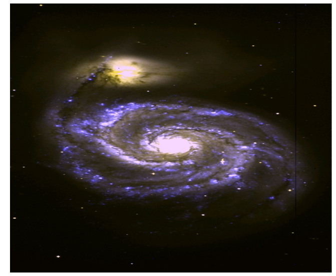
The Ohio State University



"THE IRON PROJECT: STUDY OF OUR STAR THE SUN"

SULTANA N. NAHAR

Astronomy, The Ohio State University, Columbus, USA

Under the patronage of

His Royal Highness Crown Prince Al Hussein bin Abdullah II

The University of Jordan's Third Honorary Professors Forum

The University of Jordan

School of Science

Honorary Professors visit (14/07/2026)

July 14, 2026

SUPPORT: NSF, Ohio Supercomputer Center

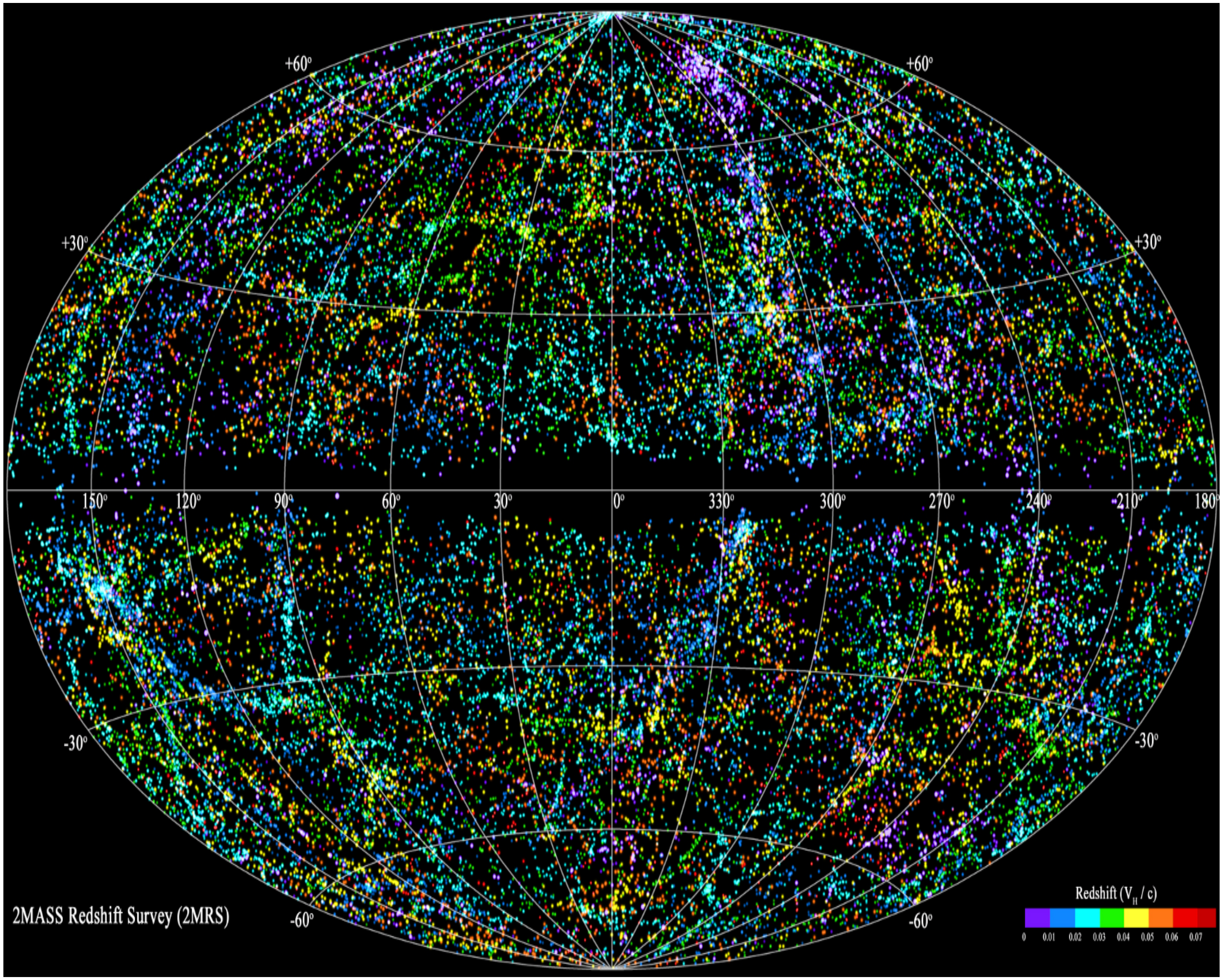
THE SUN, OUR STAR

- The Sun is very important, it is the source of our energy, and beauty of the Earth

- What is the IRON Project - Why study iron for opacity
- What is solar plasma opacity and why it is important
- Why focusing on the plasma opacity at the boundary between the radiative and convection zones inside the Sun
- What is the R-matrix method
- What are the new physics
- NORAD-Atomic-Data and Future direction with AI!

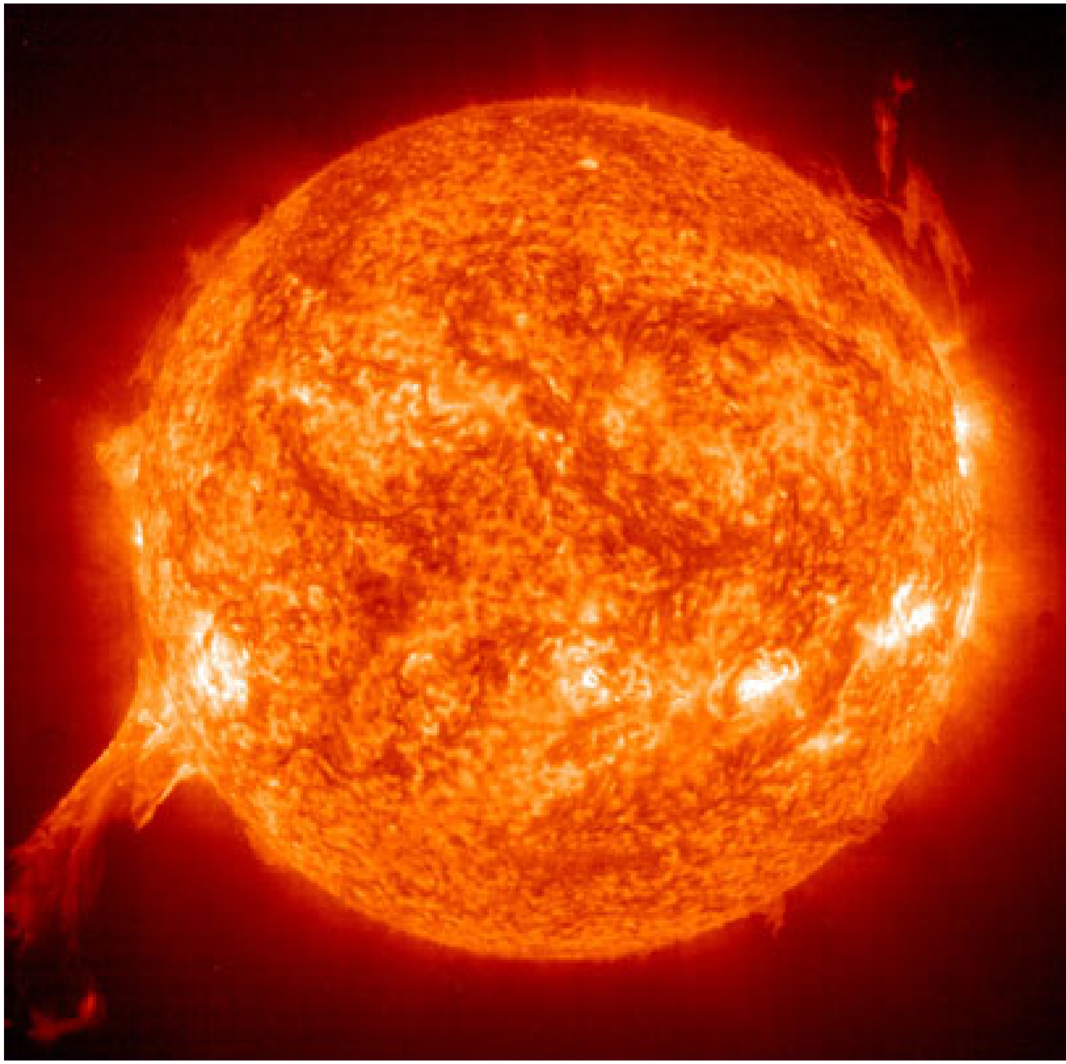
Study UNIVERSE through RADIATION:

Most Complete 3D Map



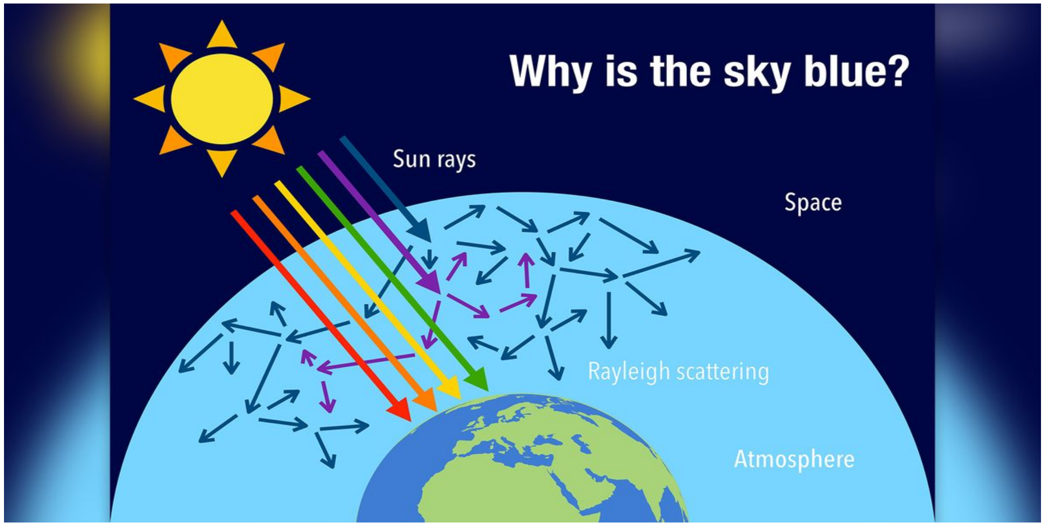
- The 2-Micron All-Sky Survey includes 43,000 galaxies within 380 million Ly
- There are at least 2 trillion galaxies in the observable universe
- Universe size: about 93 BYr. Signals can not travel faster than light, any object farther away from the age of the universe, 13.8 Byrs cannot reach us. However,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

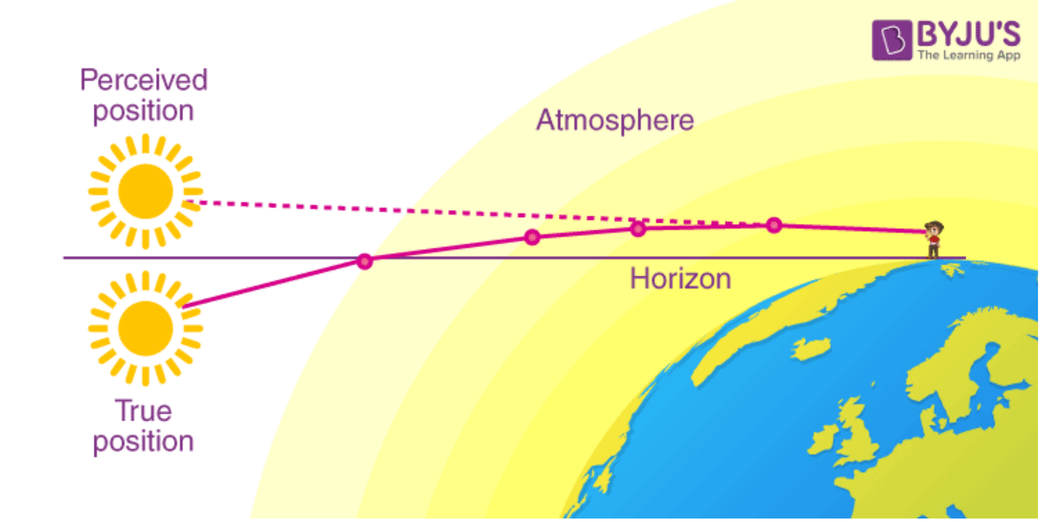
Our galaxy: MILKY WAY, Our star: the Sun

• Has 200-400 billion stars, the Sun is one of them. Located near the edge of the Milky Way, our Sun is a typical, standard star made of extremely dense and hot plasma. • The Sun is the standard to study other stars. Any change in the Sun will affect us. • Crucial to have accurate information to get accurate information of other stars

The SUN creates Blue and Red sky, makes the Earth beautiful

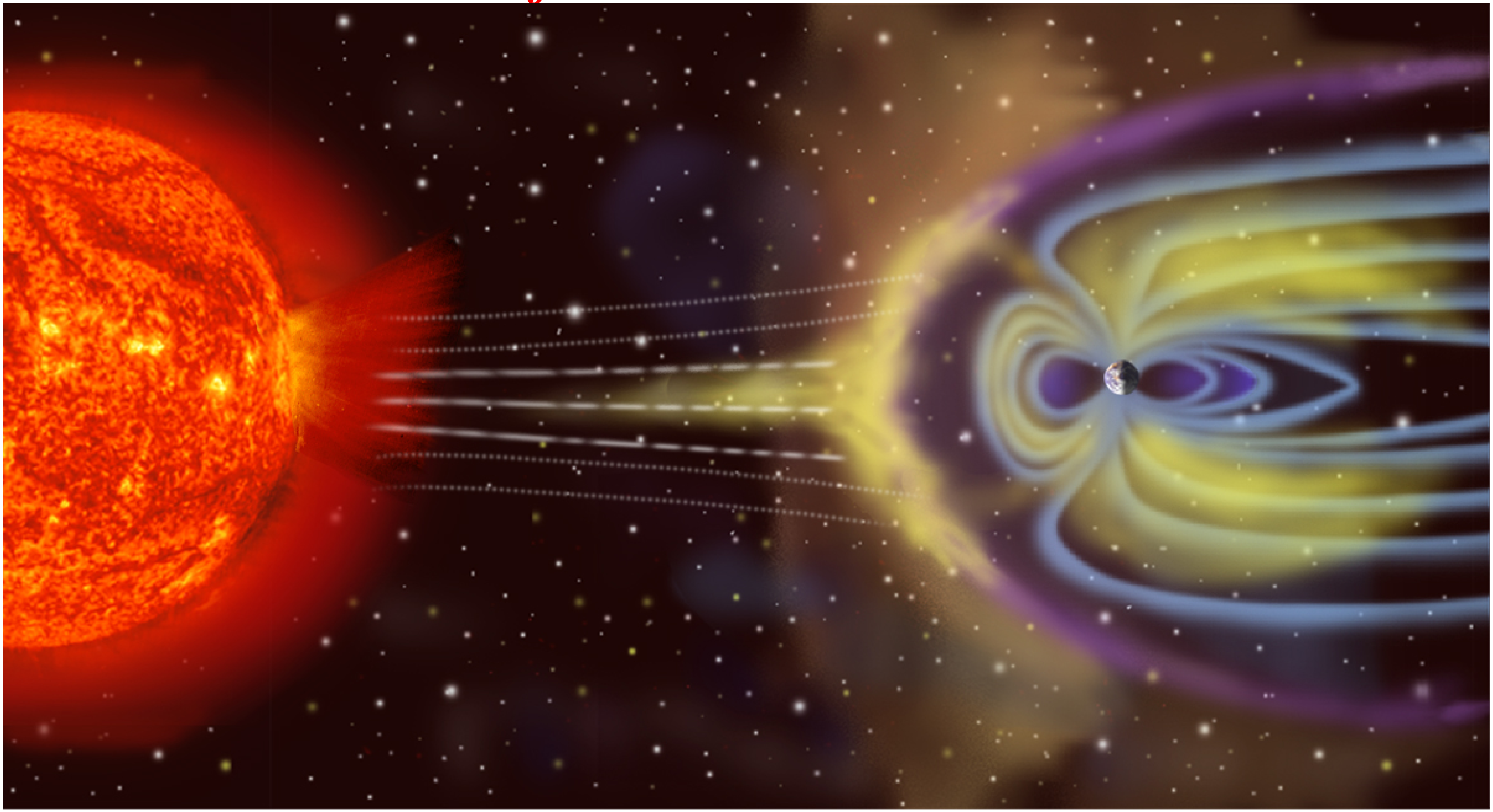




• Sky is blue at high Sun because atmospheric molecules scatter the blue photons to the earth. Blue sky is reflected on the water.

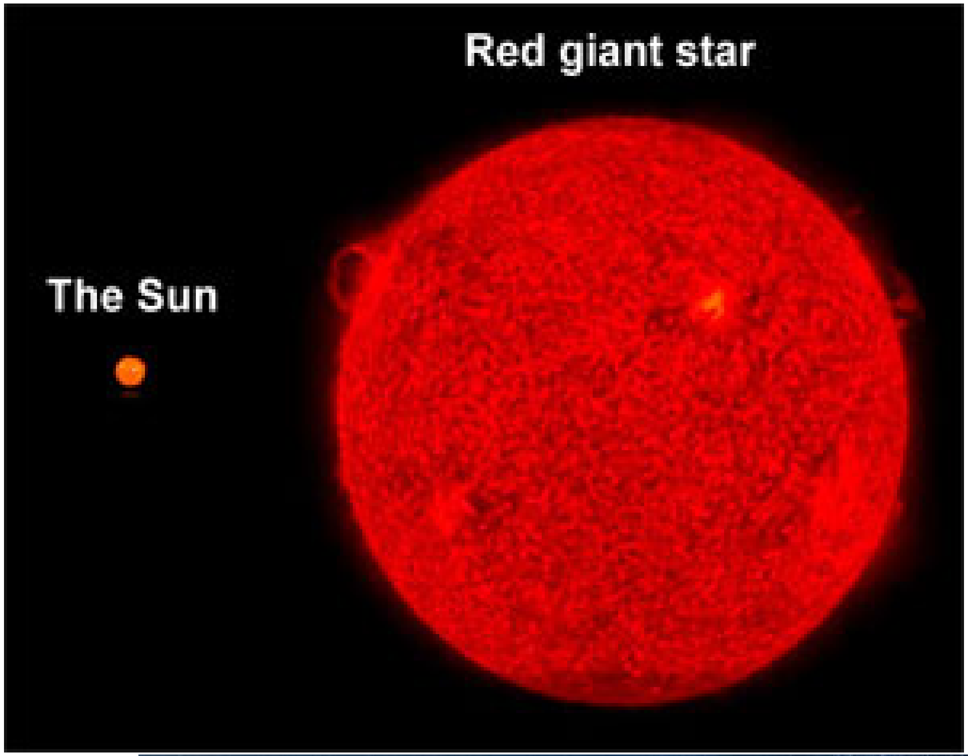
• Sunrise or sunset brings red photons as they bend toward the earth due to refraction travel through layers of atmosphere. This also causes Sun to be seen when it may be below the horizon

Solar Ejections - Radiation & Particles



- Solar storms ejects bursts of electrons, protons, & heavy ions accelerated by massive explosions inside
- Our Earth's ozone layer, atmosphere and magnetic field protects us from these massive bursts of particles and radiation by reflections, absorption, and captures
- Magnetic field captures charged particles, ozone layer blocks most ultraviolet, X-rays and Gamma rays Most dangerous particles are ions which can damage tissue, break strands of DNA, and lead to diseases like cancer

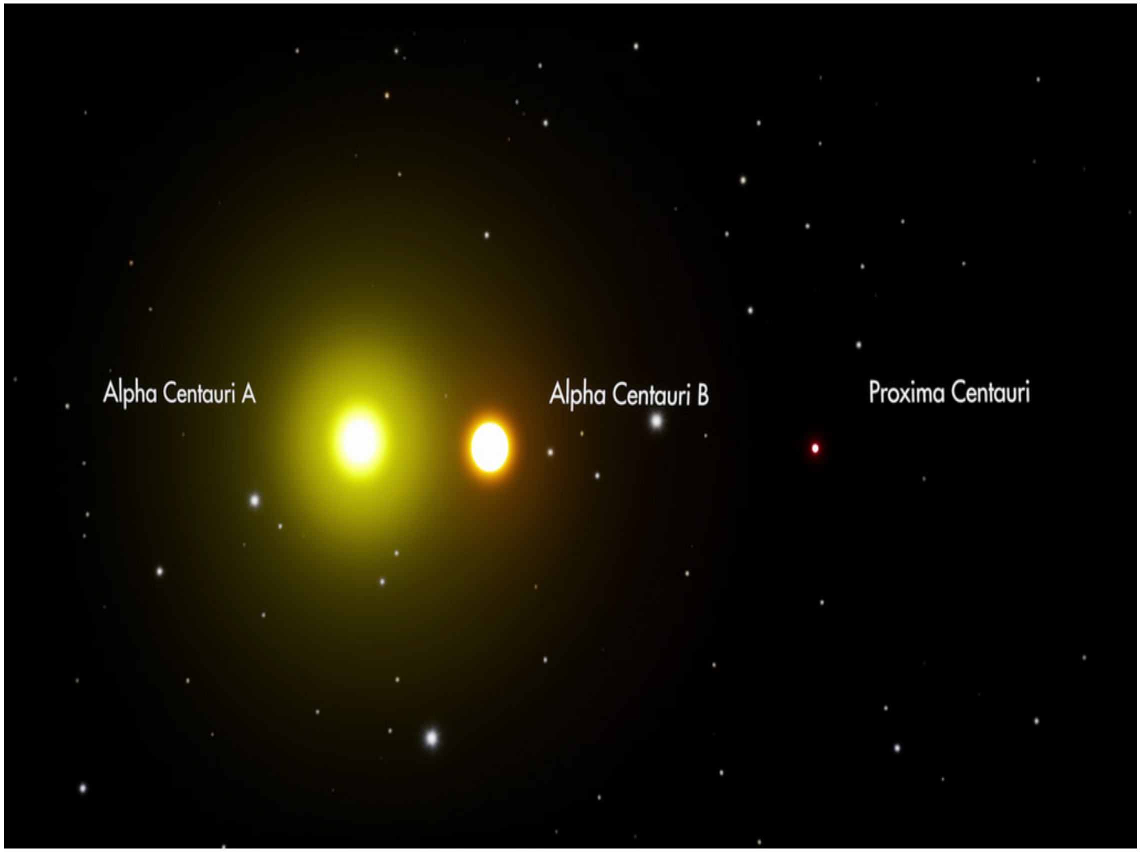
FATE OF OUR SUN IN 6-7 BYR: RED GIANT, PN, WD

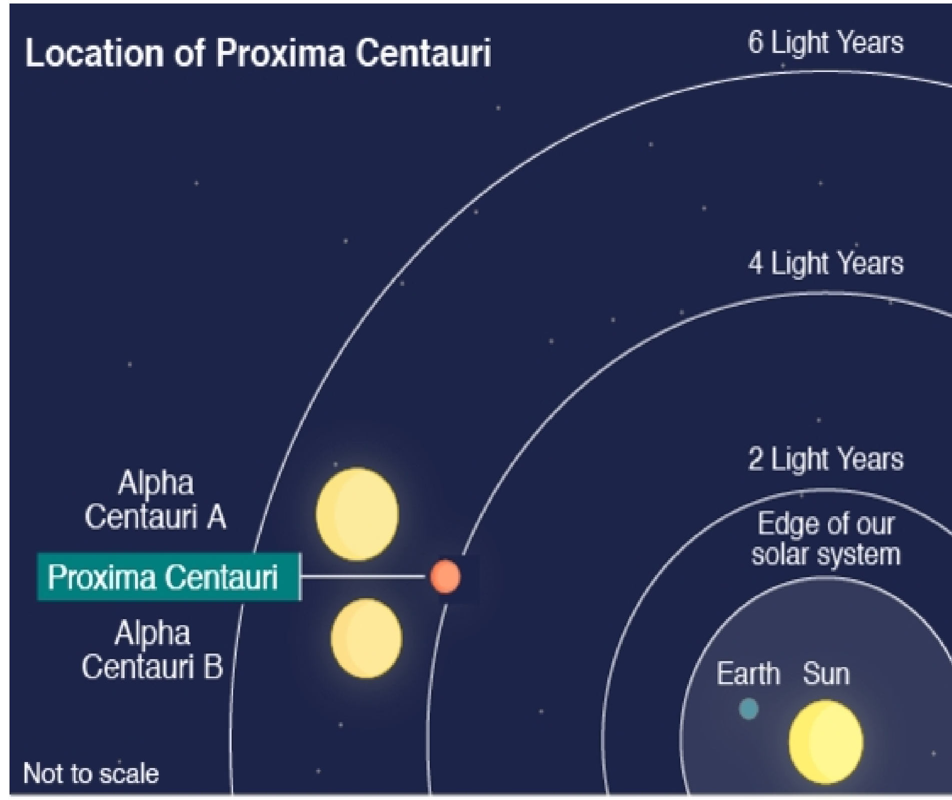


- White Dwarf (e.g. a Diamond WD, 2014)

• Red Giant is a dying expanded star with H fuel gone

OUR INTEREST: HABITABLE EXOPLANETS





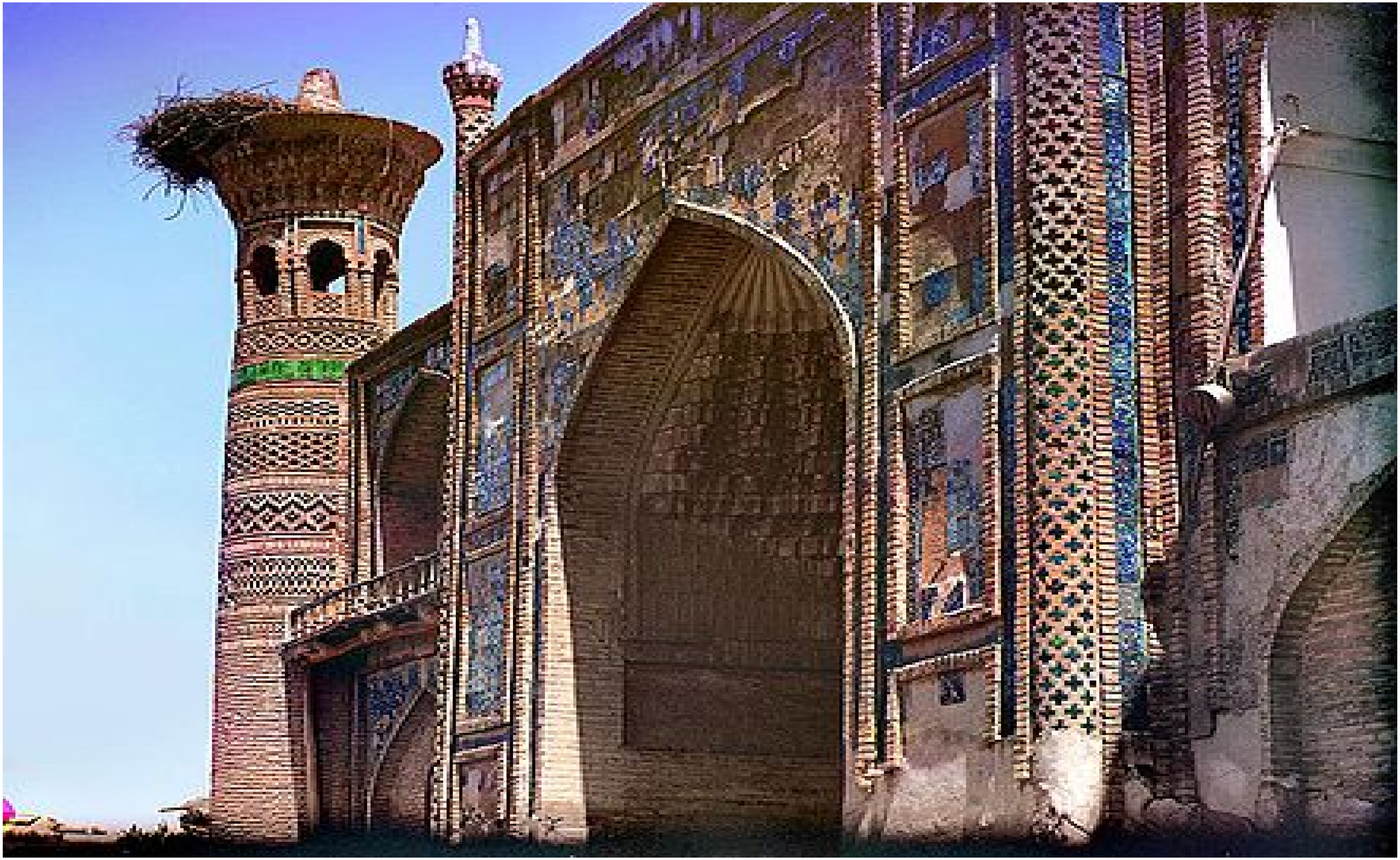
Source: ESO

- 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

- 1 in 5 sun-like stars have an earth-sized planet in the habitable zone → potentially 11B planets exist in Milky Way

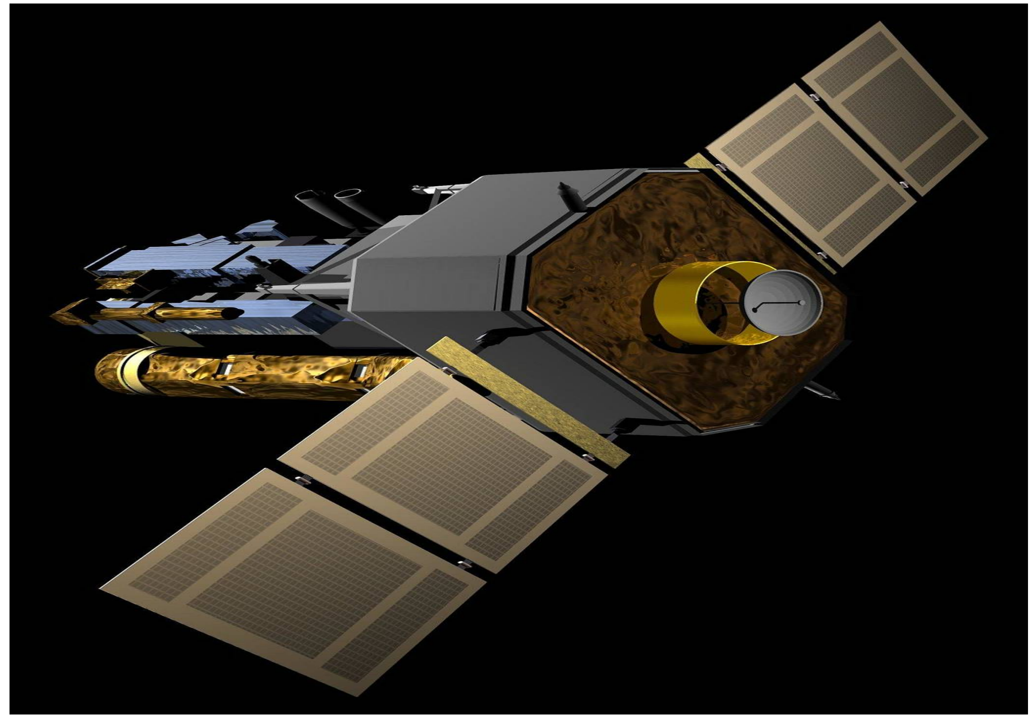
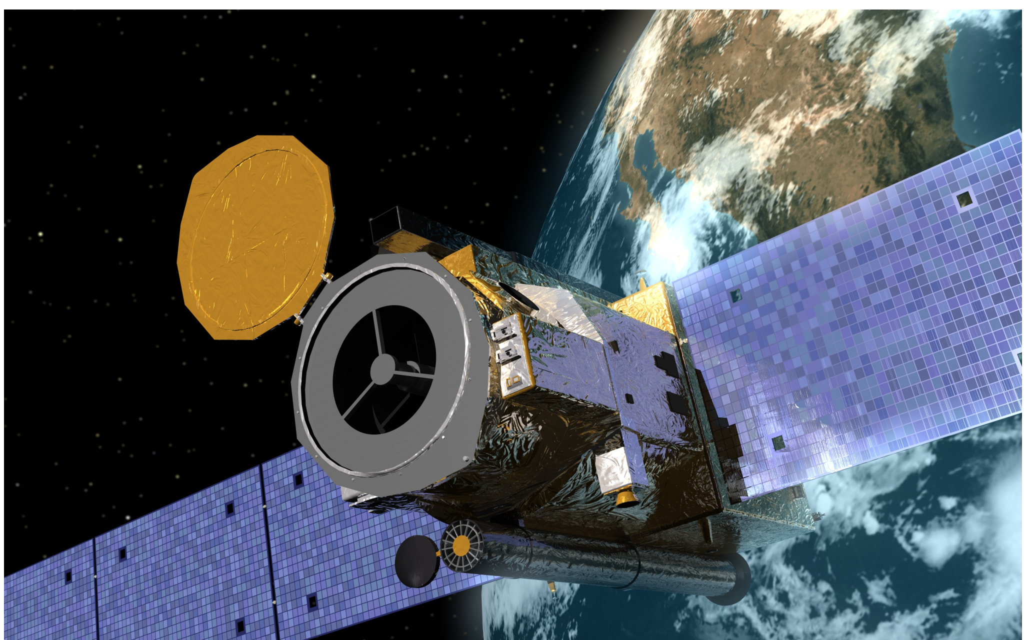
THE 1ST OBSERVATORY, SAMARKAND, 1420, BY MUSLIM RULER ULUGH BEG (Iran has an older model)



- Ulugh Beg built the madrasa in 1420 in Samarkand and extended it to an observatory

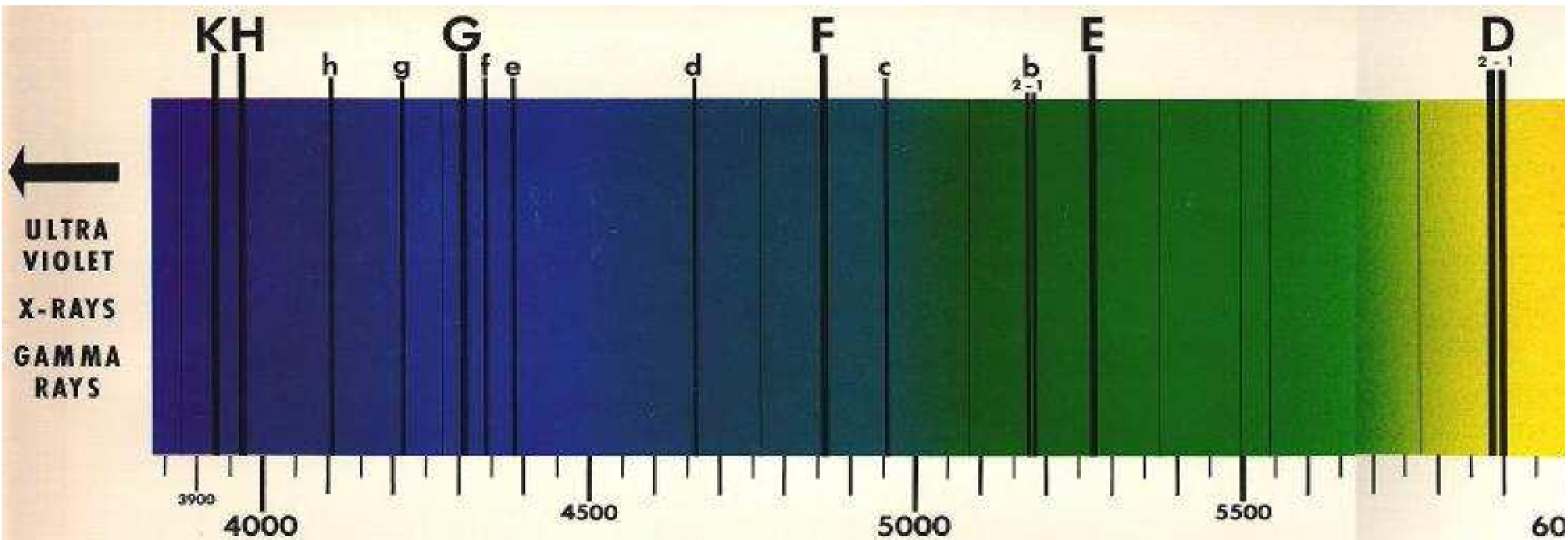
DEDICATED OBSERVATORIES FOR THE SUN

LT: SDO, RT: SODO, LB: HINODE, RB: PARKER (Parker Solar Probe makes historic pass through Sun's atmosphere withstanding intense heat)

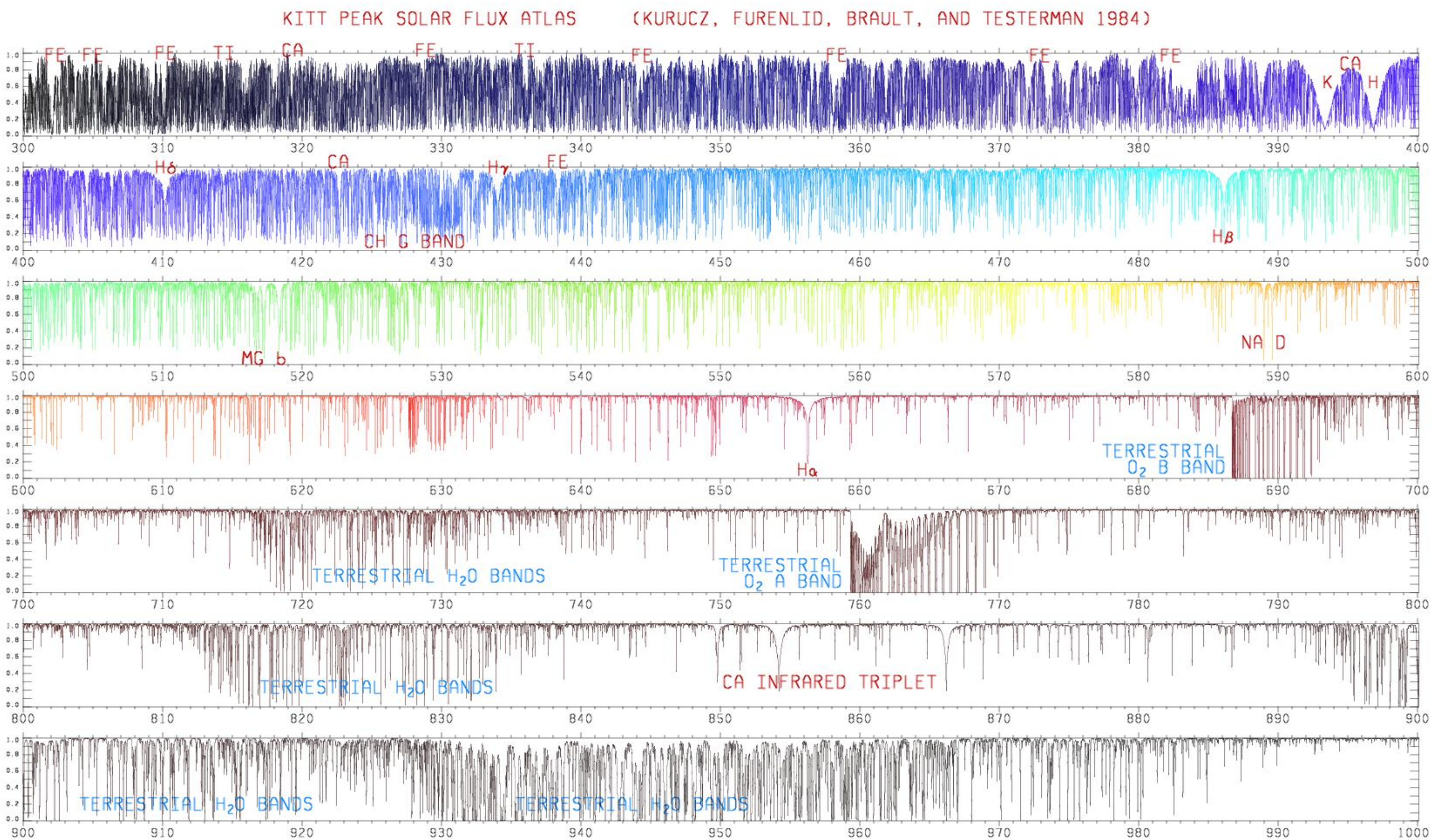

SOLAR SPECTRA: ABSORPTION & EMISSION LINES

- 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



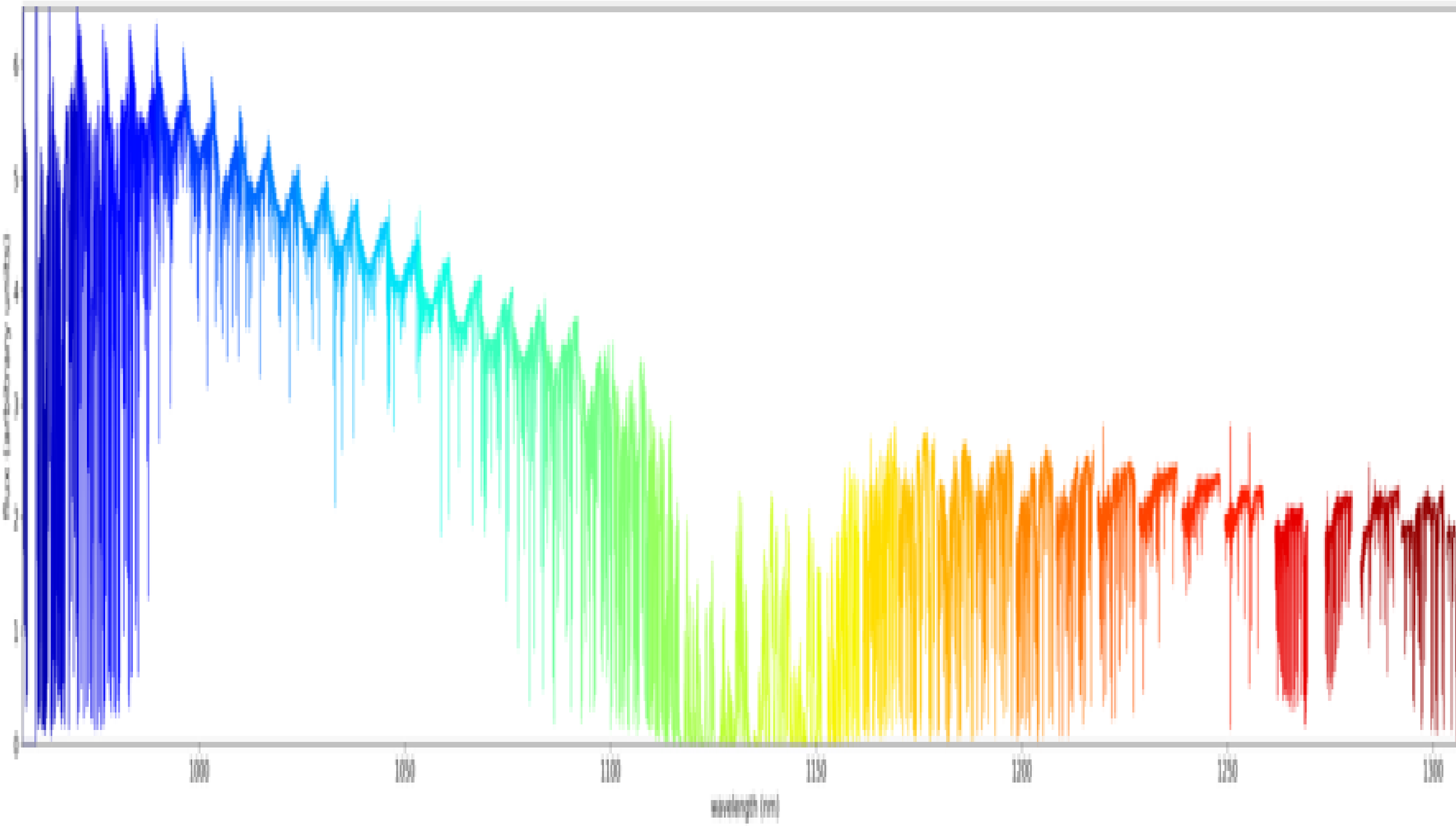
- Fraunhofer (1815) observed lines in the solar spectrum & used alphabet for designation
- Later spectroscopy with quantum mechanics identified them: A (7594 Å,O), B (6867 Å,O) (air), C (6563 Å H), D1 & D2 (5896, 5890 Å Na, yellow sun), E(5270 Å, Fe I), F (4861 Å, H), G(4300 Å, CH), H & K (3968, 3934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

SOLAR SPECTRUM AS SEEN FROM THE EARTH



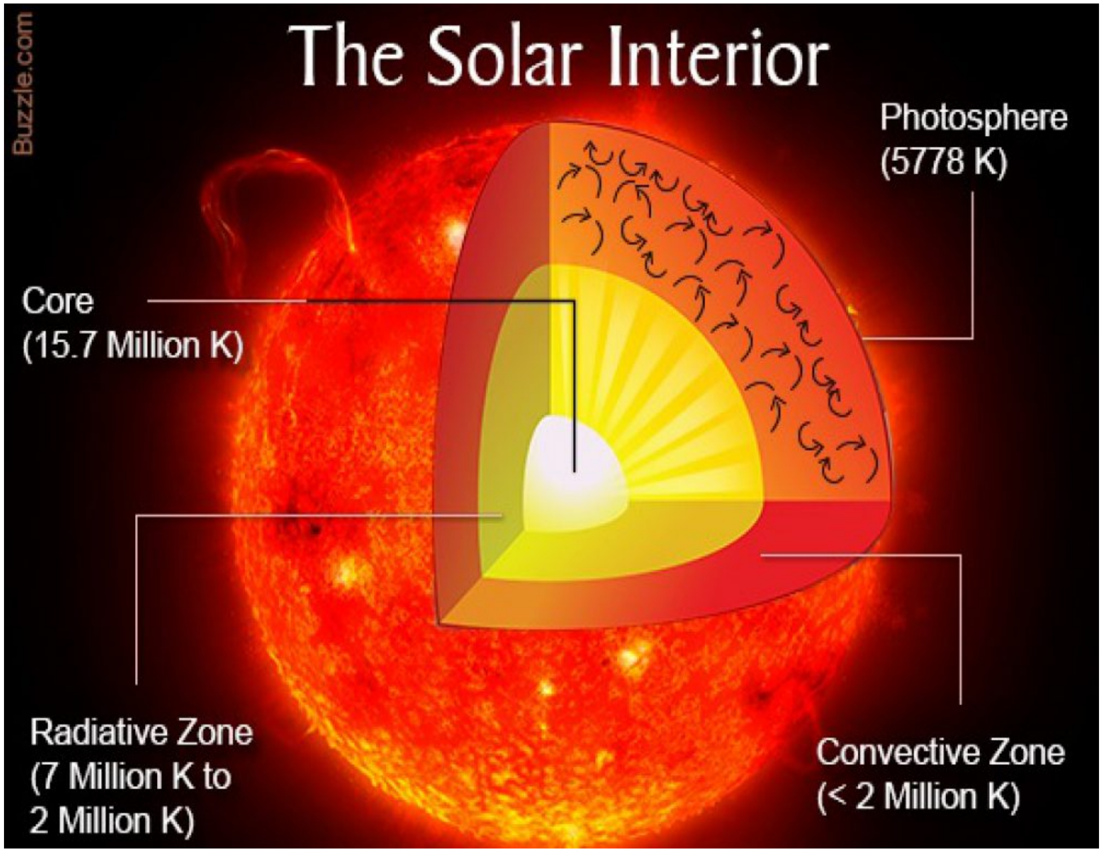
• Solar spectrum by Kurucz. The short wavelength region is mainly from Fe I, Fe II with large absorption or high opacity. - Less opacity in the yellow region, peak in the black body distribution function - reason for the yellow sun.

SOLAR SPECTRUM: iLOCATOR



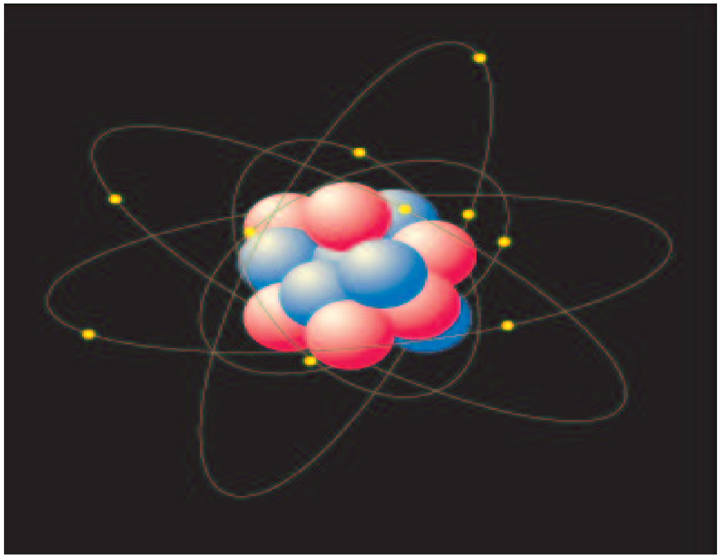
• • iLocator, an infra-red spectrograph built by OSU and Notre Dame University, was tested for benchmarking by taking the spectrum of the Sun.

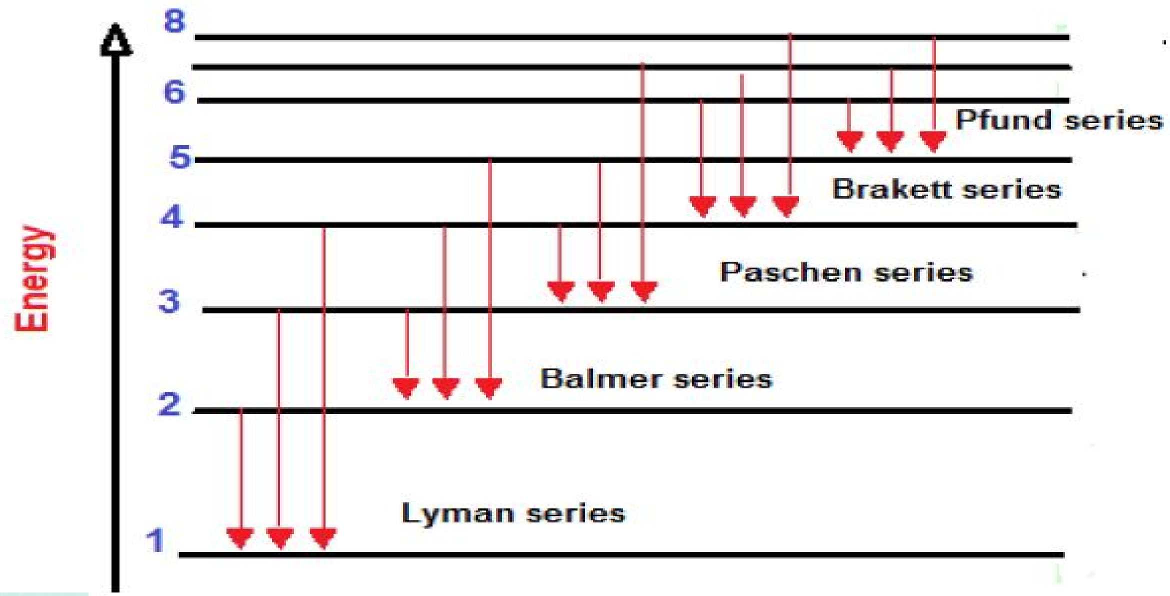
INNER AND OUTER LAYERS OF THE SUN

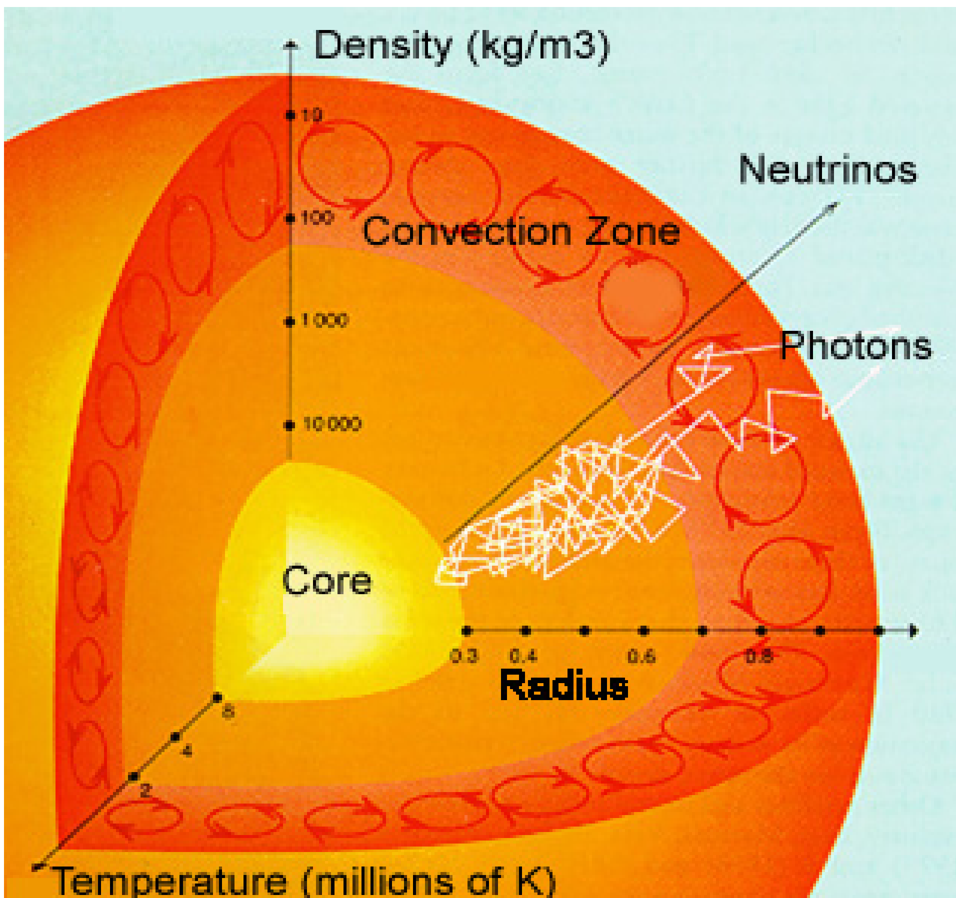


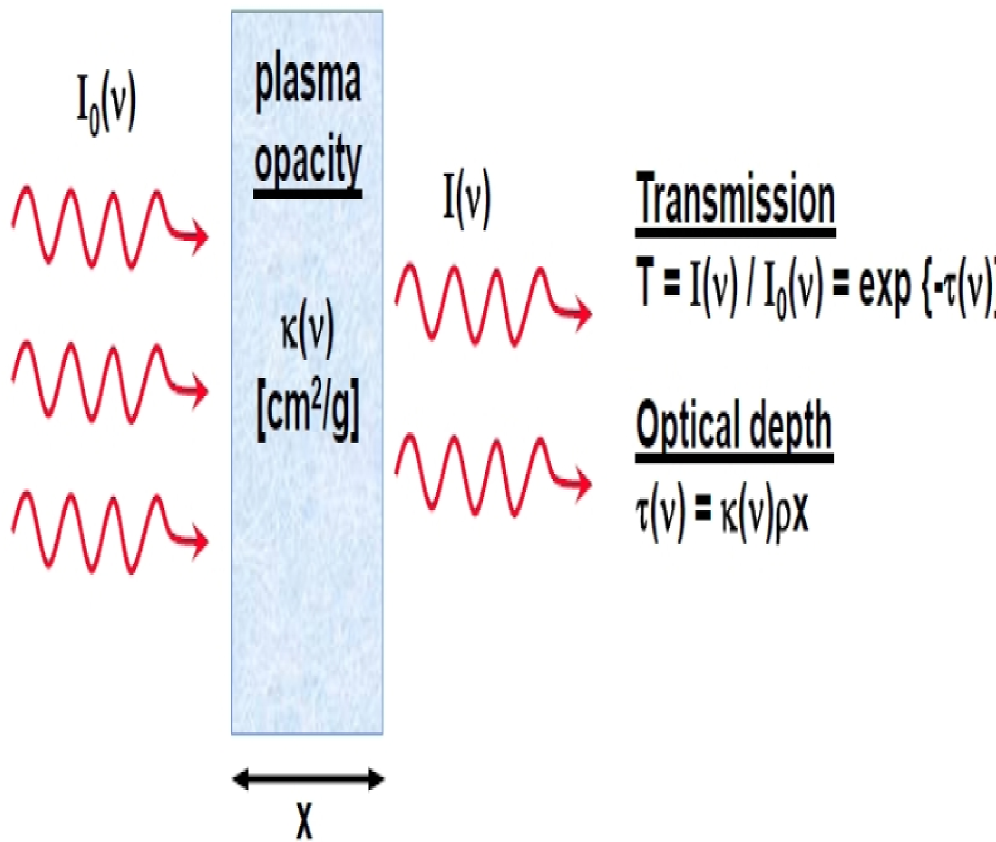
- Sun's inner layers: Core (15 MK), Radiative Zone and Convection Zone (2 MK) BCZ, Surface 5,700 K
- Full solar eclipse, a cosmological event of interest, occurs at occasional alignments of the Sun, Earth and Moon. Total eclipse gives the scope to see the surrounding of the Sun blocked by Sunlight
- 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)

RADIATION FROM ATOMS & OPACITY

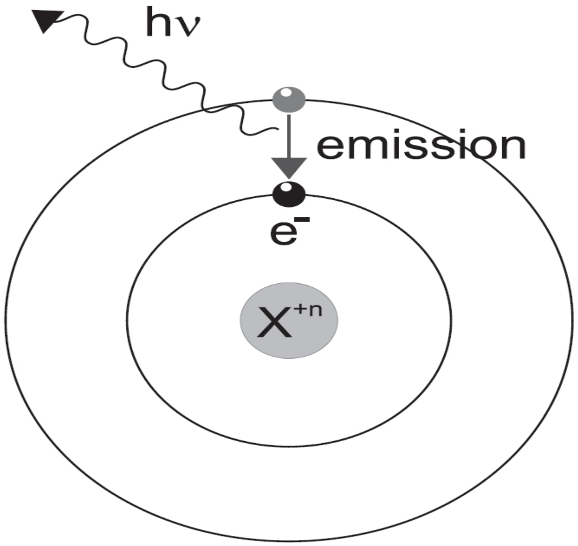




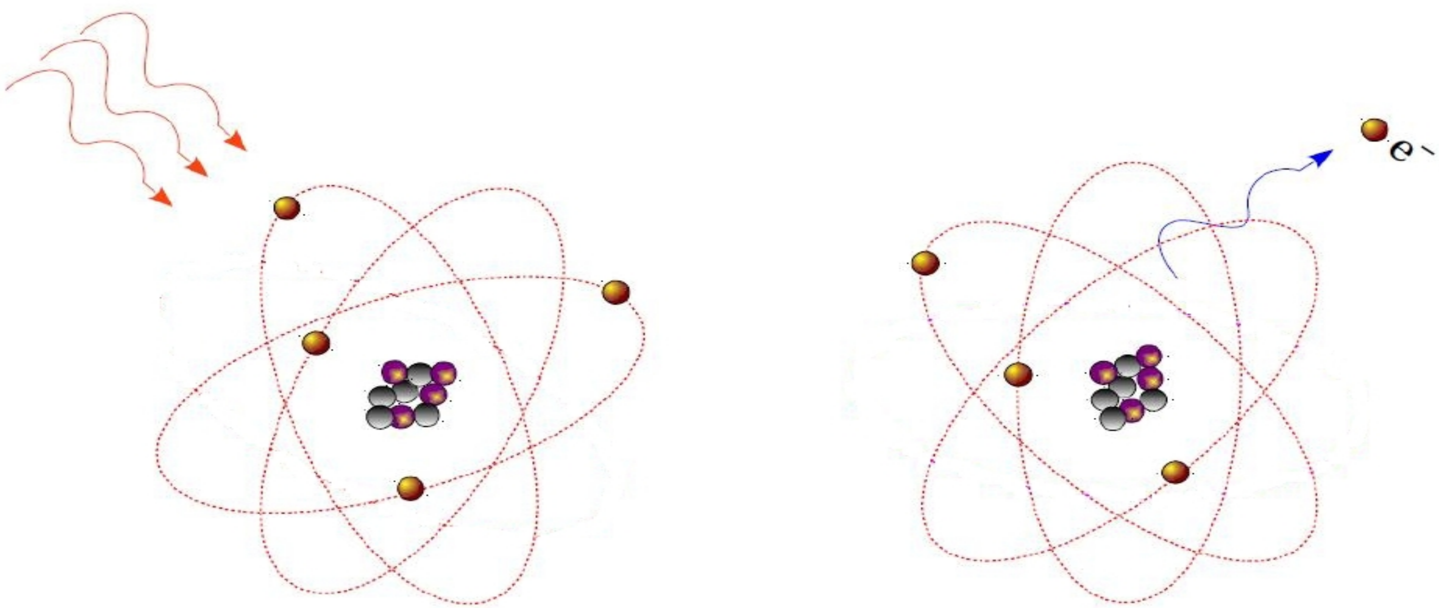




Opacity due to PHOTO-EXCITATION



Opacity due to PHOTOIONIZATION (PI):

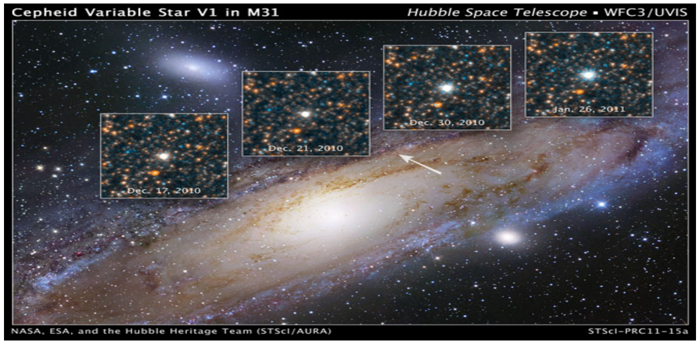


- Opacity is related to elemental abundances which are important information

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

The OPACITY Project, The IRON Project

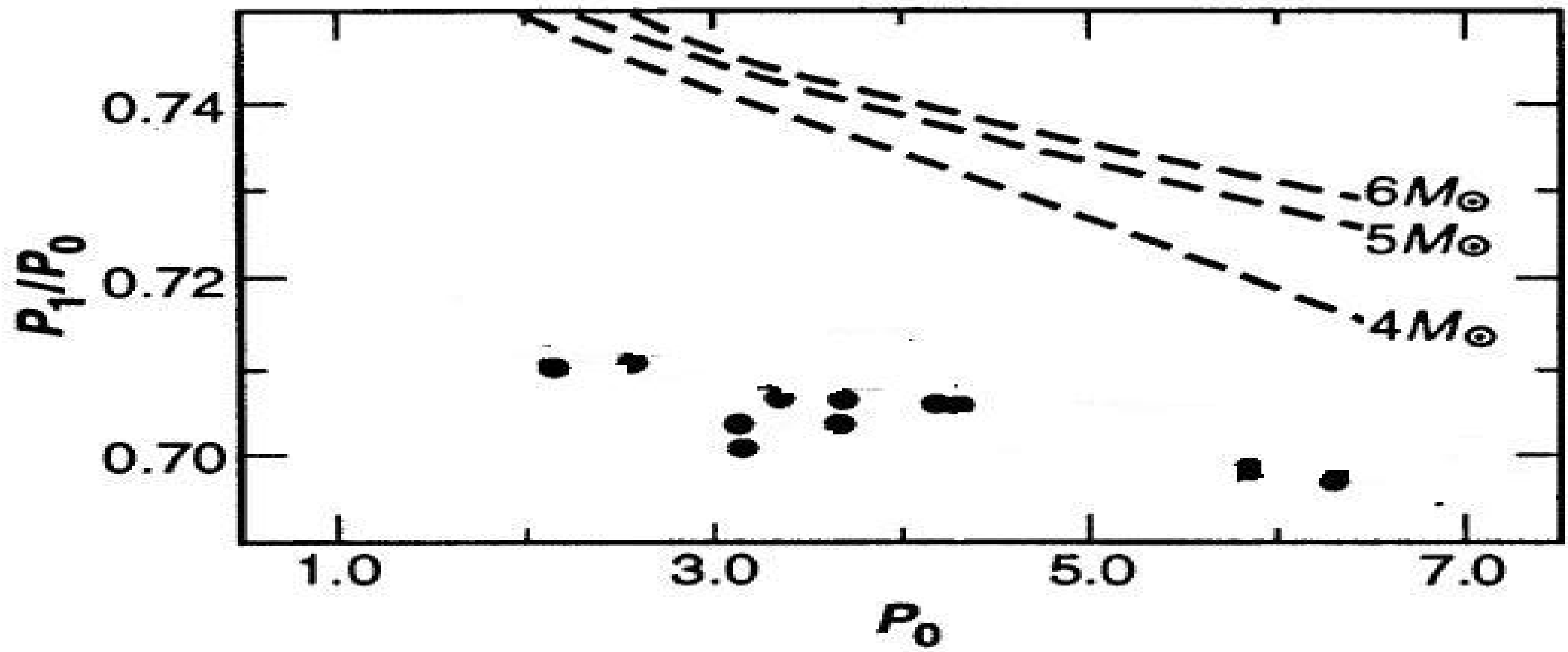
The OPACITY Project



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 metalicity

COMPUTATIONAL CHALLENGE FOR OPACITY

- **Total Opacity needs huge amount of data for radiation absorption by:**

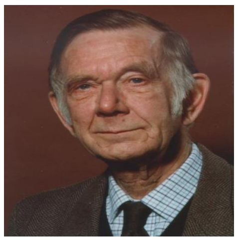
- all excitation and photo-ionization of the element
- all ionization stages of the element
- all elements exist in the plasma
- Accuracy of atomic data

- **Use of high performance computers (HPC) is the only way to compute the needed data**
- **With no fully developed theory and supercomputers it was not possible to get accurate opacities until recently. So there was misleading science, and large discrepancies between astrophysical observations and predictions.**
- **For accuracy of the underlying science of atomic process, the Opacity Project and later the IRON Project were founded. Iron has prominent existence in space, but difficult to study. IRON project focuses on iron and iron-peak elements. The purpose of these projects is to compute data from accurate study of the atomic processes for astrophysical applications.**

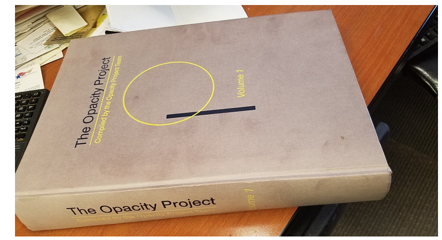
The OPACITY Project (OP) & The IRON Project (IP)

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 authors)

Close-Coupling (CC) Wave Function & R-matrix Method

• Details: "Atomic Astrophysics and Spectroscopy", A.K. Pradhan and S.N. Nahar (Cambridge press, 2011)

• CC approximation generates natural resonances

• Wave Function expansion includes excited states of the residual ion which generate resonant states:

$$\Psi_E(e+ion) = A\sum_i^N \chi_i(ion)\theta_i + \sum_j c_j\Phi_j(e+ion)$$

• Resonances increase with increase of excited residual states - this increases the Hamiltonian matrix and dimensions

• Substitution of $\Psi_E(e+ion)$ in Schrodinger equation

$$H\Psi_E = E\Psi_E$$

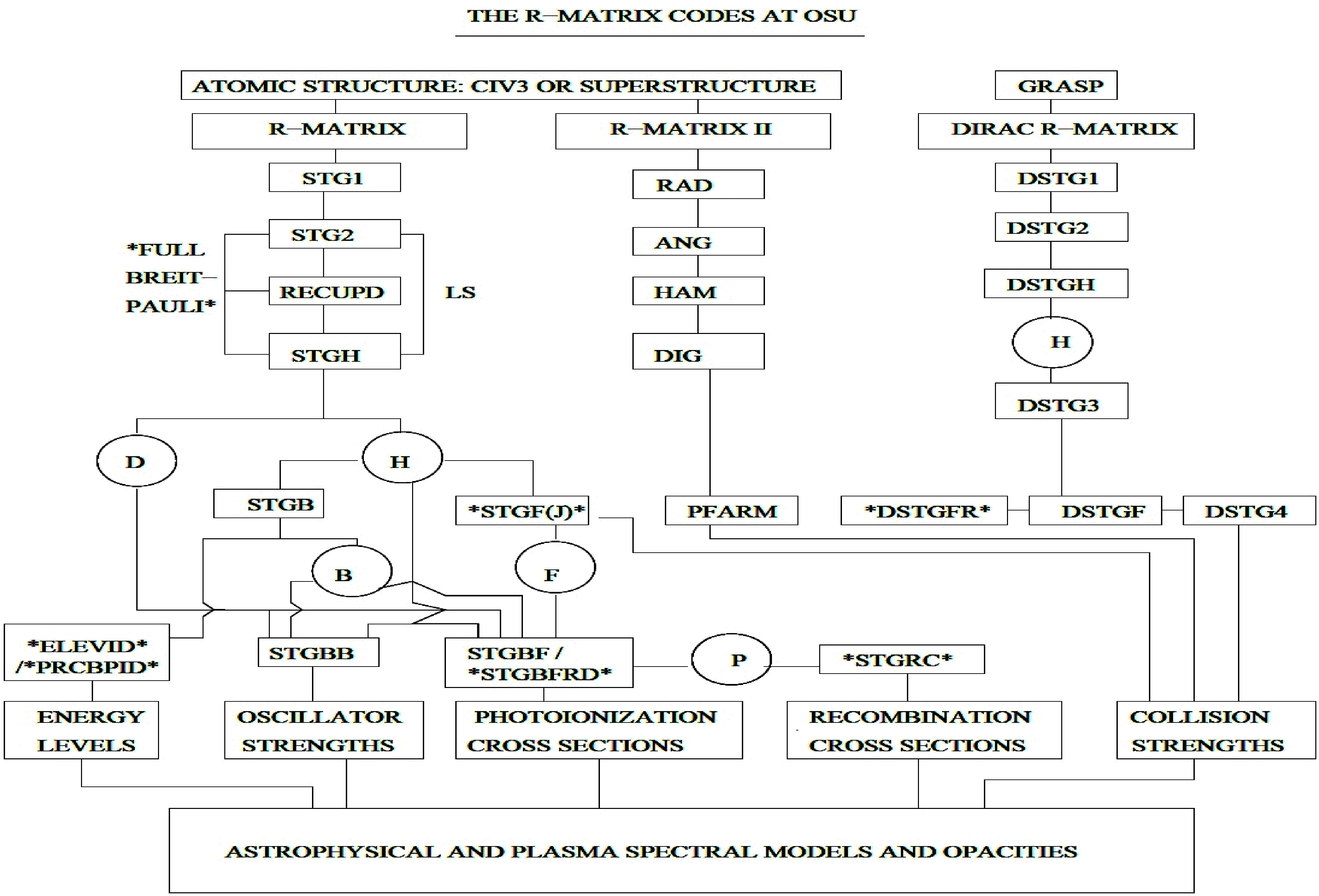
results in a set of coupled equations

• The equations are solved by the R-matrix method

Computational challenges increases with increased dimensions.

R-MATRIX CODES: Major extensions from collision to radiative processes

(Took several years for the development of the codes and the • **R-matrix calculations** • **Results - 1) Energy Levels, 2) Oscillator Strengths, 3) Photoionization Cross sections, 4) Recombination Rate Coefficients, 5) Collision Strengths; - Astrophysical Models**



OUTCOMES OF THE PROJECTS

The OPACITY Project — The IRON Project

New Physics:

- Solved many astrophysical problems
- Found new physics in photoionization - features & X-ray lines
- Develop new algorithms for R-matrix spectroscopy
- Develop new methodology for resonance broadening
- New unified method for electron-ion recombination
- High precision radiative & collisional data
- Found new applications in nanobiomedicine - RNPT

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 proceedings articles
- Book: The Opacity Project, The Opacity Project team, IOP (1995)
- Textbook: "Atomic Astrophysics and Spectroscopy" (A.K. Pradhan & S.N. Nahar, Cambridge U press, 2011)

The OPACITY Project

OUTCOMES OF THE PROJECTS

The IRON Project

• Atomic & Opacity Databases

• TOPbase (OP) at CDS: http://vizier.u-strasbg.fr/topbase/topbase.ht

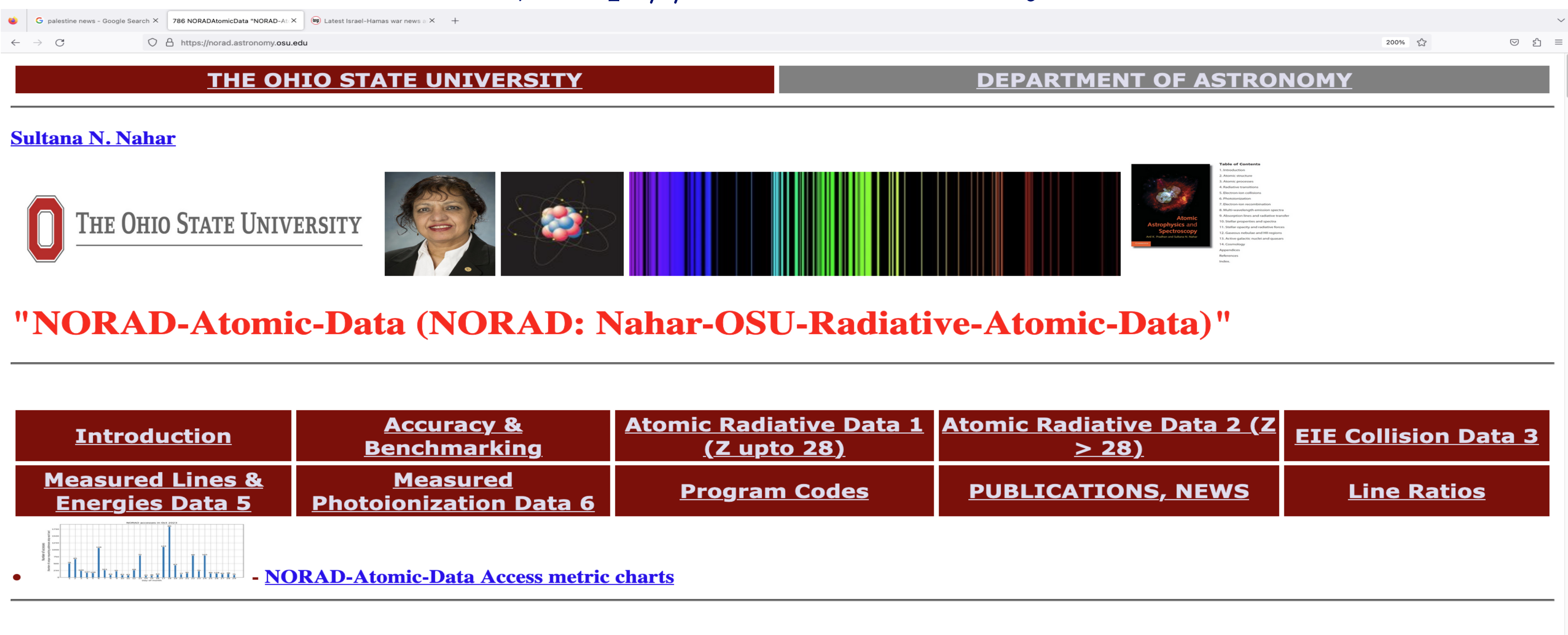
- Energy levels, Oscillator Strengths, Photoionization Cross Sections

• TIPbase (IP) at CDS: http://cdsweb.u-strasbg.fr/tipbase/home.html

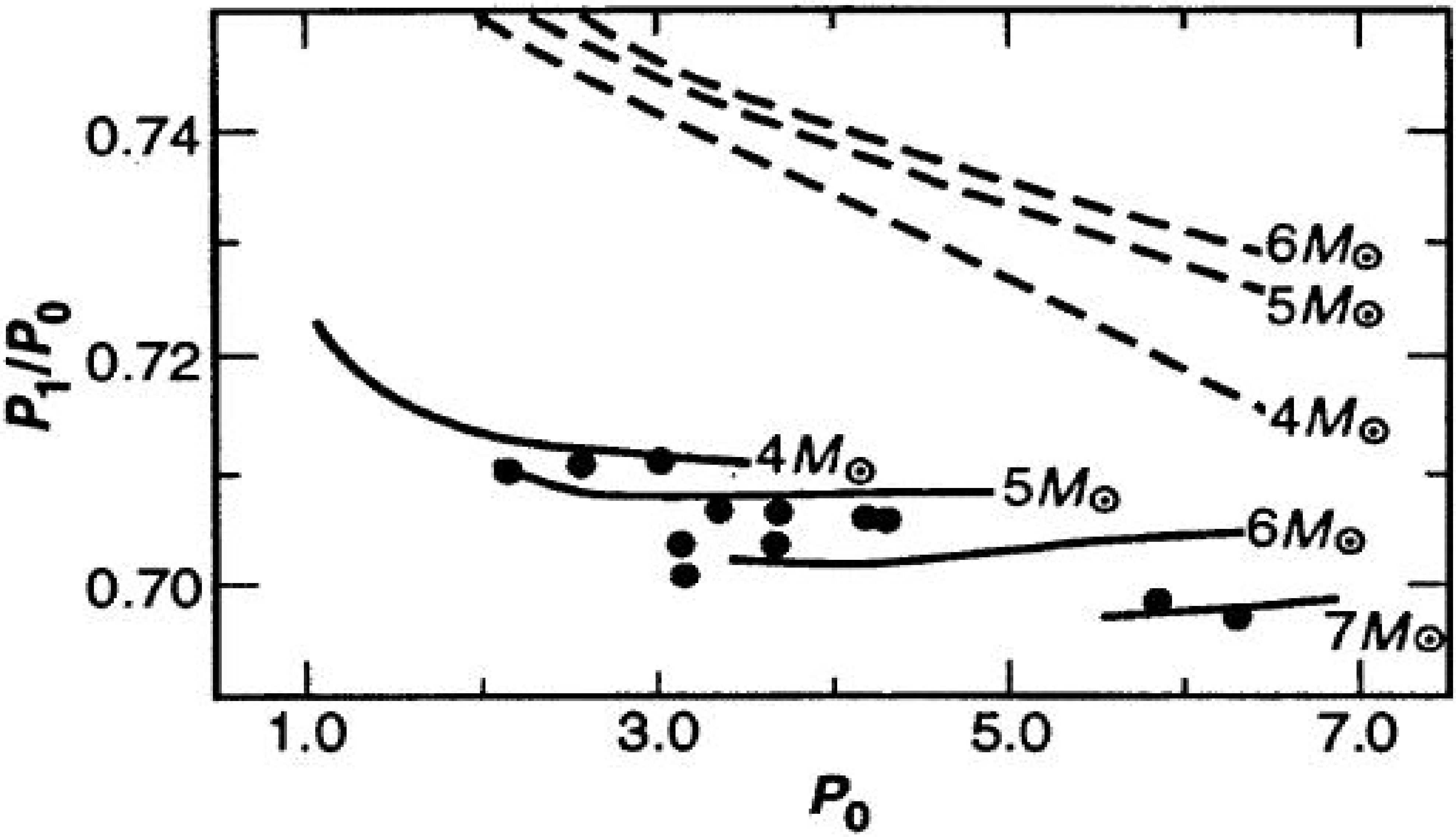
- Collisional Strengths for Electron Impact Excitation, and for Radiative Processes similar to TOPbase (not complete)

• 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

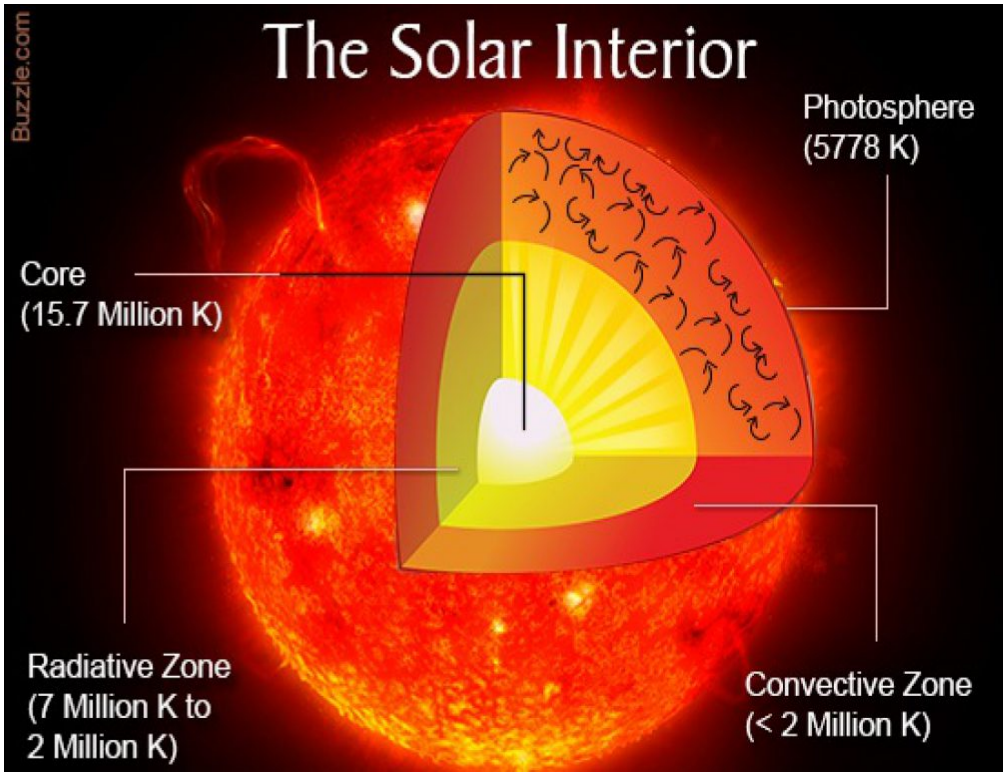


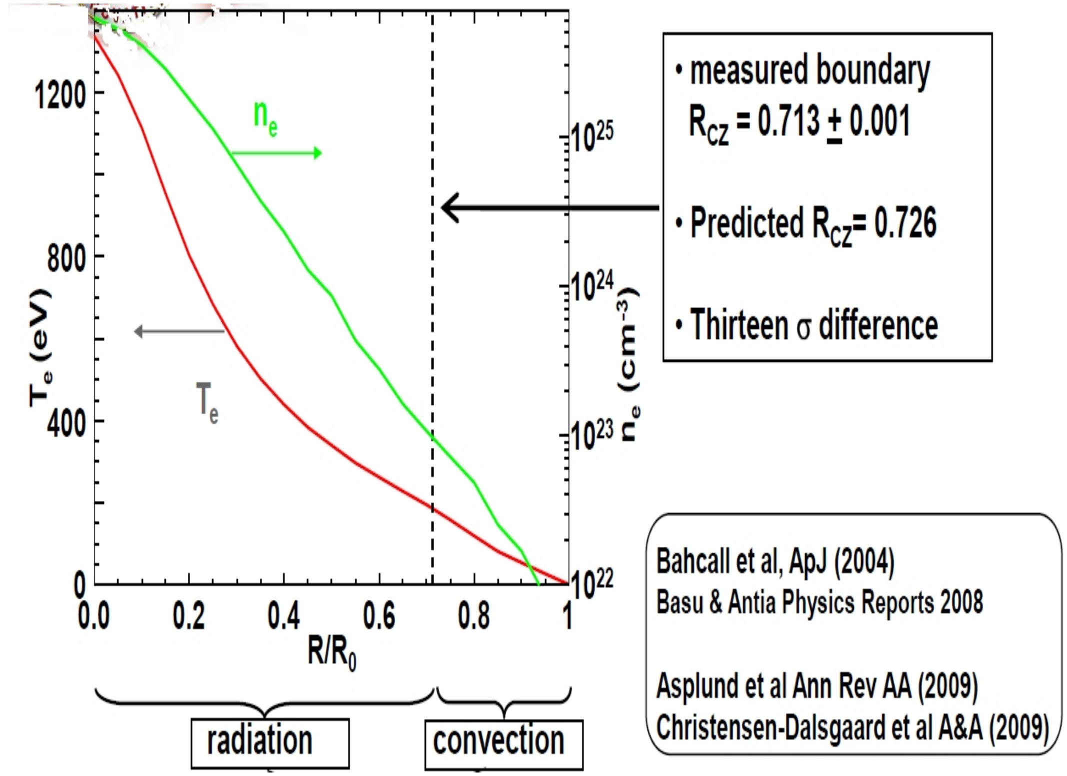
DISCREPANCY IN PULSATION PERIODS OF CLASSIC CEPHEID IS SOLVED WITH INCREASED OPACITY



- 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})

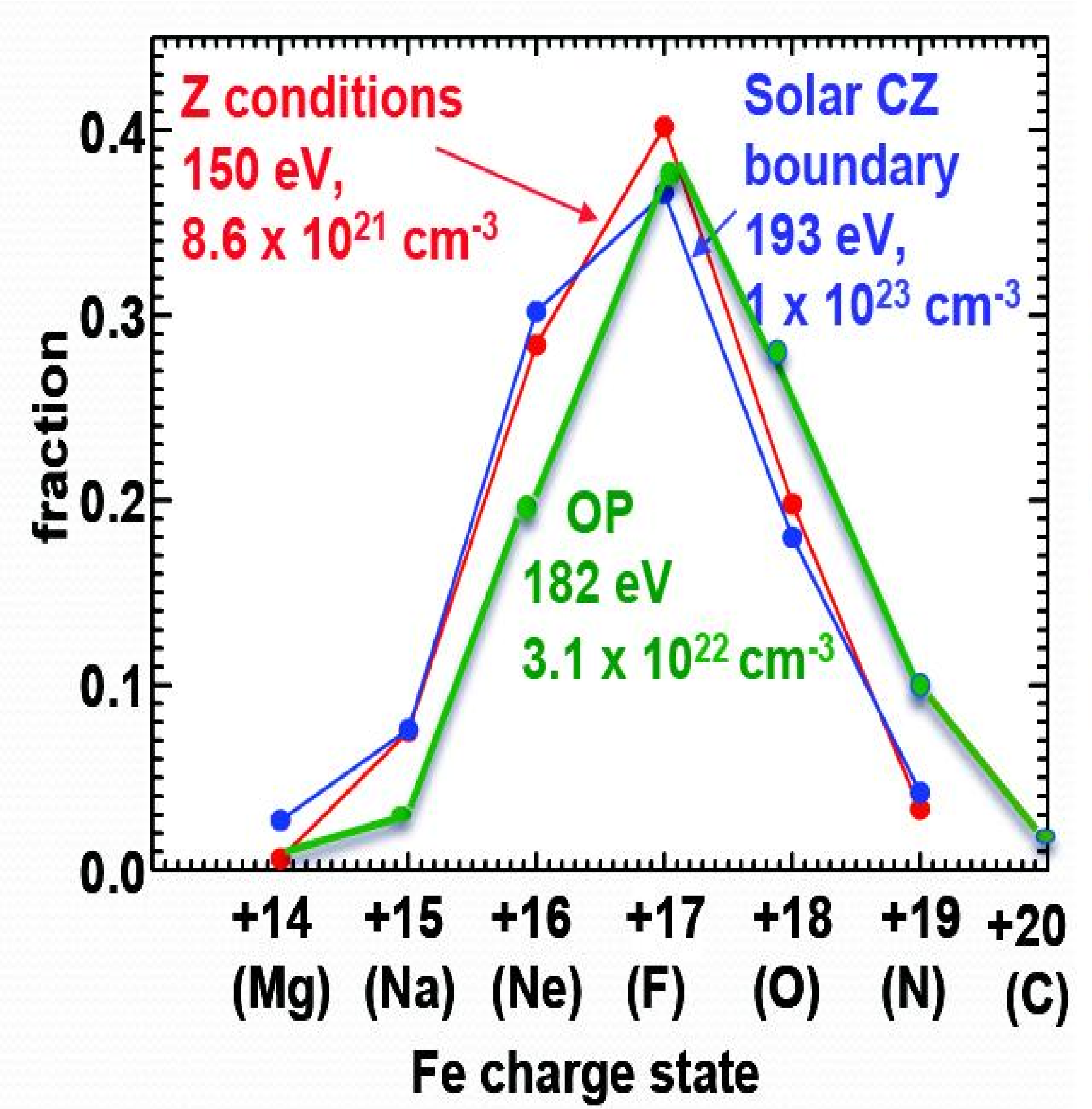


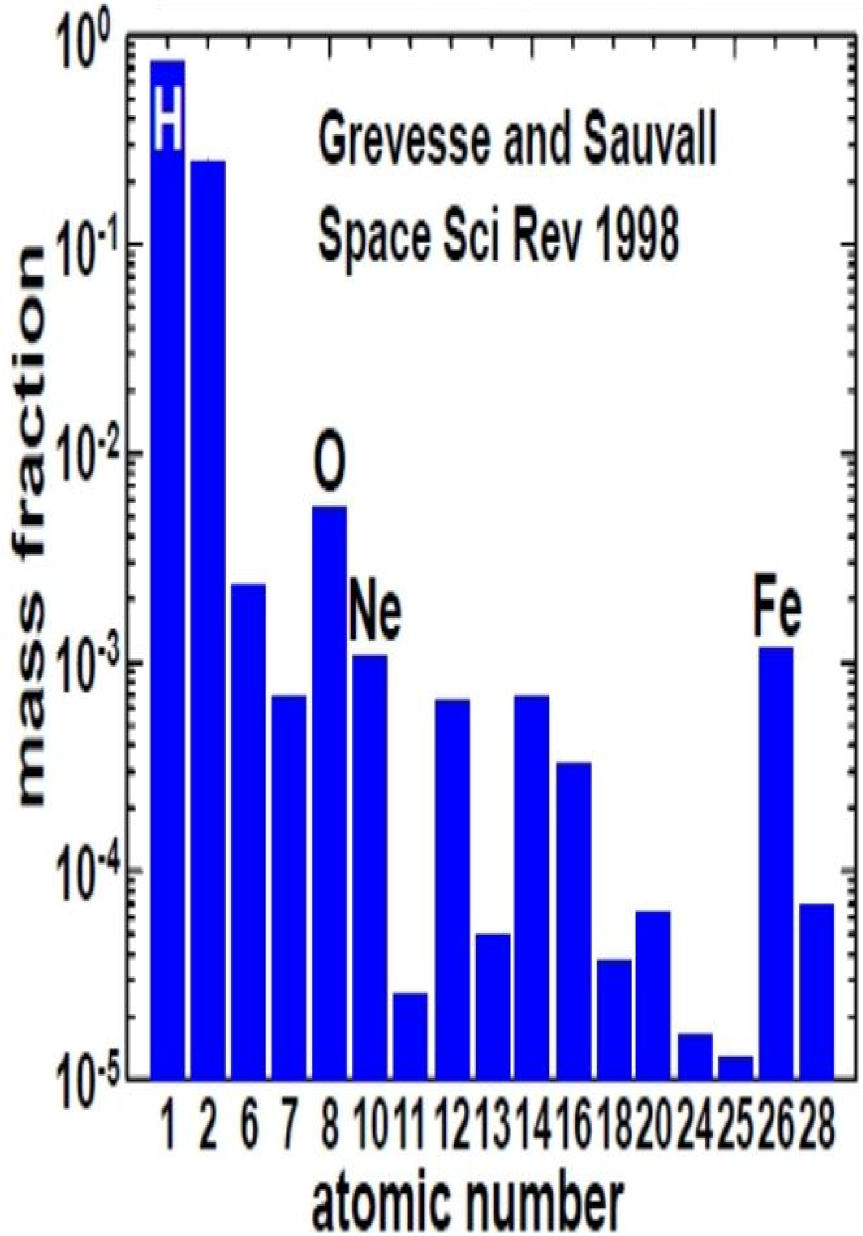


• Calculated from opacity using current atomic data, R_{CZ} = 0.726 - large (over 5600 mi difference) → changes solar structure

• 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

• Fe ionization fractions at Z and solar BCZ conditions



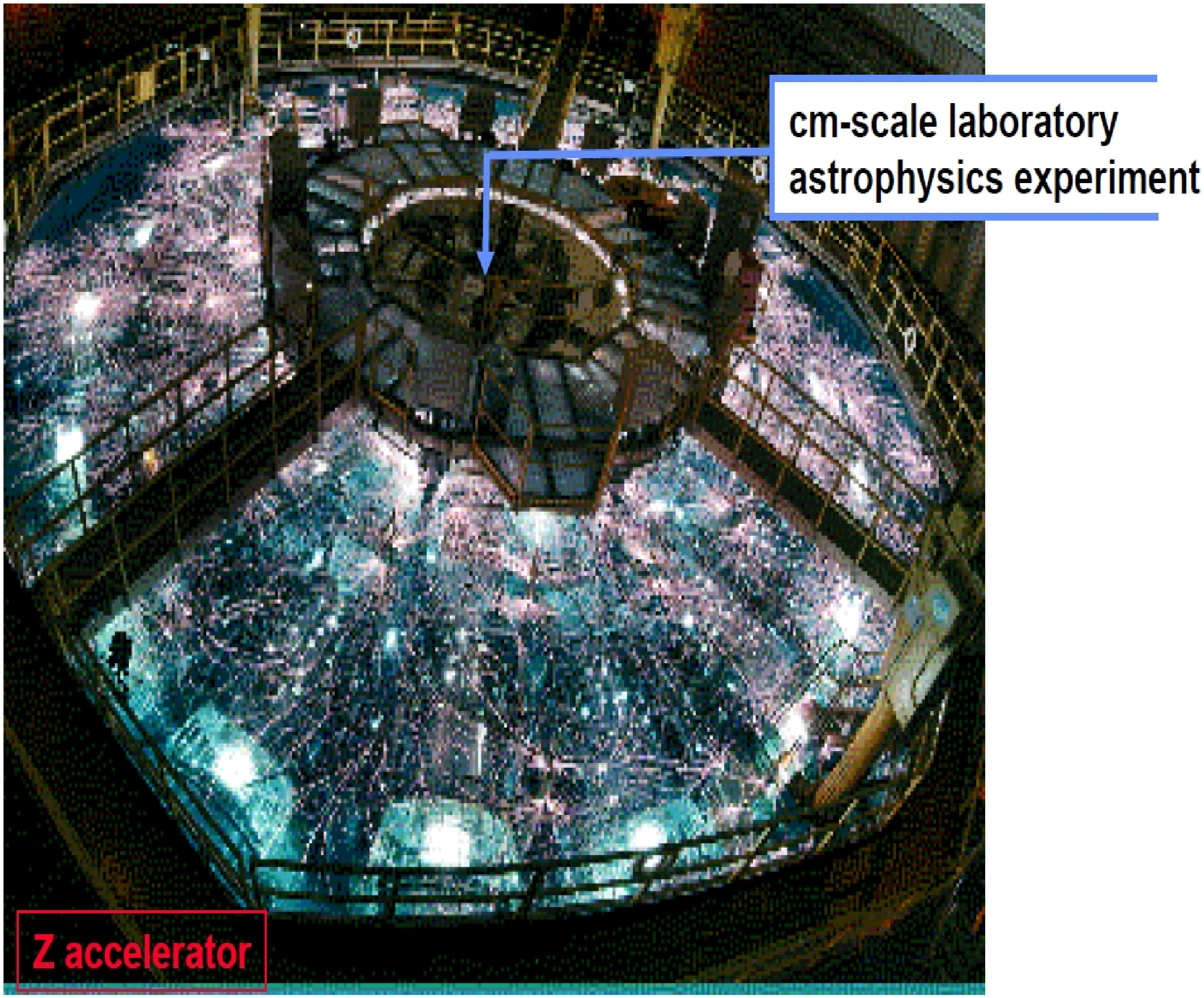


• Constructed the largest wavefunction expansions with high lying excitation assumed to have weak couplings, but turned out with stronger, orders of magnitude higher, couplings

SOLAR OPACITY DISCREPANCY HAS PERSISTED

SANDIA National Lab explore discrepancy experimentally

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



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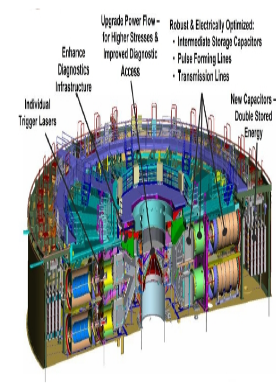
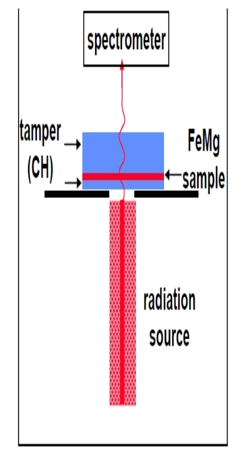




New Z

The refurbished Z delivers 24 million Amps to the load

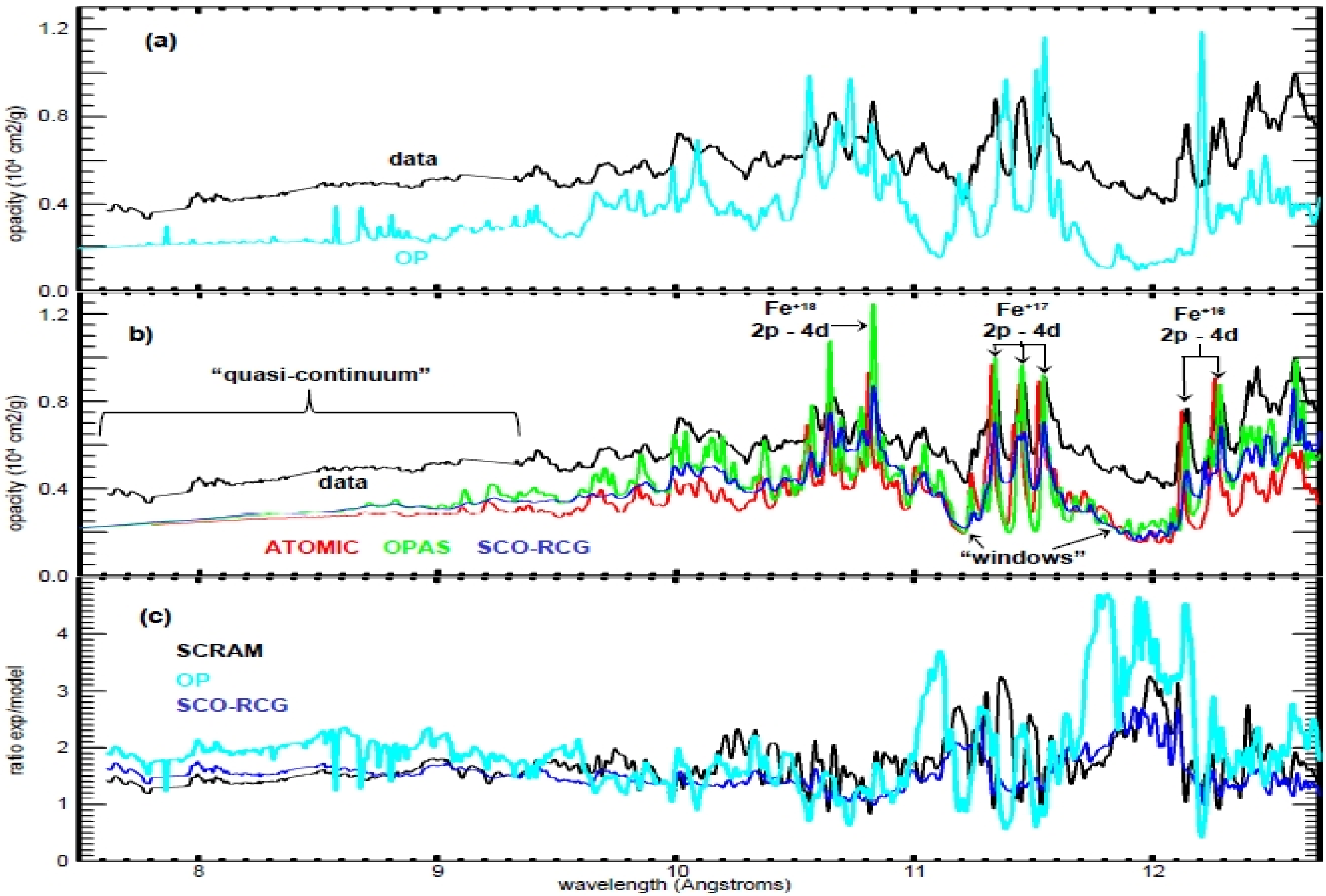
50% increase in electrical energy for present day experiments

New sample design

Increasing the rear tamper thickness delays expansion onset

This leads to higher density and higher temperature

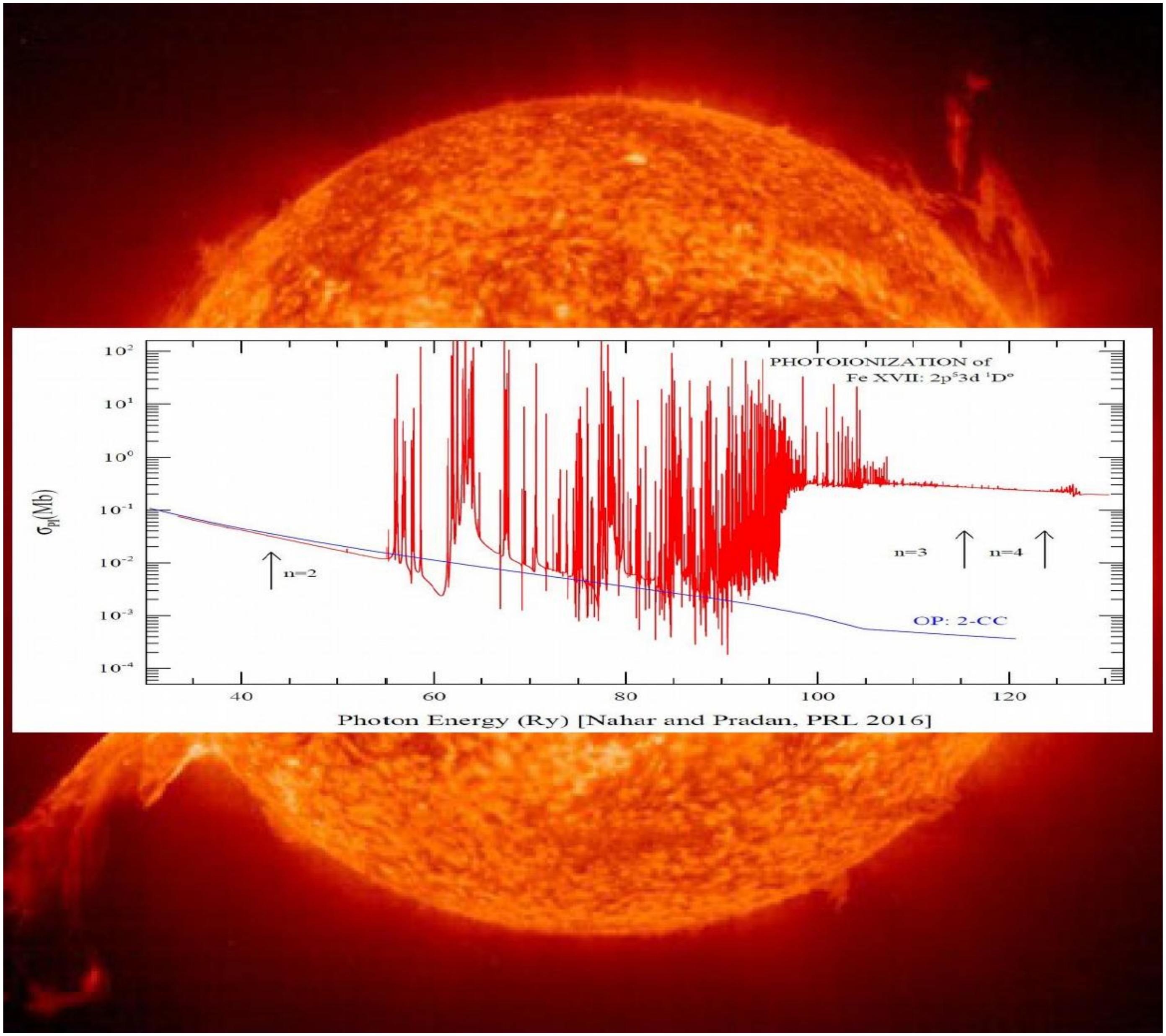
• COMPARISON OF IRON OPACITY: Experiment & Theory (Bailey et al, Nature Lett 2015)



• 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): Findings are under review in a series of 4 papers to be published at the same time in JPB



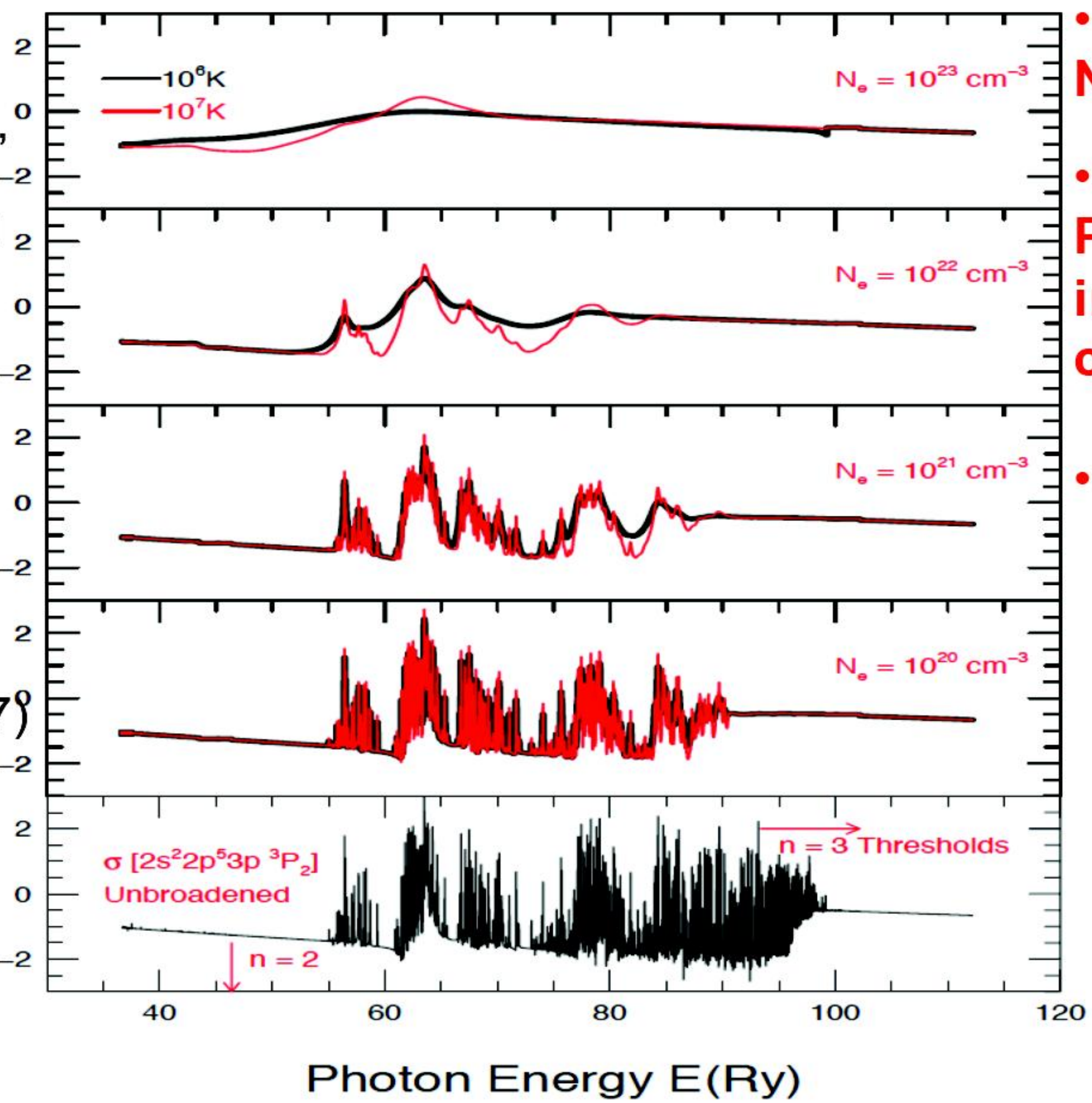
- Resonances are stronger for $\Delta n = 1$ than those of $\Delta n = 0$
- Resonances converge with higher n • The background is enhanced at high energy

New Development: Broadening of Resonances Fe XVII OPACITY SPECTRUM IN SOLAR INTERIOR

- Mean opacity increment by 35% (preliminary)

Electron Impact Broadening of Autoionizing Resonances in Plasmas

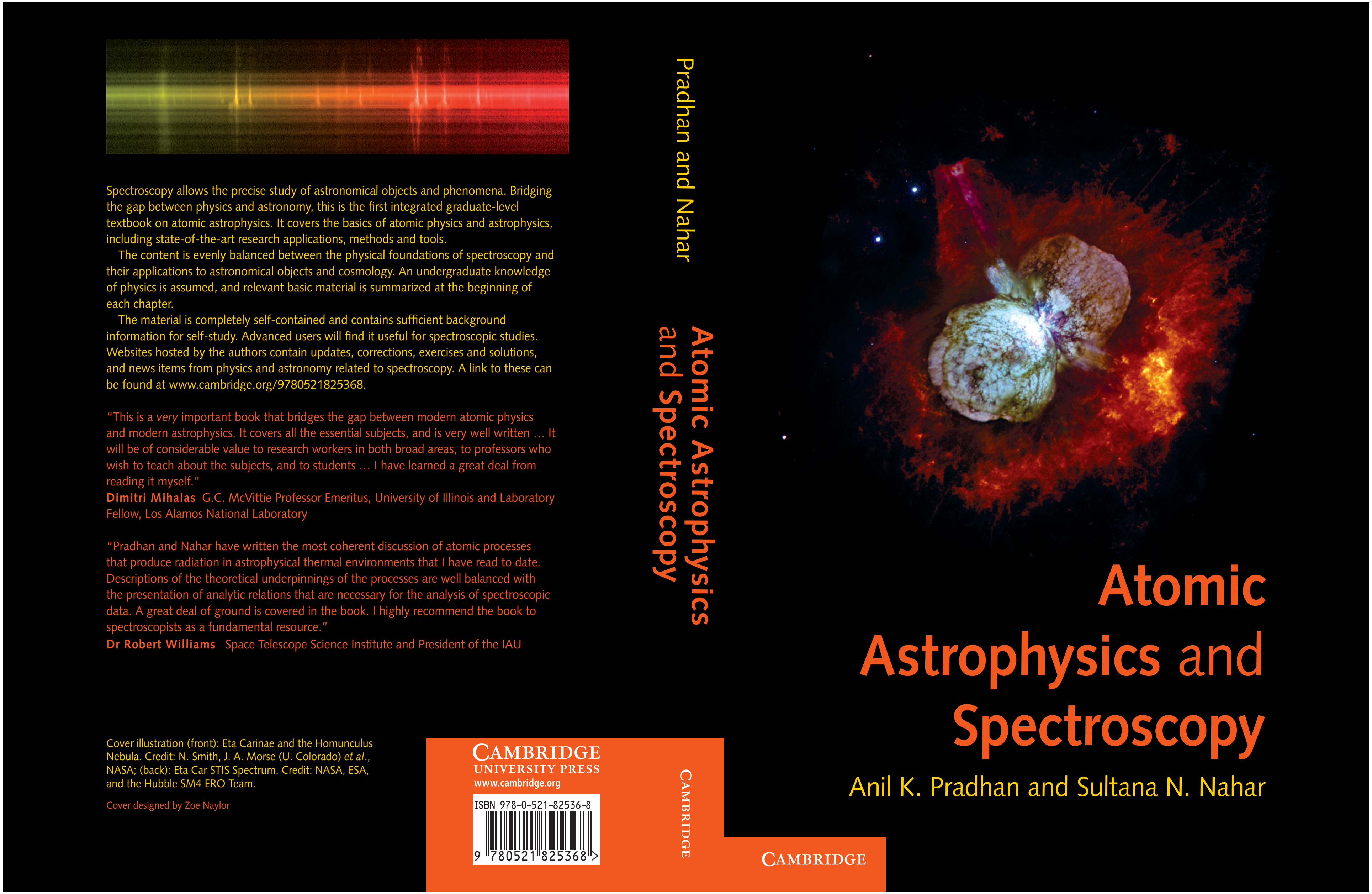
A new theoretical approximation, computational algorithm, and computer program for numerical simulation of resonances in atomic processes in plasmas (Pradhan 2017)



- 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 $N_e < N_c$

FUTURE PLAN

1. Implementation of NORAD-Atomic-DATA for solar plasma opacity
2. Exploration of AI for implementation of NORAD-Atomic-Data and development of astrophysical models.



Invite to APS membership:

AMERICAN PHYSICAL SOCIETY (APS)

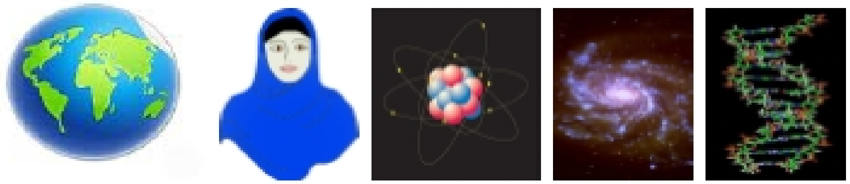
- It is the largest scientific network for physics and related subjects.
- APS journals are Phys. Rev. A, B, C, D, E, PhysRevLett, etc.
- It holds annually two general (Global Summit),and a number of conferences
- It gives many prestigious prizes and awards, and a number of grants
- APS Membership can be free for 4 years and be renewed for developing countries, free for 1 year for any US/non-US student:

Go to S.N. Nahar's Website and click on box "APS/FIP": https://www.aps.org/membership/join/physicists-worldwide or to my page http://www.astronomy.ohio-state.edu/nahar.1/fip.html

- Click on "APS MEMBERSHIP link" (https://www.aps.org/members worldwide) which will take you to APS membership page
- Click on "Apply for matching membership today" under "Apply for matching membership"
- You will taken to page where you will create an account
- Login. You will see the online membership application form. Fill it out. You should hear from APS in a week.
- After becoming member (will receive ID from APS),

\- become a member of your division & of APS unit
\- Become a FIP: Forum of International Physics member
\- Post your resume – Sign up for job alerts and apply online

بسم الله الرحمن الرحيم



INTERNATIONAL SOCIETY OF MUSLIM WOMEN IN SCIENCE (ISMWS)

ISMWS CHARTER

Founder: Dr. Sultana N. Nahar
The Ohio State University, Columbus, Ohio, USA
April 19, 2010

- **AIM:** - encourage Muslim women in science profession, form a network for various support
- **Objective:** Stay in Science (basic or applied)
- **Motto:** Out of 24 hours a day, we keep some hours for our intellectual nourishment
- **Members:** > 500 from 34 countries & additional chapters

Web: https://www.astronomy.ohio-state.edu/nahar.1/ismws.html

For membership (free) - Email: nahar.1@osu.edu