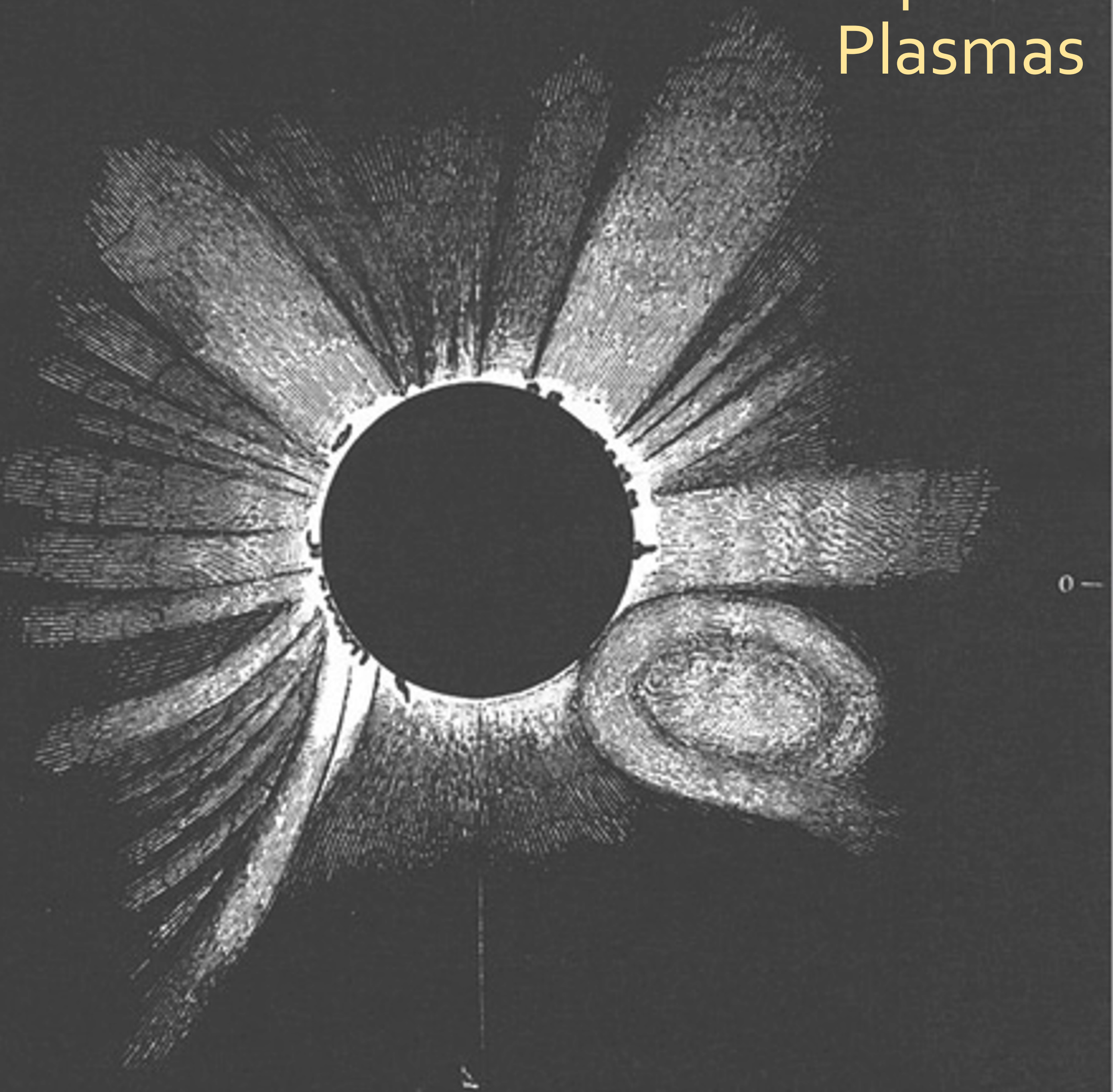
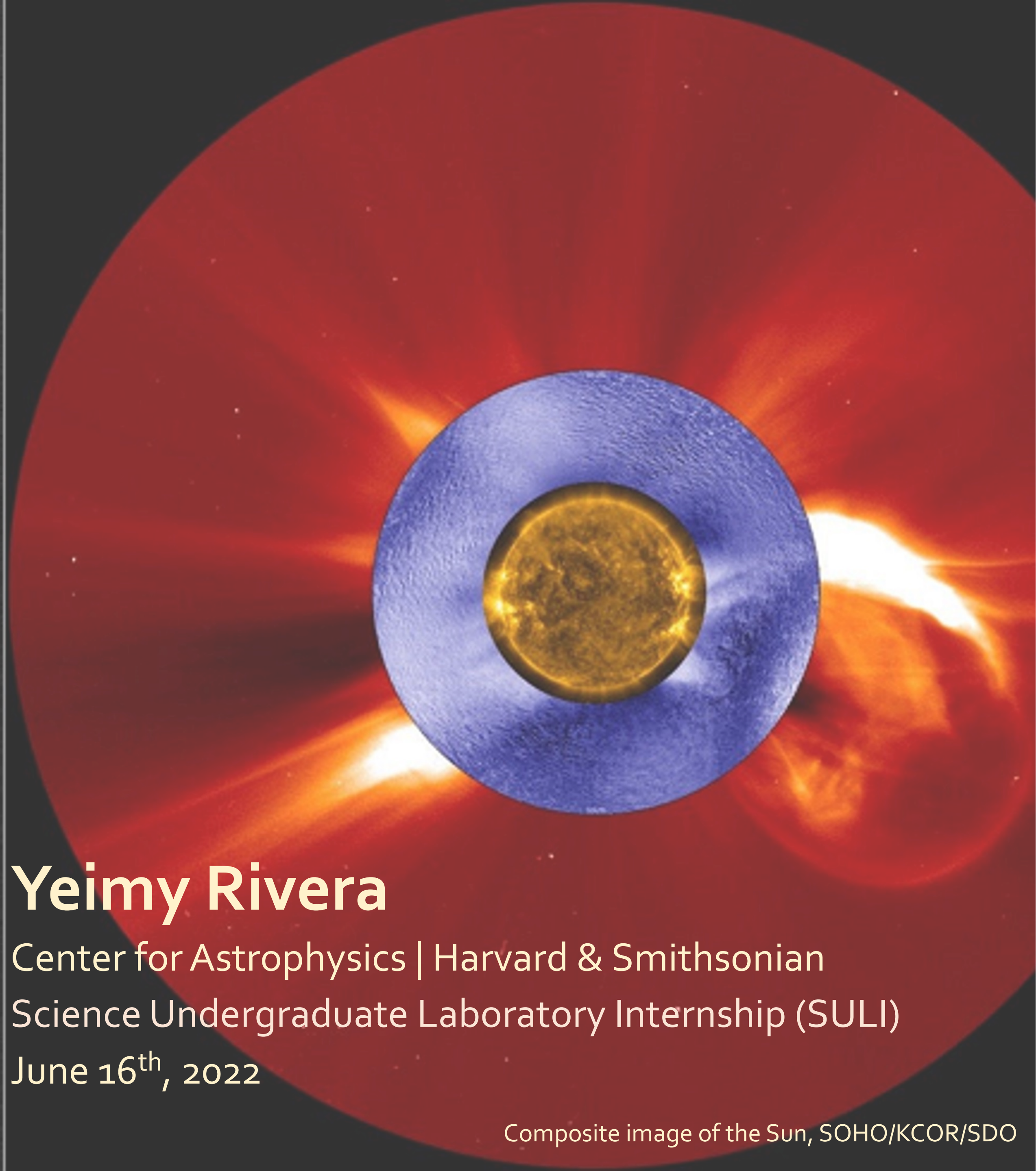
Heliospheric Plasmas



1860 eclipse drawing by G. Tempel in Torreblanca, Spain



Composite image of the Sun, SOHO/KCOR/SDO

Yeimy Rivera

Center for Astrophysics | Harvard & Smithsonian

Science Undergraduate Laboratory Internship (SULI)

June 16th, 2022

About me:

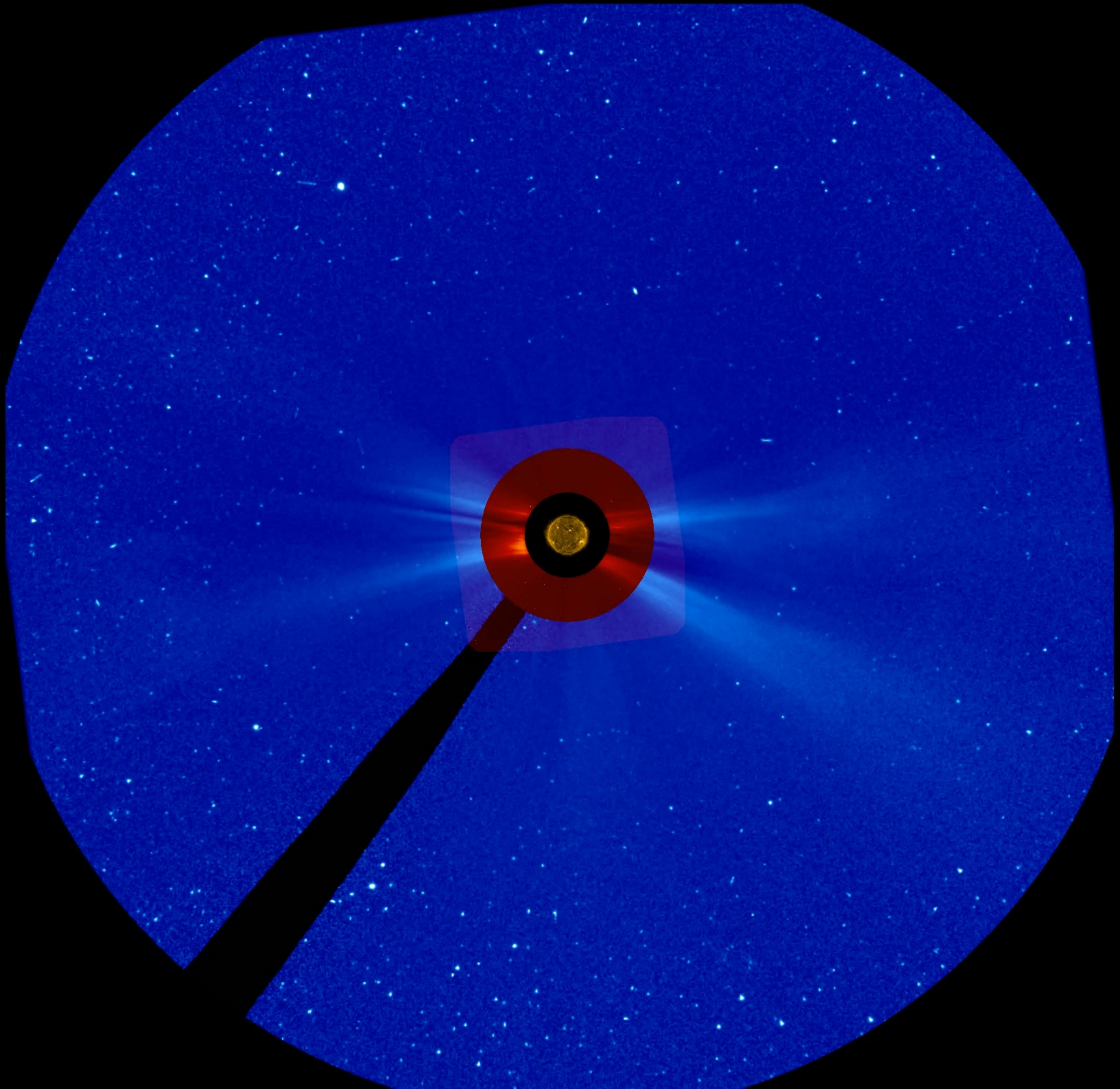
- Yeimy [yay-me!] Rivera
- Guatemalan and grew up in Los Angeles
- BS Astrophysics at UCLA, Master's Physics at California State University Northridge, PhD Space Physics at University of Michigan

Hobbies

- Beer
- Running and hiking
- Documentaries and podcasts [pandemic hobby!]

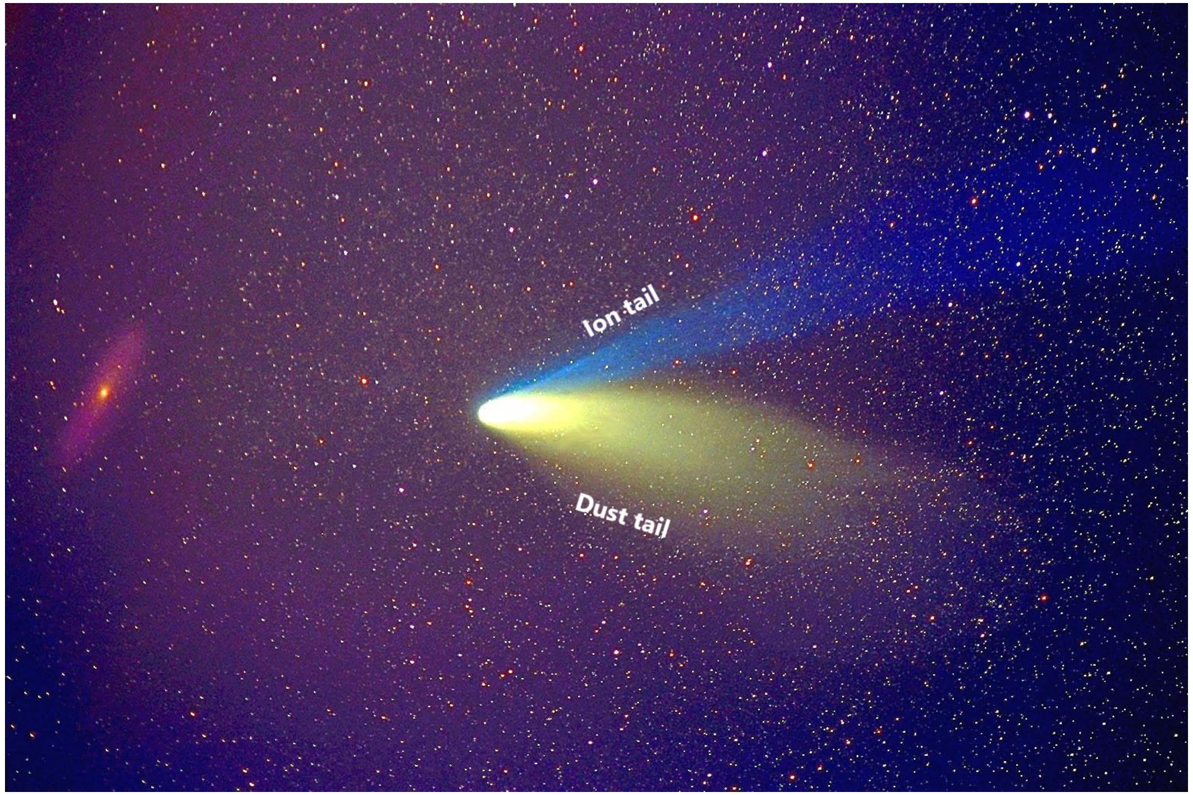
Quick overview

- [Very!] brief history of the solar wind
- Solar observatories
  - The Sun in wavelengths
  - In situ observations around the solar system
- The state of solar and heliophysics – open questions in the field
- New era of heliospheric science with Parker Solar Probe and Solar Orbiter missions
  - Traveling to the corona
  - Switchbacks
  - Campfires



Brief History of the solar wind

- Comet observations in the 19th and 20th century (space is not a vacuum)



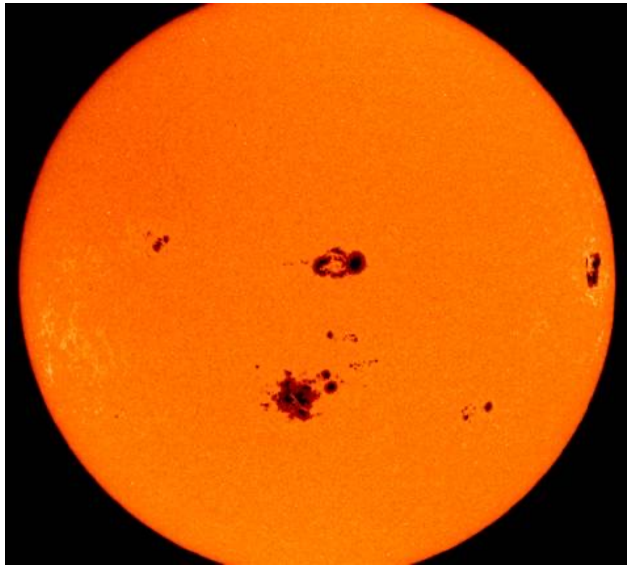
Comet Hale Bopp adapted from the Astronomy Picture of the Day on August 13, 2006

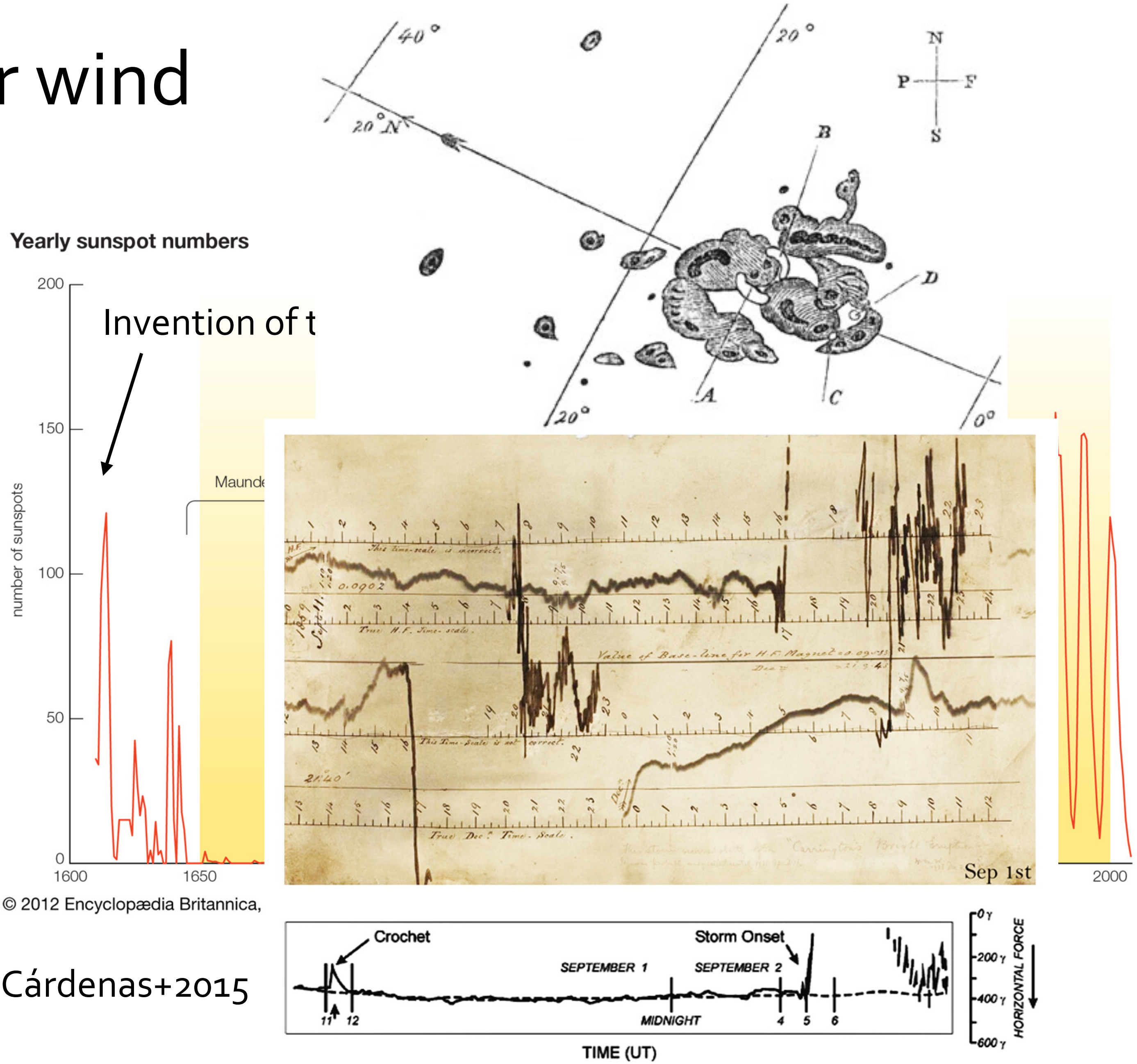
'solar corpuscular radiation'

Sept 1st, 1859

Brief History of the solar wind

- Comet observations in the 19th and 20th century (space is not a vacuum)
- Richard Carrington (pivotal sun-earth connection)





Cárdenas+2015

Brief History of the solar wind

- Comet observations in the 19th and 20th century (space is not a vacuum)
- Richard Carrington (pivotal sun-earth connection)
- Eugene Parker (1958) & Mariner 2 (1962) (propose and confirm supersonic solar wind)

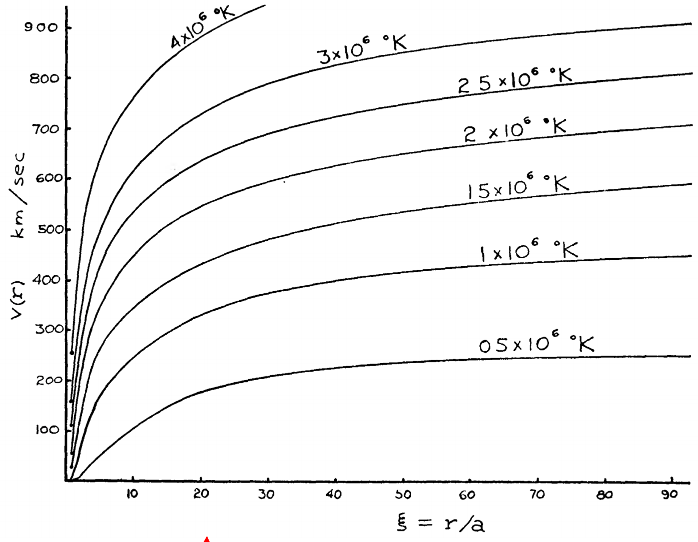
DYNAMICS OF THE INTERPLANETARY GAS AND MAGNETIC FIELDS*

E. N. PARKER
Enrico Fermi Institute for Nuclear Studies, University of Chicago

Received January 2, 1958

ABSTRACT

We consider the dynamical consequences of Biermann's suggestion that gas is often streaming outward in all directions from the sun with velocities of the order of 500–1500 km/sec. These velocities of 500 km/sec and more and the interplanetary densities of 500 ions/cm³ (10^{14} gm/sec mass loss from the sun) follow from the hydrodynamic equations for a 3×10^6 °K solar corona. It is suggested that the outward-streaming gas draws out the lines of force of the solar magnetic fields so that near the sun the field is very nearly in a radial direction. Plasma instabilities are expected to result in the thick shell of disordered field (10^{-5} gauss) inclosing the inner solar system, whose presence has already been inferred from cosmic-ray observations.



$$\frac{1}{r^2}\frac{d}{dr}(r^2\rho u) = 0$$

$$\rho u\frac{du}{dr} + \frac{dp}{dr} + \frac{\rho G M_\odot}{r^2} = 0$$

$$\frac{3}{2}u\frac{dp}{dr} + \frac{5}{2}\frac{1}{r^2}\frac{d}{dr}(r^2 u) = 0$$

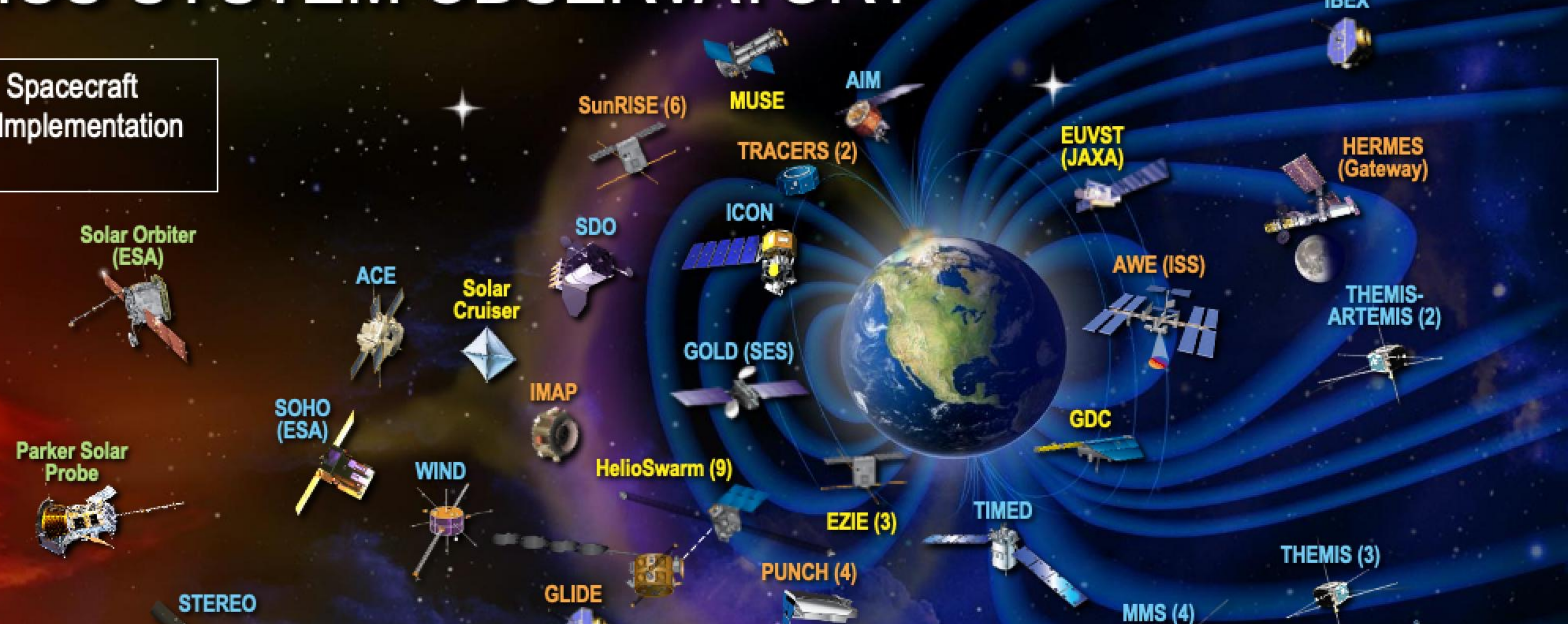
$$\frac{du}{dr} = \frac{2ru_s^2 - g_\odot R_\odot^2}{u^2 - u_s^2}\left(\frac{u}{r^2}\right)$$

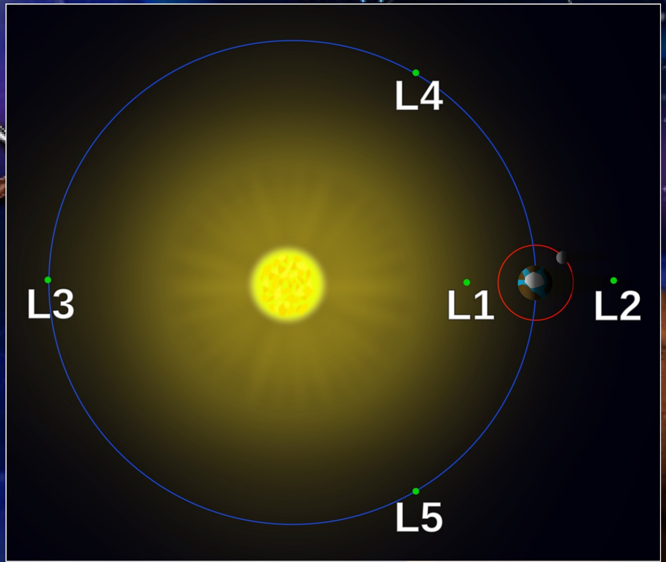
$$\frac{1}{2}u^2 - u_s^2\ln(u) = 2u_s^2\ln(r) + g_\odot\frac{R_\odot^2}{r} + C$$

Eugene Parker's historical paper (Parker 1958), connected these discoveries by proposing a supersonic expansion of the corona that forms a continuous solar wind flow.

HELIOPHYSICS SYSTEM OBSERVATORY

- **20** Operating Missions with **27** Spacecraft
- **14** Missions in Formulation or Implementation
- **1** Under Study





- FORMULATION
- IMPLEMENTATION
- PRIMARY OPS
- EXTENDED OPS

CubeSats					Hosted Payloads
In Development				On Orbit	In Development
AEPEX	*Dione*	*CubIXSS*	*SunCET*	*ELFIN*	*CODEX*
AERO / VISTA	*GTOSat*	*petitSat*	*DYNAGLO*	*SORTIE*	*LARADO*
CIRBE	*ICOVEX*	*REAL*	*WindCube*	*CuPID*	*MinXSS-3*
CURIE	*LAICE*	*SPORT*		*DAILI*	*OWLS*
CuSP	*LLITED*	*PADRE*			*STORIE*

OPERATING & FUTURE

Remote sensing

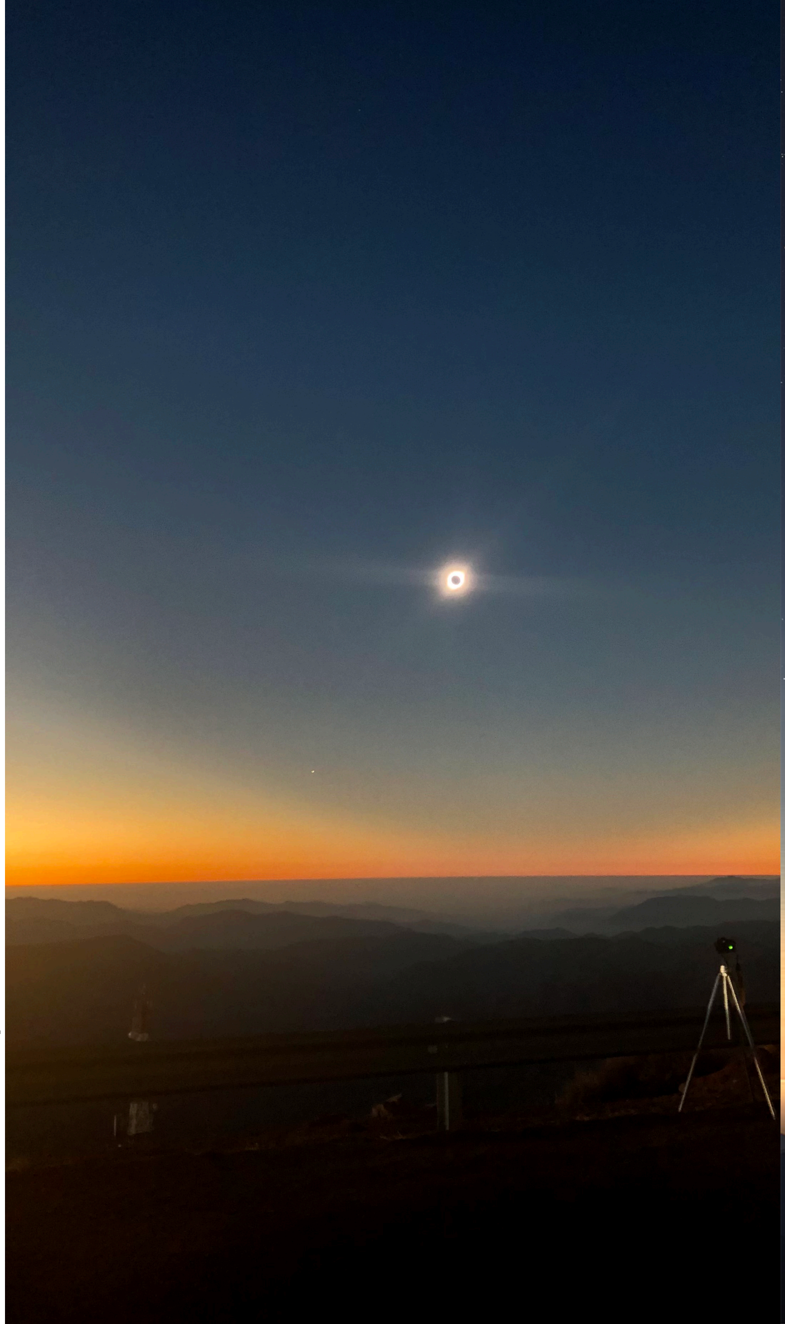
- Ground based (visible/IR and radio)
    - Telescopes – solar disk
    - Solar eclipses – corona

Ho and Hsi, the Drunk Astronomers (2137 BCE**)**

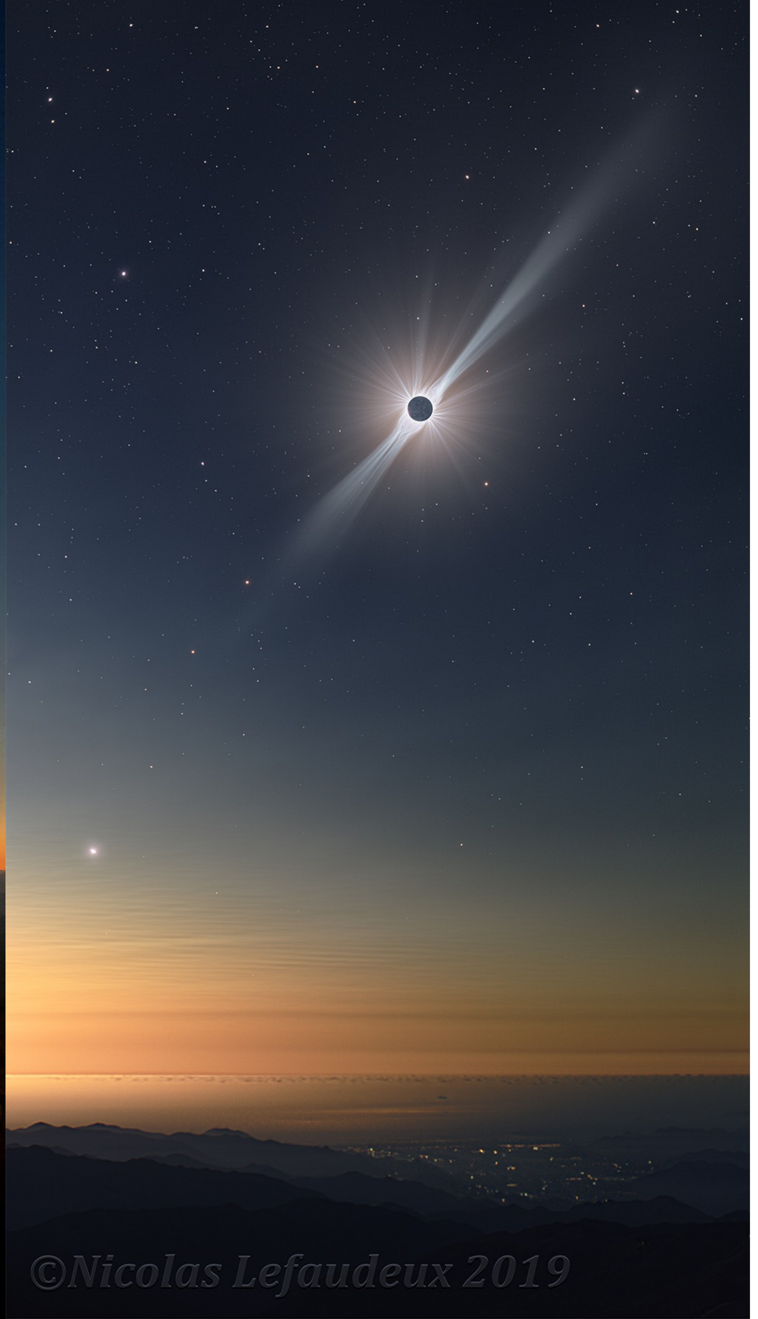
"Here lie the bodies of Ho and Hsi Whose fate though sad was visible, Being hanged because they could not spy Th'eclipse which was invisible."
- Author unknown (story may be apocryphal)

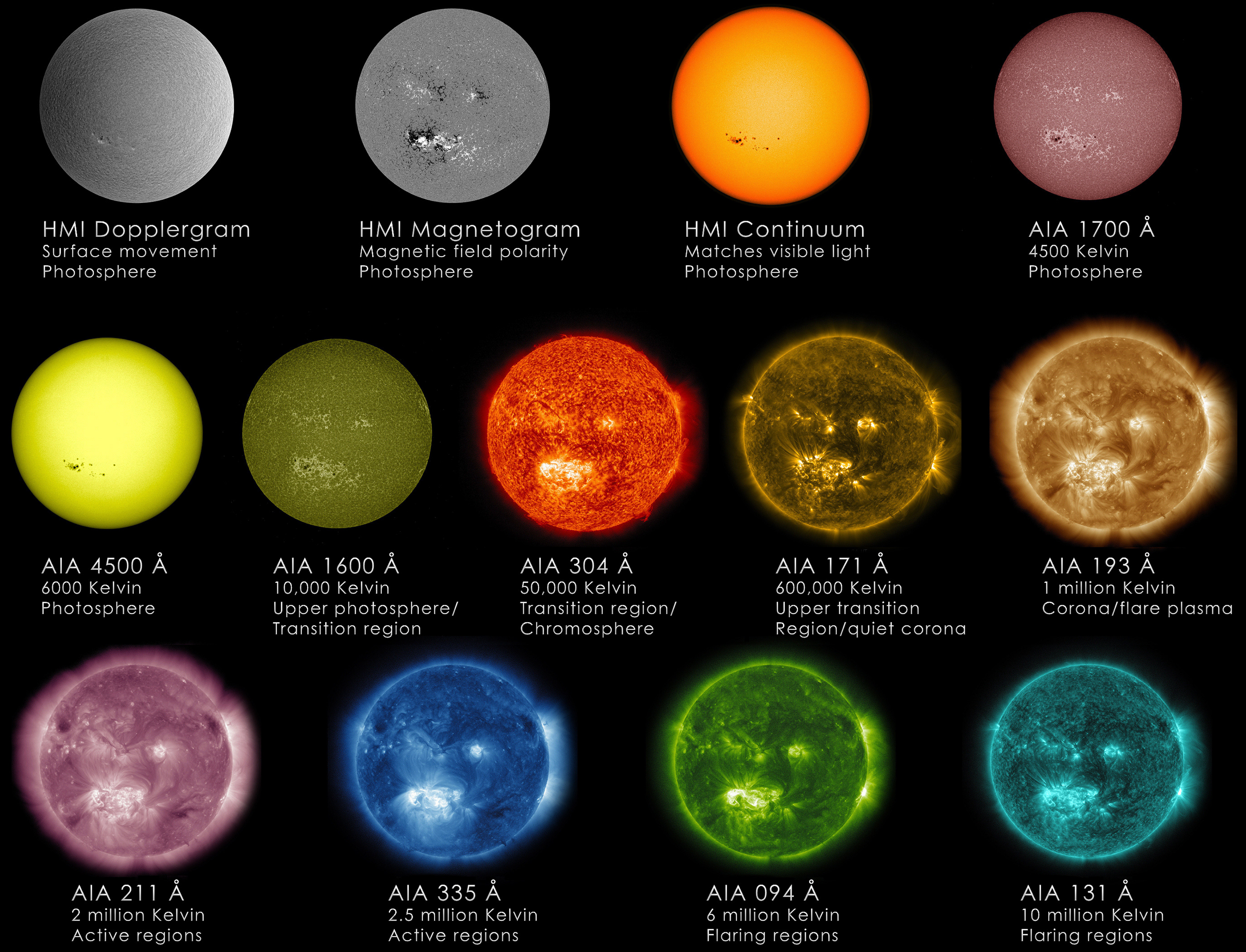
- Space based (extended to higher and lower wavelengths)

2019 Solar Eclipse Cerro Tololo, Chile (my iPhone picture!)



2019 Solar Eclipse Cerro Tololo, Chile (professional!)

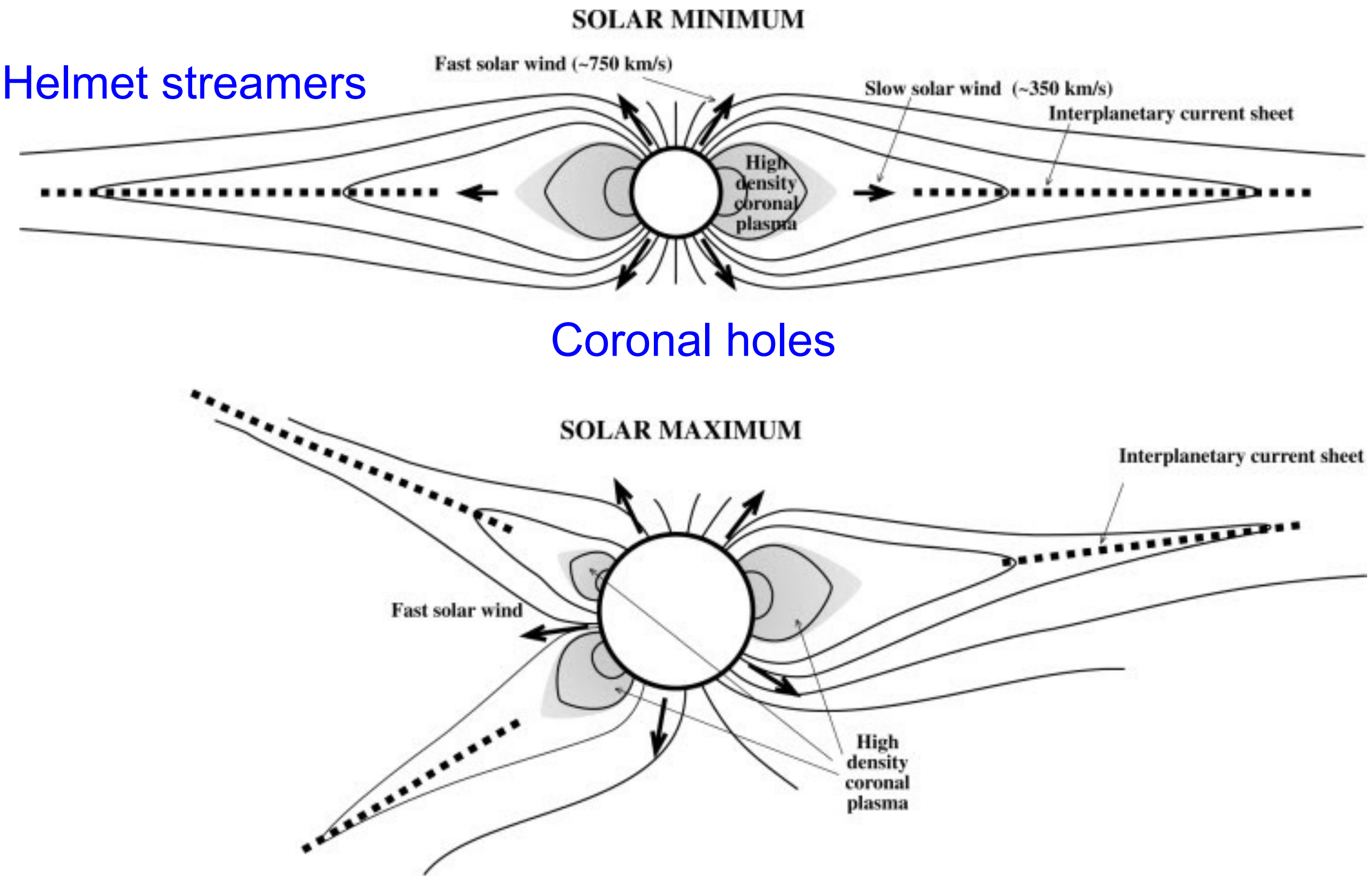



HMI Dopplergram
Surface movement
Photosphere
HMI Magnetogram
Magnetic field polarity
Photosphere
HMI Continuum
Matches visible light
Photosphere
AIA 1700 Å
4500 Kelvin
Photosphere
AIA 4500 Å
6000 Kelvin
Photosphere
AIA 1600 Å
10,000 Kelvin
Upper photosphere/
Transition region
AIA 304 Å
50,000 Kelvin
Transition region/
Chromosphere
AIA 171 Å
600,000 Kelvin
Upper transition
Region/quiet corona
AIA 193 Å
1 million Kelvin
Corona/flare plasma
AIA 211 Å
2 million Kelvin
Active regions
AIA 335 Å
2.5 million Kelvin
Active regions
AIA 094 Å
6 million Kelvin
Flaring regions
AIA 131 Å
10 million Kelvin
Flaring regions

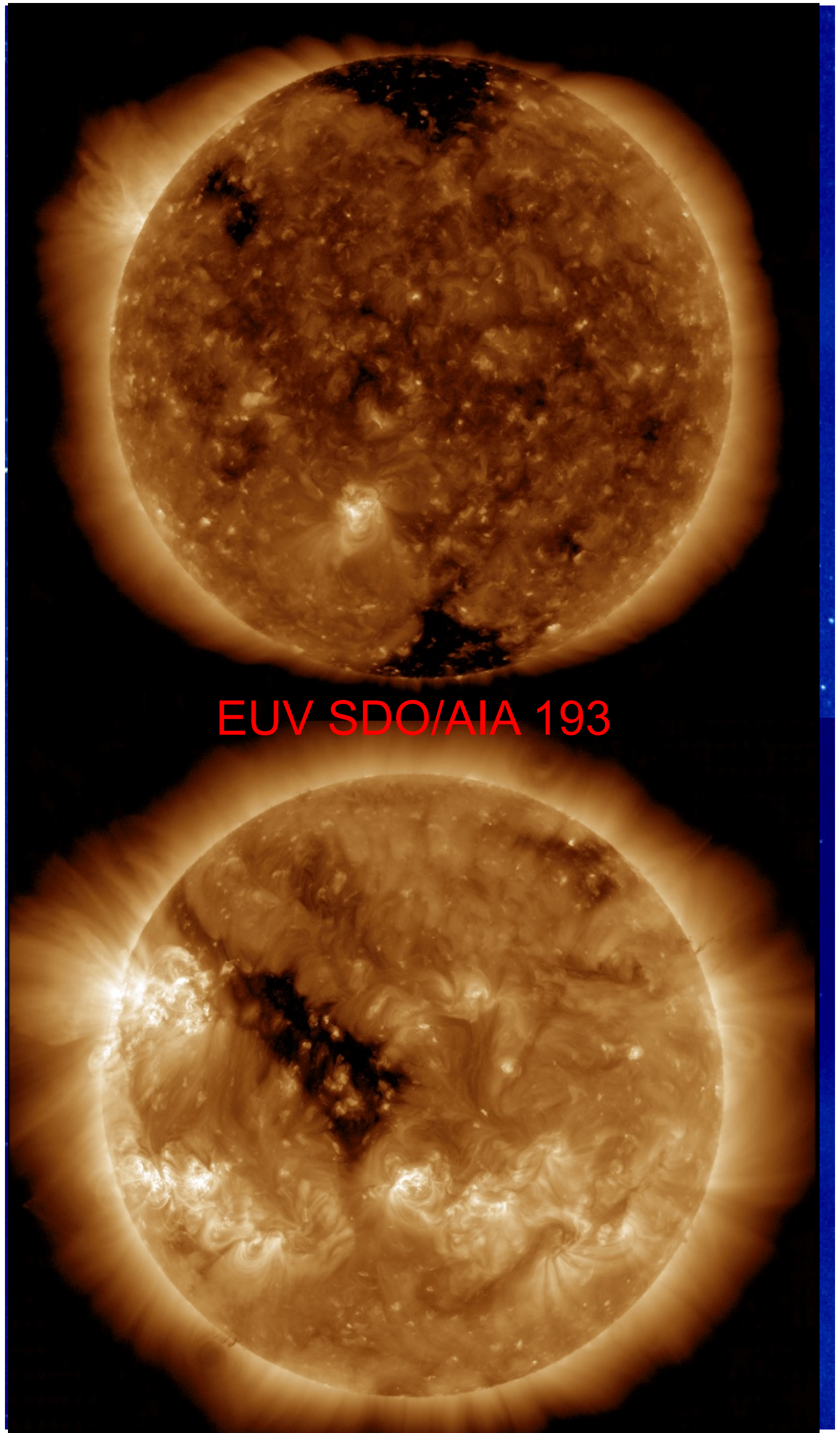
Solar Structures

Solar Minimum: Near featureless solar disk, coronal holes confined to the poles

Helmet streamers



Coronal holes



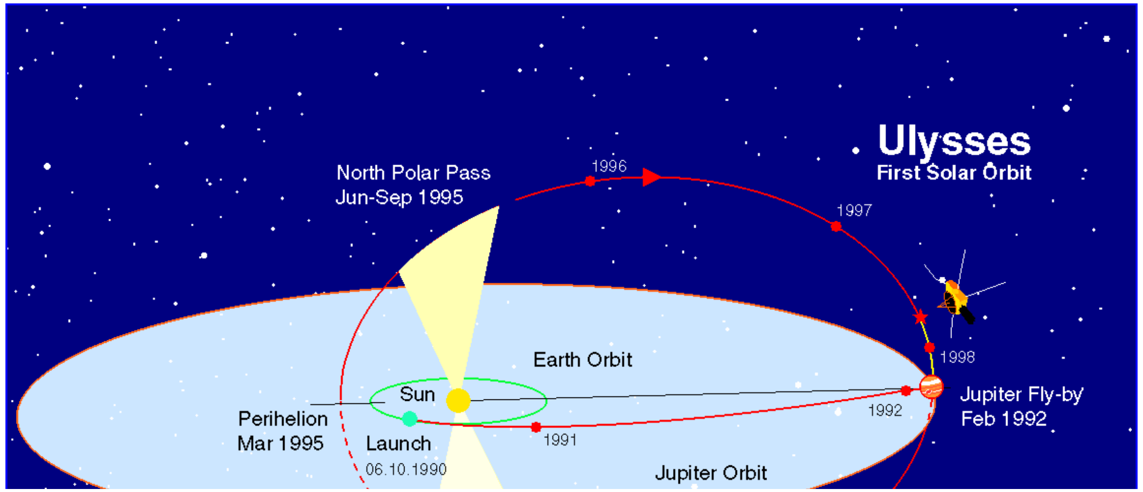
Solar Maximum: Coronal holes at lower latitudes, emergence of ARs

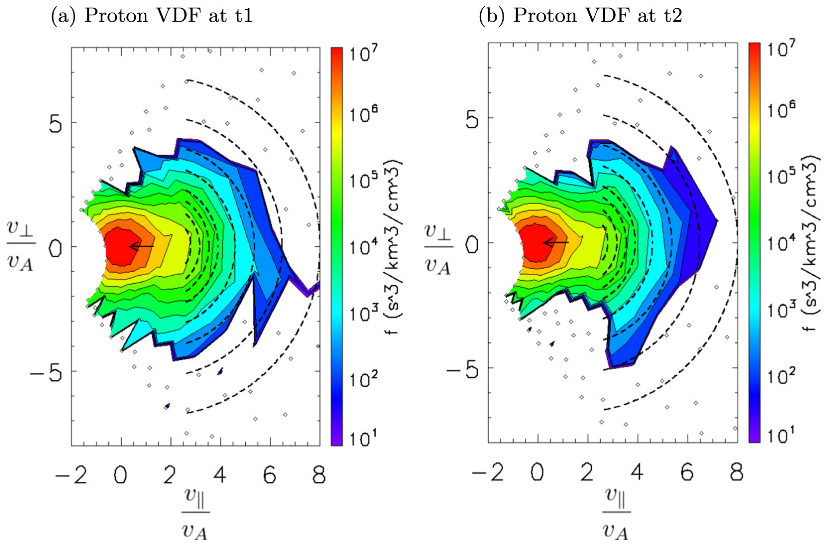
In Situ [in the original place.]

Magnetometers can measure magnetic field
- 3D magnetic field components

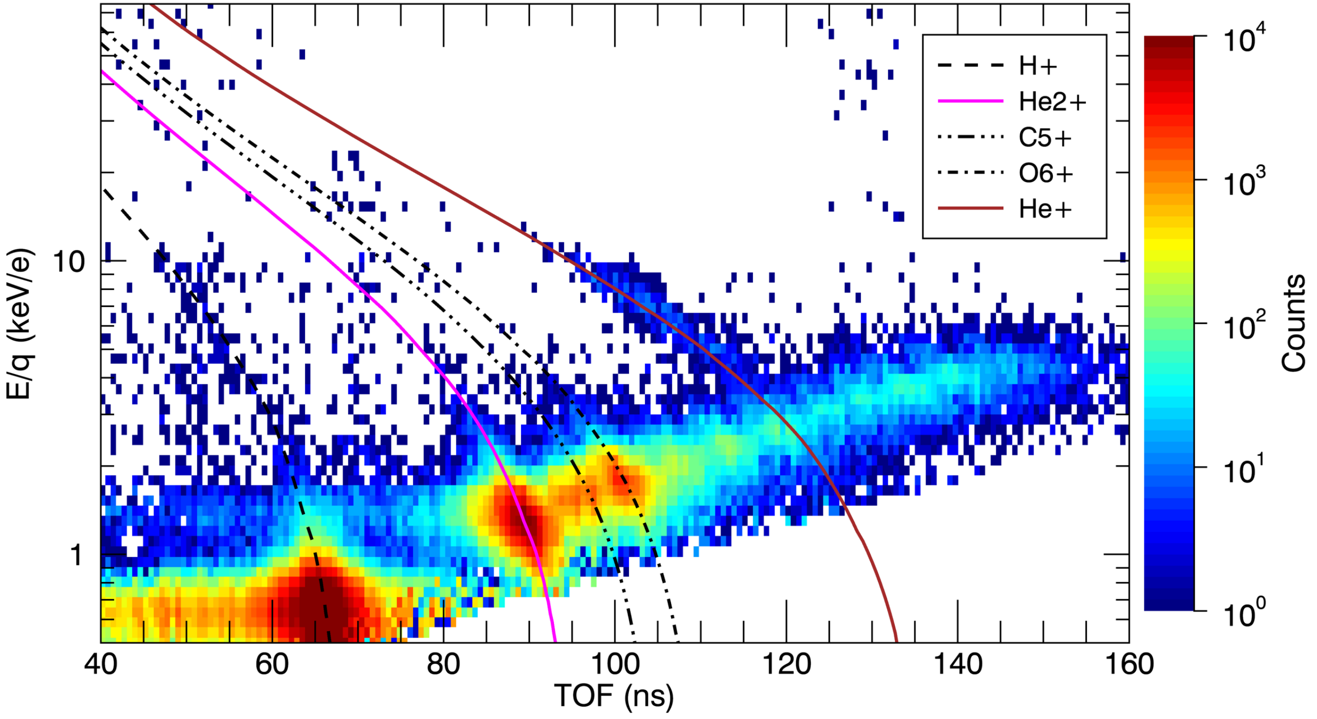
Faraday Cups / Electrostatic Analyzers
- 3D velocity distributions functions of ions and electrons - density, temperature, speed and characterize non-thermal features

Mass Spectrometers
- Measure individual heavy ion particle densities, energy, charge levels





Parker Solar Probe (Verniero et al 2022)



Solar Orbiter (Rivera AGU 2020)

Biggest questions in solar and heliophysics today

Closed field

Coronal Heating Problem (Klimchuk 2006) –

What is mechanism heats the solar atmosphere to multi-million degrees?

Fractionation processes (Laming 2015) –

What governs the changes in elemental abundances across coronal structures?

Open field

Solar wind formation (Cranmer & Winebarger 2018) –

Where does the solar wind originate and how is it released?

How is it heated and accelerated from the Sun?

Physical mechanisms operating in the solar wind (Cranmer & Winebarger 2018) –

What is the role of turbulence and wave-particle resonances in solar wind formation and evolution?

Coronal Heating Problem (Klimchuk 2006) –

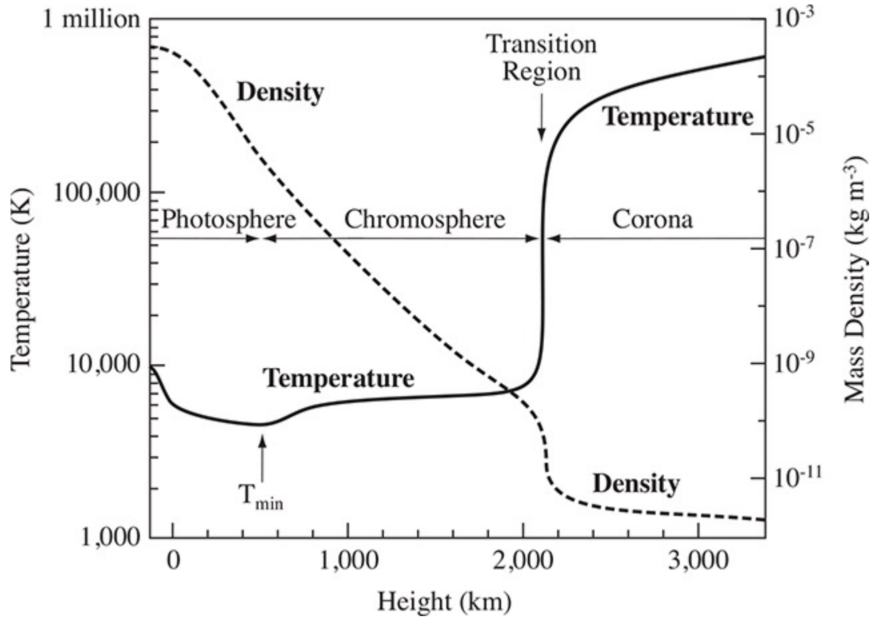
What is mechanism heats the solar atmosphere to multi-million degrees?

Emission lines seen during total solar eclipses were not due to a new element dubbed "coronium," but rather to known elements at very high stages of ionization (Grotrian 1939, Edlen 1942)

Two main theories:

Dissipation of magnetohydrodynamic (MHD) waves (Alfvén 1947)

Dissipation of small-scale current sheets from magnetic field reconnection events called 'nanoflares' (Parker 1972)

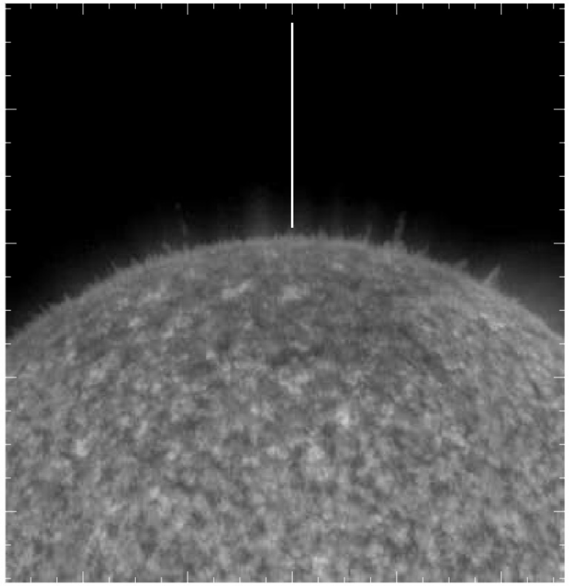


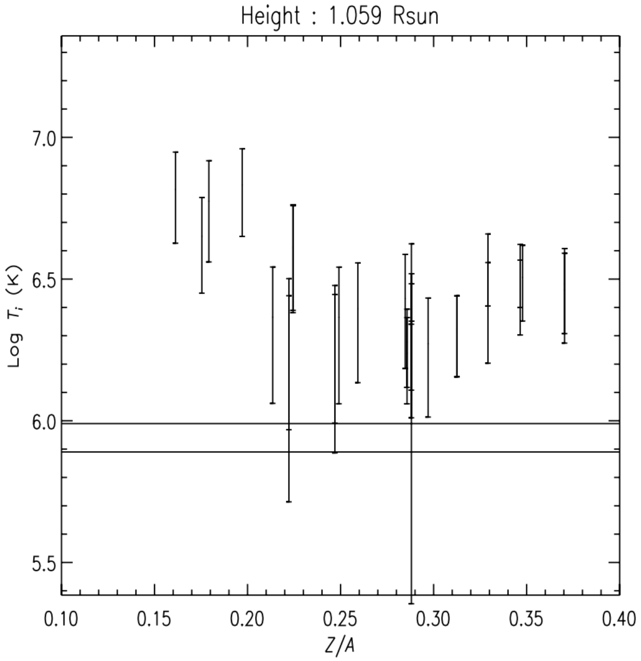
The wave theory (described in Parnell & De Moortel 2012)

Waves must be generated in (or below) the solar surface layers

Energy flux has to be transported into the corona

Waves have to dissipate (very) efficiently to convert the energy flux into heat in the right place, at the right time

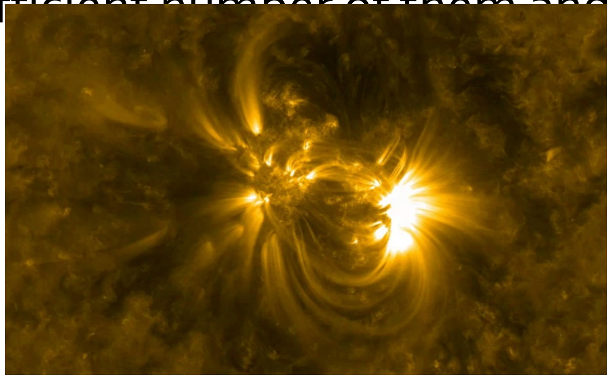


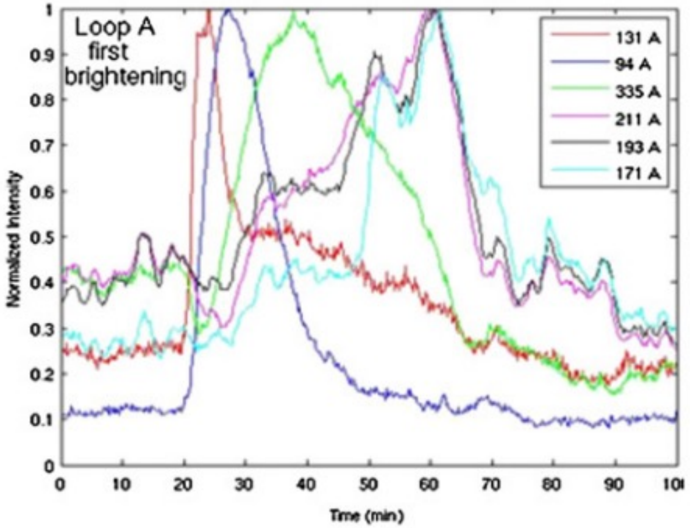


Landi & Cranmer 2009

Nanoflare theory Parker (1972) hypothesized that slow convective motions of magnetic footpoints could lead to a braiding of the magnetic field, creating small current sheets that would be continually dissipated and reformed, providing direct heating via ohmic dissipation

Requires a suf… happening all over the Sun!



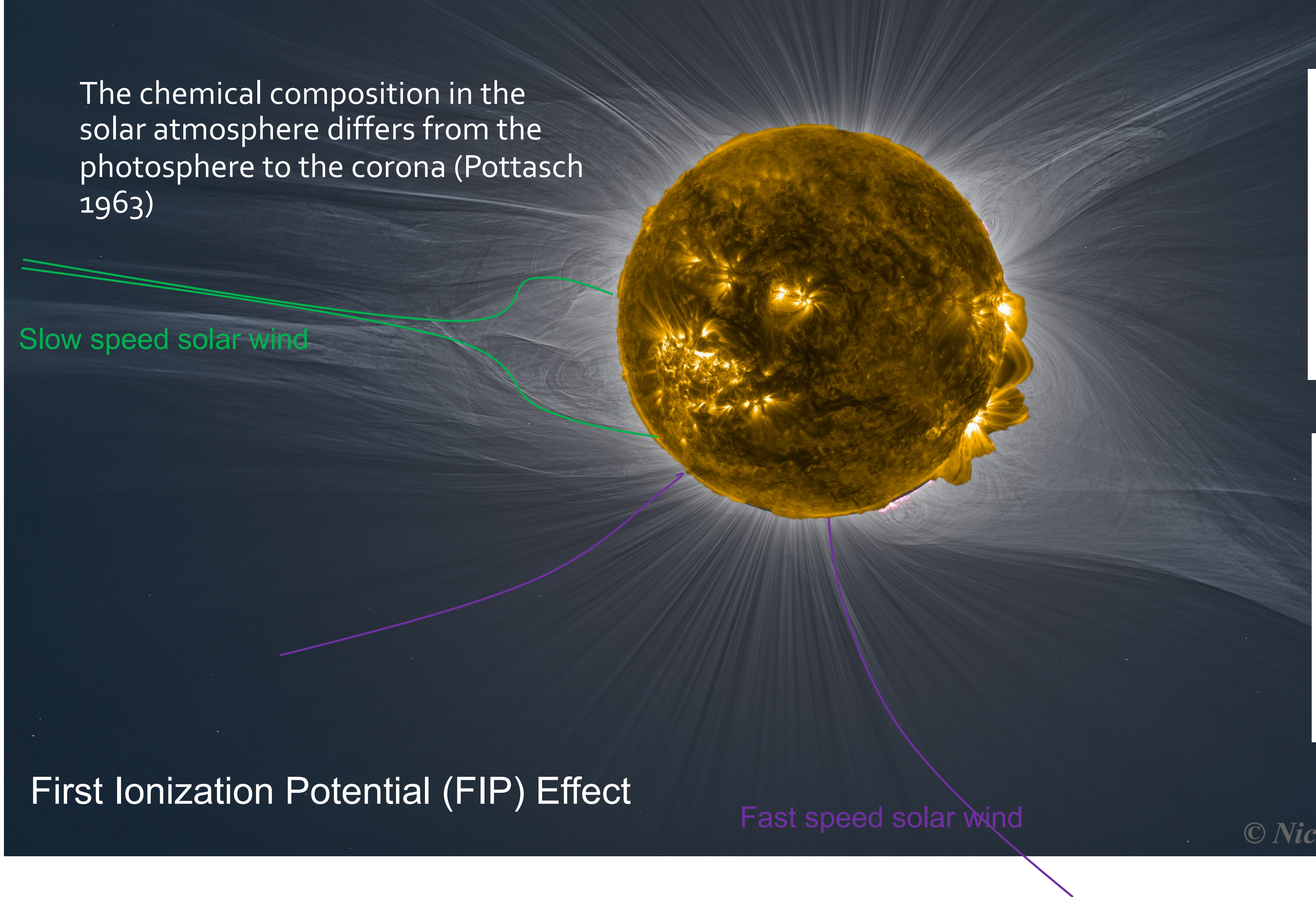


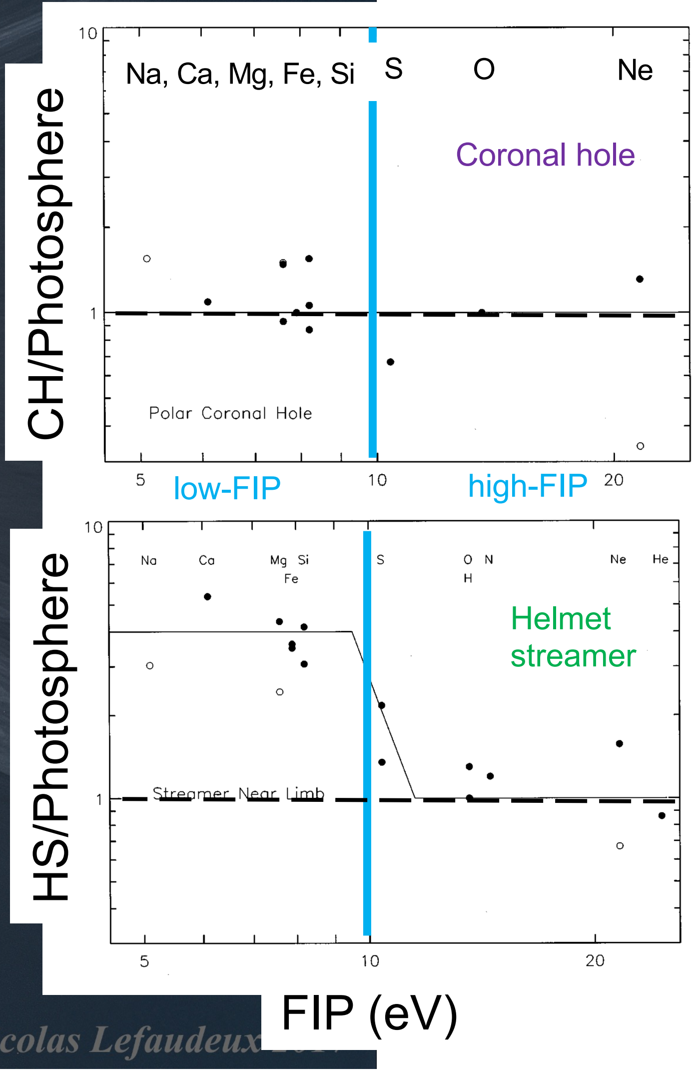
Cadavid et al 2014

Fractionation processes (Laming 2015) –

What governs the elemental abundances of different coronal structures?

The chemical composition in the solar atmosphere differs from the photosphere to the corona (Pottasch 1963)





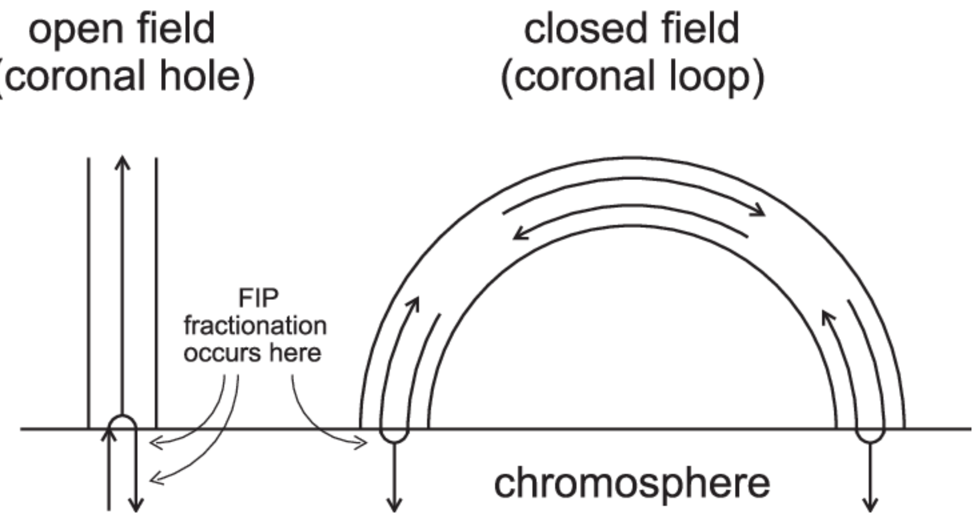
First Ionization Potential (FIP) Effect

Fractionation processes (Laming 2015) –

What governs the elemental abundances of different coronal structures?

Chromospheric Alfven waves *[could potentially be connected to coronal heating mechanism]* give rise to the separation of ions and neutrals through the action of the **ponderomotive force** leading to the First Ionization Potential Effect (FIP; Laming 2017)

- PF moves chromospheric ions, e.g., Fe, Si, and Mg, with a low FIP up into the corona, leaving the neutrals behind

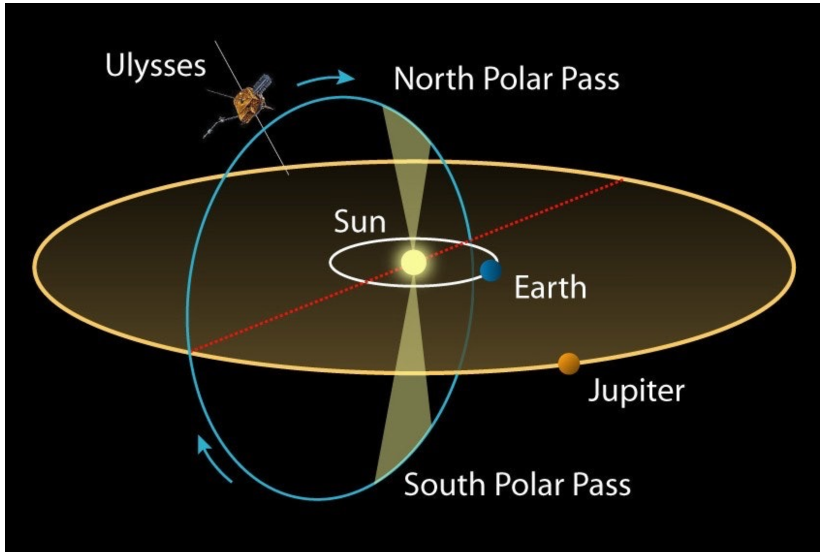


Laming et al (2019)

Solar wind formation –

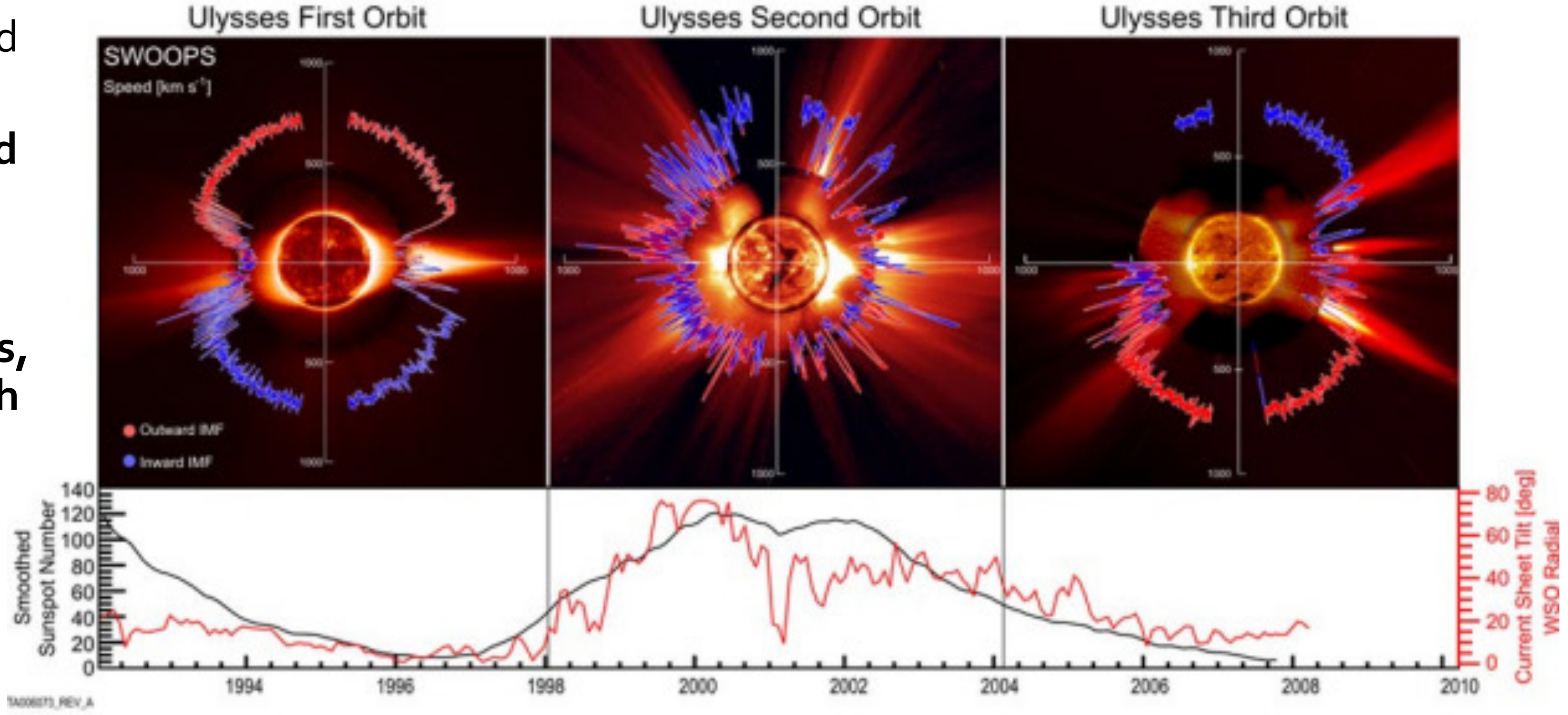
Where does the solar wind originate and how is it released?

How is it heated and accelerated from the Sun?



Distinct solar wind properties at different heliographic latitudes (Solar Minimum)

- **Faster, more tenuous, no fractionation** solar wind emanated from the poles – **coronal holes**
- **Slower, denser, low FIP enhanced** solar wind measured around the ecliptic – **active regions, helmet streamers, pseudostreamers, outer boundaries of coronal holes, and transient jets associated with interchange reconnection**



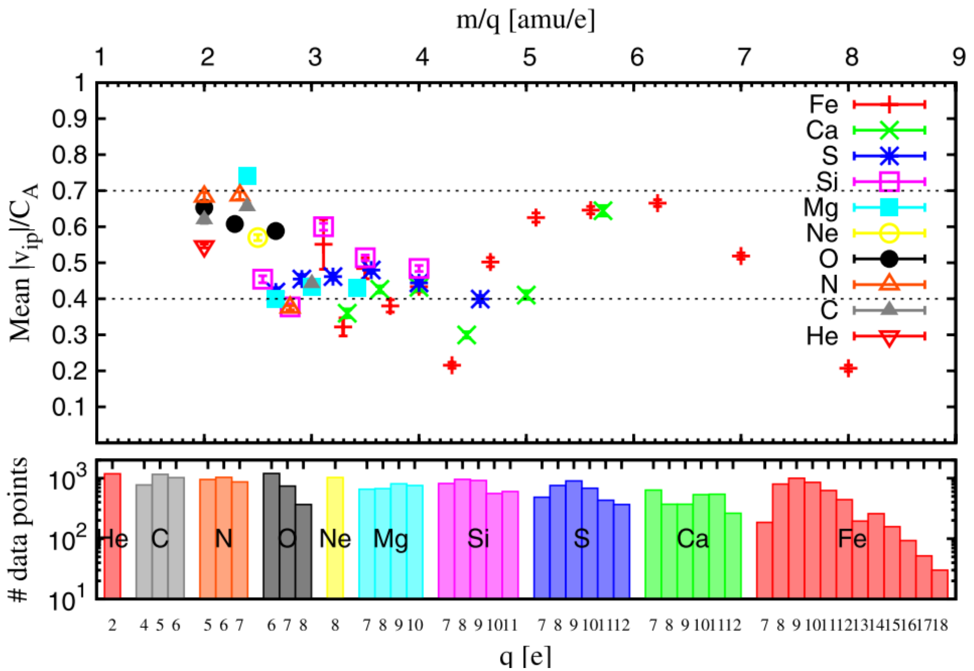
Credit: Southwest Research Institute & ESA

Solar wind formation –

Where does the solar wind originate and how is it released?

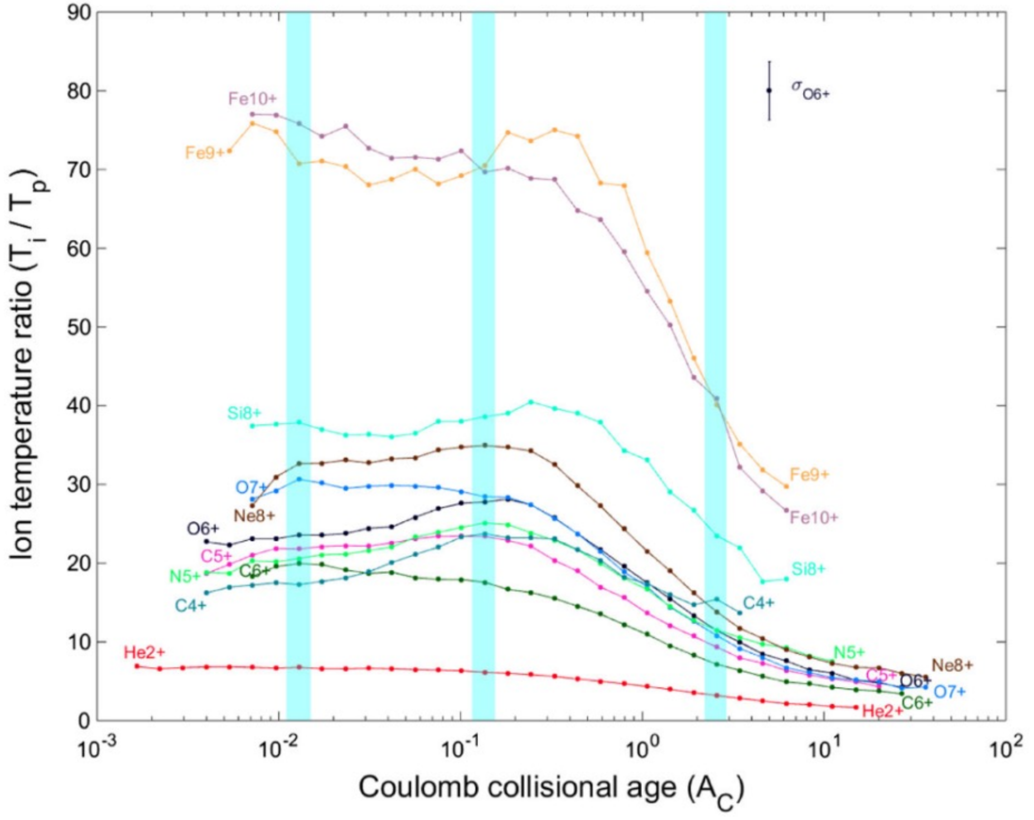
How is it heated and accelerated from the Sun?

- Solar wind heavy ions are observed to be super mass proportional heating and differential flowing!



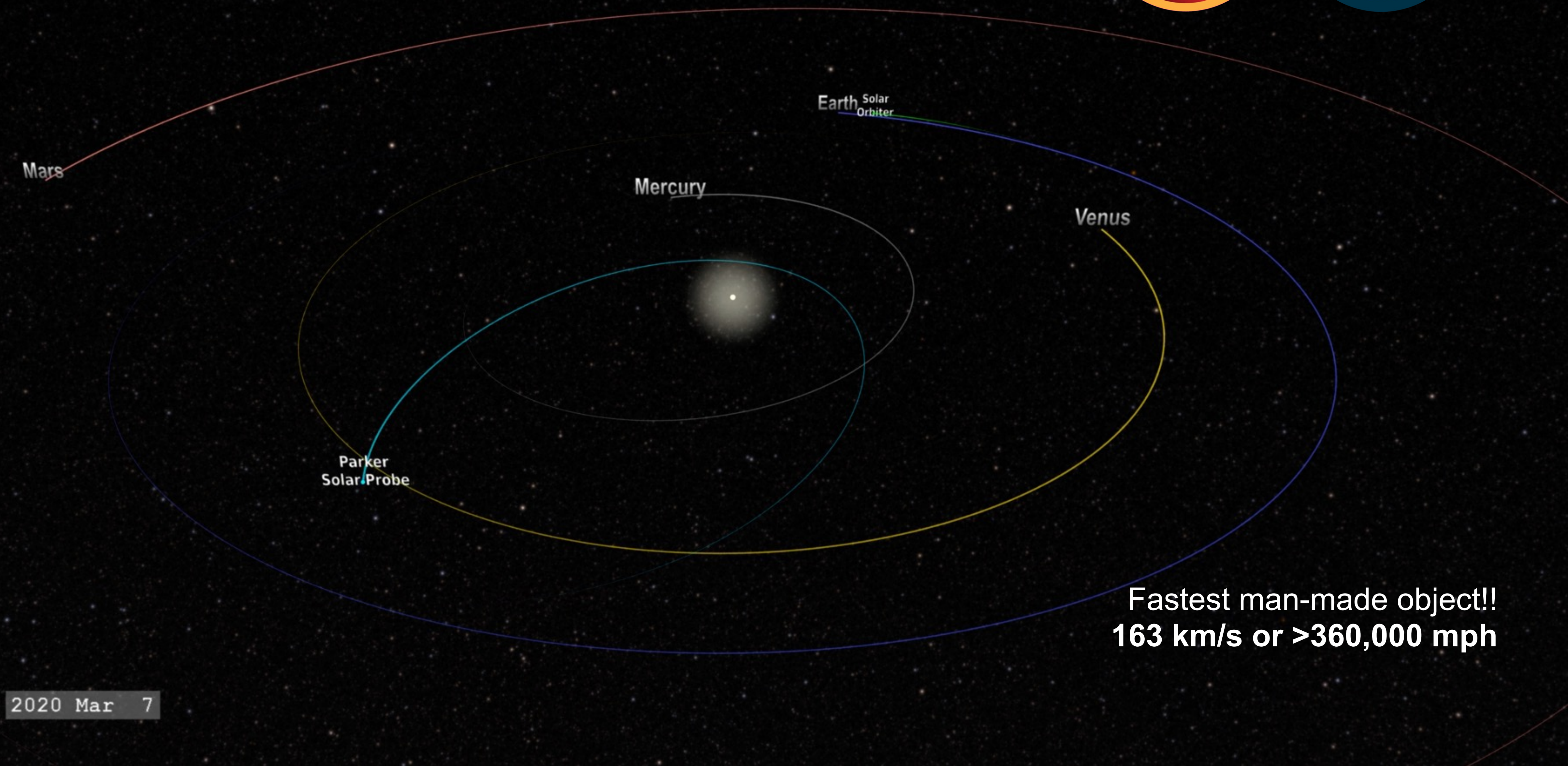
Berger et al (2011)

$A_C=\tau_{Exp}/\tau_{Coll}$



Tracy et al (2016)

New era of heliospheric science with Parker Solar Probe and Solar Orbiter



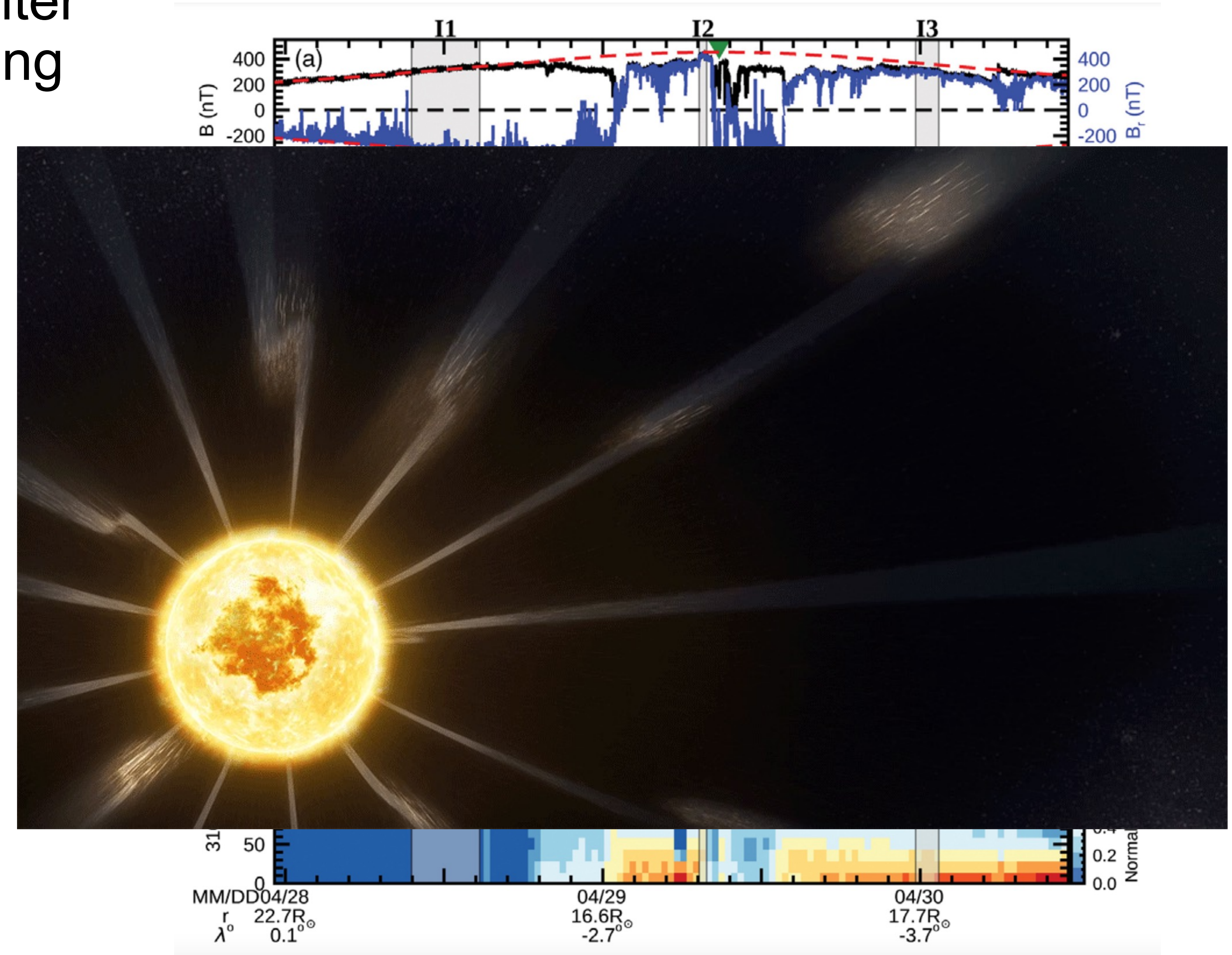
Fastest man-made object!!

163 km/s or >360,000 mph

New era of heliospheric science with Parker Solar Probe and Solar Orbiter missions: solar-heliosphere coupling

Parker Solar Probe

- Crossed below the Alfven critical surface – direct observations of the corona at 18-20Rsun
- Switchbacks



Kasper et al 2021

New era of heliospheric science with Parker Solar Probe and Solar Orbiter missions: solar-heliosphere coupling

Parker Solar Probe

- Crossed below the Alfven critical surface – direct observations of the corona at 18-20Rsun
- Switchbacks

Solar Orbiter

- Campfires
- Polar images (to come!)