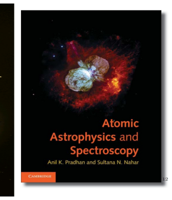
The Ohio State University



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"THE SUN"

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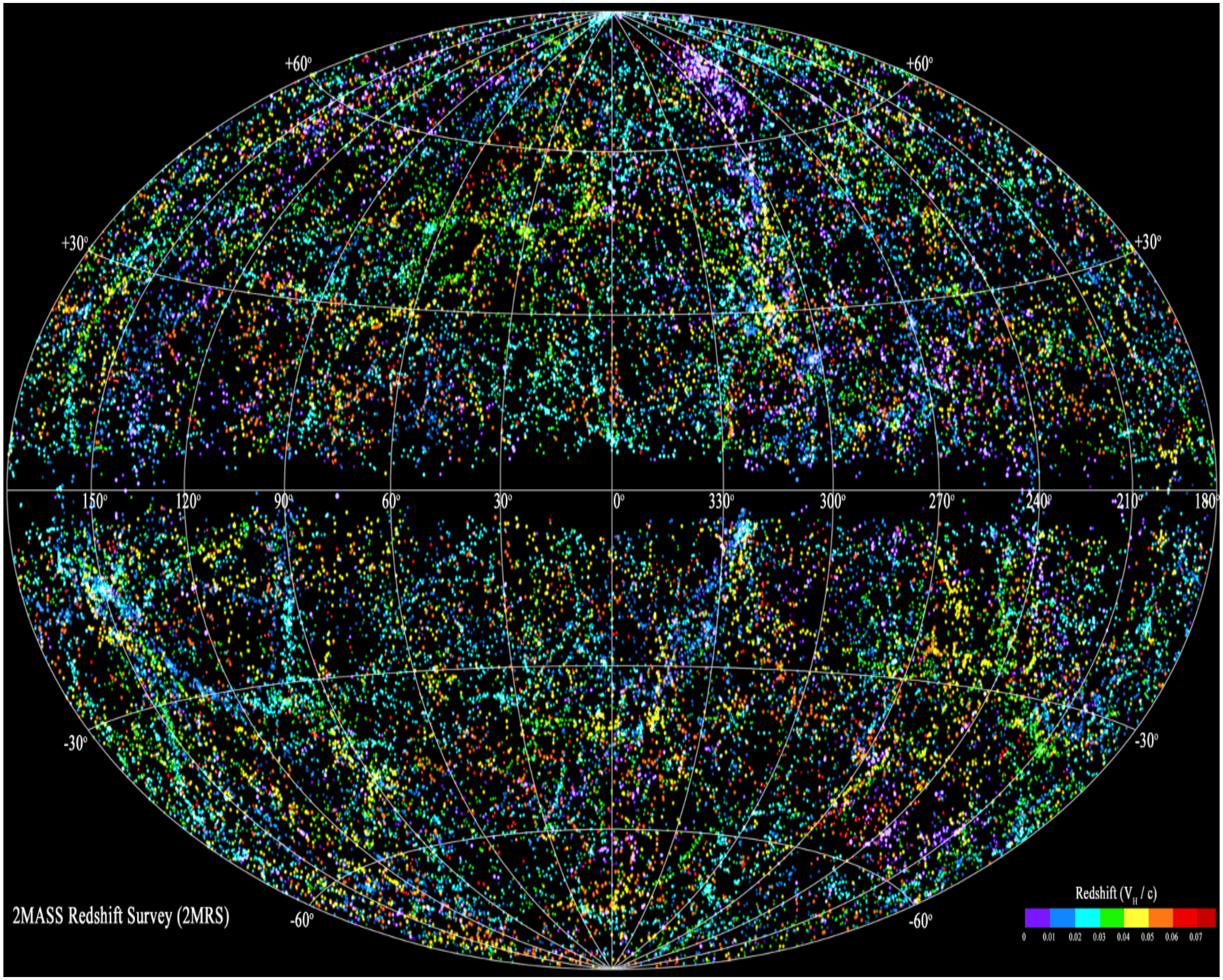
Delaware, Ohio, March 9, 2024

SUPPORT: (DOE), NSF, Ohio Supercomputer Center

UNIVERSE through RADIATION: Most Complete 3D Map

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

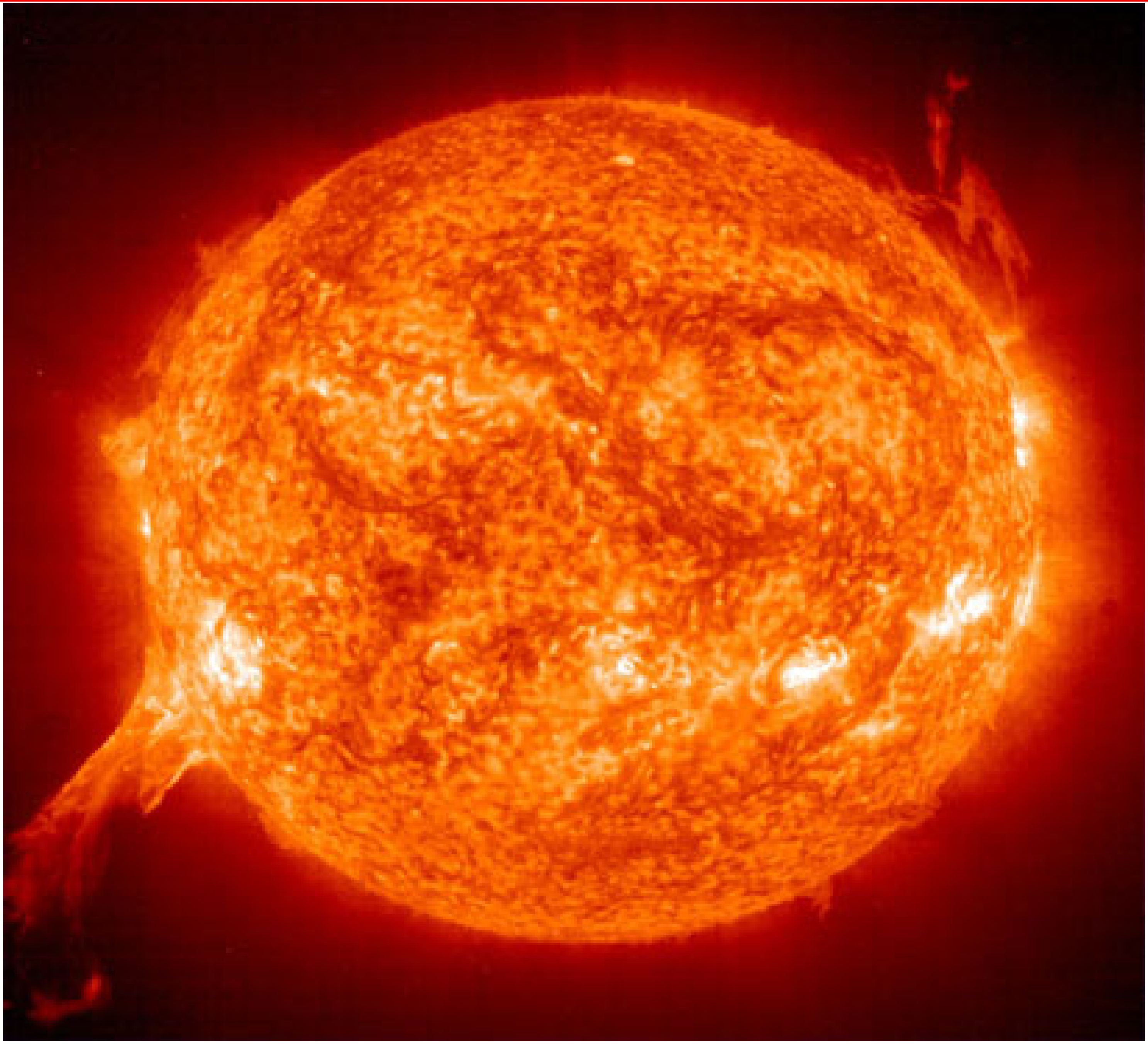


- The 2-Micron All-Sky Survey includes 43,000 galaxies within 380 million Ly
- There are at least 2 trillion galaxies in the observable universe
- Universe size: about 93 billion light years
- Signals can not travel faster than light, any object farther away from the age of the universe, 13.8 Byrs cannot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

Our galaxy: MILKY WAY

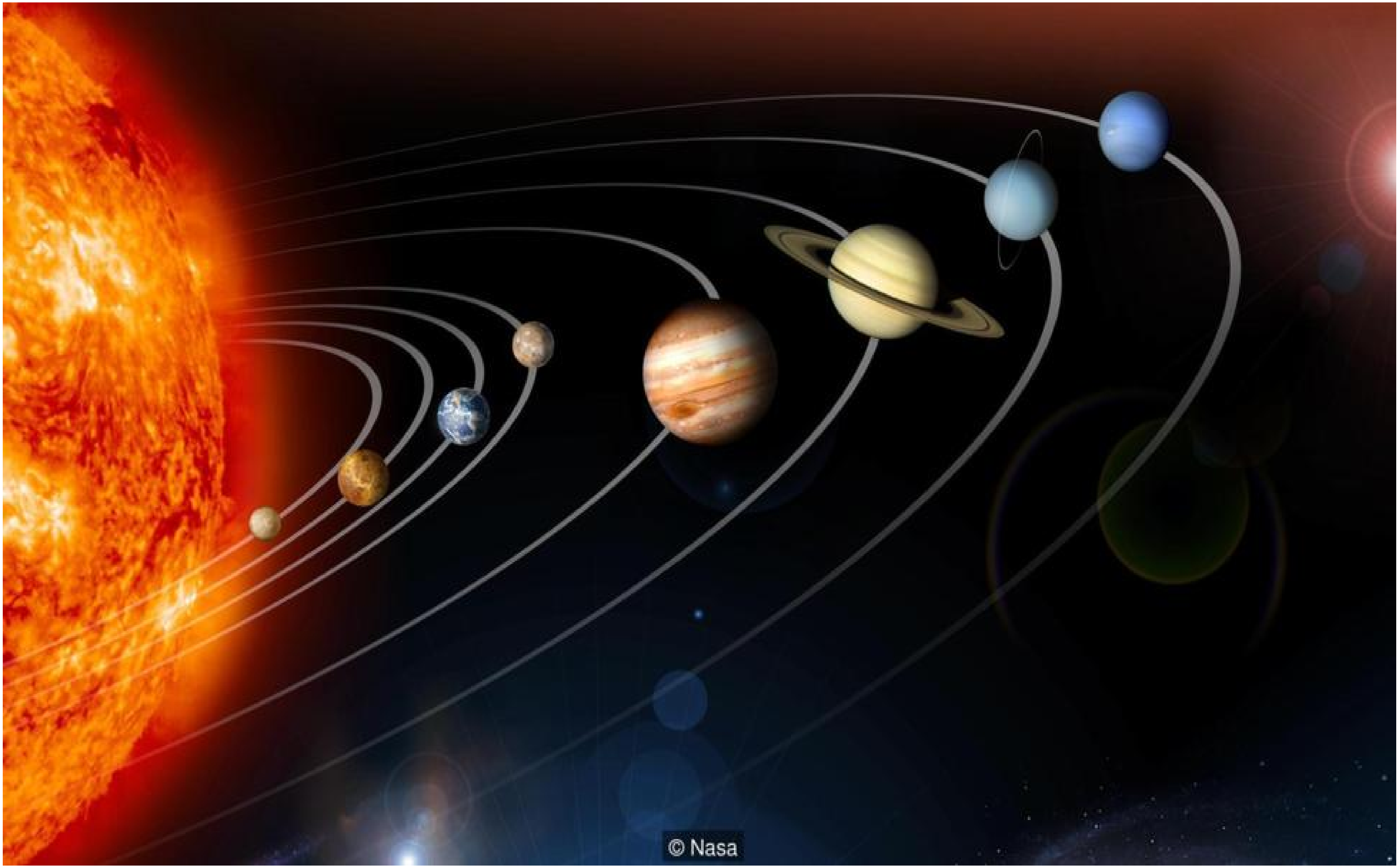
• Has 200-400 billion stars. Our Sun is a typical, standard star is one of them, located near the edge. How do we study them? - Analyzing the light coming from them. • Milky way is spherical. Crossing over will take (diameter) over 100,000 LY. The Sun is near the edge of it

MOTIVATION: STUDY OF OUR STAR, THE SUN



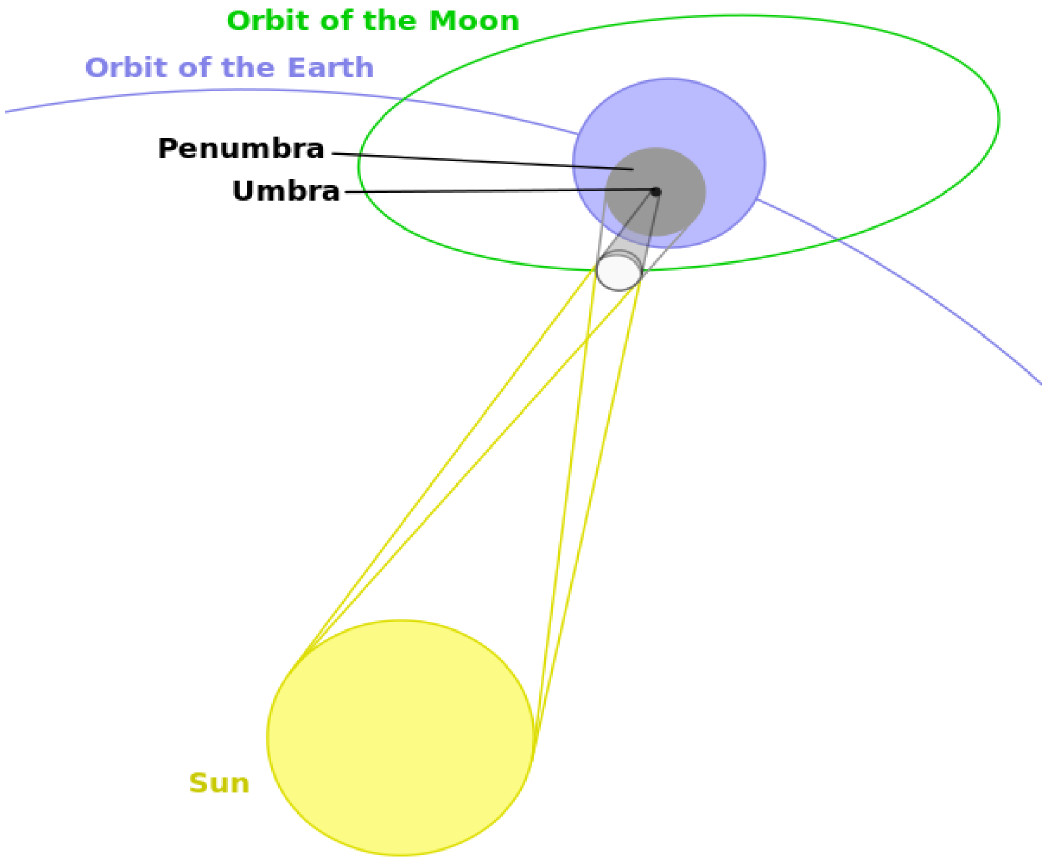
- Source of our energy, • Standard to study other stars
- Crucial to have accurate information • Has number of dedicated observatories

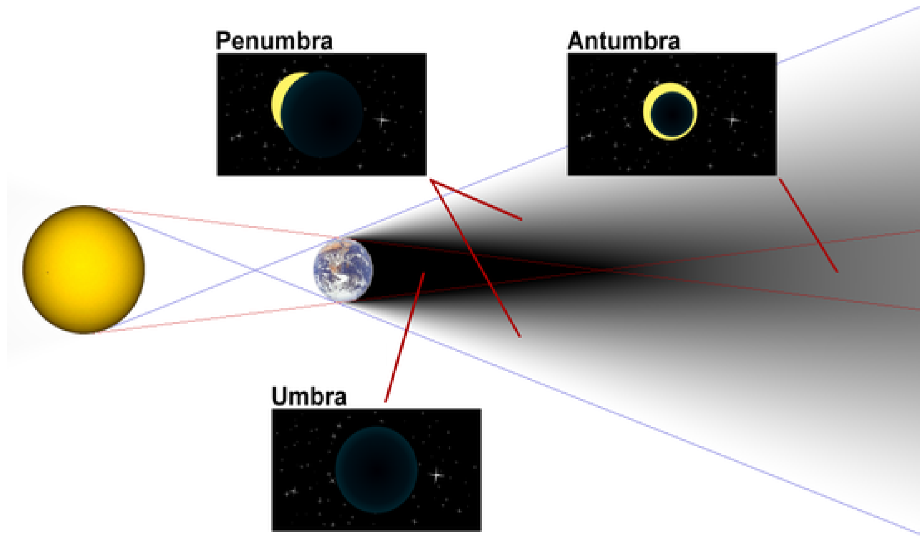
The SUN, our STAR (diameter: 110 x Diameter-earth)



- 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)

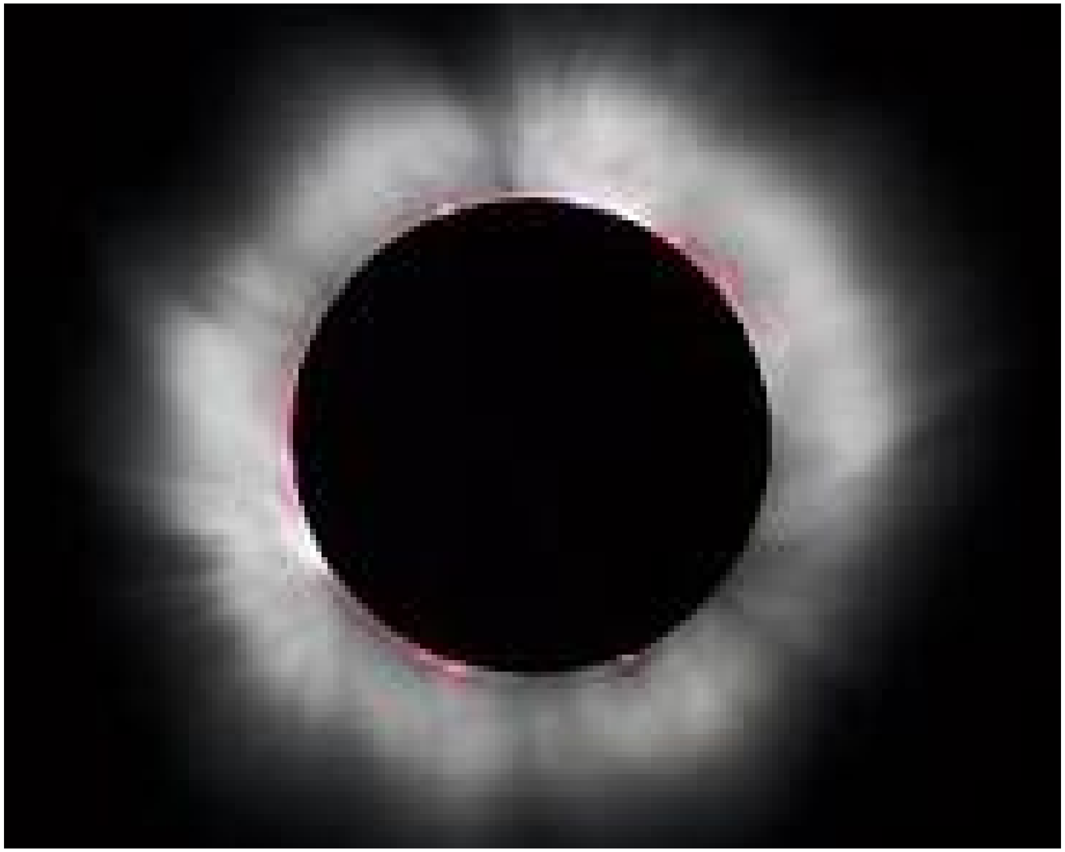


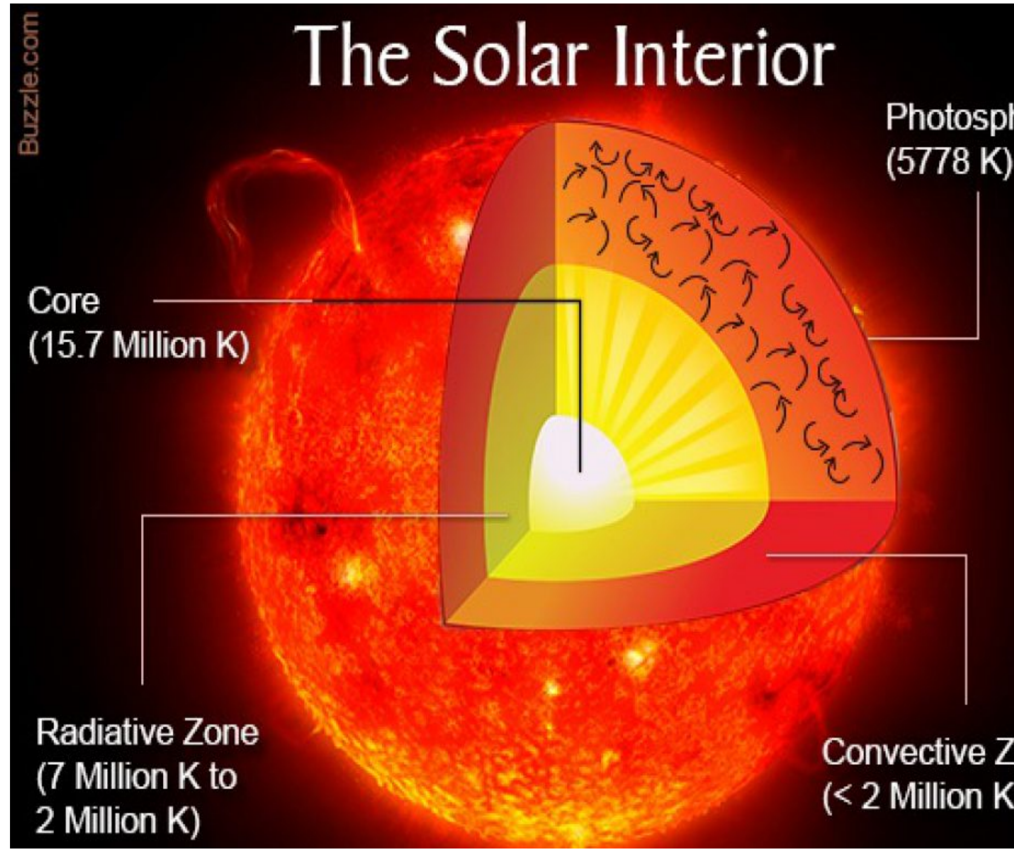


- **Alignment of the Sun, Moon, and Earth during a solar eclipse.**

- 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

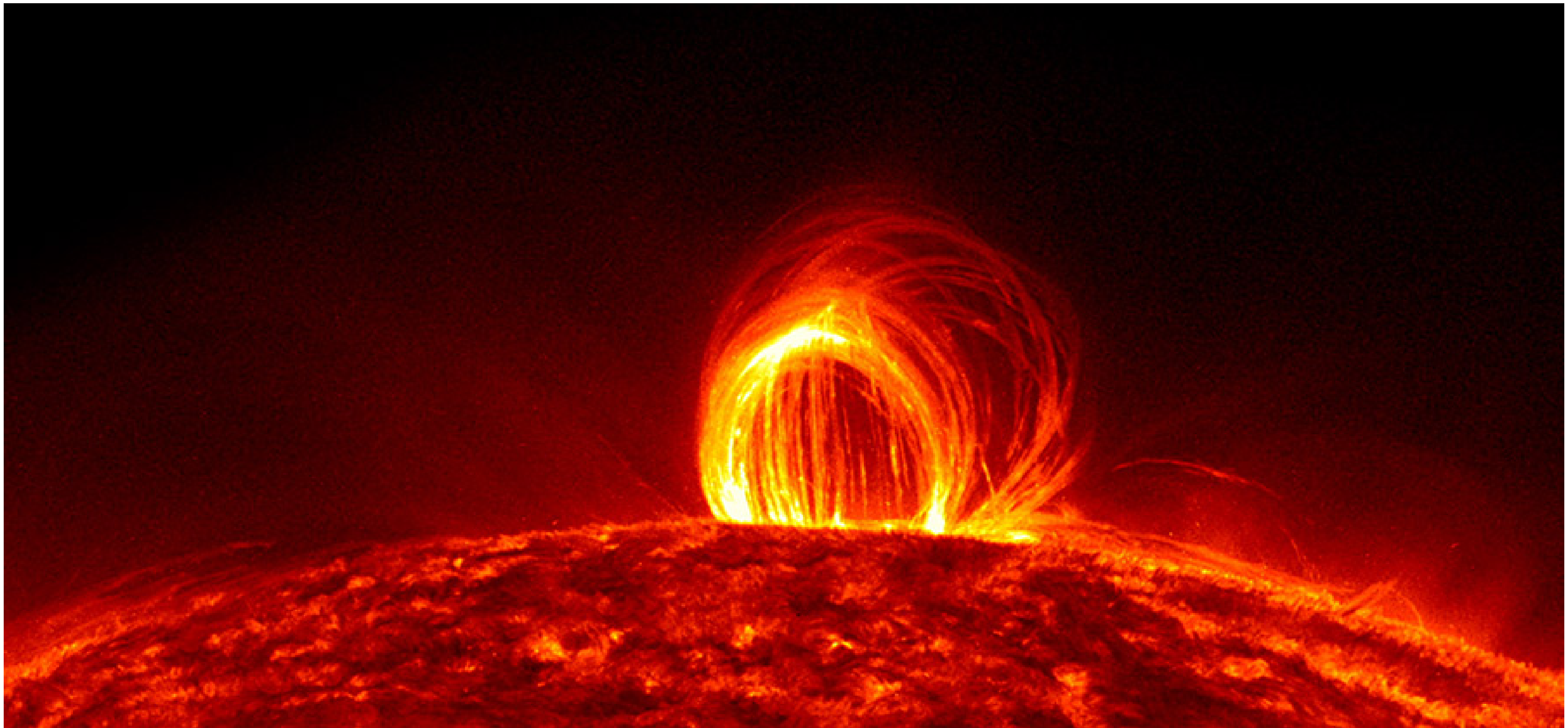
• The Sun is surrounded by three outer thin plasma regions: Photosphere (surface to 250 mi, 6500 - 400 K), Chromosphere (250-1300 mi, 4000 - 8000 K), Transition Region (60 mi, 8000 - 500,000 K) and the Corona (1300 - , 500,000 - a few Million K)

• Sun's inner layers: Core (15 MK), Radiative Zone and Convection Zone (2 MK) BCZ

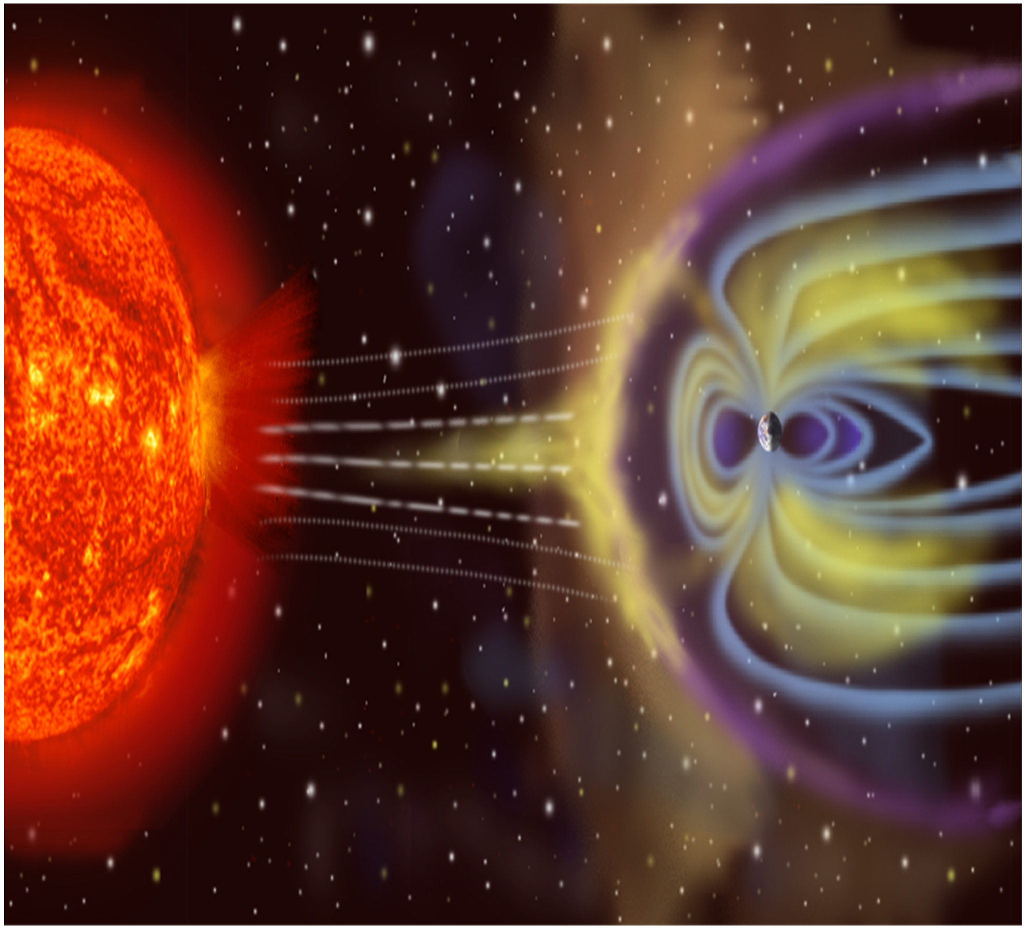
CORONAL TEMPERATURE & Fe XIII FORBIDDEN TRANSITIONS

• 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.

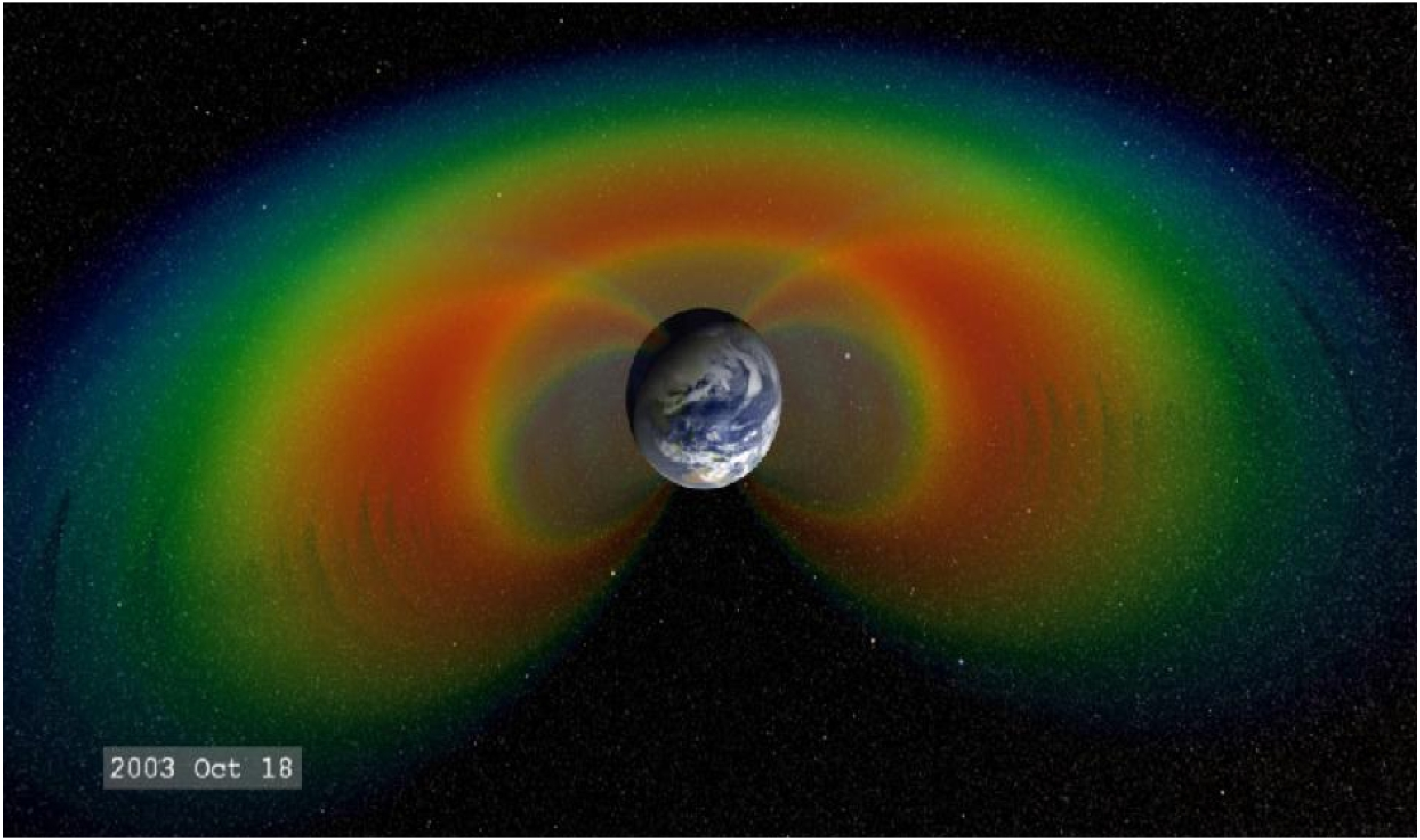


THE SOLAR STORM



- 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

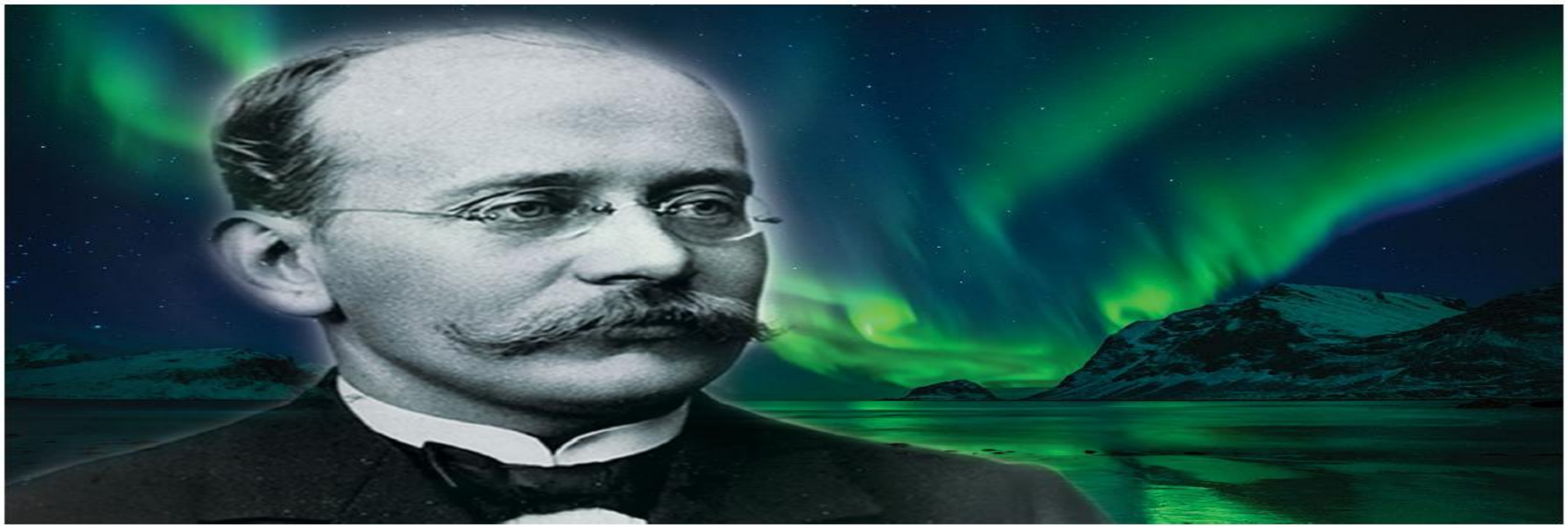
Birkeland dedicated and risked his life and fund to study Northern lights, that was associated with superstitious, and found the relation with solar spots

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.

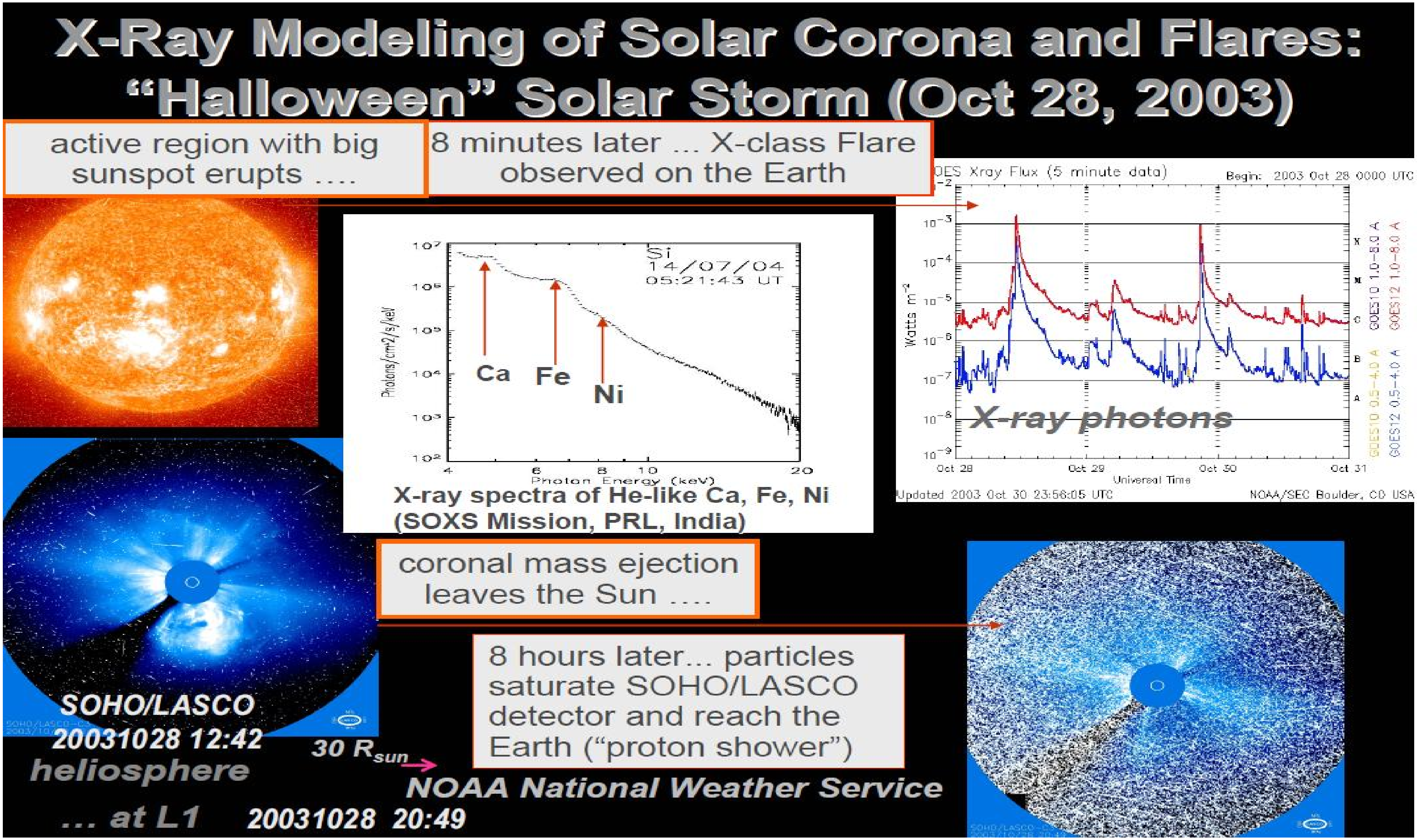
Born in 1867 in present-day Oslo, Norway, Birkeland's passion for electromagnetism grew serious in his teens under the mentorship of a math teacher. At age 18, he published his first research paper. A few years later, he became the youngest faculty member in sciences and mathematics at what was then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

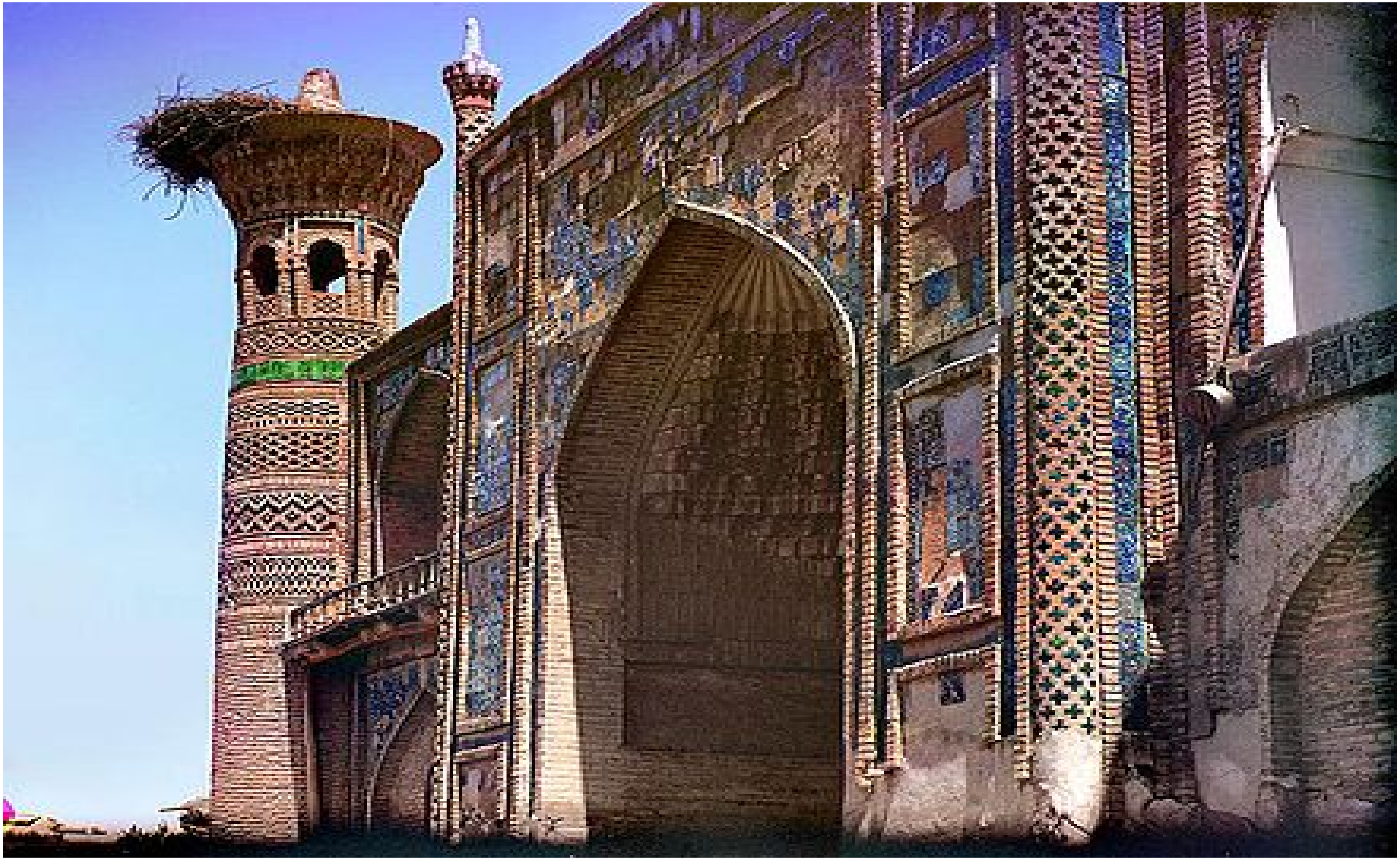
After his first expedition, Birkeland began

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



- 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

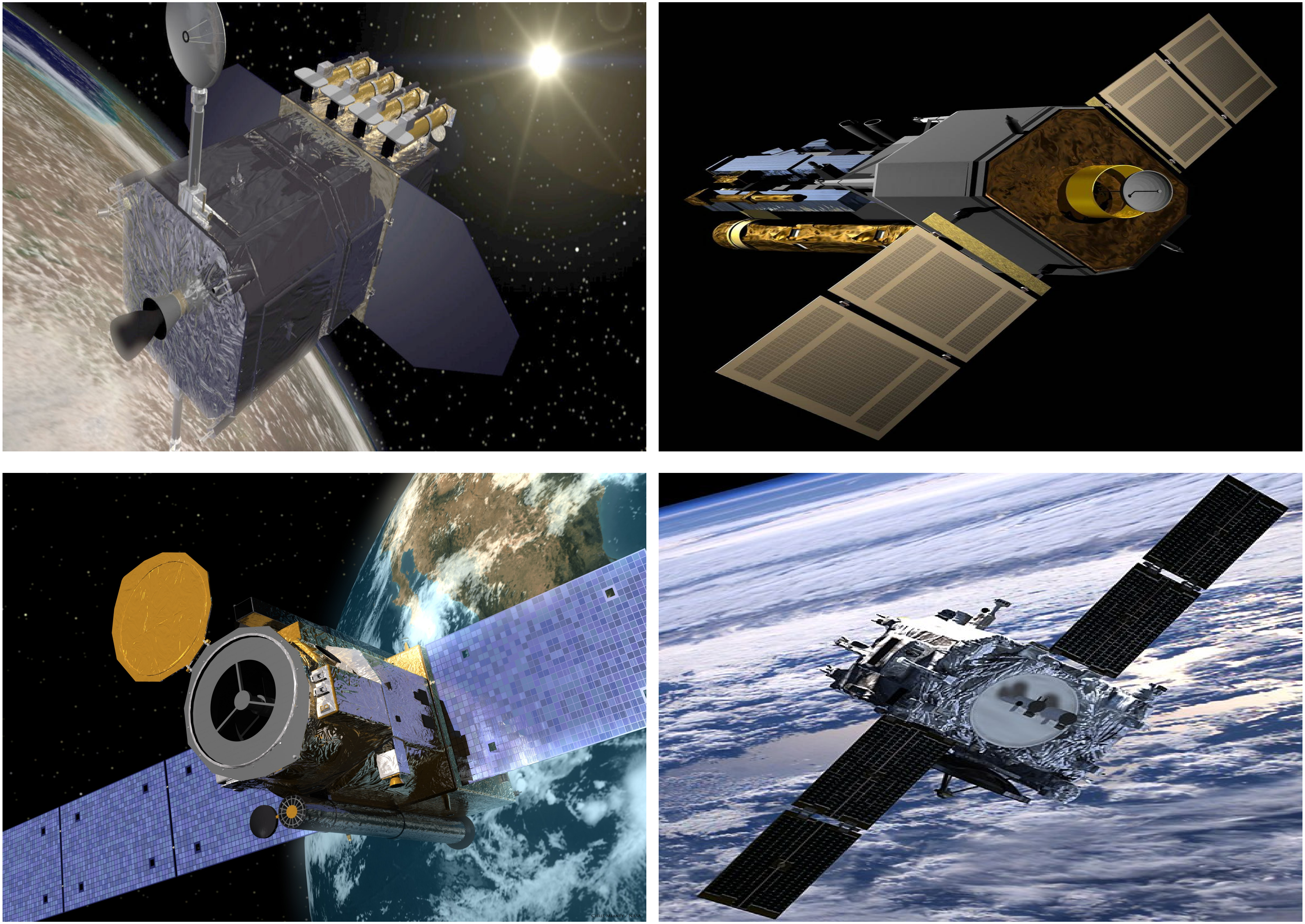
THE 1ST OBSERVATORY, SAMARKAND, 1420, BY MUSLIM RULER ULUGH BEG (Iran has an older model)



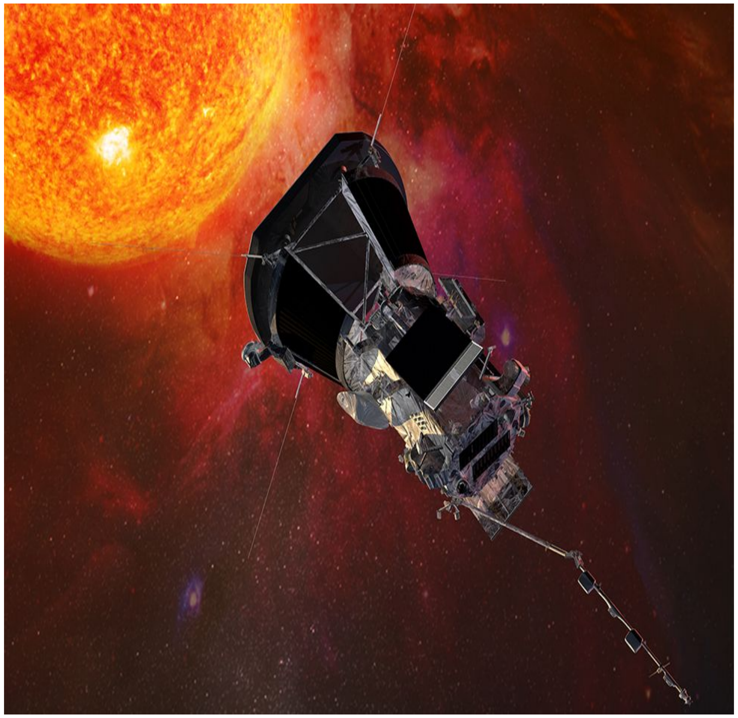
- Ulugh Beg built the madrasa in 1420 in Samarkand and extended it to an observatory
  - Beg himself cataloged over 1000 stars.

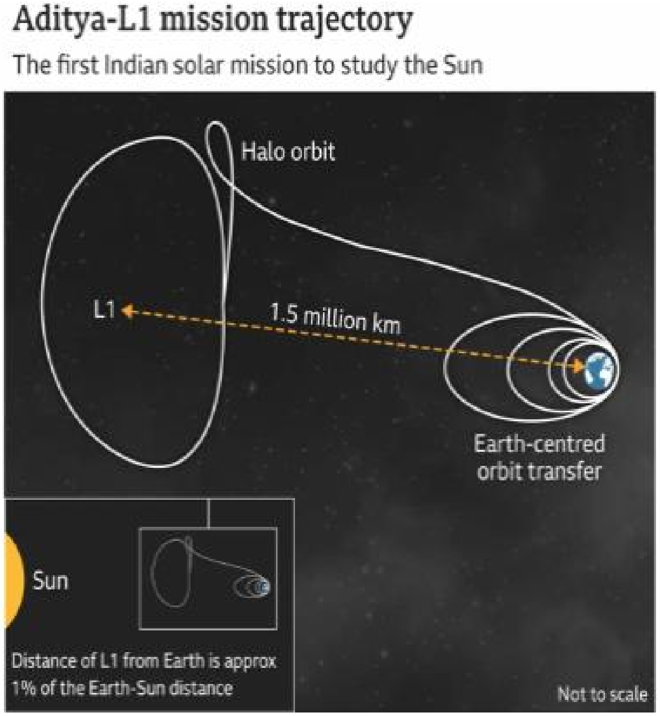
DEDICATED OBSERVATORIES FOR THE SUN

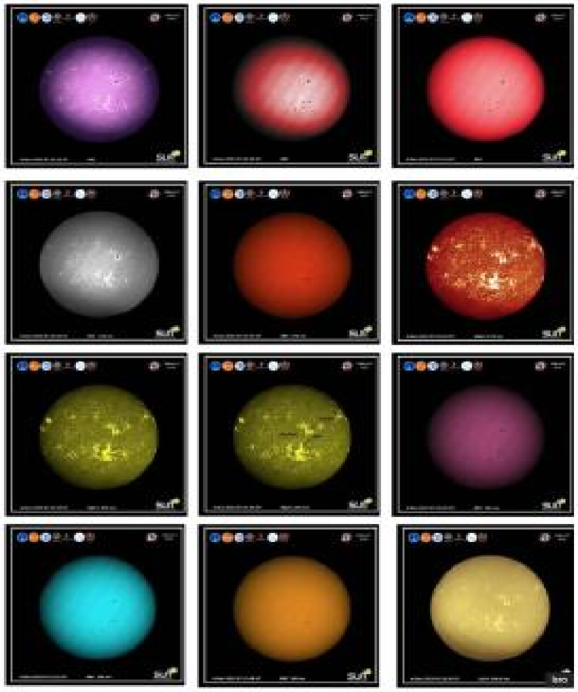
LT: SDO, RT: SODO, LB: HINODE, RB: STEREO



DEDICATED OBSERVATORIES FOR THE SUN
PARKER SOLAR PROBE & ADITYA L1

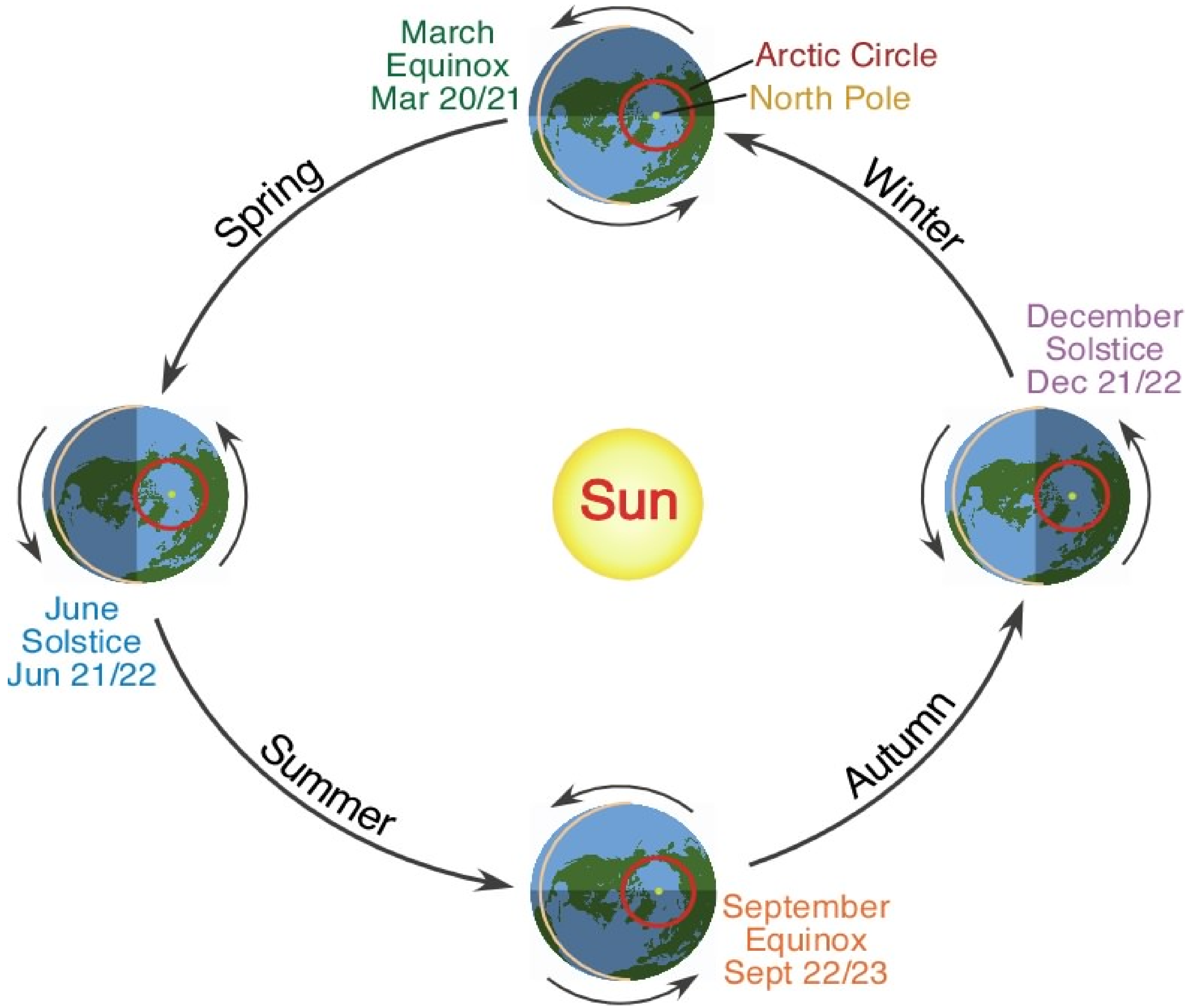






- L: Parker Solar Probe makes historic pass through Sun's atmosphere withstanding intense heat.
  - A satellite/ spacecraft goes around the earth several times, each time making a longer elliptical loop by the gravitational push, until going straight toward the object - path of Indian spacecraft Aditya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

The SUN, Our STAR



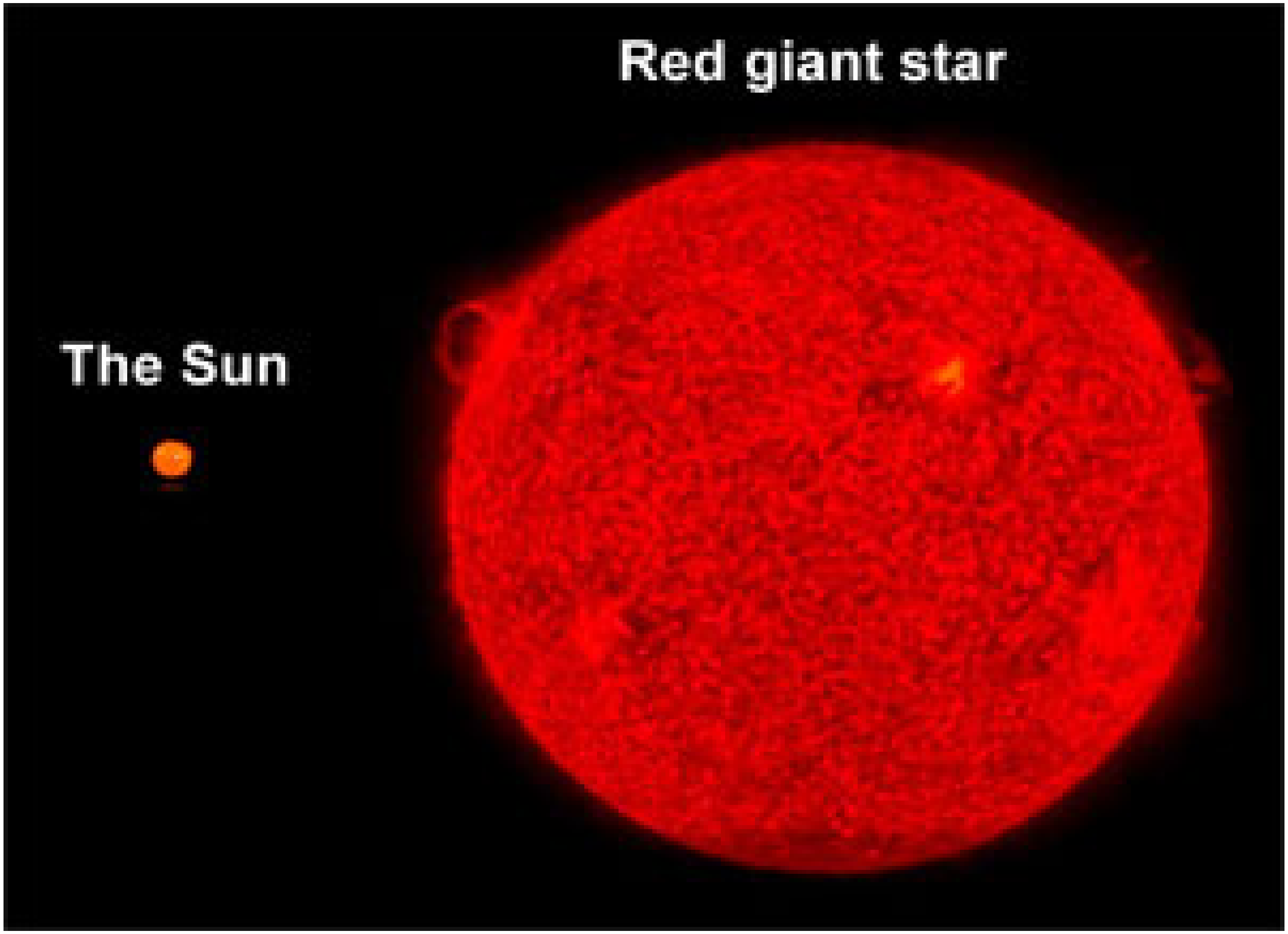
- Because of earth's tilt, we have very rich seasons

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 $\sim$ 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

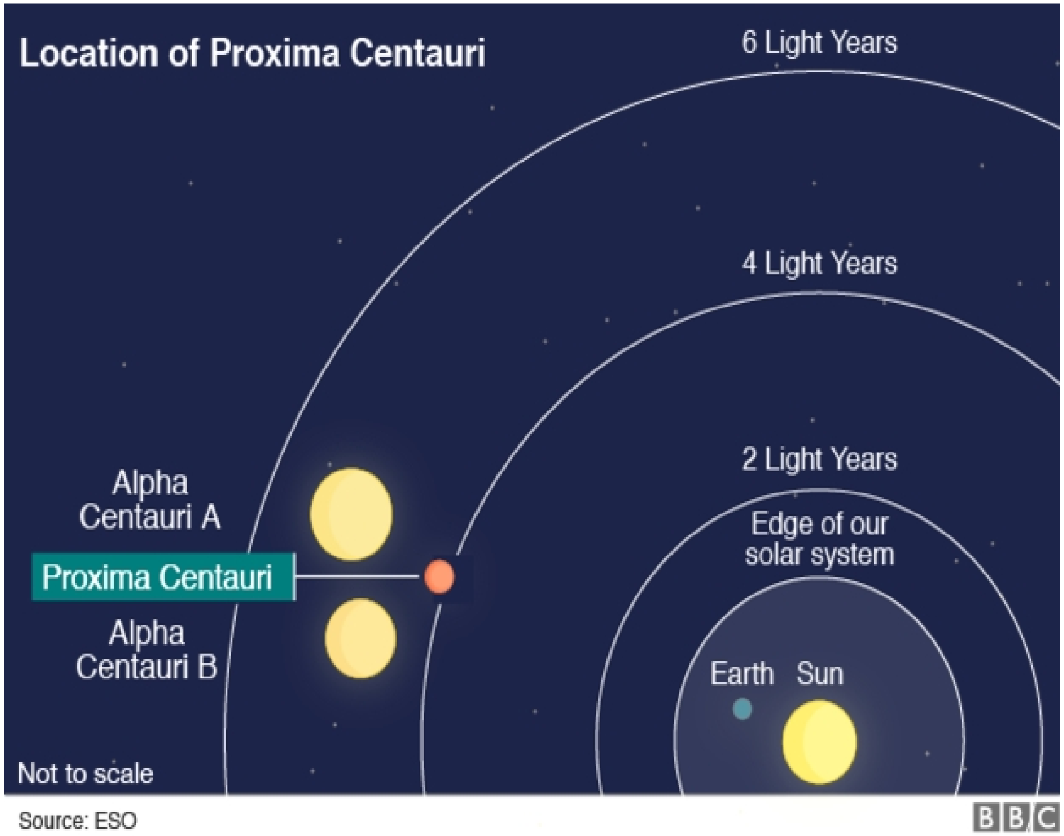
PLANETARY NEBULAE - Endpoint of a Star [PNe K 4-55 below]

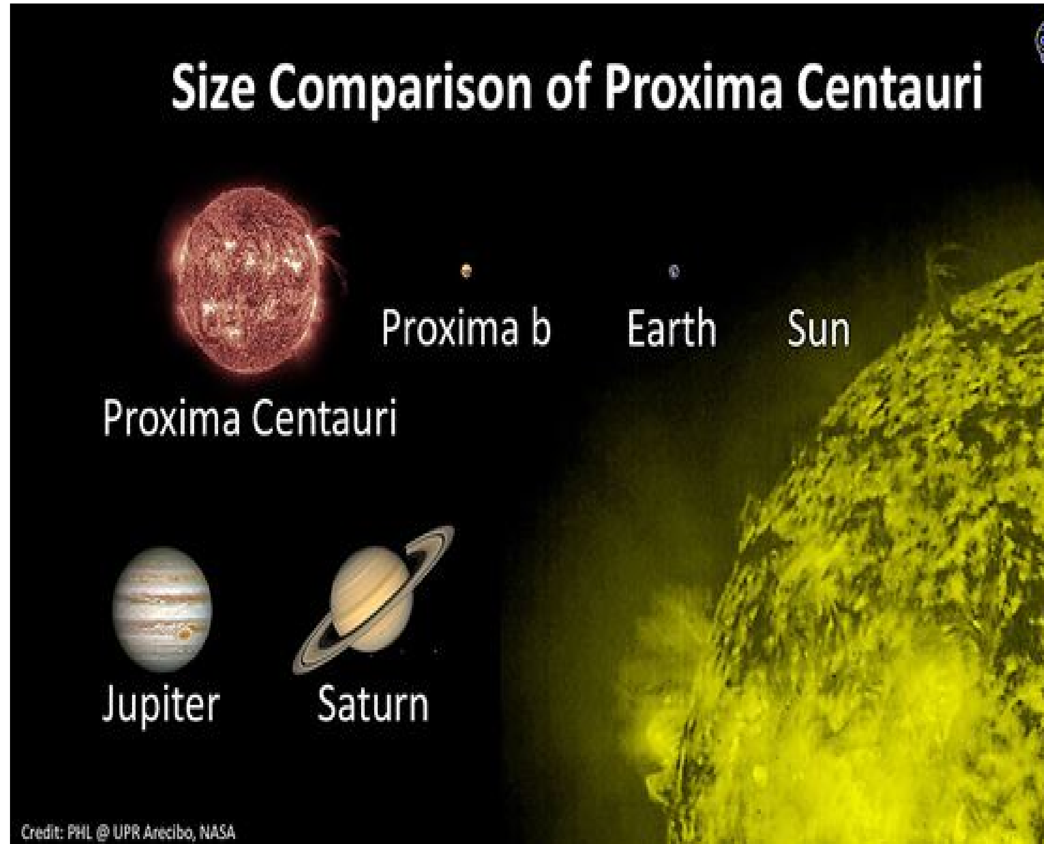
- Condensed central star: very high T $\sim$ 100,000 K ($>>$ T $\leq$ 40,000 K - typical star). Envelope: thin gas radiatively ejected & illuminated by central star radiation: red (N), blue (O). Lines of low ionization states - low ρ & low T
- Ionized gaseous nebulae: associated with birth & endpoint of stellar evolution $\longrightarrow$ 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 loosing all energies

OUR INTEREST: HABITABLE EXOPLANETS



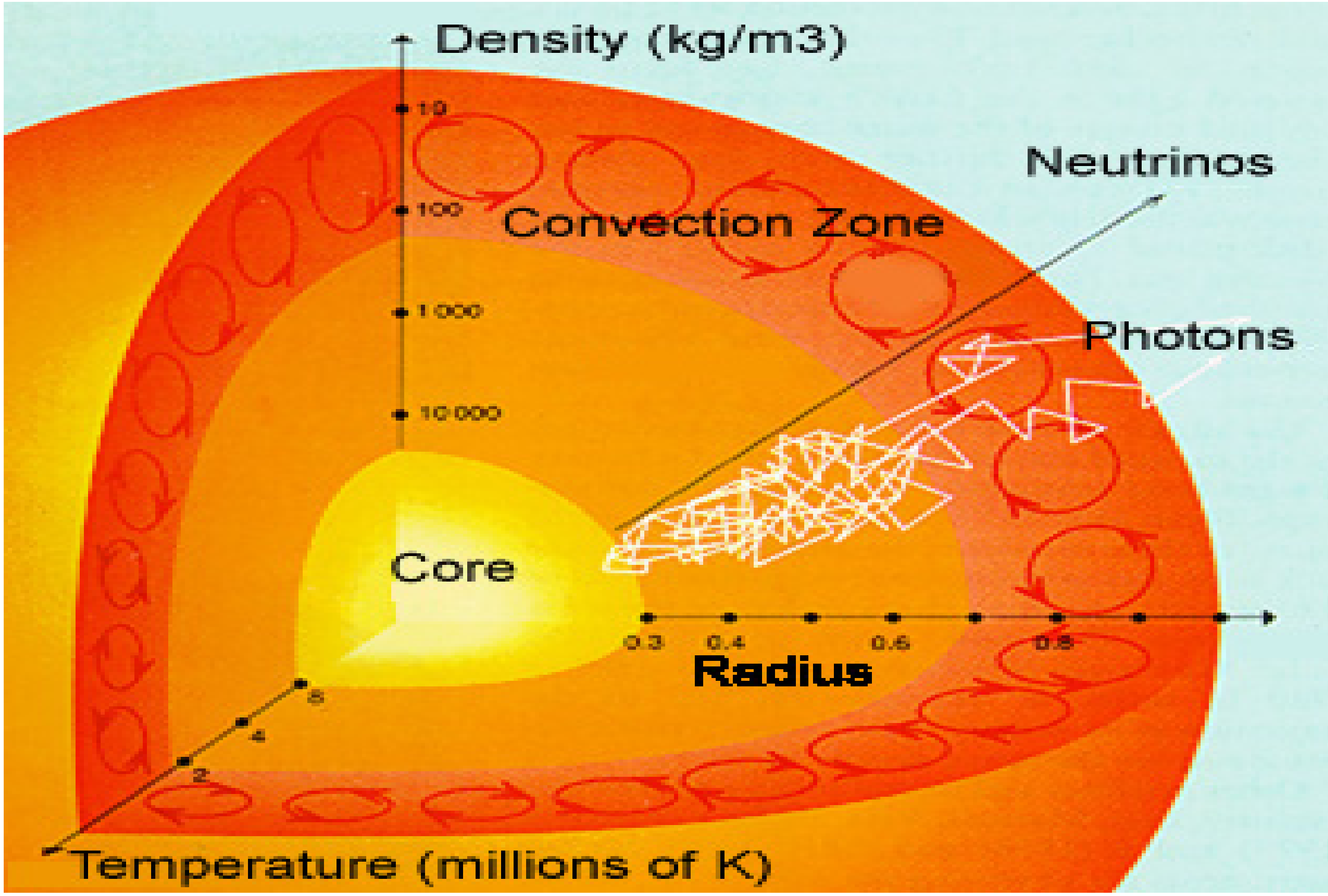


- Habitable planets where liquid water may exist
- Proxima b, exoplanet to our closest star Alpha Centauri (4 ly away: Earth-like in size, hard & rocky surface, possibility of liquid water & temperature similar to us

\- But a spacecraft using current technology will take 18 thousands of years to reach it → New idea for 20 years

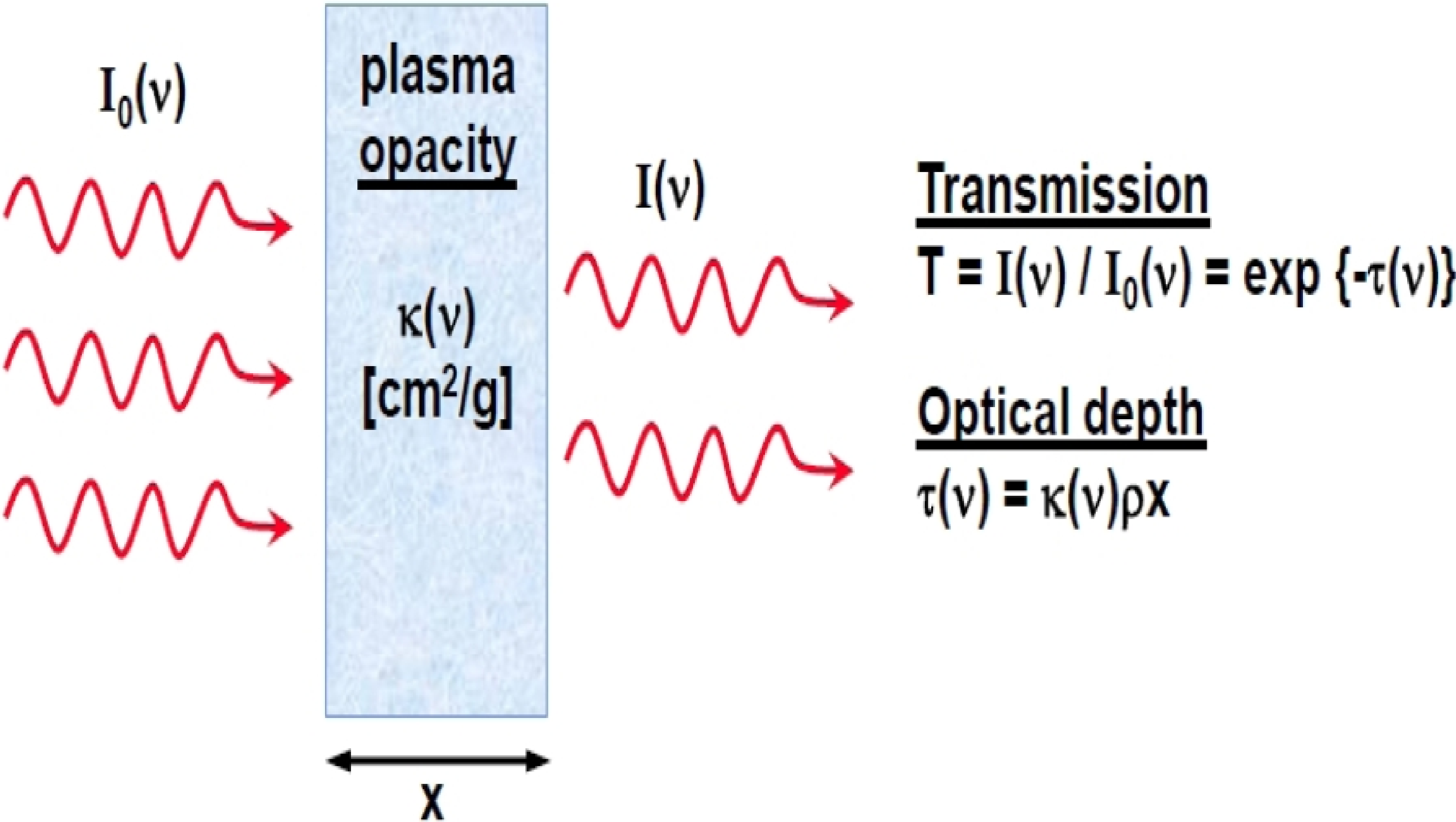
It was calculated that Proxima Centauri was moving around 3 to 5 mph toward • 1 in 5 sun-like stars have an earth-sized planet in the habitable zone → potentially 11B planets exist in Milky Way

SOLAR PLASMA OPACITY & ELEMENTAL ABUNDANCES



• 3 regions of the Sun: 1) Core: 15 mK, 150 g/cm^3 - 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

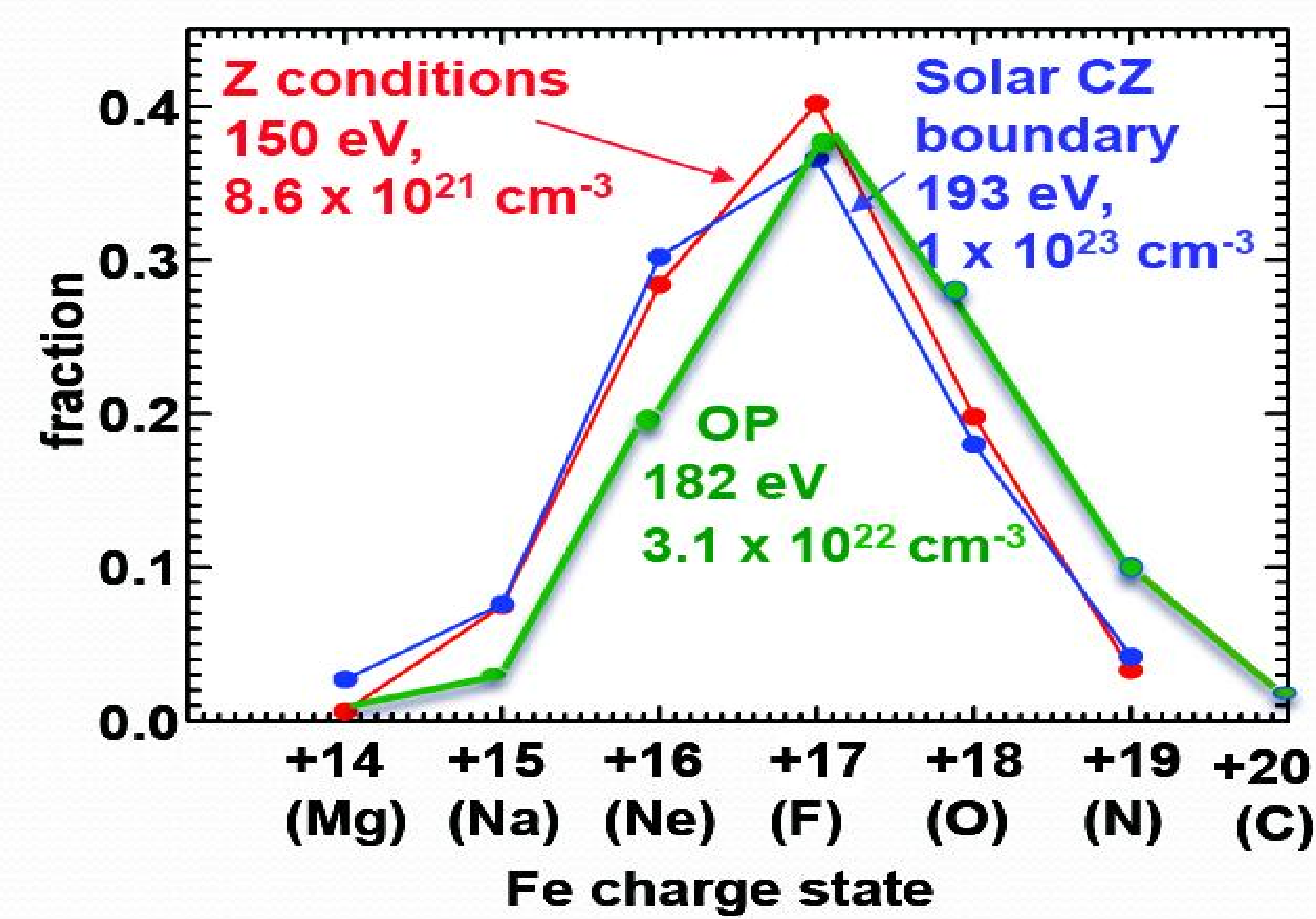
PLASMA OPACITY



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

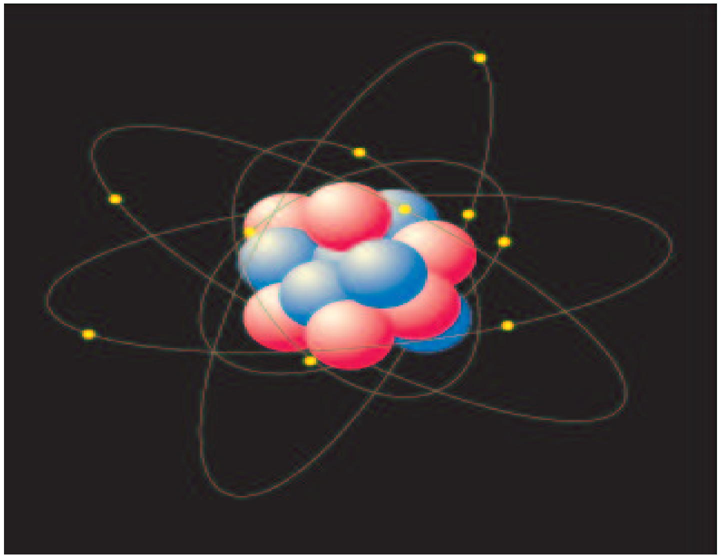
• Fe - VALVE FOR RADIATION TRANSFER

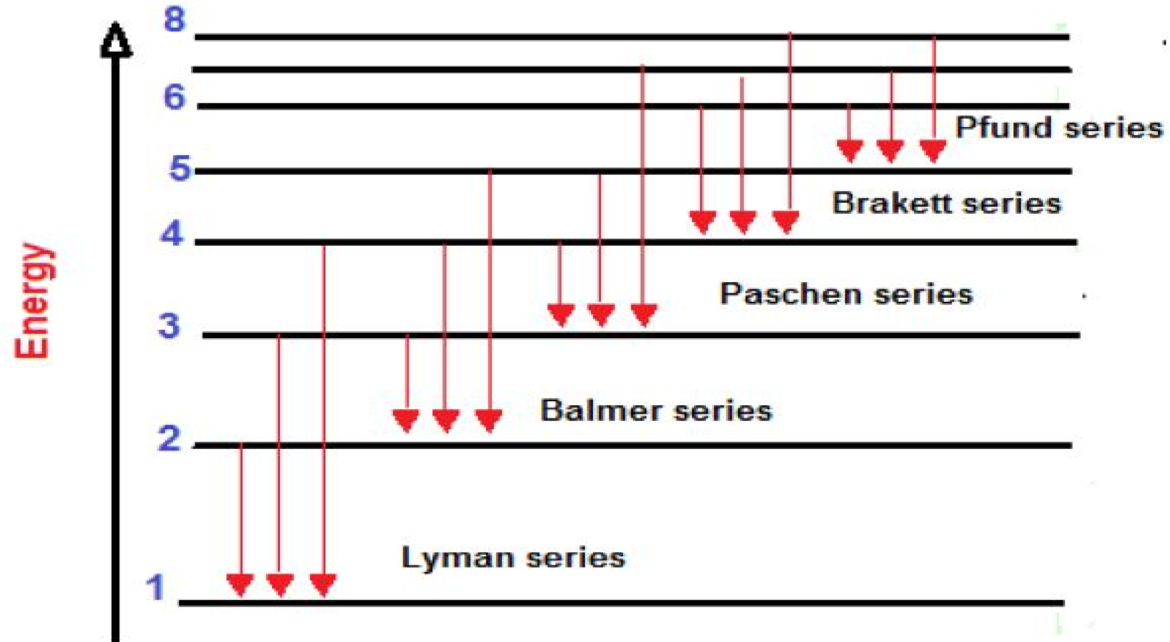
Ionization fractions at Z and solar BCZ conditions

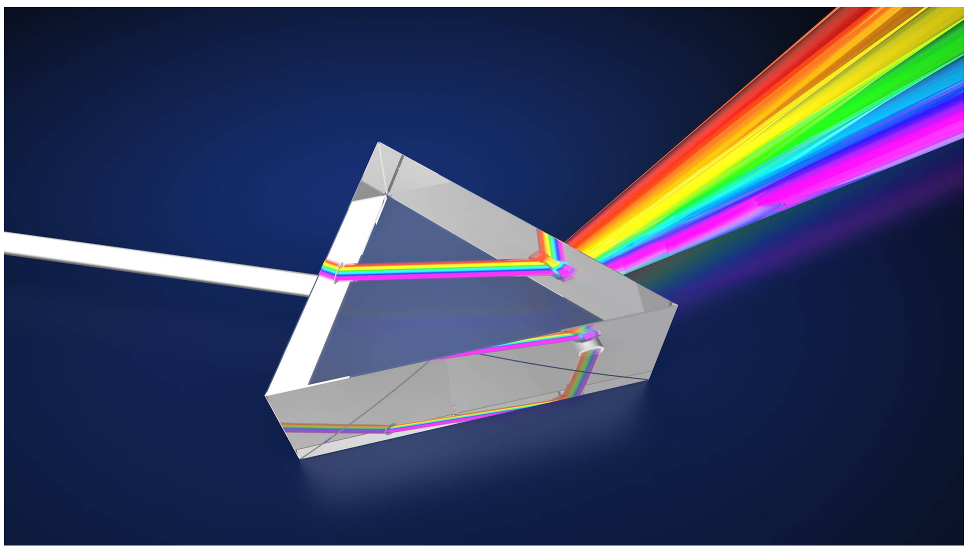


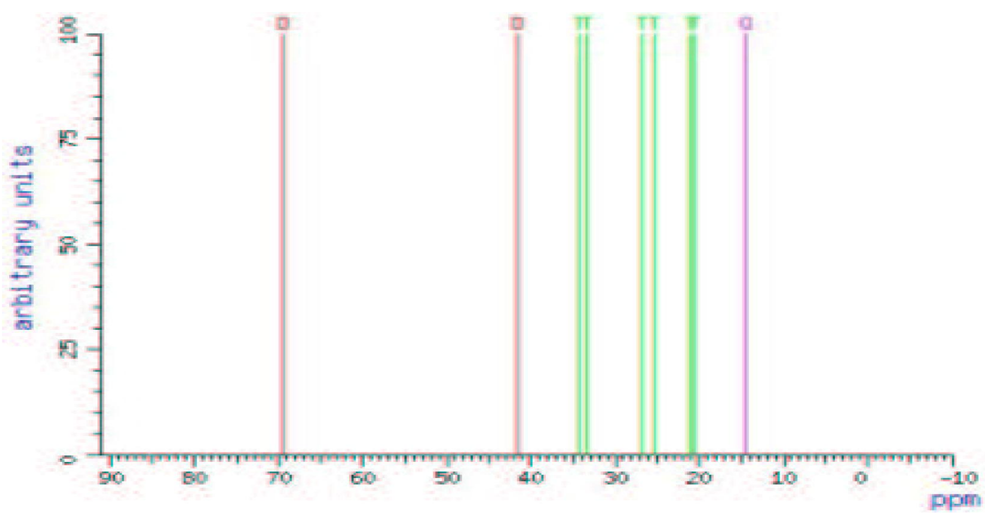
Model produces the correct change states enabling opacity models tests i) Charge state distribution, 2) Energy level description, but high density studies require further progress (Adapted from J. Bailey)

RADIATION FROM ATOMS & SPECTRUM





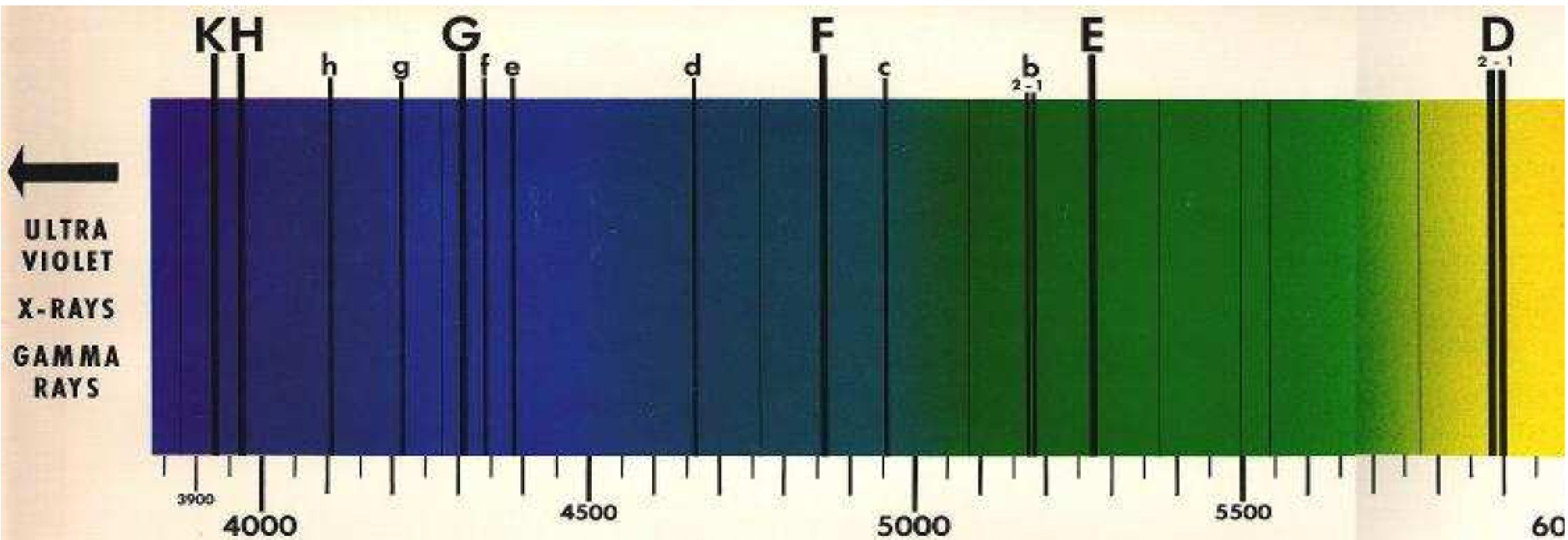




- Energy levels are quantized
- An electron can be excited to higher levels. While dropping down, it gives out a photon. Radiation contains photons of many energies
- SPECTRUM: Splitting the radiation in to its colors: Rainbow, C lines

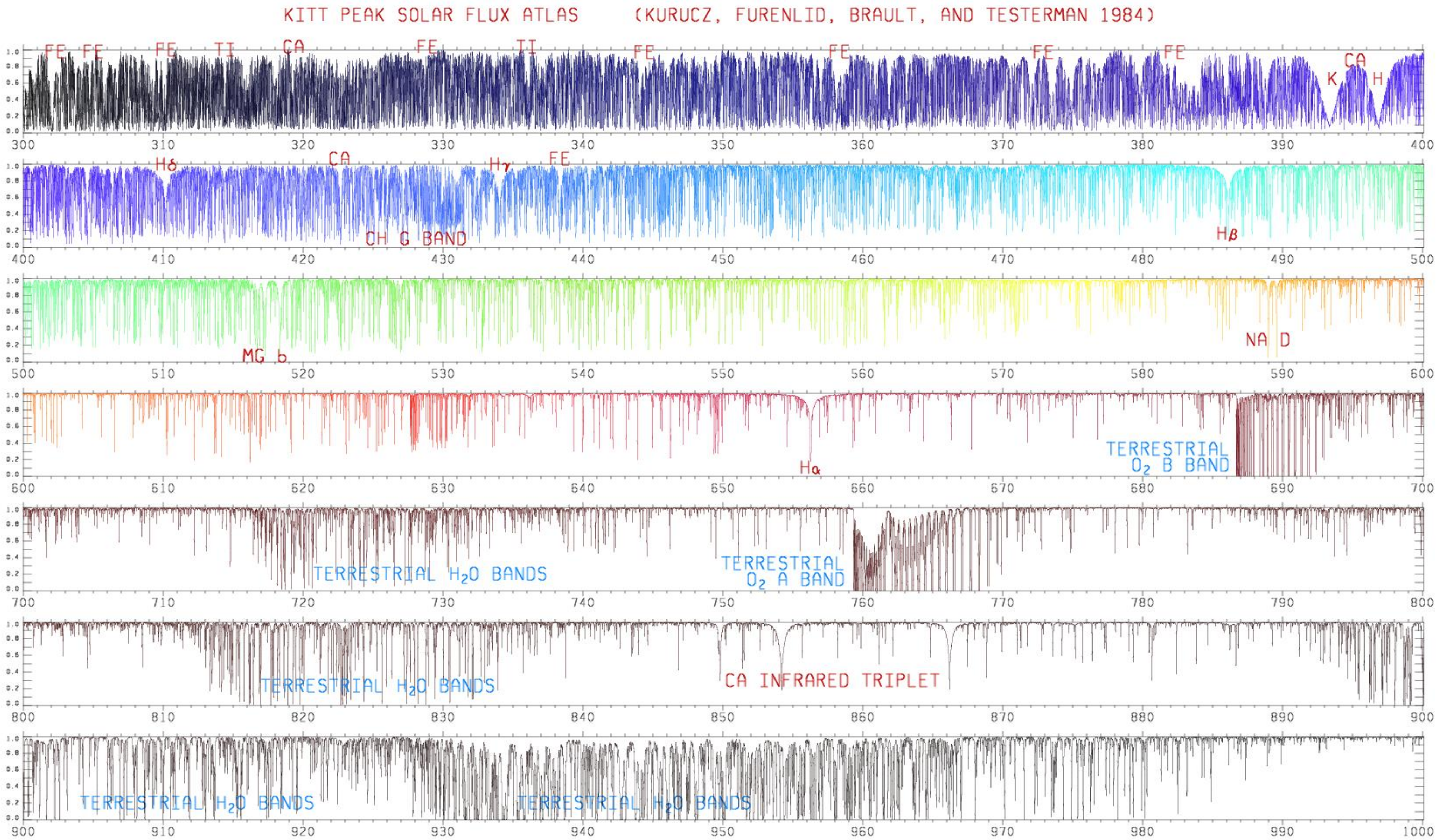
SOLAR SPECTRA: ABSORPTION & EMISSION LINES

- 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



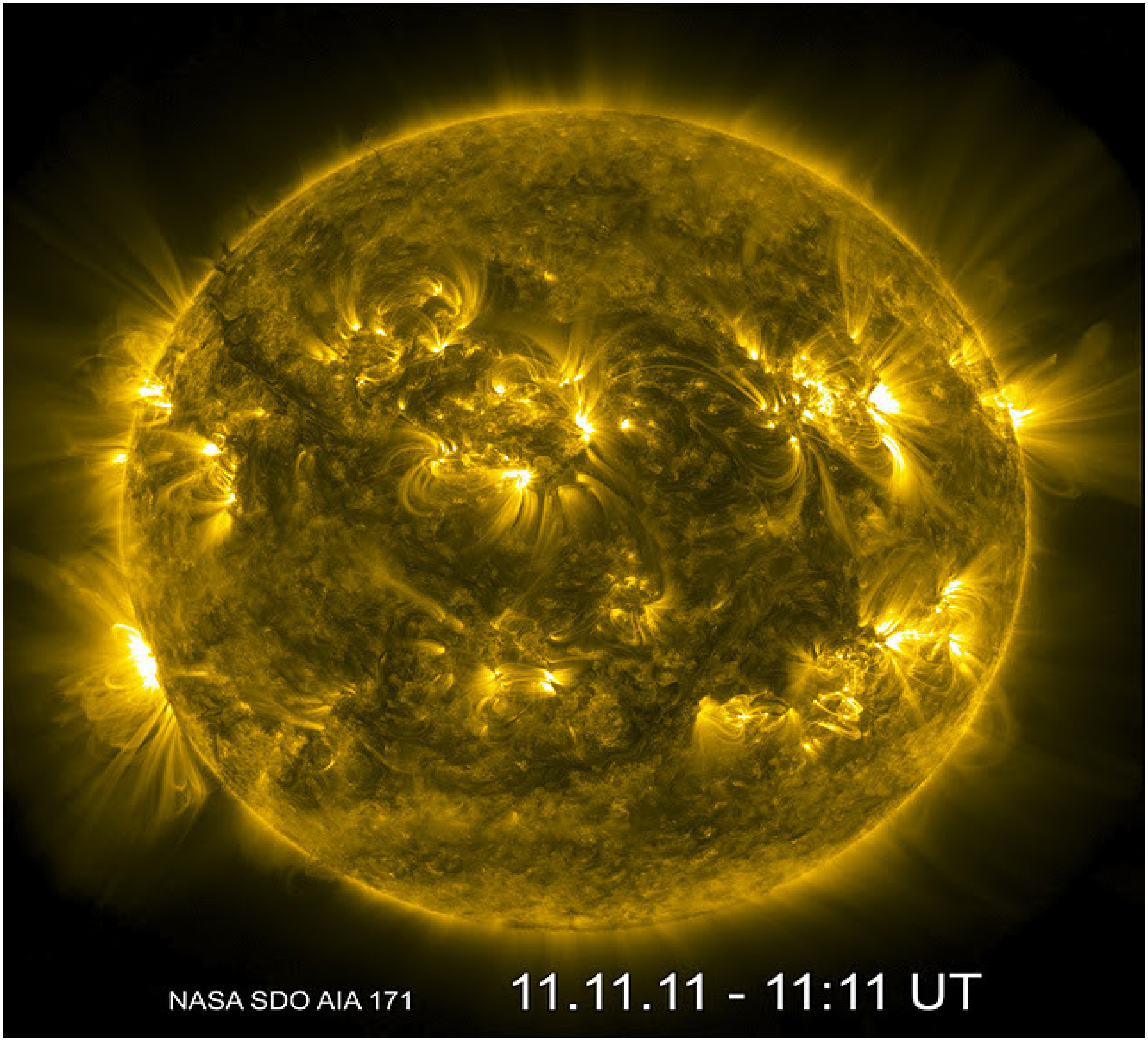
- Fraunhofer (1815) observed lines in the solar spectrum & used alphabet for designation
- Later spectroscopy with quantum mechanics identified them: A (7594 Å,O), B (6867 Å,O) (air), C (6563 Å H), D1 & D2 (5896, 5890 Å Na, yellow sun), E(5270 Å, Fe I), F (4861 Å, H), G(4300 Å, CH), H & K (3968, 3934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

SOLAR SPECTRUM AS SEEN FROM THE EARTH



- 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.

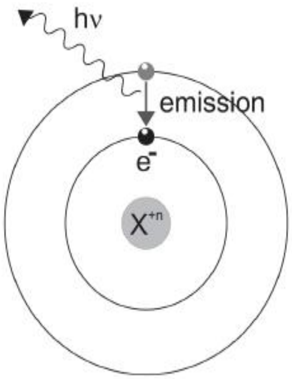
SUN IS A BLACK BODY OBJECT AT T=5570 K

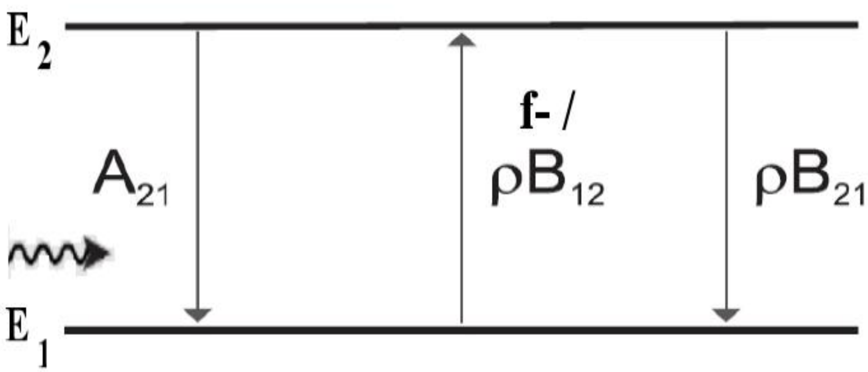


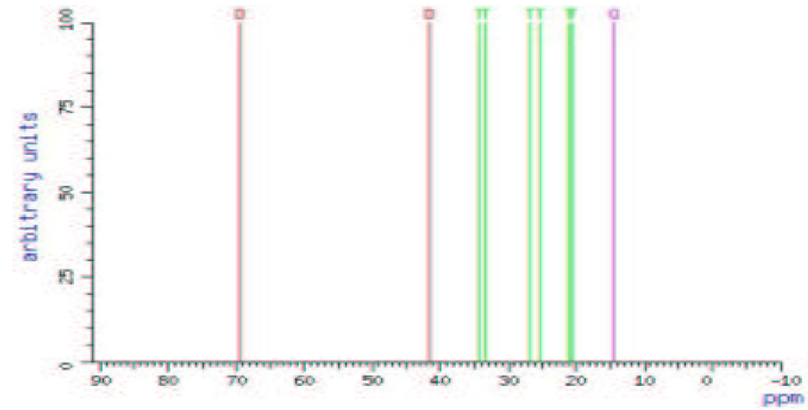
- Black body: Absorbs all radiation falling on it - the Sun
- Black body radiation: A black body at a uniform temperature emits a characteristic frequency distribution - Sun peaks at yellow color

Opacity: PHOTO-EXCITATION

$$\mathbf{X^{+Z} + h\nu \rightleftharpoons X^{+Z*}}$$







- **Atomic quantities (constant numbers):**

- A_{21} for Spontaneous Decay or Radiative Decay Rate

- f (Oscillator Strength) or B_{12} for Excitation

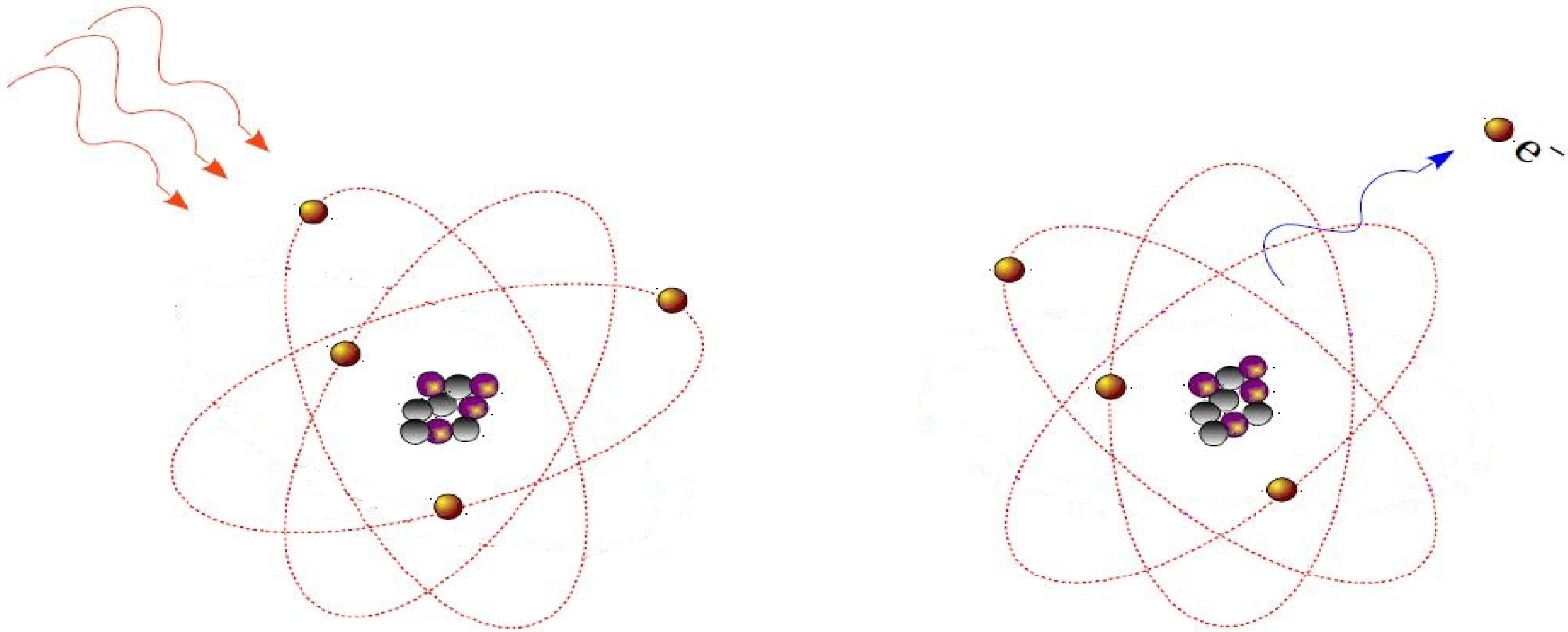
- **Monochromatic opacity (κ_ν) depends on f_{ij}**

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

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):

$$\mathbf{X^{+Z} + h}\nu \rightleftharpoons \mathbf{X^{+Z+1}} + \epsilon$$

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

$$\mathbf{X^{+Z} + h}\nu \rightleftharpoons (\mathbf{X^{+Z}})^{**} \rightleftharpoons \mathbf{X^{+Z+1}} + \epsilon$$

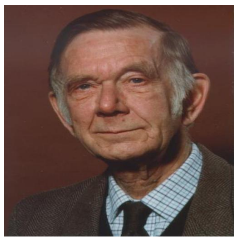
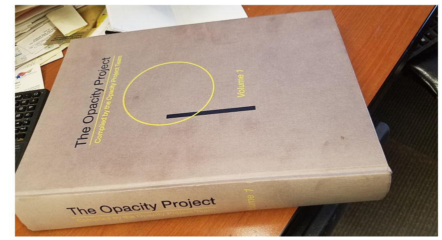
- κ_ν **depends on photoionization cross section** $\sigma_{\mathbf{PI}}$

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

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 -):**

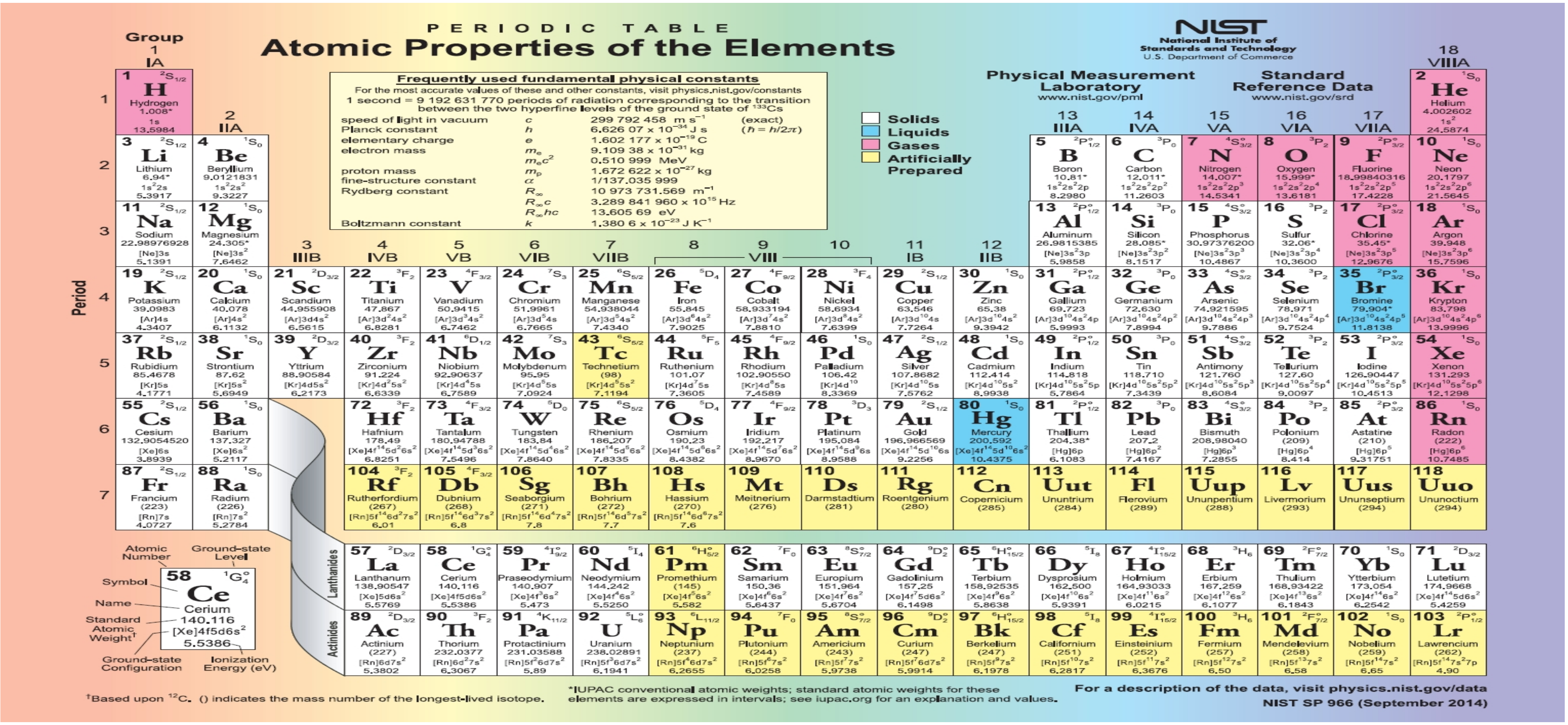
• The OP initiated and led by Seaton, - OP led to

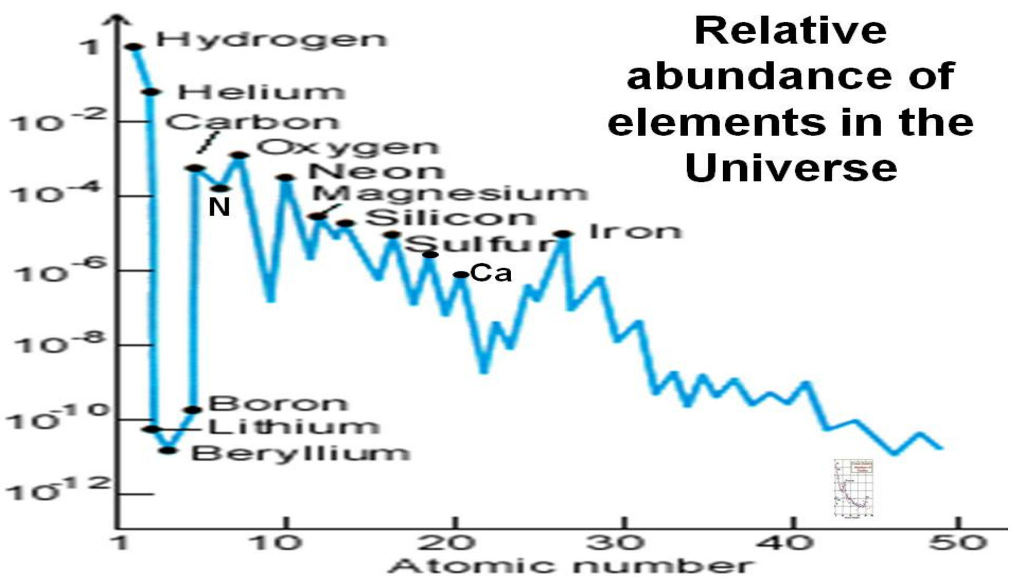
• **THE IRON PROJECT (IP) (1991 -)**

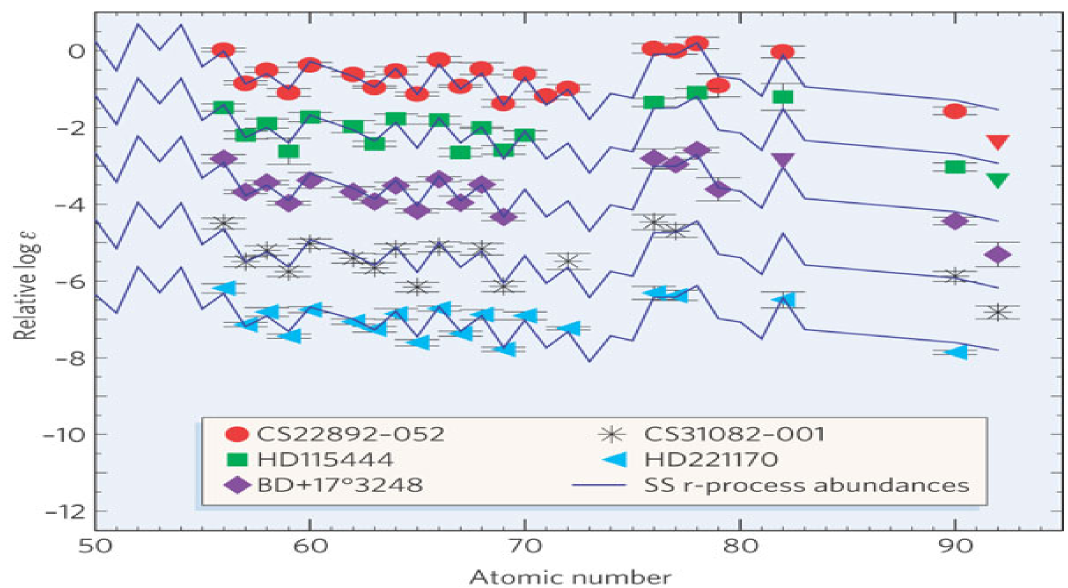
• International collaborators

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







• OP focused on all ionization states of H - Fe

OUTCOMES OF THE PROJECTS

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:

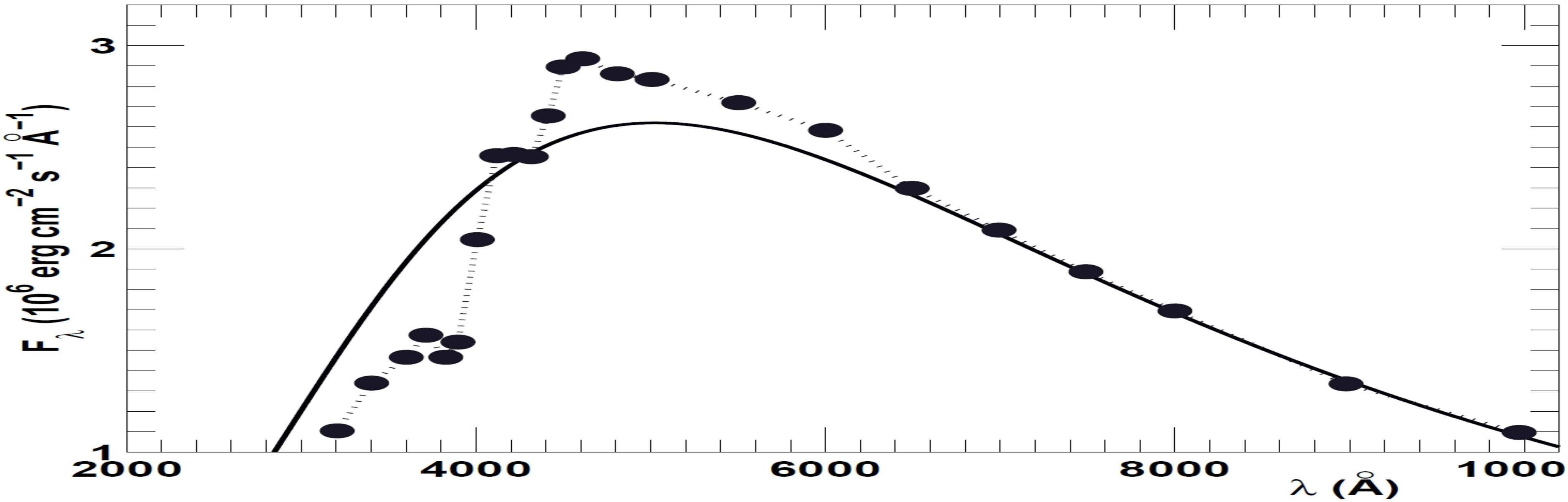
- The Opacity Project (TOP) series: 22 papers in JPB,
- The Iron Project (TIP) series: 68 in A&A + additional ones outside
- Book chapters, conference conference proceedings articles
- Book: The Opacity Project, The Opacity Project team, IOP (1995)
- Textbook: "Atomic Astrophysics and Spectroscopy" (A.K. Pradhan & S.N. Nahar, Cambridge University press, 2011)

- Atomic & Opacity Databases
- TOPbase (OP) at CDS: http://vizier.u-strasbg.fr/topbase/topbase.htr

  \- Energy levels, Oscillator Strengths, Photoionization Cross Sections
- TIPbase (IP) at CDS: http://cdsweb.u-strasbg.fr/tipbase/home.html

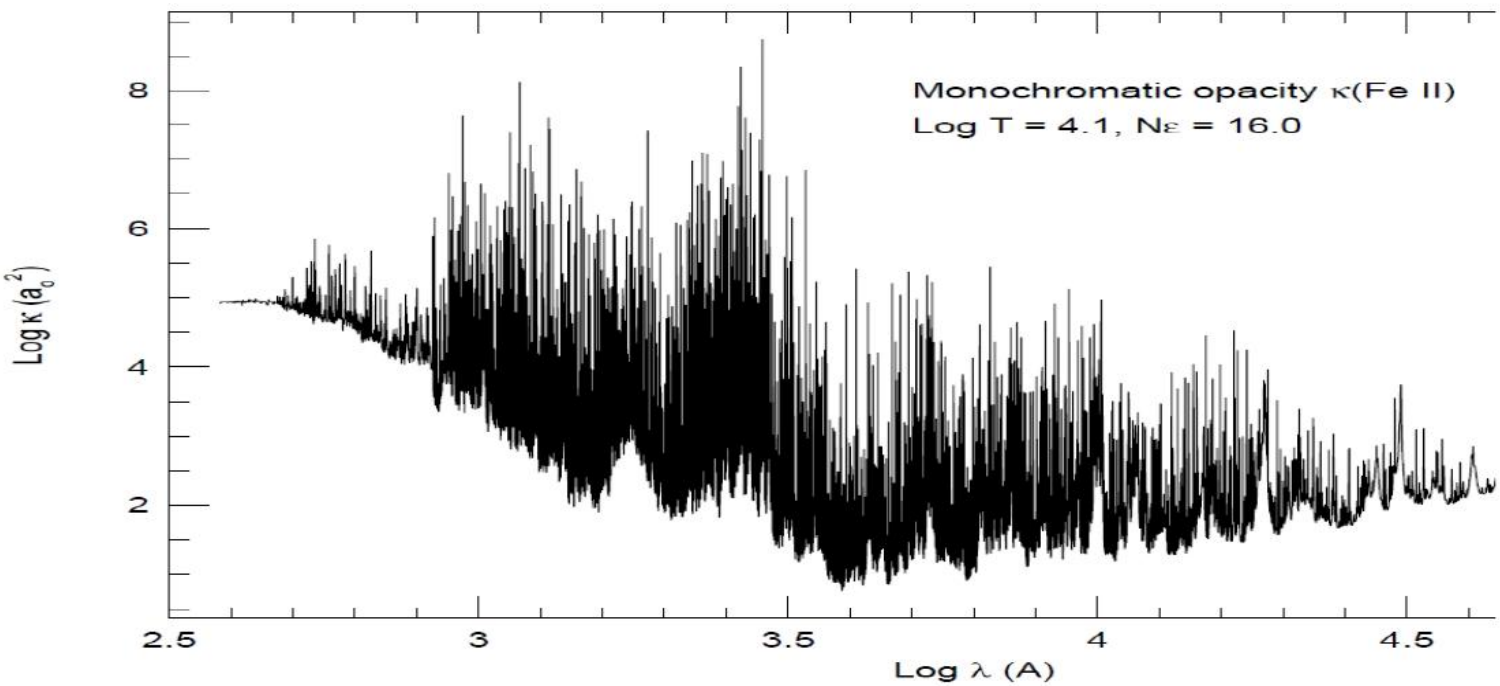
  \- Collisional Strengths for Electron Impact Excitation, and for Radiative Processes similar to TOPbase (not complete)
- OPserver for monochromatic opacities and program for mixtures at the OSC: http://opacities.osc.edu/
- NORAD-Atomic-Data at OSU: Latest radiative and electron-ion recombination data, http://norad.astronomy.ohio-state.edu

IRON ON THE SUN (Nahar & Pradhan 1993)



TOP: Black body radiation of the sun - the discrepancy below 4000 *Å*.

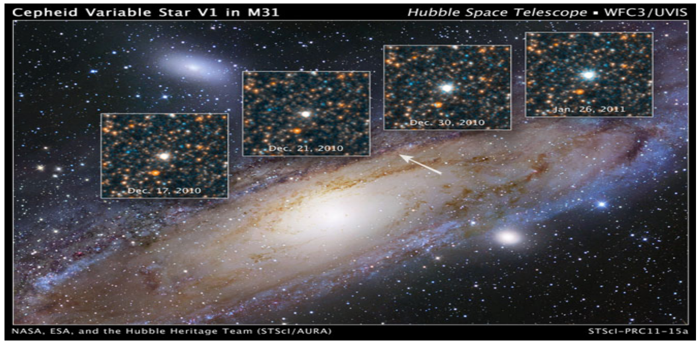
BOTTOM: Theory: High radiation absorption (opacity) by iron on surface



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

OP The OPACITY Project, IP The IRON Project

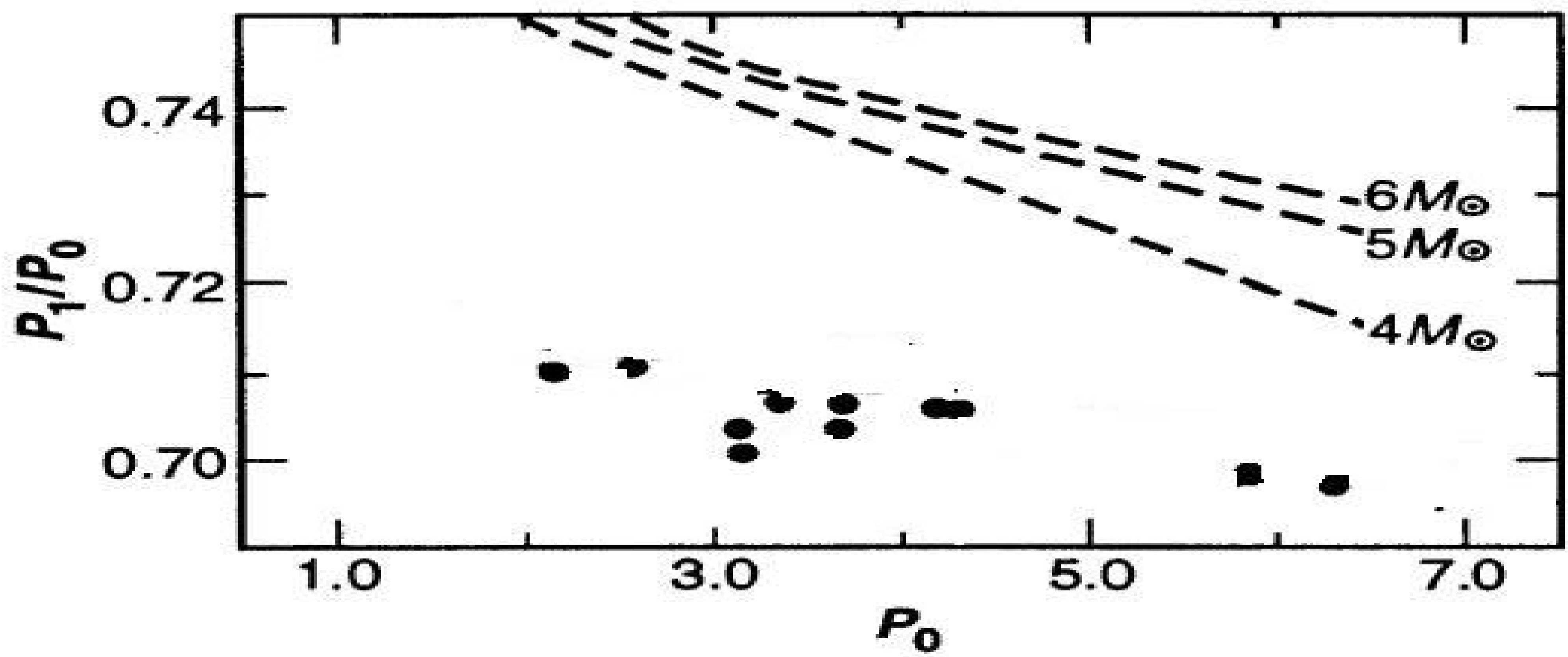
The OPACITY Project



The IRON Project

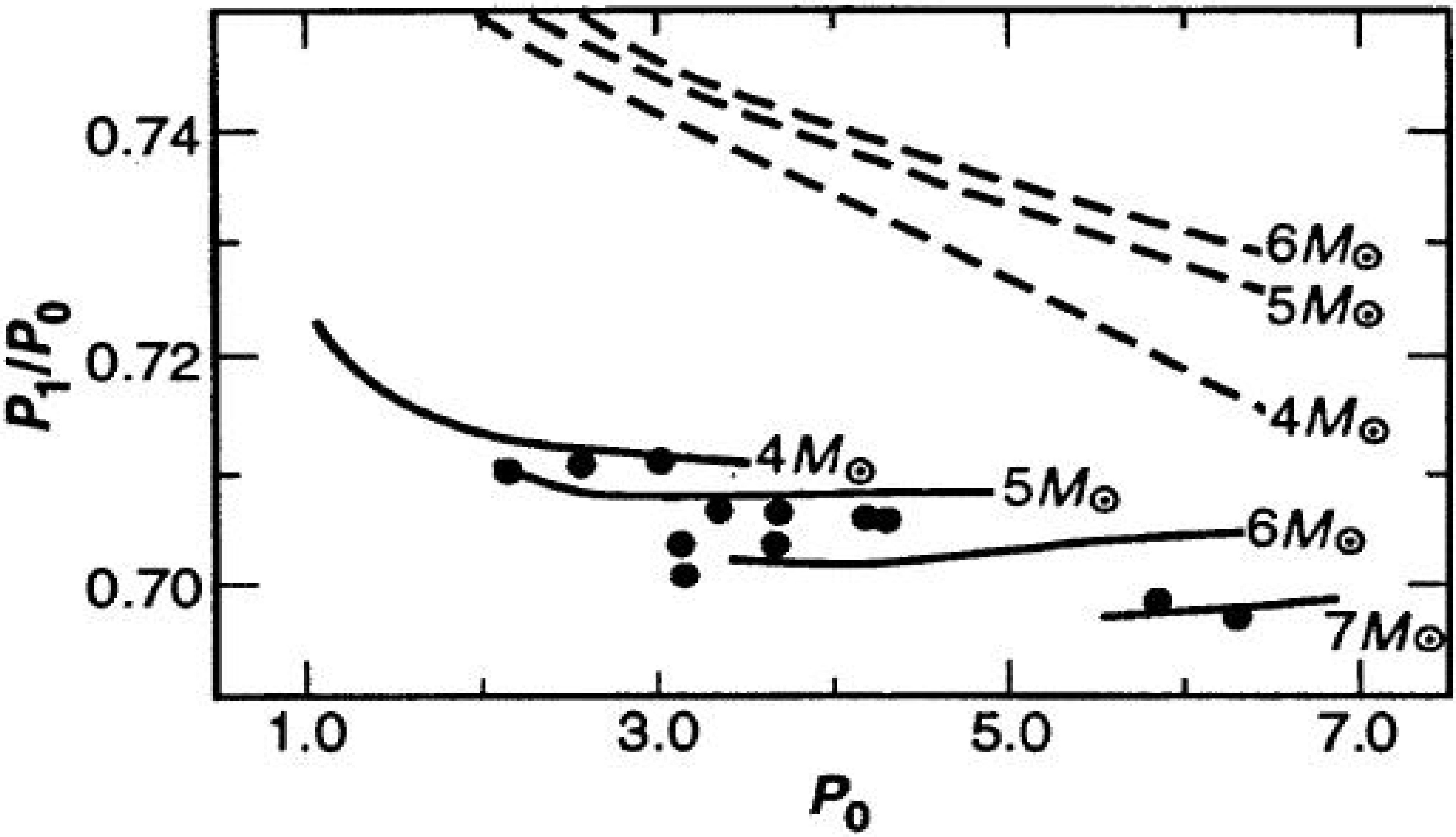
- **Cepheid are stars, larger than the Sun, and go through periodic brightness and dimming states which can last for days to months**
- **Luminosity ($M_{\rm v}$) is proportional to the mass and opacity**

Discrepancy in predicted pulsation periods of Cepheid stars - REQUIRED HIGHER METALICITY/ OPACITY



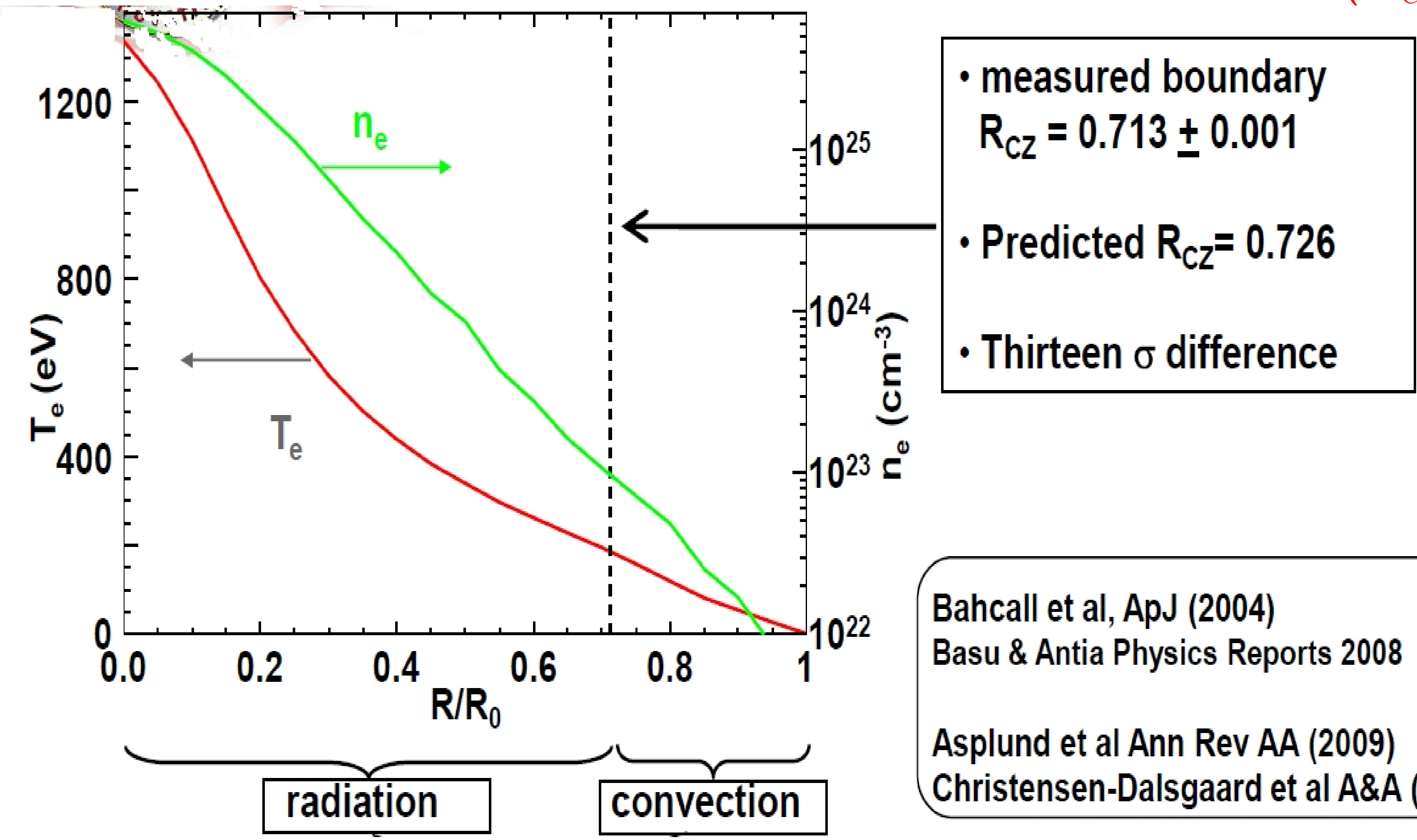
- **Astronomers plea for accurate atomic physics to find more metalicity**

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



- The project produced increased opacity
- Figure: Ratio of the observed 1st overtone(P1)/ fundamental(P0) 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})



Bahcall et al, ApJ (2004)
Basu & Antia Physics Reports 2008

Asplund et al Ann Rev AA (2009)
Christensen-Dalsgaard et al A&A (2009)

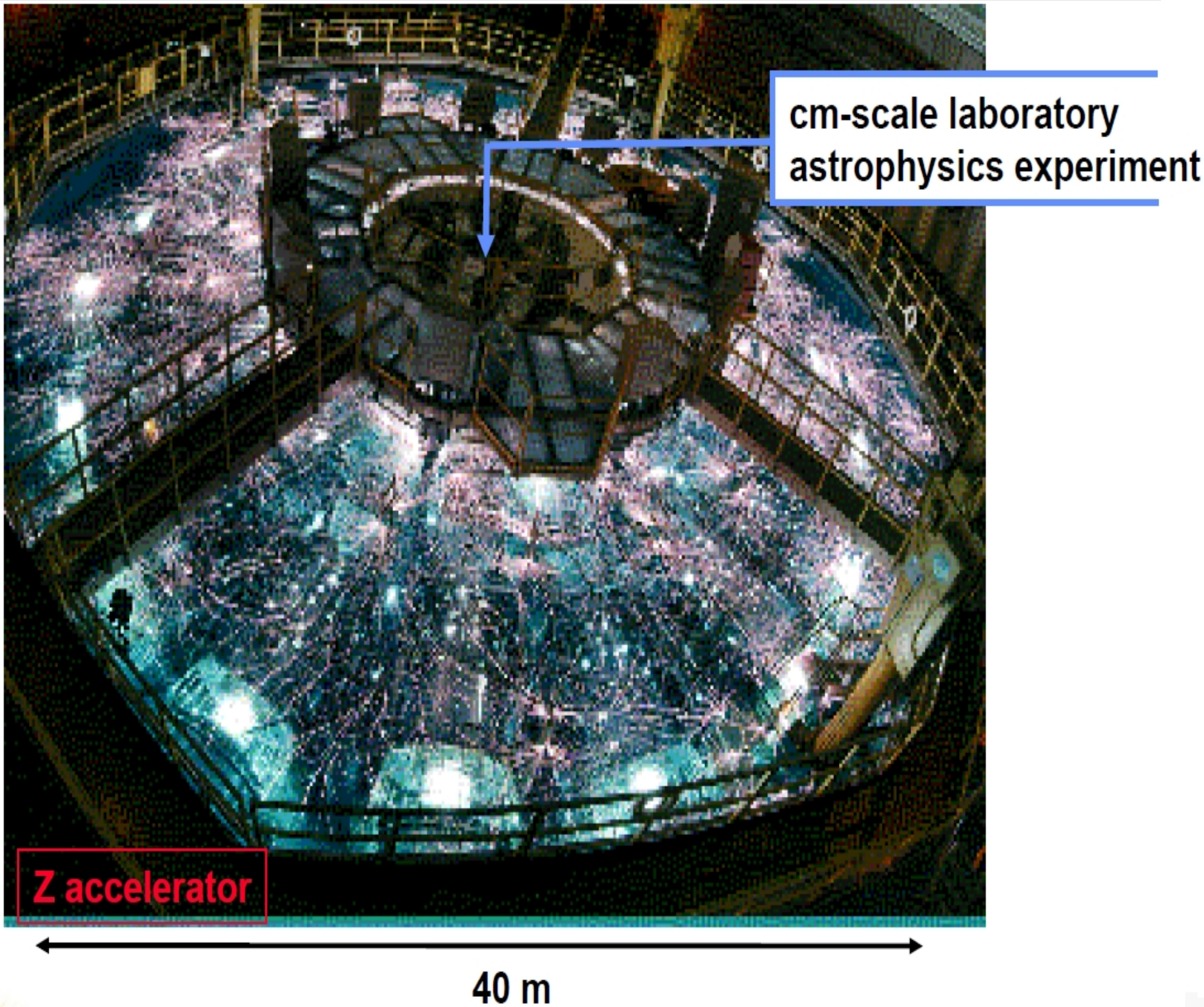
• Calculated from opacity using current atomic data, R_{CZ} = 0.726 - large (over 5600 mi difference) → changes solar structure

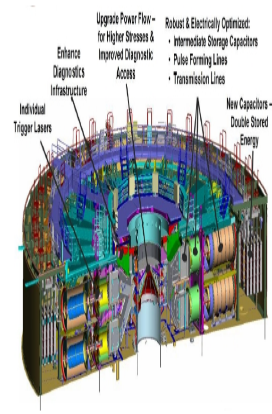
• Earlier opacities were incorrect by factors of 2 to 5 → inaccurate stellar models • Needs 10% overall increment in opacity (Bahcall et al 2005)• 3D model finds C, N & O, up to 40-50% lower (Asplund et al 2009) → MISSING PHYSICS

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

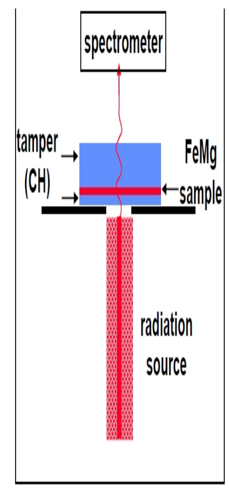




New Z

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

Z PINCH SET-UP, SANDIA NATIONAL LAB (2015)

- "Created the Sun on the earth": Plasma at T=190 eV $\sim$ 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. Bailey[1], T. Nagayama[1], G. P. Loisel[1], G. A. Rochau[1], C. Blancard[2], J. Colgan[3], Ph. Cosse[2], G. Faussurier[2], C. J. Fontes[3], F. Gilleron[2], I. Golovkin[4], S. B. Hansen[1], C. A. Iglesias[5], D. P. Kilcrease[3], J. J. MacFarlane[4], R. C. Mancini[6], S. N. Nahar[7], C. Orban[7], J.-C. Pain[2], A. K. Pradhan[7], M. Sherrill[3] & B. G. Wilson[5]

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

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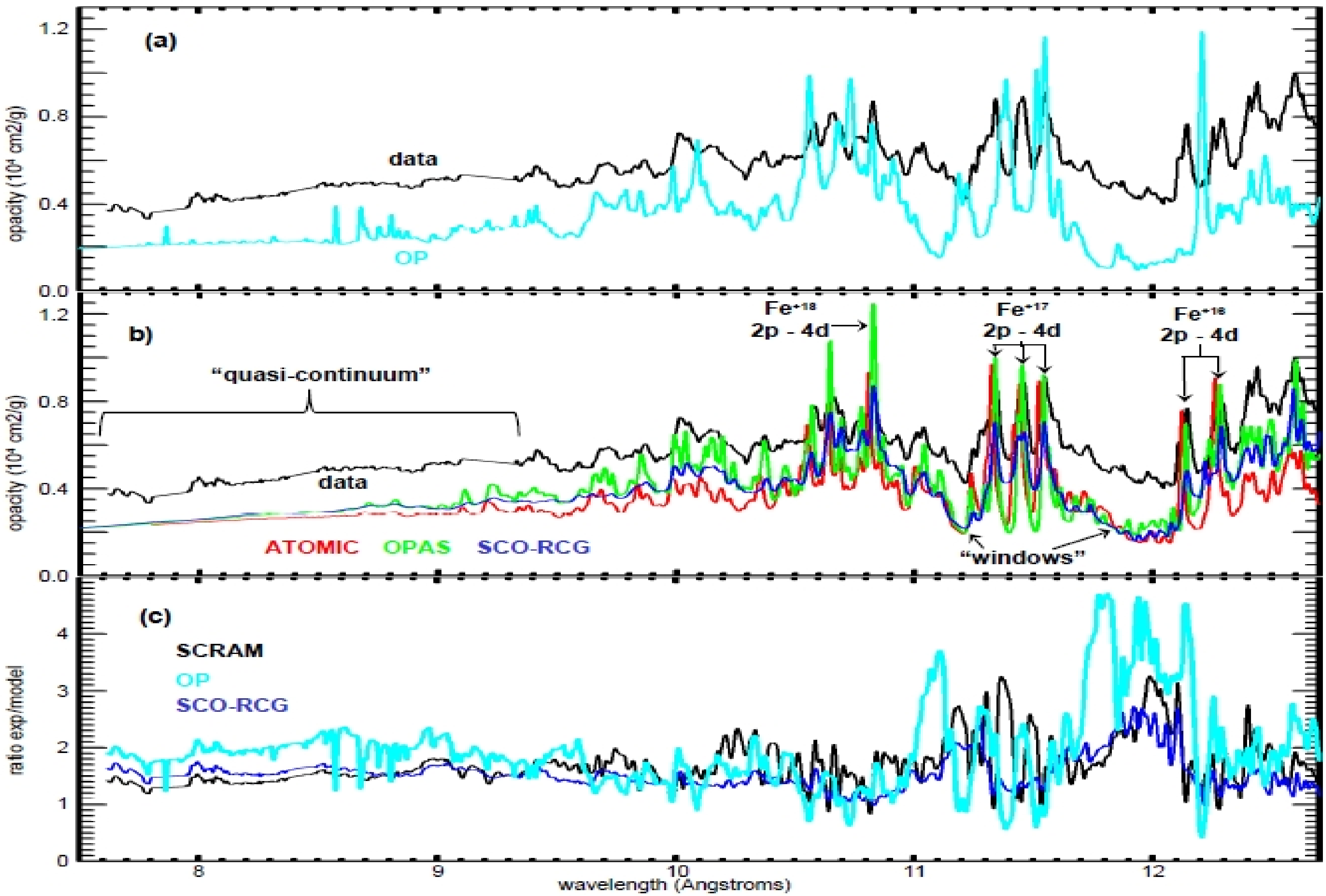
(Received 27 September 2015; revised manuscript received 12 February 2016; published 8 June 2016)

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 photo-excitations 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 photo-excitation-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.

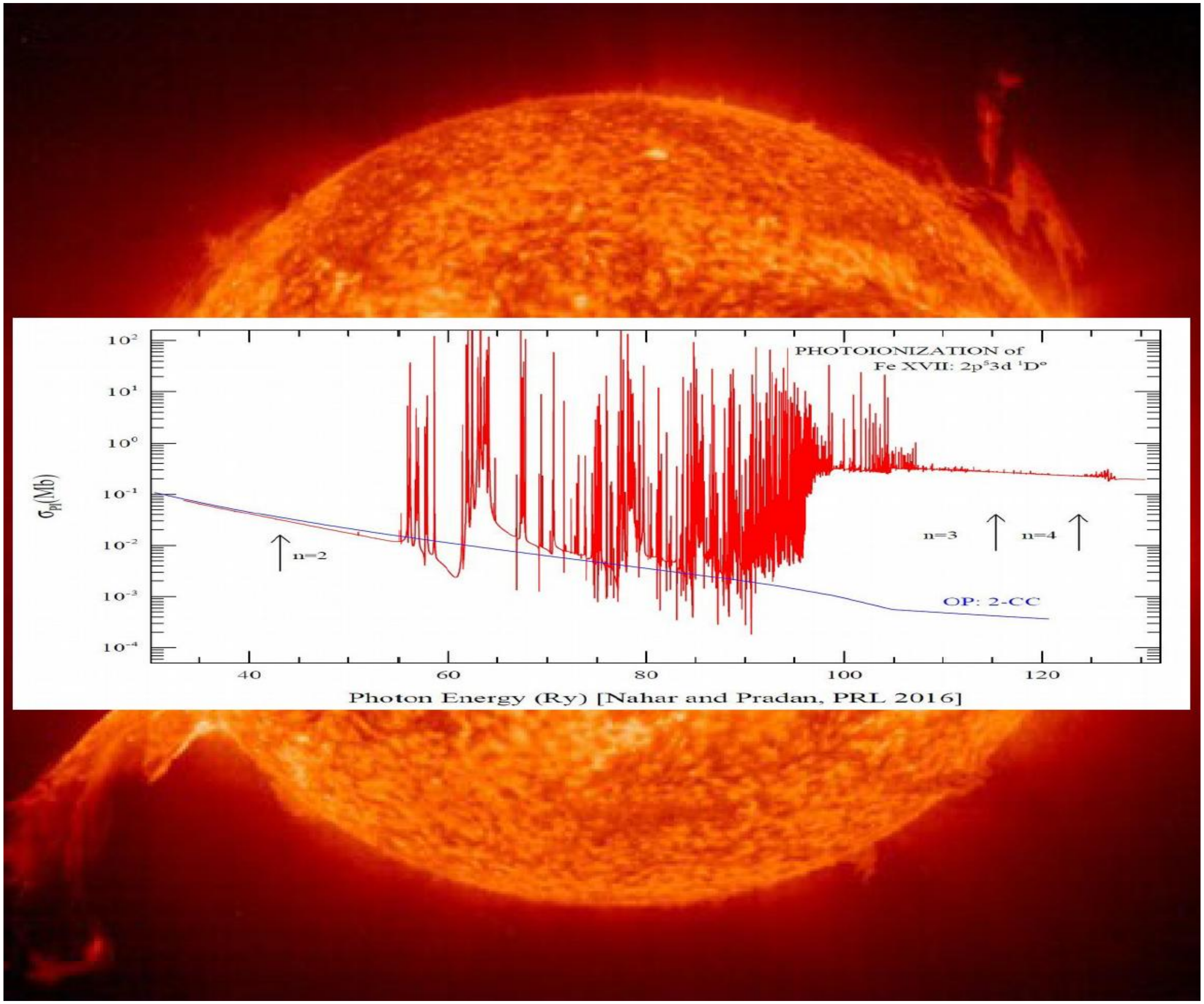
• COMPARISON OF IRON OPACITY: Experiment & Theory (Bailey et al, Nature Lett 2015)



• 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.

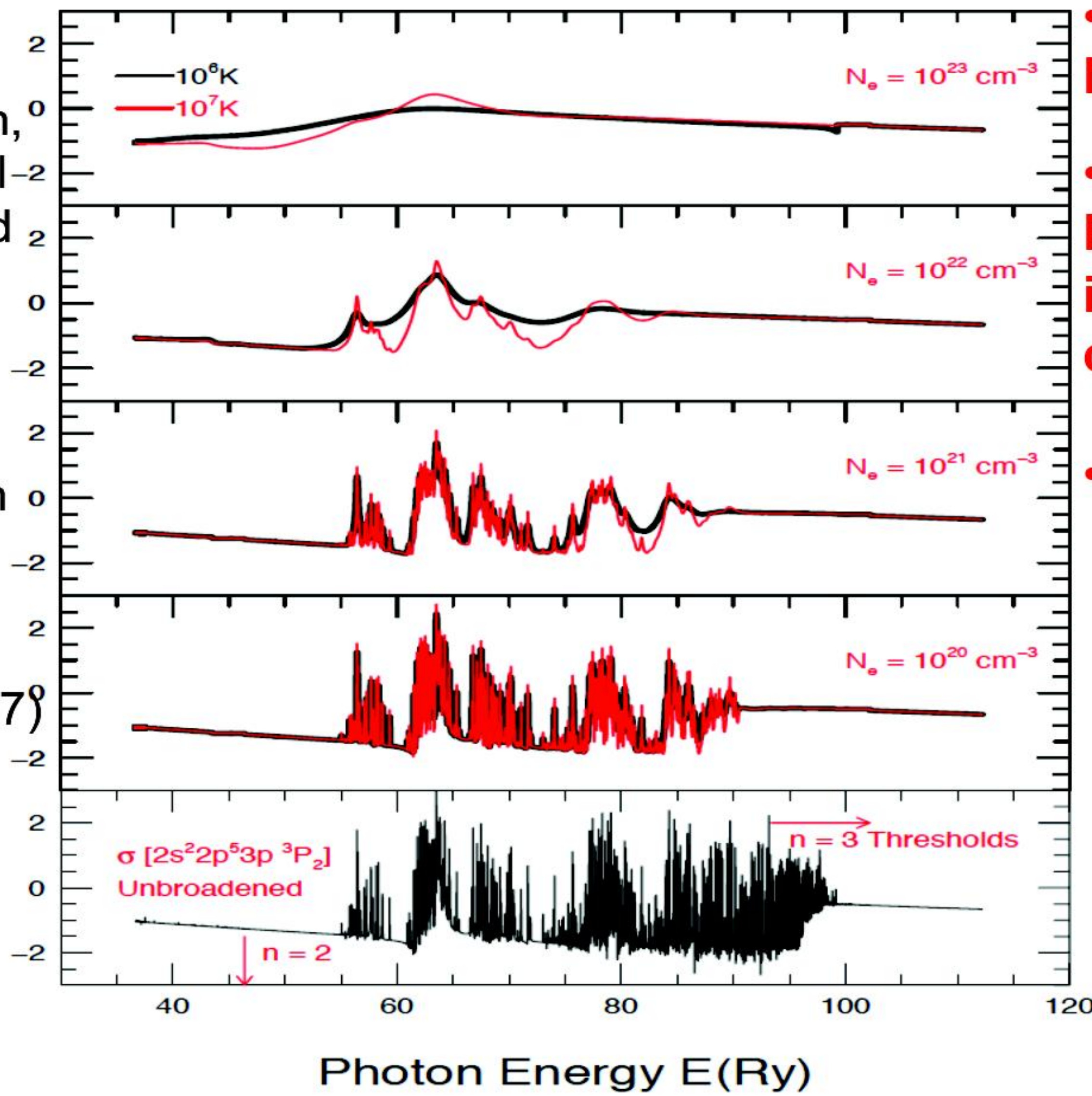
Fe XVII OPACITY SPECTRUM IN SOLAR INTERIOR

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: $N_c \sim 10^{22}$ cm^{-3}
- Dissolution of PEC Resonances into the b-f continuum
- Experimental Z data shows agreement with opacity models for $N_e < N_c$