Heliophysics Overview I: Astrospheres, solar and stellar winds, magnetic activity

Marco Velli Earth, Planetary and Space Sciences







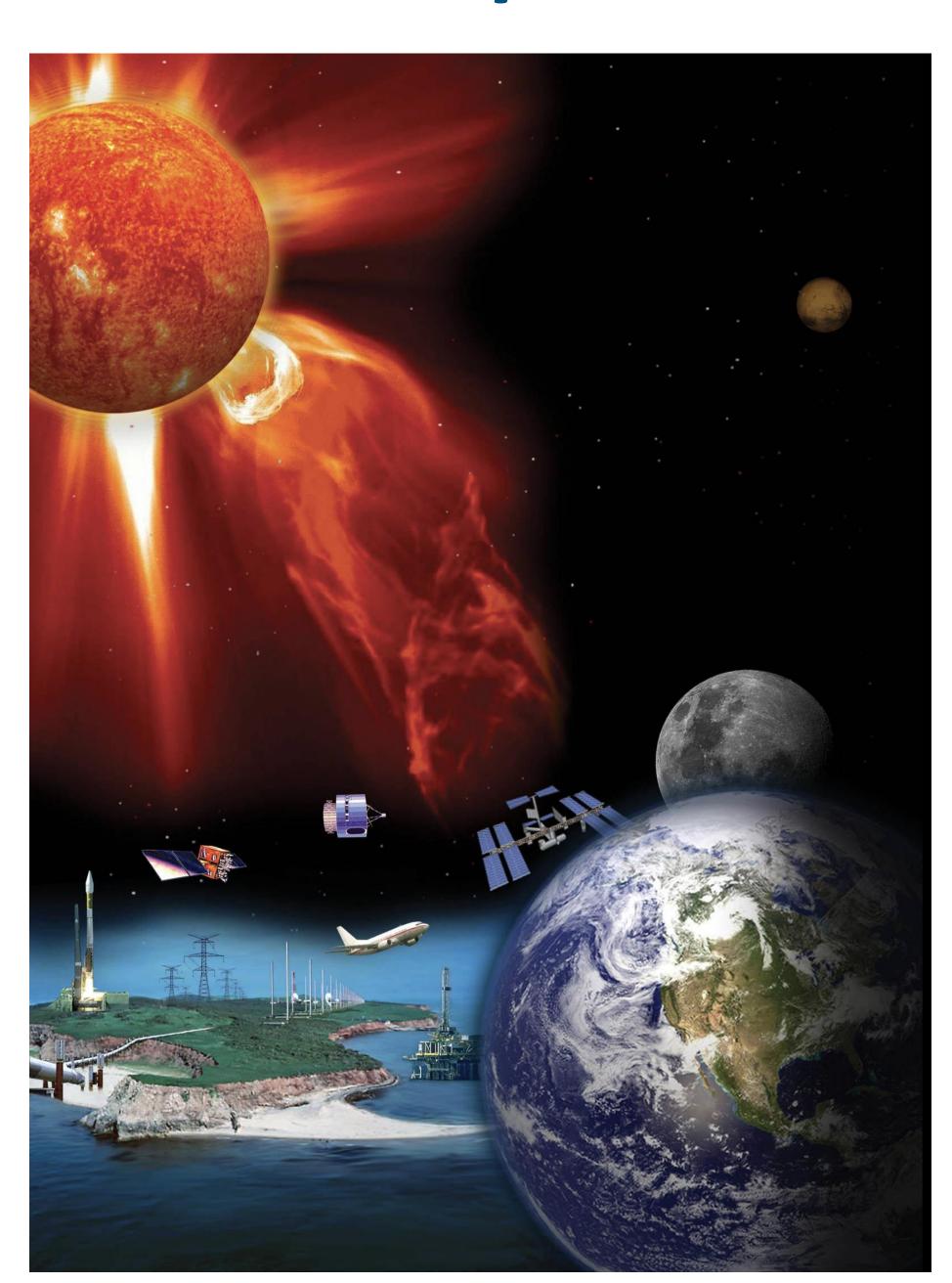
The Solar Corona, Solar Wind and Heliosphere

The Sun's influence extends throughout the solar system via the high temperature Corona and its supersonic extension into interplanetary space, the Solar Wind even though the power is 2-5/1000% of solar radiation (1.36 kW/m² at Earth)

The magnetized Solar Wind outflow creates a cavity in the interstellar medium extending about 100 AU, the HELIOSPHERE, where the flux of cosmic rays is regulated by scattering in the solar magnetic field.

Solar Magnetic Activity affects human endeavors in space.

Stellar Magnetic Activity affects the possibility of life



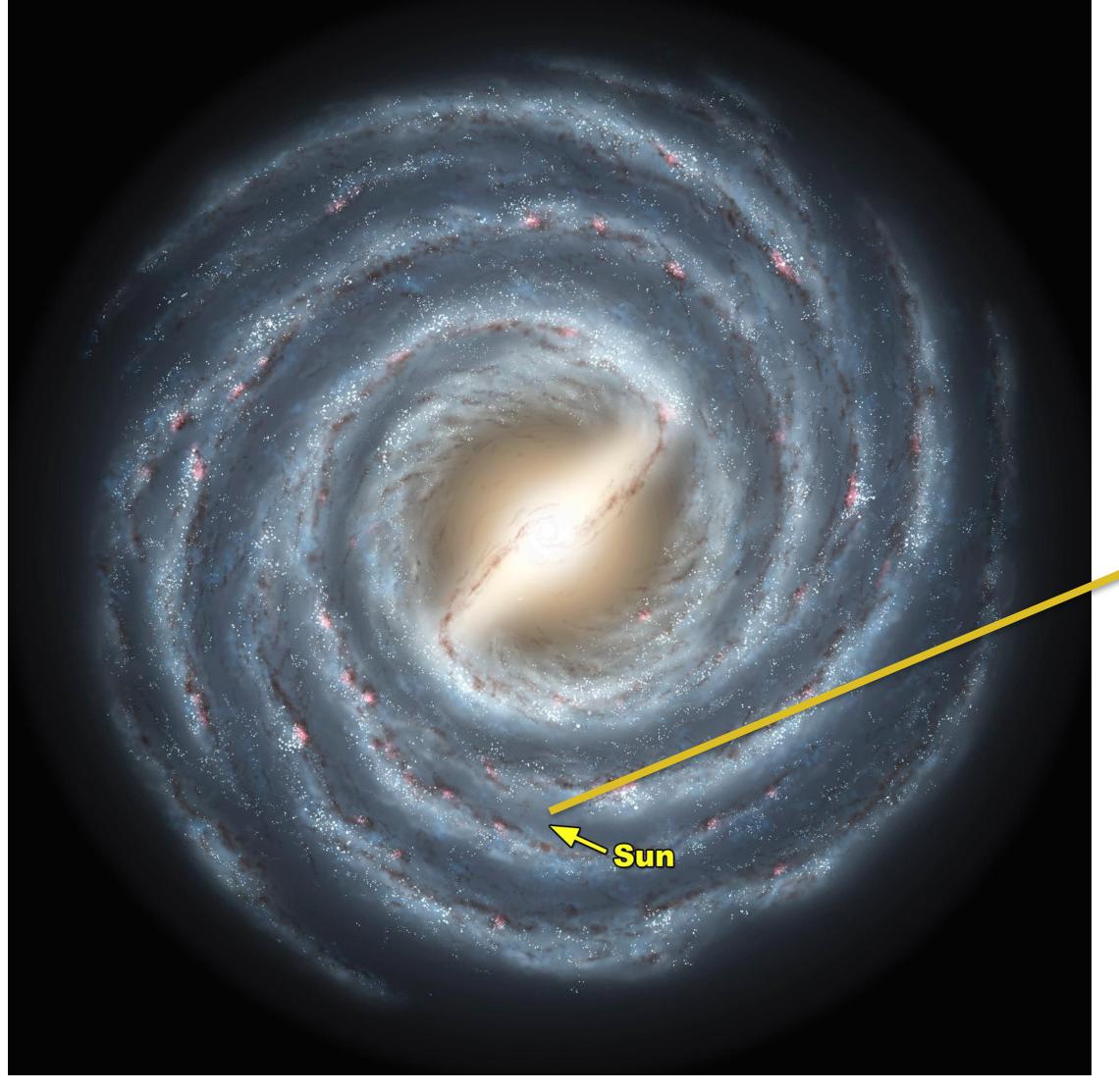
Outline

• Sun, Solar Corona and Heliosphere: a Geographical-Historical Tour with some Stellar References

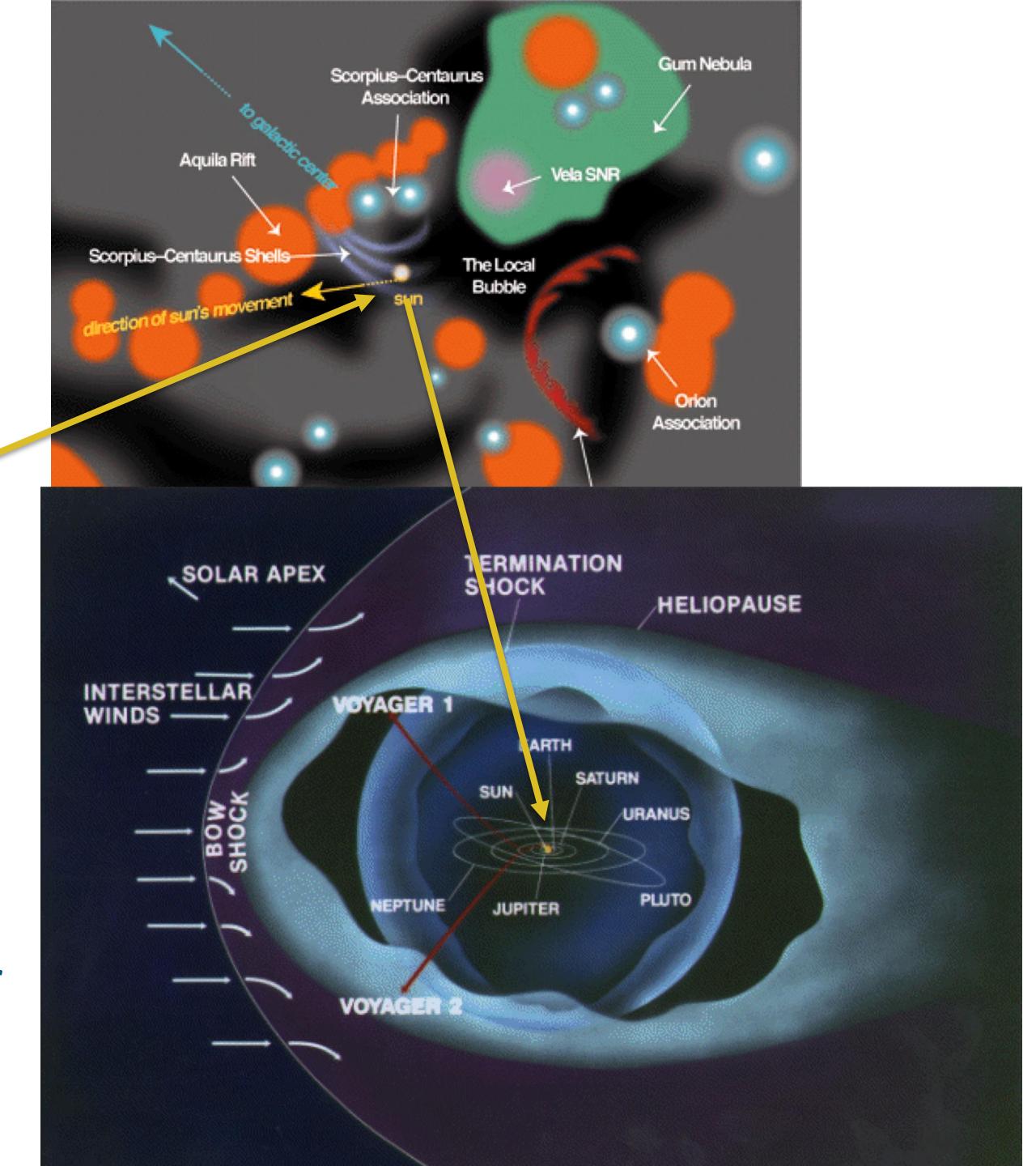
Solar and Stellar Activity

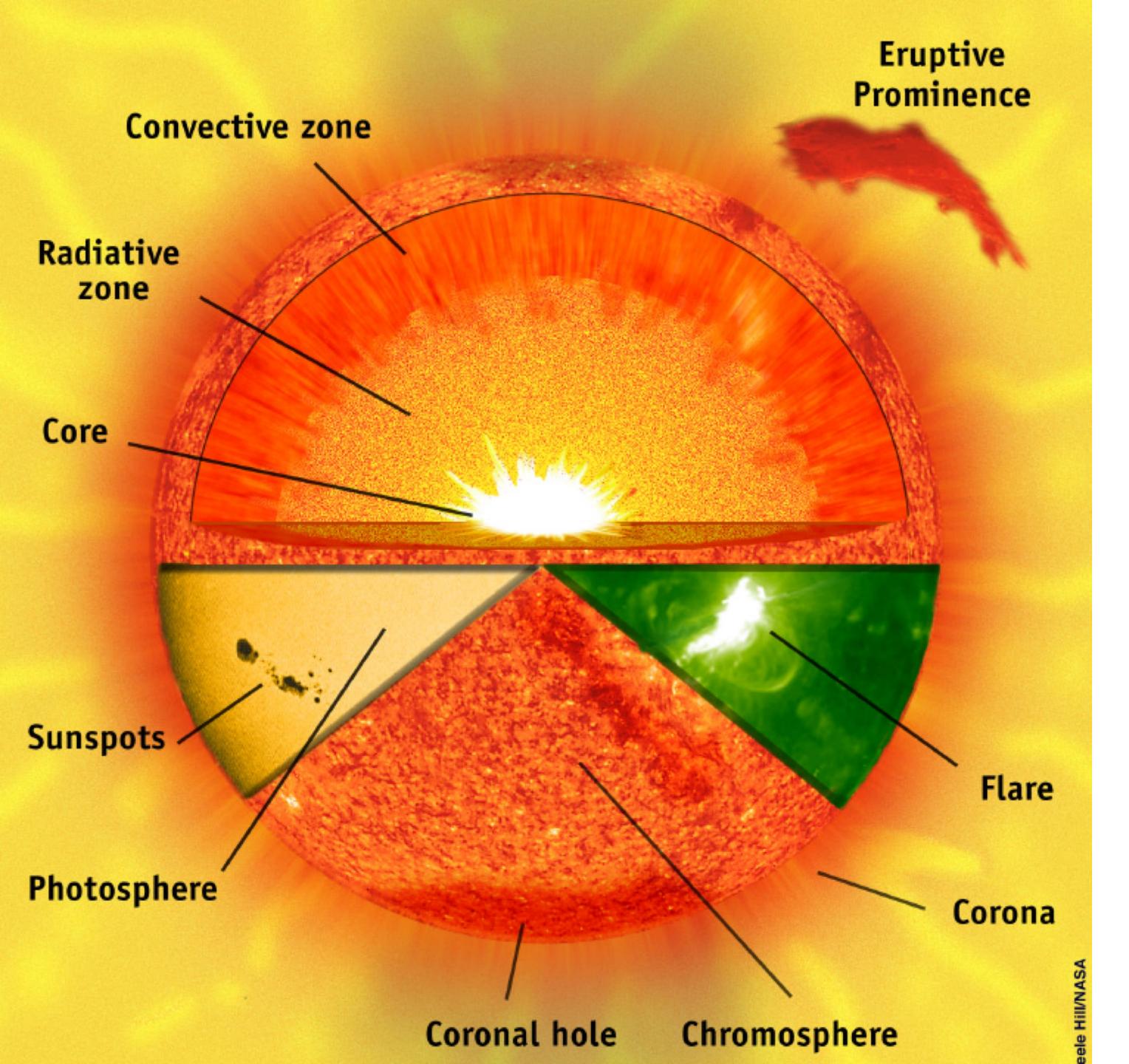
Magnetized Plasma

 Observational Properties of the Solar Corona and Wind from Mariner to Parker Solar Probe



Far out in the uncharted backwaters of the unfashionable end of the western spiral arm of the Galaxy lies a small unregarded yellow sun (Douglas Adams)





1 AU = 150,000,000 km = 215 Rs $V_{esc} = 618 \text{ km/s}$ $g_s = 28 \text{ g}$

 $R_s = 696000 \, \text{km}$

Sun rotates in 25 days (26 1/4 seen from Earth at equator) 24.9 – 29.8 Eq-Pole

Life on Earth comes from radiation from the Sun's photosphere: 1.36 kW/m²

Sunspots observed in China BC

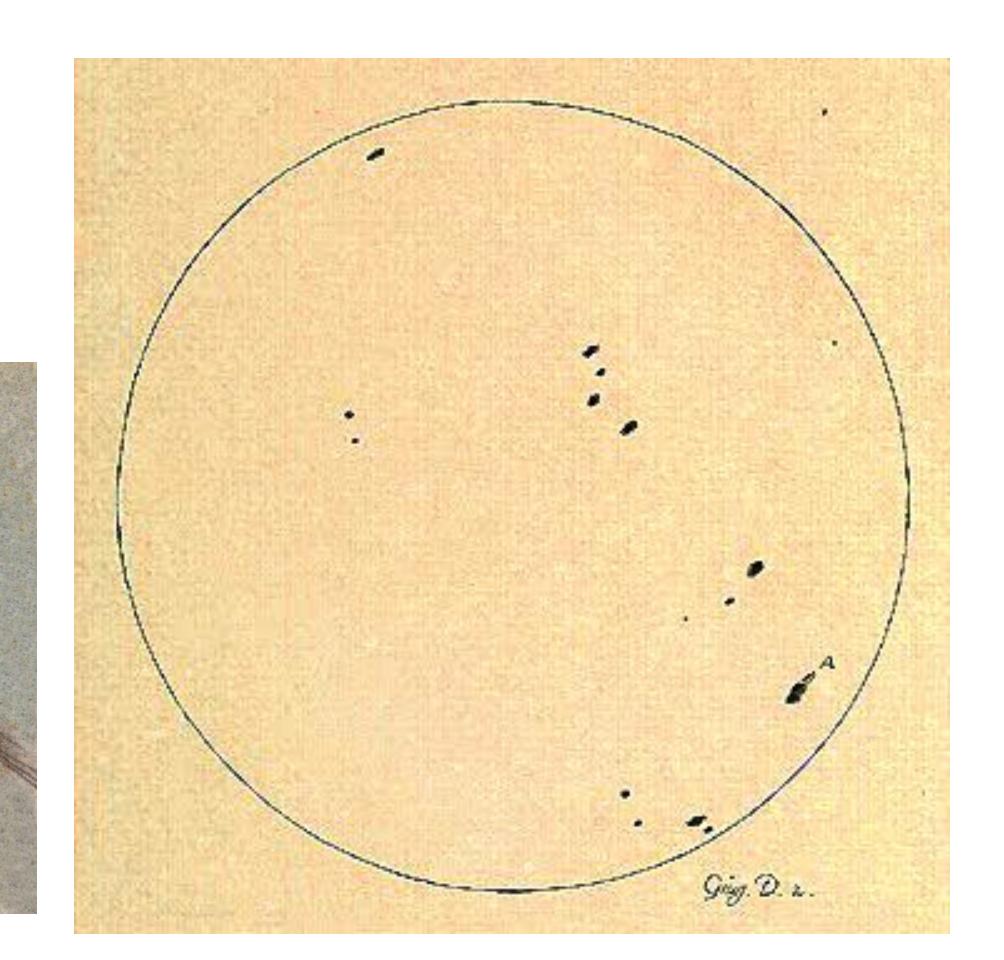
Johann Goldsmid (1587-1616) — Fabricius first publication and deduction of solar rotation

Christopher Scheiner (1575-1650) Jesuit did not publish, anonymous letters to Marcus Wesler who showed letters to Galileo

Galileo 1612 Istoria e dimostrazioni intorno alle macchie solari e loro accidenti comprese in Tre lettere scritte all'illustrissimo signor

Marco Velseri Linceo.

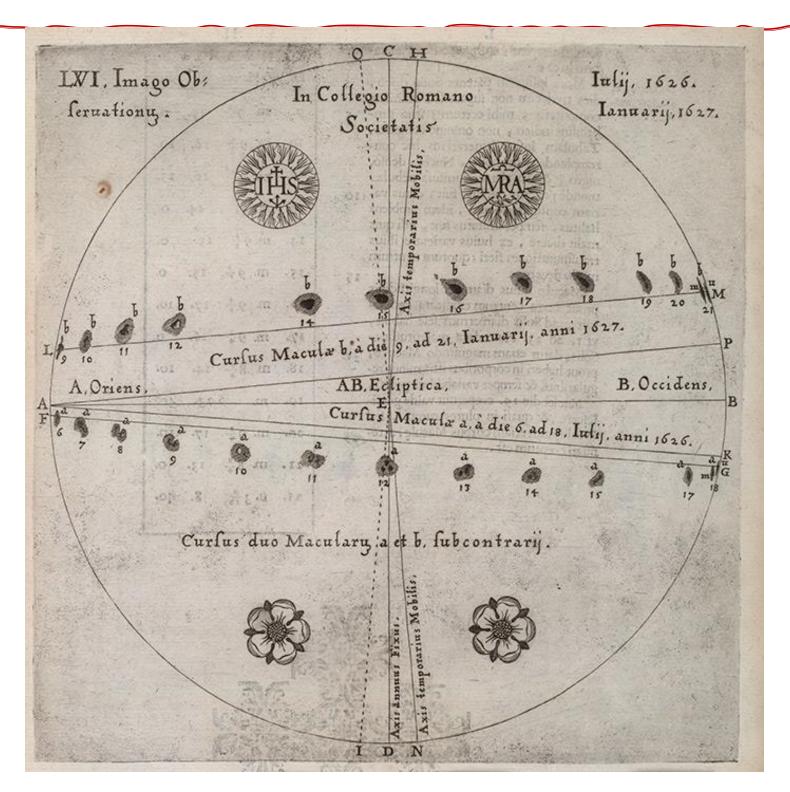
Brief brief pre-history



Scheiner published in 1630 Rosa Ursina Sive Sol('s) Variations in accordance with the Observed Appearance of Its Flares and Sunspots

(\$ 145,000 first edition)

Sunspots never occur at the poles and rotate more slowly at higher latitudes, also the Sun's rotation axis appears to be inclined 7° 15' with respect to the pole of the ecliptic.



ROSA VRSINA

SIVE

SOL

EX ADMIRANDO FACULARVM & Macularum suarum Phænomeno VARIVS,

NECNON

Circa centrum suum & axem sixum ab occasu in ortum annua, circaq. alium axem mobilem ab ortu in occasum conuersione quasi menstrua, super polos proprios, Libris quatuor MOBILIS ostensus,

A
CHRISTOPHORO SCHEINER
GERMANO SVEVO, E SOCIETATE IESV.

AD PAVLVM IORDANVM II.
VRSINVM BRACCIANI DVCEM.



BRACCIANI,

Apud Andream Phæum Typographum Ducalem.

Impressio cæpta Anno 1626. finita vero 1630. Id. lunij. Cum licentia superturum.

Schwabe 1826 (searching for inner planet) 10 year periodicity in the appearance of sunspots

Carrington – 1853-1861 white light flare, Carrington longitude (16° latitude), latitude drift of sunspots – Brewery

Fitzgerald 1892 Is it possible then that matter starting from the Sun with the explosive velocities we know possible there, and subject to an acceleration of several times solar gravitation, could reach the Earth in a couple of days?

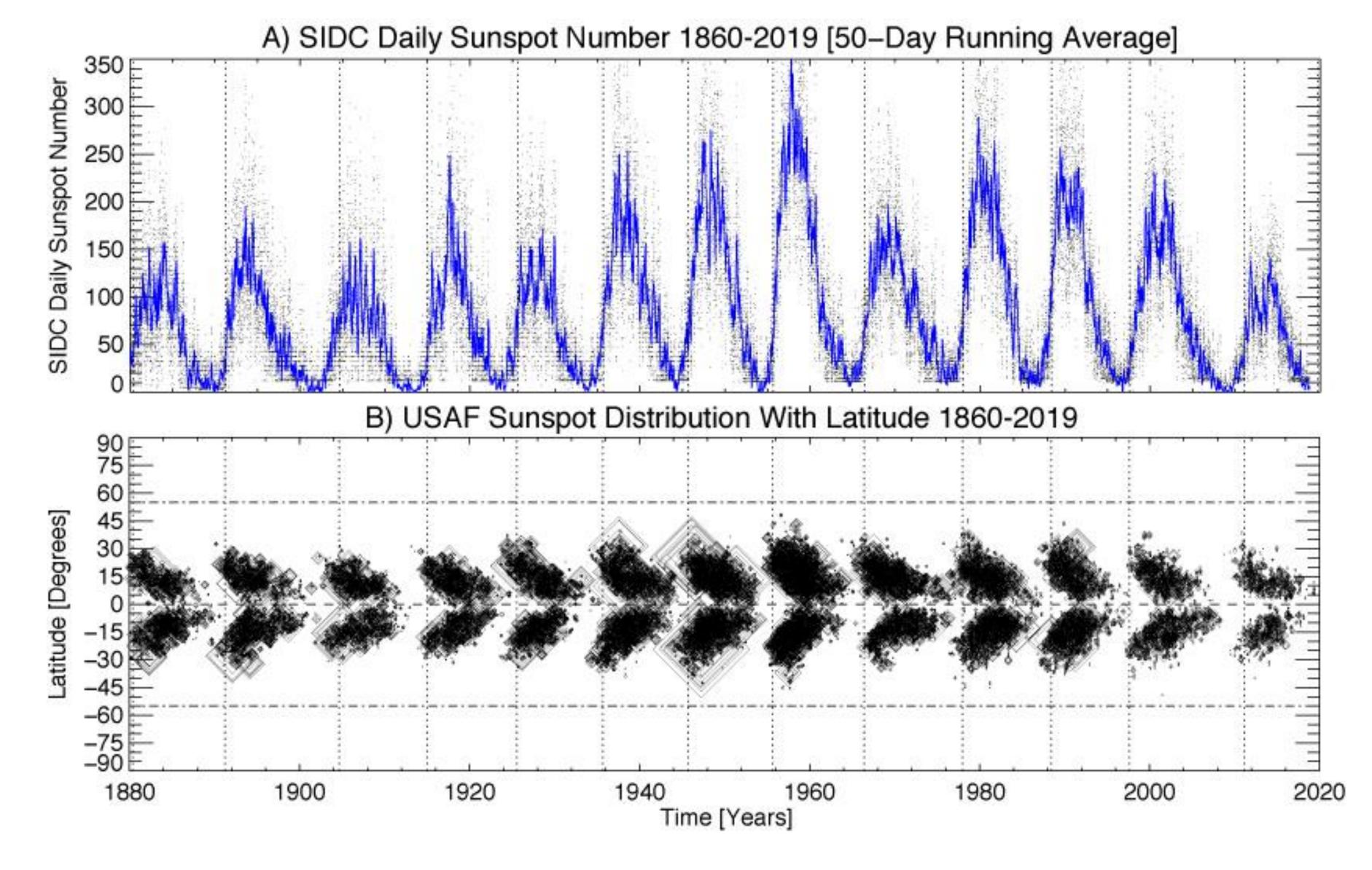
William Thompson (Lord Kelvin) we may also be forced to conclude that the supposed connexion between magnetic storms and sun-spots is unreal, and that the seeming agreement between the periods has been a mere coincidence [could not be directly due to inductive effects associated with variations in the Sun's magnetic field]

Wolf sunspot number (Zurich 1855, now Belgium Royal Observatory)

Sporer, 1860, Potsdam Latitude drift of sunspots

Secchi, 1860 Le Soleil, 2nd Edition

Maunder, 1922 Butterfly diagram



daily sunspot number (fine dots) with a 50-day running average superposed in blue.

latitude-time distribution of sunspots over the same time frame, the size of the symbol plotted represents the relative size of the sunspot

140 years of sunspot evolution as visualized by the Royal Observatory of Brussels, Solar Influences Data analysis Center (SIDC) and US AirForce.

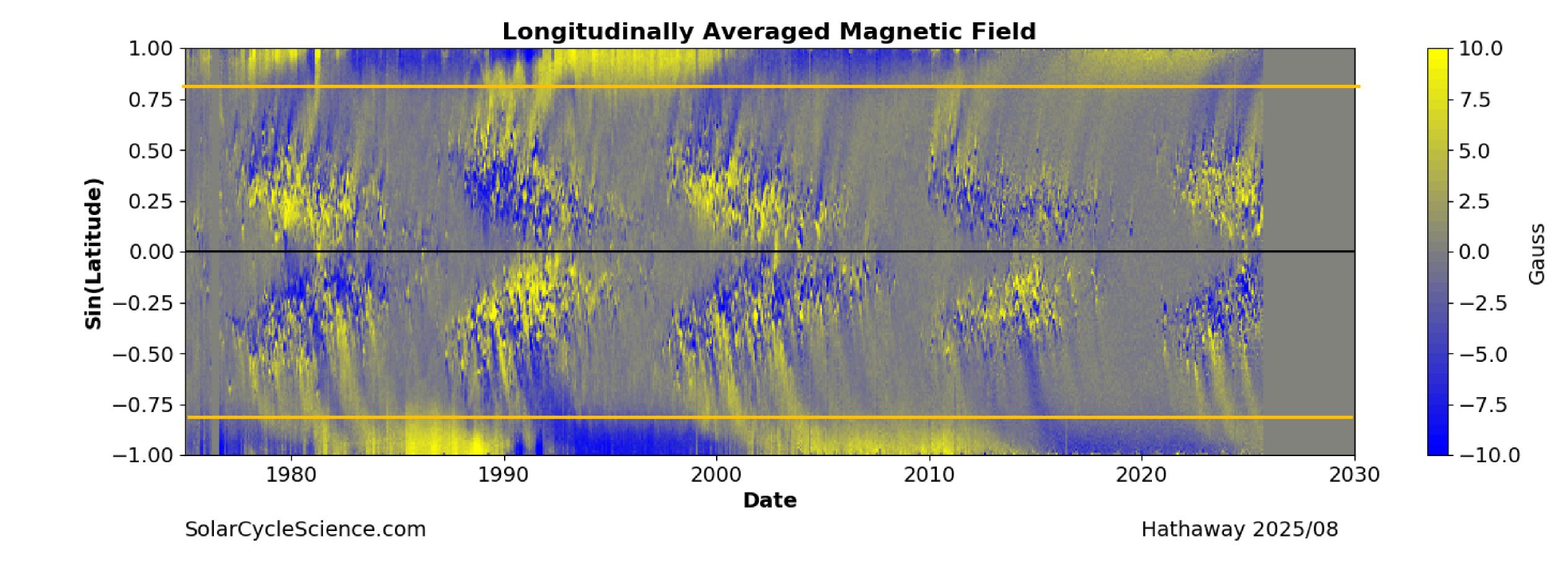
Vertical dotted lines are the times of the magnetic (Hale) cycle terminations (McIntoshet al., 2019); horizontal dot-dashed lines signify 55 latitude.

On the importance of being Magnetic

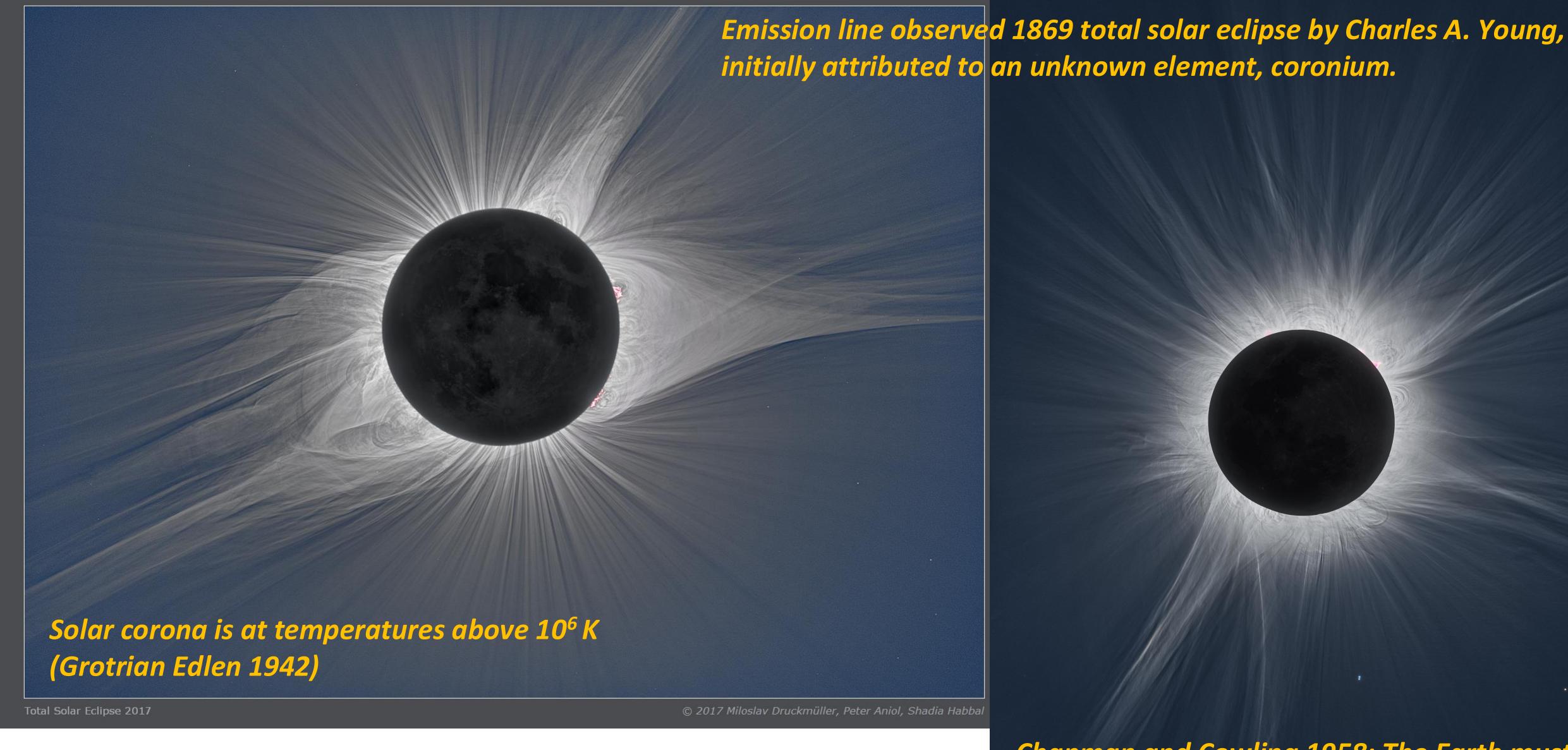


"...a sunspot is a vortex, in which electrified particles, produced by ionization in the solar atmosphere, are whirled at high velocity. This might give rise to magnetic fields in sunspots, regarded as electric vortices. A search for the Zeeman effect led to its immediate detection, and abundant proofs were found of the existence of a magnetic field in every sunspot observed"

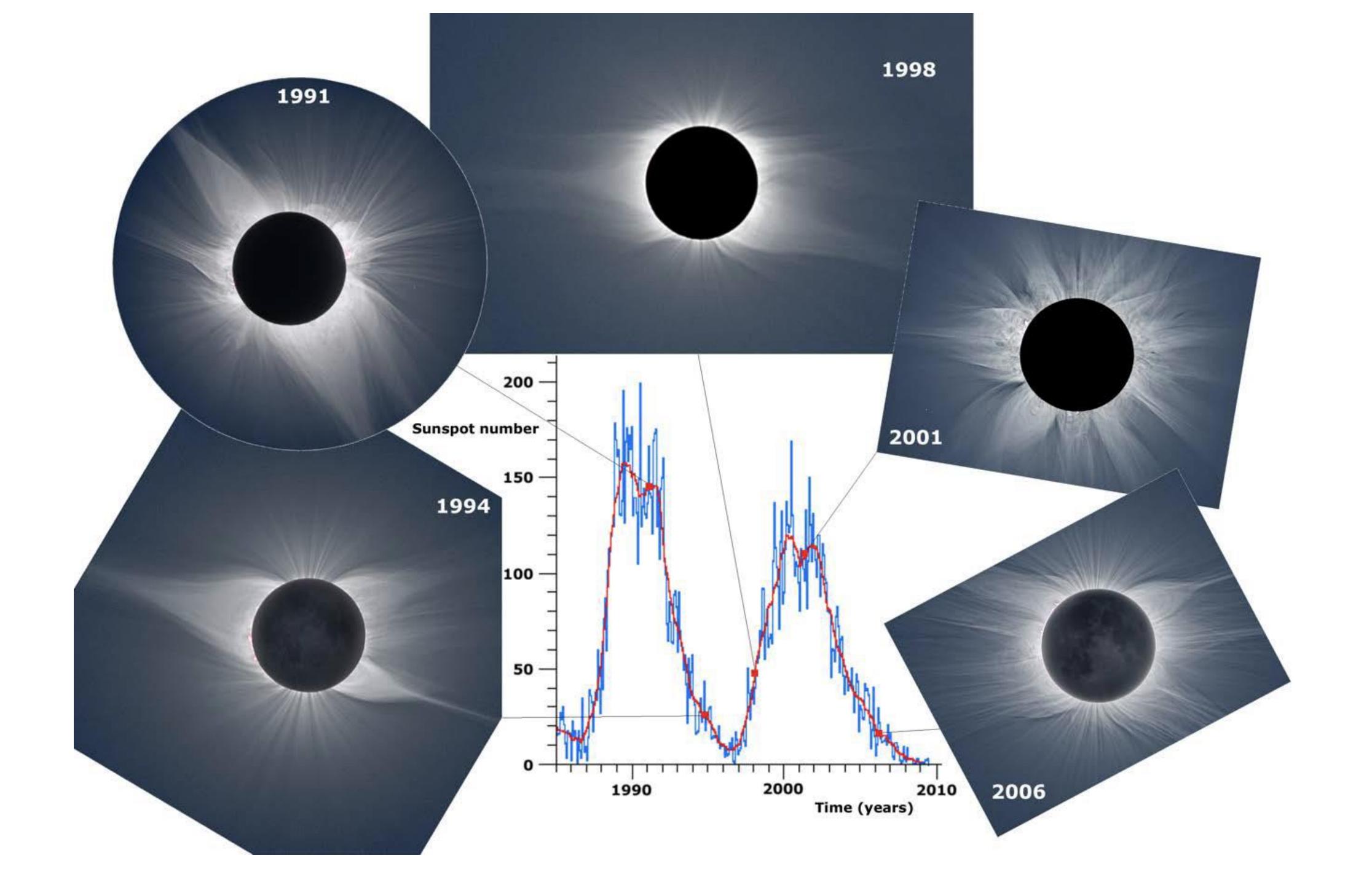
G. E. Hale 1919, Astrophysical Journal, Vol. 49 p. 153



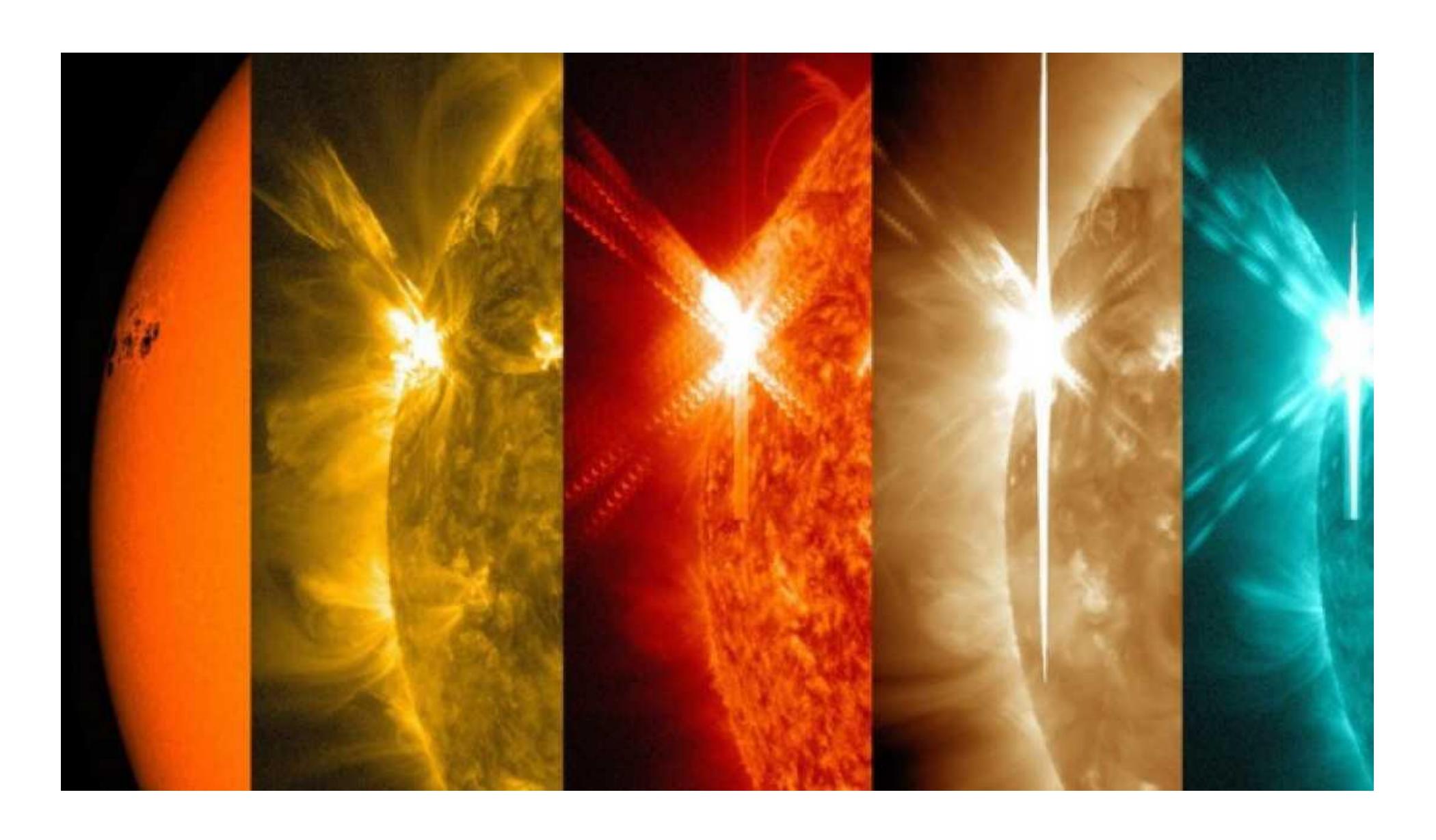
Solar Cycle and Rush to the Poles

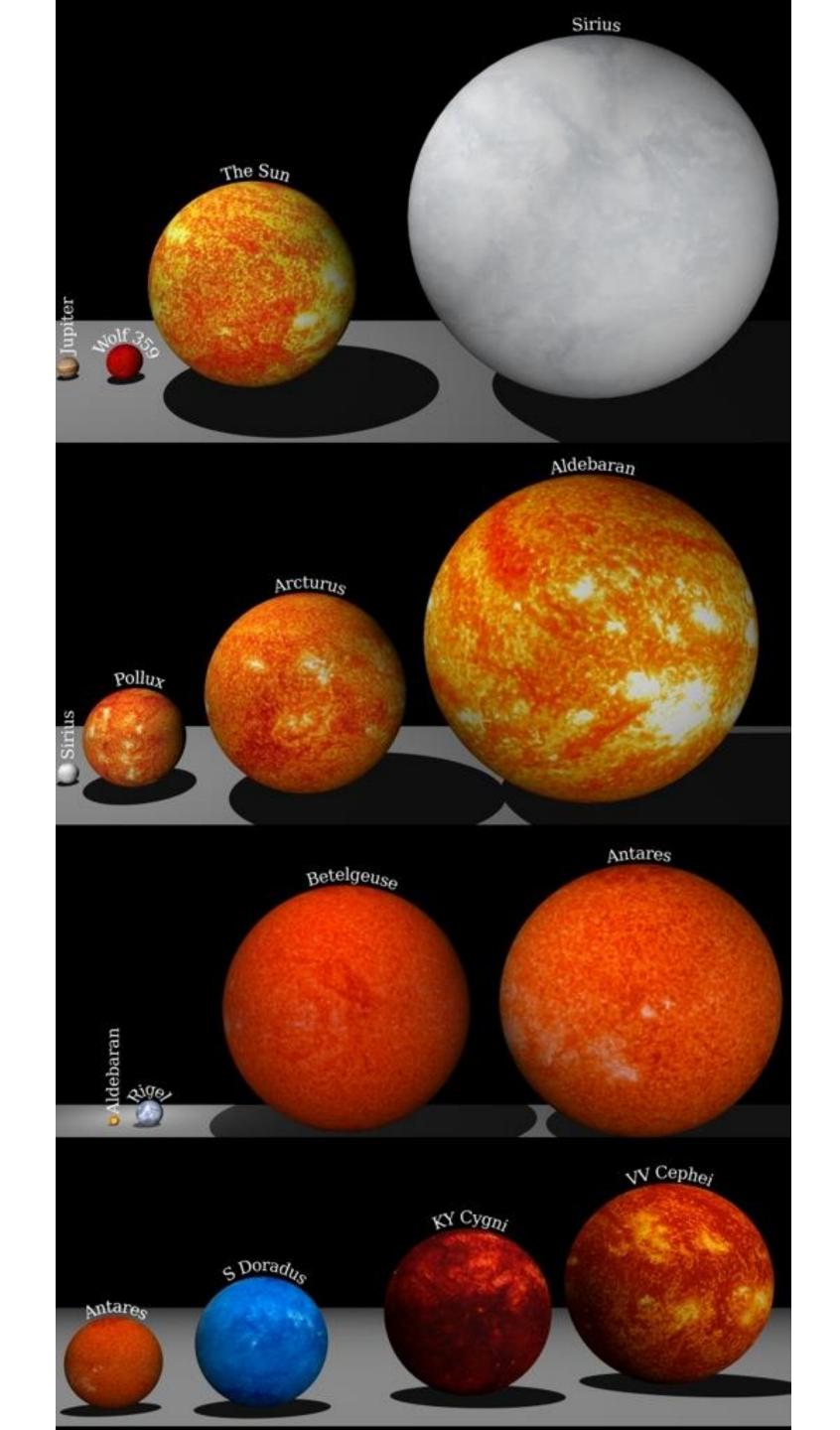


Solar Corona, Total Solar Eclipse, 2017, 2024 Temperature and Scale Height! Chapman and Cowling 1958: The Earth must be immersed in the (static) outer atmosphere of the Sun



Solar Flares (<2 x 10³²ergs)





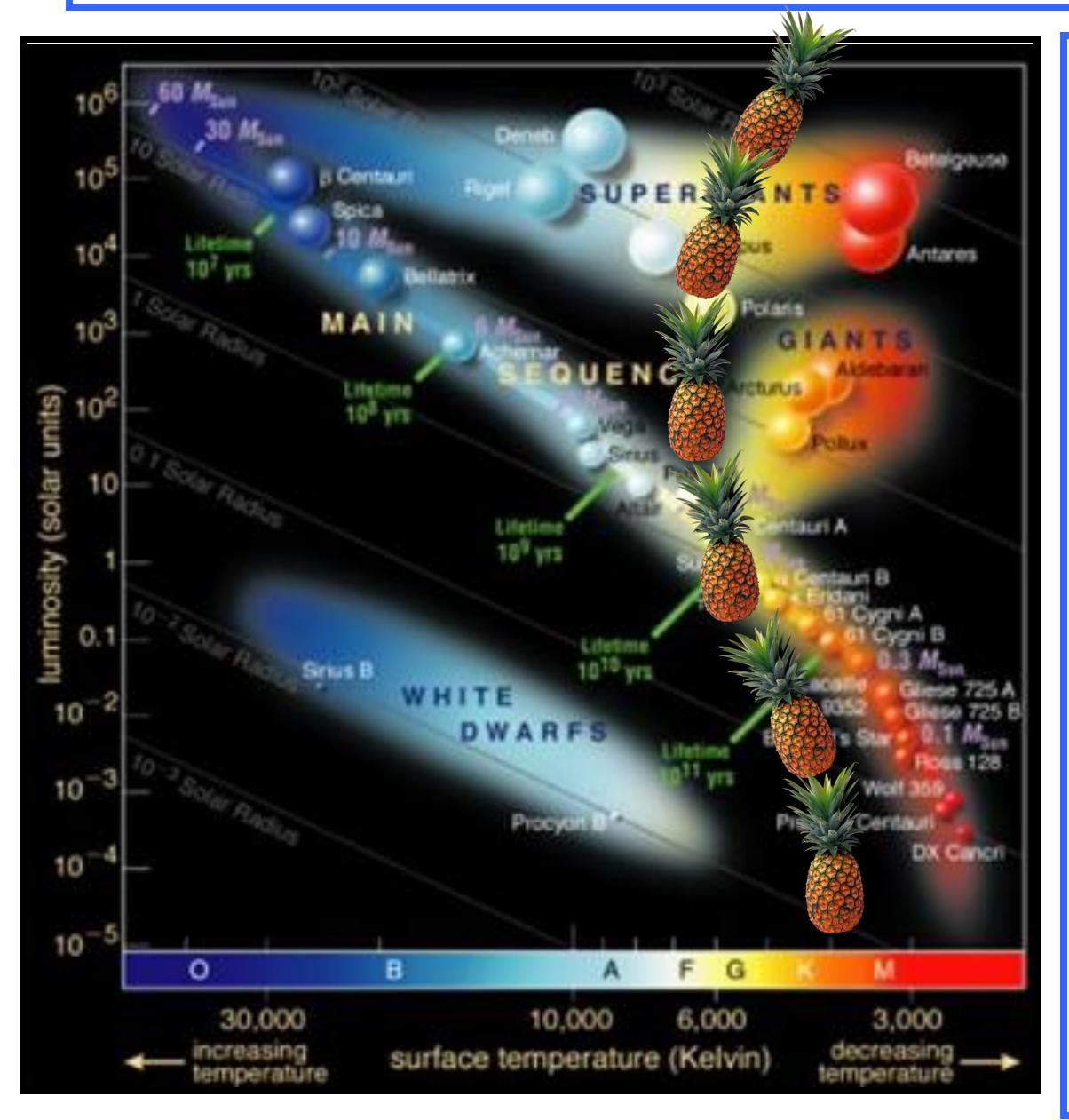
T~9,940 K 1.71R_o 2.02 M_o

T~3,910 K 44.2 R_o 1.7 M_o

T~3,400 K 883 R_o12.4 M_o

 $T \sim 3,800 \ K \ 1900 \ R_{\odot} \leq 20.4 \ M_{\odot}$

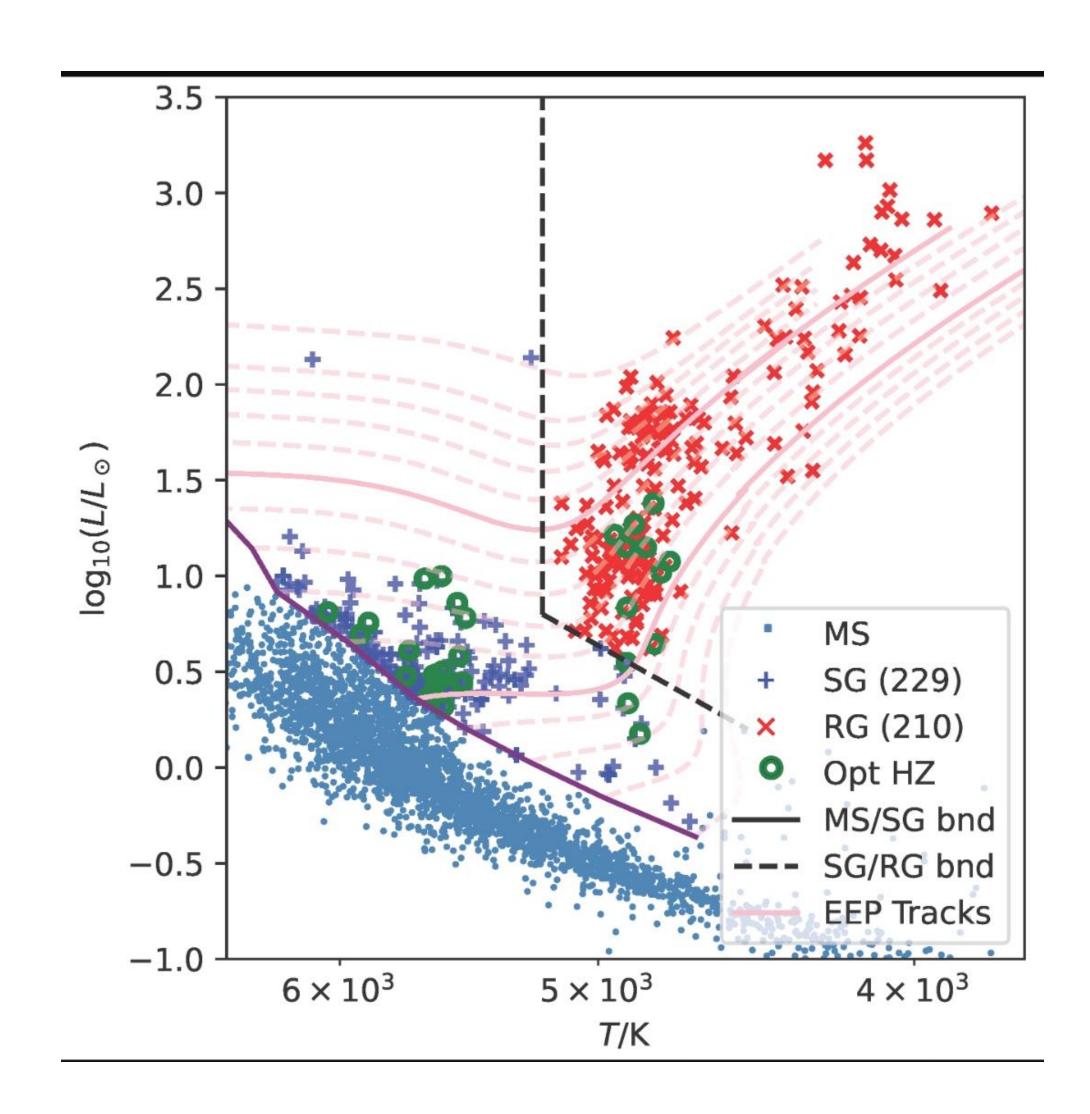
Properties: Activity H-R Diagram

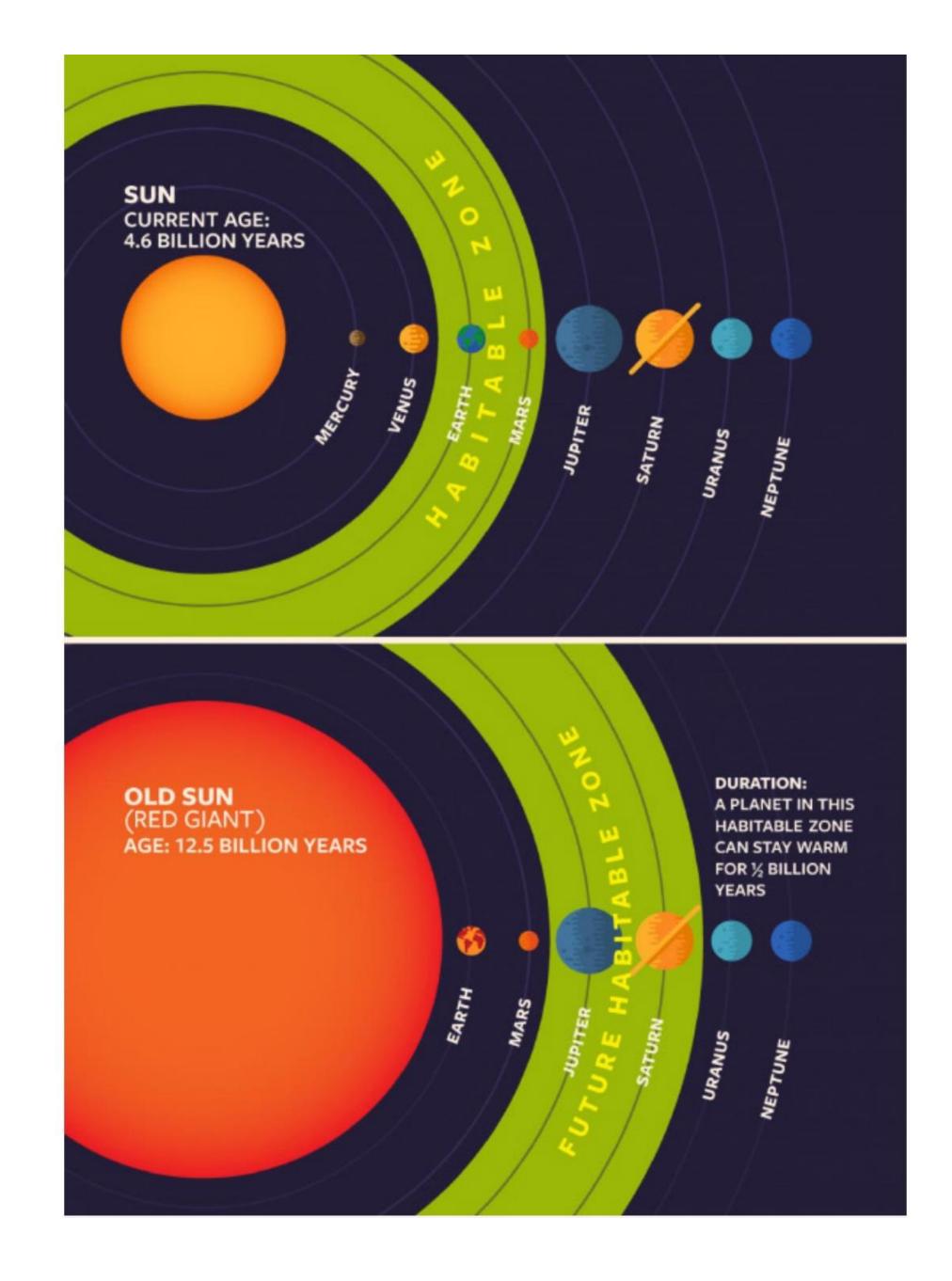


"Activity" confined to "cool stars," in convective half of H-R diagram Coronae

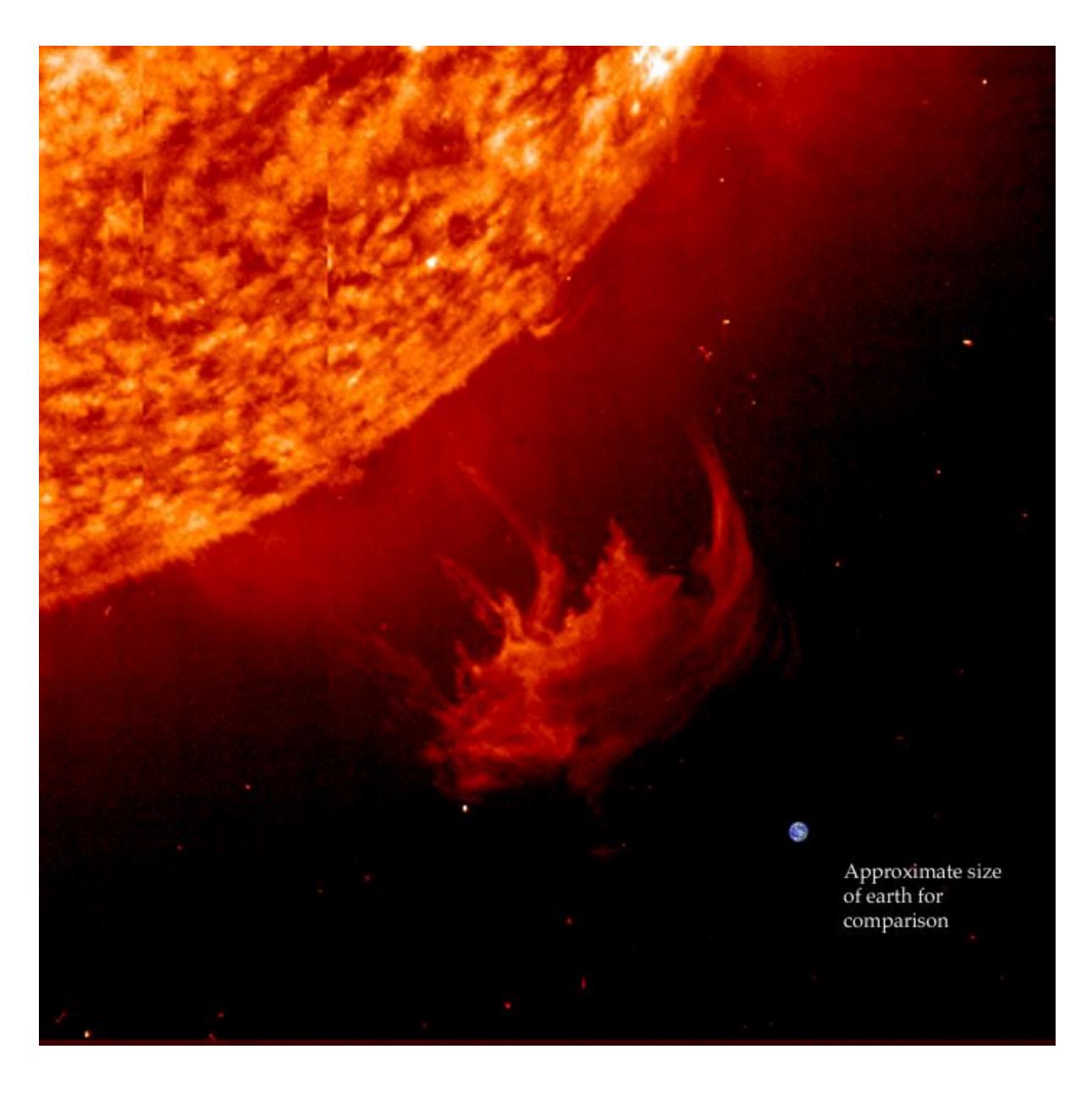
(T~1-10 MK) and Chromospheres (~10⁴ K) die out where surface convection fails

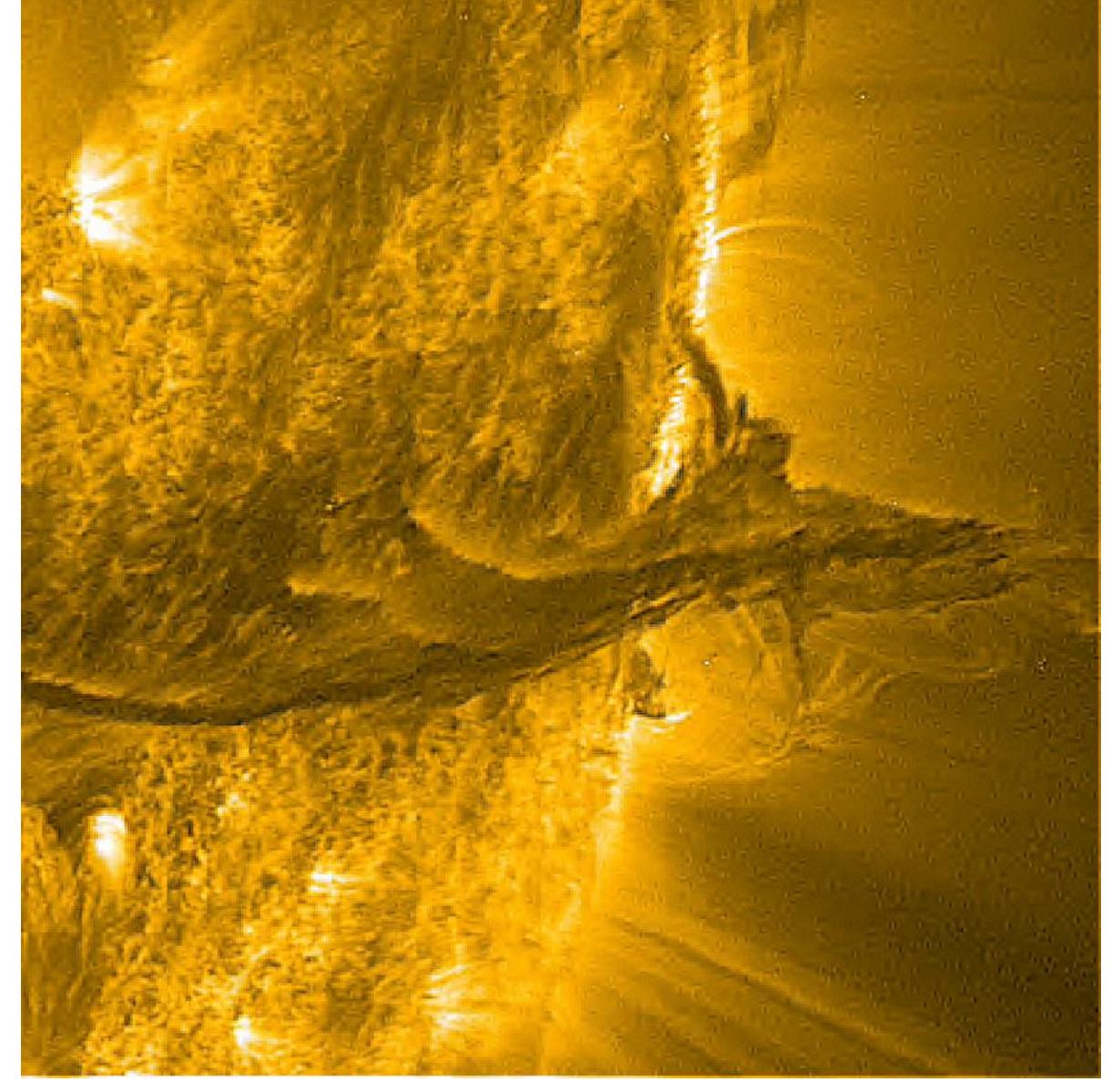
Not a coincidence! Dynamo needs convection and turbulence to work





Chen et al. 2023





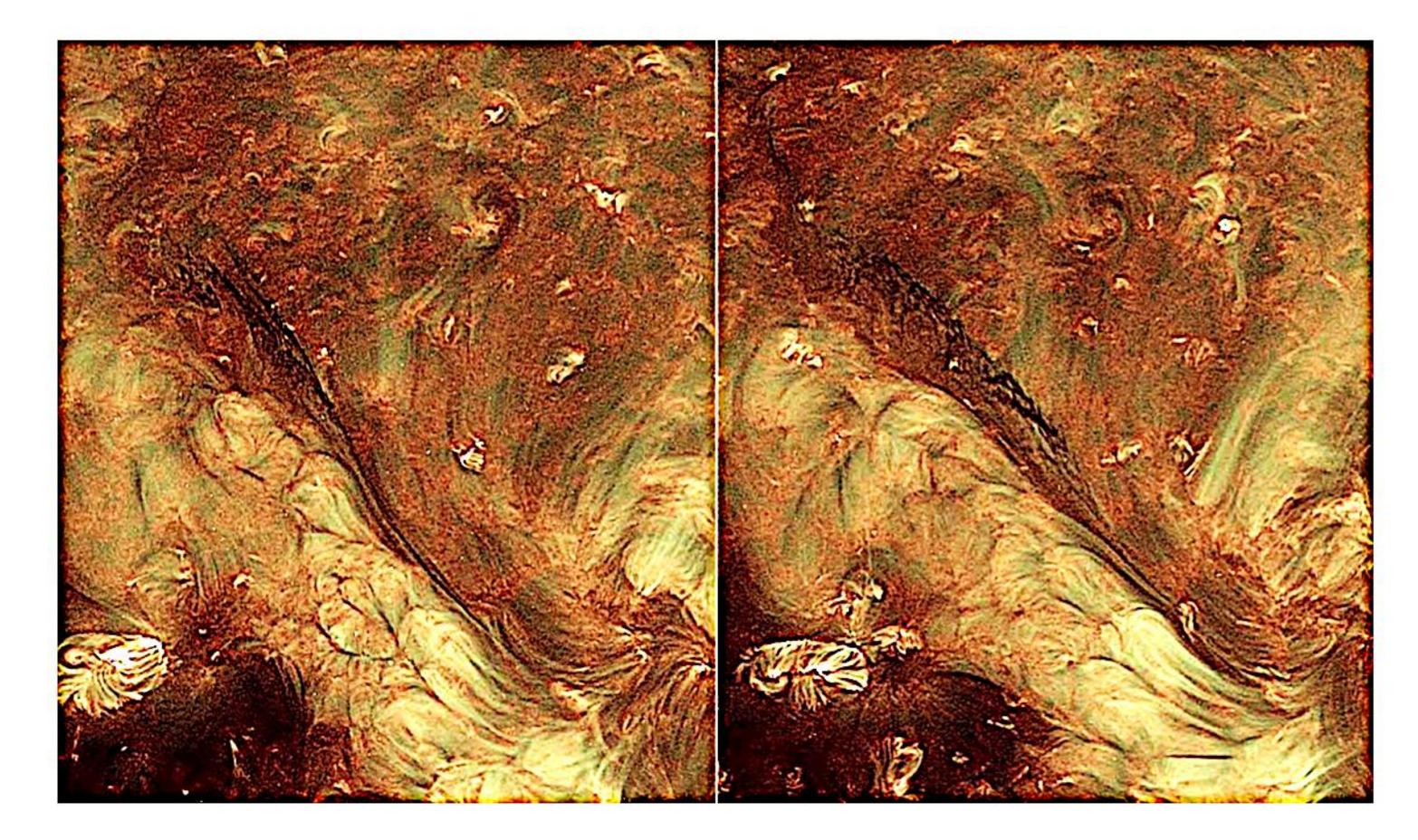
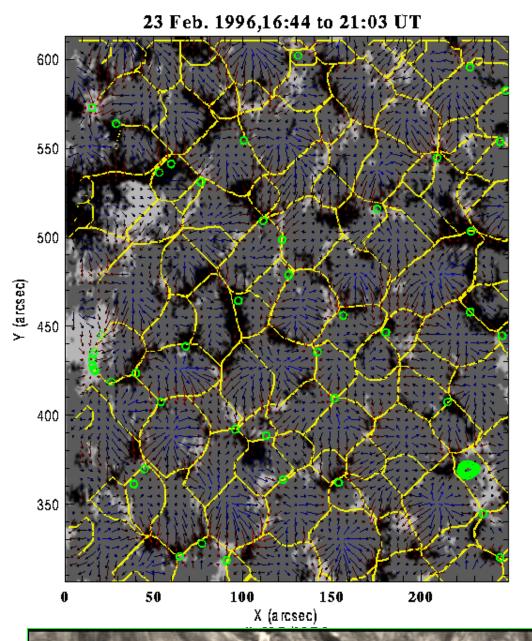
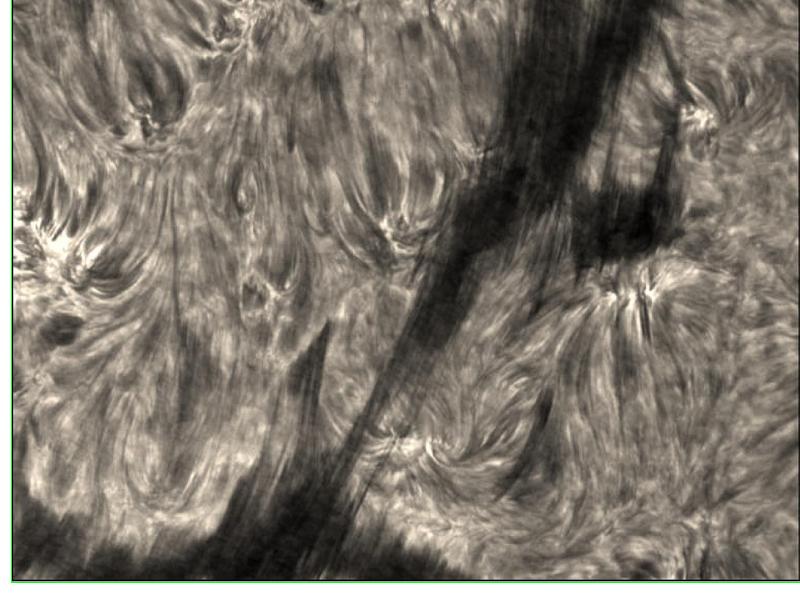


Figure 3. The corona cells on the east (left) side of the filament are significantly brighter than those on the opposite side throughout its transit across the Sun. The parts of the cells on the west side of the filament are partially masked by the filament indication that their height close to the filament does not exceed the height of the filament (2011 Sep 07, 17:29 UT (left image) and Sep 08, 21:29 UT (right image), SDO/AIA 193 and 304 Å).

Sheeley et al. 2013 (Using Coronal Cells to Infer the Magnetic Field Structure and Chirality of Filament Channels)



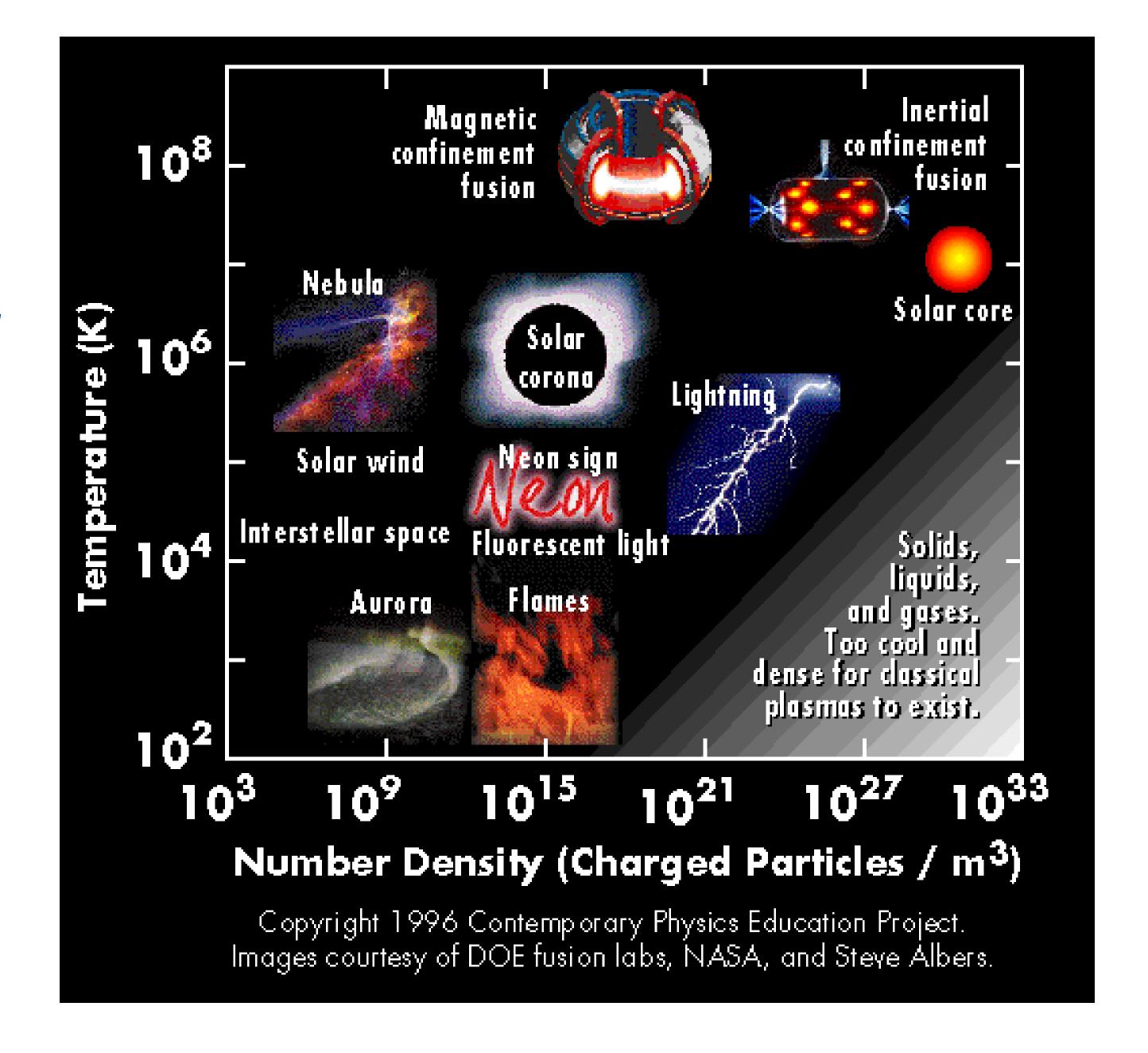


(Martin, Lin & Engvold, 2007)

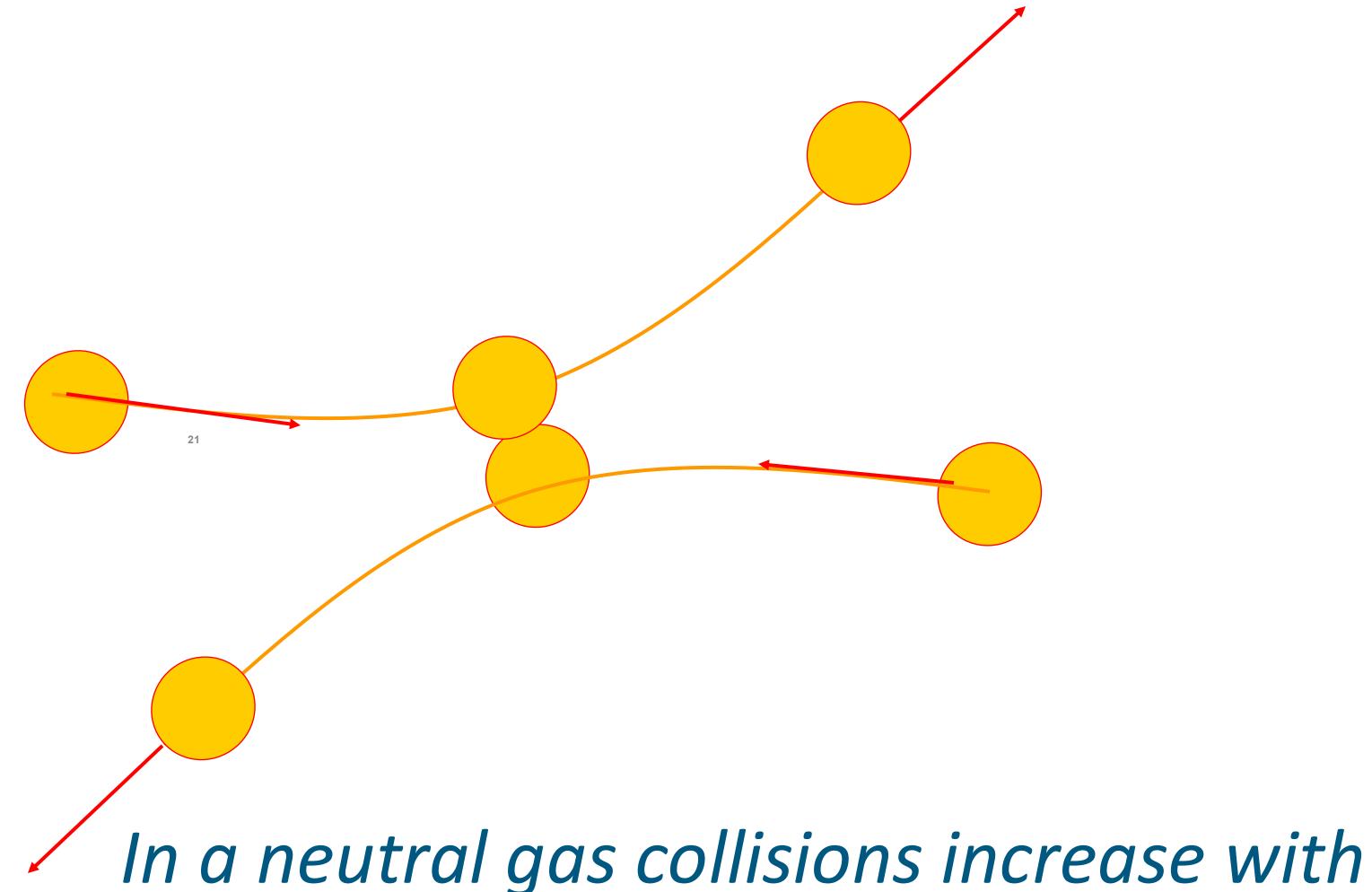
Solar Corona is a PLASMA

A PLASMA is a collection of charged particles interacting with ELECTRIC and MAGNETIC fields collectively !!!!!

PLASMAS are EVERYWHERE in the UNIVERSE and have non-intuitive PROPERTIES!

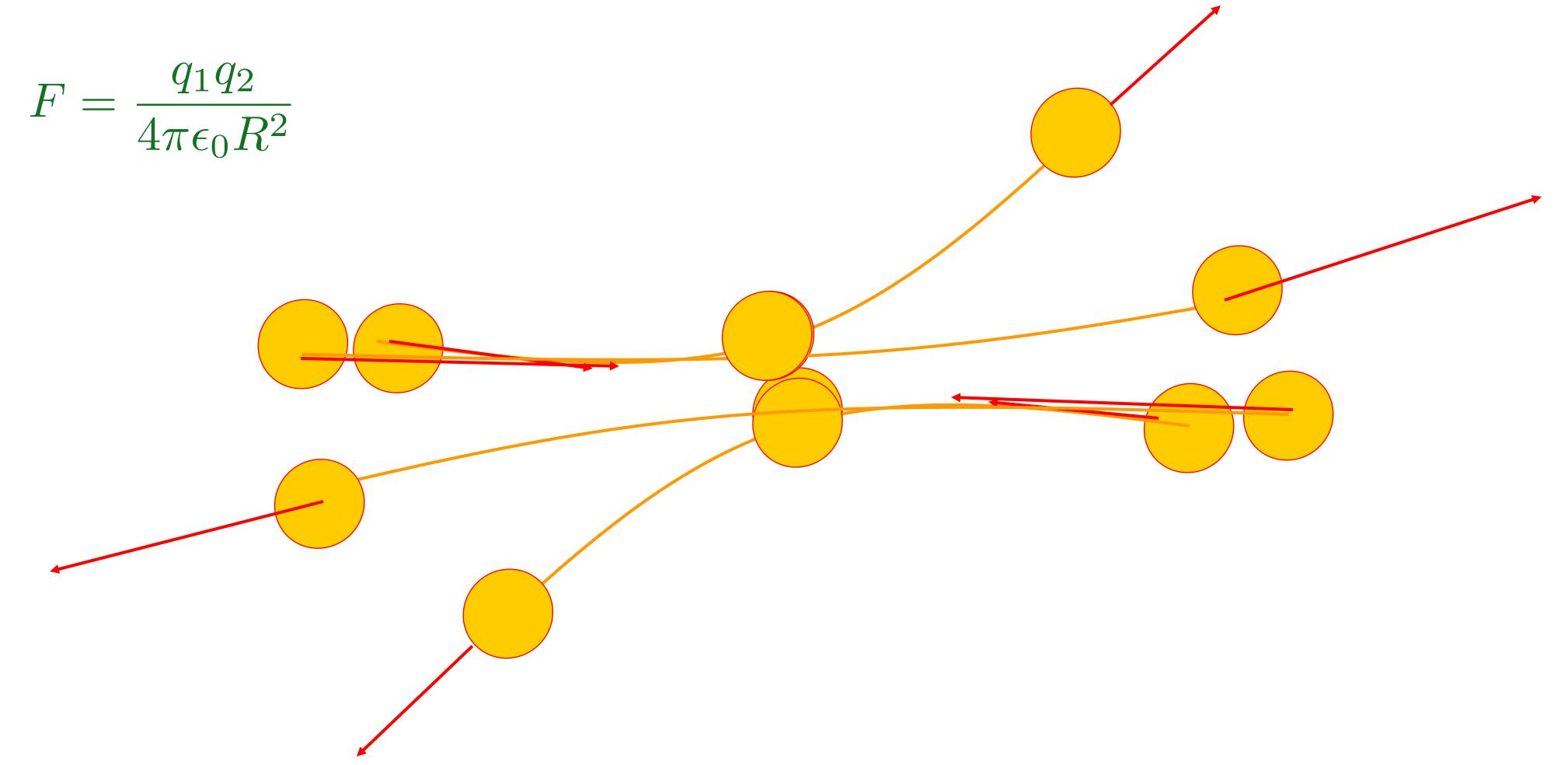


A Plasma is Different (1)

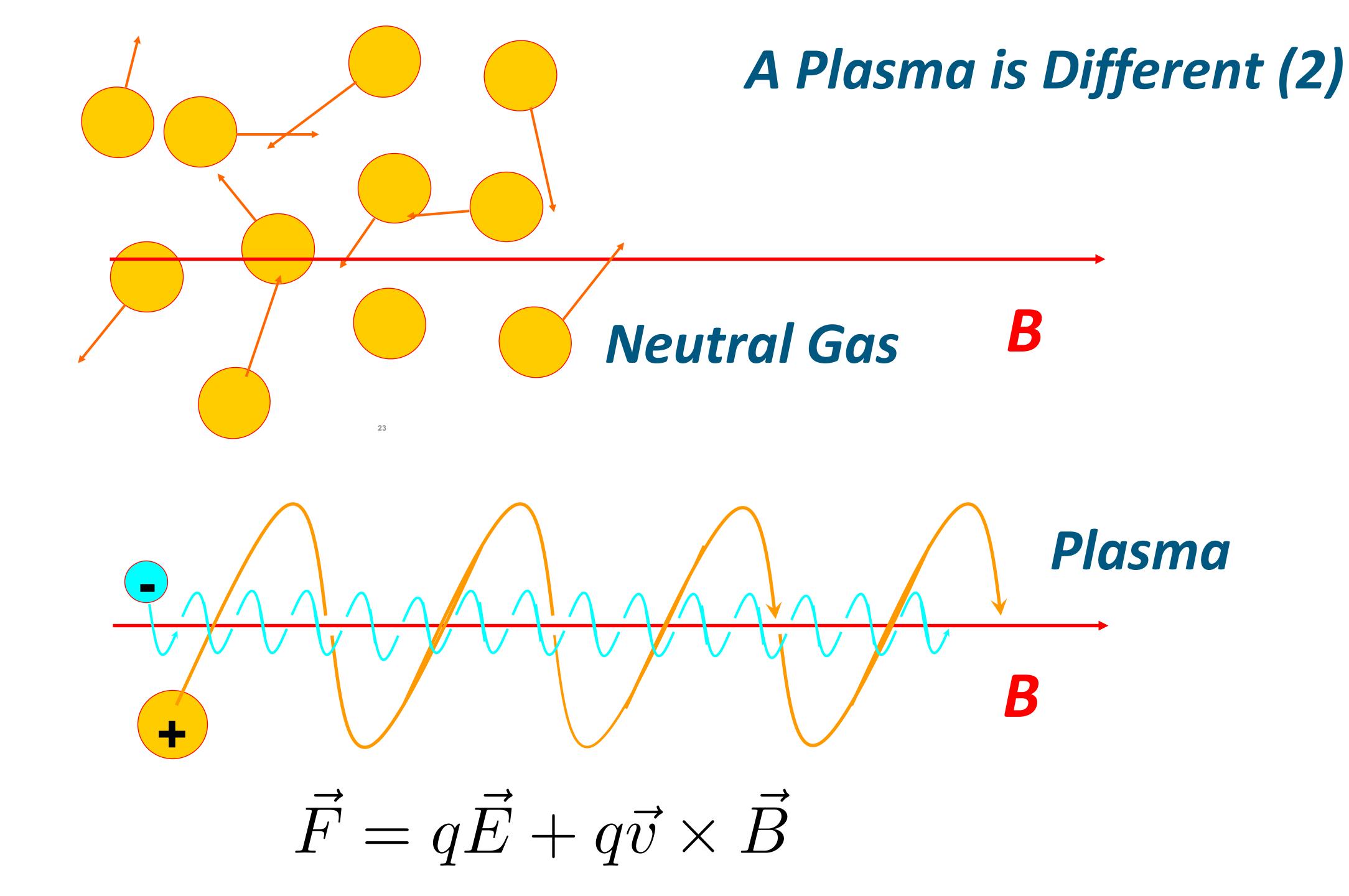


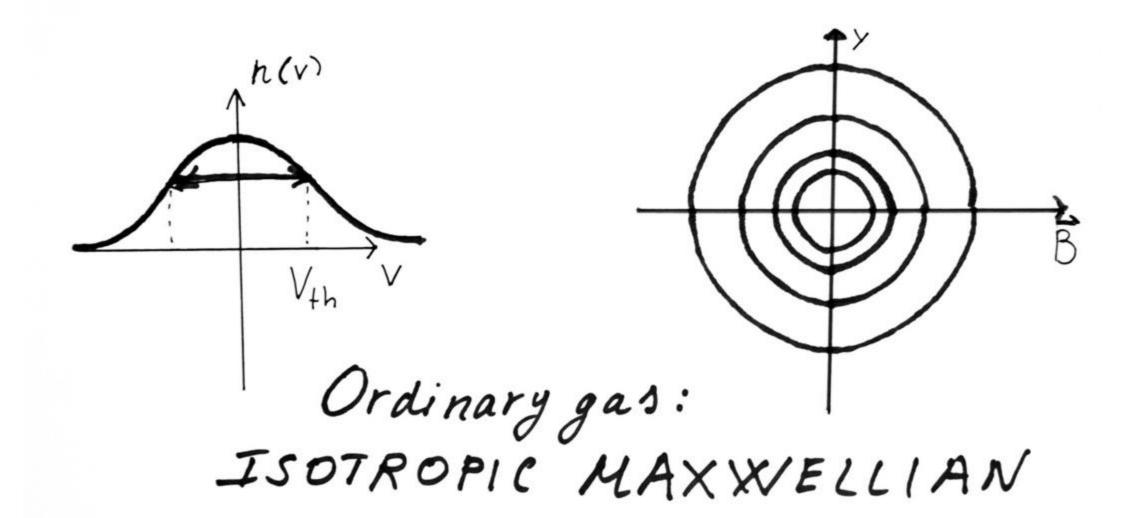
1.The number of particles 2. The speed you move ==> Fast particles slow down, slow particles go faster (Robin Hood)

In a plasma faster particles COLLIDE LESS.

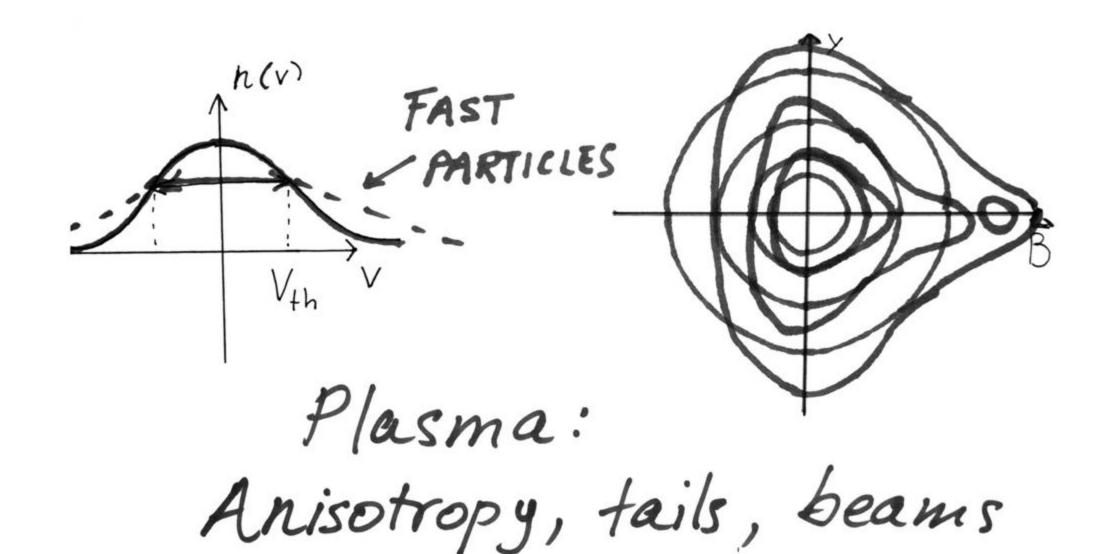


Once a particle goes fast, if there is a force it will just go faster. In a plasma, the RICH get RICHER (inverse Robin Hood D. T.?)
A RUNAWAY EFFECT is possible!





How many particles go how fast?



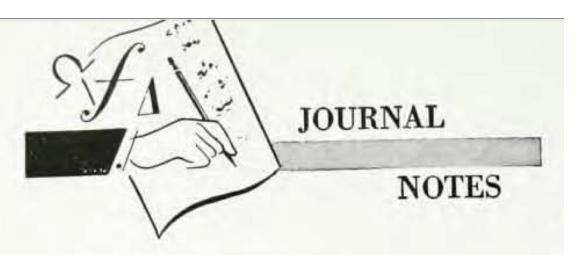
A Plasma is Different

- In a plasma collisions DECREASE as the temperature goes up. Faster particles collide less and can ACCELERATE more EASILY !!!!!
- Charged Particles to lowest order MUST FOLLOW Magnetic Field Lines.
- Magnetic Field Lines to lowest order MUST FOLLOW Charged Particles

The SELF-CONSISTENT MAGNETIC FIELD provides STRUCTURE, CONFINEMENT. Electric and Magnetic fields destabilize-accelerate.

PARTICLES AND FIELDS ARE INEXTRICABLY INTERTWINED

1942, Hannes Alfvén – the only plasma physicist to receive the Nobel prize – noted that in a magnetized plasma "a kind of combined electromagnetic -hydrodynamic wave is produced which, so far as I know, has as yet attracted no attention".



Origin of Cosmic Radiation

According to the theory proposed, cosmic rays are distributed more or less uniformly in the interstellar space of the galaxy. A cosmic proton is supposed to wander through this space for a period of time that, on the average, is of the order of one hundred million years, and which may, exceptionally, be twenty or thirty times longer for those few protons that statistically escape destroying collisions.

During this time the proton steadily acquires energy by collisions with wandering magnetic fields which are supposed to permeate the interstellar space. The rate at which the proton gains energy is shown to be roughly proportional to its total energy (including rest energy) so that the energy of the proton increases exponentially with time. The older a proton is, the larger is its energy which can reach a value of the order of 1016 electron volts for those few protons that have not had destroying collisions since the beginning of the universe.

One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain, in a straightforward way, the heavy nuclei observed in cosmic radiation.

E.F.

On the Origin of the Cosmic Radiation. By Enrico Fermi. Phys. Rev. 75: 1169, April 15, 1949.

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

I. INTRODUCTION

In recent discussions on the origin of the cosmic radiation E. Teller¹ has advocated the view that cosmic rays are of solar origin and are kept relatively near the sun by the action of magnetic fields. These views are amplified by Alfvén, Richtmyer, and Teller.² The argument against the conventional view that cosmic radiation may extend at least to all the galactic space is the very large amount of energy that should be present in form of cosmic radiation if it were to extend to such a huge space. Indeed, if this were the case, the mechanism of acceleration of the cosmic radiation should be extremely efficient.

I propose in the present note to discuss a hypothesis on the origin of cosmic rays which attempts to meet in part this objection, and according to which cosmic rays originate and are accelerated primarily in the interstellar space, although they are assumed to be prevented by magnetic fields from leaving the boundaries of the galaxy. The main process of acceleration is due to the interaction of cosmic particles with wandering magnetic fields which, according to Alfvén, occupy the interstellar spaces.

Such fields have a remarkably great stability because of their large dimensions (of the order of magnitude of light years), and of the relatively high electrical conductivity of the interstellar space. Indeed, the conductivity is so high that one might describe the magnetic lines of force as attached to the matter and partaking in its streaming motions. On the other hand, the magnetic field itself reacts on the hydrodynamics3 of the interstellar matter giving it properties which, according to Alfvén, can pictorially be described by saying that to each line of force one should attach a material density due to the mass of the matter to which the line of force is linked. Developing this point of view, Alfvén is able to calculate a simple formula for the velocity V of propagation of magneto-elastic waves:

$$V = H/(4\pi\rho)^{\frac{1}{2}},\tag{1}$$

where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar medium with energy above a certain injection threshold gains energy by collisions against the moving irregularities of the interstellar magnetic field. The rate of gain is very slow but appears capable of building up the energy to the maximum values observed. Indeed one finds quite naturally an inverse power law for the energy spectrum of the protons. The experimentally observed exponent of this law appears to be well within the range of the possibilities.

The present theory is incomplete because no satisfactory injection mechanism is proposed except for protons which apparently can be regenerated at least in part in the collision processes of the cosmic radiation itself with the diffuse interstellar matter. The most serious difficulty is in the injection process for the heavy nuclear component of the radiation. For these particles the injection energy is very high and the injection mechanism must be correspondingly efficient.

II. THE MOTIONS OF THE INTERSTELLAR MEDIUM

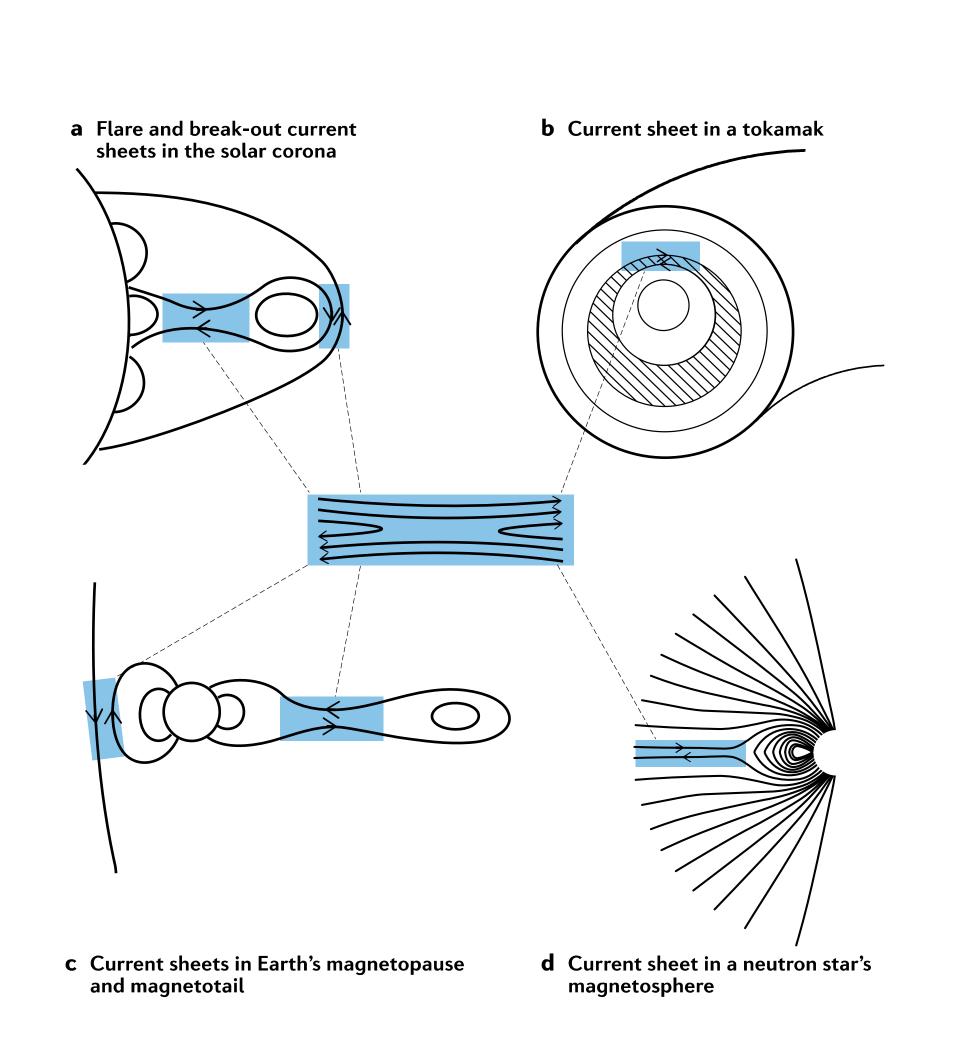
It is currently assumed that the interstellar space of the galaxy is occupied by matter at extremely low density, corresponding to about one atom of hydrogen per cc, or to a density of about 10^{-24} g/cc. The evidence indicates, however, that this matter is not uniformly spread, but that there are condensations where the density may be as much as ten or a hundred times as large and which extend to average dimensions of the order of 10 parsec. (1 parsec. = 3.1×10^{18} cm = 3.3 light years.) From the measurements of Adams⁴ on the Doppler effect of the interstellar absorption lines one knows the radial velocity with respect to the sun of a sample of such clouds located at not too great distance from us. The root mean square of the radial velocity, corrected for the proper motion of the sun with respect to the neighboring stars, is about 15 km/sec. We may assume that the root-mean-square velocity

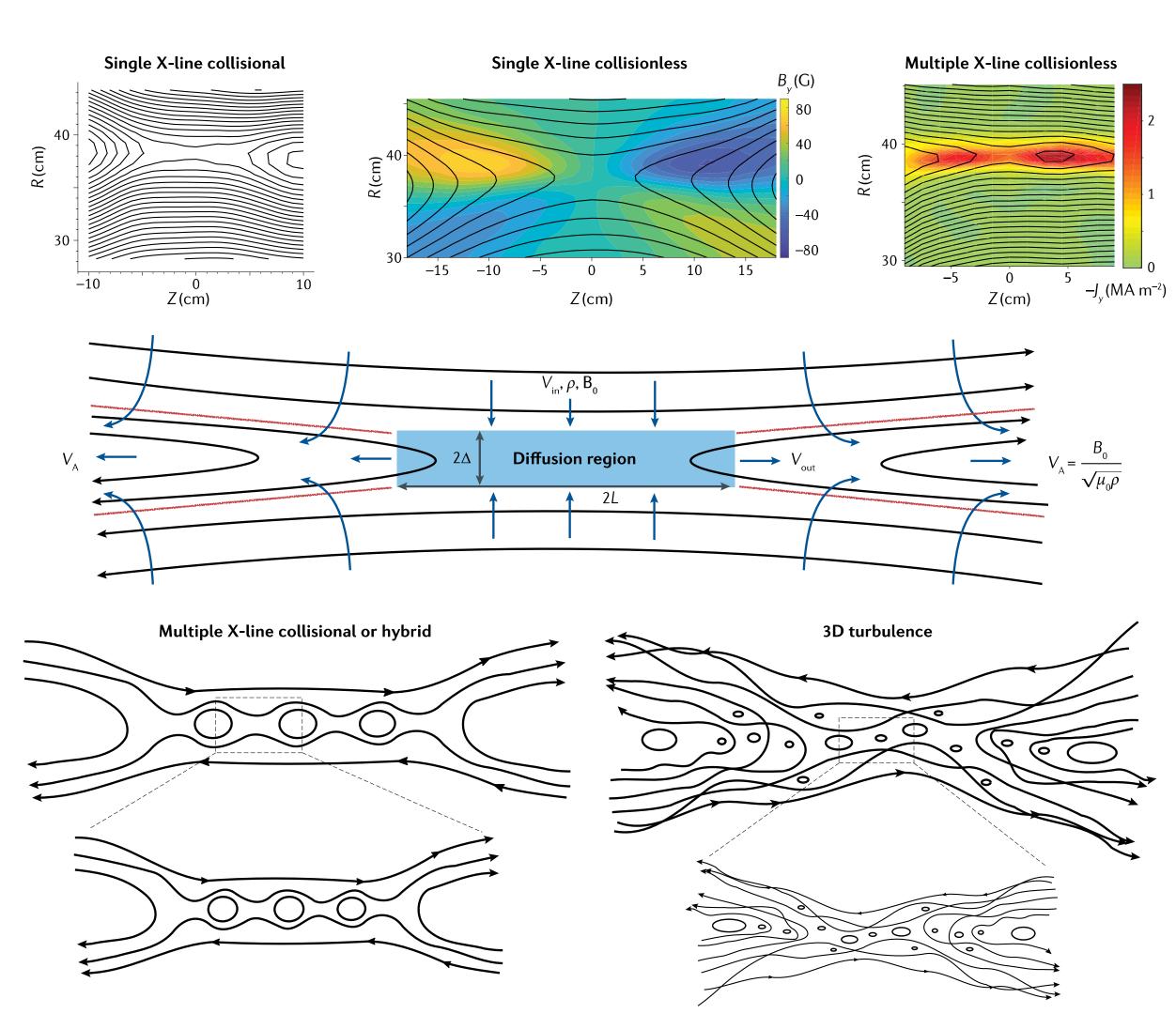
¹ Nuclear Physics Conference, Birmingham, 1948. ² Alfvén, Richtmyer, and Teller, Phys. Rev., to be pub-

⁸ H. Alfvén, Arkiv Mat. f. Astr., o. Fys. 29B, 2 (1943).

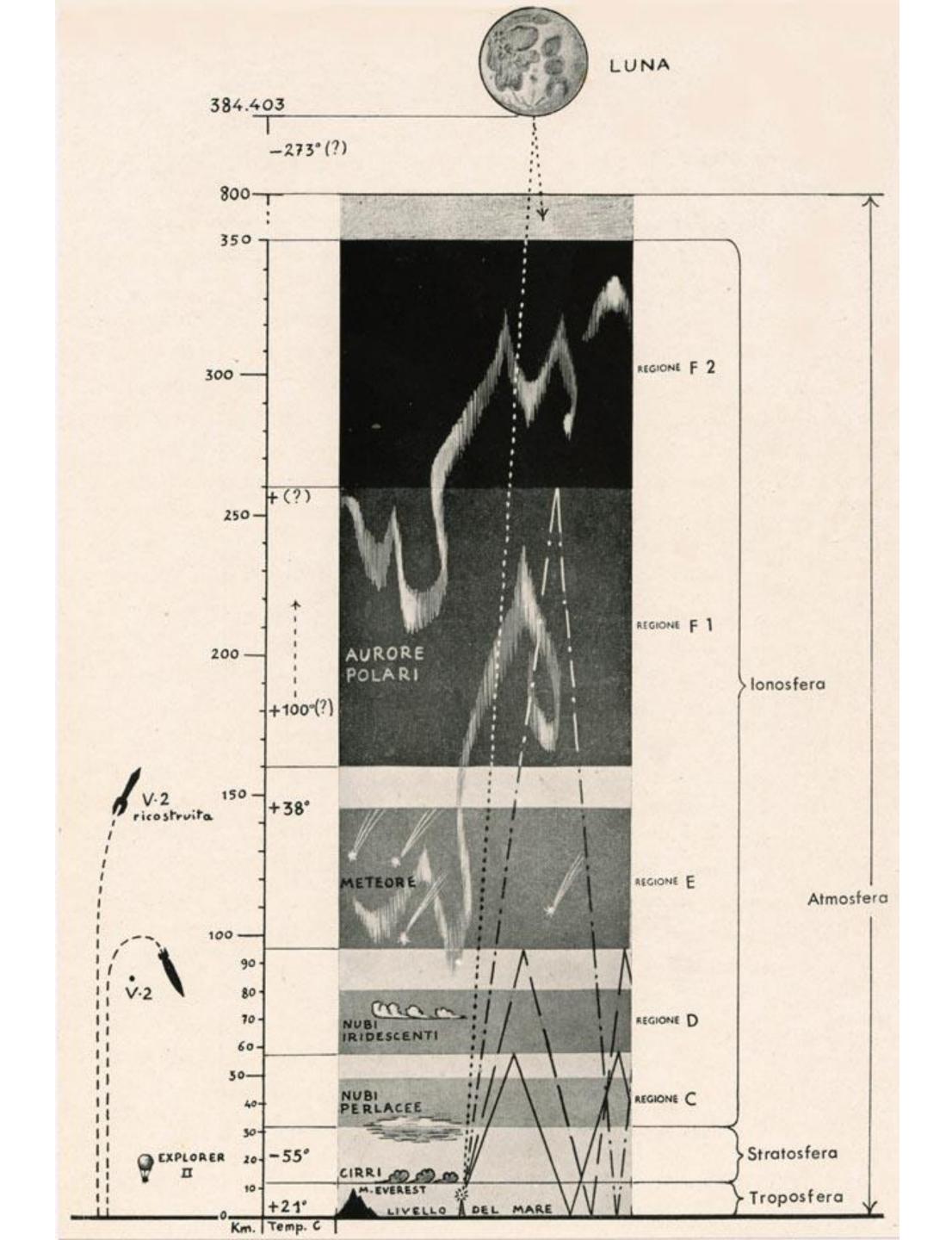
⁴ W. S. Adams, A.p.J. 97, 105 (1943).

Magnetic Fields can be used for Plasma Confinement Fusion Research – Sherwood Conferences 1952-1958 Instabilities and Magnetic Reconection





Mario Turani 1948: From the Earth to the Moon



Biermann 1951-53 estimates Solar Corpuscular Radiation escapes from the sun as source of the cometary ion tails at $V \approx 470 \text{ km/s}$.





/12/2025

The New York Times. In Saturday October 5, 1957

SOVIET FIRES EARTH SATELLITE INTO SPACE: IT IS CIRCLING THE GLOBE AT 18,000 M. P. H.;





the North Remark Laboratory, Lane of the month.

Military experts have said that the satellites SPHERE TRACKED IN 4 CROSSINGS OVER U.S. would have no practicable military the miles with application in the foreseeable future. The With Simpler satellites could not be used to drop atomic of hydrogen bombs or anything else on the earth, scientists have said. Real significance would be in providing scientists with important new information concerning the nature of the sun, cosmic radiation, solar radio interference and static- producing

phenomena radiating from the north and south magnetic poles. All this information would be of inestimable value for those who The Description of the latest and the part of the latest and th The first interesting of the collision o The first Figure F. Histories and to indigened the using process of the first format o



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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/cm^3 (10^{14} gm/sec mass loss from the sun) follow from the hydrodynamic equations for a $3 \times 10^6 \text{ }^\circ\text{K}$ 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.

I. INTRODUCTION

Biermann (1951, 1952, 1957a) has pointed out that the observed motions of comet tails would seem to require gas streaming outward from the sun. He suggests that gas is often flowing radially outward in all directions from the sun with velocities ranging from 500 to 1500 km/sec; there is no indication that the gas ever has any inward motion. Biermann infers densities at the orbit of earth ranging from 500 hydrogen atoms/cm³ on magnetically quiet days to perhaps 10⁵/cm³ during geomagnetic storms (Unsöld and Chapman 1949). The mass loss to the sun is 10¹⁴–10¹⁵ gm/sec. It is the purpose of this paper to explore some of the grosser dynamic consequences of Biermann's conclusions.

For instance, we should like to understand what mechanism at the sun might conceivably be responsible for blowing away the required 10¹⁴–10¹⁵ gm of hydrogen each second with velocities of the order of 1000 km/sec. All known mechanisms, such as

How does a hot corona expand?

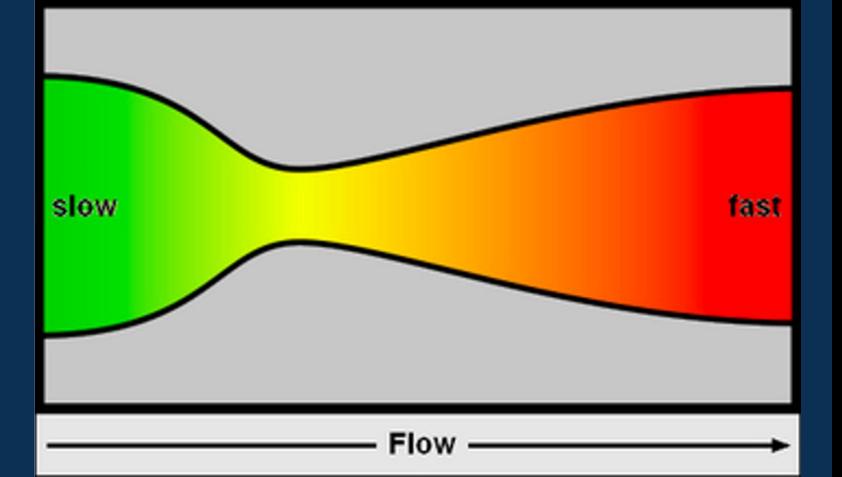
$$g_s = \frac{GM_{\odot}}{R_s^2} \quad r = \frac{R}{R_s} \quad \frac{\partial p}{\partial r} = -\frac{2m_p ngR_s}{r^2} \quad p = 2nkT$$

$$p(r) = p_0 \exp\left(-\int_1^r dr' \frac{m_p g_s R_s}{kT \, r^2}\right)$$

T(r) falls slower than 1/r a finite pressure at infinity is required confine atmosphere. In a hot plasma atmosphere thermal conduction is proportional $k \sim T^{5/2}$ and therefore $T(r) \sim r^{-2/7}$

Since we know of no general pressure at infinity which could balance the $p(\infty)$ computed from equation (9) with the expected values of n, we conclude that probably it is not possible for the solar corona, or, indeed, perhaps the atmosphere of any star, to be in complete hydrostatic equilibrium out to large distances. We expect always to find some continued outward hydrodynamic expansion of gas—without considering the evaporation from the high-velocity tail of the Maxwellian distribution (Spitzer 1947; van de Hulst 1953).

Parker, 1958



$$(U - \frac{V_T^2}{U})\frac{dU}{dr} = \frac{V_T^2}{A}\frac{dA}{dr} - \frac{V_g^2}{2}\frac{1}{r^2}$$

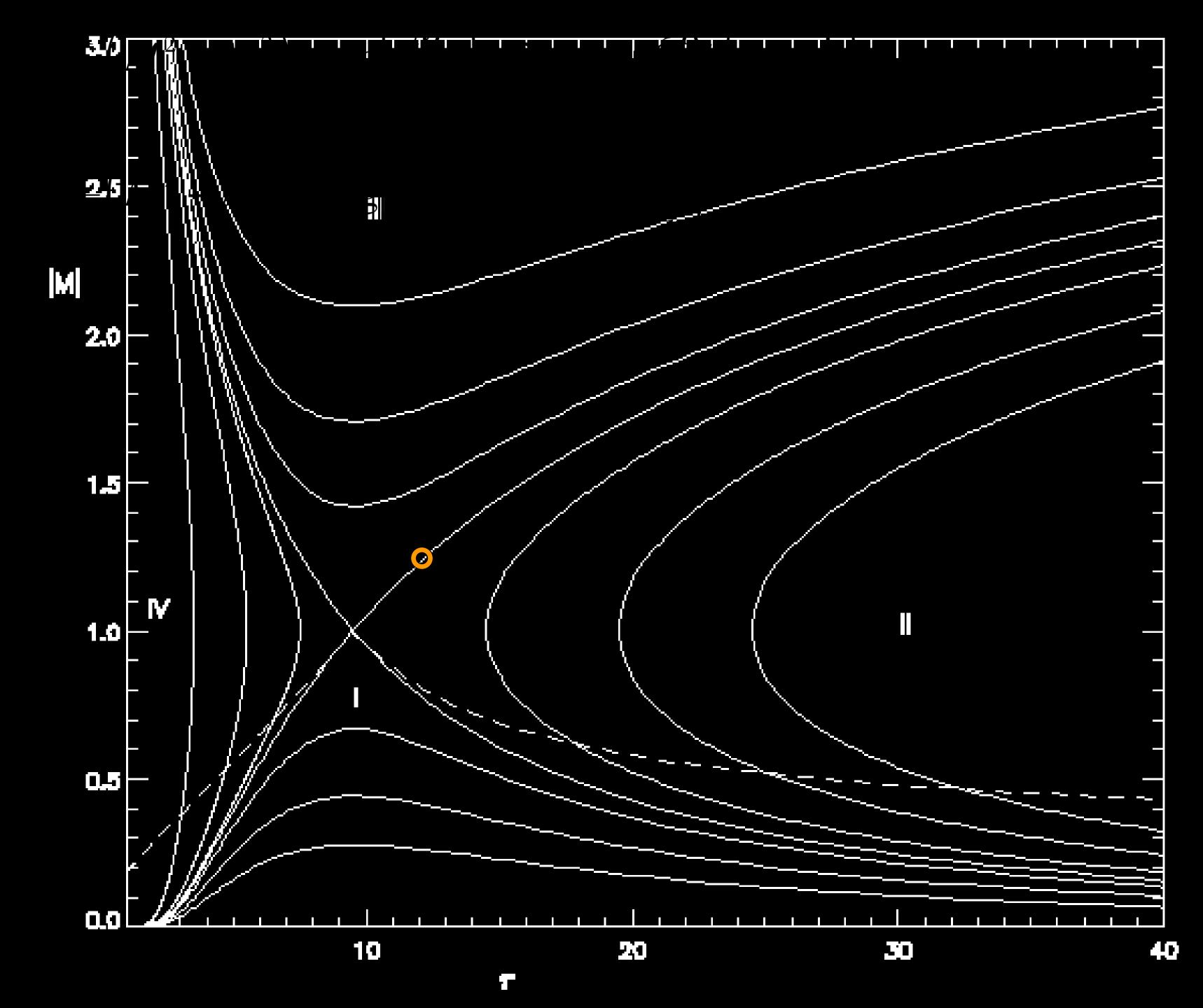
I Breezes

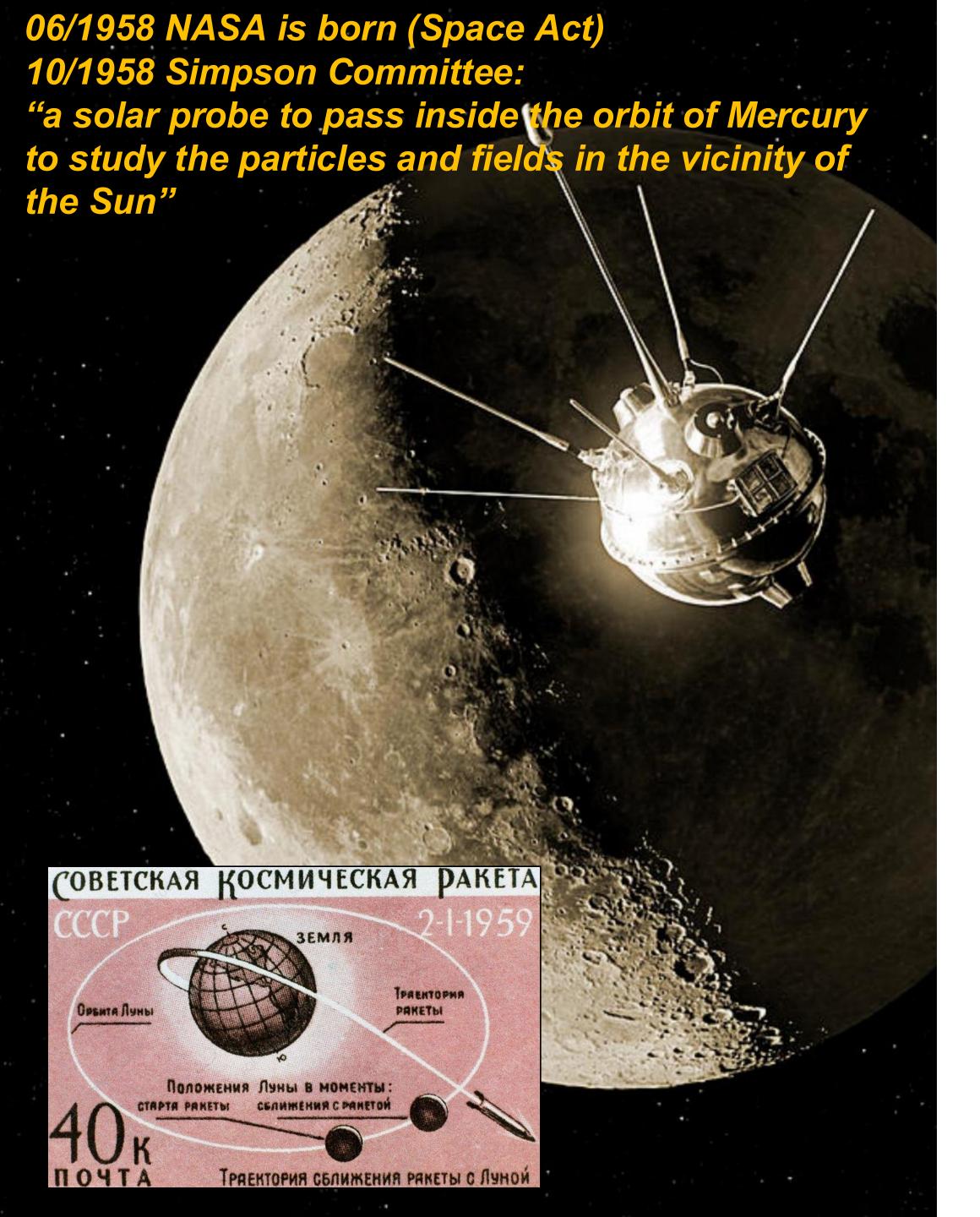
II ?

III Supersonic

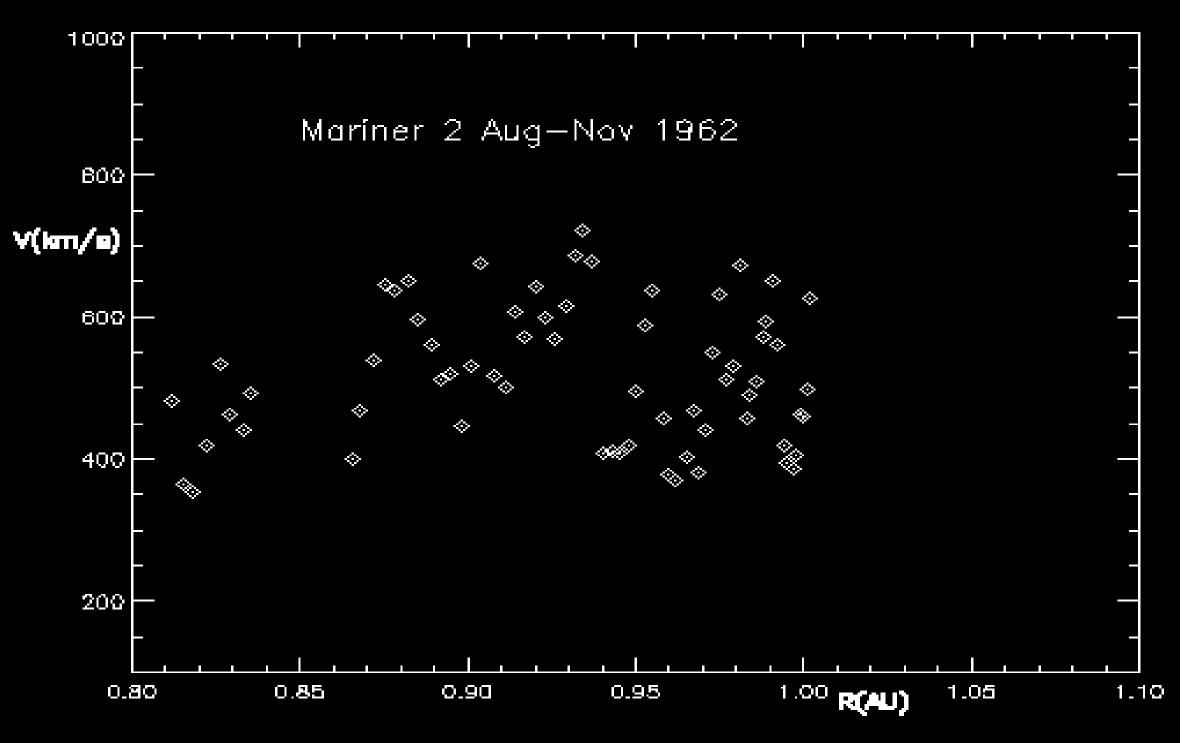
IV?

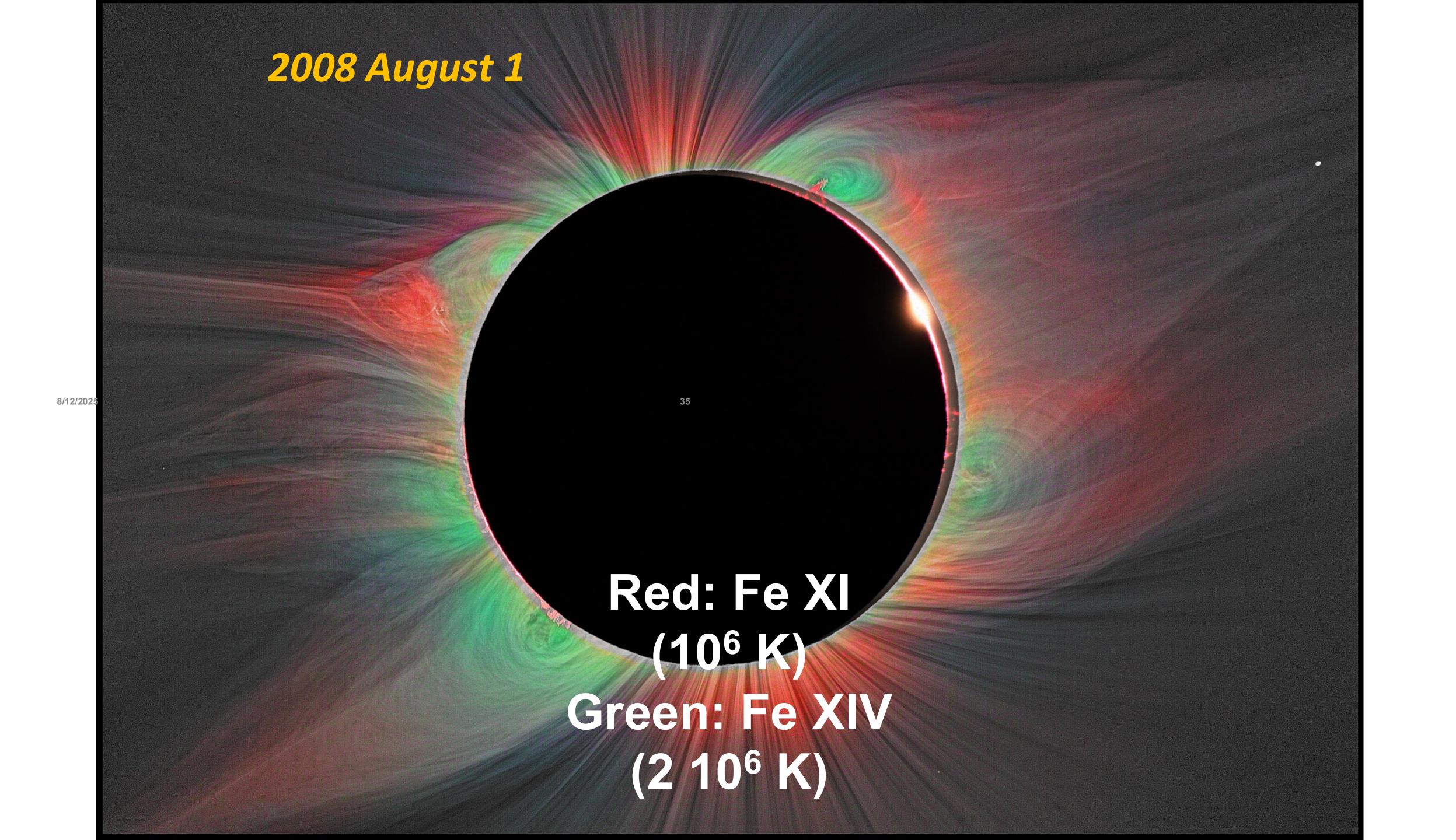
Transonic

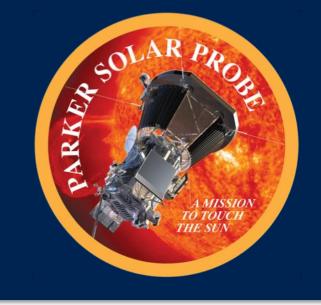






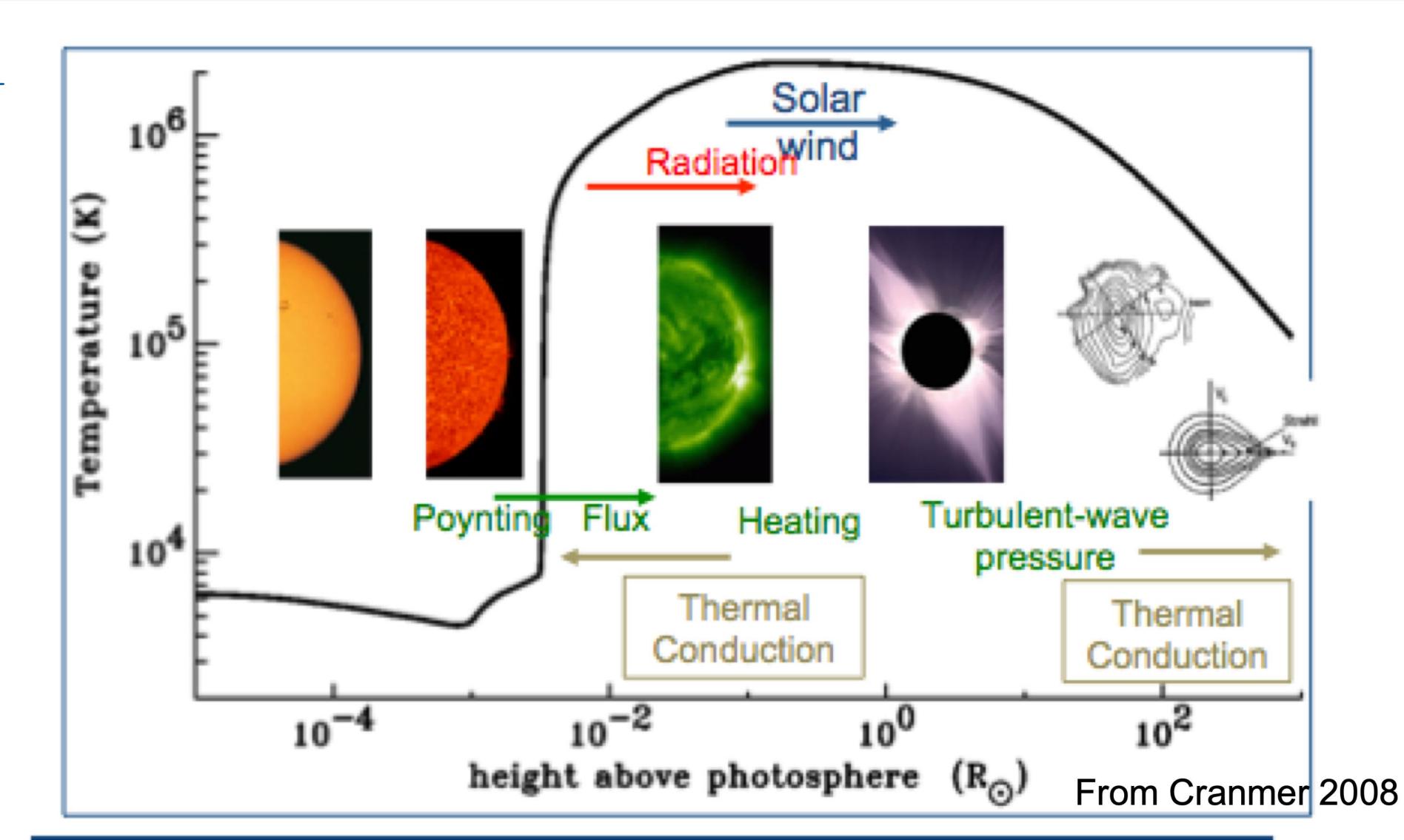




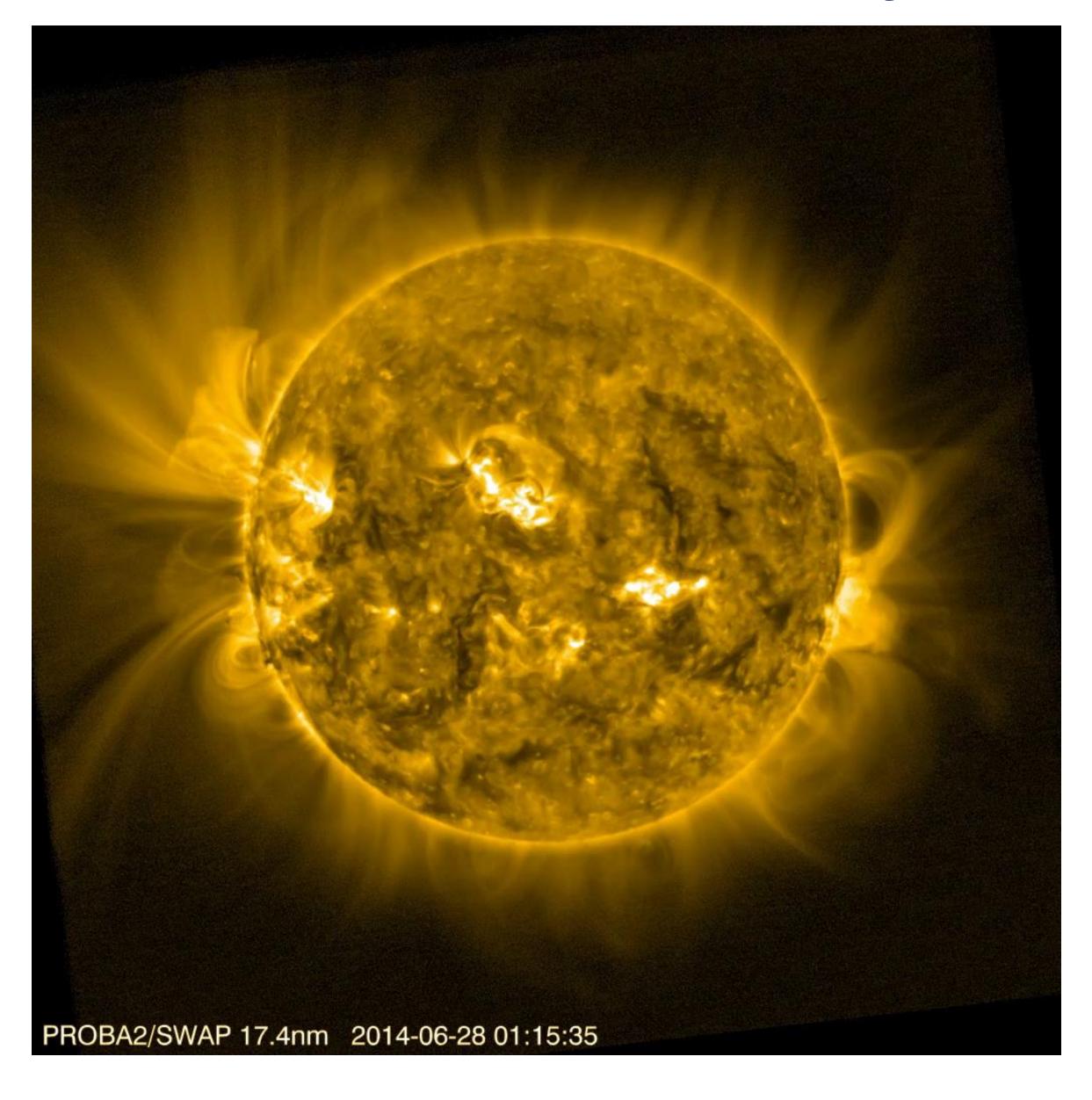


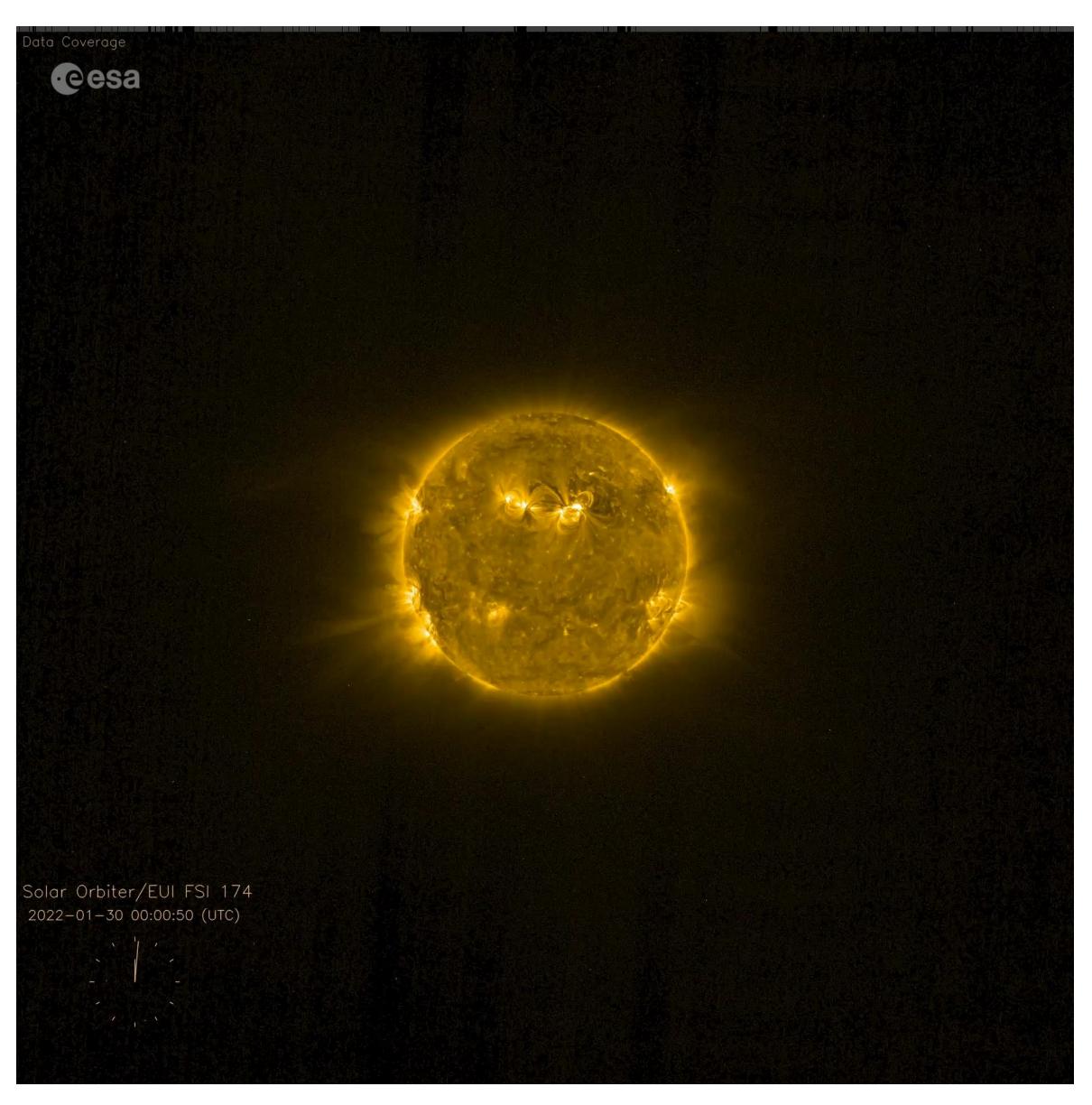
Solar coronal temperature profile

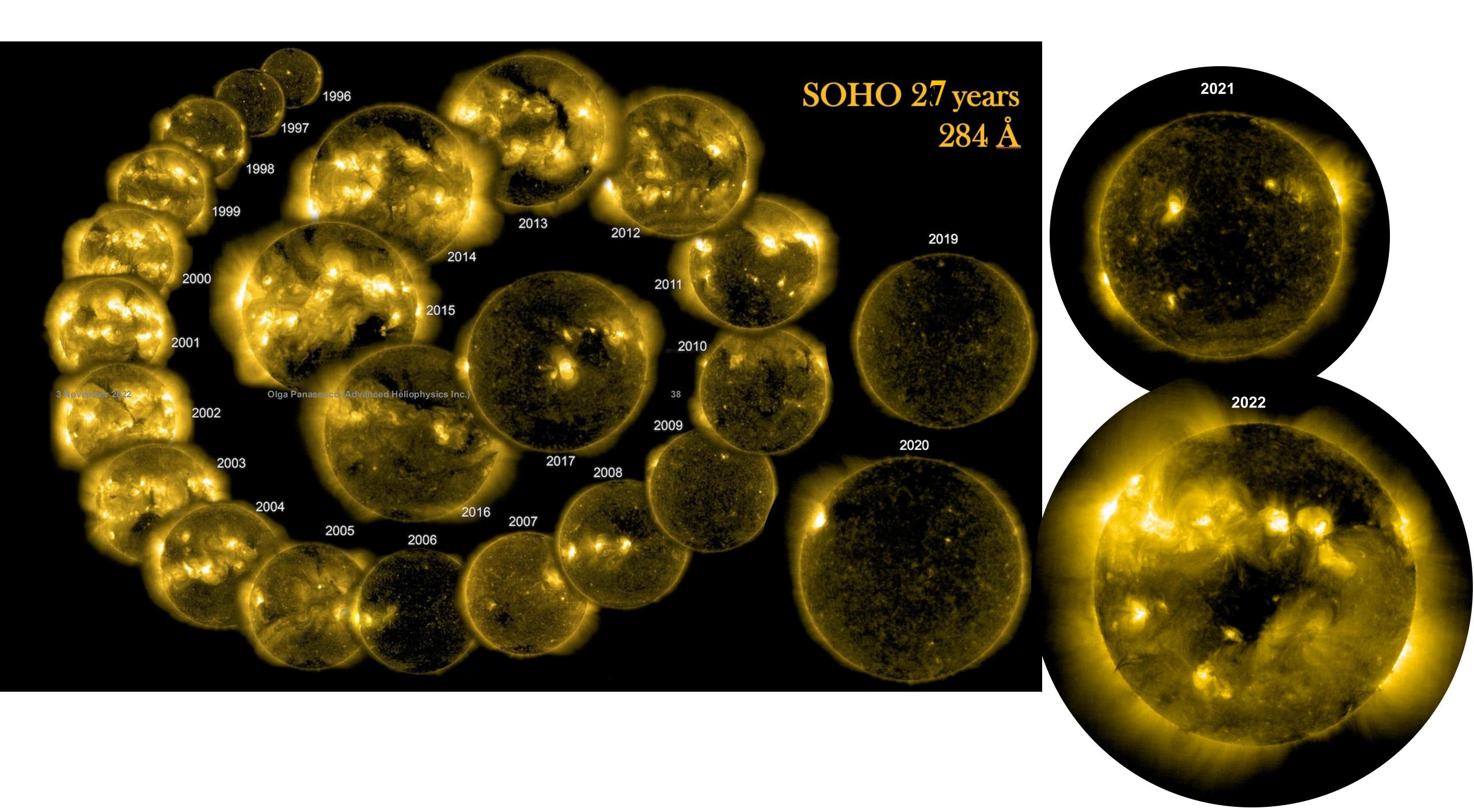
$$\mathbf{S} \cdot \mathbf{n} = \frac{1}{4\pi} \left[\mathbf{B}_{\perp}^{2} \left(\mathbf{u}_{ph} \cdot \mathbf{n} \right) - \left(\mathbf{B} \cdot \mathbf{n} \right) \left(\mathbf{B}_{\perp} \cdot \mathbf{u}_{ph} \right) \right]$$



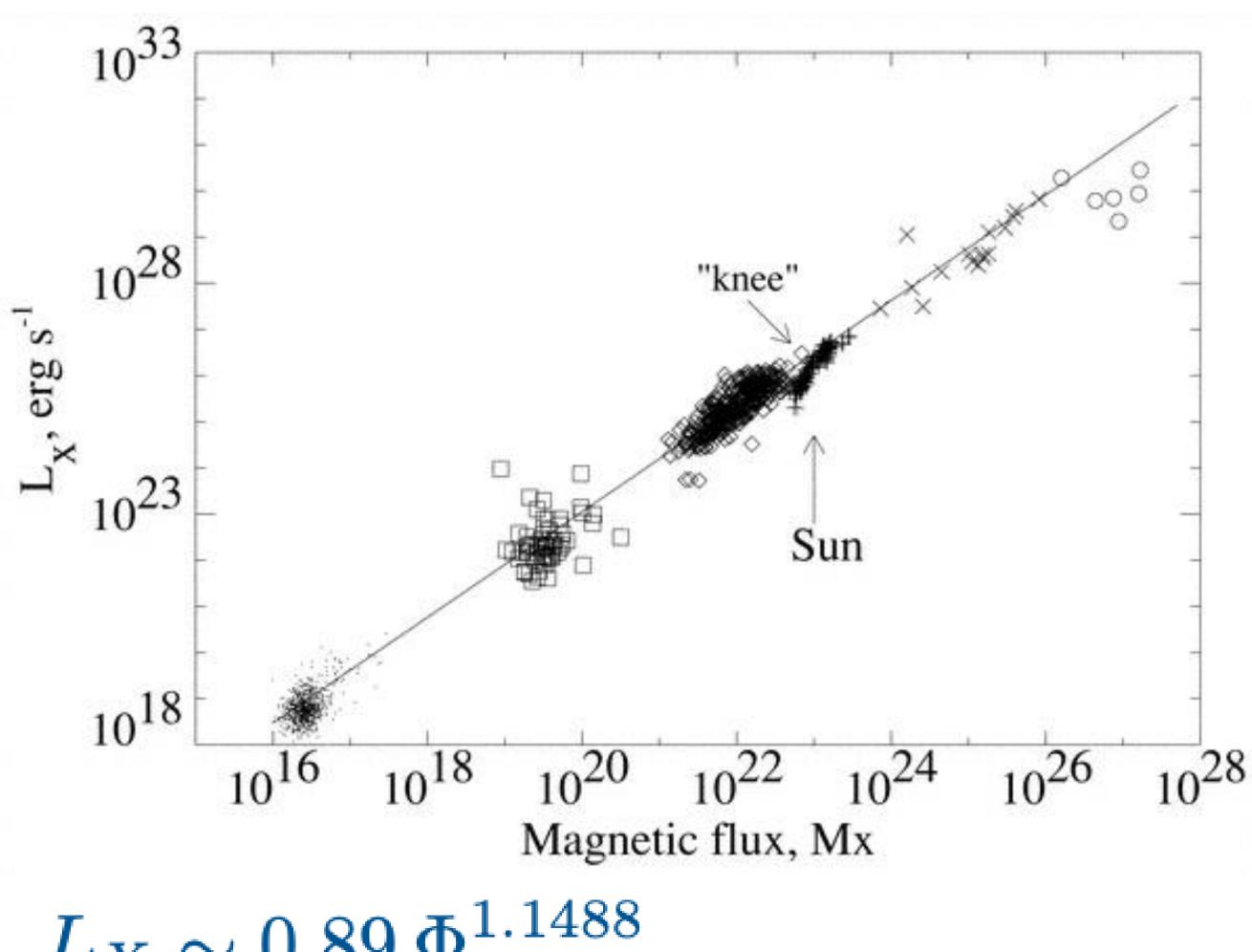
The dynamic solar corona







Magnetic Flux Correlates With X-ray flux

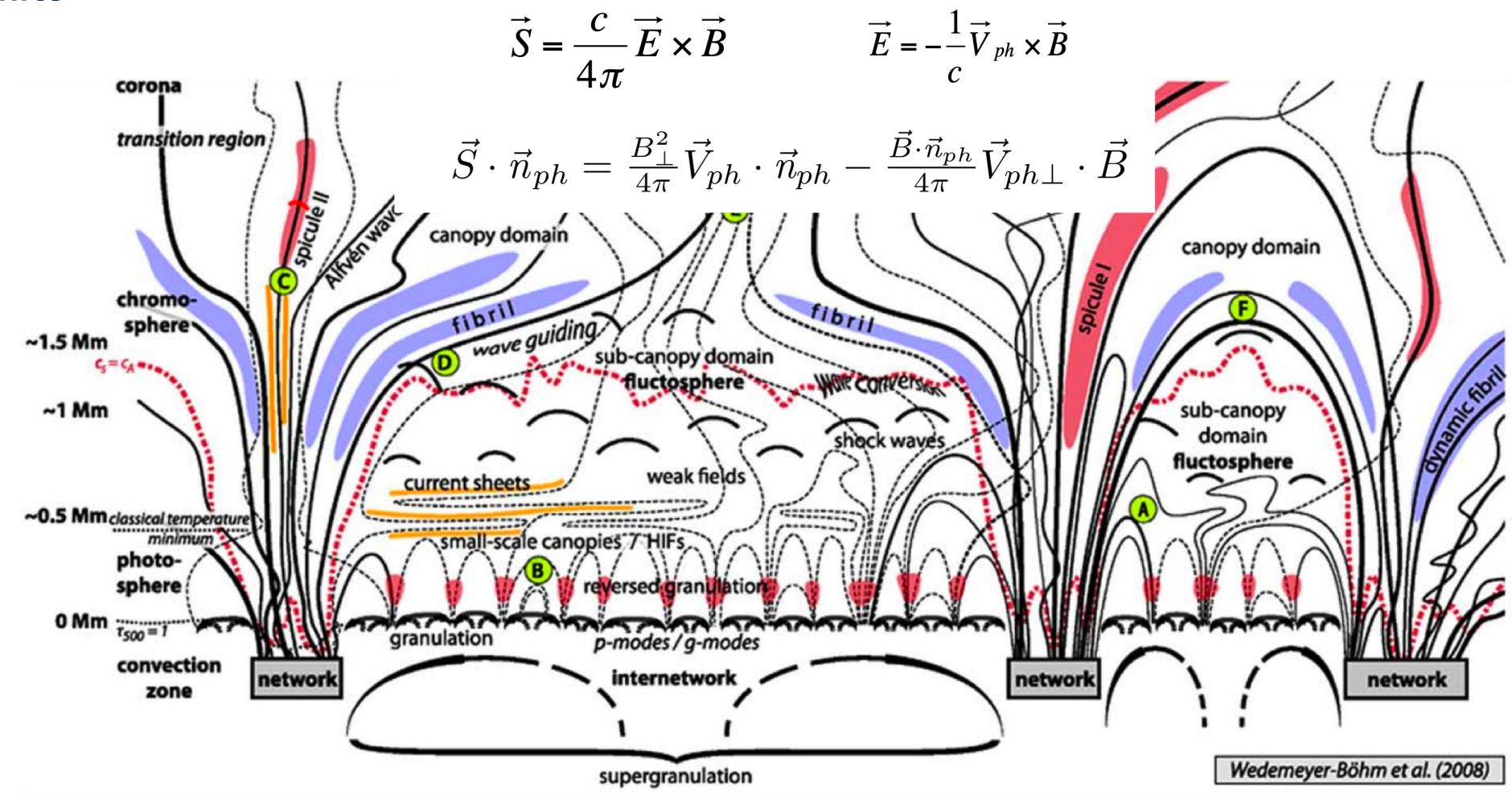


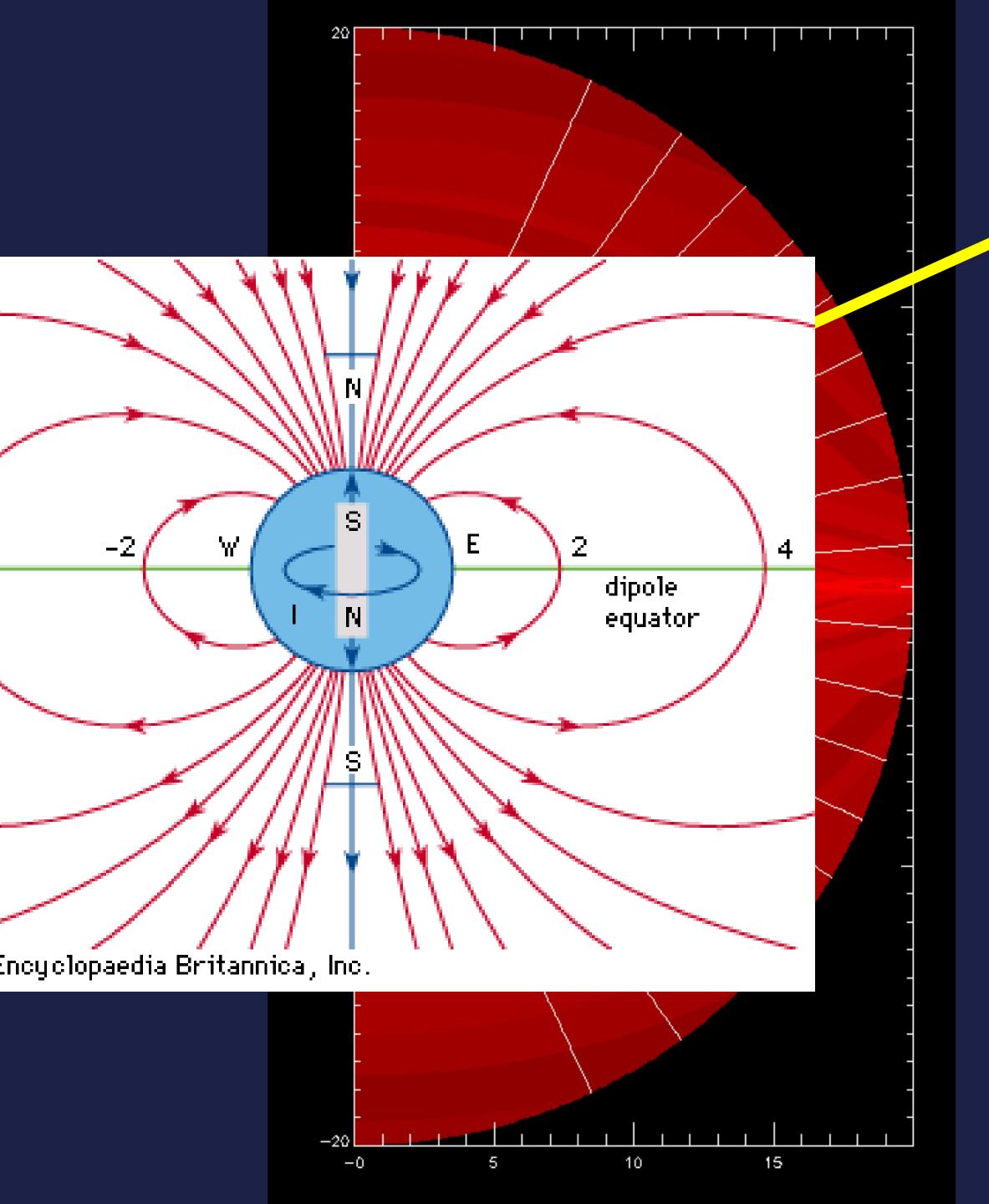
 $L_X \sim 0.89 \, \Phi_*^{1.1488}$

Pevtsov et al. (2003)

Source of heliospheric energy flux

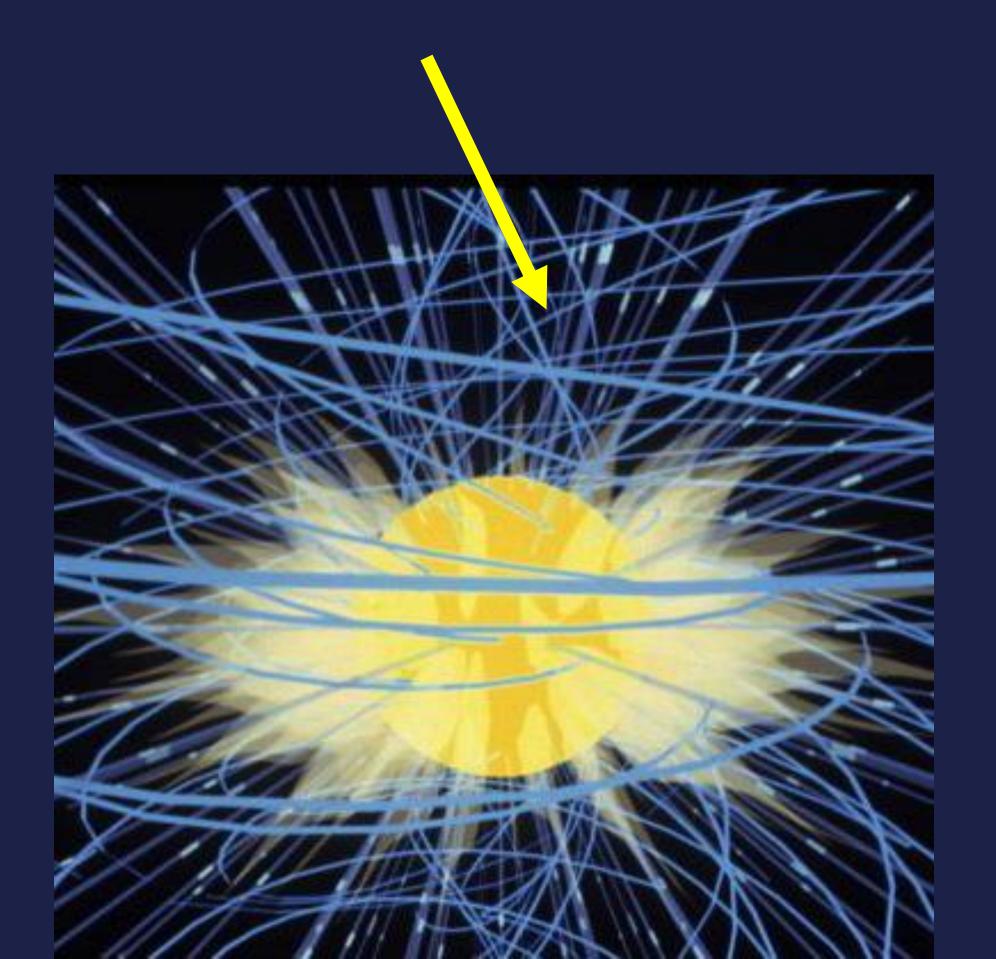
Photospheric motions produce field line tangling and emerging flux resulting in a Poynting flux crossing the photosphere. However, the approximation of line-tying is questionable and begs the question of chromospheric heating and dynamics

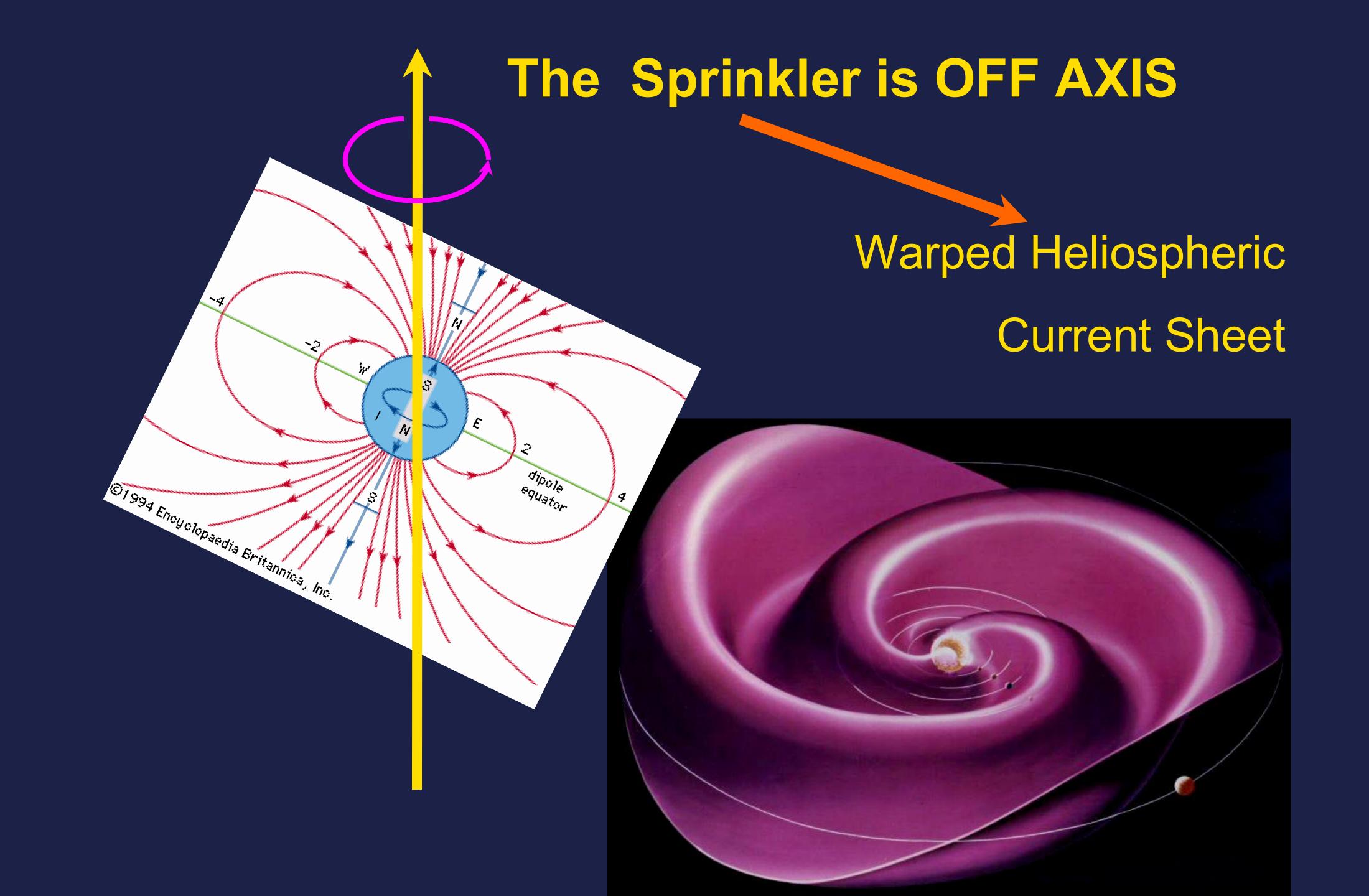


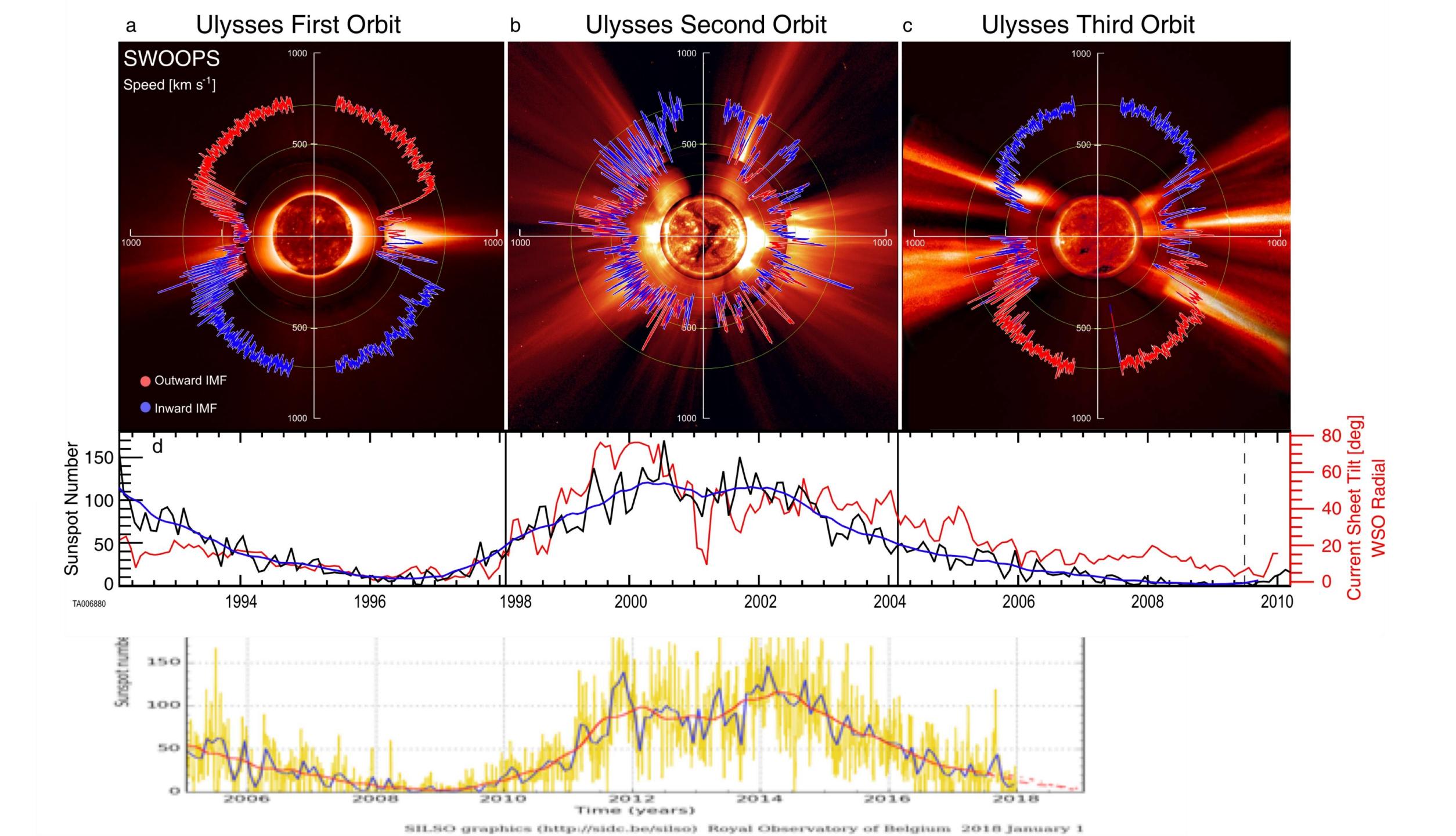


Solar Corona Expands: drags out and opens up the field lines.

Solar Rotation: wraps the field lines up into a spiral (sprinklers)

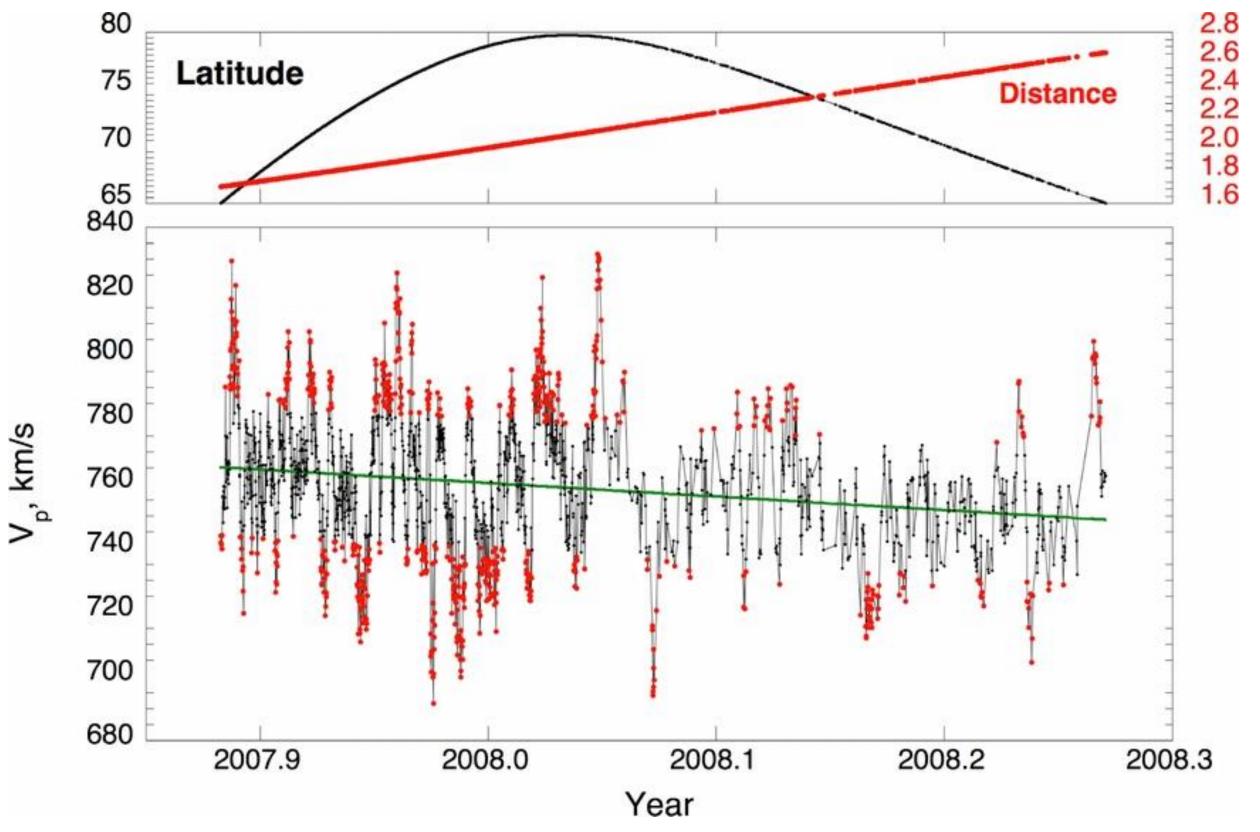




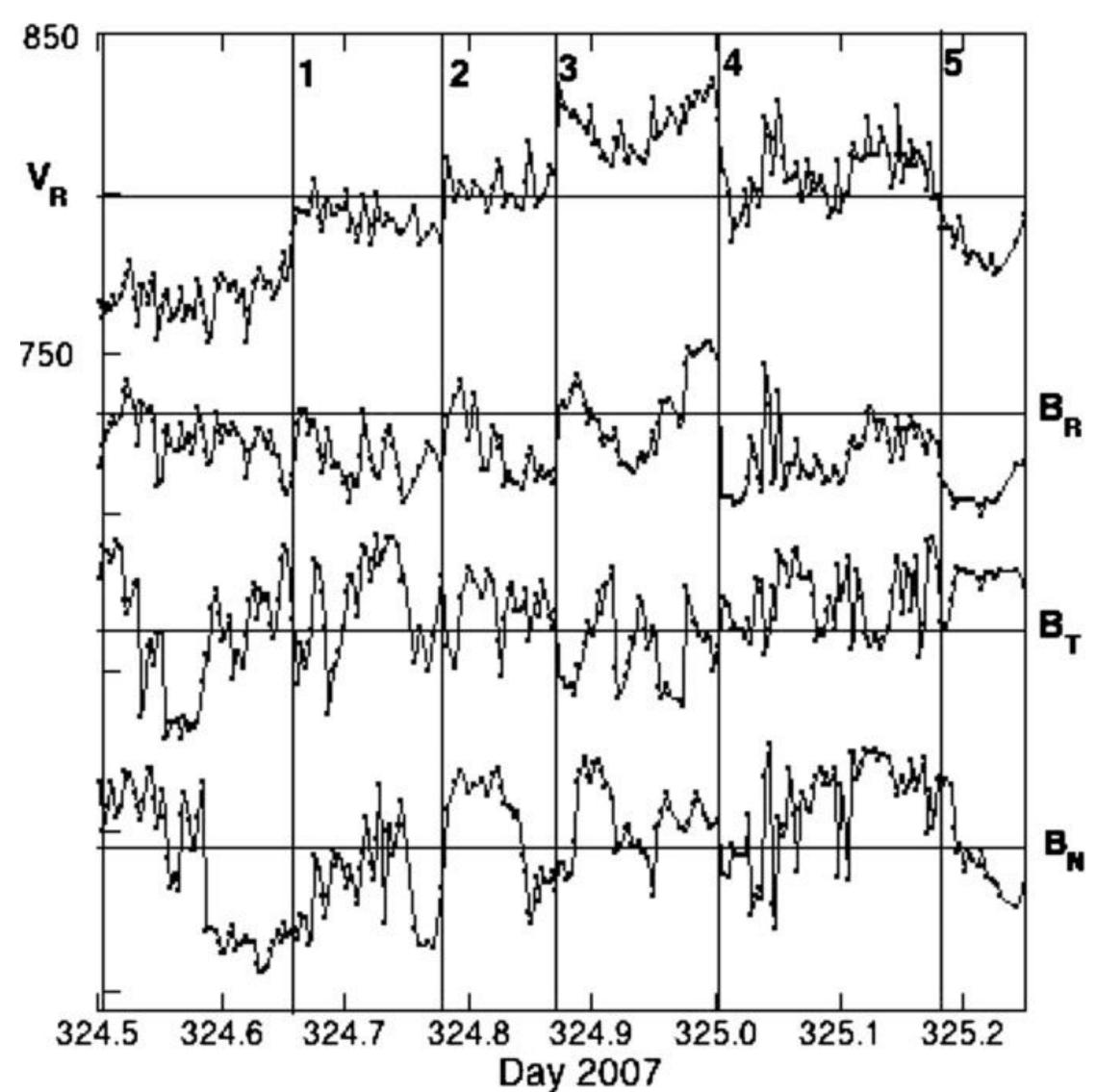


Ulysses: High speed streams microstreams/

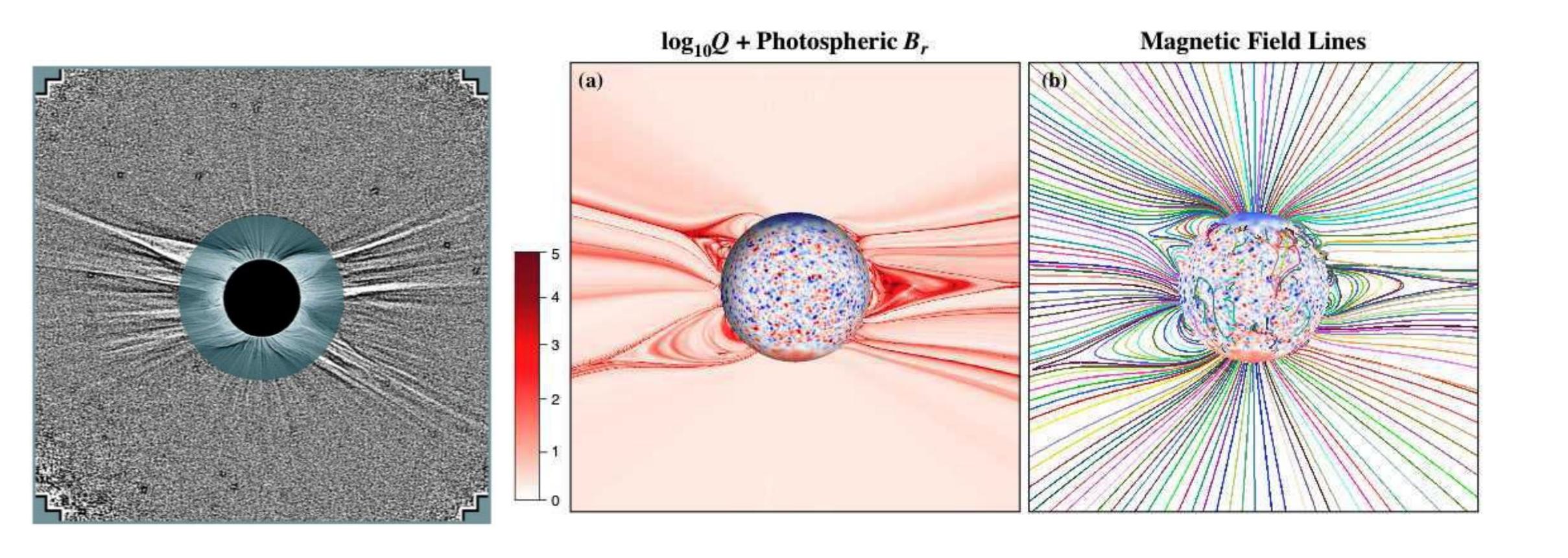
Alfvenic Jets



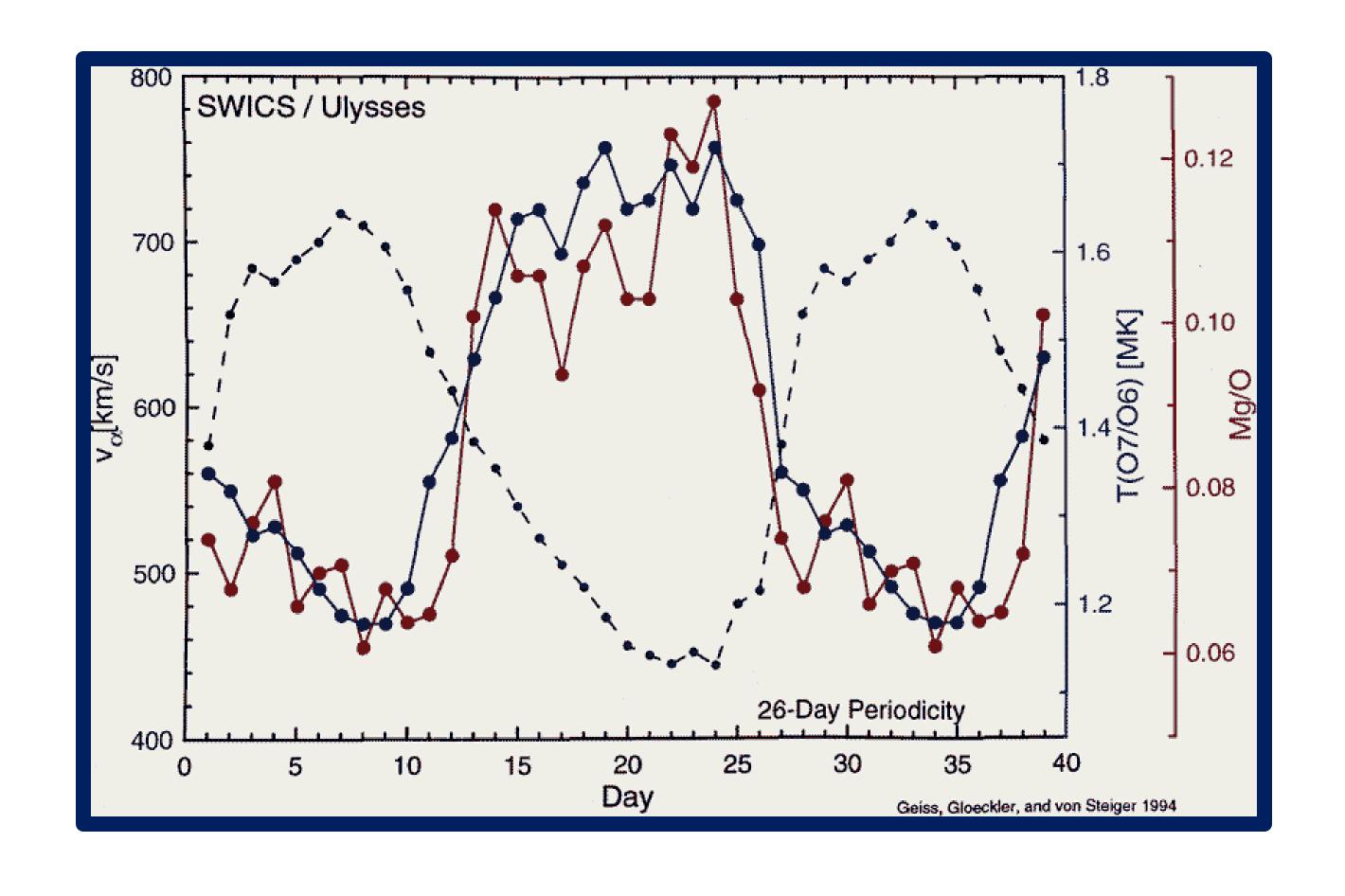
Neugebauer 2012 Matteini et al. 2013-2016

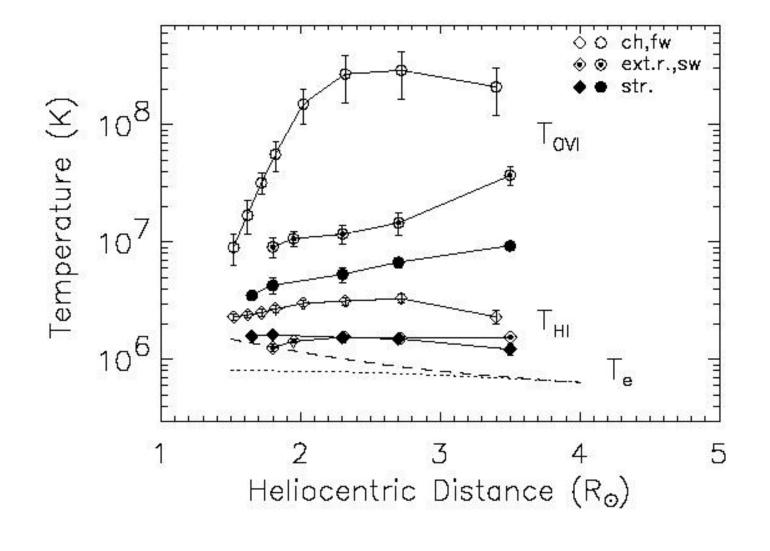


Connection between coronal sources, streamer belt, and heliospheric current sheet (S-Web, Antiochos 2007.2011)



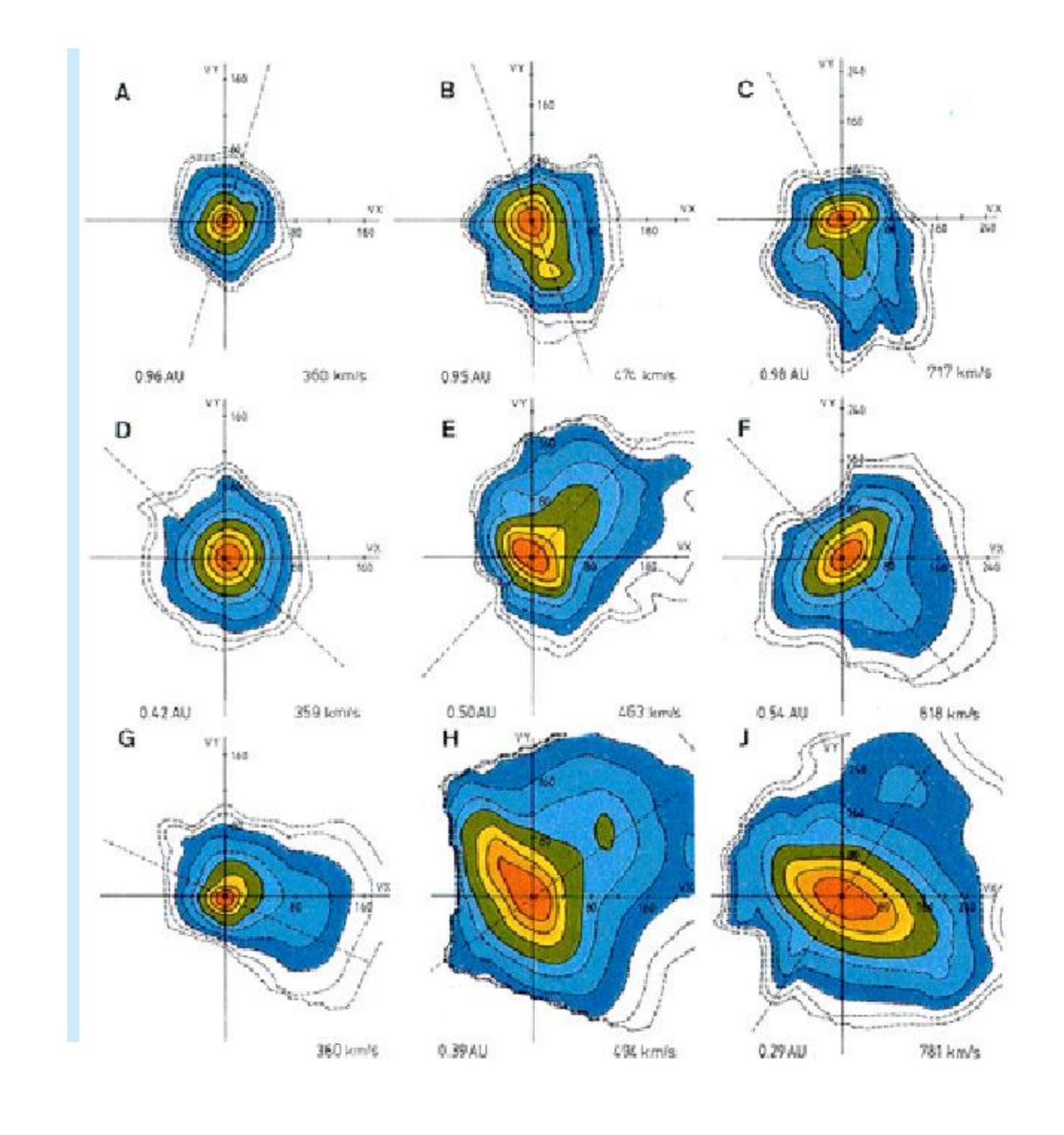
Given the corona, do we understand the wind? Not quite.... Fast Wind is 1) Too FAST 2) Temperature and speed OPPOSITE TO EXPECTED!!!!!



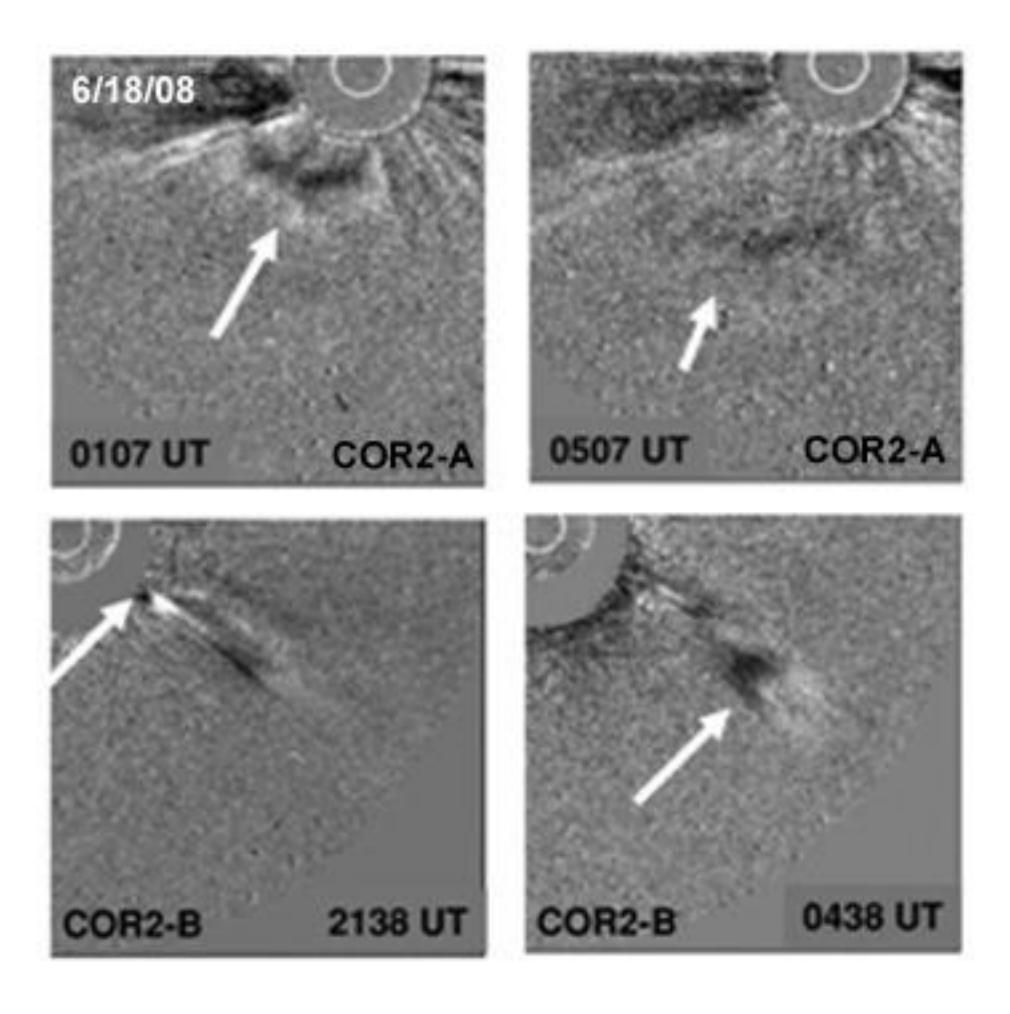


	fast	slow
speed (km/s)	600-800	300-500
T_{p} (10 ⁵ K)	2.4	0.4
T_{e}^{r} (10 ⁵ K)	1.0	1.3
T_{ion} / T_{p} $O^{7+}/O^{6+}, Mg/O$	$> m_{ion}/m_{p}$	< m _{ion} /m _p
O^{7+}/O^{6+} , Mg/O	low	high

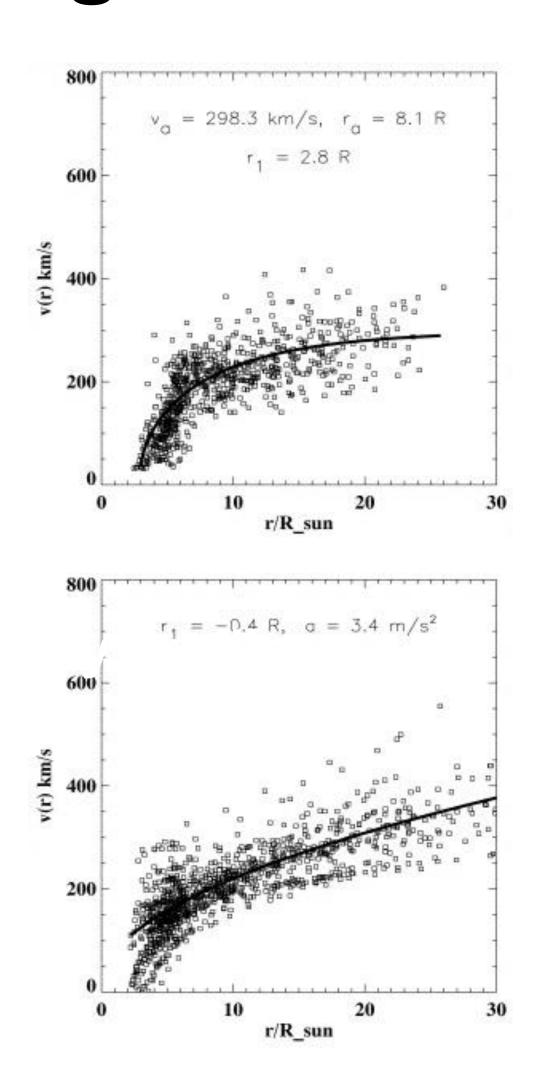
Proton solar wind distribution functions Marsch et al., JGR, 87, 52, 1982 (Helios data)



Fast and Slow Solar Wind Origins



Sheeley et al 2009/Sheeley & Rouillard 2010



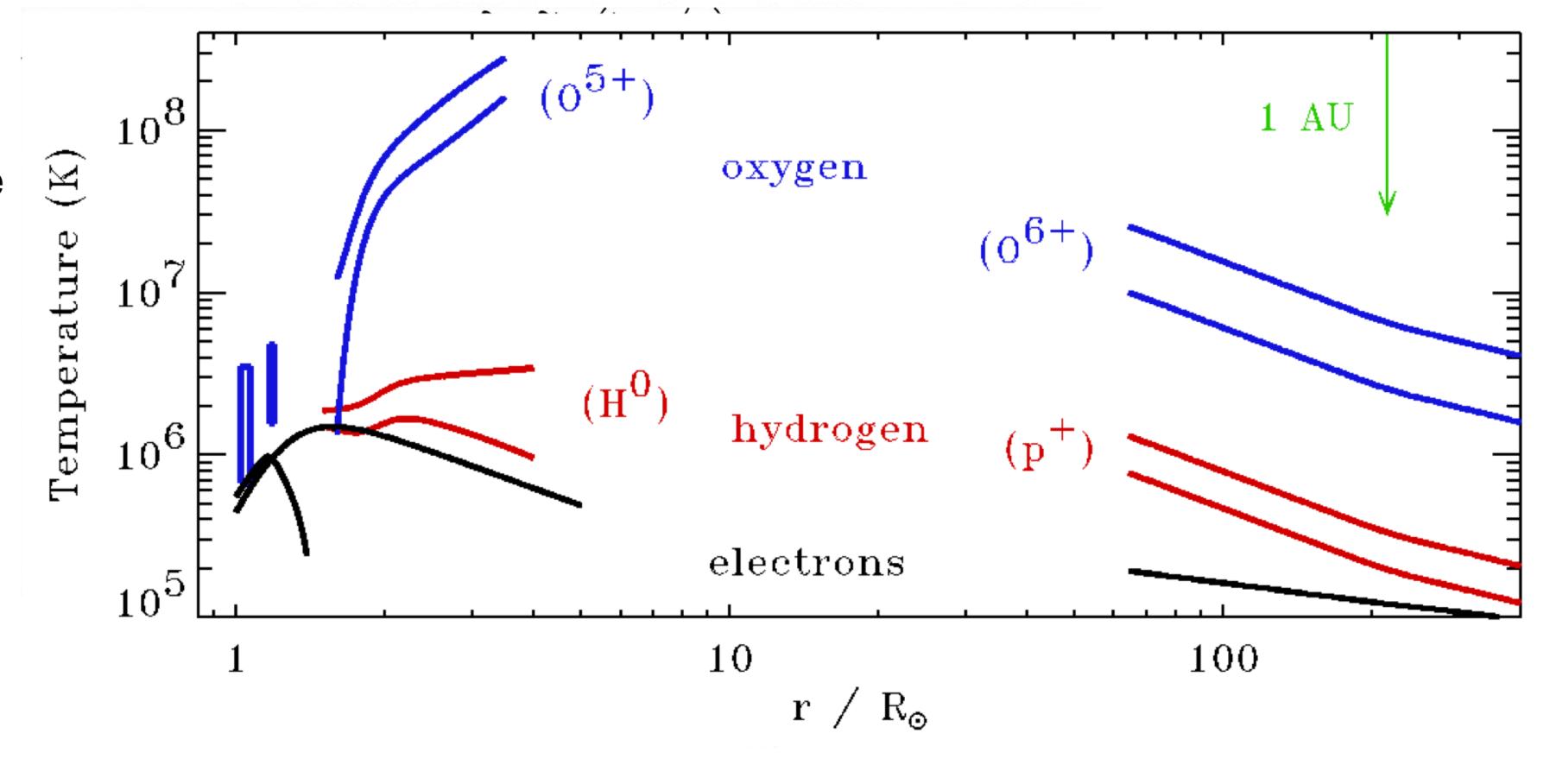
Sheeley, et al., 1997

Parker Solar Probe Objectives

To determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what mechanisms accelerate and transport energetic particles.

Observations inside 20Rs:

- coronal magnetic structure still channels the flow
 - waves, turbulence are strongest
 - temperature maximum.
- Collisional Collisionless transition.



Solar Orbiter Objectives

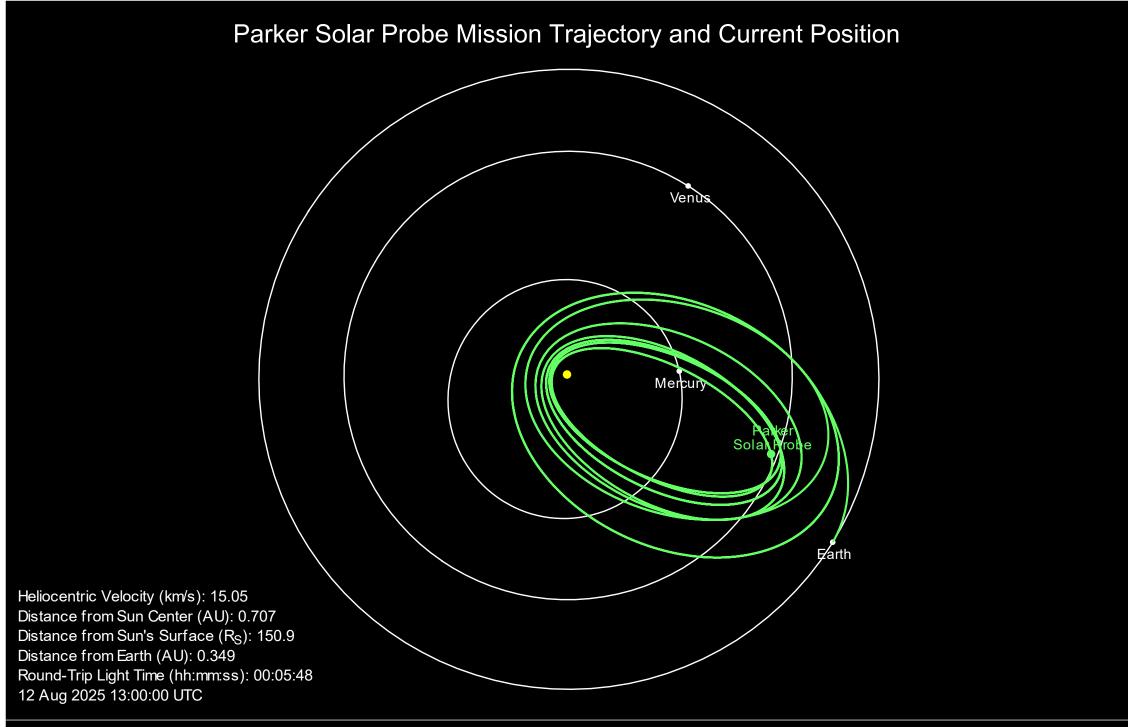
What drives the solar wind and where does the coronal magnetic field originate from?

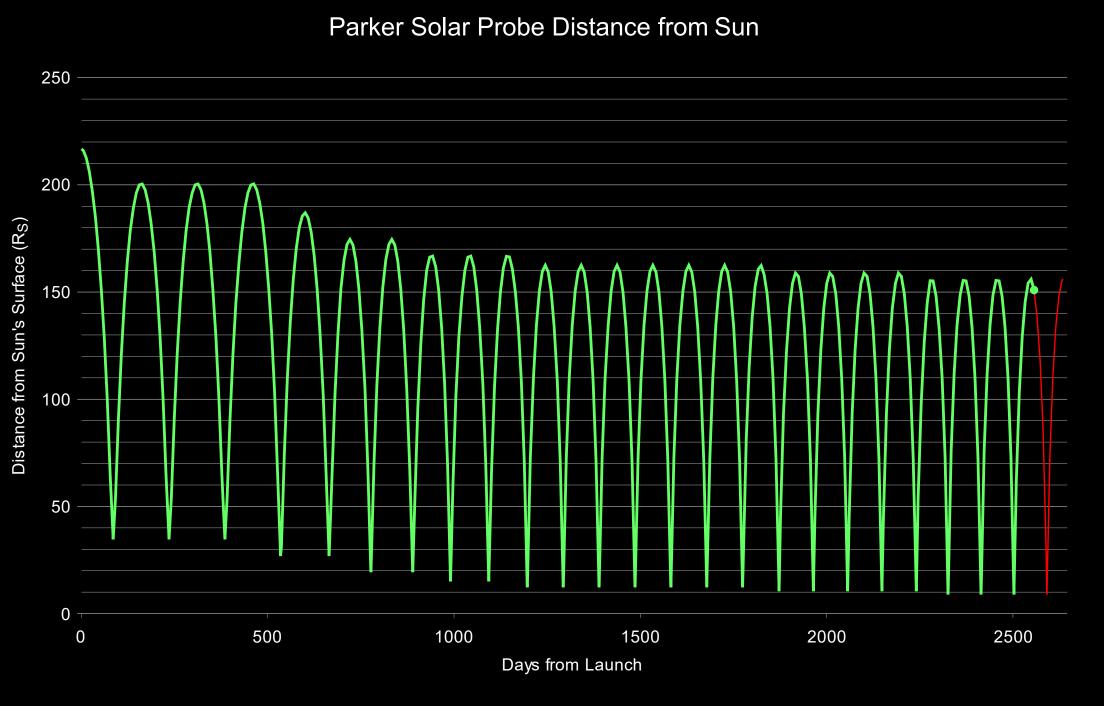
How do solar transients drive heliospheric variability?

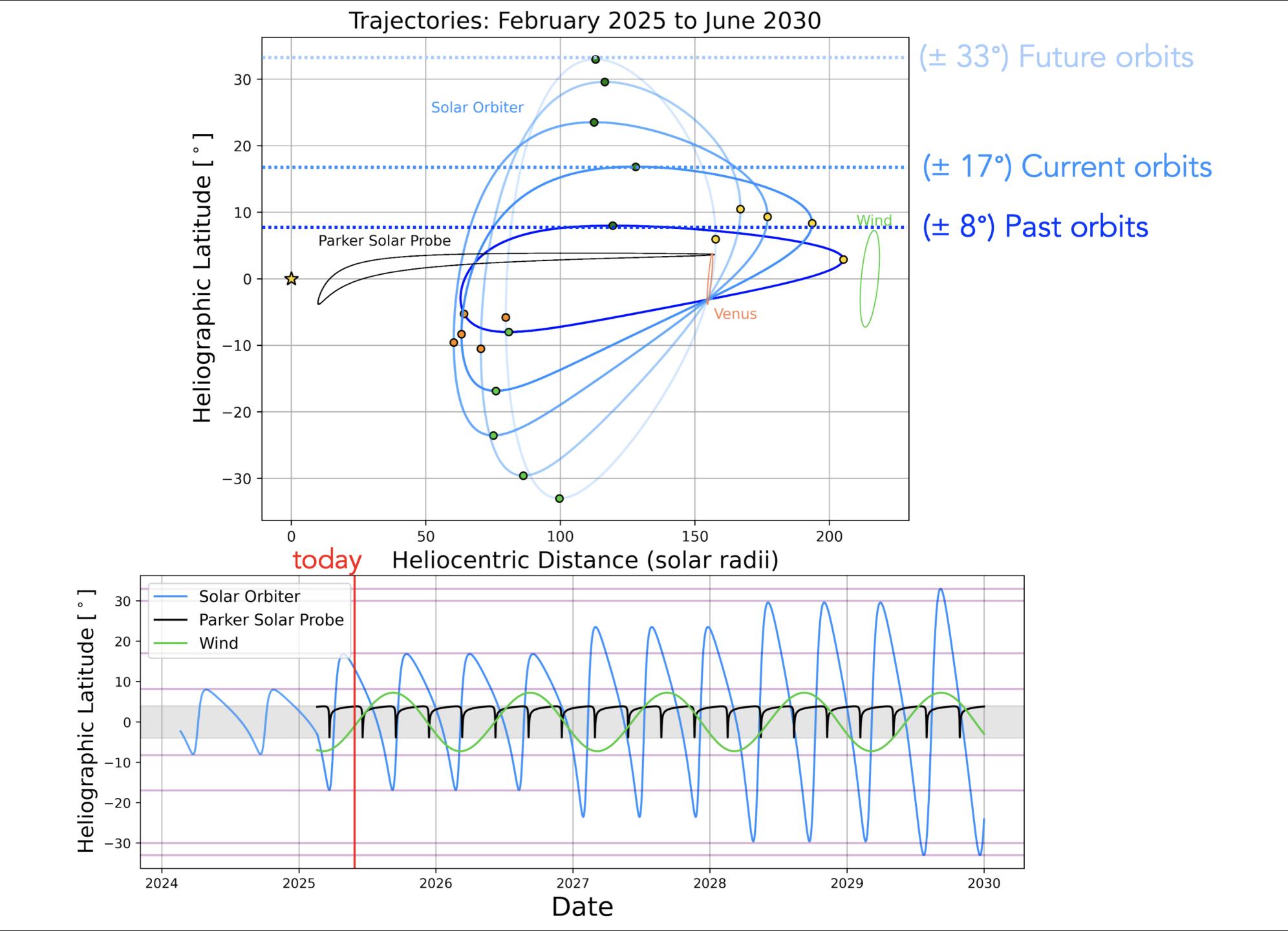
How do solar eruptions produce energetic particle radiation that fills the heliosphere?

How does the solar dynamo work and drive connections between the Sun and the heliosphere?

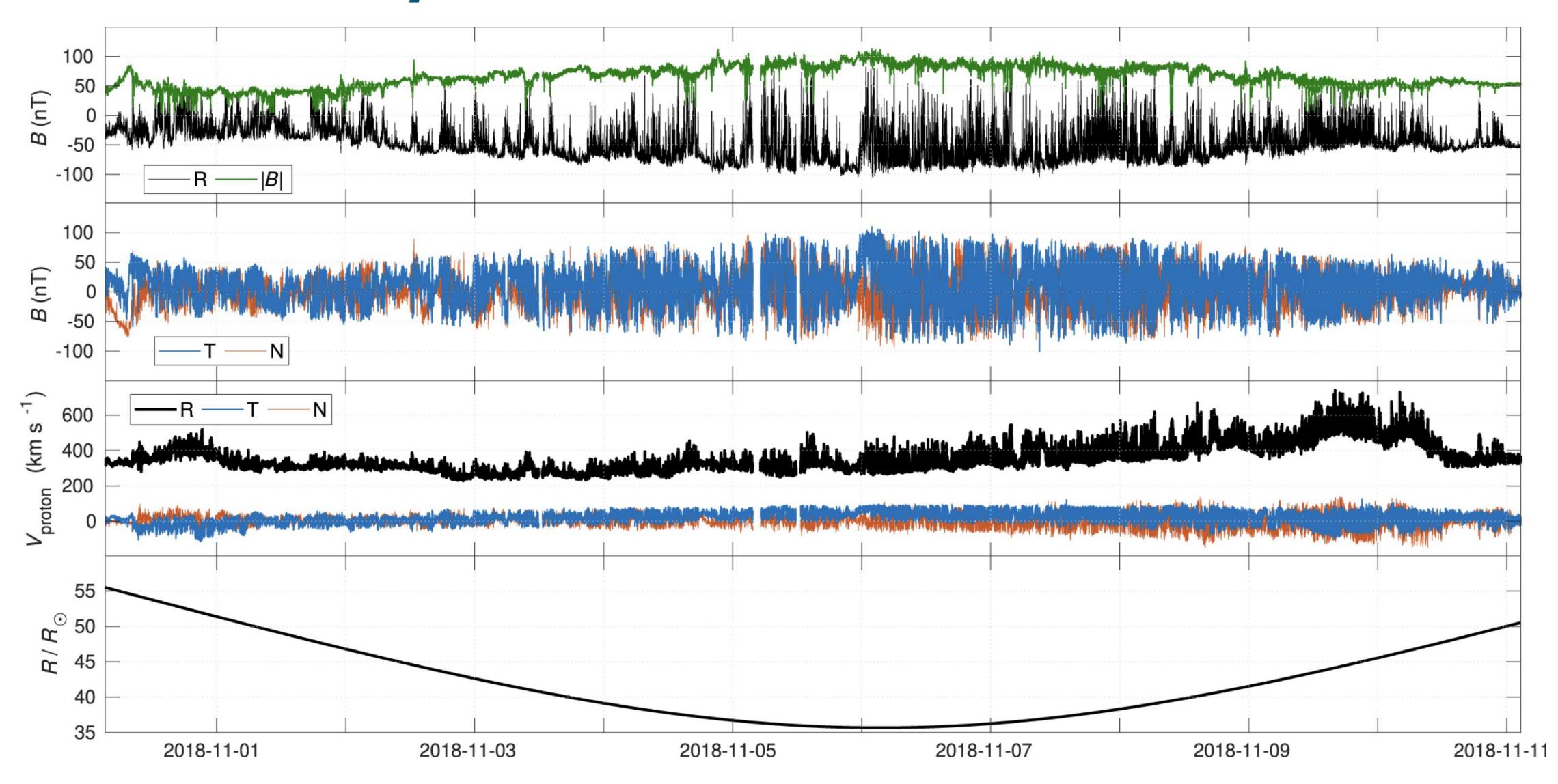
Perihelion #	Date of Perihelion	Perihelion (Rs)	30 Rs	20 Rs	15 Rs	10 Rs
1	11/1/18	35.66				
2	3/31/19	35.66				
3	8/28/19	35.66				
4	1/24/20	27.85	61.04			
5	6/2/20	27.85	61.06			
6	9/22/20	20.35	104.22			
7	1/13/21	20.35	104.22			
8	4/24/21	15.98	108.55	48.06		
9	8/5/21	15.98	108.55	48.06		
10	11/16/21	13.28	107.27	55.13	24.75	
11	2/21/22	13.28	107.27	55.13	24.75	
12	5/28/22	13.28	107.27	55.12	24.75	
13	9/1/22	13.28	107.27	55.13	24.75	
14	12/6/22	13.28	107.27	55.12	24.74	
15	3/13/23	13.28	107.27	55.12	24.74	
16	6/17/23	13.28	107.27	55.12	24.73	
17	9/23/23	11.42	105.03	56.91	32.23	
18	12/24/23	11.42	105.03	56.91	32.23	
19	3/25/24	11.42	105.03	56.91	32.23	
20	6/25/24	11.42	105.03	56.91	32.23	
21	9/25/24	11.42	105.03	56.91	32.23	
22	12/19/24	9.86	102.40	57.02	35.22	4.94
23	3/18/25	9.86	102.40	57.02	35.22	4.95
24	6/14/25	9.86	102.40	57.02	35.22	4.95





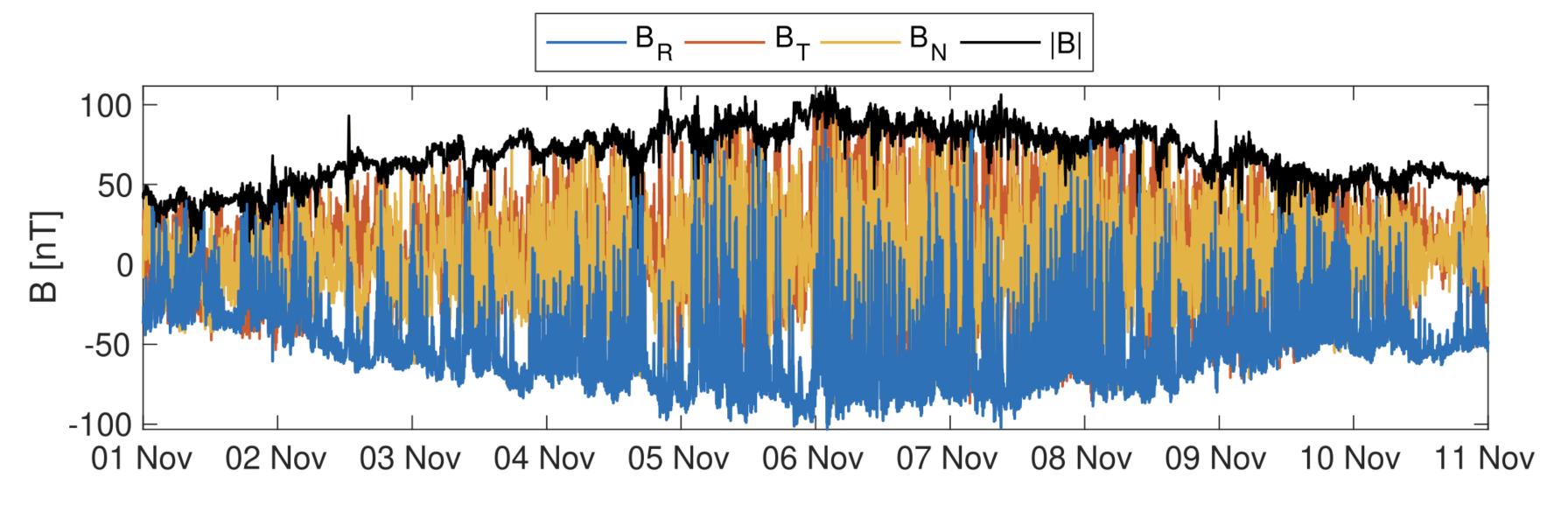


Probe-1st perihelion

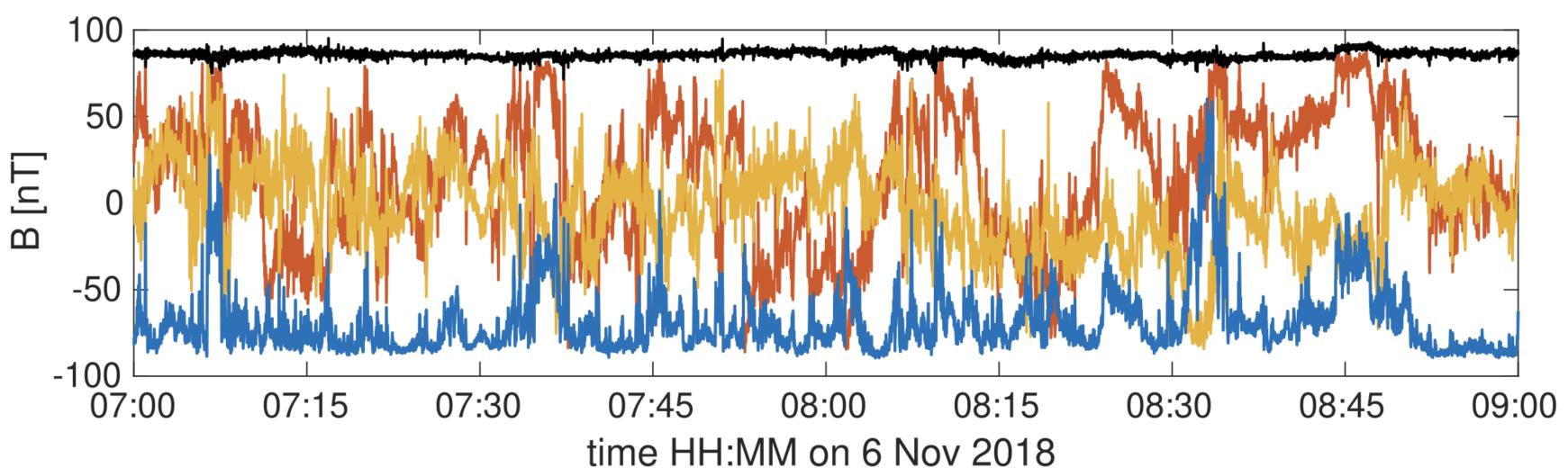


Kasper et al., 2019, Nature, Volume 576, Issue 7786, p.228-231

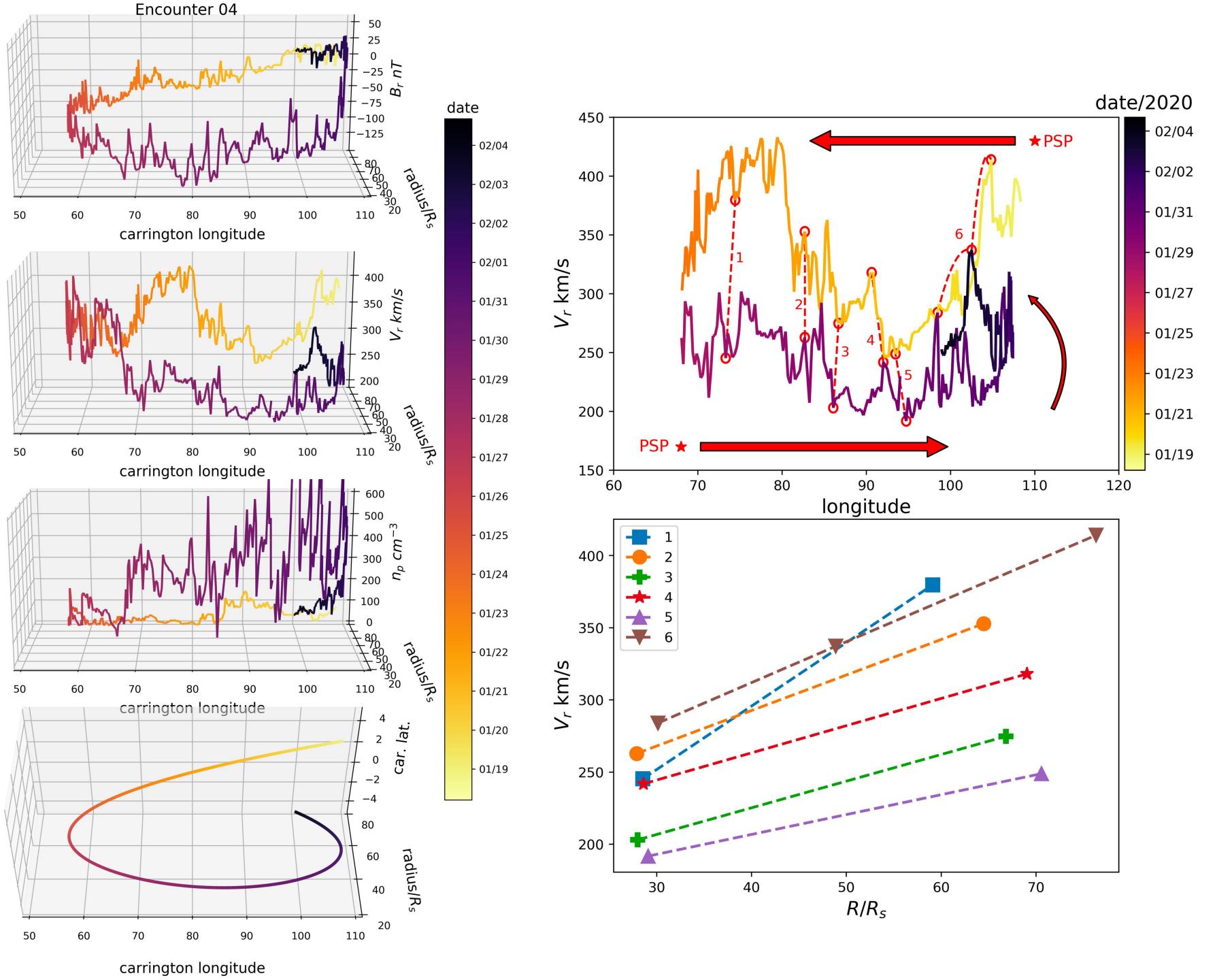
Probe-1st perihelion Magnetic Field



Highly Alfvenic magnetic field 'switchbacks' are ubiquitous in the inner heliosphere and are organized into 'patches' separated by quieter wind (Bale et al., 2019, Dudok de Wit et al., 2020, Horbury et al., 2020, Mozer et al., 2020, Squire et al., 2020 and many more)

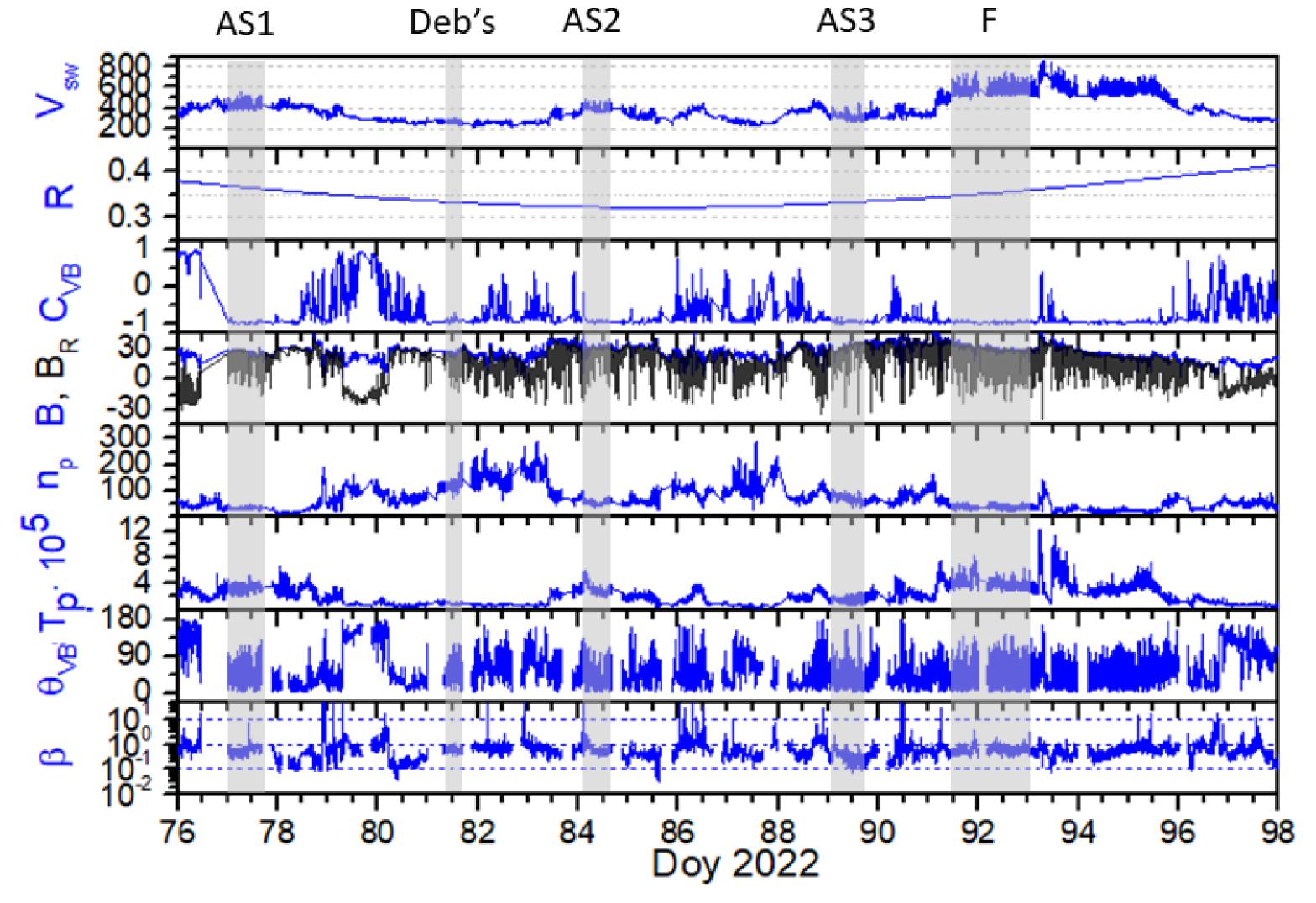


Small, equatorial coronal holes can be a source of solar wind that expands laterally, slowing down, and filling the inner heliosphere (Bale et al., 2019, Nature Panasenco et al. 2019, 2020 ApJS)



Probe Encounter 4 Shi et al 2021

Solar Orbiter observations: first perihelion of the nominal phase



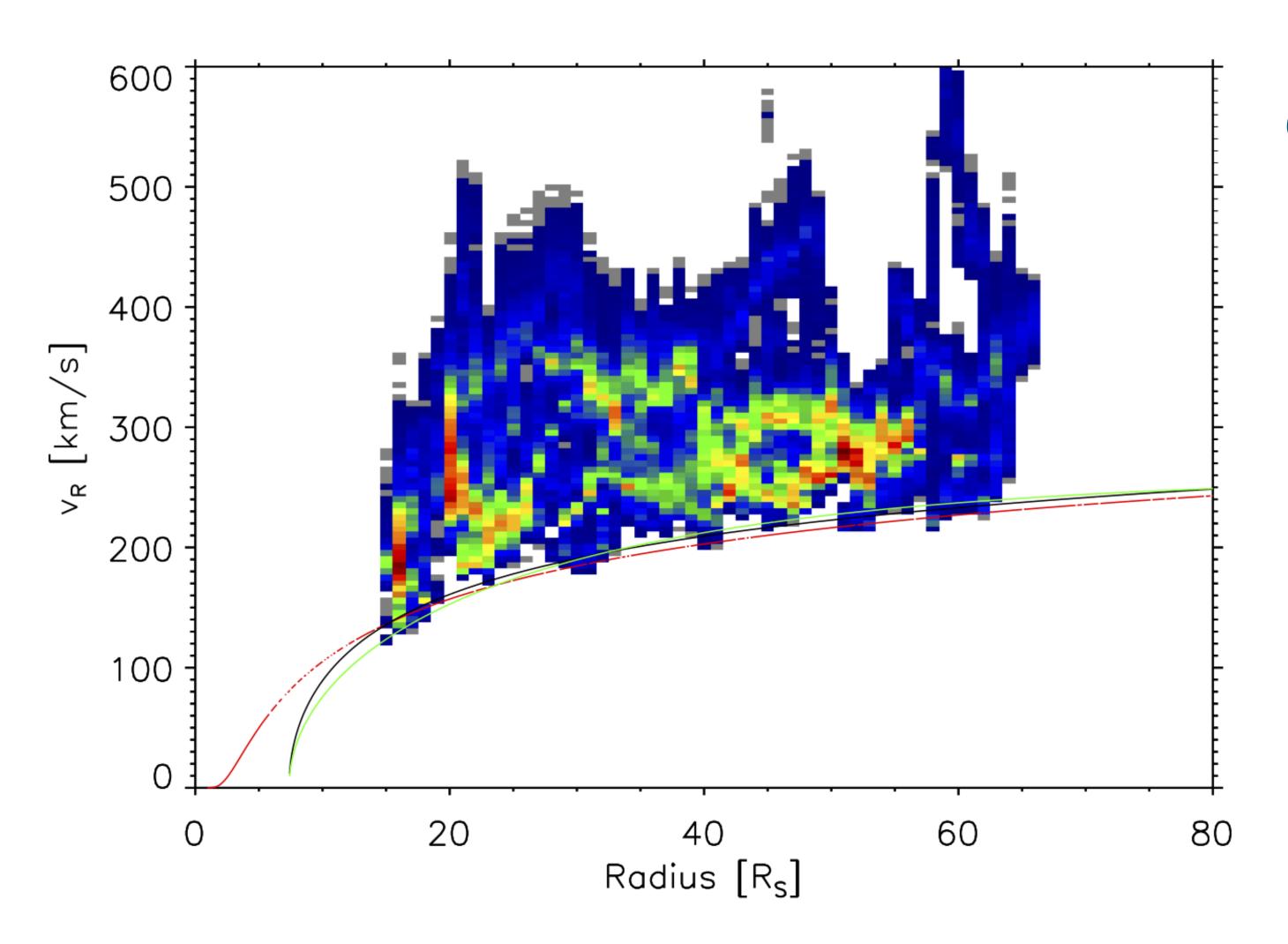
SWA	and	MAG	1.2	data
DVVA	anu	IVIA		uata

	AS 1	AS 2	AS3	FAST
R (AU)	0.366	0.324	0.334	0.353
n (cm ⁻³)	35.4	59.8	69.5	39.8
V (km/s)	417	386	313	572
B (nT)	26.9	31.4	33.4	30.3
10 ⁵ T (K)	3.29	3.20	1.67	4.19
Θ_{VB} (°)	39.3	44.4	41.1	45.4
β	0.576	0.733	0.376	0.652

- Different bulk speeds
- Different number densities
- Similar magnetic field magnitudes and v-b angles
- β<1

17/03 19/03 21/03 23/03 25/03 27/03 29/03 31/03 02/04 04/04 06/04 08/04

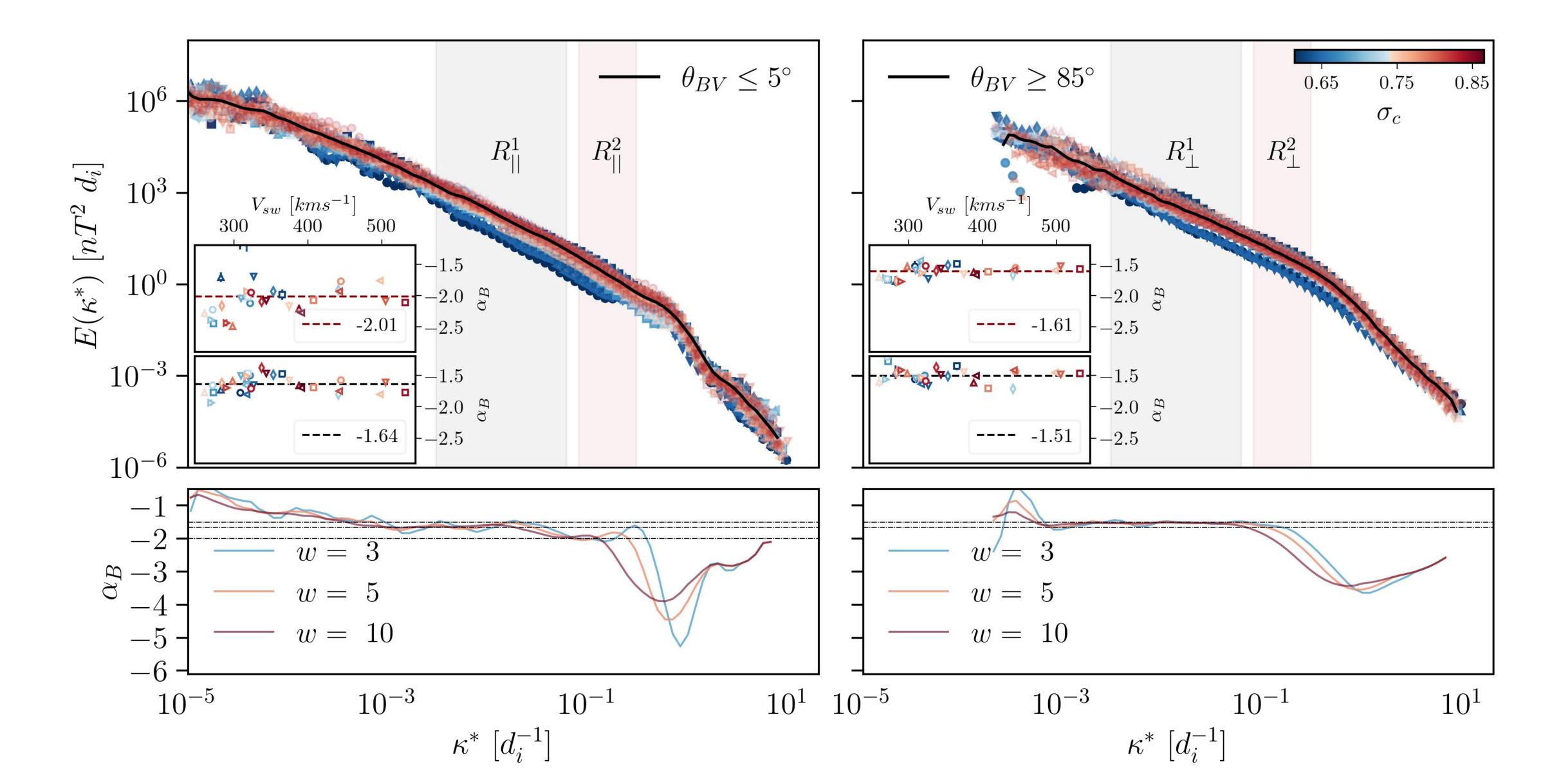
(D'Amicis et al, in preparation)

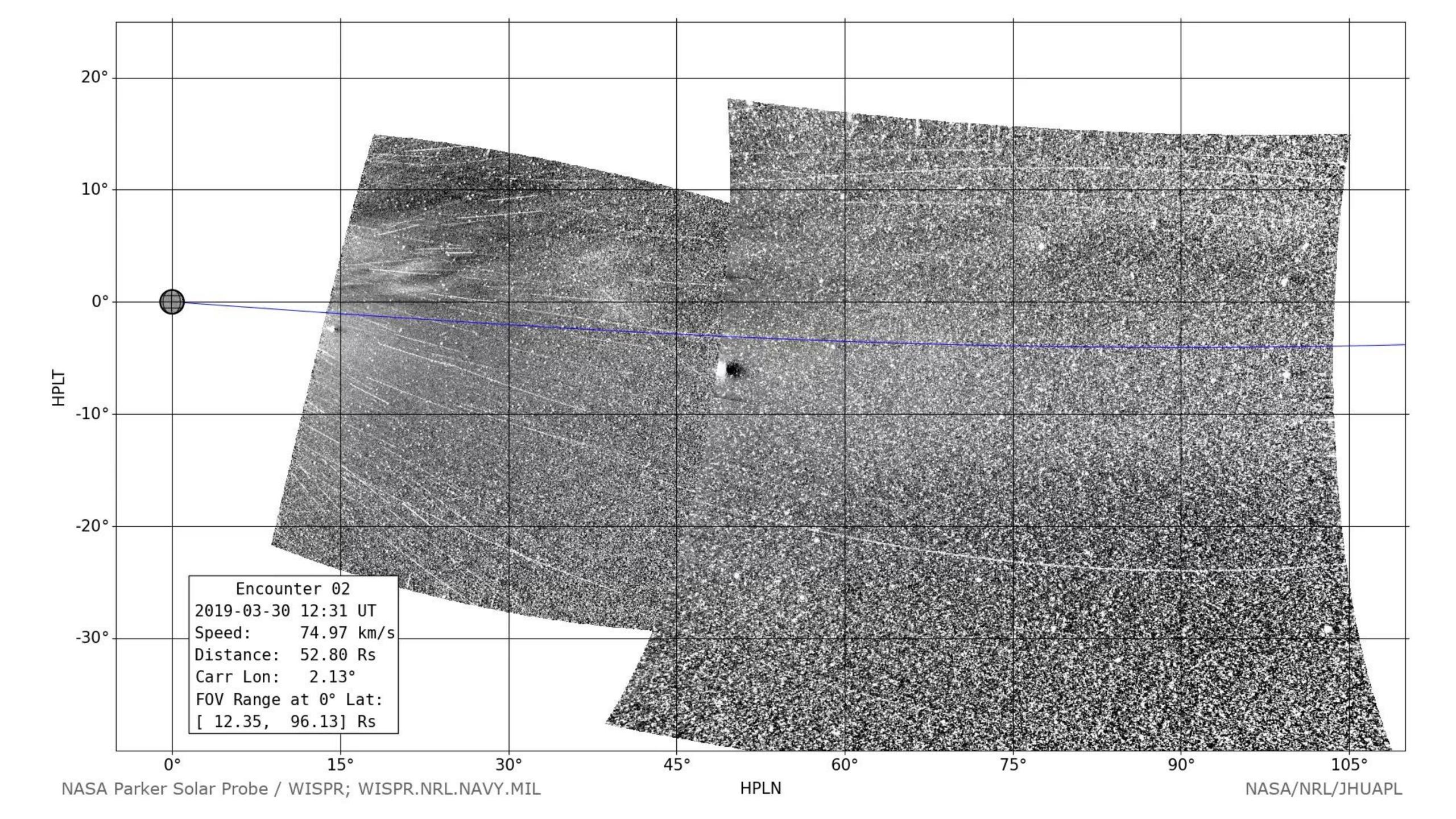


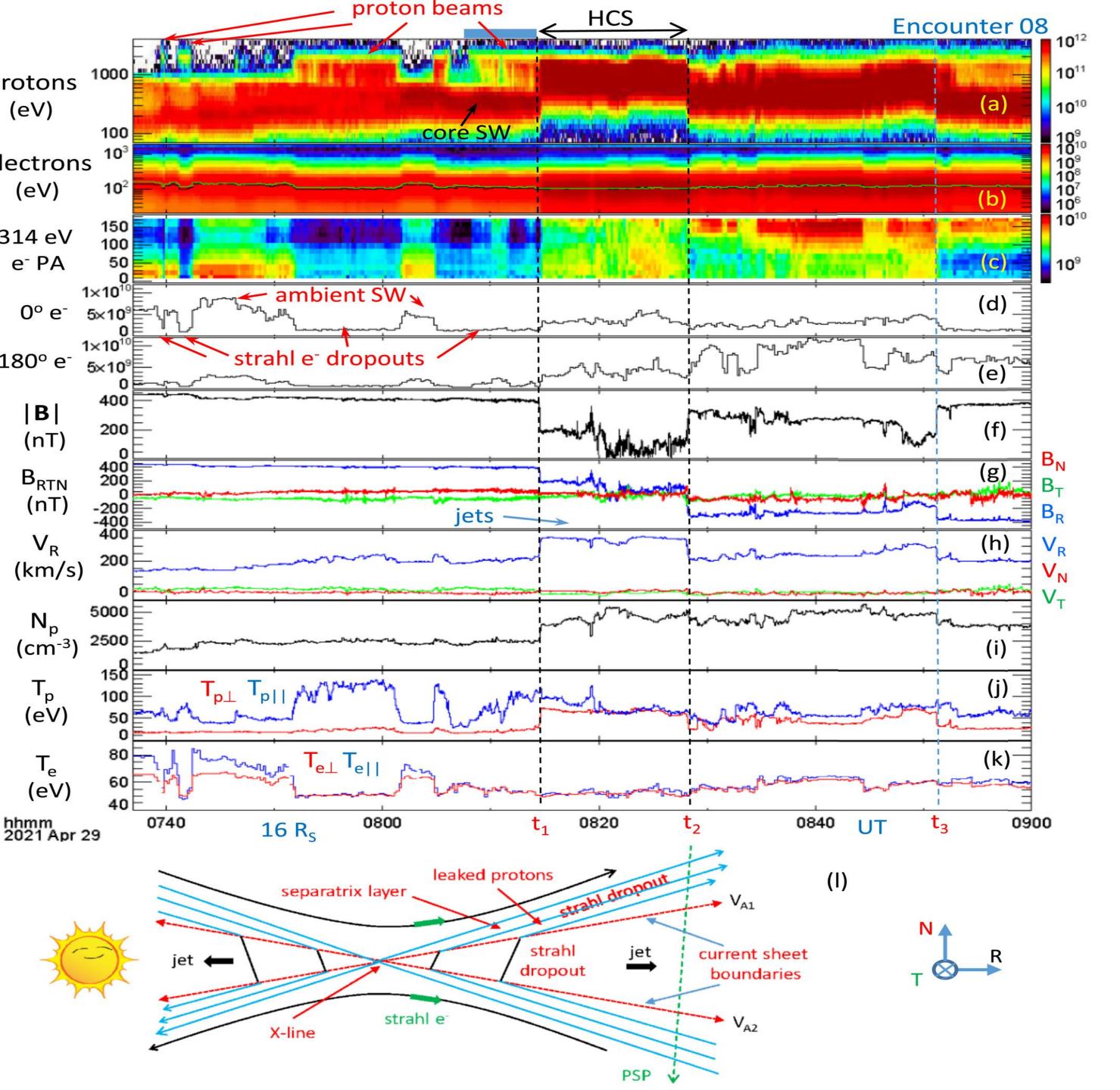
Overall Solar Wind Outflow

The solar wind is structured as a 'baseline' Parker-like wind beneath smaller-scale microstreams that emerge from supergranulation cell boundaries (Bale et al., 2021, Bale et al., 2022)

Solar Wind Turbulent Spectra

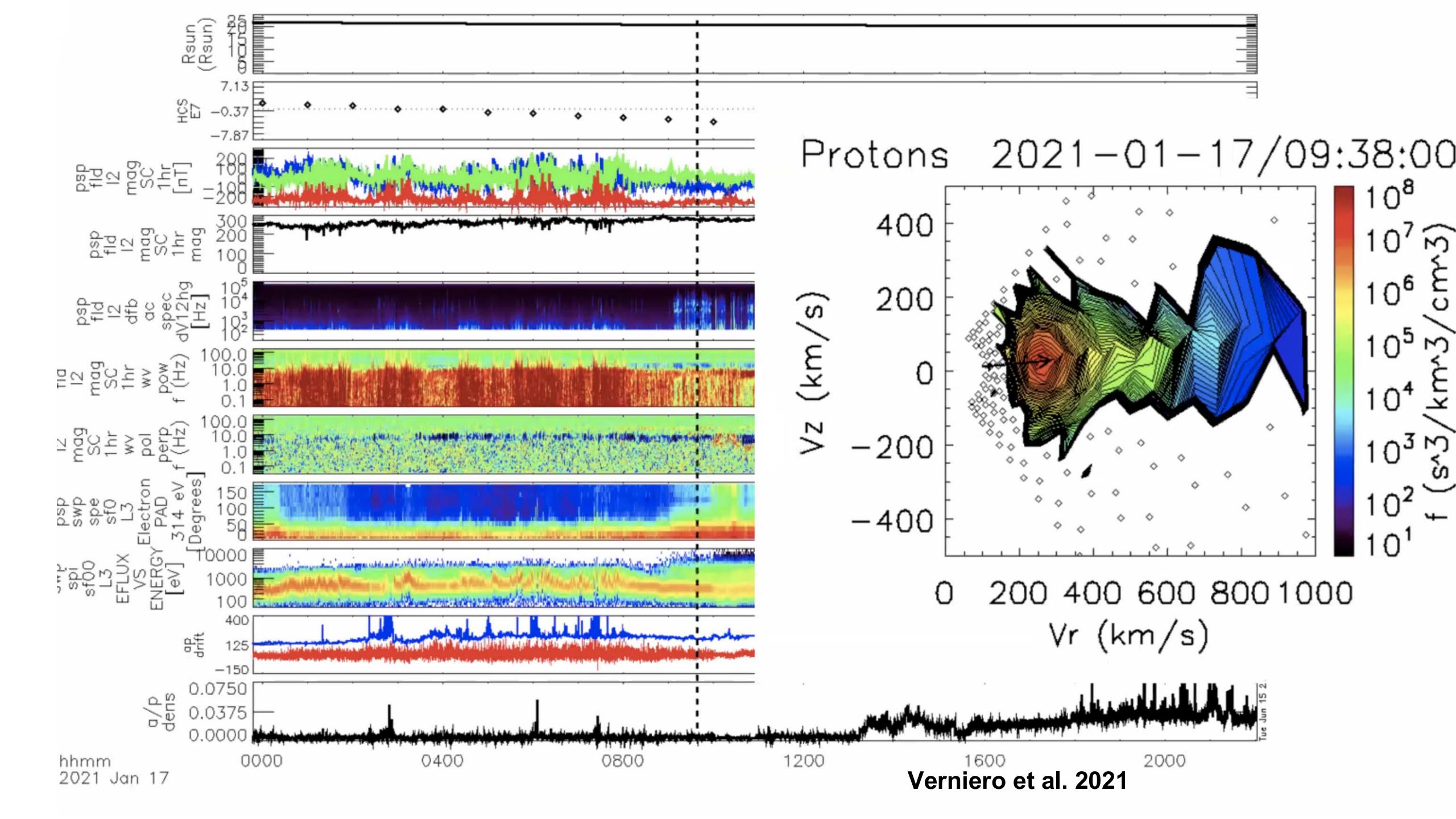




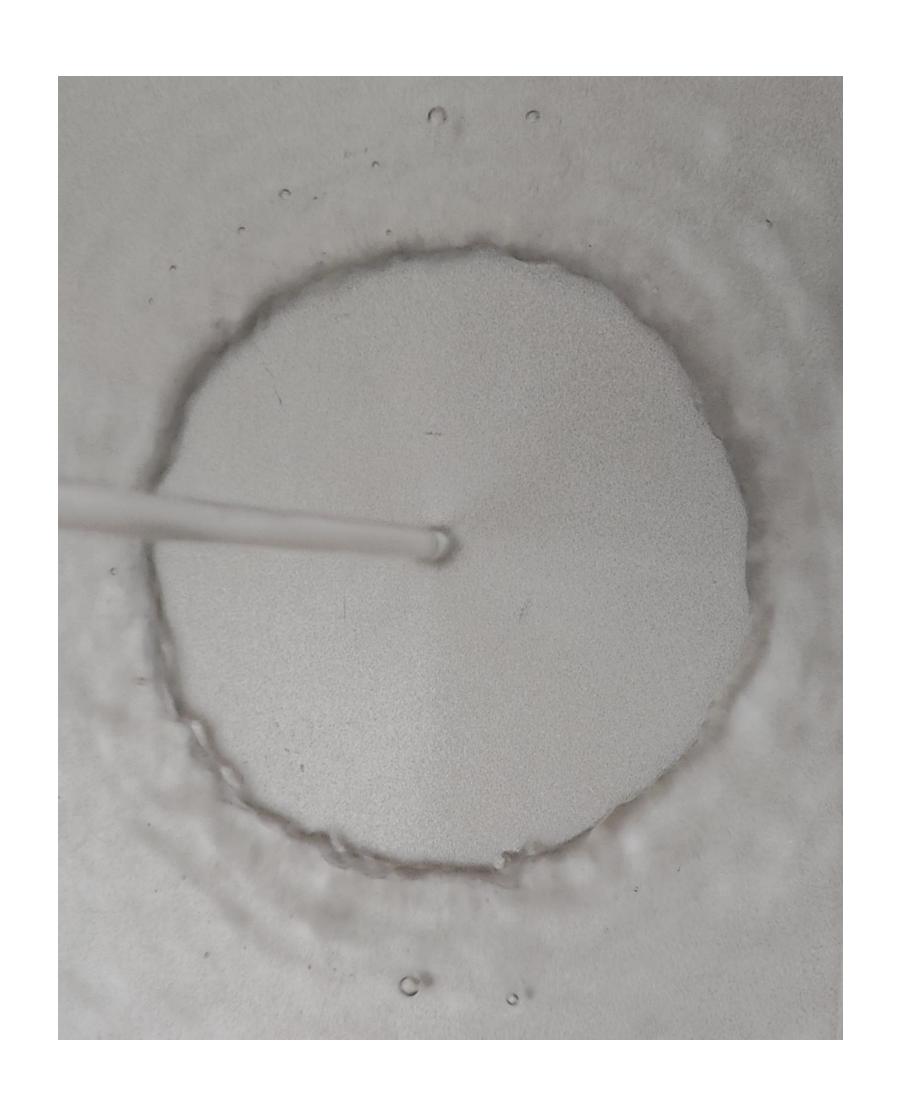


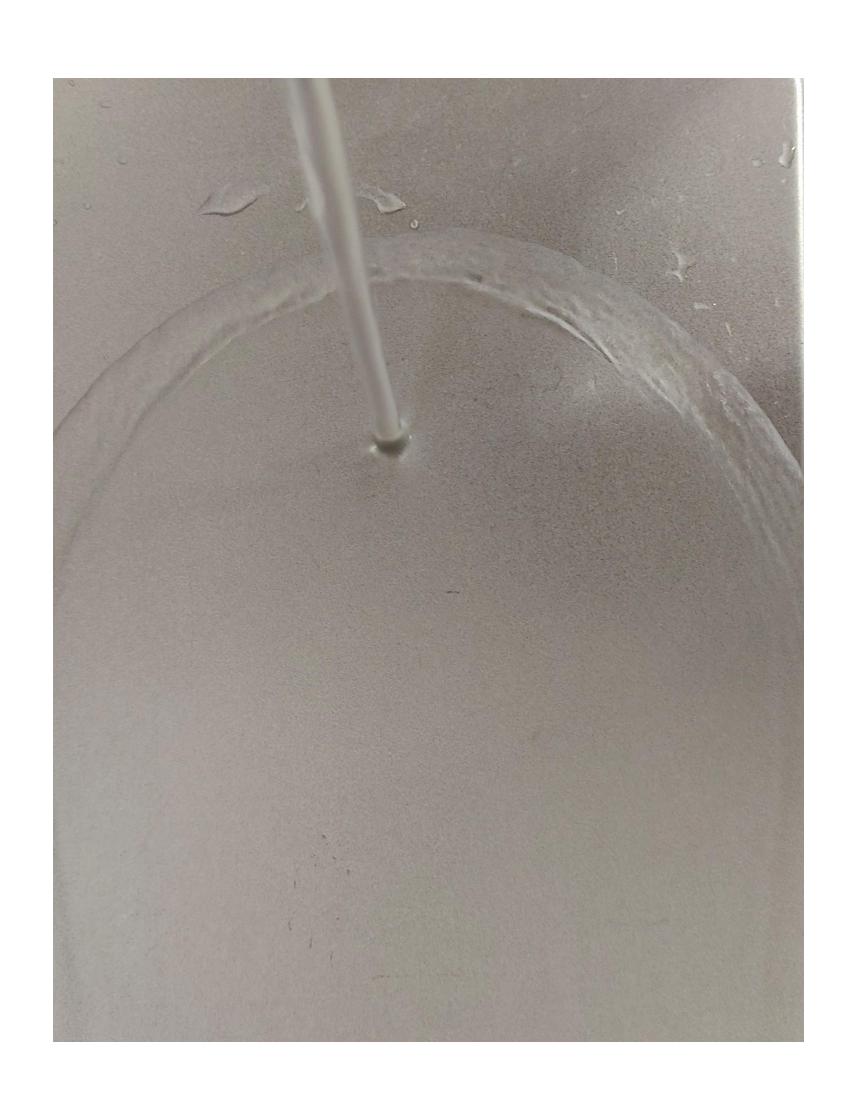
Magnetic
Reconnection seen
in the Solar Wind
Heliospheric
Current Sheet

Phan et al. 2022

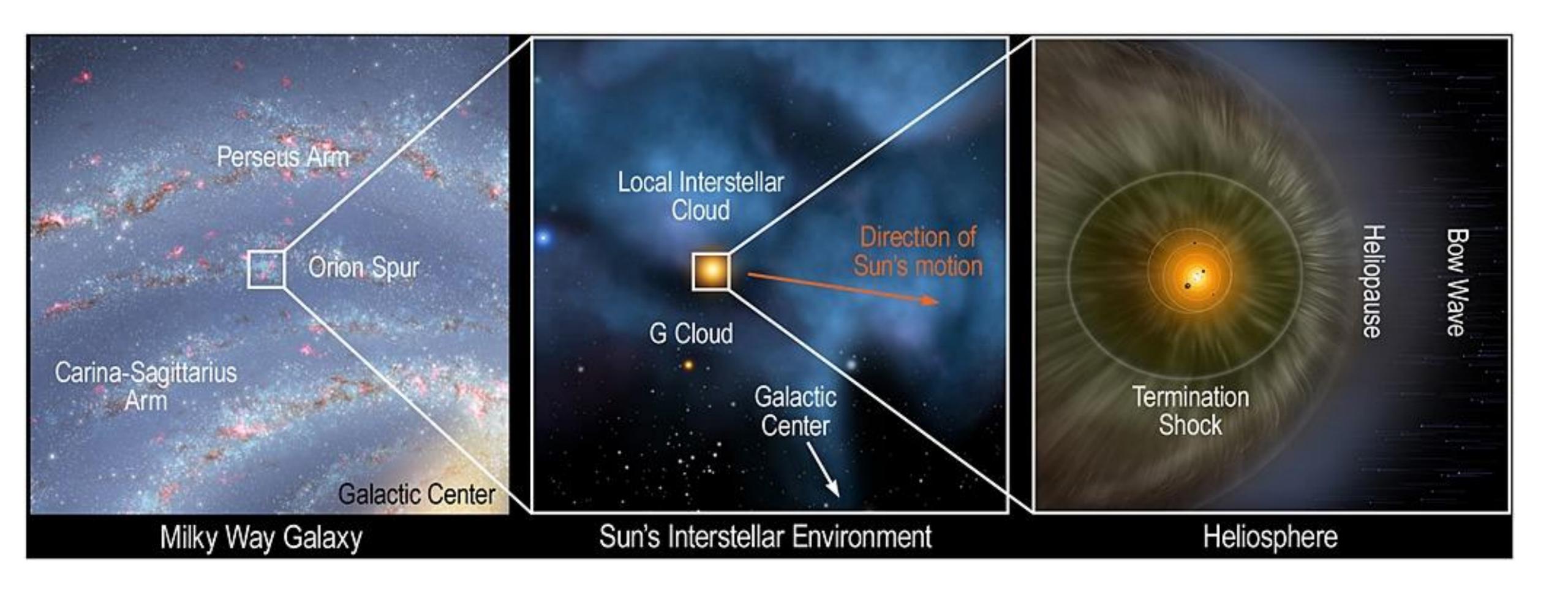


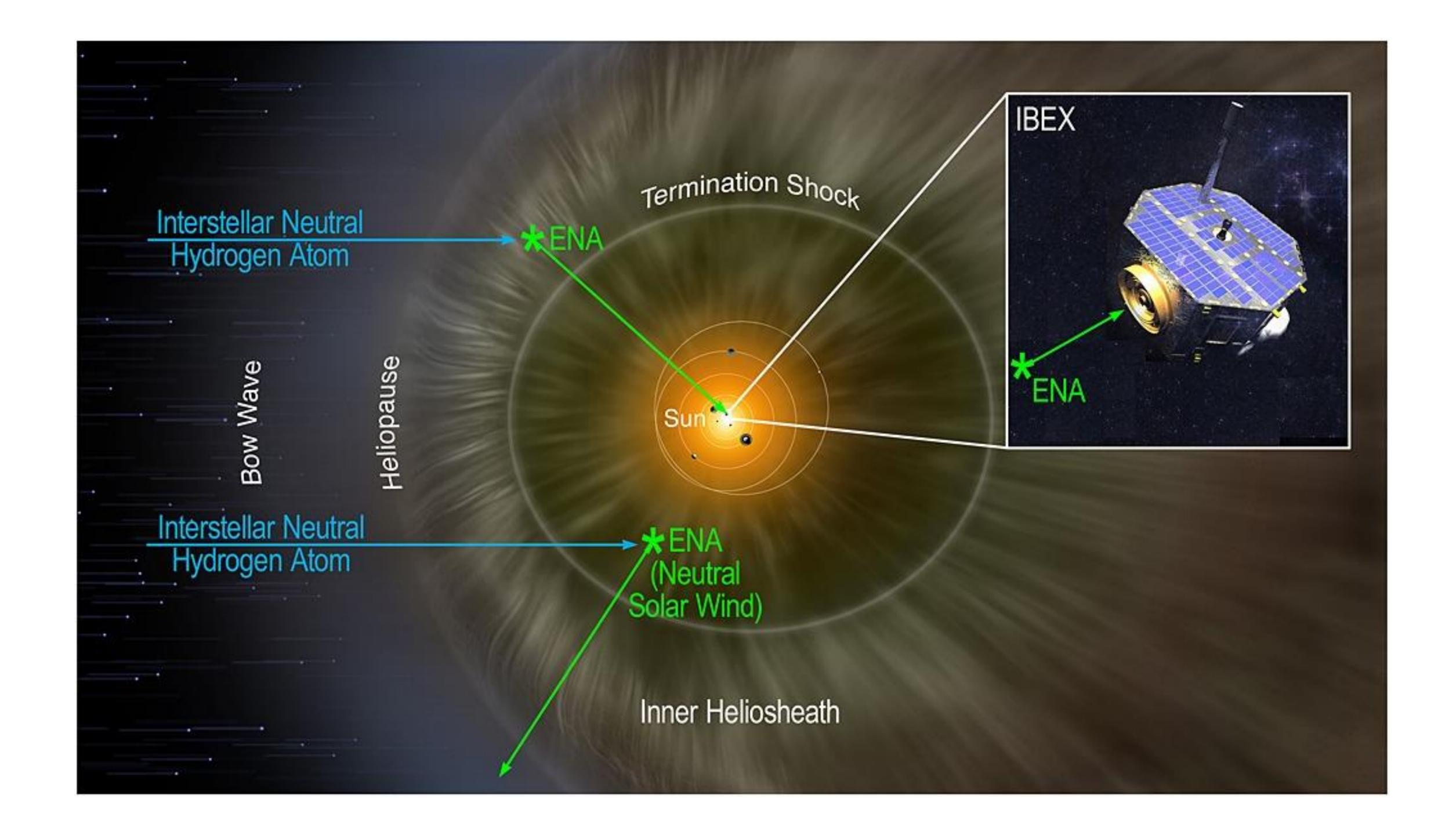
How does the Heliosphere end?





How does the Heliosphere end?



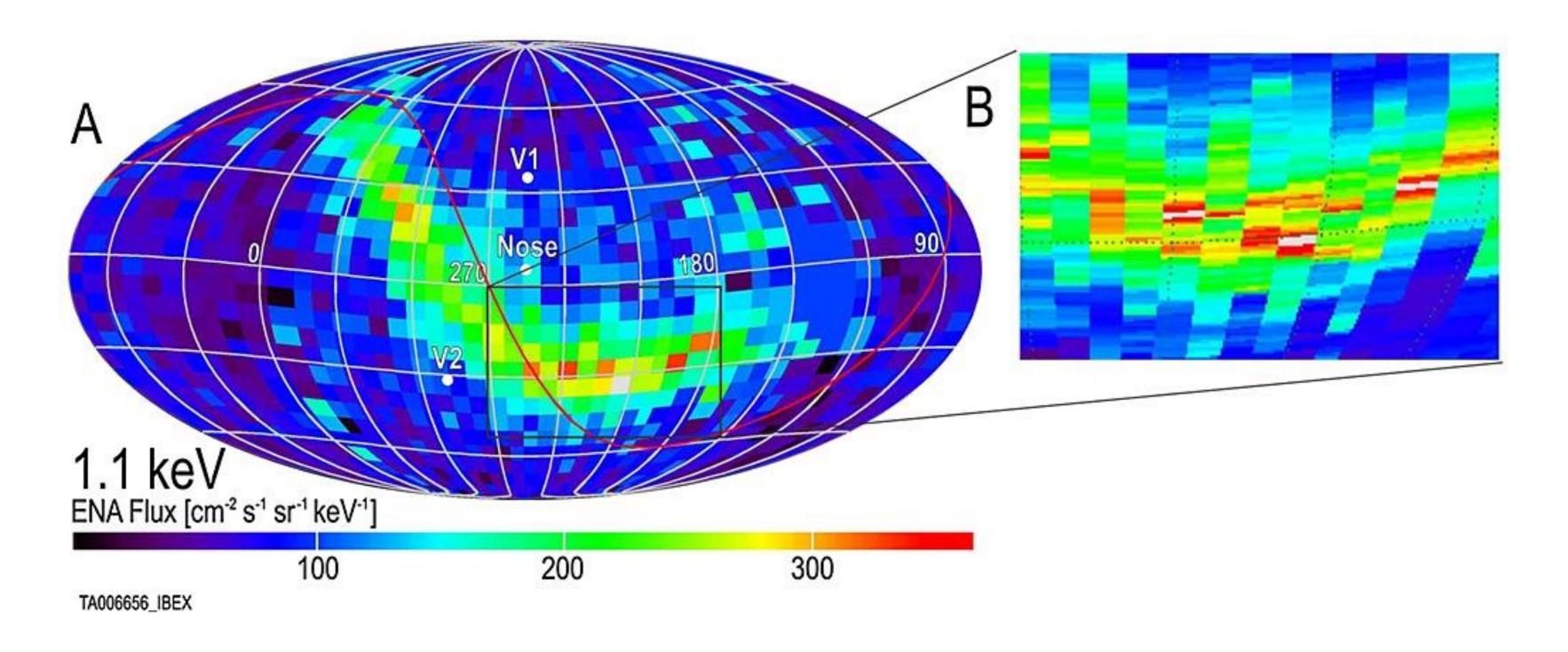


Reasonable LISM plasma parameters indicate that the LISM flow may be either marginally super-fast magnetosonic or sub-fast magnetosonic.

Because the Mach number is only barely super-fast magnetosonic in the $3\mu G$ case, the hot and fast neutral H can completely mediate the transition and impose a charge exchange length scale on the structure, making the solar-wind-LISM interaction effectively bow-shock-free.

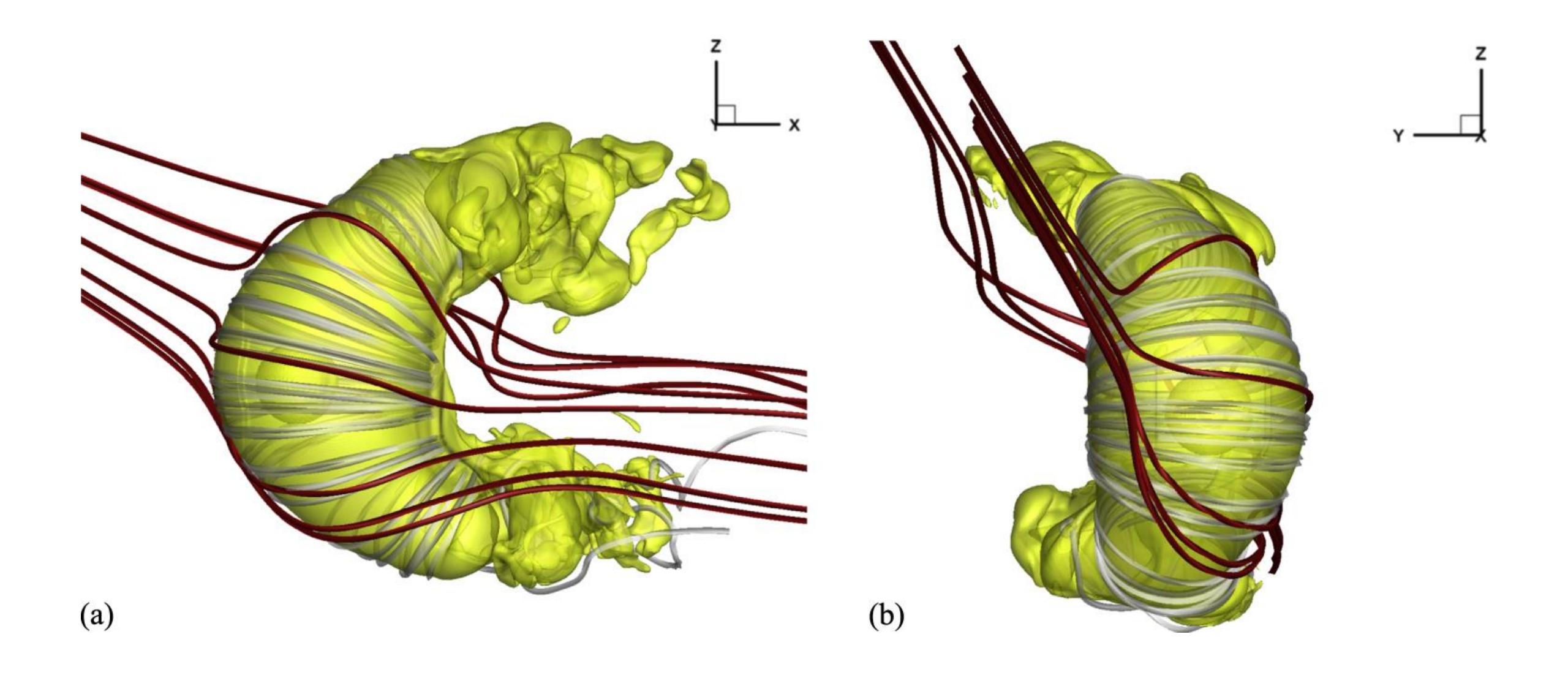
The charge exchange of fast and hot heliospheric neutral H therefore provides a primary dissipation mechanism at the weak heliospheric bow shock, in some cases effectively creating a one-shock heliosphere (i.e., a heliospheric termination shock only).

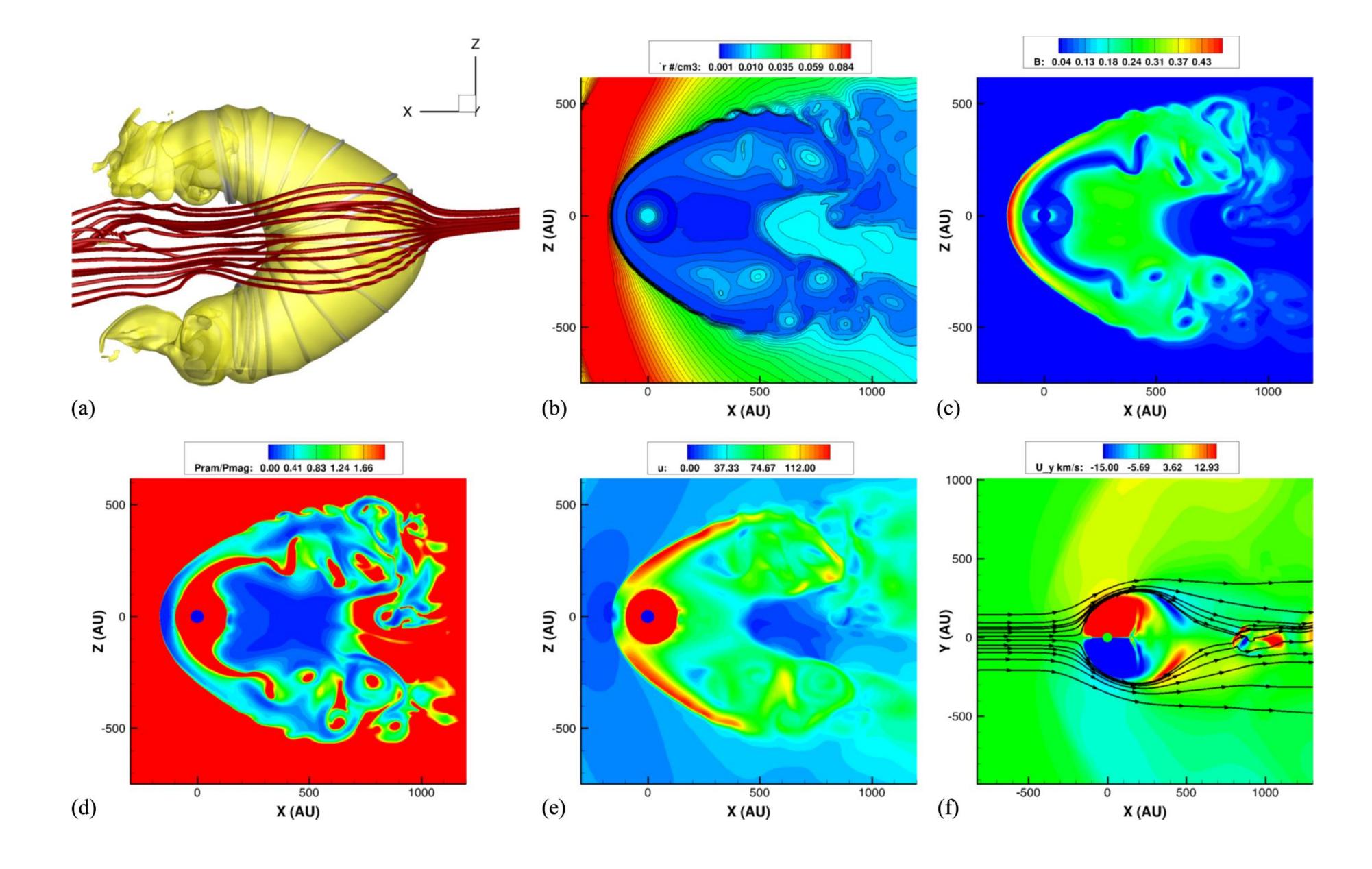
(Zank et al. 2013)



The ribbon is formed by the secondary ENA mechanism. ENAs created in the outward-propagating solar wind (SW) or from the inner heliosheath (IHS) exit the heliosphere into the denser local interstellar medium (LISM). These ENAs eventually charge exchange with interstellar ions, producing pickup ions (PUIs) that gyrate around the ISMF lines. The PUIs will neutralize again after a period of time depending on the PUI energy and the local neutral density, and they may travel back into the heliosphere. Due to their long mean free paths inside the heliosphere, some of these "secondary" ENAs can travel close to the Sun and be observed by IBEX. The ribbon, therefore, is likely formed from secondary ENAs whose intensity is greatest where the observer's line of sight (r) is approximately perpendicular to the ISMF (B) draped around the heliosphere, i.e., $B \cdot r = 0$. The $B \cdot r = 0$ plane is warped as a function of distance from the heliopause by the draping of the ISMF around the heliosphere (Pogorelov et al. 2011), forming a complex, 3D structure of the ribbon source region as a function of ENA energy (Zirnstein et al. 2015).

Overall Shape of the Heliosphere, Opher et al. 2020





To be continued.....

Fluids and Plasmas, MHD, Turbulence