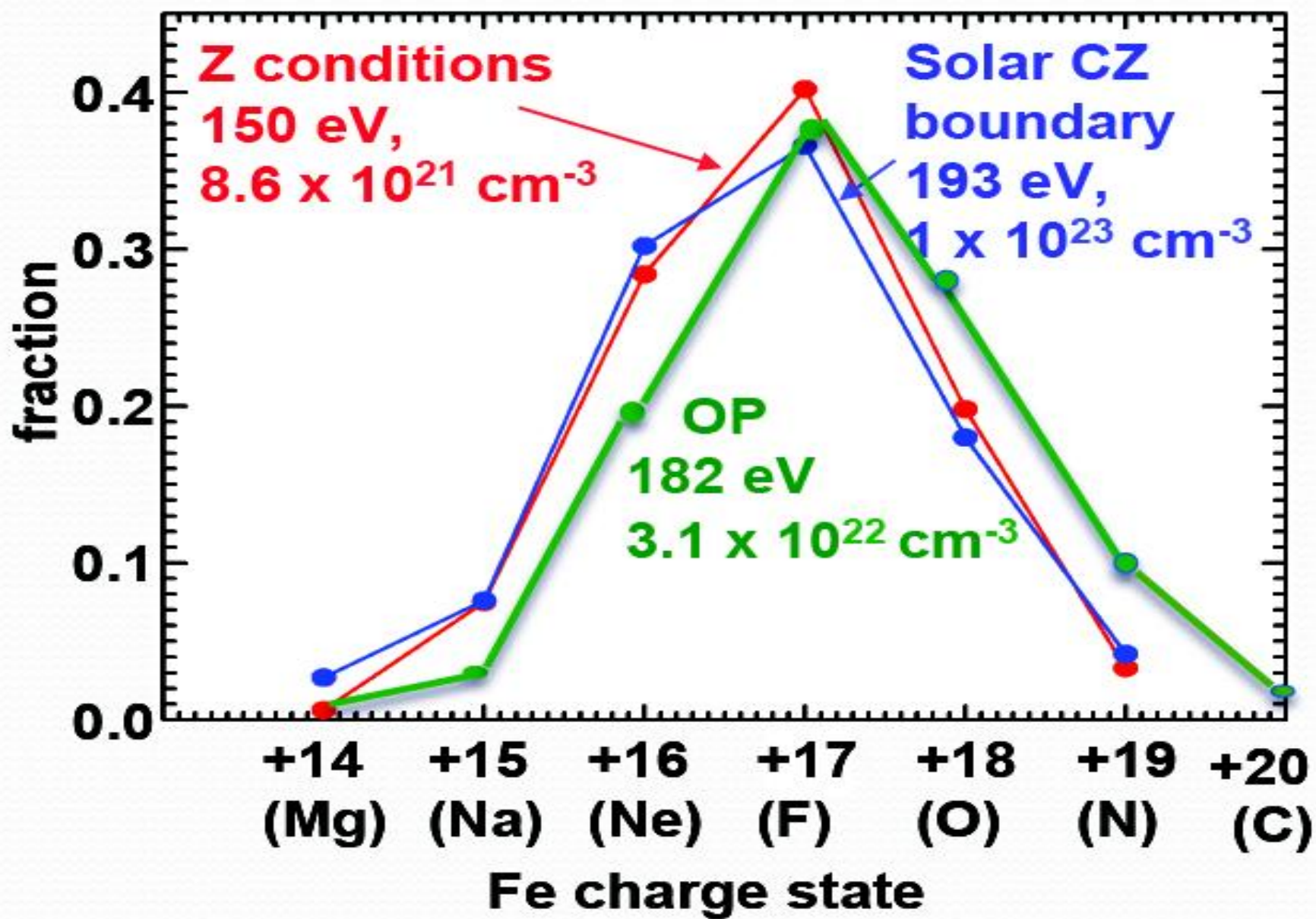
PLASMA OPACITY



- Opacity $\kappa(\nu)$ is a fundamental quantity for radiation absorption during transmission in plasma. Microscopically monochromatic opacity $\kappa(\nu)$ depends on two radiative processes:

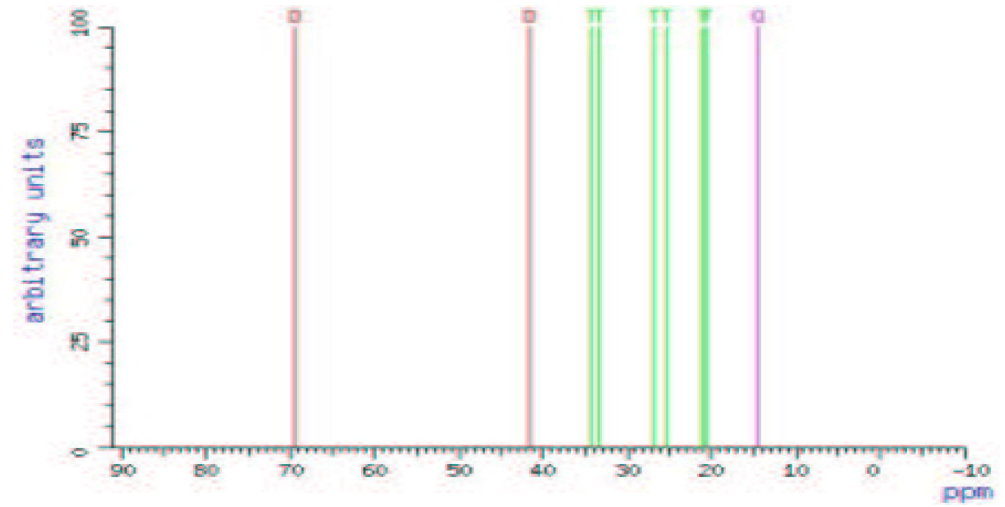
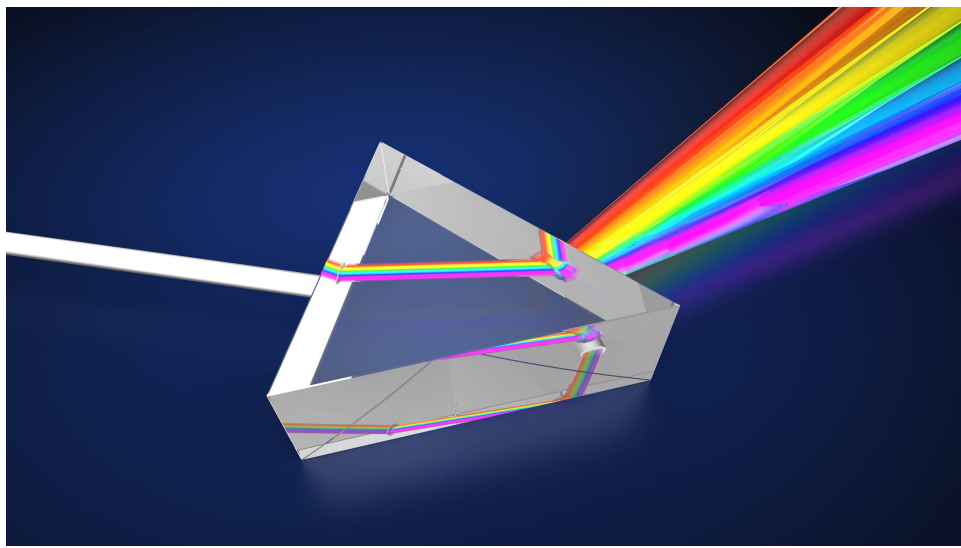
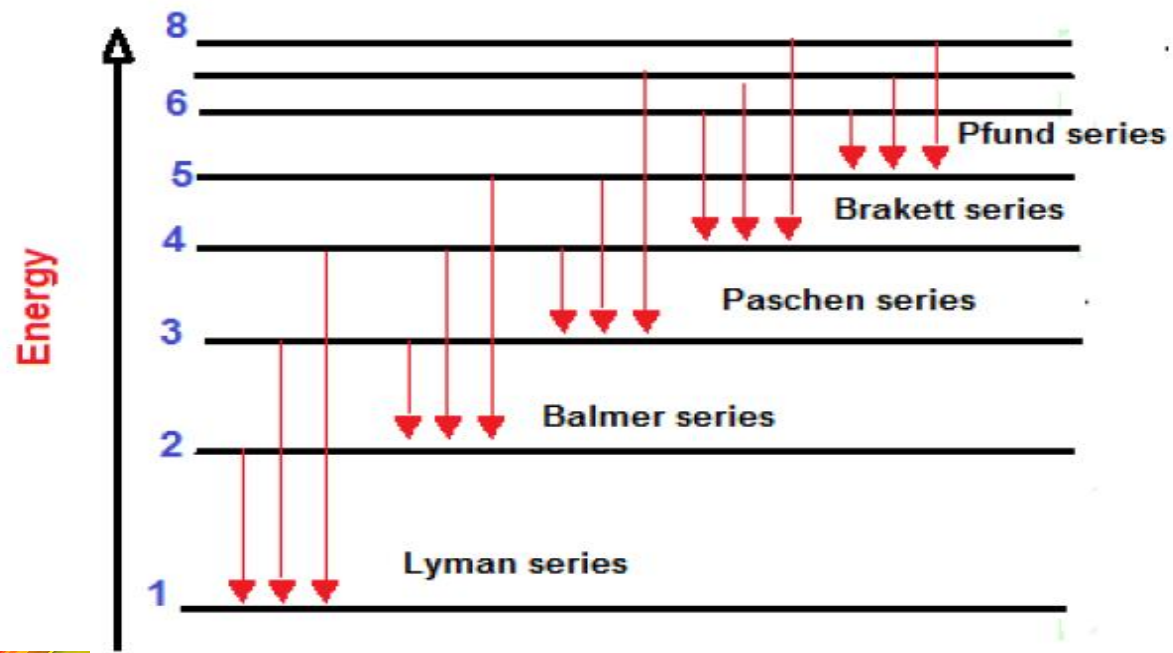
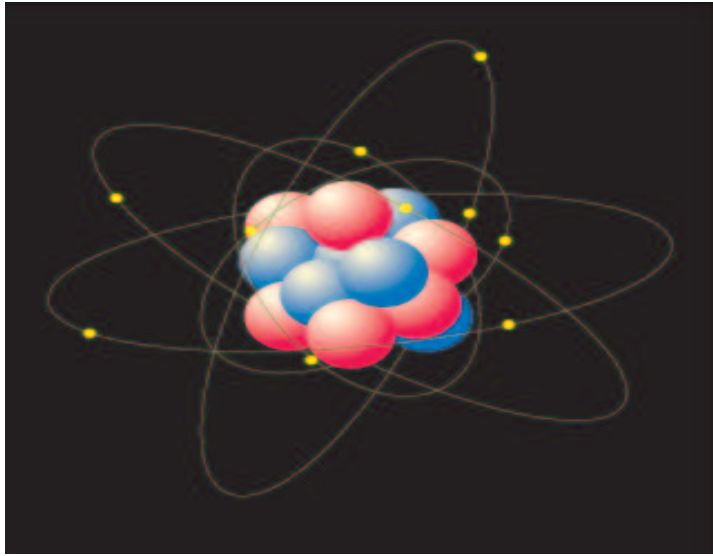
• Fe - VALVE FOR RADIATION TRANSFER

Ionization fractions at Z and solar BCZ conditions



Model produces the correct charge states enabling opacity models tests
i) Charge state distribution, 2) Energy level description, but high density studies require further progress (Adapted from J. Bailey)

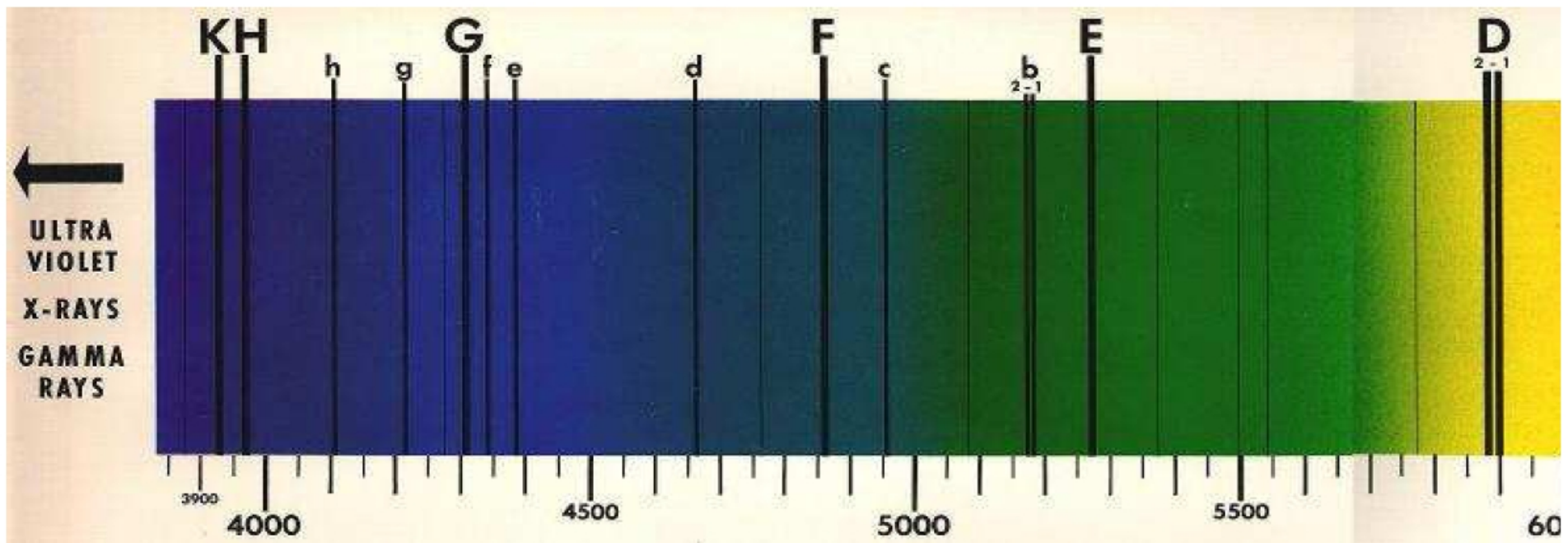
RADIATION FROM ATOMS & SPECTRUM



- 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
- SPECTRUM: Splitting the radiation in to its colors: Rainbow, C lines

SOLAR SPECTRA: ABSORPTION & EMISSION LINES

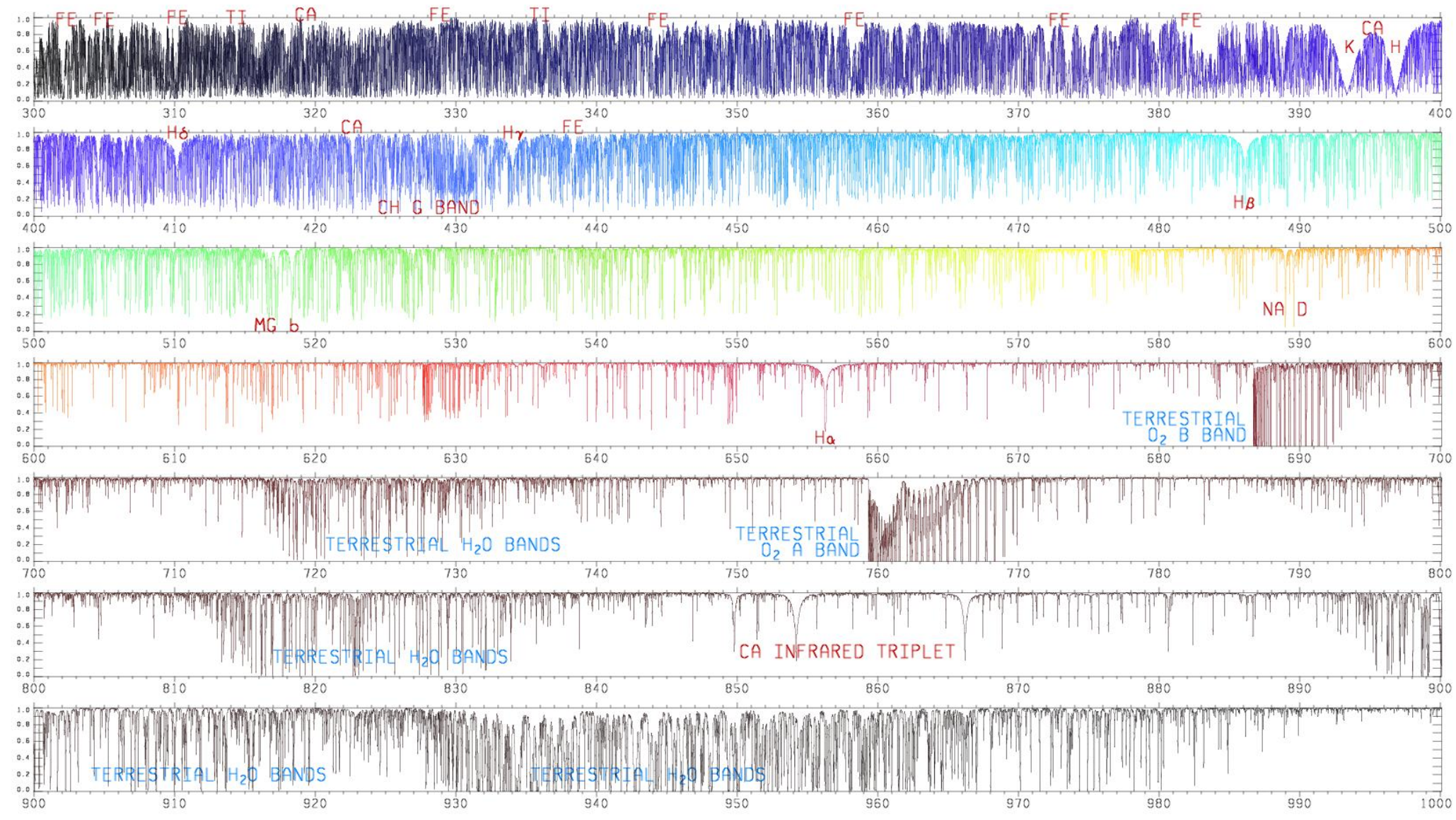
- Absorption line - forms as an electron absorbs a photon to jump to a higher energy level
- Emission line - forms as a photon is emitted due to the electron dropping to a lower energy level
- For the same transition levels, lines form at the same energy position



- Fraunhofer (1815) observed lines in the solar spectrum & used alphabet for designation
- Later spectroscopy with quantum mechanics identified them: A (7594 Å, O), B (6867 Å, O) (air), C (6563 Å H), D1 & D2 (5896, 5890 Å Na, yellow sun), E (5270 Å, Fe I), F (4861 Å, H), G (4300 Å, CH), H & K (3968, 3934 Å, Ca II)

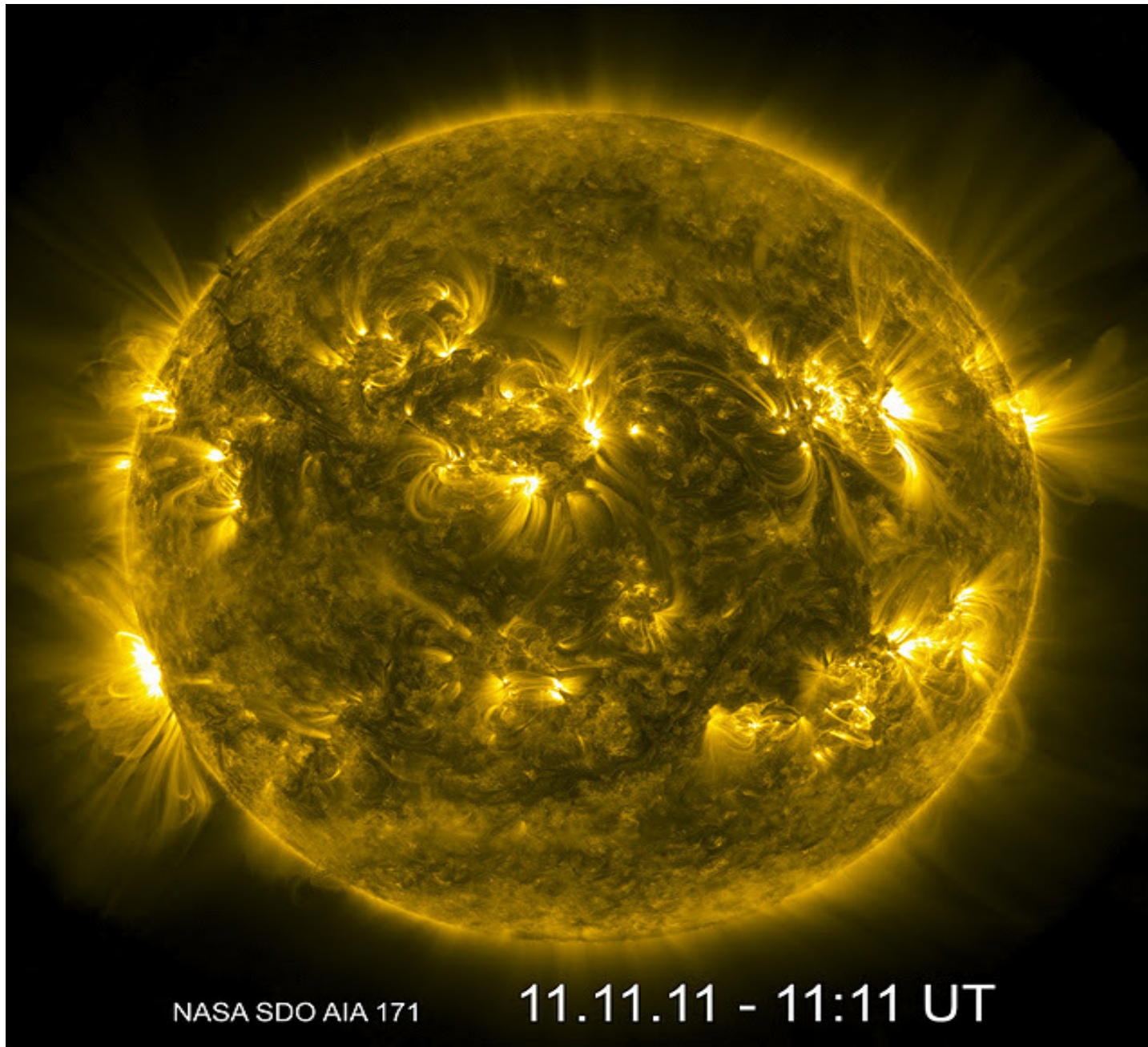
SOLAR SPECTRUM AS SEEN FROM THE EARTH

KITT PEAK SOLAR FLUX ATLAS (KURUCZ, FURENLID, BRAULT, AND TESTERMAN 1984)



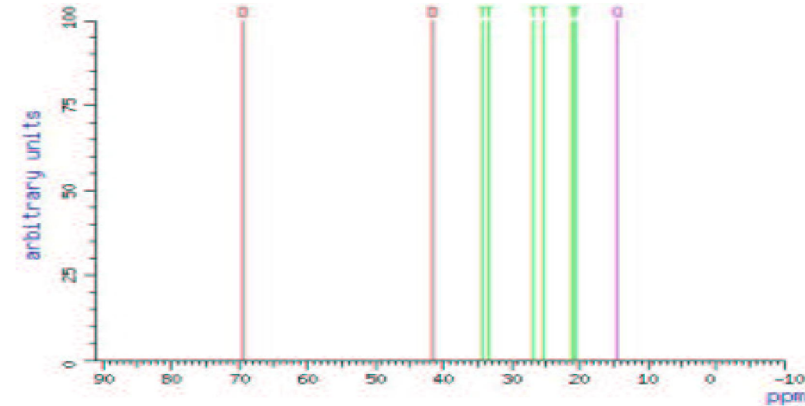
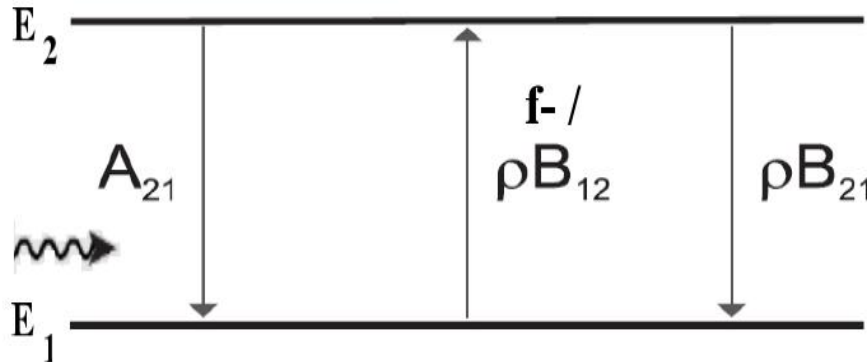
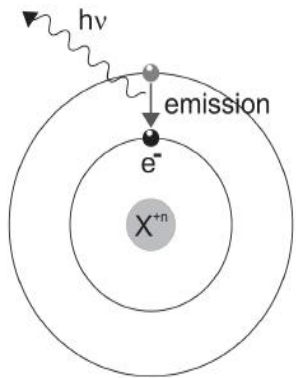
- Solar spectrum by Kurucz. The short wavelength region is mainly from Fe I, Fe II with large absorption or high opacity. - Less opacity in the yellow region, peak in the black body distribution function - reason for the yellow sun.

SUN IS A BLACK BODY OBJECT AT $T=5570$ K



- Black body: Absorbs all radiation falling on it - the Sun
- Black body radiation: A black body at a uniform temperature emits a characteristic frequency distribution - Sun peaks at yellow color

Opacity: PHOTO-EXCITATION



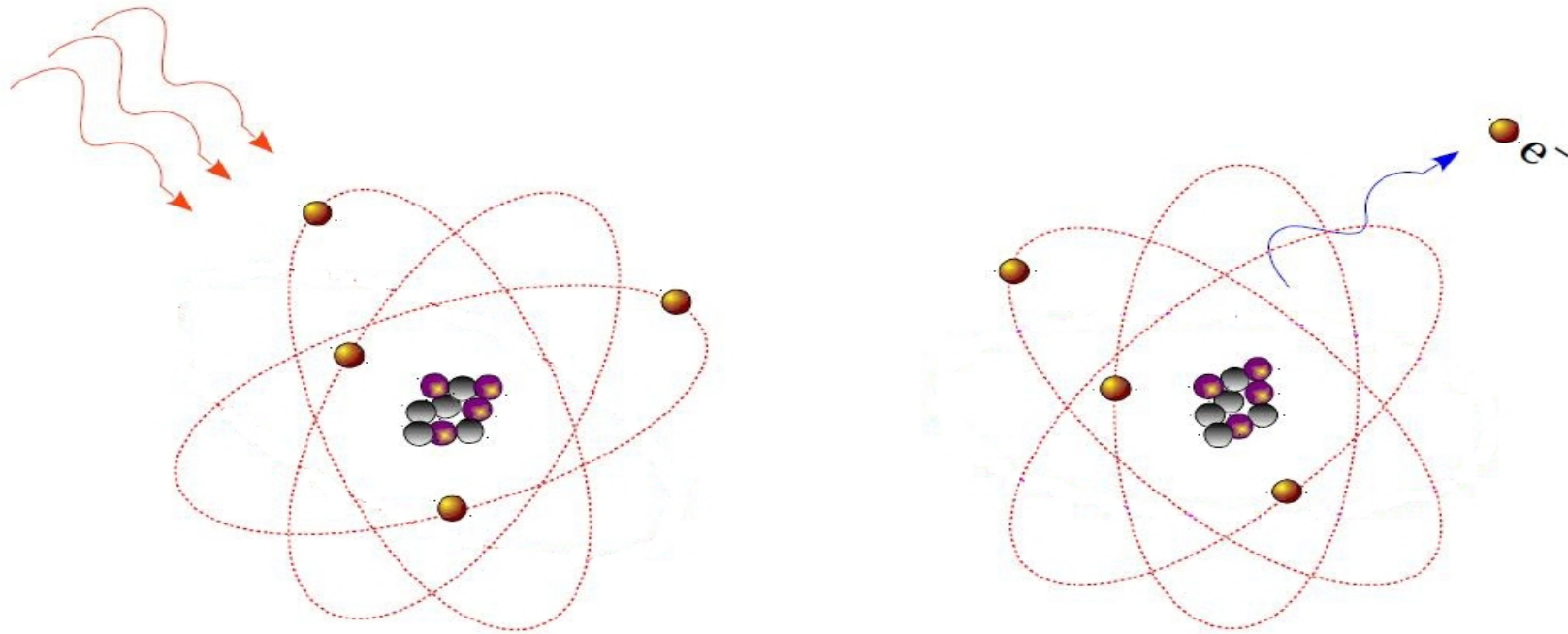
- Atomic quantities (constant numbers):
 - A_{21} for Spontaneous Decay or Radiative Decay Rate
 - f (Oscillator Strength) or B_{12} for Excitation
- Monochromatic opacity (κ_ν) depends on f_{ij}

$$\kappa_\nu(i \rightarrow j) = \frac{\pi e^2}{mc} N_i f_{ij} \phi_\nu$$

N_i = ion density in state i , ϕ_ν = profile factor

- κ includes thousands to millions of transitions

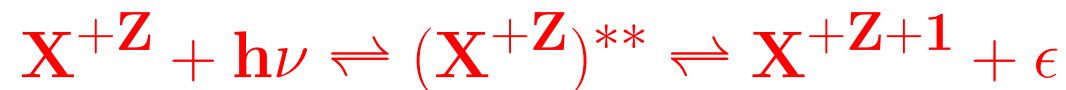
Opacity: PHOTOIONIZATION (PI):



i) Direct Photoionization (background):



ii) Resonant Photoionization: an intermediate state before ionization \rightarrow "Autoionizing state" \rightarrow Resonant lines



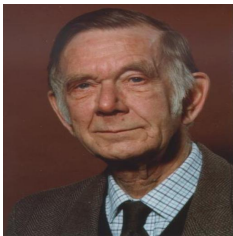
• κ_ν depends on photoionization cross section σ_{PI}

$$\kappa_\nu = N_i \sigma_{\text{PI}}(\nu)$$

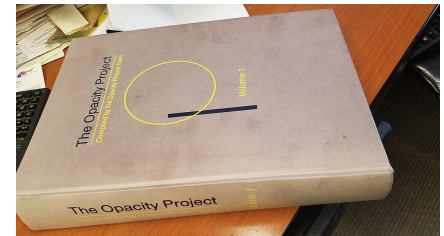
The OPACITY Project (OP) & The IRON Project (IP)

AIM: • Accurate Study of Atomic systems and process in astrophysical plasma, • Obtain plasma opacities, • Applications to astrophysical problems

Needed: i) Development of Theory, ii) package of computer programs, and iii) a large team of scientists



Prof. M.J. Seaton (1923 - 2007), UCL, UK



• **THE OPACITY PROJECT (OP) (1983 - 2007, 2007 -):**

• The OP initiated and led by Seaton, - OP led to

• **THE IRON PROJECT (IP) (1991 -)**

• International collaborators

M.J. Seaton, W. Eissner, N. Badnell, M. Bautista, K.A. Berrington, AM Binello, P. Burke, V.M. Burke, K. Butler, G.X. Chen, MC Chidichimo, F. Delahaye, M Le Dourneuf, J.A. Fernley, M.E. Galavis, M Graziani, A. Hibbert, D.G. Hummer, A.E. Kingston, R Kisielius, D.J. Lennon, D. Luo, AE Lynas-Gray, H.E. Mason, M Melendez, C. Mendoza, D. Mihalas, M. Montenegro, S.N. Nahar, H. Nausbaumer, S Nakazaki, P. H. Norrington, P. Palmeri, G. Peach, J Pelan, A.K. Pradhan, P. Quinet, P Romano, H.P. Saraph, P.M.J. Sawey, M.P. Scot, P.J. Storey, K.T. Taylor, J.F. Thornbury, J.A. Tully, MC Witthoeft, Y. Yan, PR Young, C.J. Zeippen, V Zeman, G. Del Zenna, H.L. Zhang (52 authros)

ASTROPHYSICALLY ABUNDANT ELEMENTS: H - Fe

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 c 299 792 458 m s⁻¹ (exact)

Planck constant h 6.626 07 × 10⁻³⁴ J s ($h = h/2\pi$)

elementary charge e 1.602 177 × 10⁻¹⁹ C

electron mass m_e 9.109 38 × 10⁻³¹ kg

$m_e c^2$ 0.510 999 MeV

proton mass m_p 1.672 622 × 10⁻²⁷ kg

fine-structure constant α 1/137.035 999 074

Rydberg constant R_∞ 10 973 731.569 m⁻¹

$R_\infty c$ 3.289 841 960 × 10¹⁵ Hz

$R_\infty h c$ 13.605 69 eV

Boltzmann constant k 1.380 6 × 10⁻²³ J K⁻¹

Physical Measurement Laboratory
www.nist.gov/pml

Standard Reference Data
www.nist.gov/srd

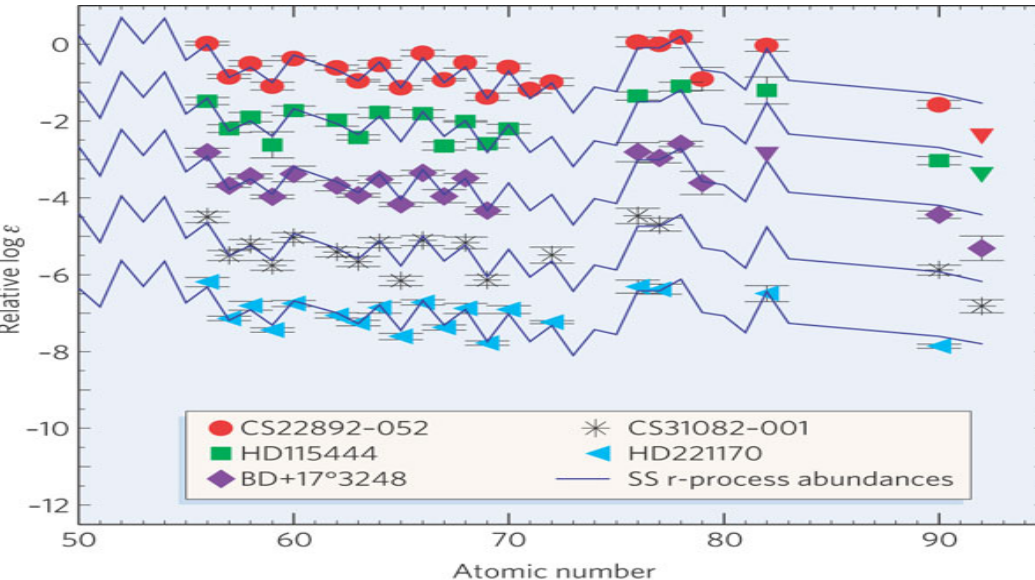
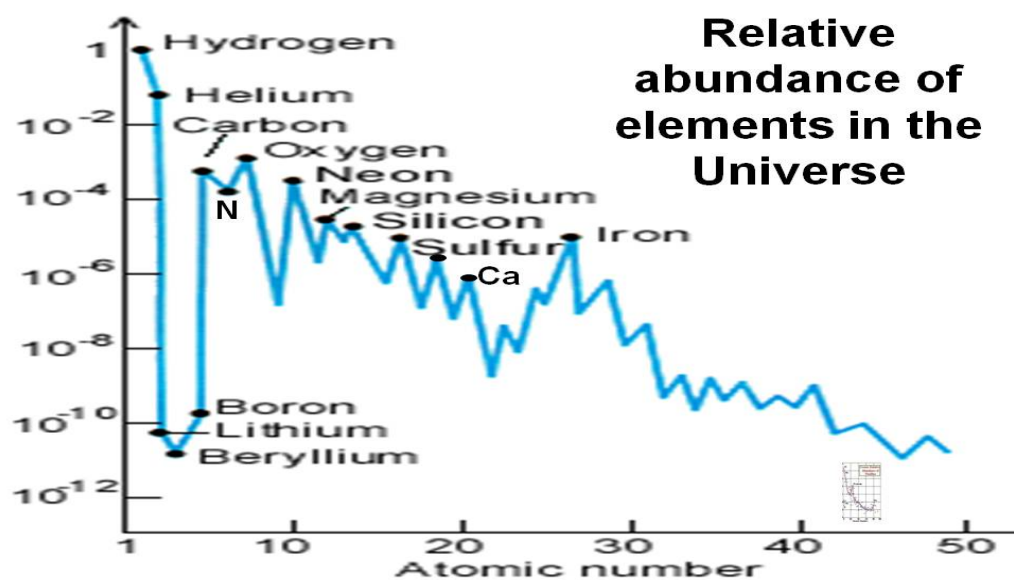
Legend:
■ Solids
■ Liquids
■ Gases
■ Artificially Prepared

Group	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	¹ H Hydrogen 1.008 1s																	² He Helium 4.002602 1s ²
2	³ Li Lithium 6.941 1s ² 2s ¹	⁴ Be Beryllium 9.0121831 1s ² 2s ²																¹⁰ Ne Neon 20.1797 1s ² 2s ² 2p ⁶
3	¹¹ Na Sodium 22.98976928 [Ne]3s ¹	¹² Mg Magnesium 24.304 [Ne]3s ²											¹³ Al Aluminum 26.98153858 [Ne]3s ² 3p ¹	¹⁴ Si Silicon 28.0855 [Ne]3s ² 3p ²	¹⁵ P Phosphorus 30.97376200 [Ne]3s ² 3p ³	¹⁶ S Sulfur 32.059 [Ne]3s ² 3p ⁴	¹⁷ Cl Chlorine 35.45 [Ne]3s ² 3p ⁵	¹⁸ Ar Argon 39.948 [Ne]3s ² 3p ⁶
4	¹⁹ K Potassium 39.0983 [Ar]4s ¹	²⁰ Ca Calcium 40.078 [Ar]4s ²	²¹ Sc Scandium 44.955908 [Ar]3d ¹ 4s ²	²² Ti Titanium 47.867 [Ar]3d ² 4s ²	²³ V Vanadium 50.9415 [Ar]3d ³ 4s ²	²⁴ Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹	²⁵ Mn Manganese 54.938044 [Ar]3d ⁵ 4s ²	²⁶ Fe Iron 55.845 [Ar]3d ⁶ 4s ²	²⁷ Co Cobalt 58.933194 [Ar]3d ⁷ 4s ²	²⁸ Ni Nickel 58.6934 [Ar]3d ⁸ 4s ²	²⁹ Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹	³⁰ Zn Zinc 65.38 [Ar]3d ¹⁰ 4s ²	³¹ Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹	³² Ge Germanium 72.630 [Ar]3d ¹⁰ 4s ² 4p ²	³³ As Arsenic 74.921595 [Ar]3d ¹⁰ 4s ² 4p ³	³⁴ Se Selenium 78.9718 [Ar]3d ¹⁰ 4s ² 4p ⁴	³⁵ Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	³⁶ Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶
5	³⁷ Rb Rubidium 85.4678 [Kr]5s ¹	³⁸ Sr Strontium 87.62 [Kr]5s ²	³⁹ Y Yttrium 88.90584 [Kr]4d ¹ 5s ²	⁴⁰ Zr Zirconium 91.224 [Kr]4d ² 5s ²	⁴¹ Nb Niobium 92.90637 [Kr]4d ⁴ 5s ¹	⁴² Mo Molybdenum 95.95 [Kr]4d ⁵ 5s ¹	⁴³ Tc Technetium 98.90625 [Kr]4d ⁵ 5s ²	⁴⁴ Ru Ruthenium 101.07 [Kr]4d ⁷ 5s ¹	⁴⁵ Rh Rhodium 102.90550 [Kr]4d ⁸ 5s ¹	⁴⁶ Pd Palladium 106.42 [Kr]4d ¹⁰ 5s ⁰	⁴⁷ Ag Silver 107.8682 [Kr]4d ¹⁰ 5s ¹	⁴⁸ Cd Cadmium 112.414 [Kr]4d ¹⁰ 5s ²	⁴⁹ In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p ¹	⁵⁰ Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 5p ²	⁵¹ Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³	⁵² Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴	⁵³ I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 5p ⁵	⁵⁴ Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶
6	⁵⁵ Cs Cesium 132.9054520 [Xe]6s ¹	⁵⁶ Ba Barium 137.327 [Xe]6s ²	⁵⁷ La Lanthanum 138.90547 [Xe]5d ¹ 6s ²	⁵⁸ Ce Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ²	⁵⁹ Pr Praseodymium 140.907 [Xe]4f ³ 6s ²	⁶⁰ Nd Neodymium 144.242 [Xe]4f ⁴ 6s ²	⁶¹ Pm Promethium 144.9128 [Xe]4f ⁵ 6s ²	⁶² Sm Samarium 150.36 [Xe]4f ⁶ 6s ²	⁶³ Eu Europium 151.964 [Xe]4f ⁷ 6s ²	⁶⁴ Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ²	⁶⁵ Tb Terbium 158.92535 [Xe]4f ⁹ 6s ²	⁶⁶ Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ²	⁶⁷ Ho Holmium 164.93033 [Xe]4f ¹¹ 6s ²	⁶⁸ Er Erbium 167.259 [Xe]4f ¹² 6s ²	⁶⁹ Tm Thulium 168.93422 [Xe]4f ¹³ 6s ²	⁷⁰ Yb Ytterbium 173.054 [Xe]4f ¹⁴ 6s ²	⁷¹ Lu Lutetium 174.9668 [Xe]4f ¹⁴ 5d ¹ 6s ²	
7	⁸⁷ Fr Francium 223 [Rn]7s ¹	⁸⁸ Ra Radium 226 [Rn]7s ²	⁸⁹ Ac Actinium 227 [Rn]6d ¹ 7s ²	⁹⁰ Th Thorium 232.0377 [Rn]6d ² 7s ²	⁹¹ Pa Protactinium 231.03588 [Rn]5f ² 6d ¹ 7s ²	⁹² U Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ²	⁹³ Np Neptunium 237 [Rn]5f ⁴ 6d ¹ 7s ²	⁹⁴ Pu Plutonium 244 [Rn]5f ⁶ 7s ²	⁹⁵ Am Americium 243 [Rn]5f ⁷ 7s ²	⁹⁶ Cm Curium 247 [Rn]5f ⁸ 7s ²	⁹⁷ Bk Berkelium 247 [Rn]5f ⁹ 7s ²	⁹⁸ Cf Californium 251 [Rn]5f ¹⁰ 7s ²	⁹⁹ Es Einsteinium 252 [Rn]5f ¹¹ 7s ²	¹⁰⁰ Fm Fermium 257 [Rn]5f ¹² 7s ²	¹⁰¹ Md Mendelevium 258 [Rn]5f ¹³ 7s ²	¹⁰² No Nobelium 259 [Rn]5f ¹⁴ 7p ¹	¹⁰³ Lr Lawrencium 262 [Rn]5f ¹⁴ 7p ²	

Note: Elements 113-118 are labeled Uut, Uuq, Uup, Uuq, Uus, Uuo.

Element Detail for Cerium (Ce):
 Atomic Number: 58
 Ground-state Level: 1G₀
 Symbol: Ce
 Name: Cerium
 Standard Atomic Weight: 140.116
 Ground-state Configuration: [Xe]4f¹5d¹6s²
 Ionization Energy (eV): 5.5386

Footnote: *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 lupac.org for an explanation and values. For a description of the data, visit physics.nist.gov/data NIST SP 966 (September 2014)



- OP focused on all ionization states of H - Fe

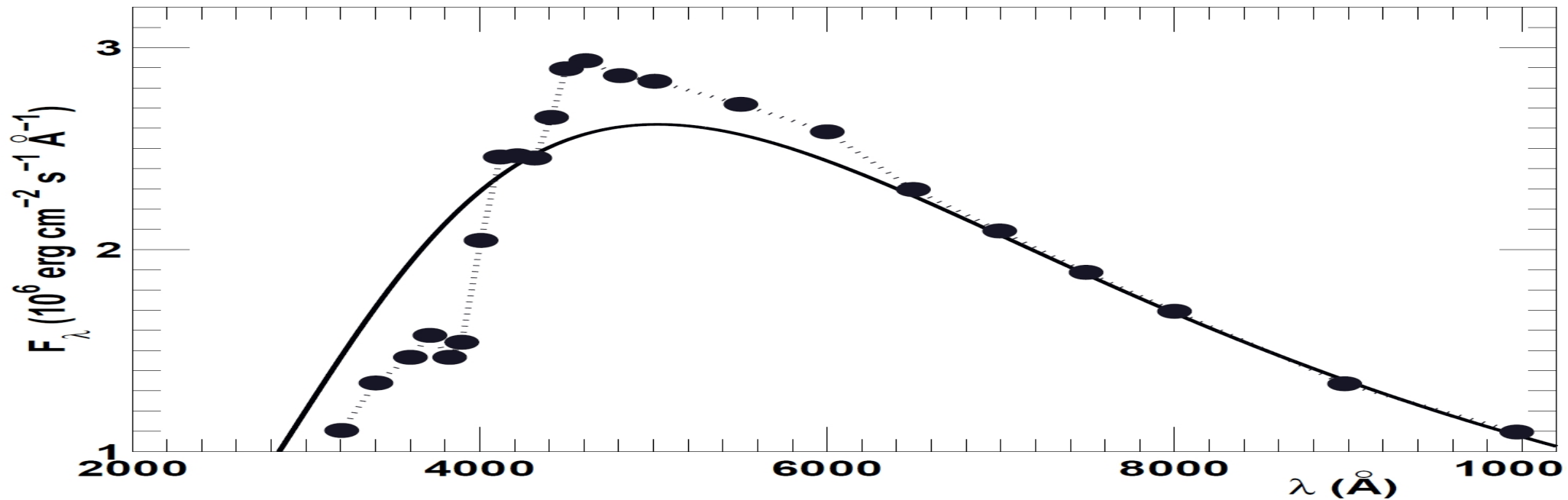
New Physics:

- Solved many astrophysical problems
- Found new physics in photoionization - features & X-ray lines
- Unified method for electron-ion was introduced
- High precision radiative and collisional data for applications
- Found new applications in nanobiomedicine

Publications:

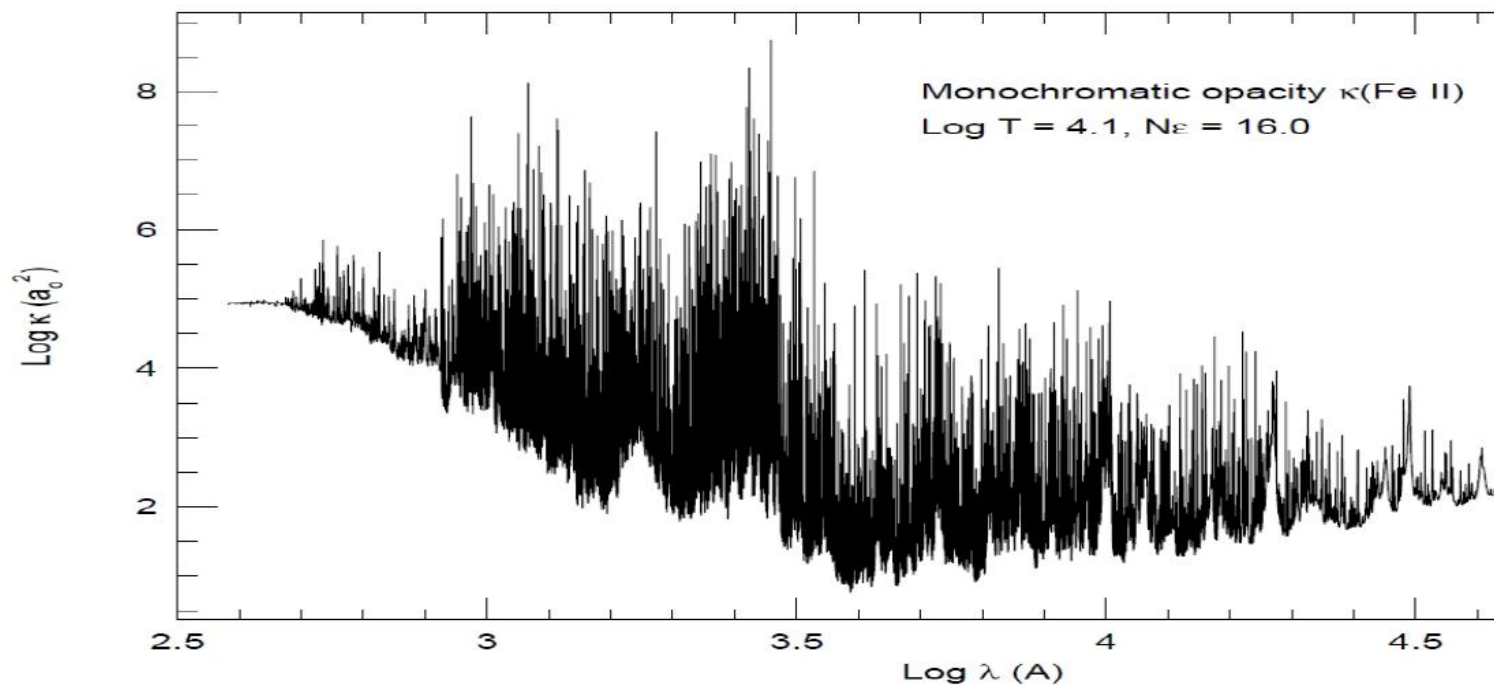
- The Opacity Project (TOP) series: 22 papers in JPB,
- The Iron Project (TIP) series: 68 in A&A + additional ones outside
- Book chapters, conference conference proceedings articles
- Book: **The Opacity Project**, The Opacity Project team, IOP (1995)
- Textbook: **"Atomic Astrophysics and Spectroscopy"** (A.K. Pradhan & S.N. Nahar, Cambridge University press, 2011)
- **Atomic & Opacity Databases**
- **TOPbase (OP)** at CDS: <http://vizier.u-strasbg.fr/topbase/topbase.htm>
 - Energy levels, Oscillator Strengths, Photoionization Cross Sections
- **TIPbase (IP)** at CDS: <http://cdsweb.u-strasbg.fr/tipbase/home.html>
 - Collisional Strengths for Electron Impact Excitation, and for Radiative Processes similar to TOPbase (not complete)
- **OPserver** for monochromatic opacities and program for mixtures at the OSC: <http://opacities.osc.edu/>
- **NORAD-Atomic-Data** at OSU: Latest radiative and electron-ion recombination data, <http://norad.astronomy.ohio-state.edu>

IRON ON THE SUN (Nahar & Pradhan 1993)



TOP: Black body radiation of the sun - the discrepancy below 4000 \AA .

BOTTOM: Theory: High radiation absorption (opacity) by iron on surface



DISCREPANCY IN STUDY OF PULSATIONS OF CEPHEID VARIABLES (RS PUPPIS)



OP

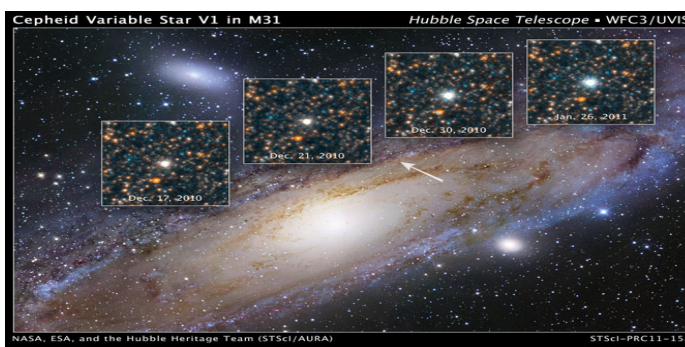
The OPACITY Project,

IR

The IRON Project

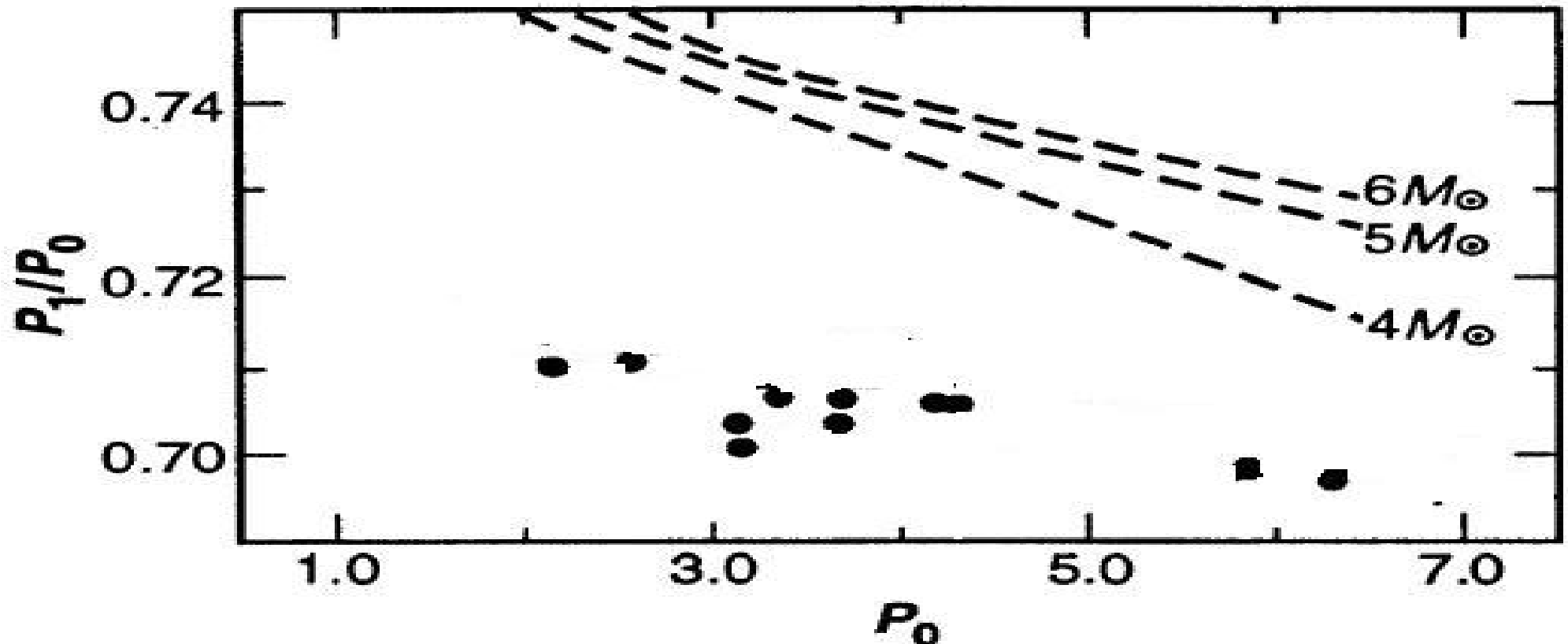


The OPACITY Project



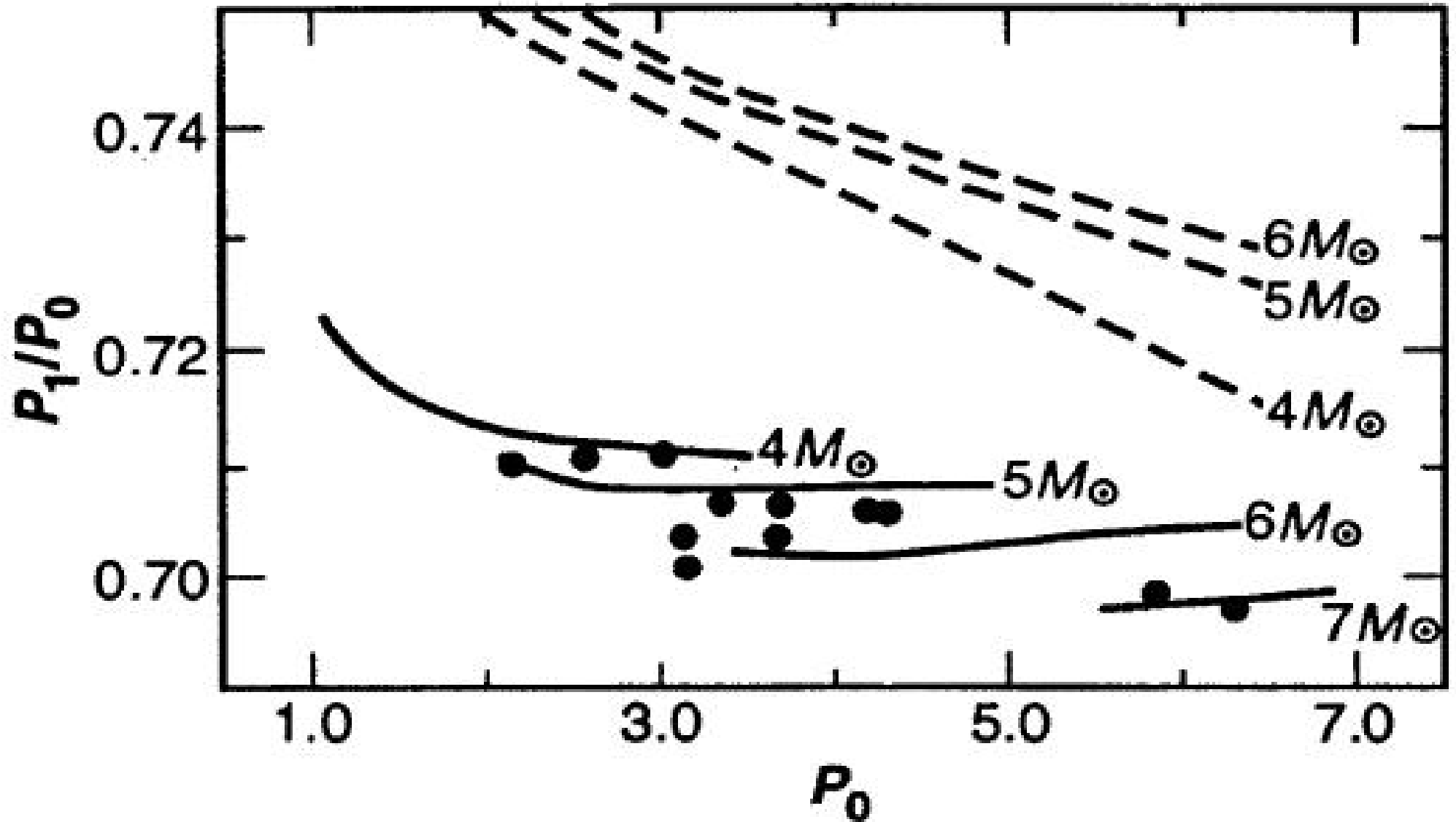
The IRON Project

- **Cepheid are stars**, larger than the Sun, and go through periodic brightness and dimming states which can last for days to months
 - Luminosity (M_V) is proportional to the mass and opacity
- Discrepancy in predicted pulsation periods of Cepheid stars - REQUIRED HIGHER METALICITY/ OPACITY**



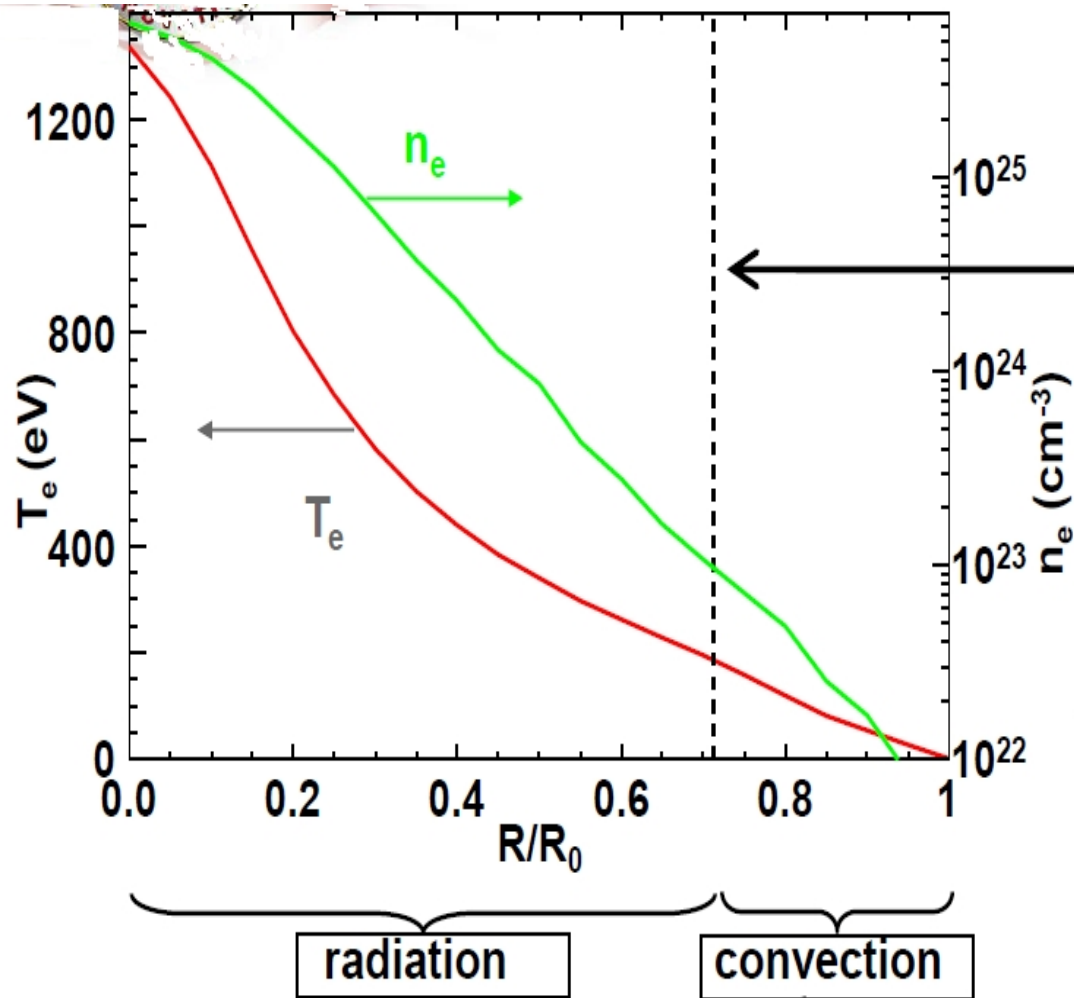
- Astronomers plea for accurate atomic physics to find more metallicity

DISCREPANCY IN PULSATION PERIODS OF CLASSIC CEPHEID IS SOLVED WITH INCREASED OPACITY



- The project produced increased opacity
- Figure: Ratio of the observed 1st overtone(P_1)/ fundamental(P_0) periods of brightness (filled circles) now match the predicted curves (solid)

DISCREPANCY: MEASURED AND PREDICTED BOUNDARY AT THE SOLAR RADIATIVE AND CONVECTION ZONES (R_{CZ})



- measured boundary $R_{CZ} = 0.713 \pm 0.001$
- Predicted $R_{CZ} = 0.726$
- Thirteen σ difference

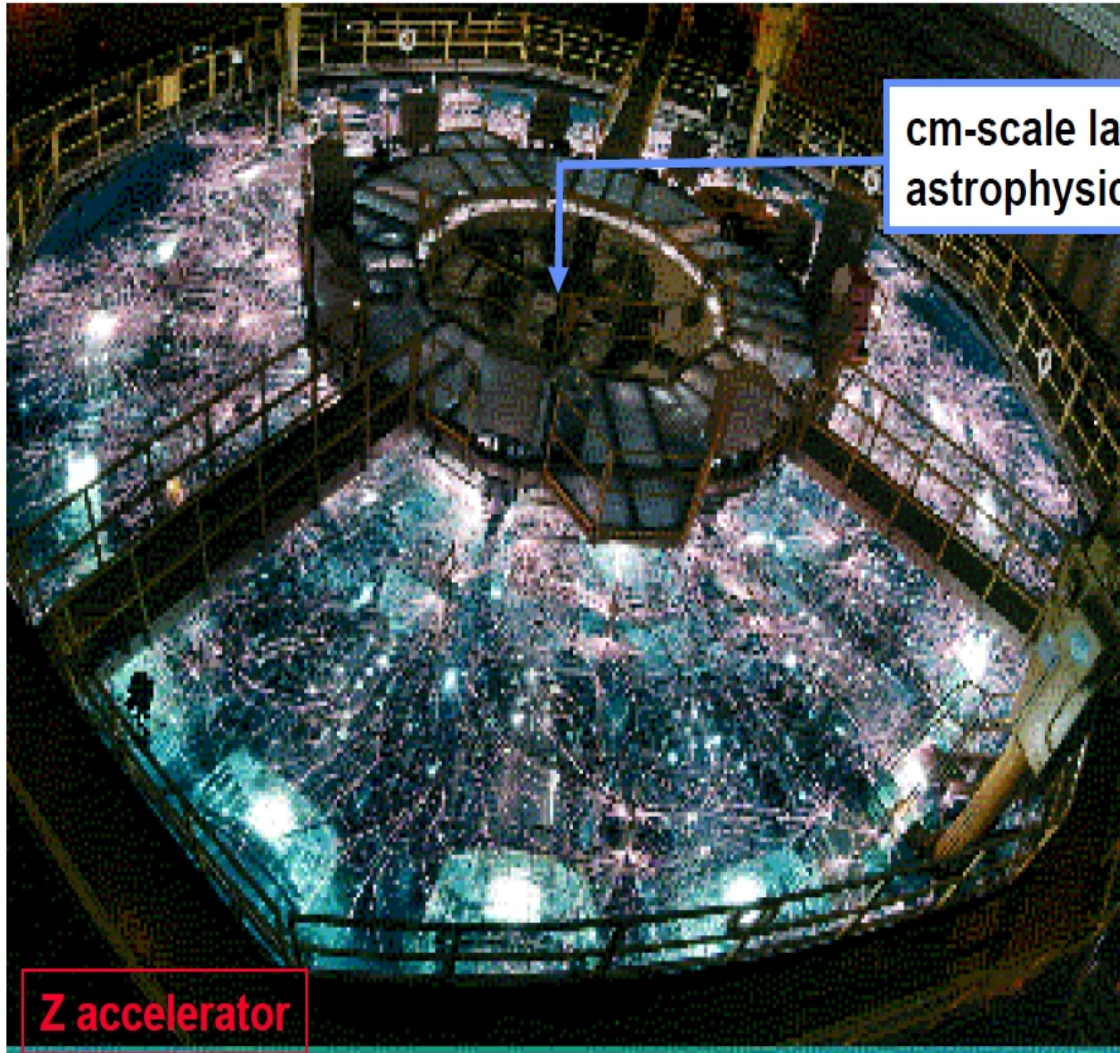
Bahcall et al, ApJ (2004)
 Basu & Antia Physics Reports 2008
 Asplund et al Ann Rev AA (2009)
 Christensen-Dalsgaard et al A&A (2009)

- Calculated from opacity using current atomic data, $R_{CZ} = 0.726$ - large (over 5600 mi difference) → changes solar structure
- Earlier opacities were incorrect by factors of 2 to 5 → inaccurate stellar models
- Needs 10% overall increment in opacity (Bahcall et al 2005)
- 3D model finds C, N & O, up to 40-50% lower (Asplund et al 2009) → **MISSING PHYSICS**

HOW MUCH DO WE KNOW ABOUT THE SUN?

- Bahcall et al (2005): "Solar opacity needs overall 10% increment to explain the solar abundances".
- 3D model of Asplund et al (2009) "Solar C,N,O abundances are lower than they are assumed"

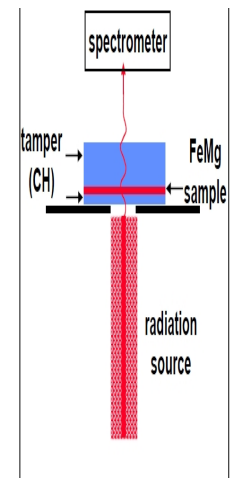
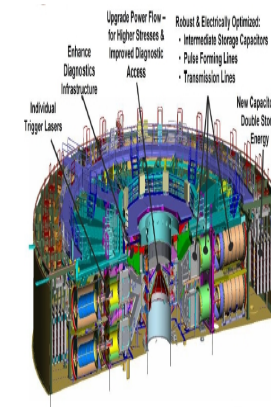
The 20million Amp current provided by the Z accelerator enables this research



cm-scale laboratory astrophysics experiment

Z accelerator

40 m



New Z

The refurbished Z delivers 24 million Amps to the load
50% increase in electrical energy for present day experiments

New sample design

Increasing the rear tamper thickness delays expansion onset
This leads to higher density and higher temperature

- "Created the Sun on the earth": Plasma at $T=190$ eV ~ 2 MK, $\rho = 2.8 \times 10^{22}/\text{cm}^3$ at same condition as inside the Sun

LETTER

doi:10.1038/nature14048

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey¹, T. Nagayama¹, G. P. Loisel¹, G. A. Rochau¹, C. Blancard², J. Colgan³, Ph. Cosse², G. Faussurier², C. J. Fontes³, F. Gilleron², I. Golovkin⁴, S. B. Hansen¹, C. A. Iglesias⁵, D. P. Kilcrease³, J. J. MacFarlane⁴, R. C. Mancini⁶, S. N. Nahar⁷, C. Orban⁷, J.-C. Pain², A. K. Pradhan⁷, M. Sherrill³ & B. G. Wilson⁵

PRL **116**, 235003 (2016)

PHYSICAL REVIEW LETTERS

week ending
10 JUNE 2016

Large Enhancement in High-Energy Photoionization of Fe XVII and Missing Continuum Plasma Opacity

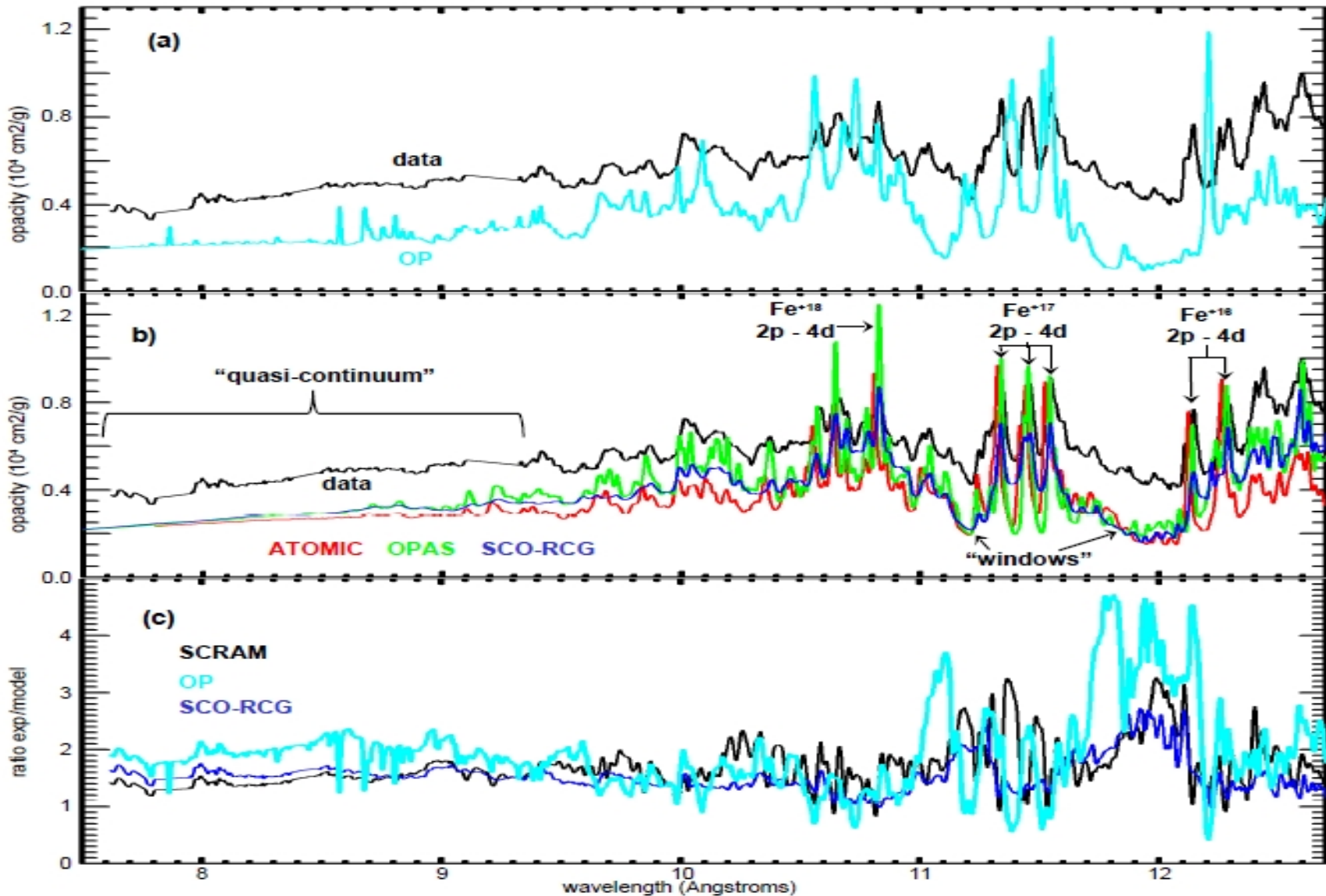
Sultana N. Nahar^{*} and Anil K. Pradhan[†]

Department of Astronomy, The Ohio State University, Columbus, Ohio 43210, USA

(Received 27 September 2015; revised manuscript received 12 February 2016; published 8 June 2016)

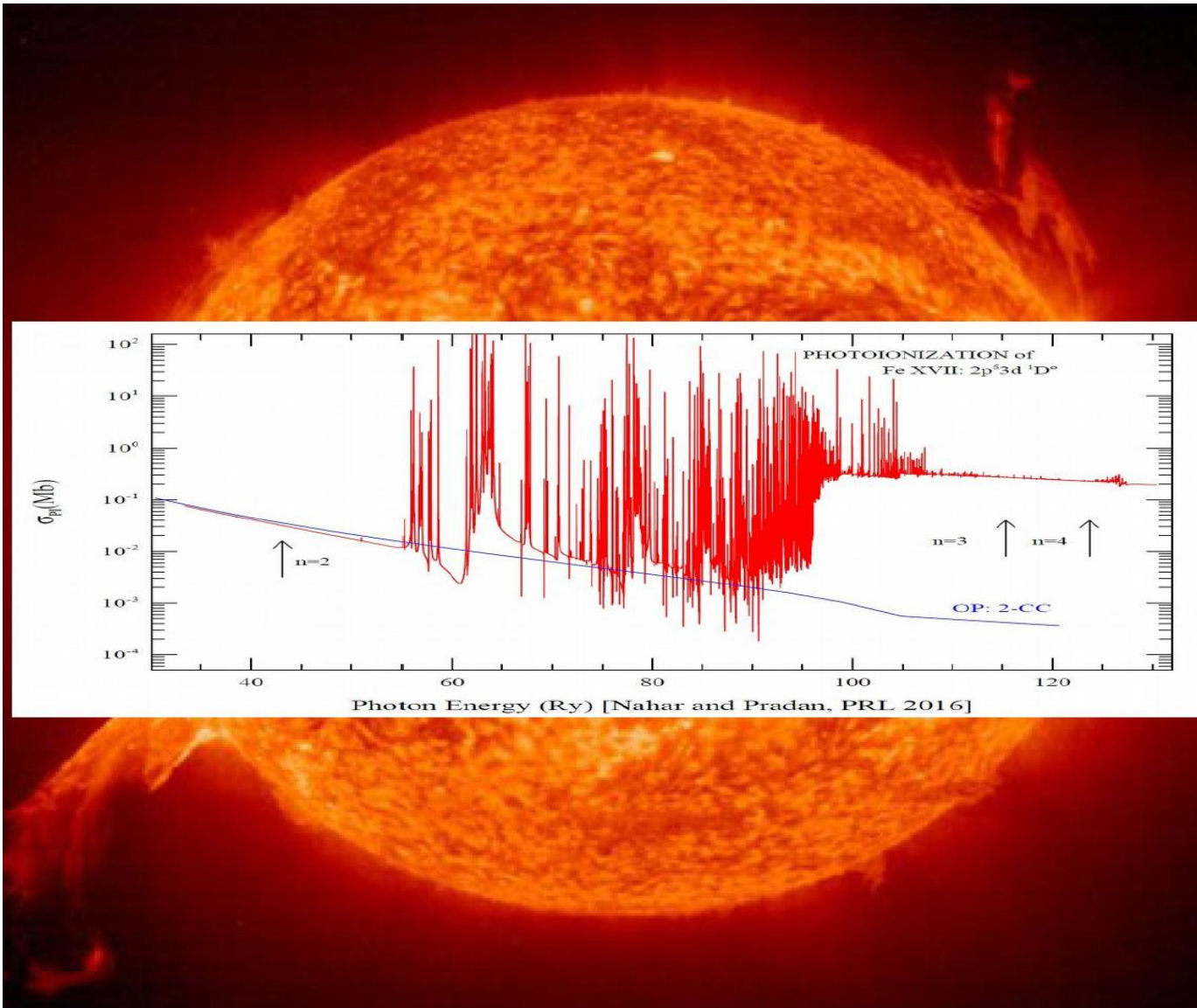
Aimed at solving the outstanding problem of solar opacity, and radiation transport plasma models in general, we report substantial photoabsorption in the high-energy regime due to atomic core photoexcitations not heretofore considered. In extensive *R*-matrix calculations of unprecedented complexity for an important iron ion Fe XVII (Fe^{16+}), with a wave function expansion of 99 Fe XVIII (Fe^{17+}) *LS* core states from $n \leq 4$ complexes (equivalent to 218 fine structure levels), we find (i) up to orders of magnitude enhancement in background photoionization cross sections, in addition to strongly peaked photoexcitation-of-core resonances not considered in current opacity models, and ii) demonstrate convergence with respect to successive core excitations. The resulting increase in the monochromatic continuum, and 35% in the Rosseland mean opacity, are compared with the "higher-than-predicted" iron opacity measured at the Sandia Z-pinch fusion device at solar interior conditions.

● COMPARISON OF IRON OPACITY: Experiment & Theory (Bailey et al, Nature Lett 2015)



- Present models use photoionization data - no resonances, except those in TOPbase database
- Problems (theory): i) Deep windows, ii) lower background

PHOTOIONIZATION FEATURES: Fe XVII (Nahar and Pradhan, PRL 2016, 4 in a series 2024): Found new features impacting opacity increase



- Resonances are stronger for $\Delta n = 1$ than those of $\Delta n = 0$
- Resonances converge with higher n
- The background is enhanced at high energy
- Seaton resonances enhance the background.

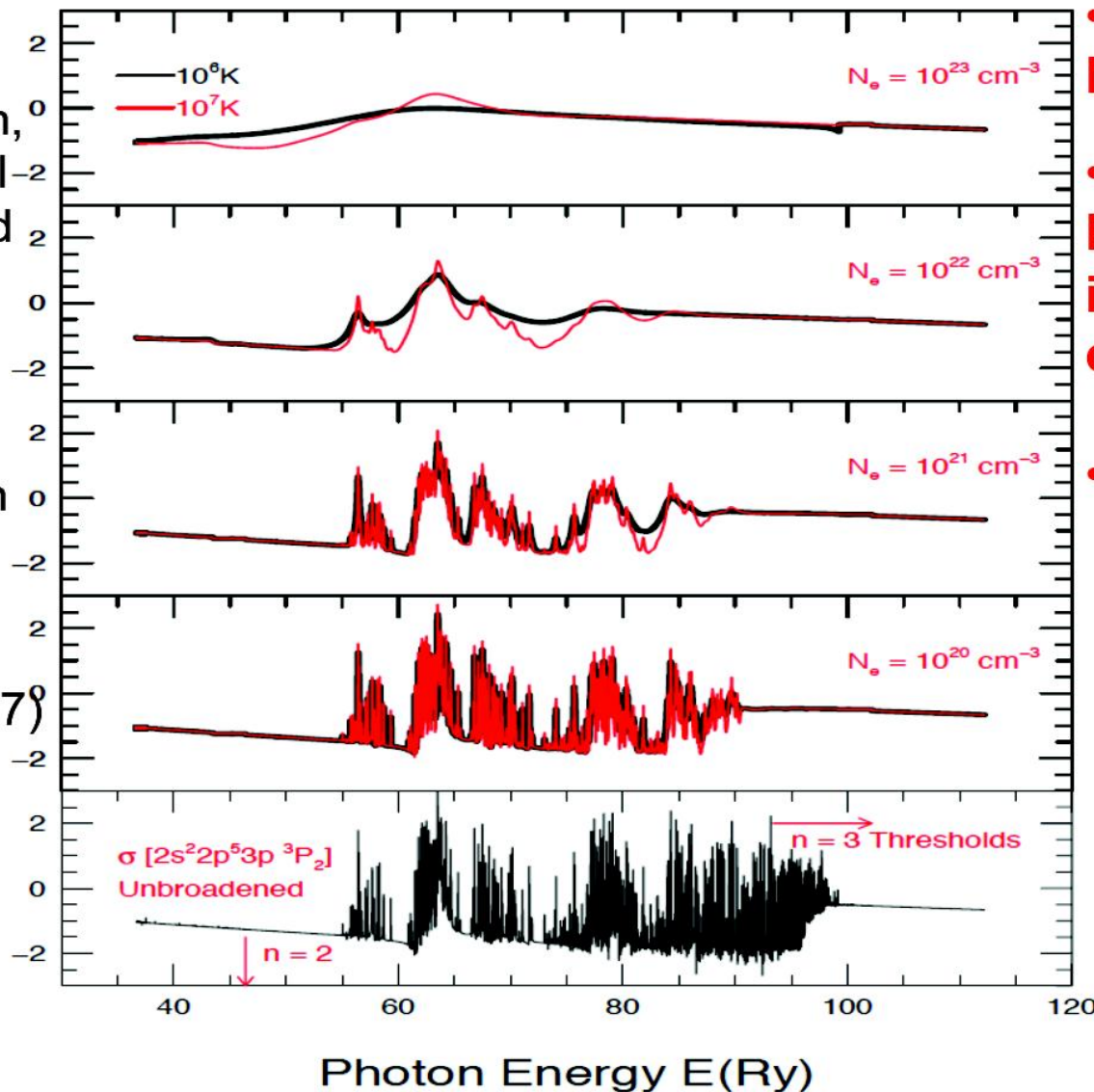
Fe XVII OPACITY SPECTRUM IN SOLAR INTERIOR

Latest Fe XVII spectrum (Pradhan, Nahar, Lianshui, Orban, Werner, in progress)

- Mean opacity increment by 35%

Electron Impact Broadening of Autoionizing Resonances in Plasmas

A new theoretical approximation, computational algorithm, and computer program for numerical simulation of resonances in atomic processes in plasmas (Pradhan 2017)



• Critical Density:
 $N_c \sim 10^{22}\text{ cm}^{-3}$

• Dissolution of
PEC Resonances
into the b-f
continuum

• Experimental Z
data shows
agreement with
opacity models
for $N_e < N_c$