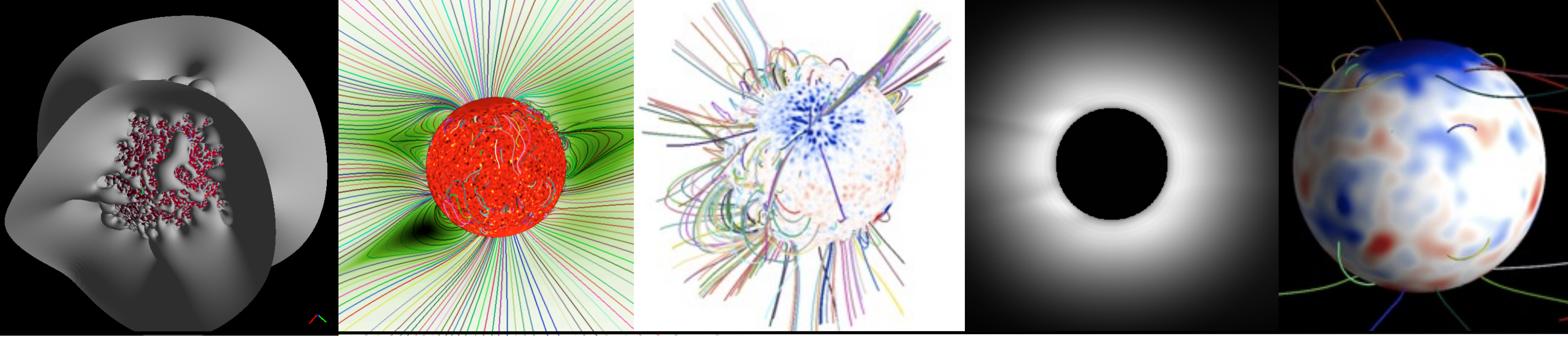

Modeling the Global Structure of the Solar Corona and Inner Heliosphere during the Unusual 2008/2009 Solar Minimum: A Proxy for the Maunder Minimum?

http://www.predsci.com

Pete Riley, Roberto Lionello, Jon Linker, and Zoran Mikic

Predictive Science, Inc. (PSI), San Diego, CA, USA

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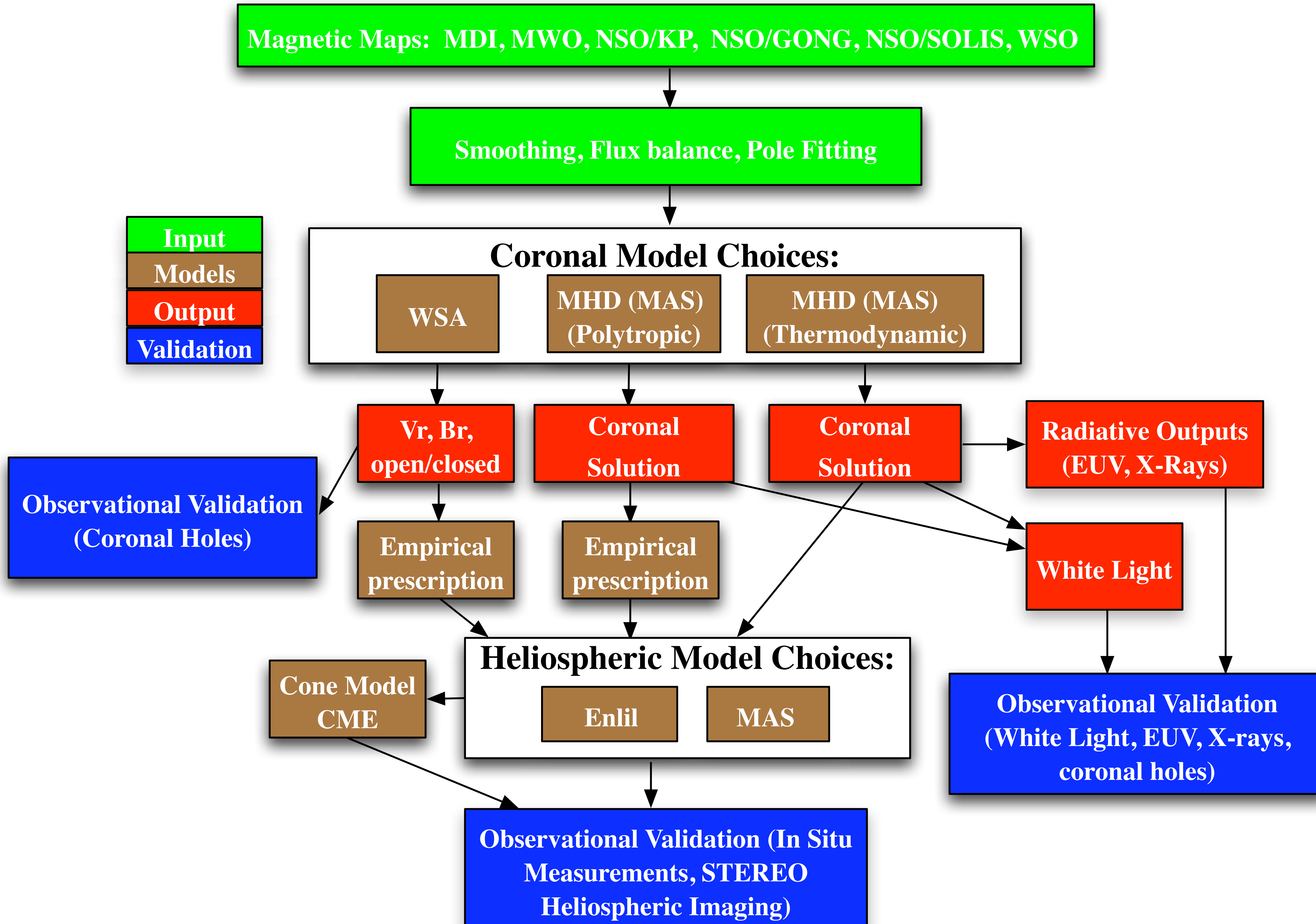
Predictive Science, Inc.

OVERVIEW

- Introduction: Global MHD modeling
- PRESENT: The properties of the corona and inner heliosphere during the 2008/2009 solar minimum
- PAST: Speculation on the structure of the corona and inner heliosphere during the Maunder Minimum
- FUTURE: Future Progress:
  - Observations
  - Modeling
- Summary

Modeling the global solar corona and inner heliosphere using CORHEL



MHD Equations
(Improved Energy Equation Model)

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \frac{1}{c} \mathbf{J} \times \mathbf{B} - \nabla p - \boxed{\nabla p_w} + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}) = (\gamma - 1) \left(-p \nabla \cdot \mathbf{v} \boxed{- \nabla \cdot \mathbf{q} - n_e n_p Q(T) + H} \right)$$

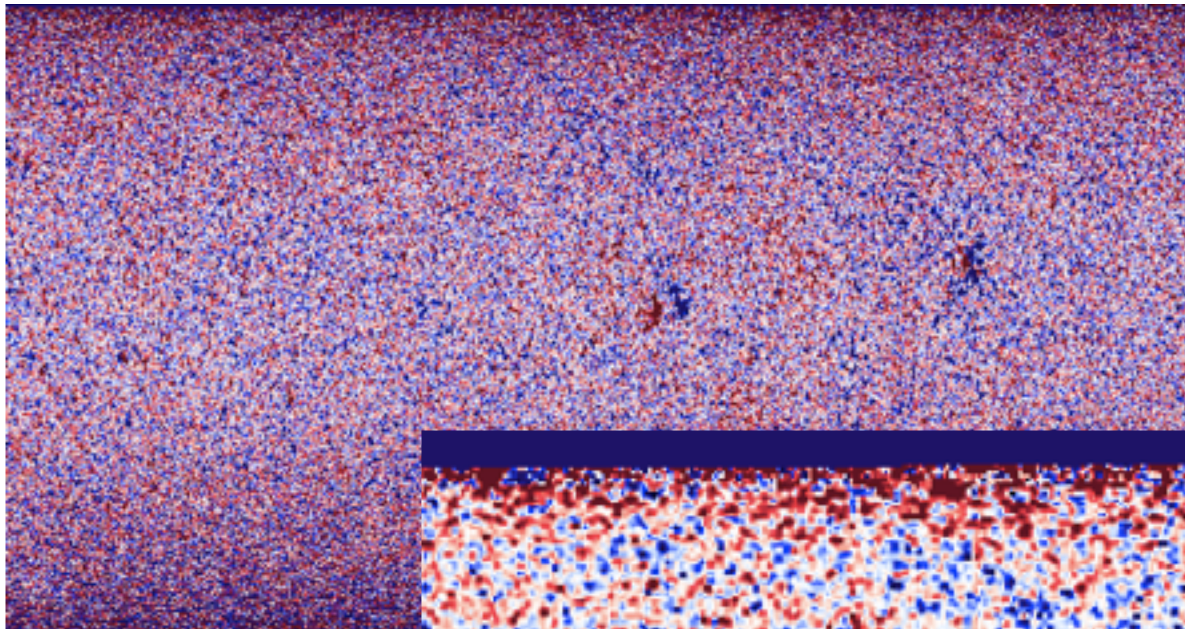
$$\gamma = 5/3$$

$$\mathbf{q} = -\kappa_{\parallel} \hat{\mathbf{b}} \hat{\mathbf{b}} \cdot \nabla T \qquad \text{(Close to the Sun, } r \lesssim 10 R_S\text{)}$$

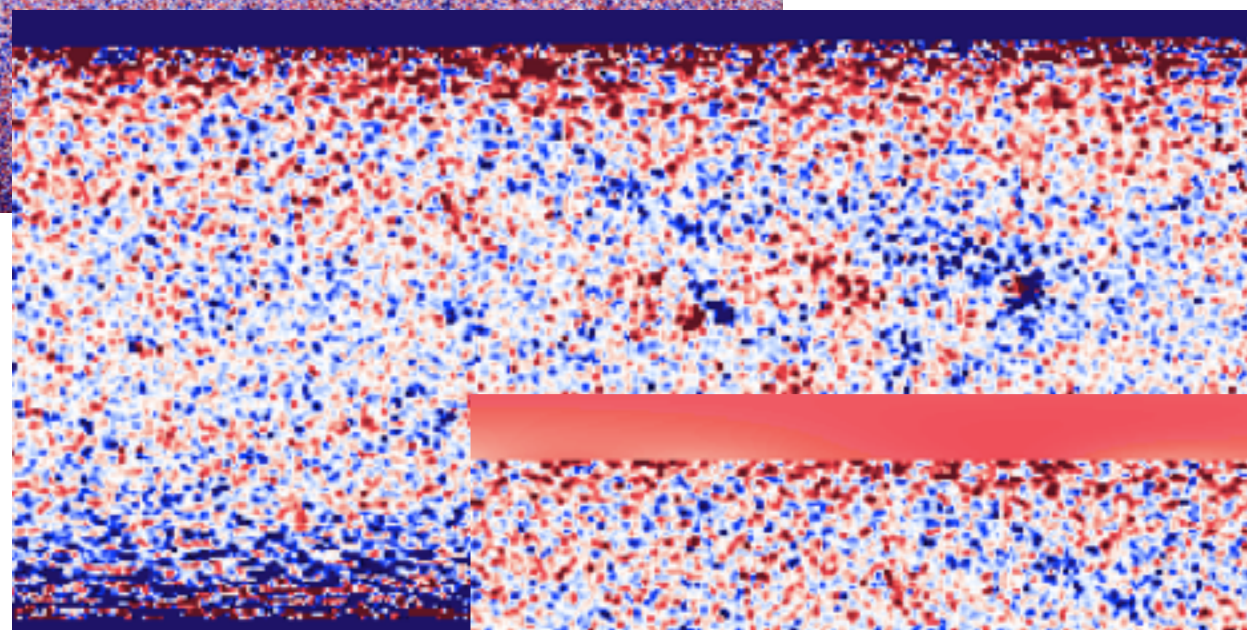
$$\mathbf{q} = 2 \alpha n_e T \hat{\mathbf{b}} \hat{\mathbf{b}} \cdot \mathbf{v} / (\gamma - 1) \qquad \text{(Far from the Sun, } r \gtrsim 10 R_S\text{)}$$

+ WKB equations for Alfvén wave pressure p_w evolution

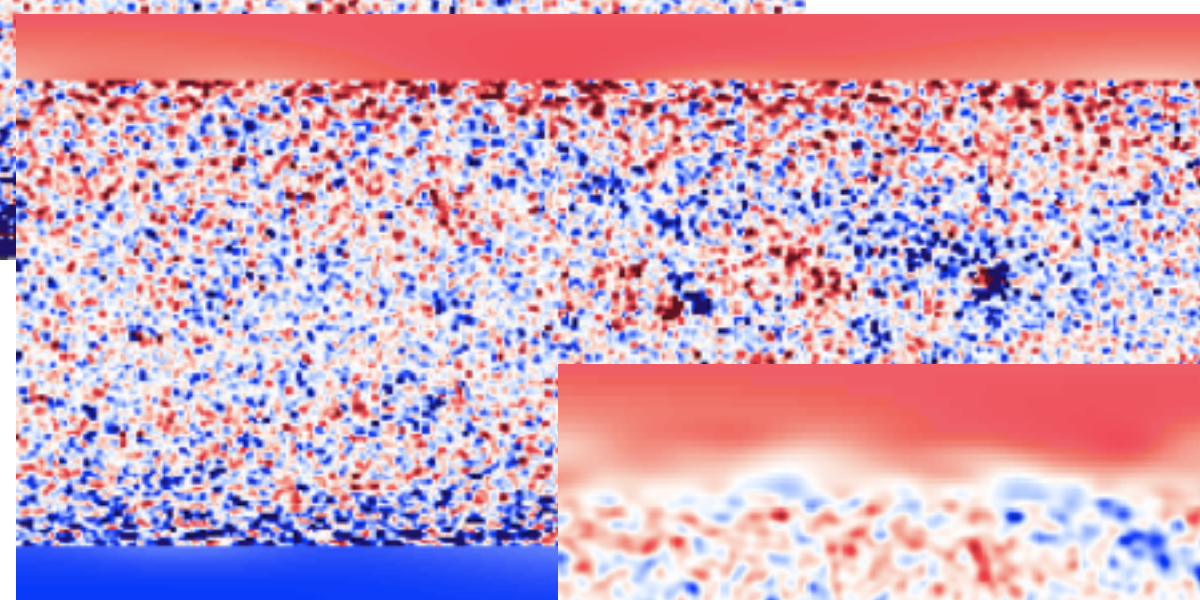
Synoptic Maps: CR2071 (June 9 - July 6, 2008)



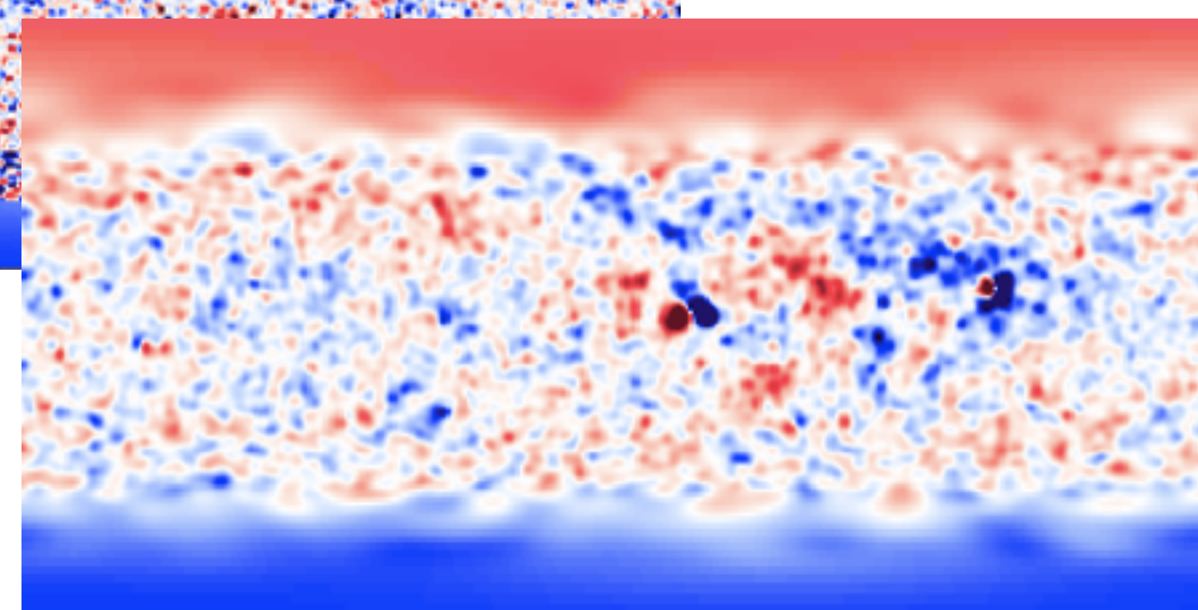
MDI Synoptic Map:
1080x3600 points
distributed as sin(latitude)



Interpolated B_r map:
180x360 points
distributed as latitude

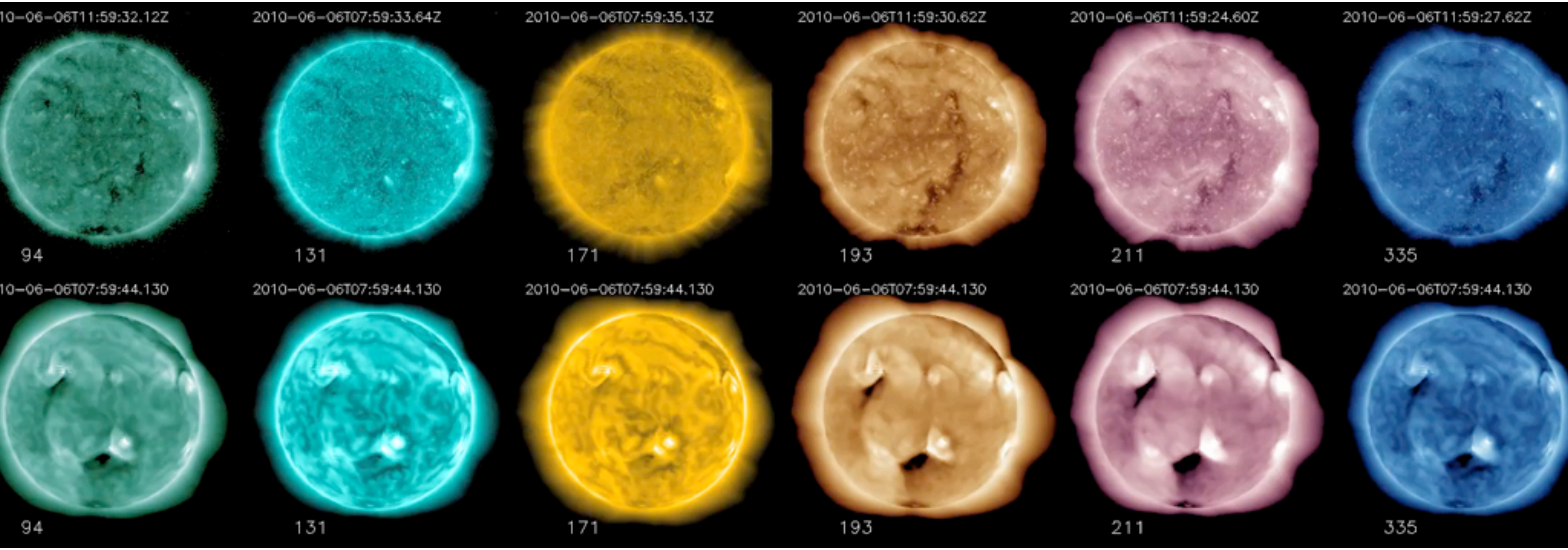


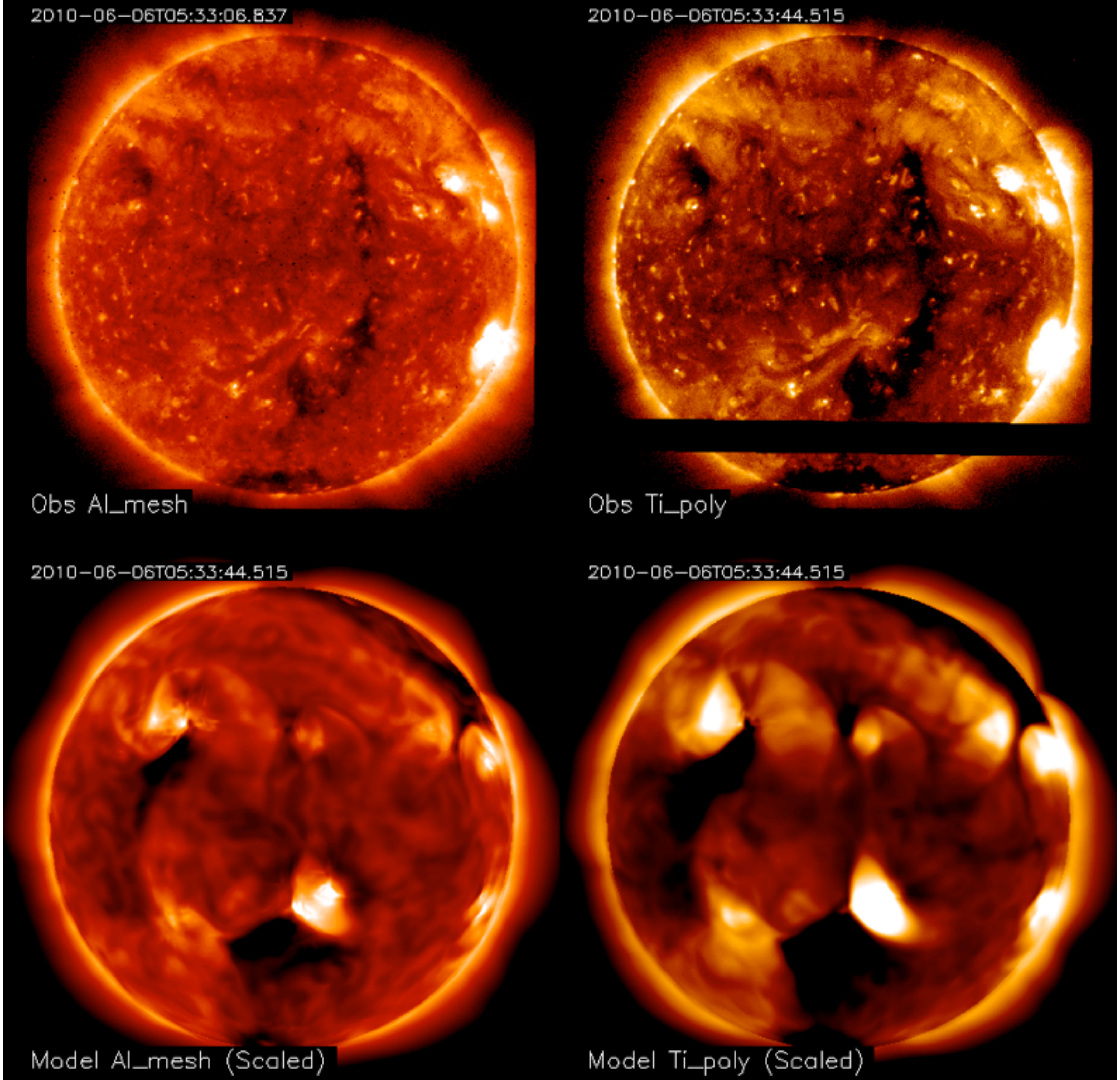
Interpolated B_r map:
180x360 points
Poles fit with polynomial to
lower m modes



Interpolated B_r map:
150x360 nonuniform cells
Field smoothed with diffusive operator
Flux Balanced

Global MHD models that include energy transport processes can reproduce emission observations relatively well

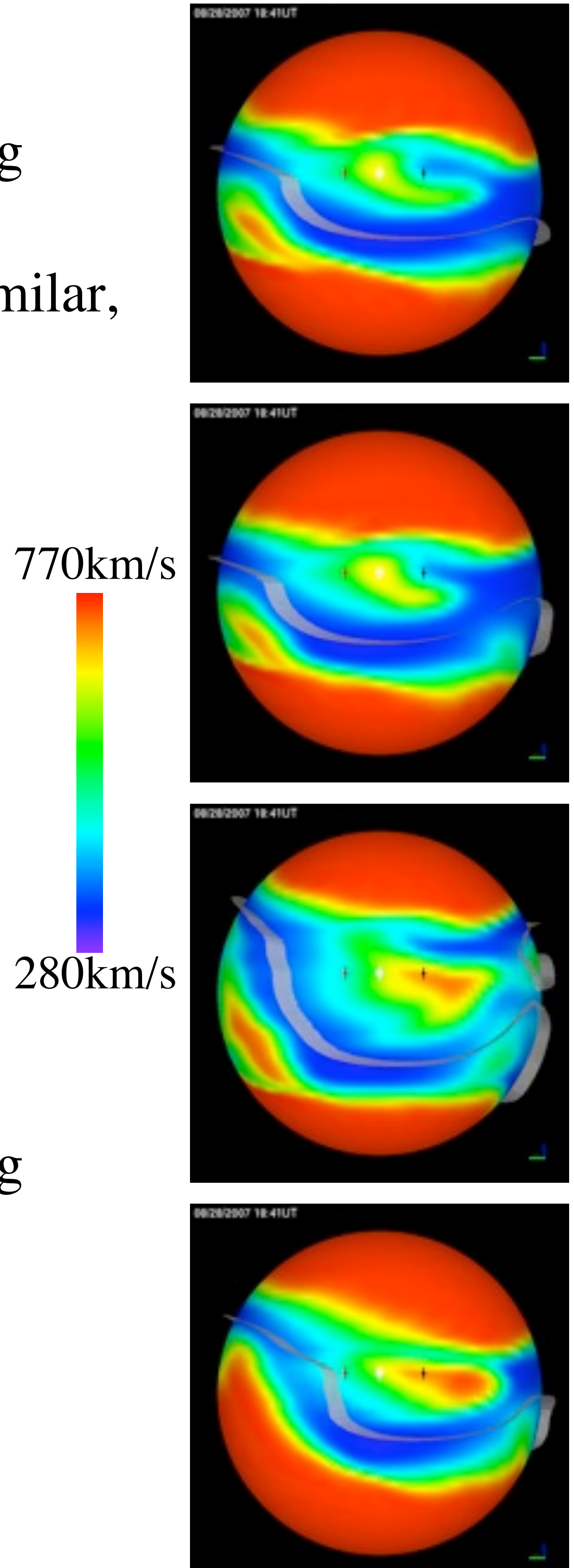


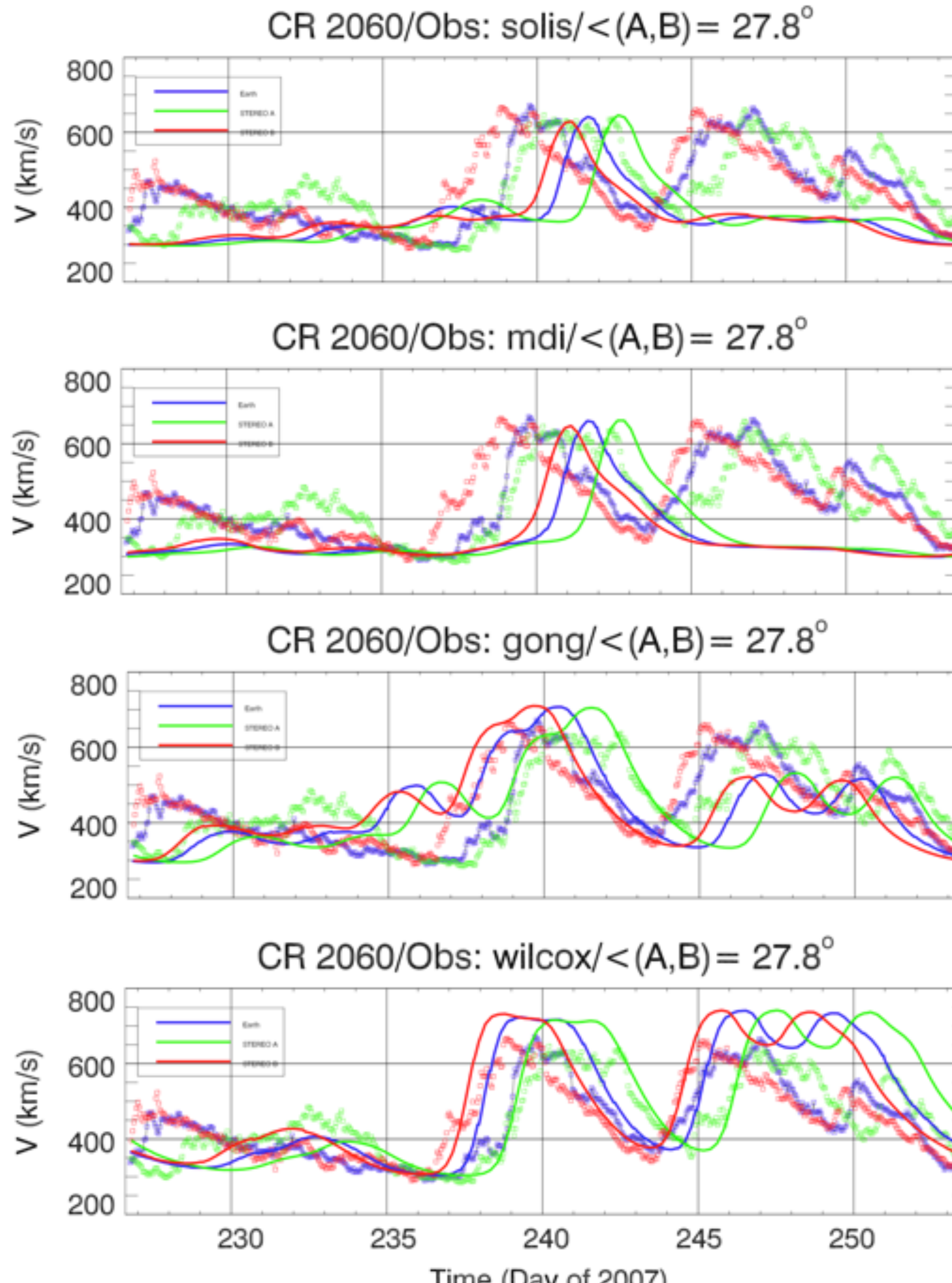

2010-06-06T05:33:06.837
Obs Al_mesh
2010-06-06T05:33:44.515
Obs Ti_poly
2010-06-06T05:33:44.515
Model Al_mesh (Scaled)
2010-06-06T05:33:44.515
Model Ti_poly (Scaled)

CORHEL Simulations for CR2060: Different Results for Different Observatories

CORHEL Simulations for CR2060: Different Results for Different Observatories

- Simulations using NSO/SOLIS and SOHO/MDI are similar, predict 1 stream

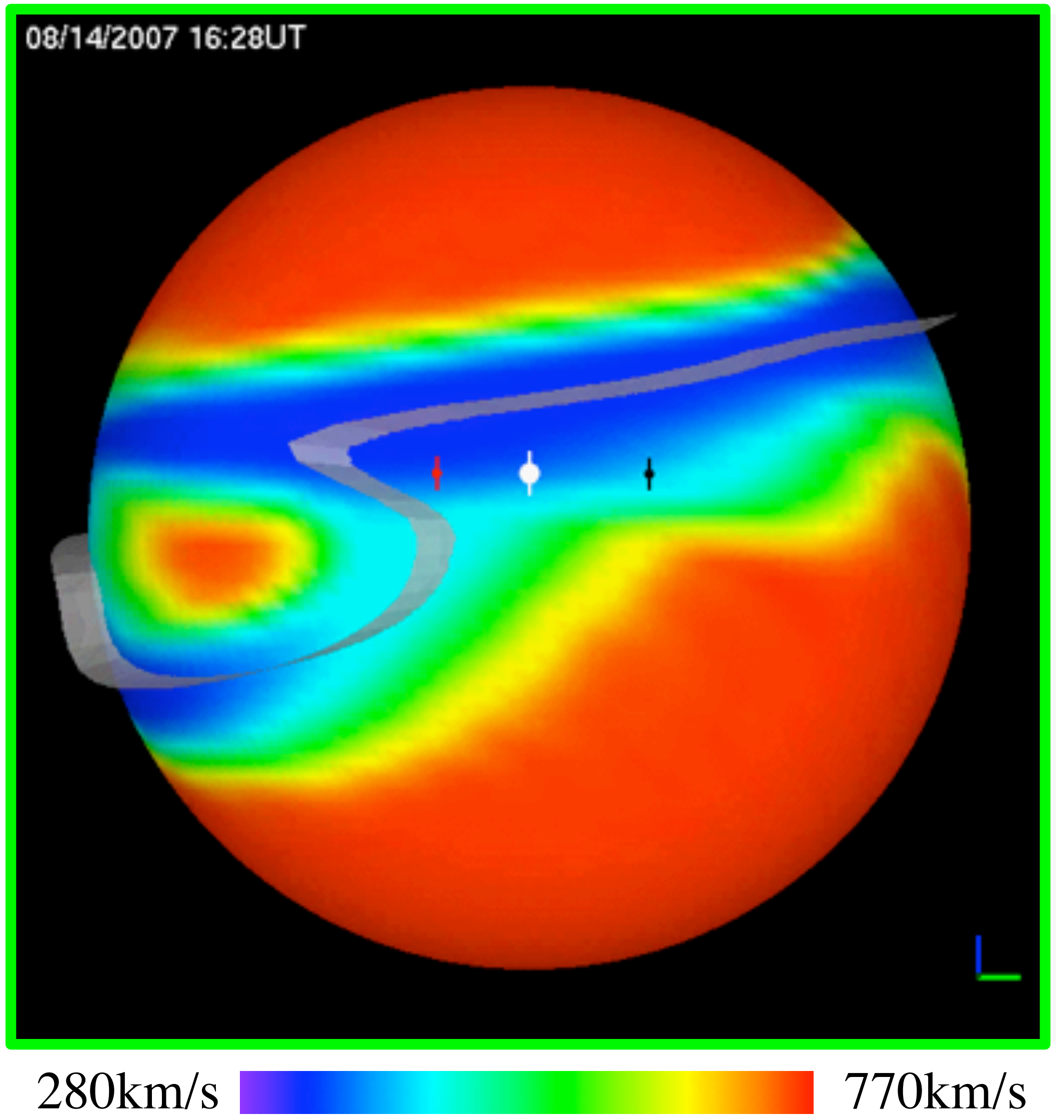


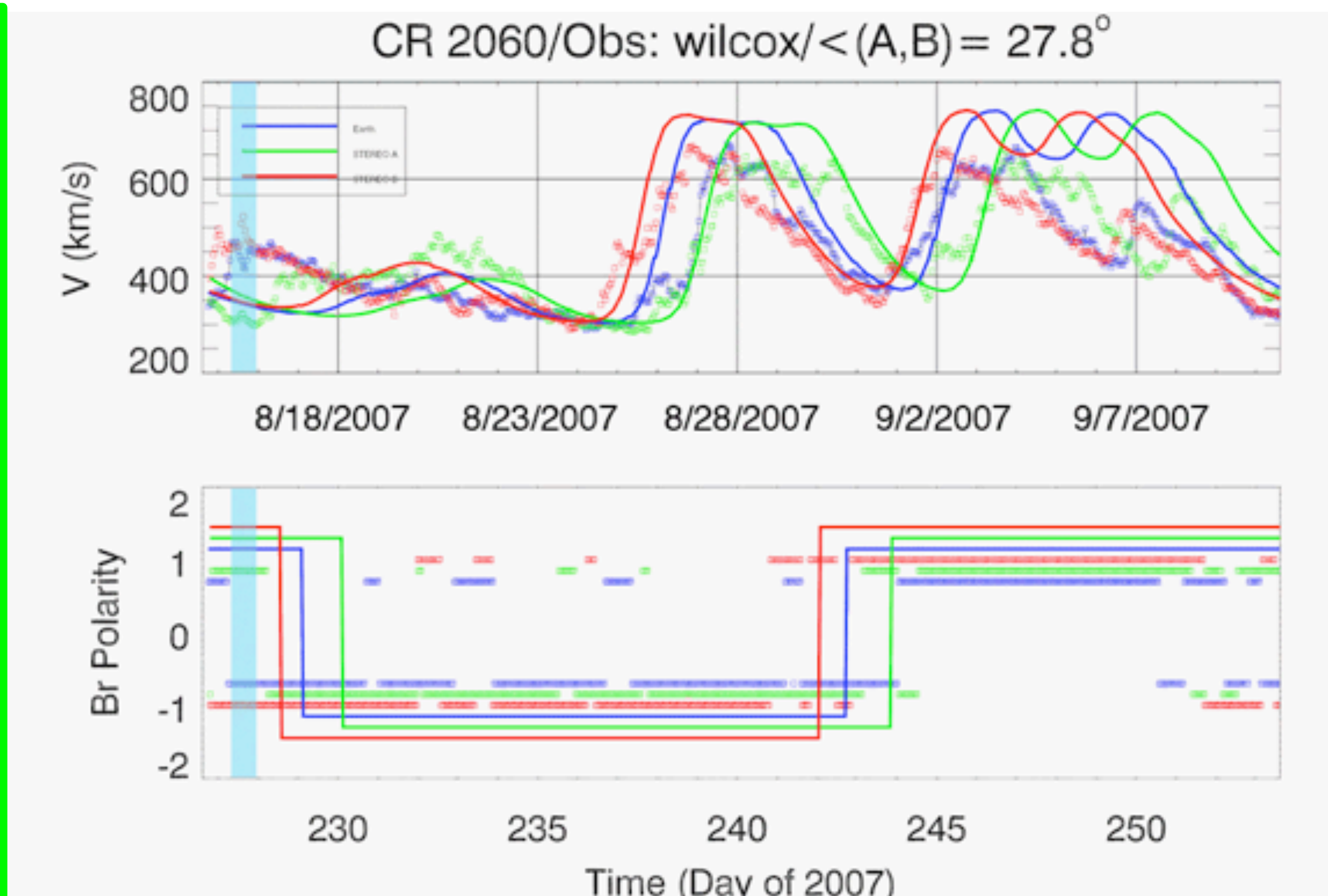


- Simulations using NSO/GONG and Wilcox predict 2 streams

CORHEL Simulations for CR2060: Different Results for Different Observatories

Stanford/Wilcox





Structural Differences between 2008/2009 (WHI) and 1996 (WSM) Minima

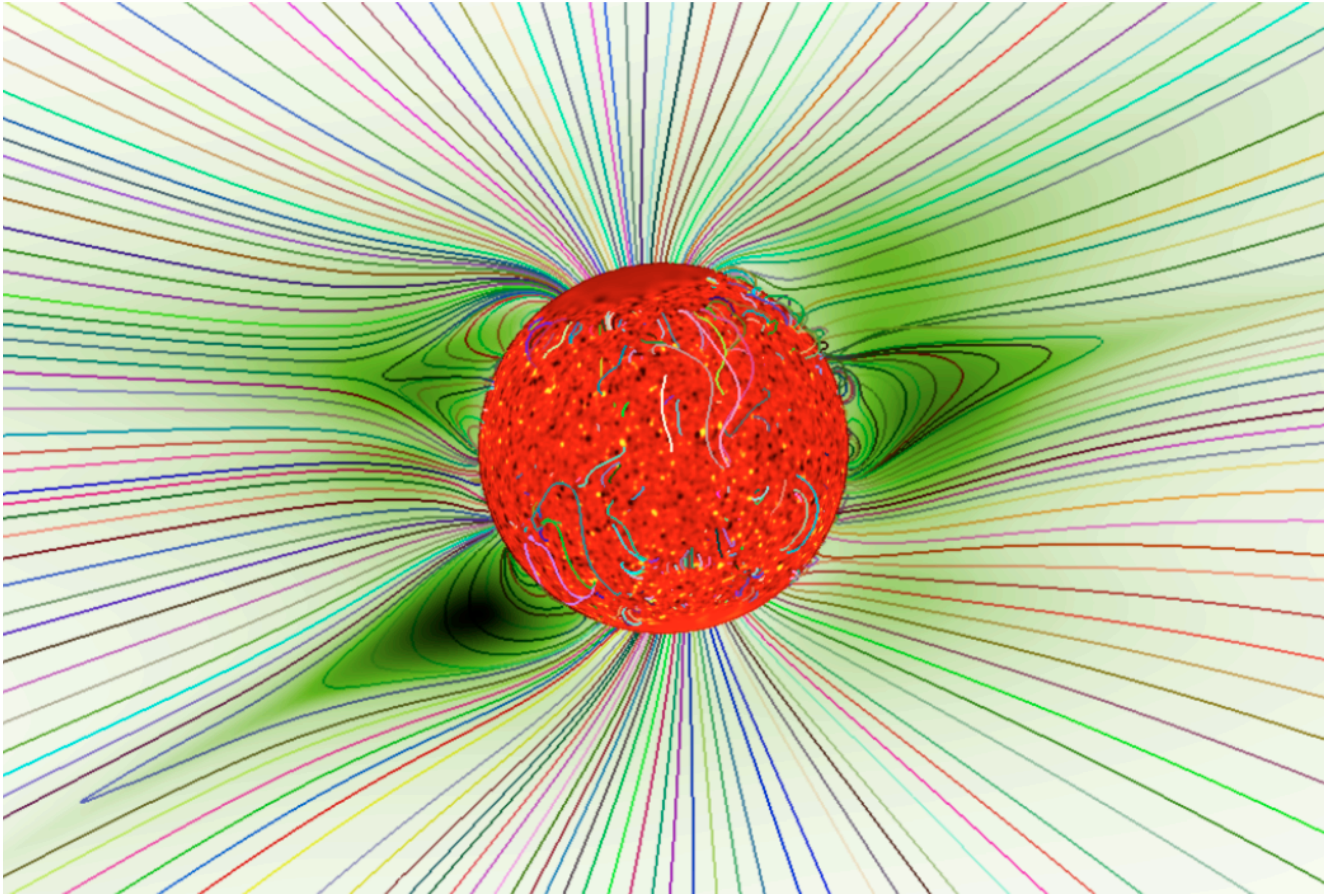
- Coronal streamer structure:
  - Presence of pseudo-streamers (*Wang et al*., 2007)
- Coronal Holes:
  - Polar holes were smaller (*Kirk et al*., 2009)
  - More equatorial holes (*Gibson et al*., 2009)
- Solar wind streams

  Stronger

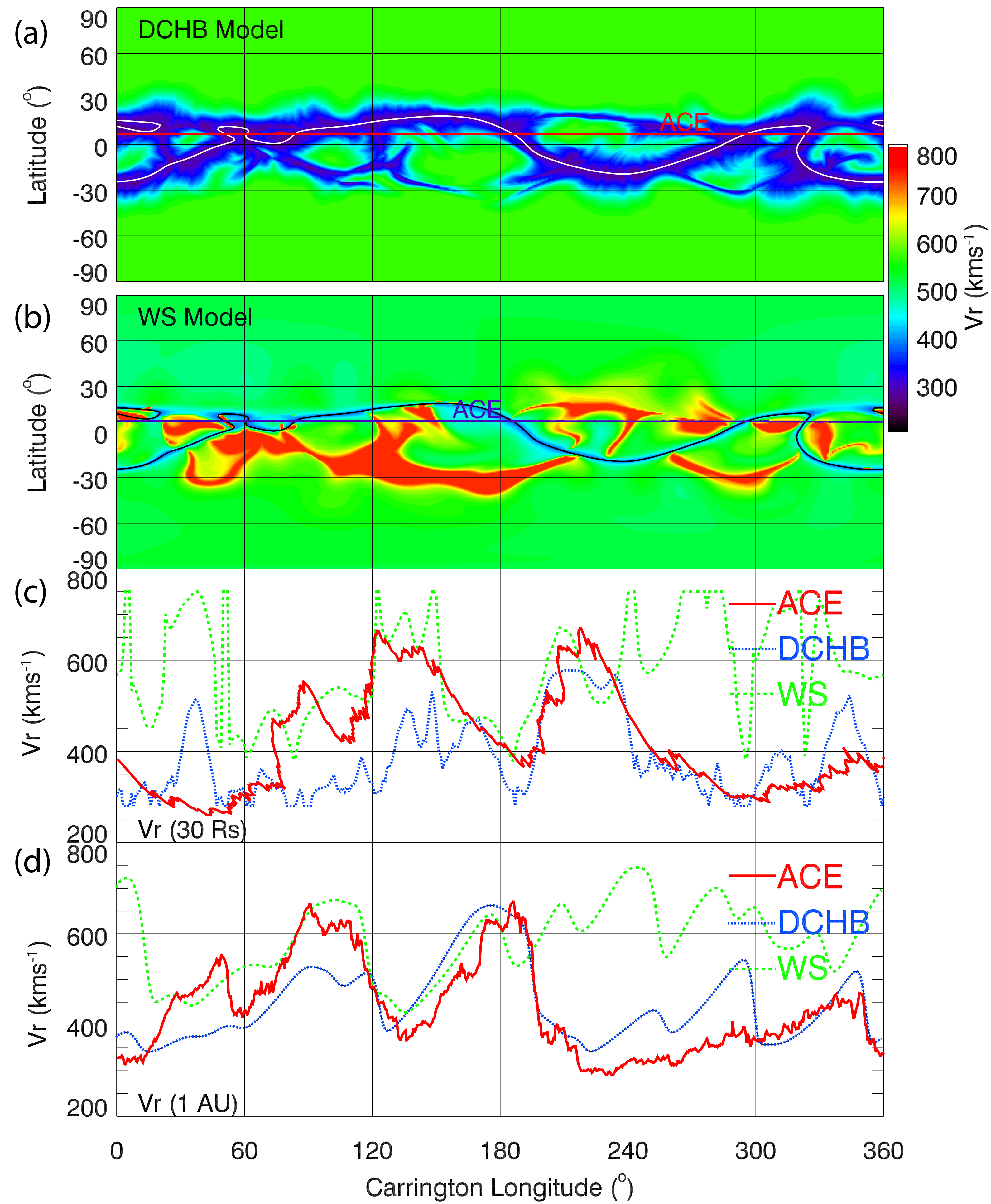
  Longer in duration

  More recurrent (*Gibson et al.,* 2009)

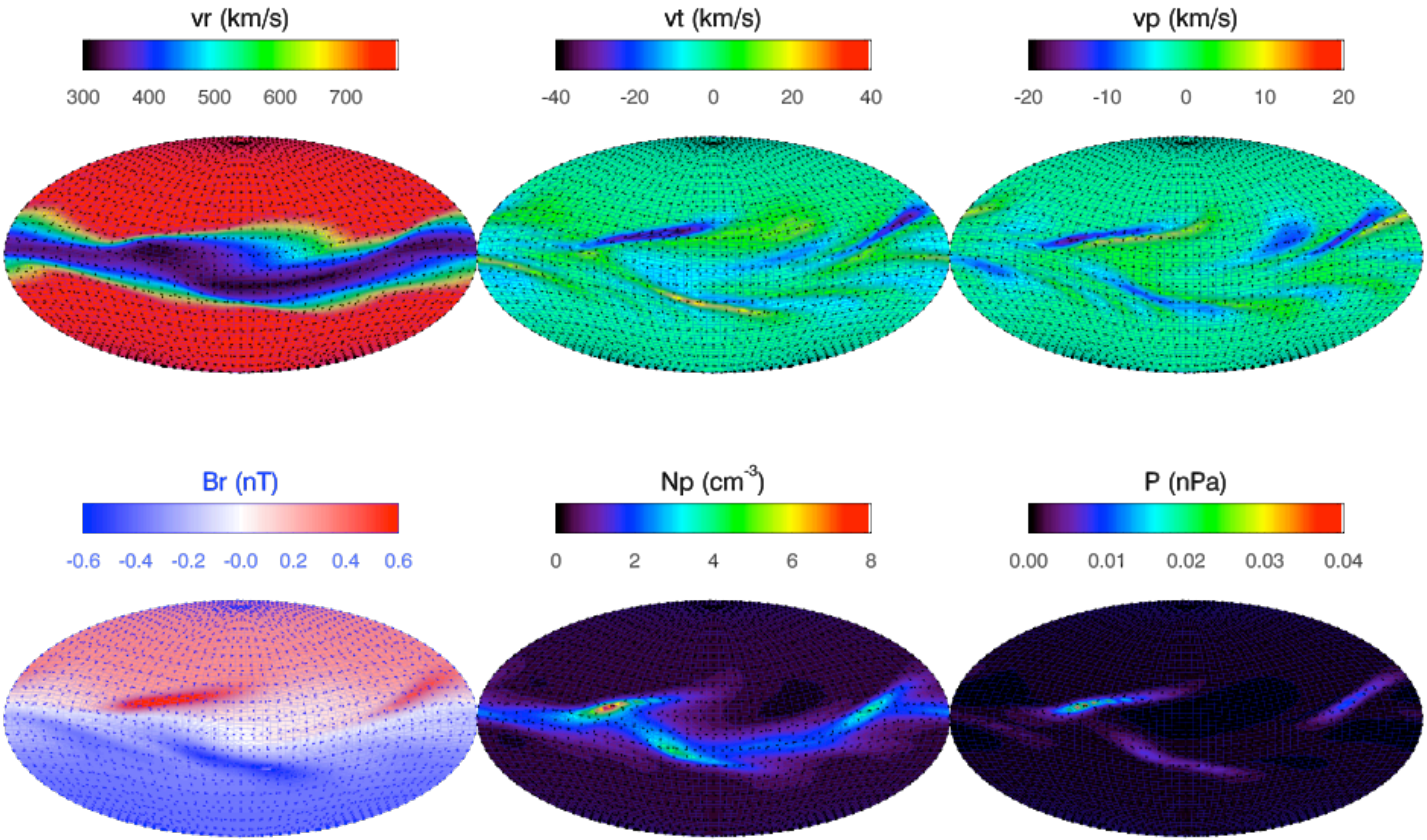
Structure of the corona during the 2008/2009 minimum: Pseudo-Streamers



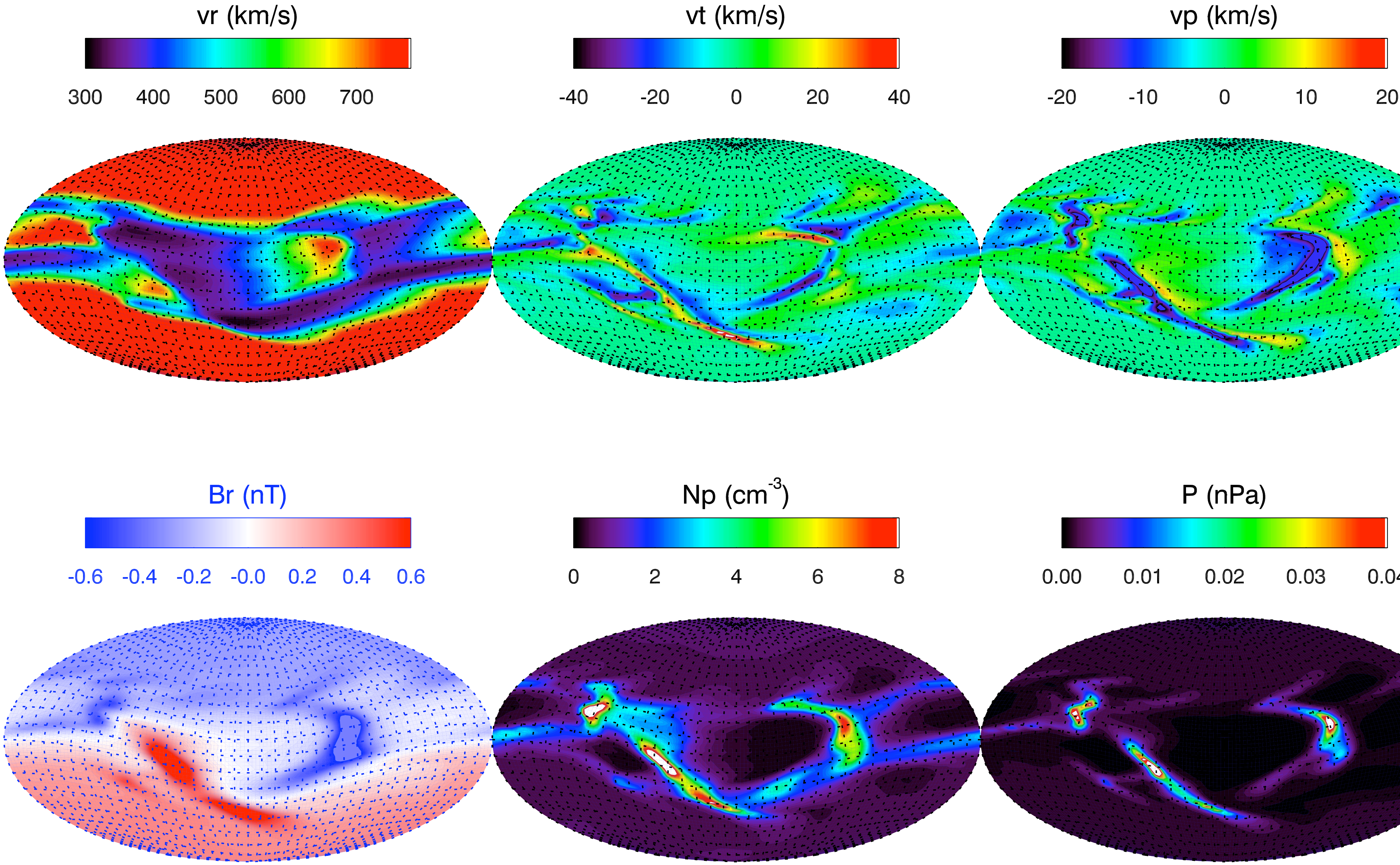
Pseudo-streamers can help us to differentiate between theories for the origin of the slow solar wind



Global structure of heliosphere at 2.2 AU for 1913(WSM, Aug/Sept 1996)



Global structure of heliosphere at 2.2 AU for 2068 (WHI, Mar/Apr 2008)

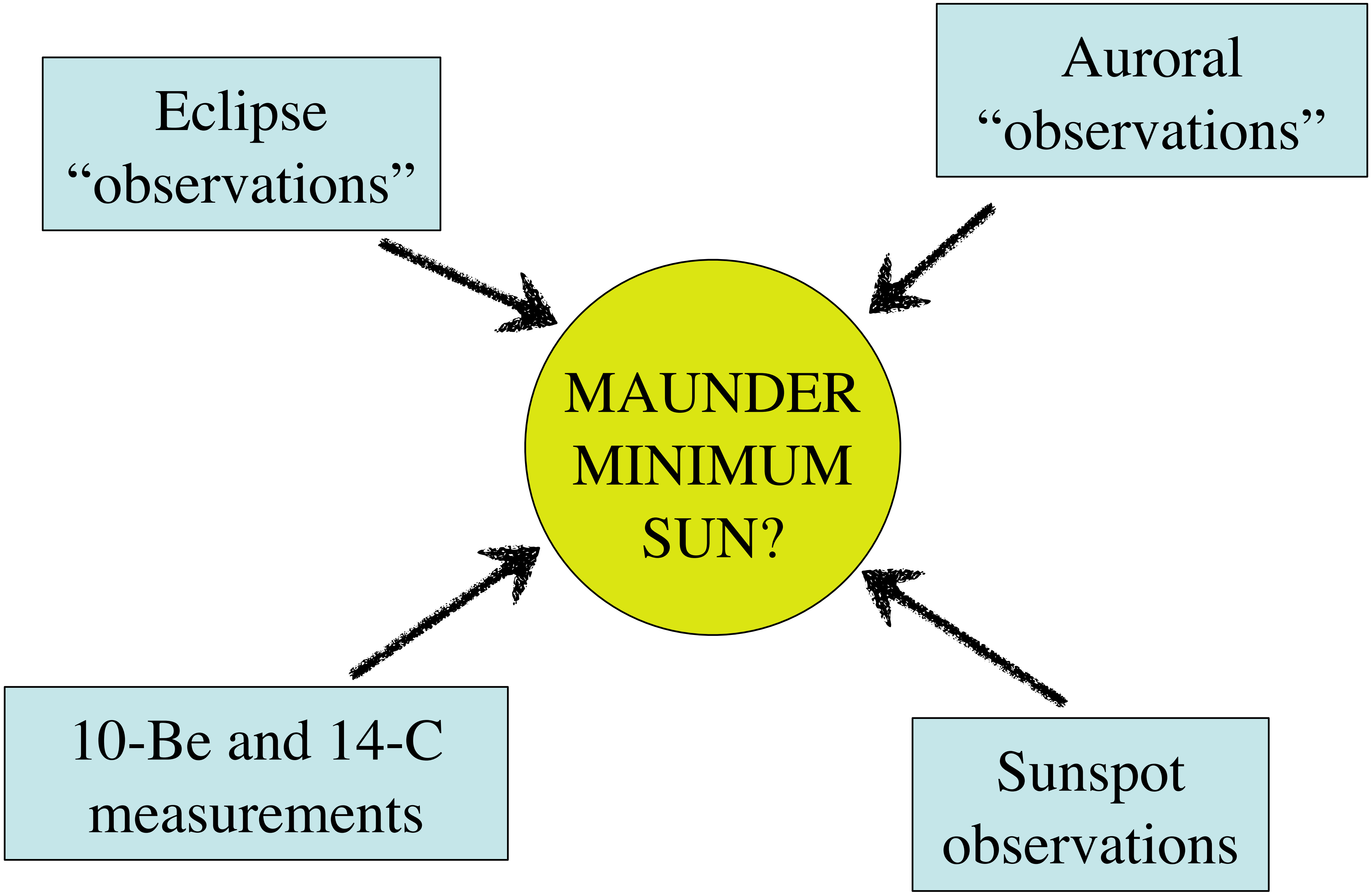


THE MAUNDER MINIMUM

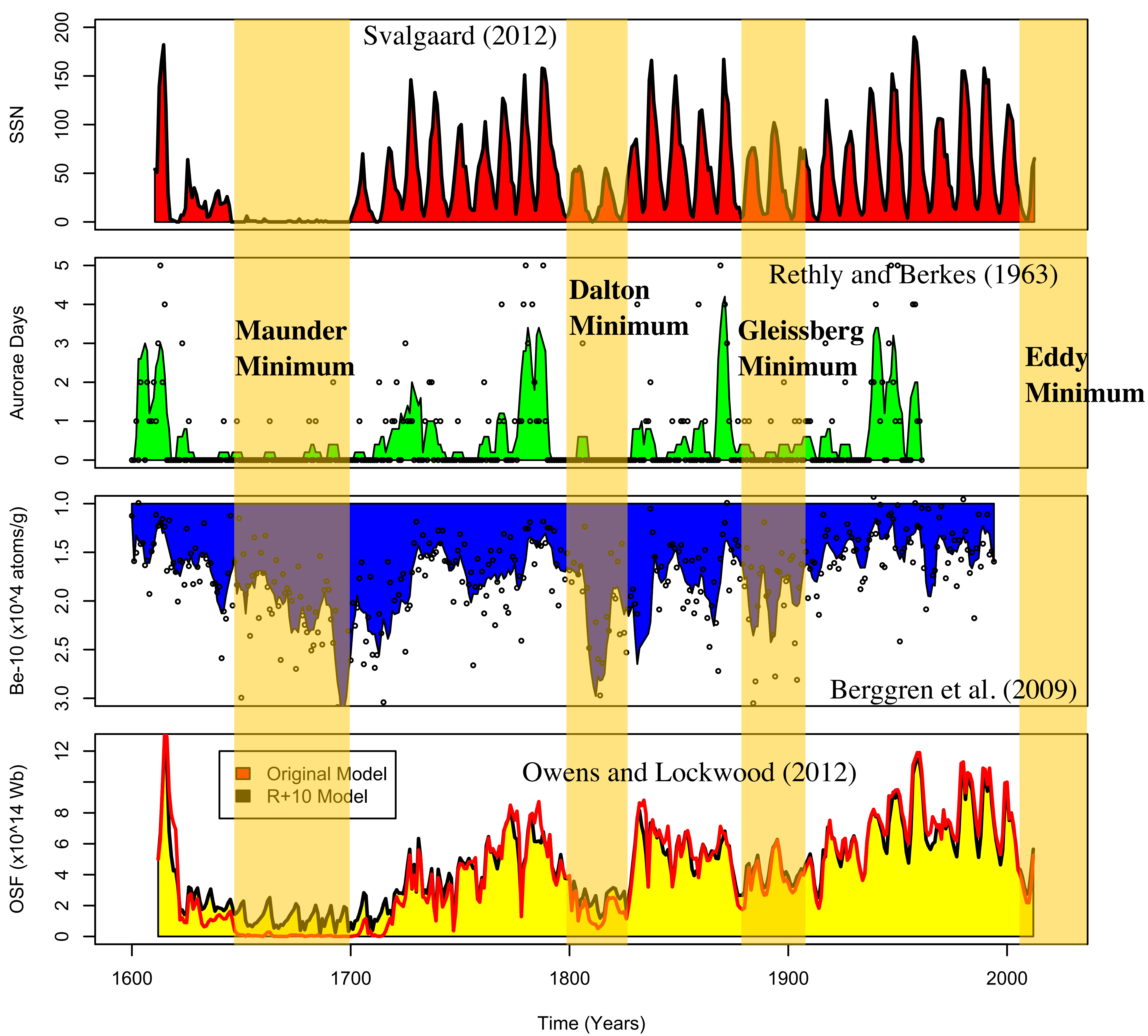
Previous speculation on the properties of the Maunder Minimum:

- **Eugene Parker**: "In view of the absence of a white light corona, we may conjecture whether the Sun was entirely shrouded in a coronal hole, yielding a fast steady solar wind, or whether there simply was no solar wind at all. I would guess the former, but I know of no way to prove the answer.
- **Jack Eddy**: "The solar wind would have blown steadily and isotropically, and possibly at gale force, since high-speed streams of solar wind are associated with the absence of closed structure in the solar corona."
- **Steve Suess**: "Firstly, C-14 data indicate an enhanced cosmic ray intensity, with the conclusion that the interplanetary magnetic field was smooth and perhaps of low intensity. Secondly, the apparent absence of a corona during eclipses requires low coronal density, suggesting an absence of closed magnetic loops. Thirdly, the absence of sunspots eliminates the possibility of a solar maximum type of corona of low emission intensity and implies a low large-scale photospheric field intensity. Finally, the absence of mid-latitude aurorae implies either that the solar wind speed or the IMF intensity, or both, were low and not irregular."
- **Karel Schrijver**: "the best estimate of magnetic activity...for the least-active Maunder Minimum phases appears to be provided by direct measurements in 2008-2009."

Observational Constraints on the Maunder Minimum



Observational Constraints from Long-Period Records:



OBSERVATIONAL CONSTRAINTS: ECLIPSE OBSERVATIONS

De Eclipsi Solis, 29 Martii, 1652.

Quam anteà ex *Tabulis Lansbergianis* exactè subduxeram ad *Meridianum Londinensem*; Et dabant *Deliquium* maximum, dig.10 $\frac{2}{5}$: & tempus ejusdem (pro visibili ☌) *h.* 9, *m.*26: & principium, *h.*8, *m.*10: finem, *h.*10, *m.*35: atquè sic medium, *h.*9, *m.*23: (viz. prius visâ ☌ue, *m.*3) totámque proindè durationem, 2 *h.*25 *m.* Ego autèm tùnc *Carigfergi* (seu *Knocfergi*) in *Hibernia*, juxtà mare, existens, (ùt Medicus, ex Senatusconsulto, Copiis Anglicanis, in partibus istius Regionis septentrionalibus) notavi hanc Eclipsin per totum ejus decursum, Cœlo existente sereno: (præsente uno mihi familiari, qui ibi in horto quodam, Sciatericum, seu Solarium horizontale, su-

Dr. John Wybard describes his personal observation of the 1652 eclipse, while he was stationed in Carrickfergus (p. 99 of Vincent Wing's Treatise of 1656 "A New and Compendius Restauration of Astronomie in Four Parts"):

"This circle or corona, which was fastened around the margins of the opaque moon, could be seen equivalent to some brightness or flashing from the sun as from inside (or extending beyond) the margin of the moon underneath, or the visible periphery, such as from a dense or opaque cloud adjacent to the Sun, around its extremities projecting fringes or (as it occurs frequently) flanks."

Dr. Wybard reports that the eclipse was observed also by the vice-prefect of Carrickfergus, who had a telescope:

"The somewhat bright corona rather appeared to us to be the reddish margin itself, or some small portion of the sun itself beyond or inside from everywhere the opaque disc of the moon, than something springing forth or in so far as some radiating from it or diffusion of light beyond or beside it; such as from a cloud around its extremities, flaps or fringe, as I said before."

OBSERVATIONAL CONSTRAINTS: ECLIPSE OBSERVATIONS

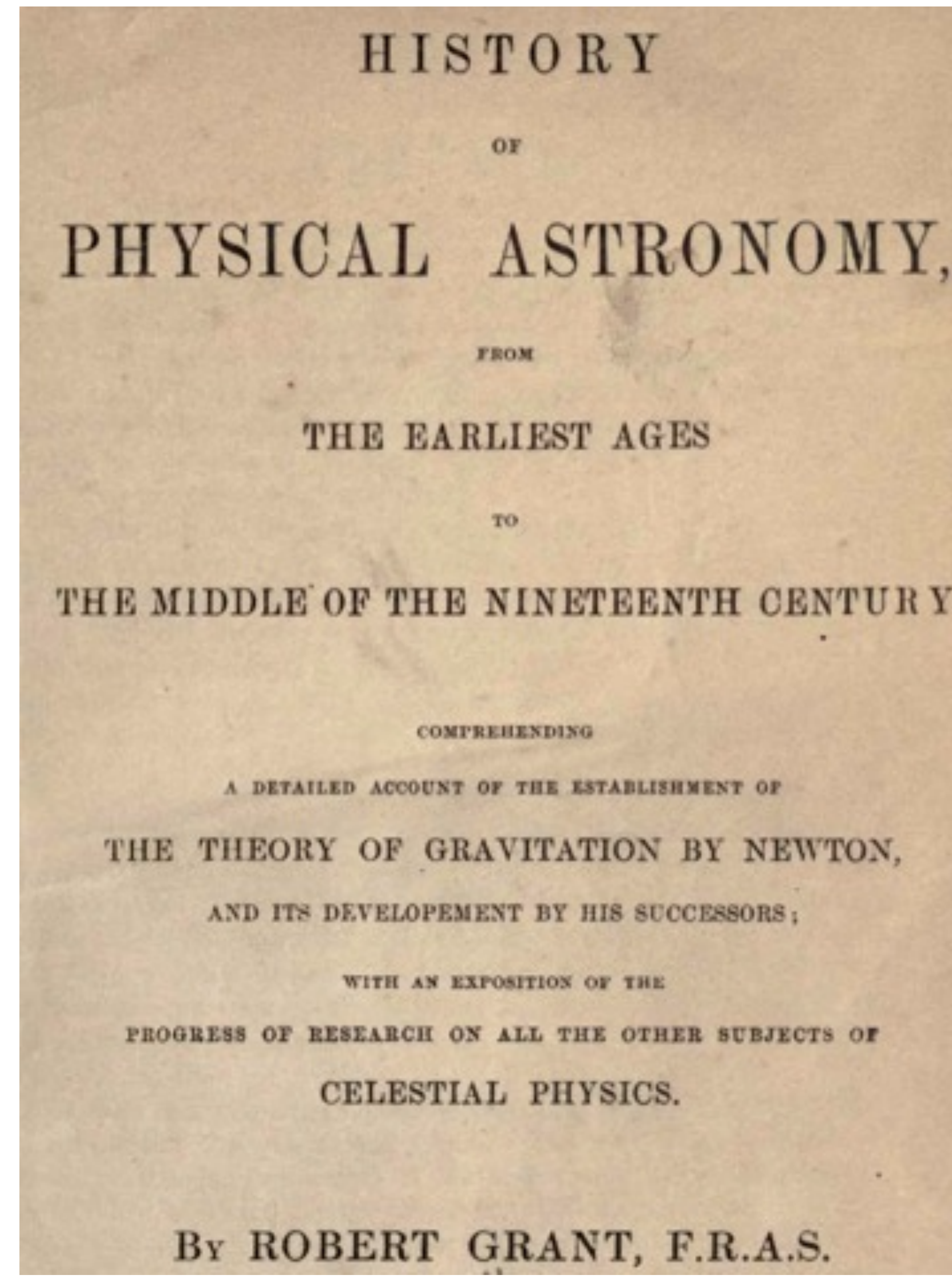
From Grant (1852):

The luminous ring formed a conspicuous accompaniment of the total eclipse of the sun which happened on the 12th of May, 1706. The description of it given by MM. Plantade and Capies, who observed the eclipse at Montpellier, is clearer and more precise than any other that had been hitherto recorded. As soon as the sun was totally eclipsed, there appeared around the moon a very white light forming a kind of corona, the breadth of which was equal to about 3'. Within these limits the light was everywhere equally vivid, but beyond the exterior contour, it was less intense, and was seen to fade off gradually into the surrounding darkness, forming an **annulus** around the moon of about 8 in diameter.

Of the 1652, eclipse, Dr. Wyberd, who observed this eclipse at Carrickfergus in the north of Ireland, has stated: “that in reality the sun was totally eclipsed, and that the appearance was due to a corona of light around the moon, arising from some unknown cause. He adds, that it had a uniform breadth of half a digit, or a third of a digit at least, that it emitted a bright and radiating light, and that it appeared concentric with the sun and moon when the two bodies were in conjunction.”

Halley has given an interesting account of the total eclipse of the sun which happened at London on the 3rd of May, 1715. The total obscuration lasted 3 m 22 s . The planets Jupiter, Mercury, and Venus, as well as Capella and Aldebaran, were visible to the naked eye. There appeared a luminous ring around the moon as on the occasion of the eclipse of 1706.

On the 9th of February, 1766, a total eclipse of the sun occurred, which was observed in the Southern Ocean by the persons on board the French ship of war the Comte d'Artois. The total obscuration lasted only 53 s . There was seen a luminous ring about the moon, which had four remarkable expansions situate at a distance of 90 [degrees] from each other.



HISTORY

OF

PHYSICAL ASTRONOMY,

FROM

THE EARLIEST AGES

TO

THE MIDDLE OF THE NINETEENTH CENTURY.

COMPREHENDING

A DETAILED ACCOUNT OF THE ESTABLISHMENT OF

THE THEORY OF GRAVITATION BY NEWTON,

AND ITS DEVELOPEMENT BY HIS SUCCESSORS;

WITH AN EXPOSITION OF THE

PROGRESS OF RESEARCH ON ALL THE OTHER SUBJECTS OF

CELESTIAL PHYSICS.

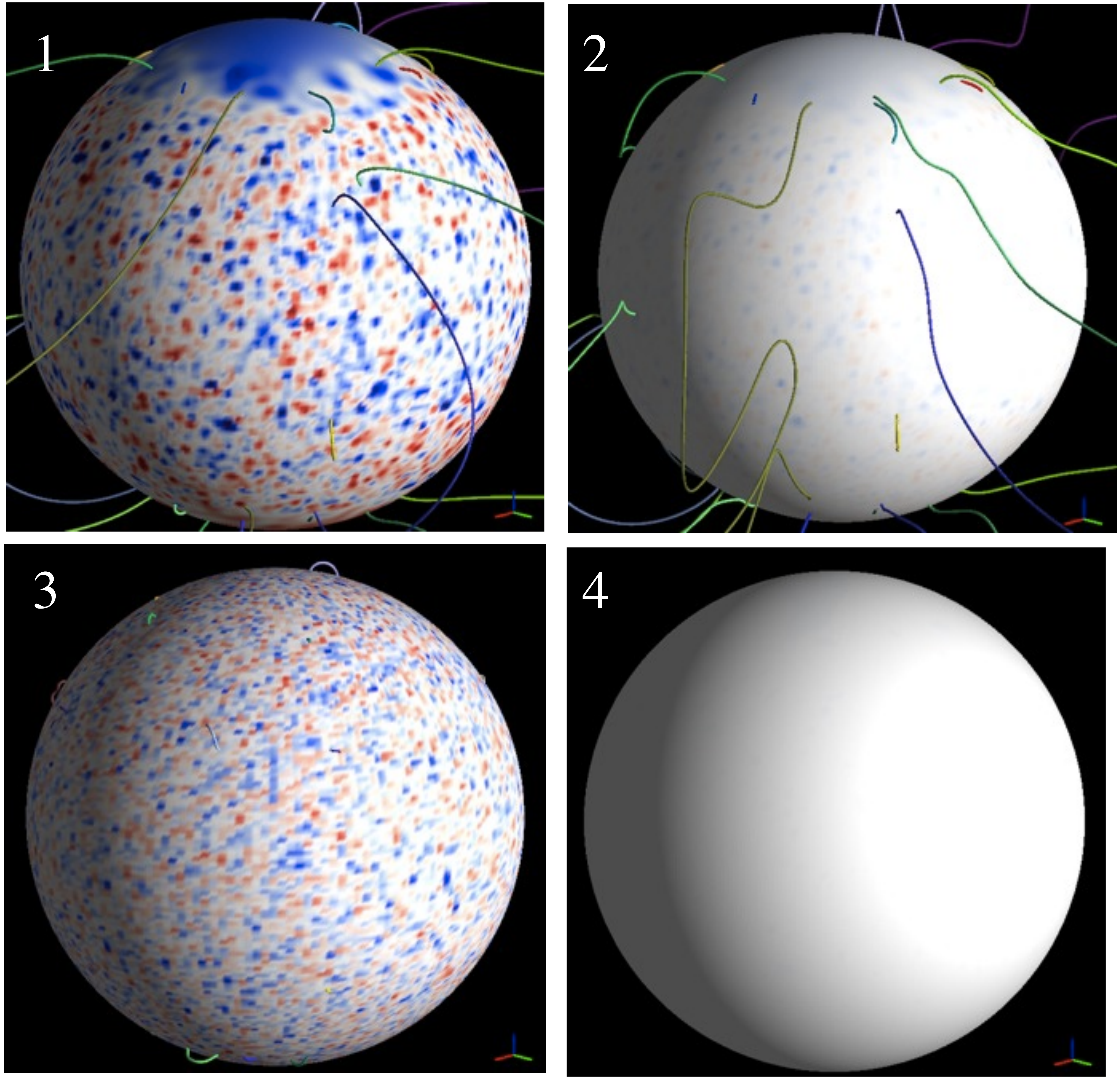
By ROBERT GRANT, F.R.A.S.

Possible Maunder Minimum Scenarios:

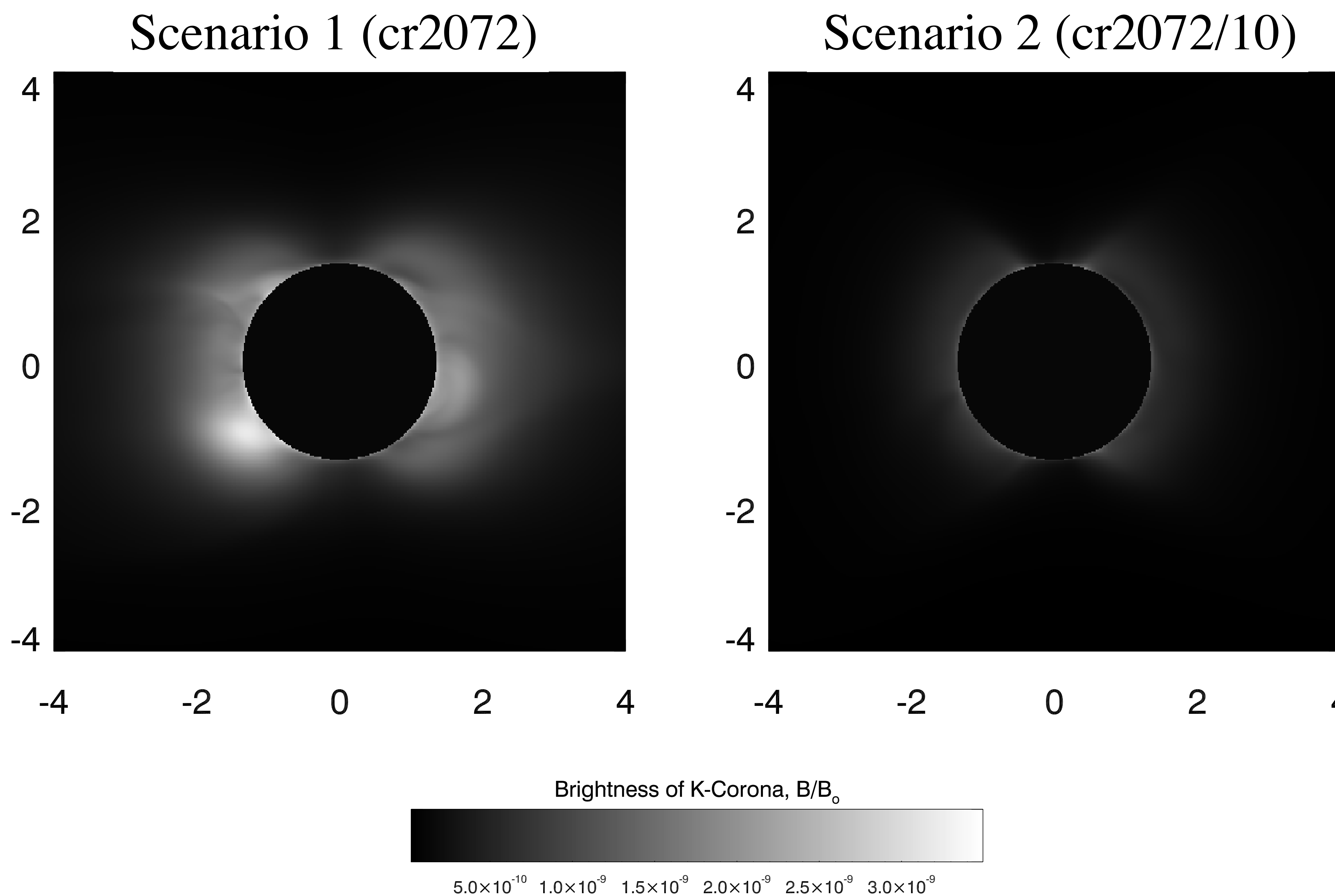
- The photospheric magnetic field during the Maunder Minimum interval was:

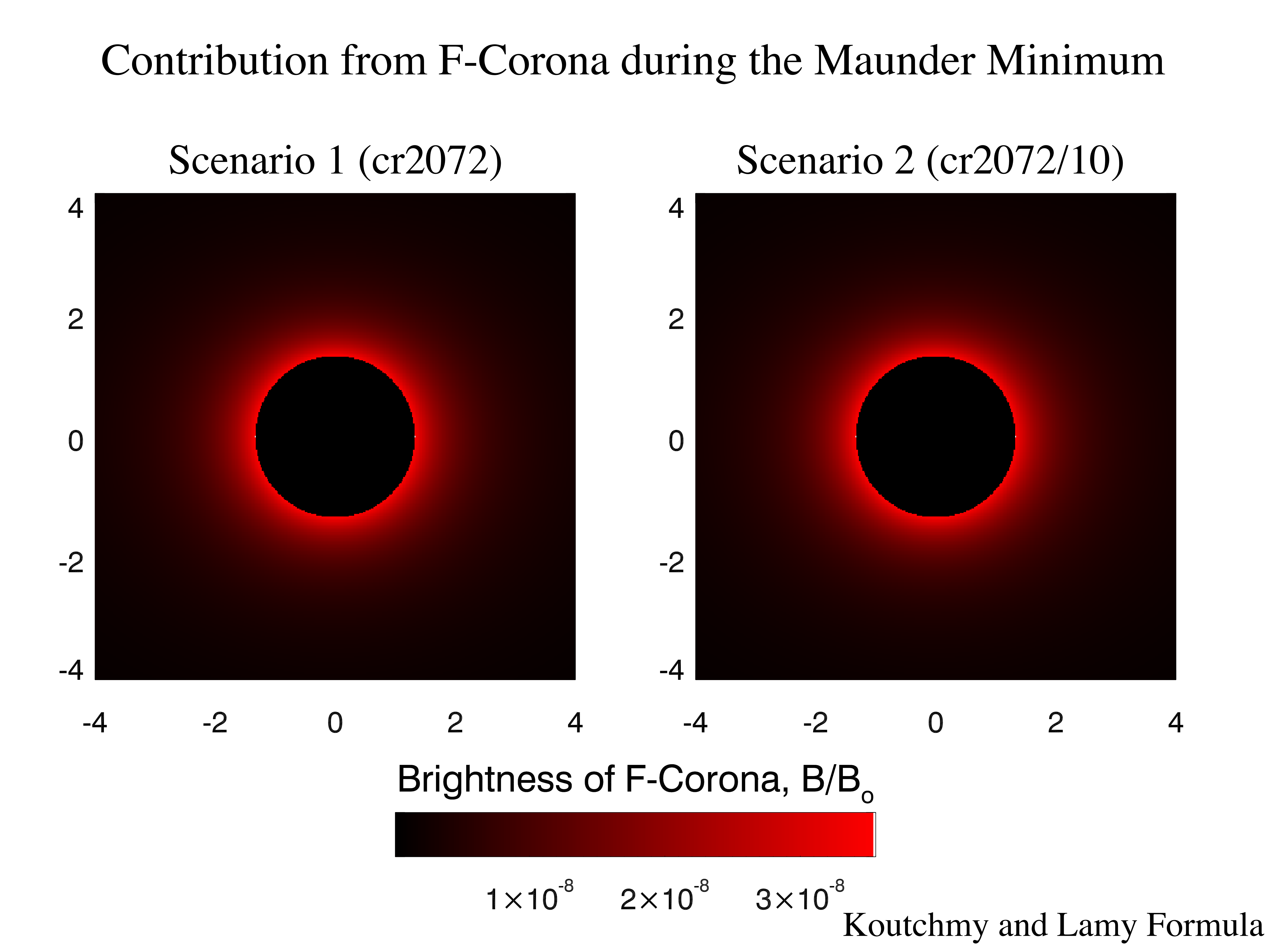
- Similar to the recent (2008/9) solar minimum (Scenario 1)
- Similar in structure, but substantially less than 2008/9 values (10%, 50%?) (Scenario 2)
- Devoid of any active regions or large-scale polar fields (i.e., parasitic polarities only) (Scenario 3)
- Zero (Scenario 4)

Possible Maunder Minimum Scenarios:

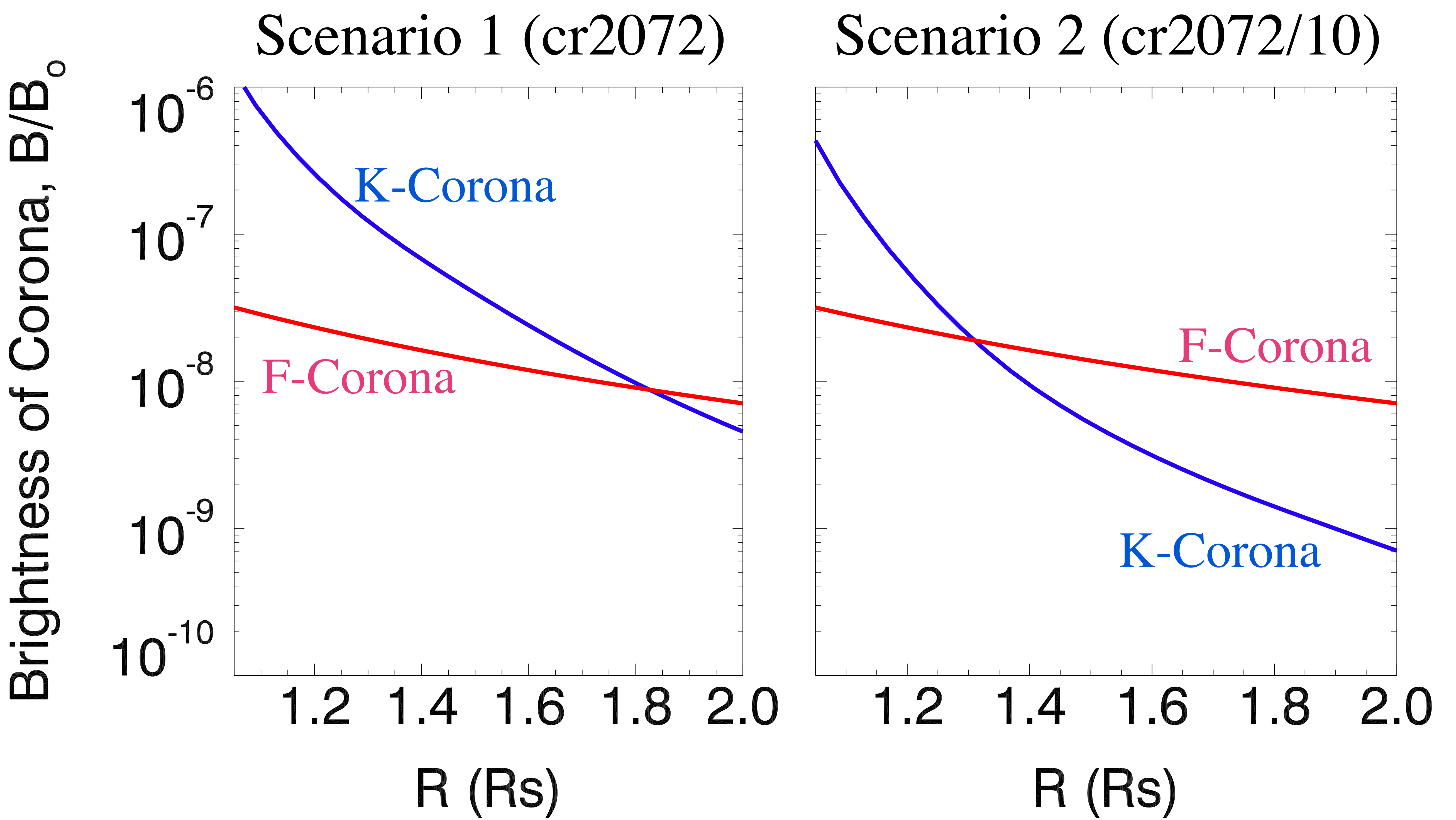


Comparison of White Light Predictions for Scenarios 1 and 2




Contribution from F-Corona during the Maunder Minimum
Scenario 1 (cr2072)
Scenario 2 (cr2072/10)
4
2
0
-2
-4
-4
-2
0
2
4
Brightness of F-Corona, B/B_o
1×10^{-8}
2×10^{-8}
3×10^{-8}
Koutchmy and Lamy Formula

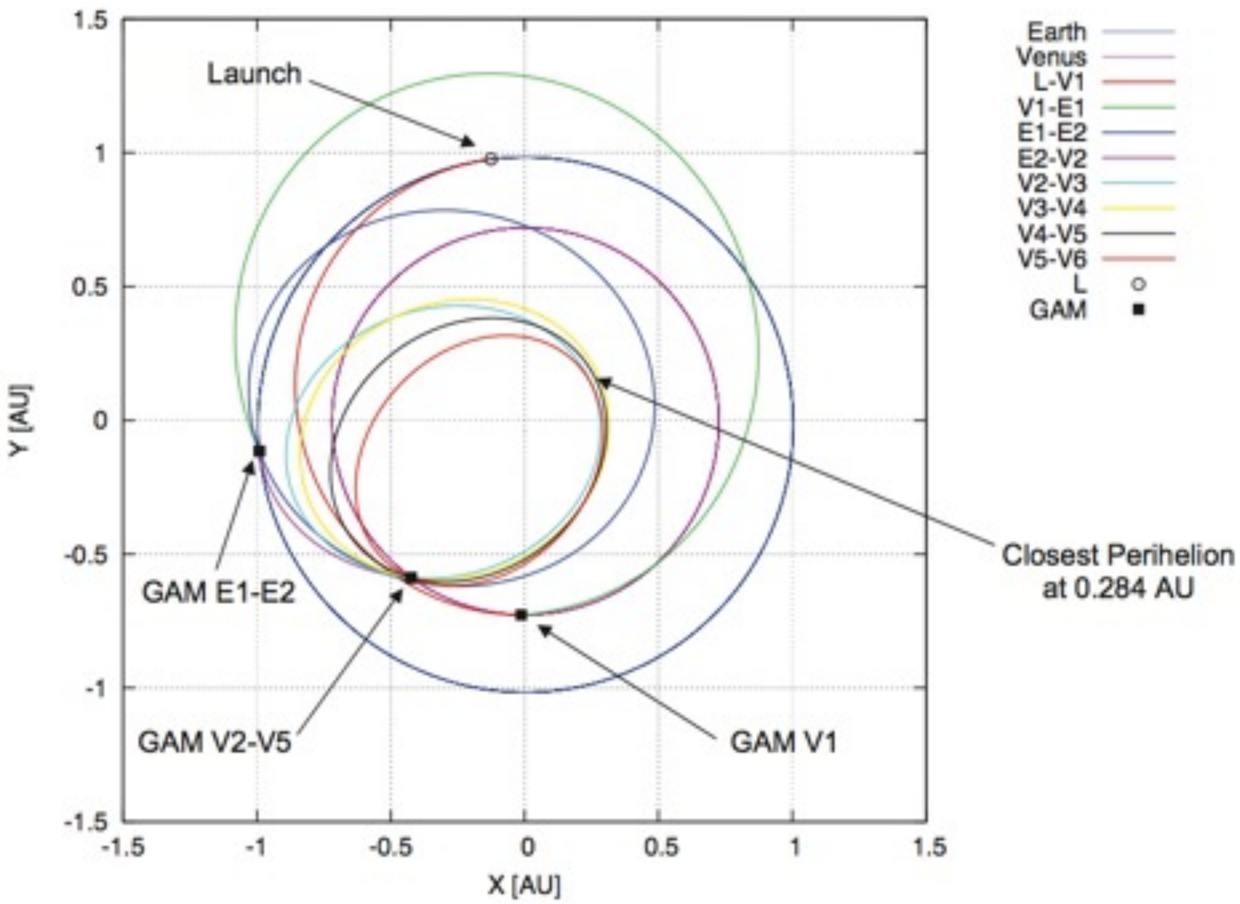
Relative Contributions to Brightness from the K- and F-corona during Recent Solar Minimum (CR 2072) and 1/10-th scaled magnetogram proxy for Maunder Minimum

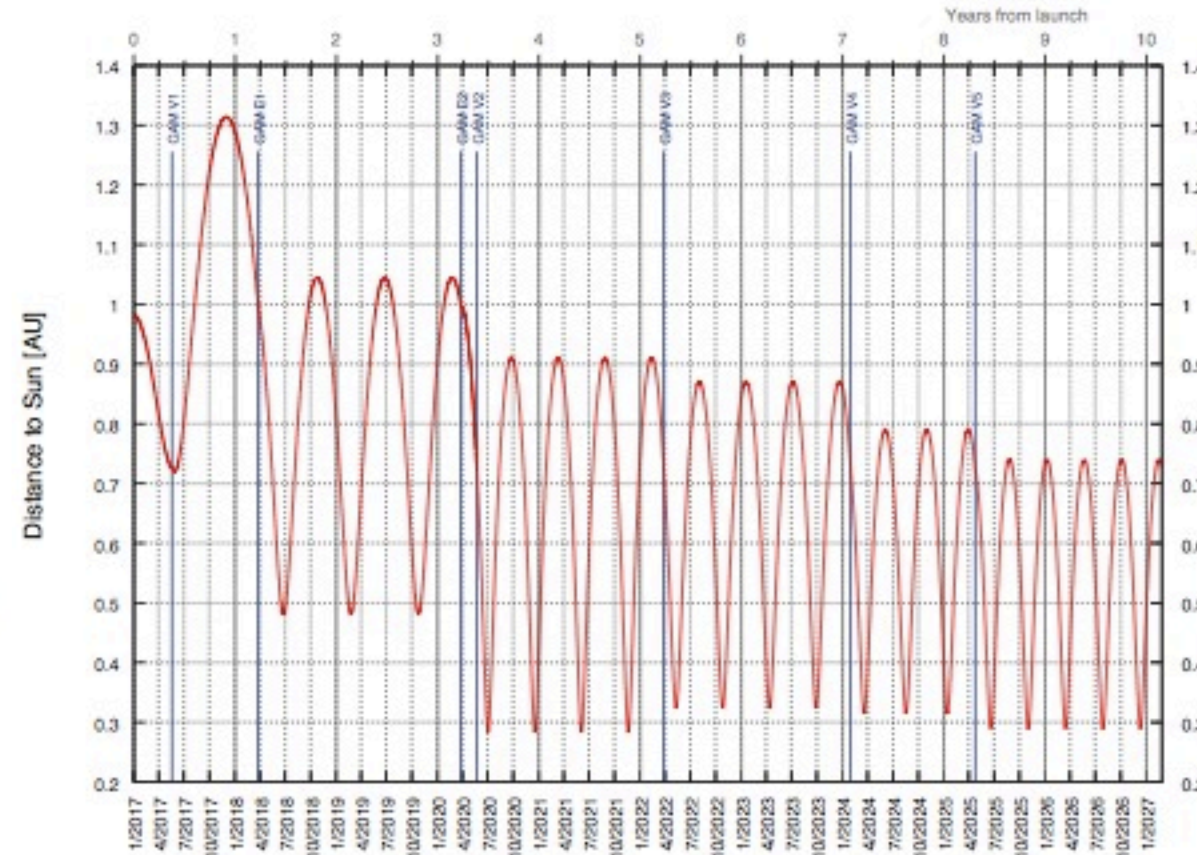


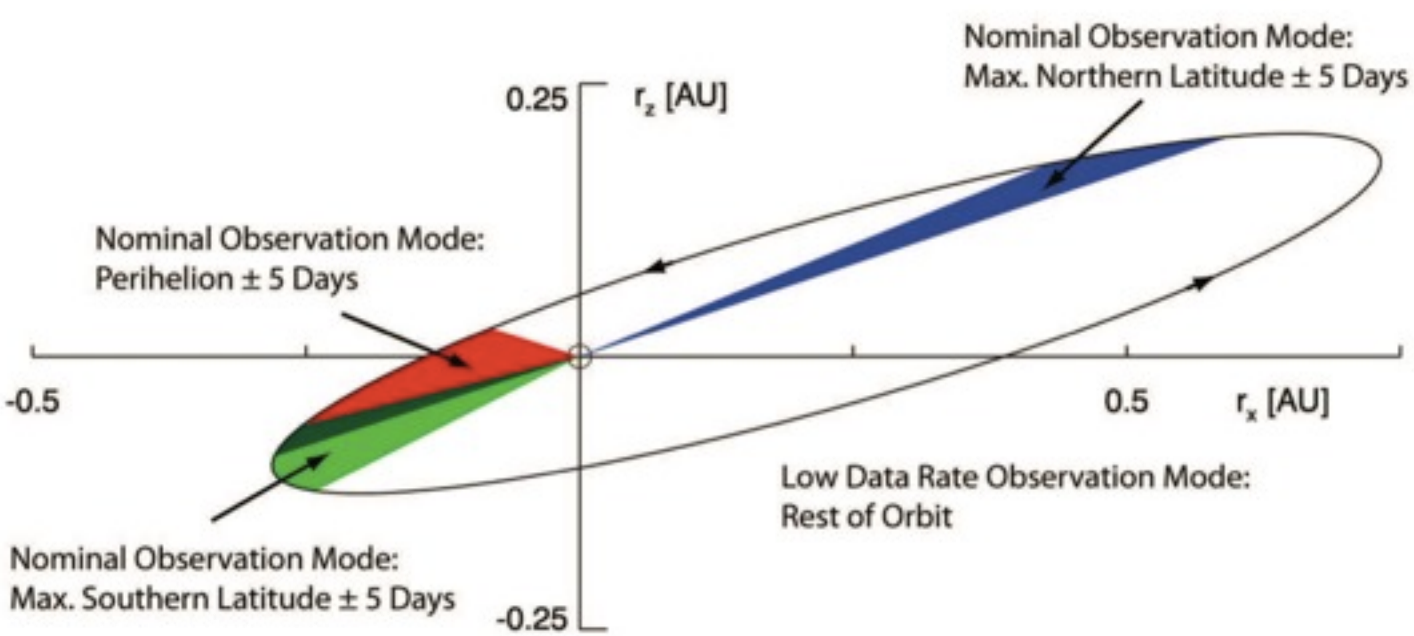
What is the best candidate for Maunder Minimum Sun?

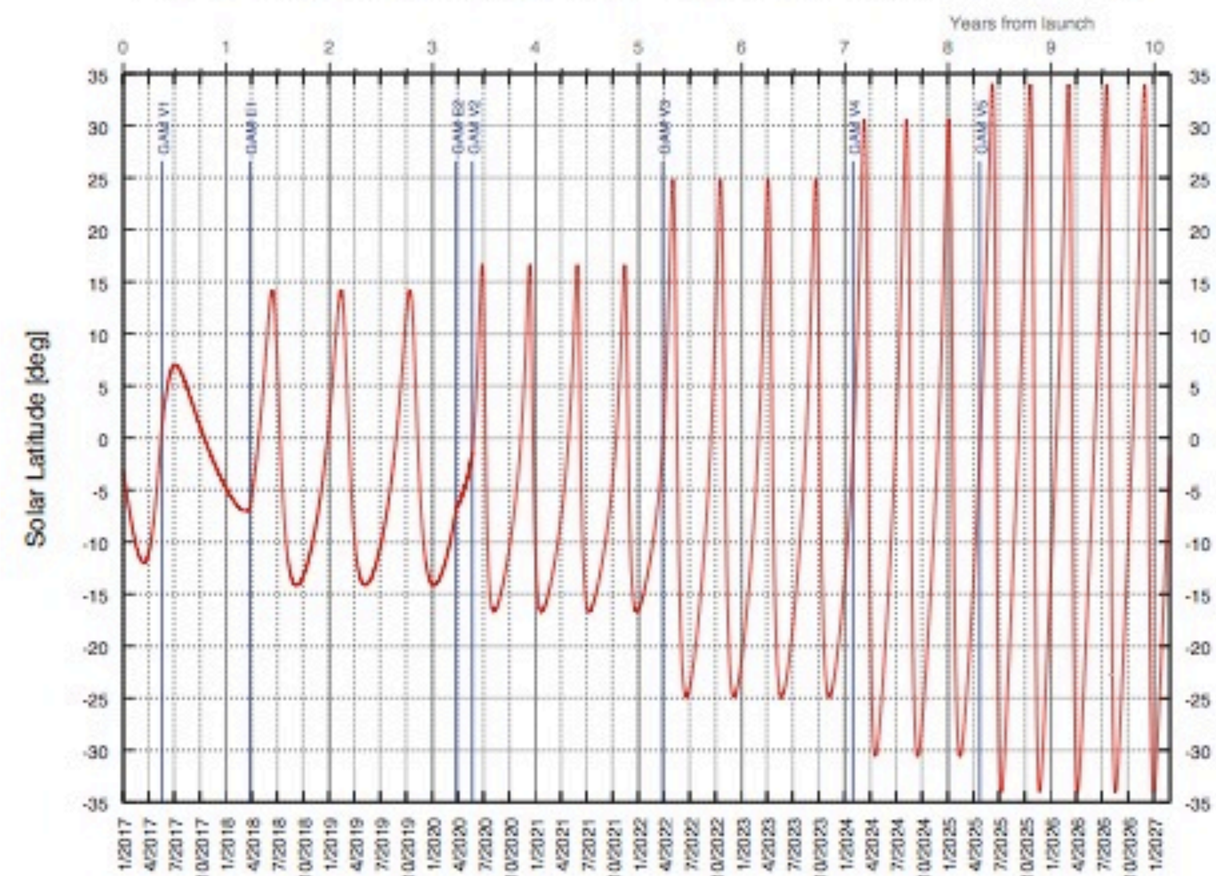
- It is difficult to constrain the structure/properties of the solar wind during the MM based on the limited "observations"
- It is unlikely that the MM corona was:
  - like the 2008/2009 minimum;
  - randomly-oriented small scale dipoles; or
  - "magnetic-free"
- The "more likely" scenario appears to be that of a "scaled-down" ($B_{\mathrm{MM}} \sim B_{2008}/10$) version of 2008 solar minimum conditions

Future Progress: New Observations from Solar Orbiter



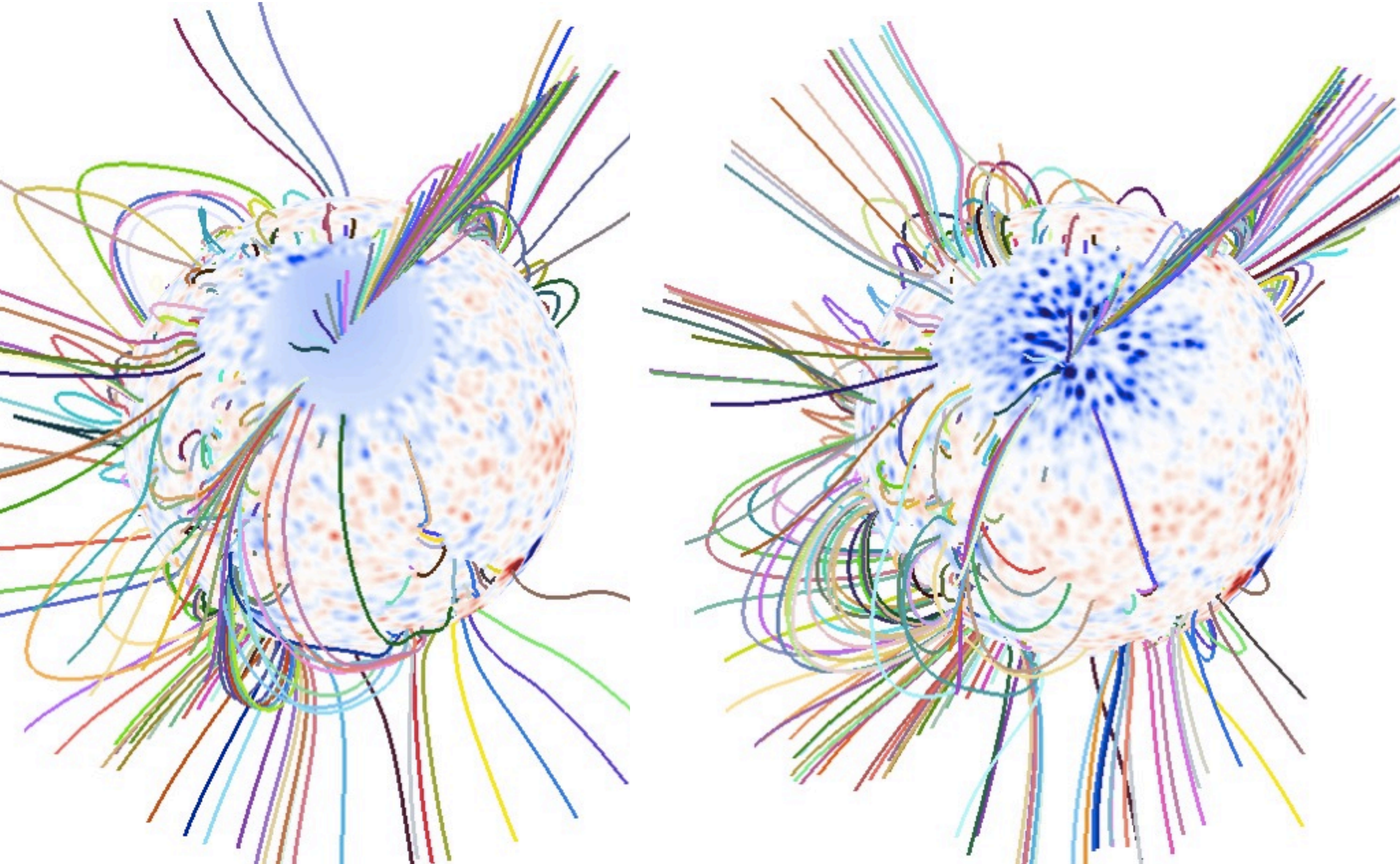






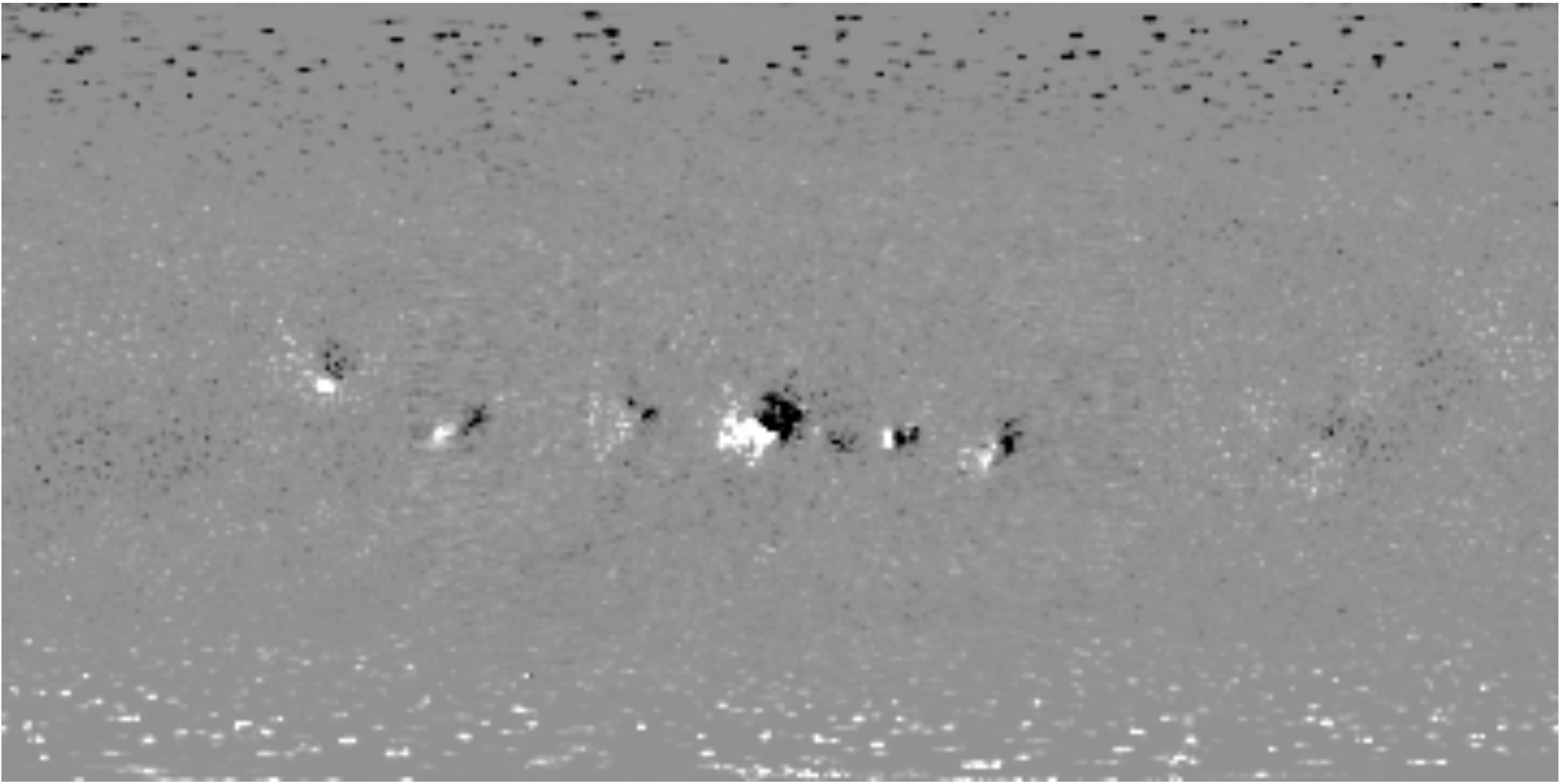
Müller et al. (2012)

Future Progress: Polar Boundary Conditions



Can ADAPT solve the “missing flux” problem?

Future Progress: Synchronic, Time-Dependent Boundary Conditions



Summary

- Global MHD model solutions provide a global context for interpreting multi-point observations (www.predsci.com)
- **PAST**: The "most likely" scenario for the structure of the Maunder Minimum heliosphere is that of a 1/10-th scaled version of solar minimum conditions
- **PRESENT**: The 2008/2009 solar minimum can be understood in terms of the changes in the photospheric magnetic field, particularly the weaker polar field strengths
- **FUTURE**: Future missions (Orbiter/Probe) offer the potential to:
    - Test the importance of driving global models with multi-point synchronic observations
    - Provide crucial polar magnetic field measurements