Plasma Unbound:
New Insights into Heating the Solar Corona and Accelerating the Solar Wind

Steven R. Cranmer . . . . . *University of Colorado Boulder, APS & LASP*

A. Schiff, S. Van Kooten, C. Gilbert, M. Molnar, A. Lattimer, L. Woolsey, A. van Ballegooijen, S. Owocki, J. Kohl, C. DeForest, A. Caspi, S. Gibson, A. Kowalski, M. MacGregor, A. Winebarger

Outline

1. Brief history & motivation
2. "The problems" (coronal heating & the solar wind)
3. New ideas under development
    - Applicability & practical importance
    - To test theories, we need *DATA*
4. The future . . .

Outline

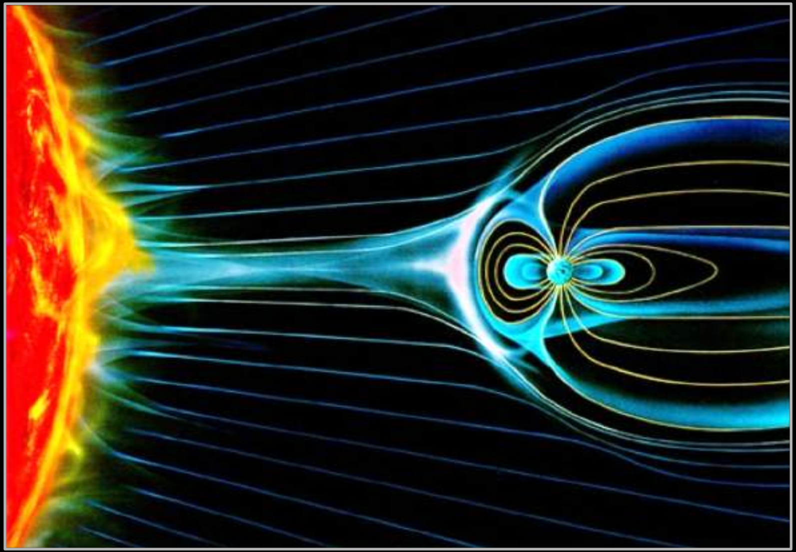
1. Brief history & motivation
2. "The problems" (coronal heating & the solar wind)
3. New ideas under development
   - Applicability & practical importance
   - To test theories, we need *DATA*
4. The future . . .

Why do we care?

- Stellar coronae (X-rays, UV) and winds (gas outflow) affect how stars & galaxies evolve… from pre-main-sequence accretion to post-main-sequence "death" & mass recycling.

- Consequently, they affect the formation & habitability of **planets,** too.

- In our own solar system, "space weather" affects satellites, power grids, pipelines, and safety of astronauts & high-altitude airline crews.



- If you can understand how plasmas behave in turbulent, expanding stellar atmospheres, you'll have a superb grounding in many fields.

Image credit: Miloslav Druckmüller

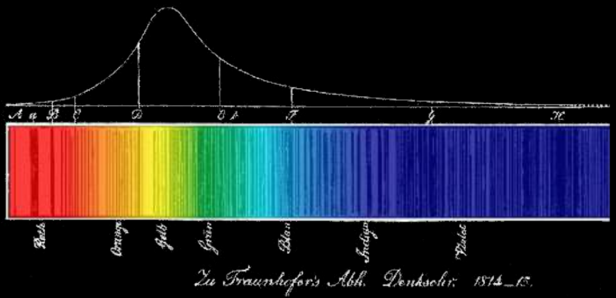
The solar corona: beginning & end?

The solar corona

- 1706: Giovanni Cassini first describes a total solar eclipse as *"une couronne d'une lumière pâle."*

- 1860s: Janssen & Lockyer begin applying the new science of **spectroscopy** to solar eclipses.

- Three major discoveries:

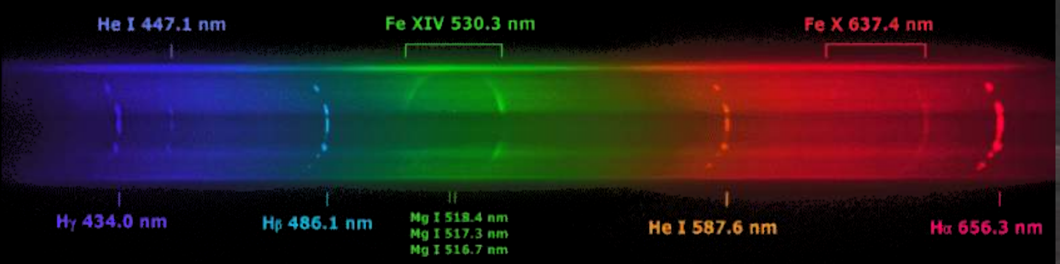


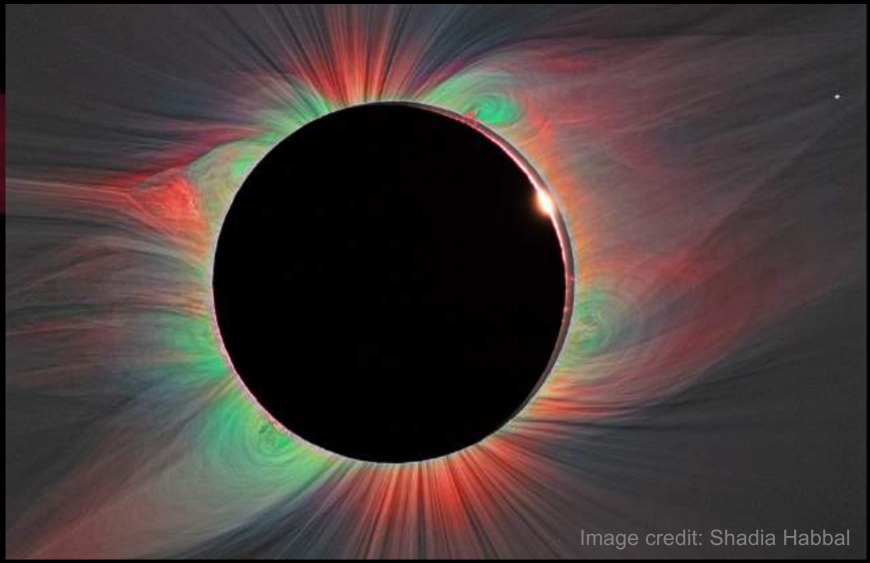
1. Near the Sun, the coronal spectrum contains Fraunhofer's absorption lines. The corona is part of the **Sun,** not the Moon!

2. In prominences, the sodium "doublet" is really a triplet! That extra line is due to **helium,** which Janssen & Lockyer discovered more than 20 years prior to chemists isolating helium from cleveite ore.

The solar corona

3. Further out in the corona, the Fraunhofer lines faded away & gave rise to emission lines... some unknown. **("Coronium?")**



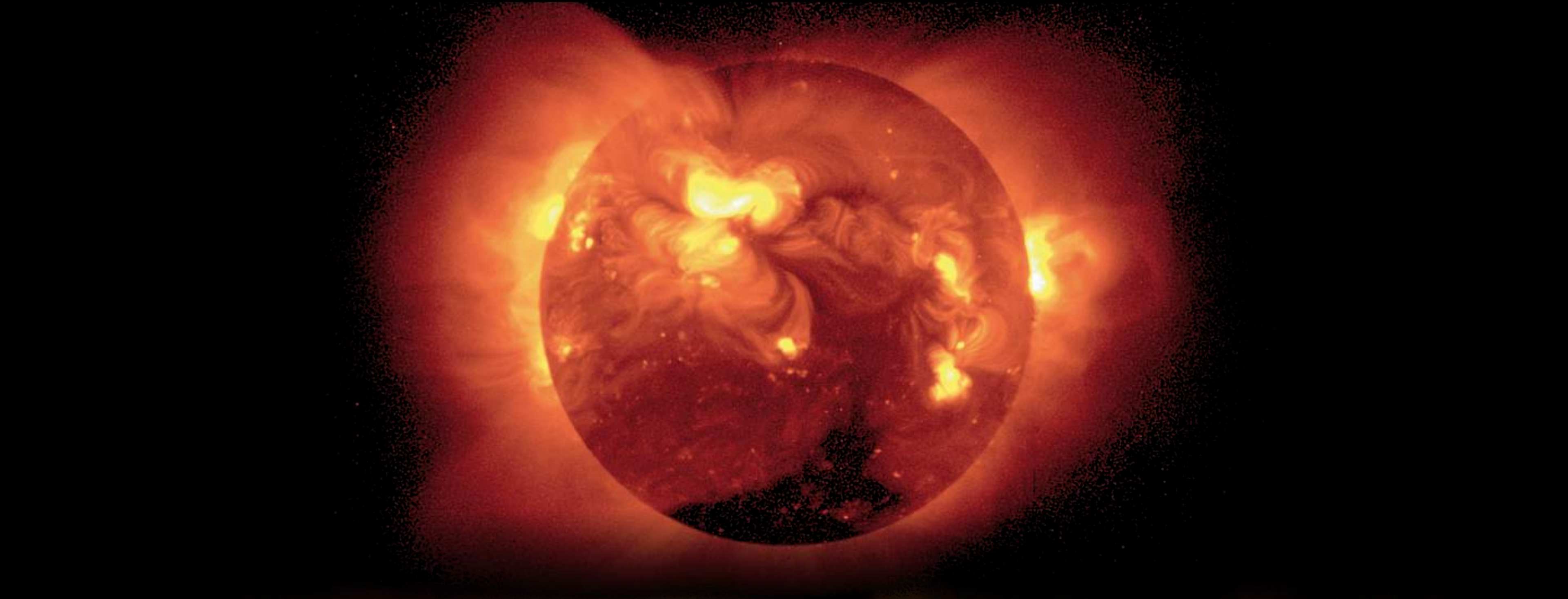
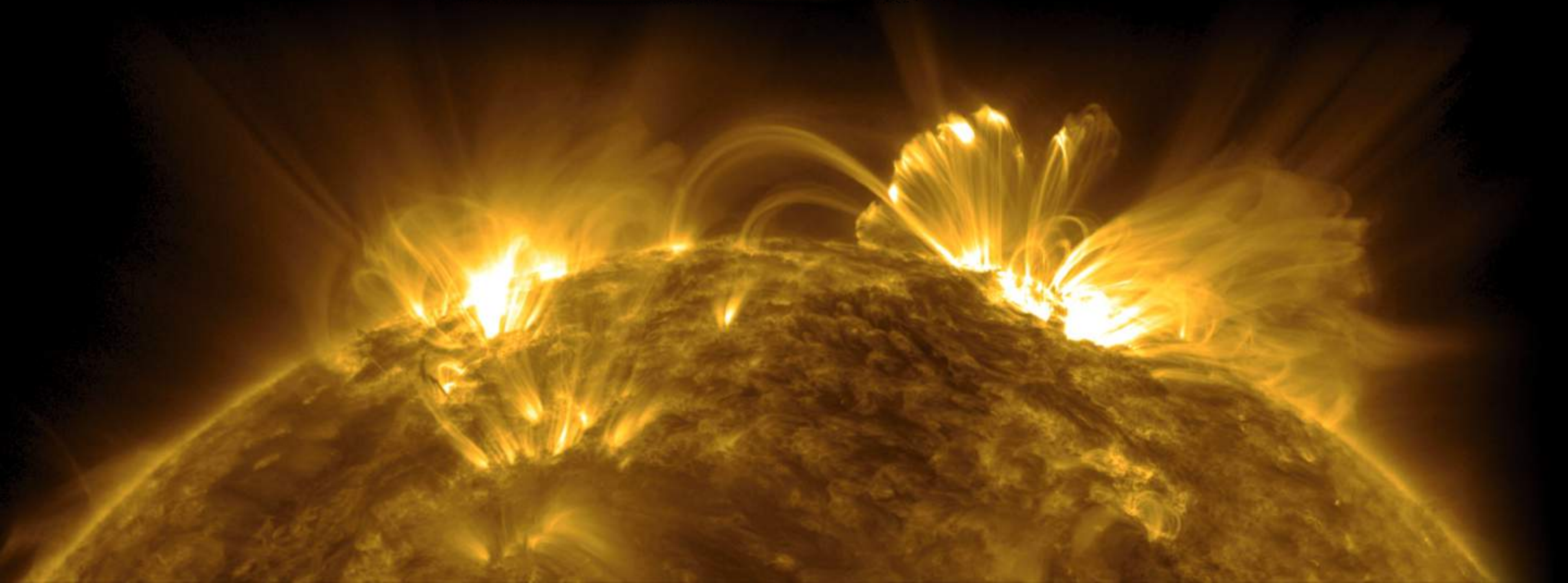


green line at 530.3 nm = Fe XIV

red line at 637.4 nm = Fe X

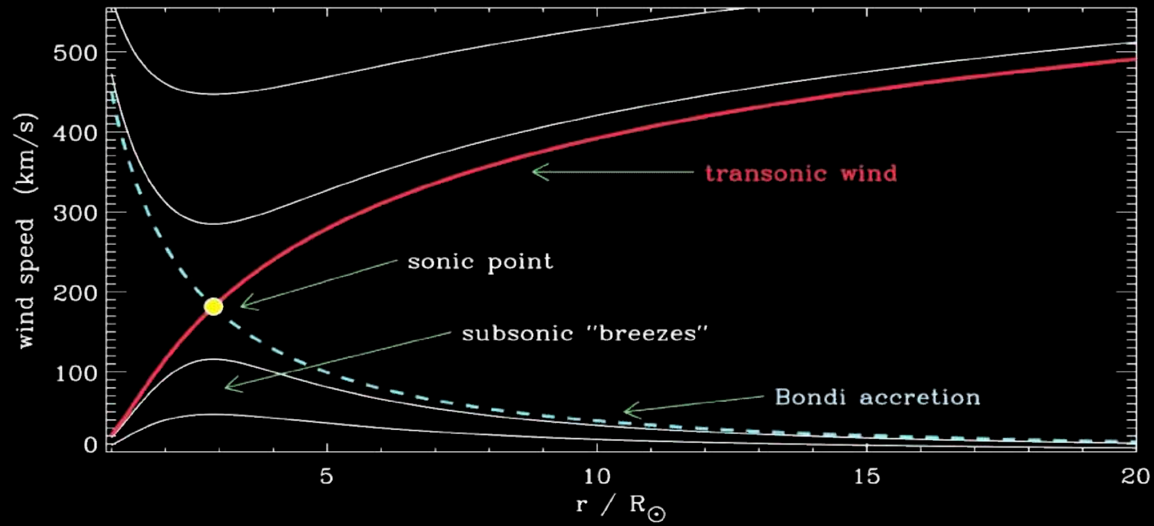
yellow line at 569.4 nm = Ca XV

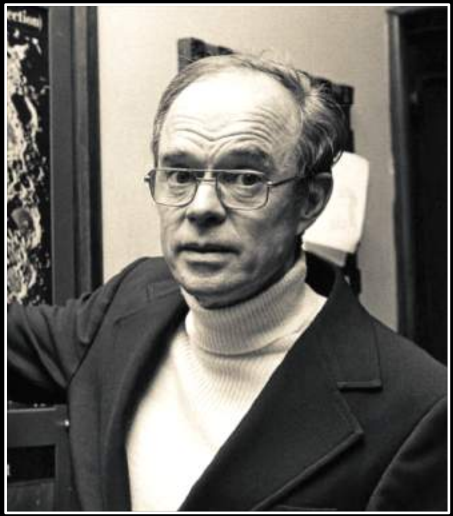
- Late 1930s: Grotrian, Edlén, & Alfvén realized these were lines formed by ions that can only exist at **$T > 1$ million K.** The corona is hot!
- After WWII, rockets & satellites began observing the Sun in UV & X-rays...

The solar wind: prediction & discovery

- 1958: Gene Parker proposed the hot corona has such a high **gas pressure** that it naturally expands as a steady outflow…

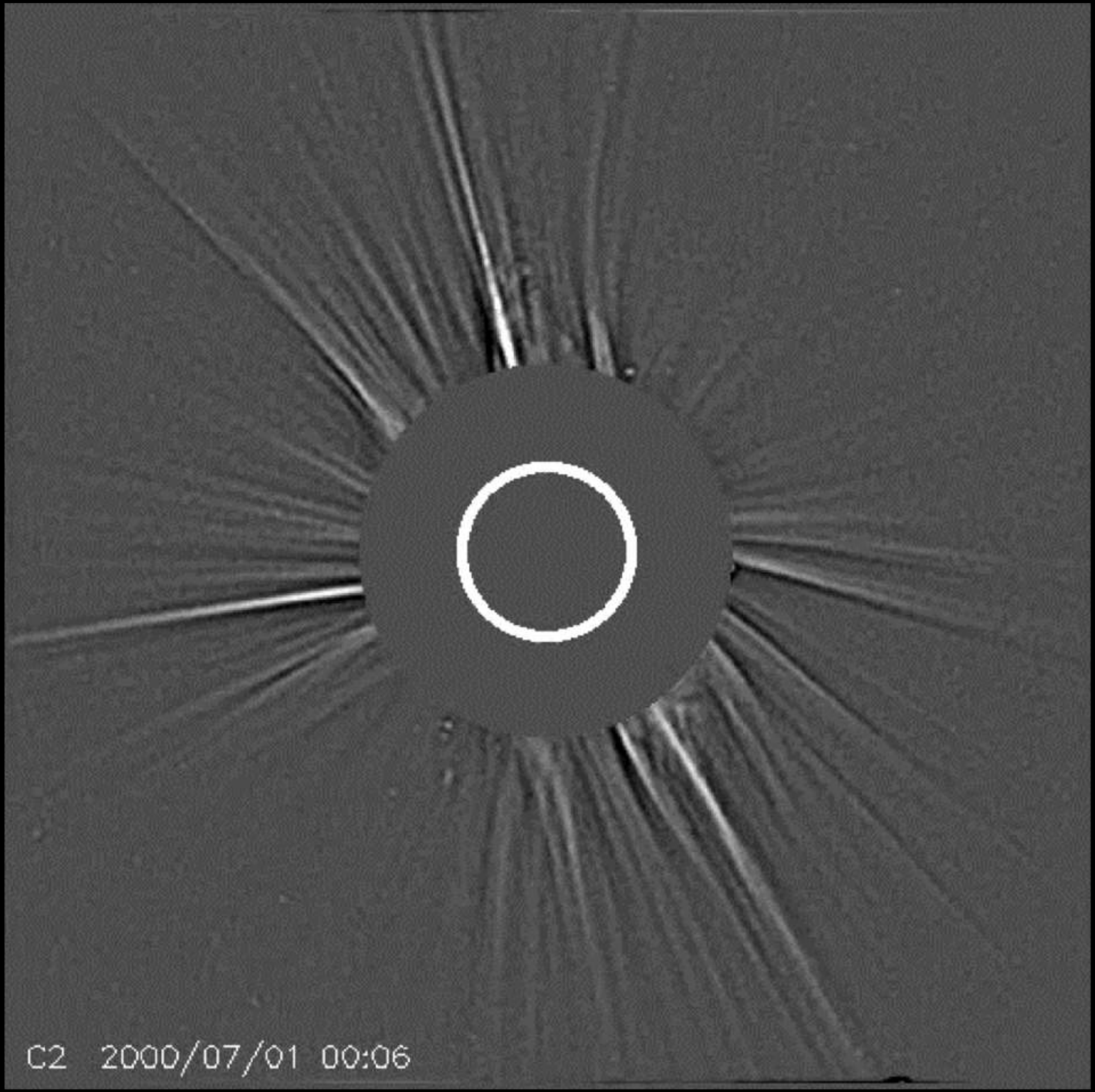




- 1959-1961: Intermittent detections: Russian *Lunik, Venera;* American *Explorer 10.*
- 1962: Marcia Neugebauer & colleagues got **continuous** data from *Mariner 2* on its journey to Venus.
- The corona essentially fills the solar system!

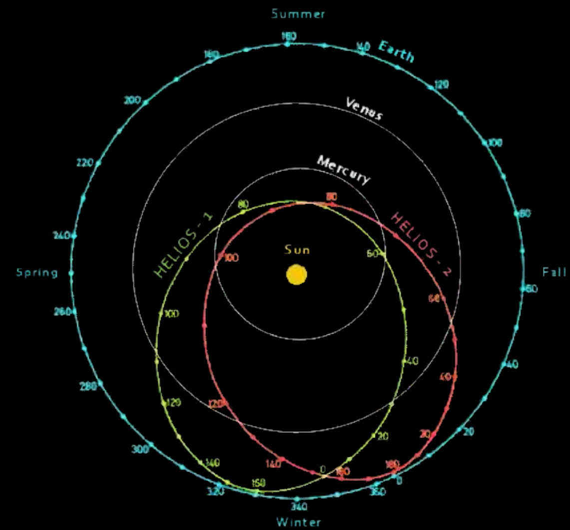
The solar wind

- It's observable with a **coronagraph** (i.e., a telescope with an occulter to generate an "artificial eclipse").
- LASCO coronagraph on *SOHO* has been operating since 1996…
- Images processed with wavelet filtering to enhance outflowing structures (Stenborg & Cobelli 2003).

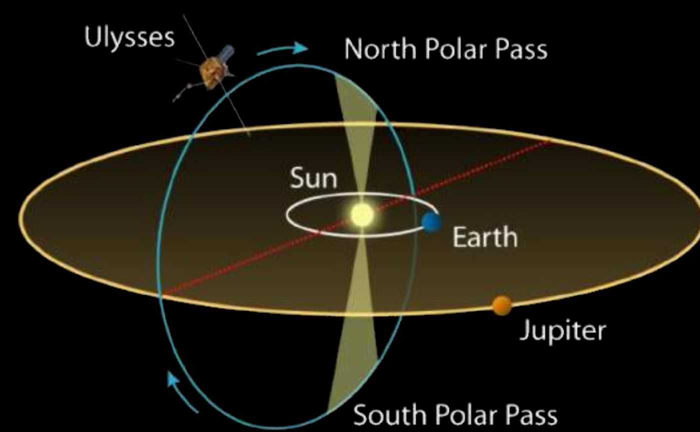


The solar wind

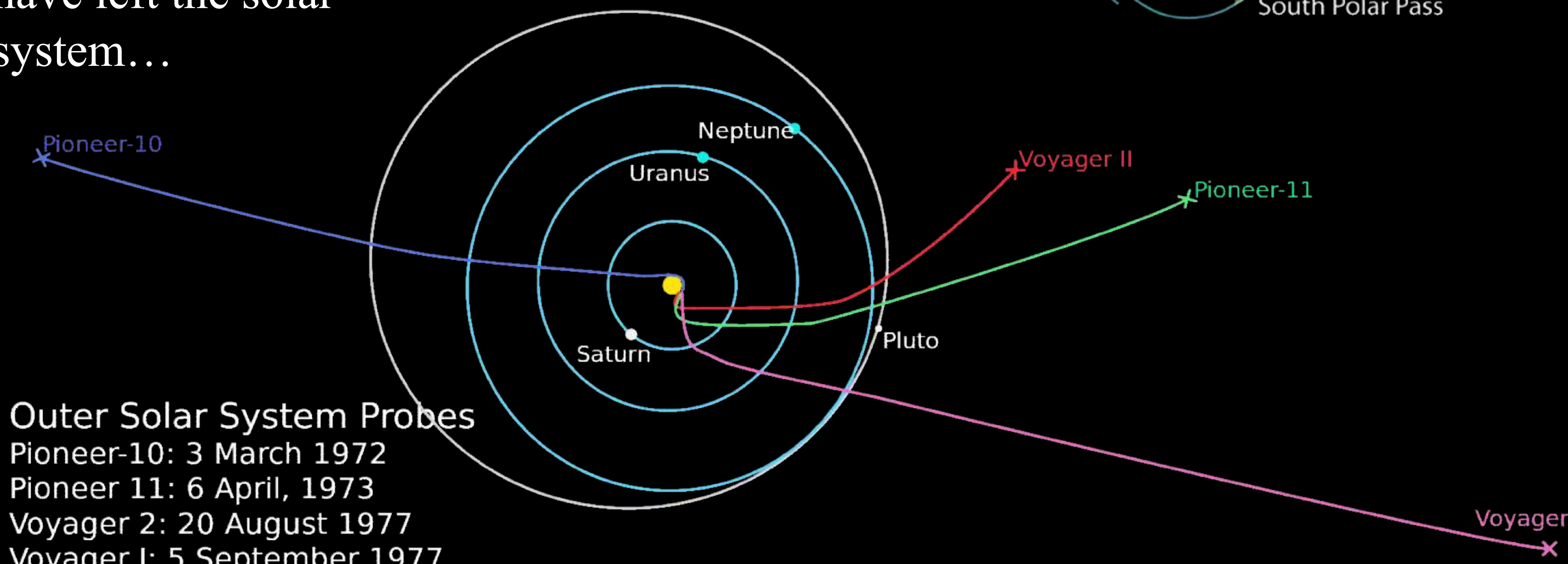
Helios probes went in past Mercury's orbit



Ulysses went up & out of the ecliptic plane



Voyagers & Pioneers have left the solar system…



Outline

1. Brief history & motivation

2. "The problems" (coronal heating & the solar wind)

3. New ideas under development

   - Applicability & practical importance

   - To test theories, we need *DATA*

4. The future . . .

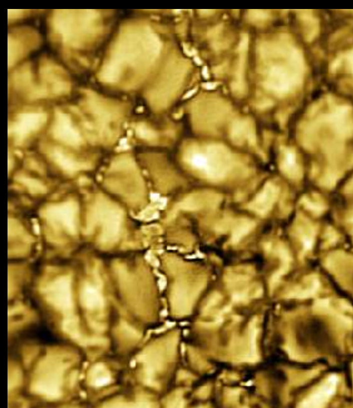
Outline

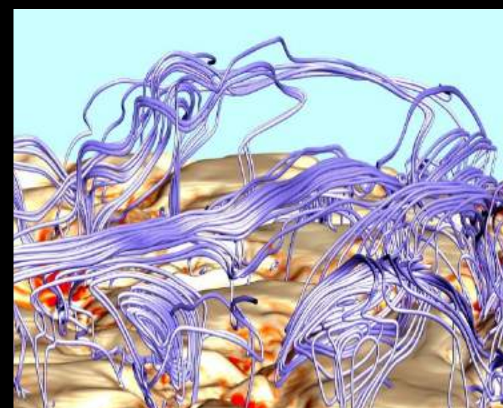
1. Brief history & motivation
2. "The problems" (coronal heating & the solar wind)
3. New ideas under development
    - Applicability & practical importance
    - To test theories, we need *DATA*
4. The future . . .

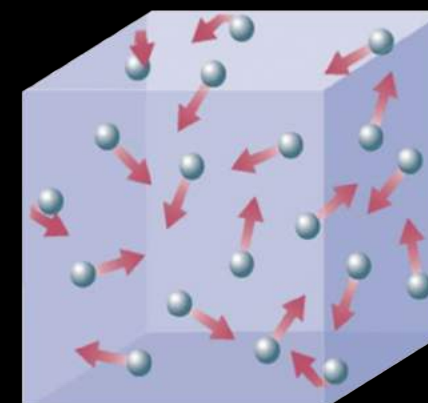
The "coronal heating problem"

- Why is the corona's $T \approx 1$ million K, when underlying atmosphere is ~6000 K ?
- The first few steps of energy flow are reasonably well understood...

kinetic energy | **magnetic energy** | **thermal energy**





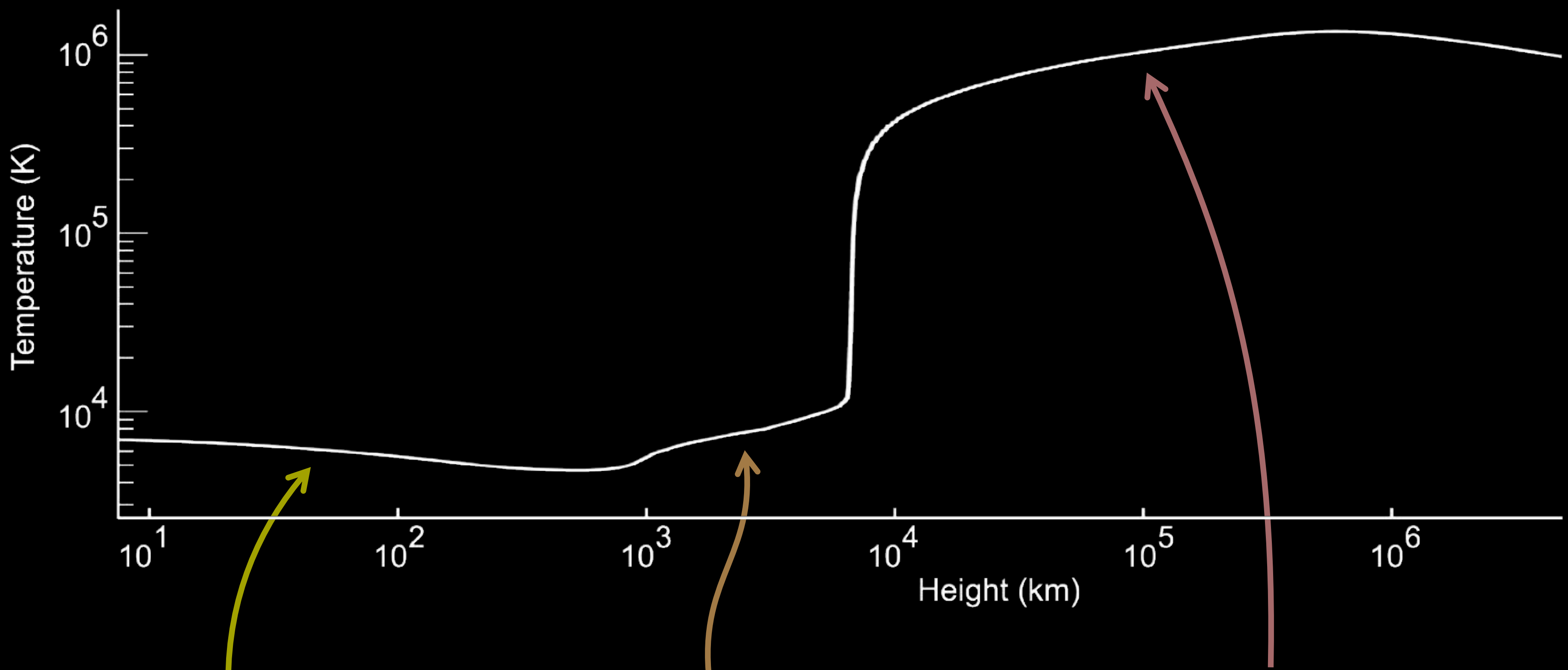


$F \sim$ **500** kW/m^2 | $F \sim$ **5 → 50** kW/m^2 | $F \sim$ **0.3 → 10** kW/m^2

(Van Kooten & Cranmer 2017)

(Kazachenko et al. 2014, 2015)

Also, a corona is kind of inevitable...



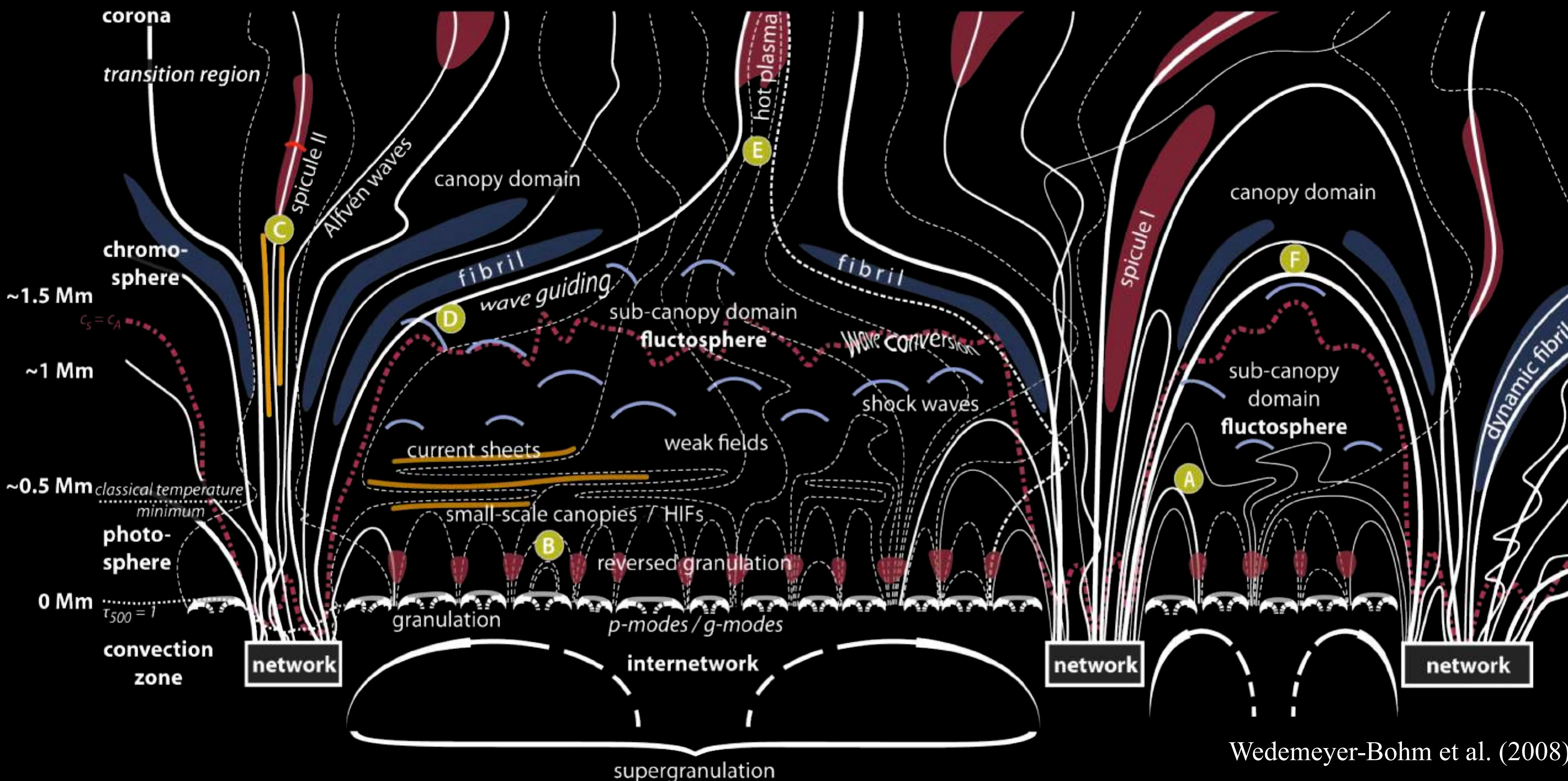
Photosphere: intense radiation slowly cools the plasma with increasing height.

Chromosphere: something starts heating it, but radiation cooling still keeps a lid on it.

Corona: density drops to a point where radiation can no longer cool down the plasma. Any heating makes T ↑↑↑↑↑

So why haven't we solved it already?

So why haven't we solved it already?



Wedemeyer-Bohm et al. (2008)

Which of the dozens of proposed ways to heat the plasma are **actually** occurring?

Table 1: Coronal Heating Theories & Efficiency Scalings Relative to the Poynting Flux

Model description	Efficiency ($\mathcal{E}$)	Example reference
Wave Dissipation (AC) Models		
Alfvén-wave collisional damping	$\Lambda^1\Theta^2 Re^{-1}$	Osterbrock (1961)
Resonant absorption	$\Lambda^1\Theta^1$	Ruderman et al. (1997)
Phase mixing	$\Lambda^1\Theta^{4/3} Re^{-1/3}$	Roberts (2000)
Surface-wave damping	$\Lambda^{1/2}\Theta^{3/2}(\Sigma/Re)^{1/2}$	Hollweg (1985)
Fast-mode shock train	$\Lambda^2\Theta^3$	Hollweg (1985)
Switch-on MHD shock train	$\Lambda^3\Theta^4$	Hollweg (1985)
Turbulence Models		
Kolmogorov-Obukhov cascade	$\Lambda^1\Theta^2$	Hollweg (1986)
Iroshnikov-Kraichnan cascade	$\Lambda^2\Theta^3$	Chae et al. (2002)
Hybrid triple-correlation cascade	$\Lambda^1\Theta^3(1+\Theta)^{-1}$	Zhou & Matthaeus (1990)
Reflection-driven cascade	$\Lambda^1\Theta^2(f_+^2 f_- + f_-^2 f_+)$	Hossain et al. (1995)
2D boundary-driven cascade	$\Lambda^{2/3}\Theta^{1/3}$	Heyvaerts & Priest (1992)
Line-tied reduced MHD cascade	$\Lambda^1\Theta^{1/2}$	Dmitruk & Gómez (1999)
Footpoint Stressing (DC) Models		
Current-layer random walk	Λ^1	Sturrock & Uchida (1981)
Current-layer shearing	$\Lambda^1(1+\Theta^2)^{1/2}(1+\Lambda^2)^{-1/2}$	Galsgaard & Nordlund (1996)
Braided discontinuities	$\Lambda^2\Theta^1$	Parker (1983)
Flux cancellation	$\Lambda^1\Theta^1(\phi^{8/3}-\phi^{4/3})$	Priest et al. (2018)
Taylor Relaxation Models		
Tearing-mode reconnection	$\Lambda^1\Theta^1(1-\alpha L)^{-5/2}$	Browning & Priest (1986)
Hyperdiffusive reconnection	$\Lambda^1\Theta^{-1}(\alpha L)^2$	van Ballegooijen & Cranmer (2008)
Non-ideal/slipping reconnection	$\Theta^{-1}(\alpha L)^1$	Yang et al. (2018)

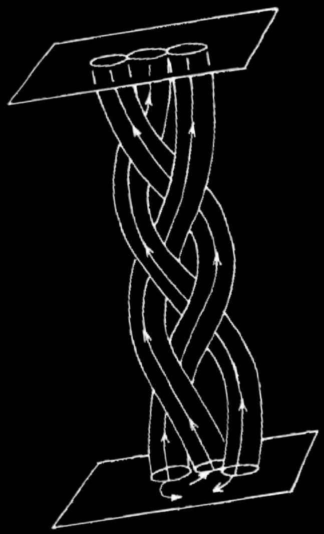
$Q \approx \mathcal{E}\,\rho V_A^2 v_\perp / L \qquad \Lambda = \lambda_\perp / L\,, \quad \Theta = \tau_A/\tau_{ph}$

AC: alternating current, $\tau_A \gg \tau_{ph}$

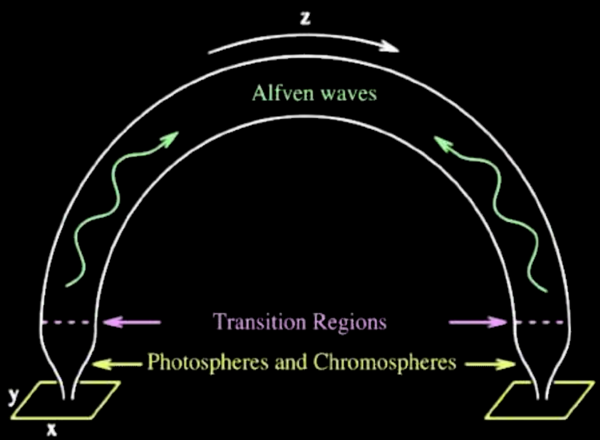
DC: direct current, $\tau_A \ll \tau_{ph}$

(see Cranmer & Winebarger 2019, *Annual Review of Astron. & Astrophys.*, **57**, 157−187, arXiv:1811.00461)

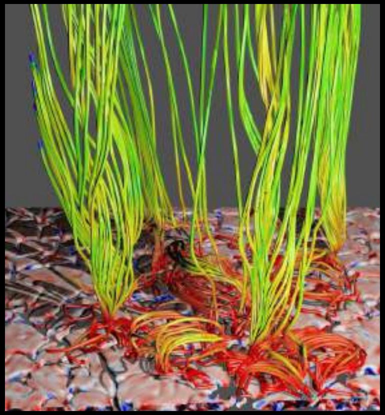
Main points of debate

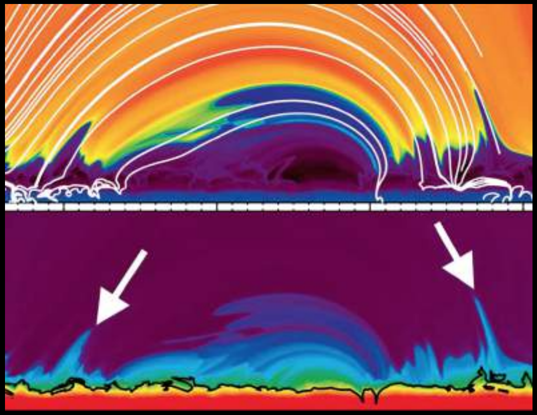


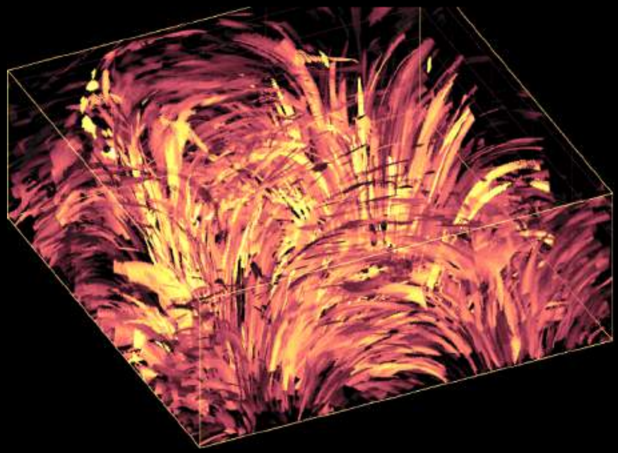
- If motions are slow **(DC),** the field gets slowly tangled & braided. Bursty "nanoflare" heating events happen once it goes unstable.
  - If motions are fast **(AC),** energy is transported by waves, which are eventually damped out to make heat.



- 3D MHD simulations seem to be dominated by **DC** processes, but they cannot yet resolve AC-like turbulence **within** the flux tubes…



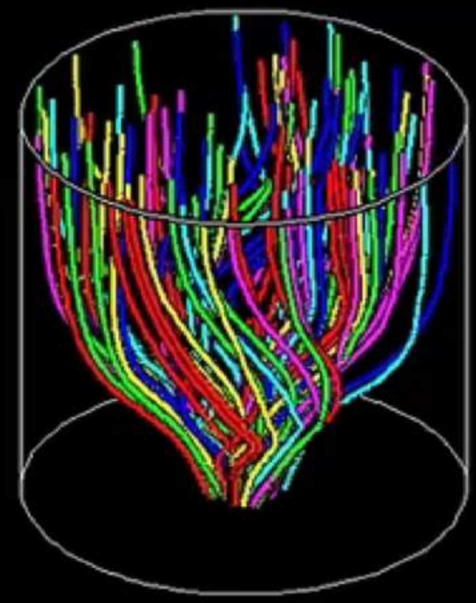




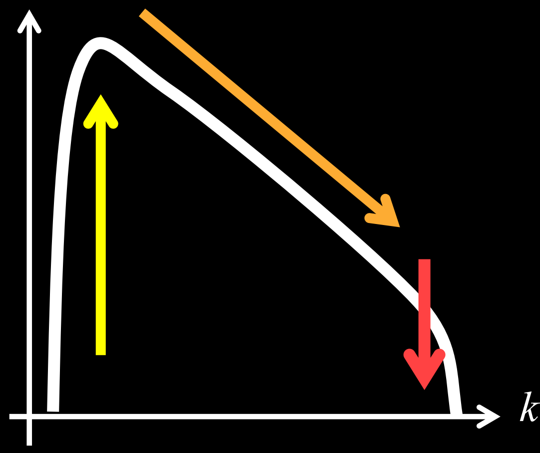
(Peter 2015; Amari et al. 2015; Martinez-Sykora et al. 2017; Kanella & Gudiksen 2017; Rempel 2017)

Turbulence: a unifying "language?"

- Plasmas often develop spontaneously into turbulent (complex, nonlinear, chaotic) flows...
- When some systems are **stirred** on large scales,
- there's a natural **cascade** of energy from large to small scales (i.e., wave-packets get "shredded"),



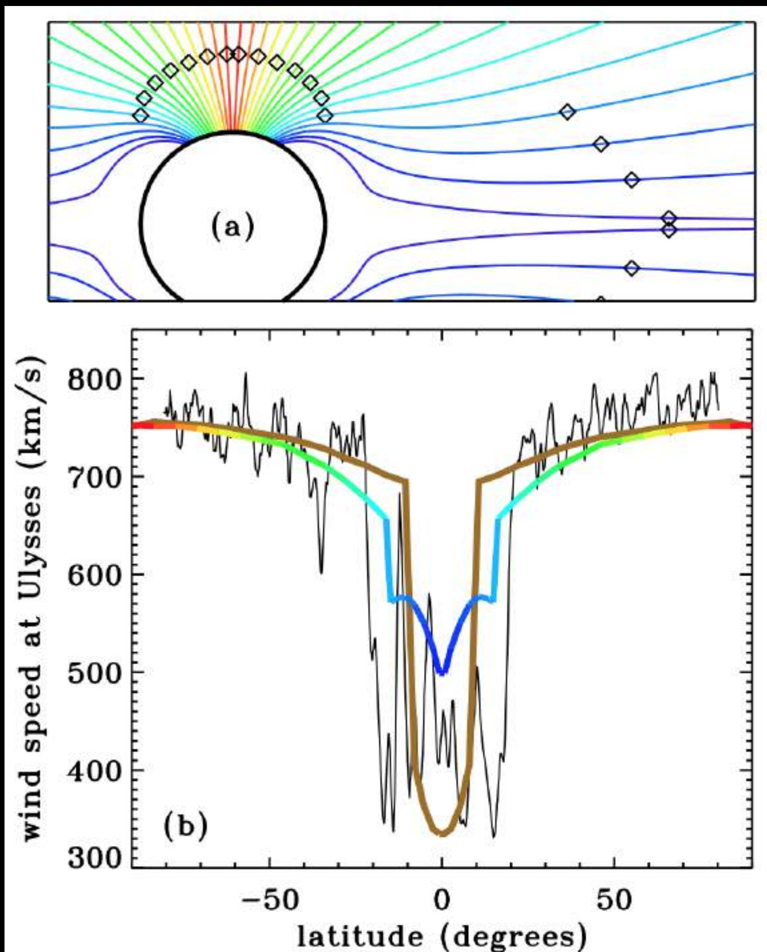
- and eventually the energy in the smallest packets is irreversibly converted to heat (**dissipation**), often in a bursty/intermittent (**"nanoflare"**) way!

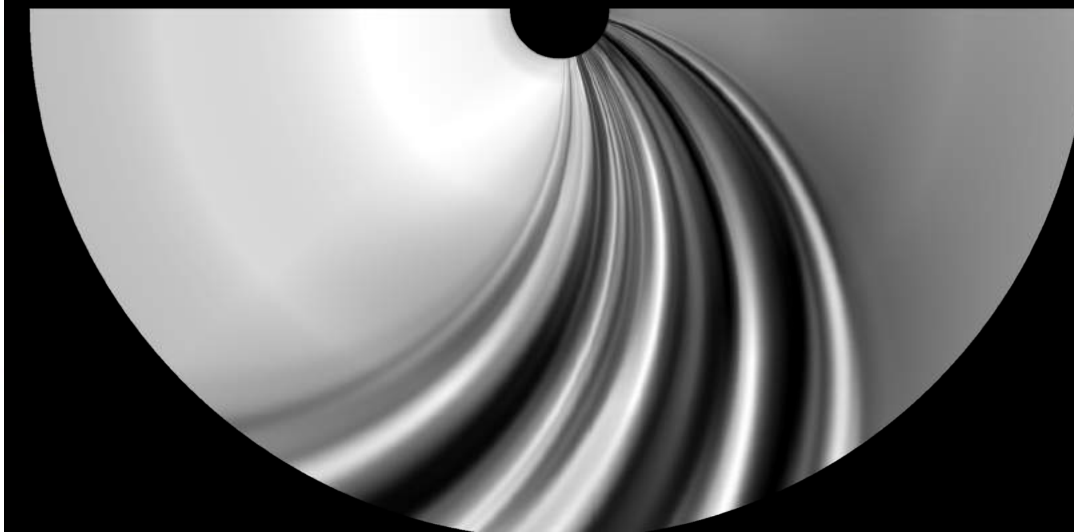


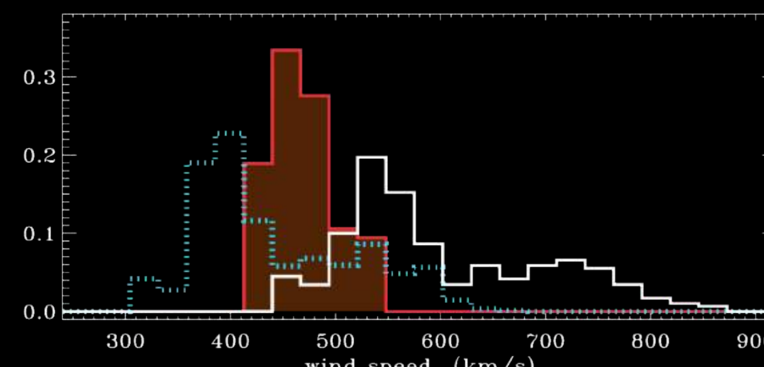
(Hollweg 1986; Velli et al. 1991; Matthaeus et al. 1999; Dmitruk et al. 2002; Suzuki & Inutsuka 2006; Cranmer et al. 2007, 2013; Verdini et al. 2010; van Ballegooijen et al. 2011, 2017; Perez & Chandran 2013, 2019; Velli et al. 2015; Lionello et al. 2014; Shoda et al. 2018; & many more!)

Turbulence appears to work…

Models succeed in reproducing many **observed** solar wind properties (Cranmer et al. 2007, 2013; van Ballegooijen et al. 2011; Woolsey & Cranmer 2014).

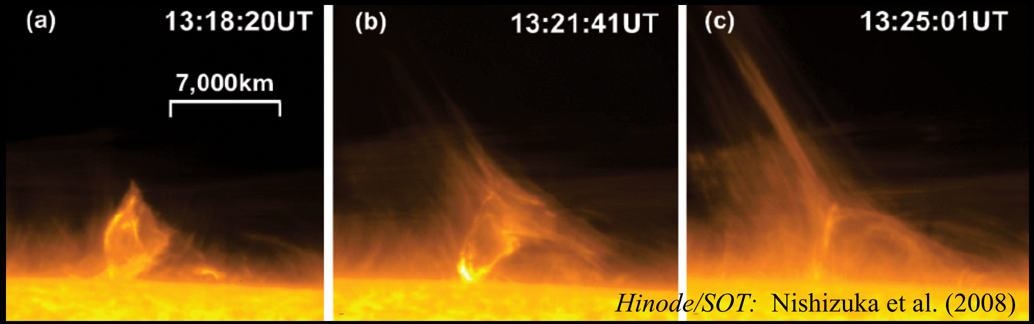




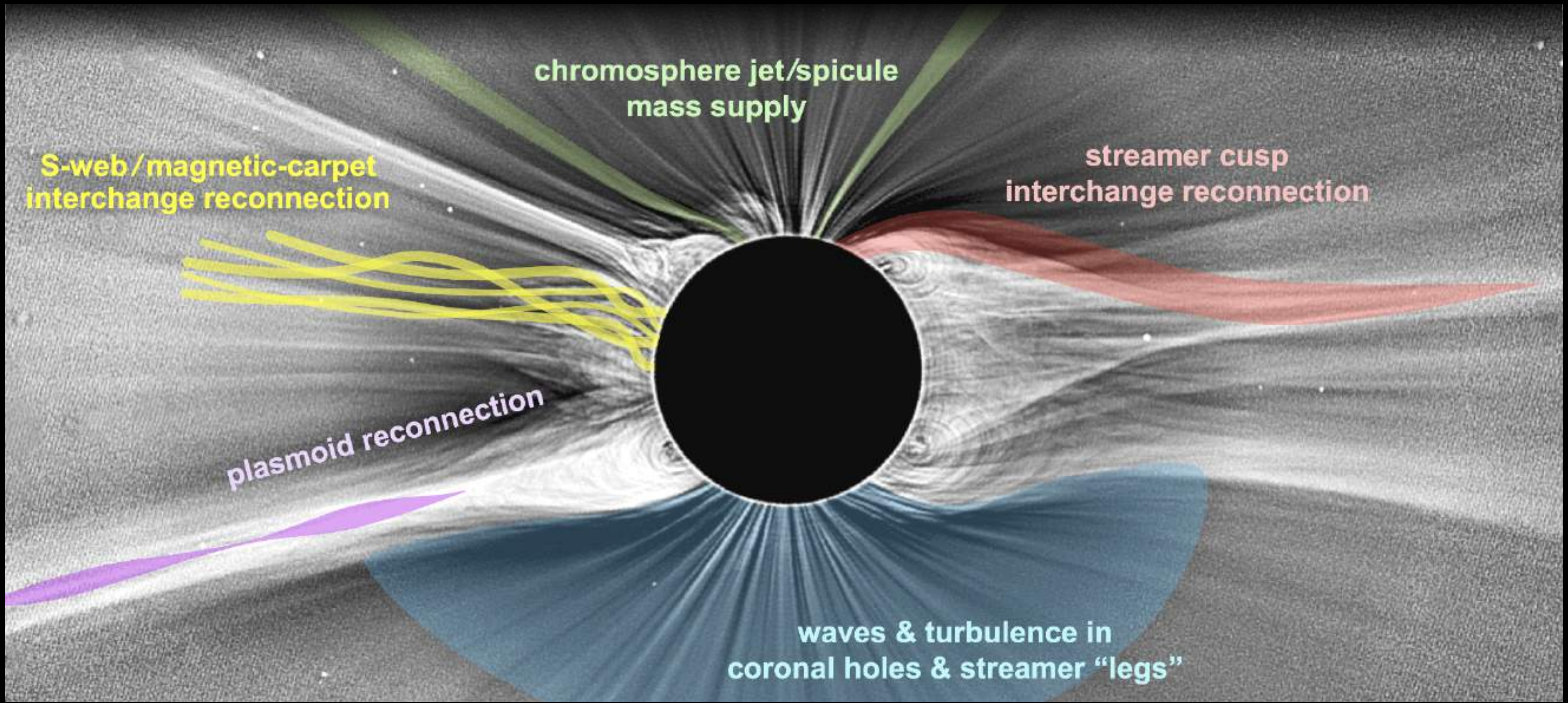


What about magnetic reconnection?

- We see frequent jet-like reconnection events. Are they ubiquitous enough to power the solar wind, too?



Hinode/SOT: Nishizuka et al. (2008)



Outline

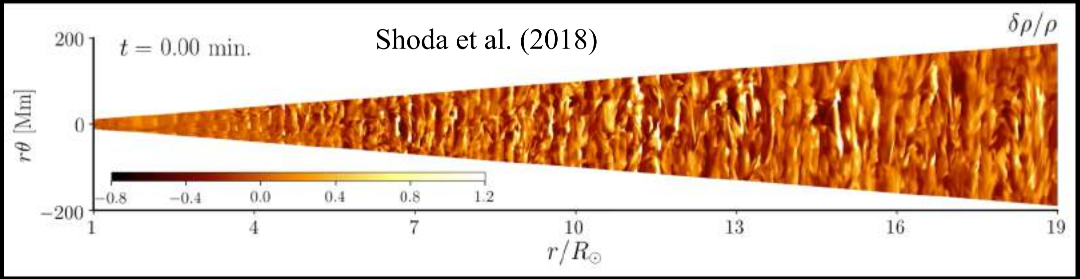
1. Brief history & motivation
2. "The problems" (coronal heating & the solar wind)
3. New ideas under development
   - Applicability & practical importance
   - To test theories, we need *DATA*
4. The future . . .

Outline

1. Brief history & motivation
2. "The problems" (coronal heating & the solar wind)
3. New ideas under development
   - Applicability & practical importance
   - To test theories, we need *DATA*
4. The future . . .

Next-generation hybrid simulations

- We're building a new set of tools to produce self-consistent models of coronal heating & solar wind acceleration using...
  - Updates to MHD turbulence heating "recipes" from the most recent supercomputer simulations.
  - New proposed pathways to generate turbulence via density fluctuations:

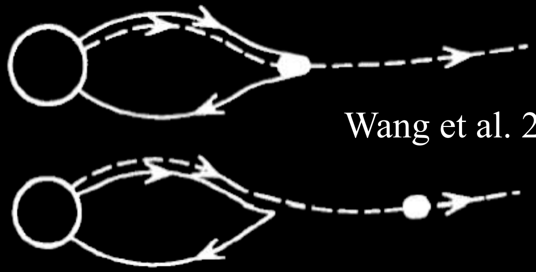


  - Improved description of **electron heat conduction** (using "eight-moment" non-Maxwellian kinetic theory), which is key for determining how coronal temperature is distributed through space...

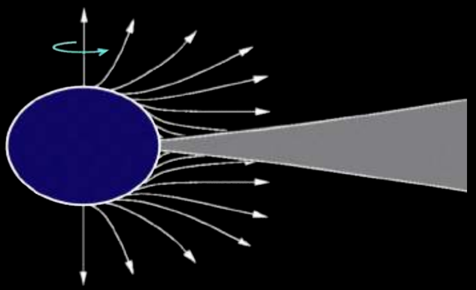
(Schiff & Cranmer 2019)

Next-generation hybrid simulations

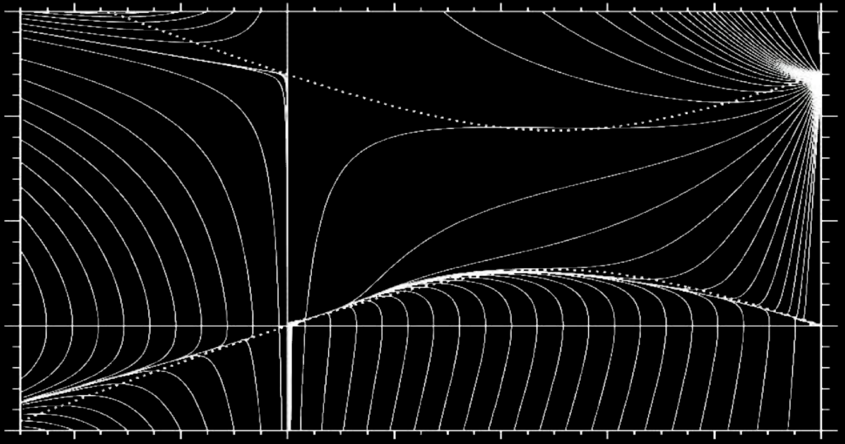
- Injection of mass, momentum, and energy from magnetic reconnection will also be included as **mass-loading** source terms.



- Usually these terms are reserved for "creation" of new particles due to ionization or charge-exchange in comets.



- Cranmer (1996, PhD thesis) began working out how to apply these terms to mass injection to a 2D disk from the north & south.

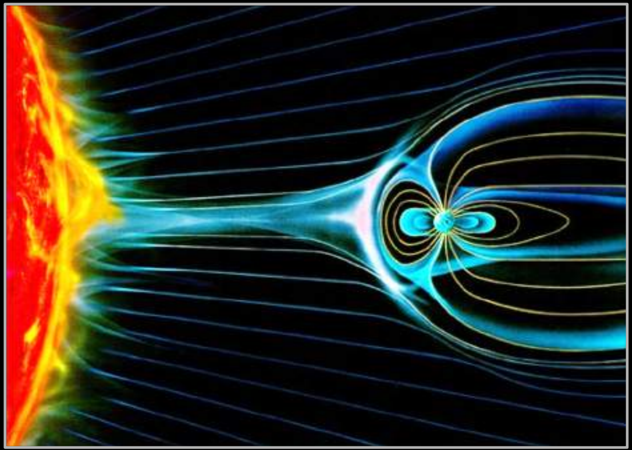


- It's time to dust off that work...

Why do we need to get this right?

- To forecast accurately, we need to know the contributions of relevant processes.

- Variability in the "ambient" solar wind impacts space weather...
  - **high-speed streams** accelerate electrons in the Earth's radiation belts
  - heliospheric evolution of **CMEs** depends on what solar-wind structures they flow through



- CU Boulder's *Space Weather Technology, Research, and Education Center* is on the job!

SWx TREC

Grand Challenge
UNIVERSITY OF COLORADO **BOULDER**
SPACE WEATHER CENTER

Tom Berger, Director

Jeff Thayer, Research

Chris Pankratz, MADTech

Steve Cranmer, Education

Outline

1. Brief history & motivation
2. "The problems" (coronal heating & the solar wind)
3. New ideas under development
   - Applicability & practical importance
   - To test theories, we need *DATA*
4. The future . . .

Outline

1. Brief history & motivation
2. "The problems" (coronal heating & the solar wind)
3. New ideas under development
    - Applicability & practical importance
    - To test theories, we need *DATA*
4. The future . . .

DKIST

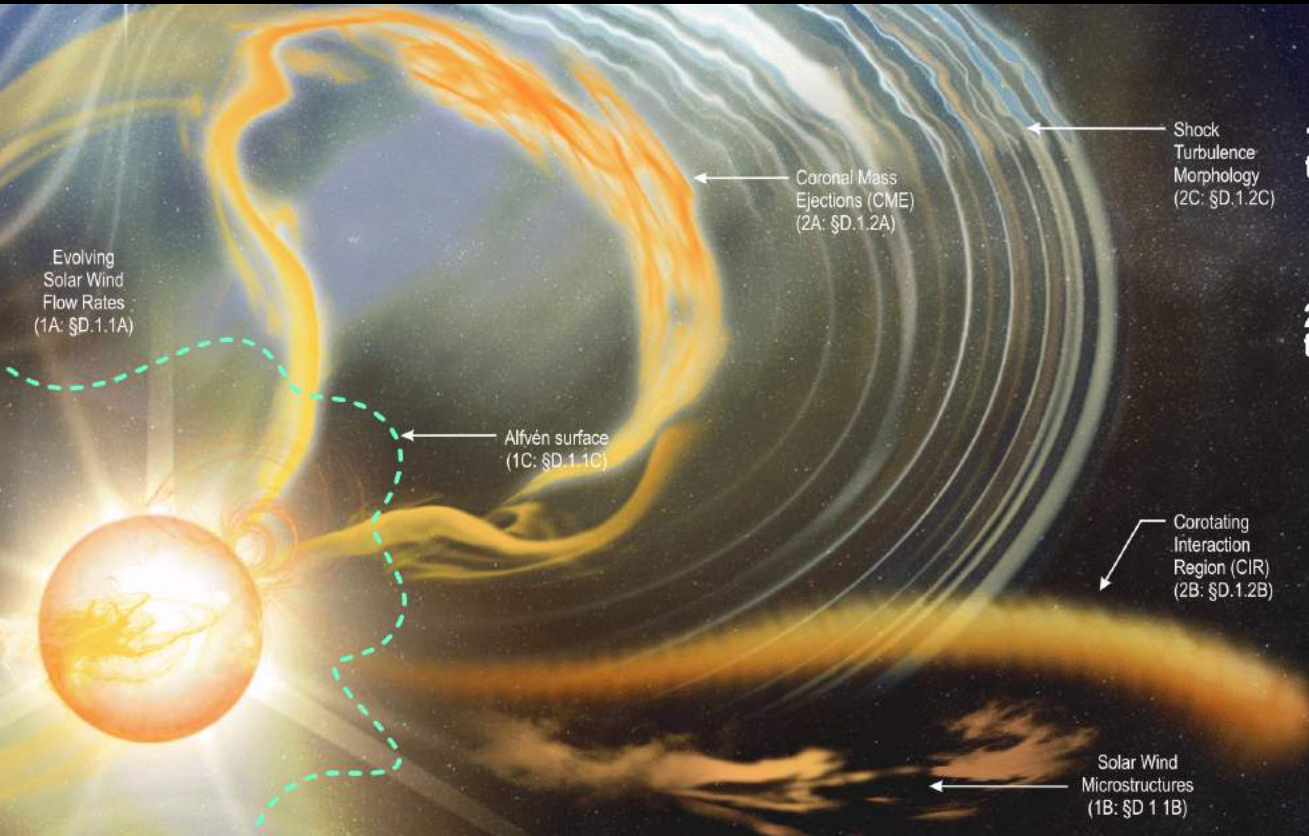
- NSO's 4-meter diameter Daniel K. Inouye Solar Telescope, on Haleakalā (Maui, Hawai'i), is coming online in early 2020.
  - Unprecedented imaging & spectropolarimetry will characterize energy present in photospheric **drivers of turbulence.**
  - Off-limb coronagraph will measure **waves** as they propagate thru chromosphere & corona.

(Molnar et al. 2019)

NSO

New coronagraphs

- In June 2019, NASA Small Explorer *PUNCH* (the *"Polarimeter to UNify the Corona and Heliosphere"*) got approved for flight.
- PI: Craig DeForest (SwRI)... 1+3 constellation of smallsats observing coronal density & polarization from 6 to 180 $R_\odot$
- Also: X-ray spectrometer built by students @ Colorado Space Grant



PUNCH Science Objectives

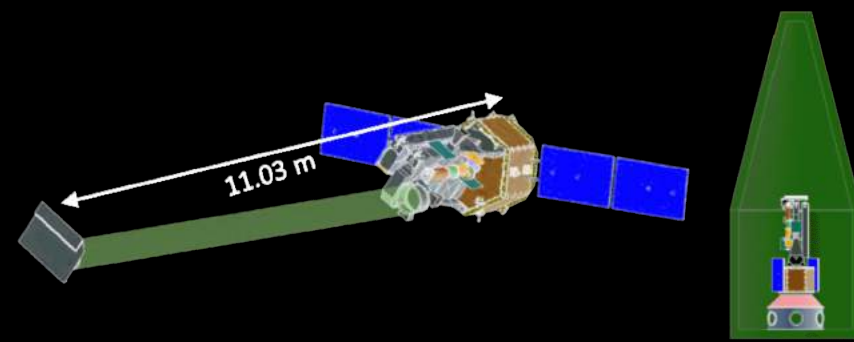
1. Understand how coronal structures become the ambient solar wind.
- Map evolving solar wind flow
- Identify microstructure and turbulence
- Locate the Alfvén surface

2. Understand the dynamic evolution of transient structures in the young solar wind.
- Track CMEs and their evolution in 3D
- Measure CIR formation & evolution
- Determine large-scale shock dynamics

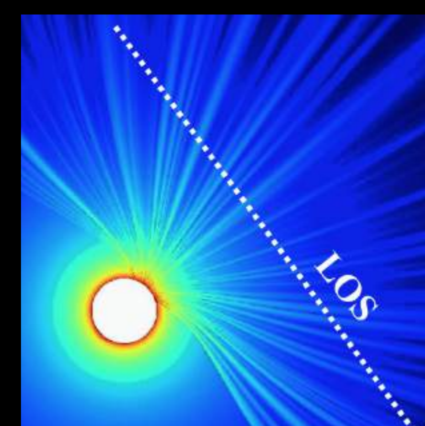
New coronagraphs + spectroscopy

- In October 2019, the proposal went in for a next-generation version of the SOHO Ultraviolet Coronagraph Spectrometer.
- PI: Angelos Vourlidas (JH/APL)
- Instruments behind a 11-meter boom to provide near-eclipse-quality occultation.
- Here at CU, we're busily preparing to use those UV emission lines to measure properties of **MHD turbulence** & non-Maxwellian ion velocity distributions...

LOCKYER
LARGE OPTIMIZED CORONAGRAPHS FOR KEY EMISSION LINE RESEARCH



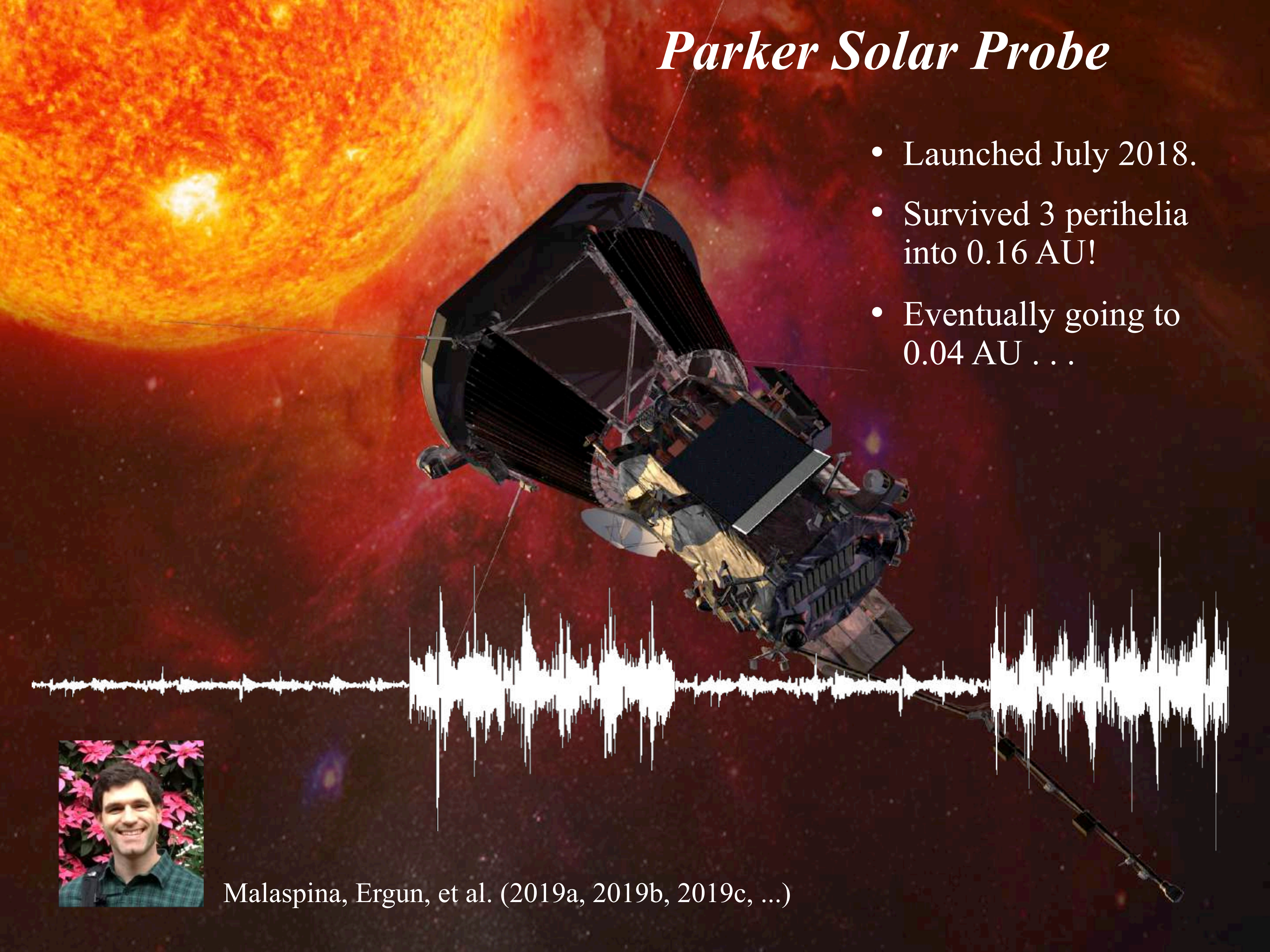
(Gilbert & Cranmer 2019)



Parker Solar Probe

- Launched July 2018.
- Survived 3 perihelia into 0.16 AU!
- Eventually going to 0.04 AU . . .

Malaspina, Ergun, et al. (2019a, 2019b, 2019c, ...)


Parker Solar Probe
Launched July 2018.
Survived 3 perihelia into 0.16 AU!
Eventually going to 0.04 AU . . .
Malaspina, Ergun, et al. (2019a, 2019b, 2019c, ...)

New & old perspectives

COHERENT

DEFINE · RESEARCH · COMMUNICATE · INNOVATE

- Earlier in 2019, colleagues at SwRI, CU, HAO, NASA, APL, and more, proposed the creation of a DRIVE science center called *COHERENT ("Corona as a Holistic Environment Research NeTwork")*.
- Goal: develop new multi-perspective, cross-disciplinary approaches to **solving the coronal heating problem!**

- How quantitative can this process get?

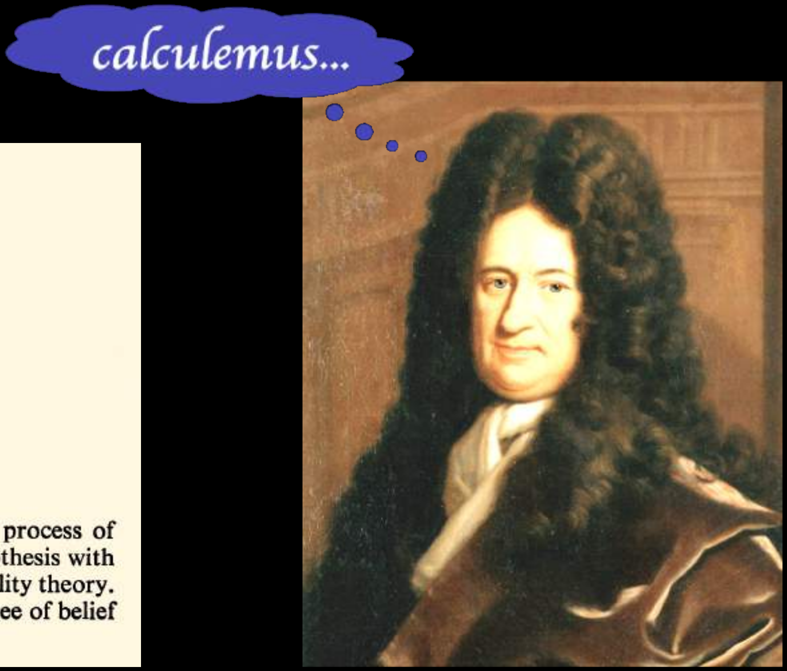
THE ASTROPHYSICAL JOURNAL, **182**: 569–580, 1973 June 1

EVALUATION OF ASTROPHYSICAL HYPOTHESES

P. A. STURROCK
Institute for Plasma Research, Stanford University
Received 1972 August 7; revised 1973 January 11

ABSTRACT

The aim of this article is to set out a bookkeeping procedure for formalizing the process of assessing a hypothesis by comparison of conclusions drawn theoretically from this hypothesis with facts obtained by reduction of observational data. The formalism used is that of probability theory. A key role is played by Bayes's rule representing the inductive process of adjusting a degree of belief in response to new information.



The Solar-Stellar Connection

- The Sun serves as a benchmark for our understanding of the physical processes that occur in other stars & astrophysical plasmas.

“Stars with Steve”

- The Sun serves as a benchmark for our understanding of the physical processes that occur in other stars & astrophysical plasmas.

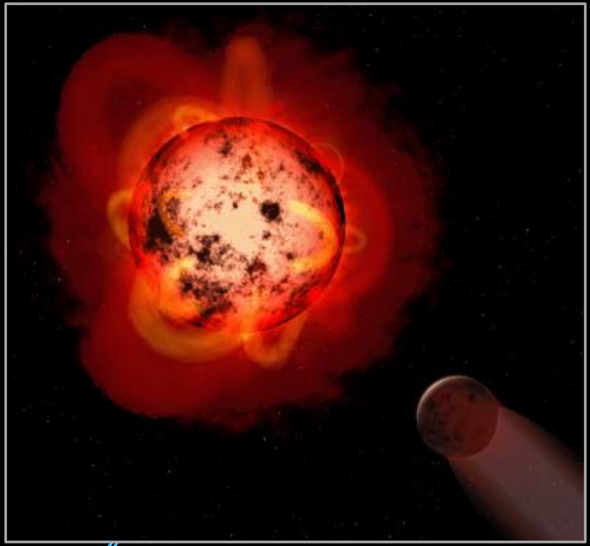
"Stars with Steve"

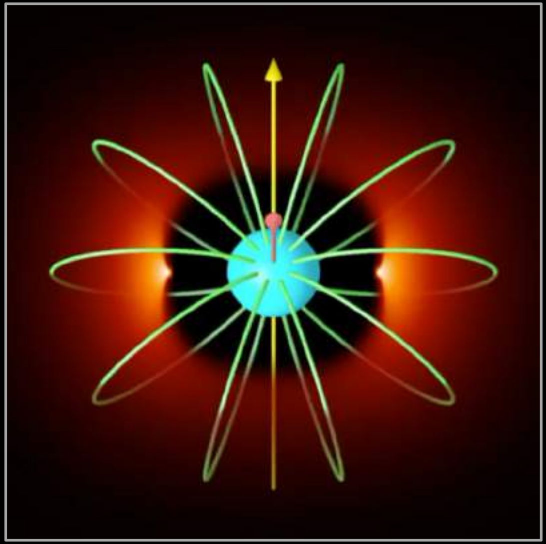
- The Sun serves as a benchmark for our understanding of the physical processes that occur in other stars & astrophysical plasmas.
- Come find me to hear another ~hour's worth of talk about these projects...

MacGregor et al. (2016, 2018)

Owocki & Cranmer (2018)

Lattimer & Cranmer (2020)





Conclusions

- Although the solar "problems" are not yet solved, we're including more and more real physics in models that are doing better at explaining what we see.

- Understanding is greatly aided by ongoing collaboration between the solar physics, plasma physics, space physics, & astrophysics communities.

- Additional observational validation is needed…

@solarstellar