Statistical Analysis of the Interplanetary Magnetic Field (IMF) across the Planets

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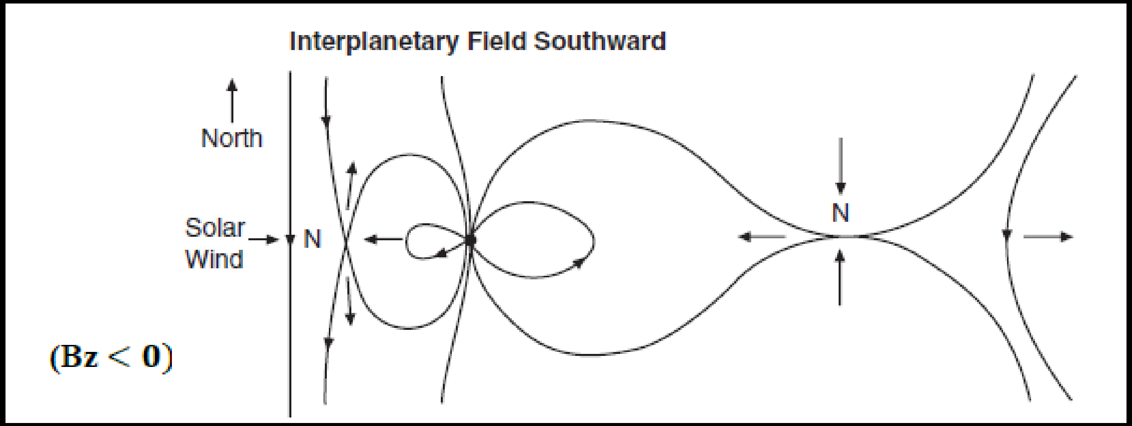
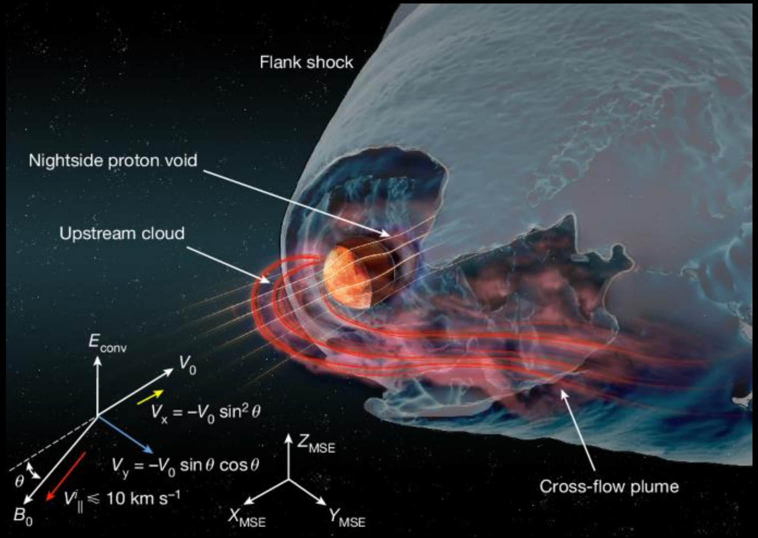
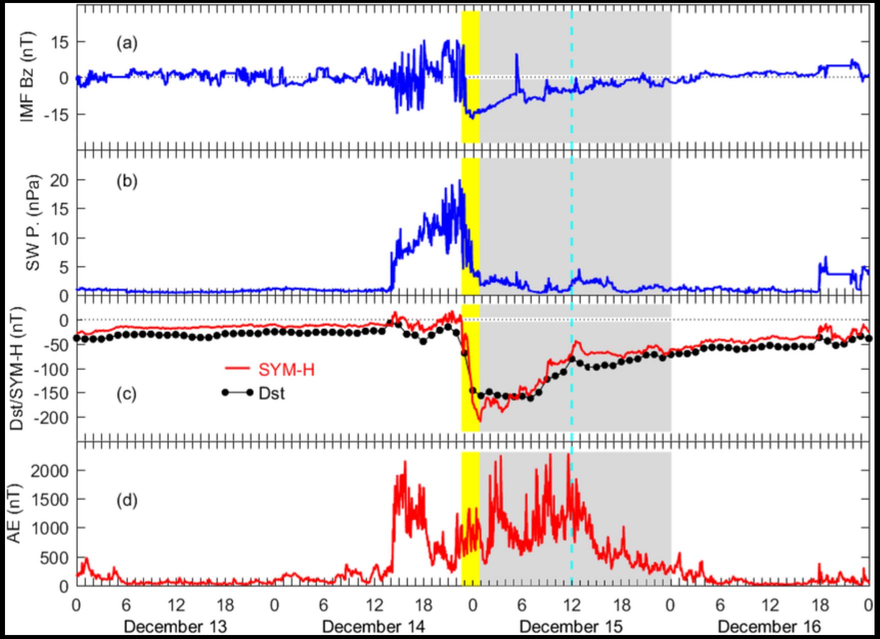
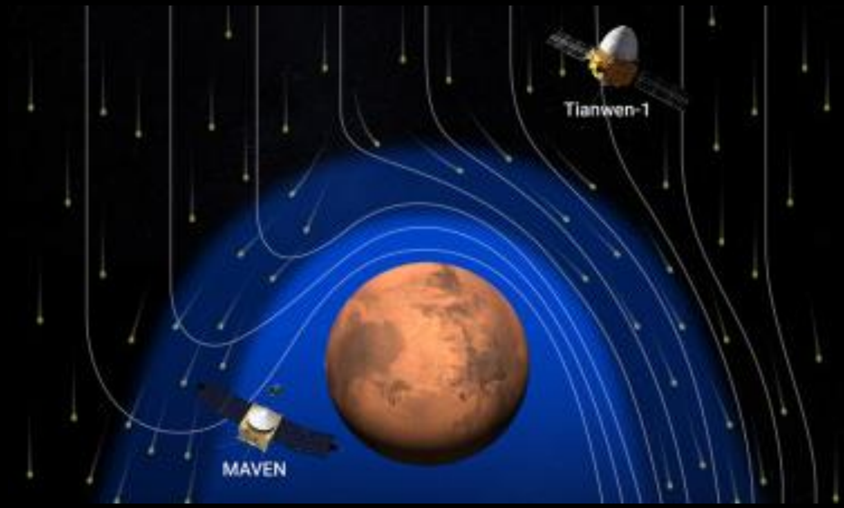
IMF is A DRIVER for Planetary Magnetosphere

Under Southern IMF, Planetary Substorm (Dungey Cycle) Happens [Earth & Mercury]



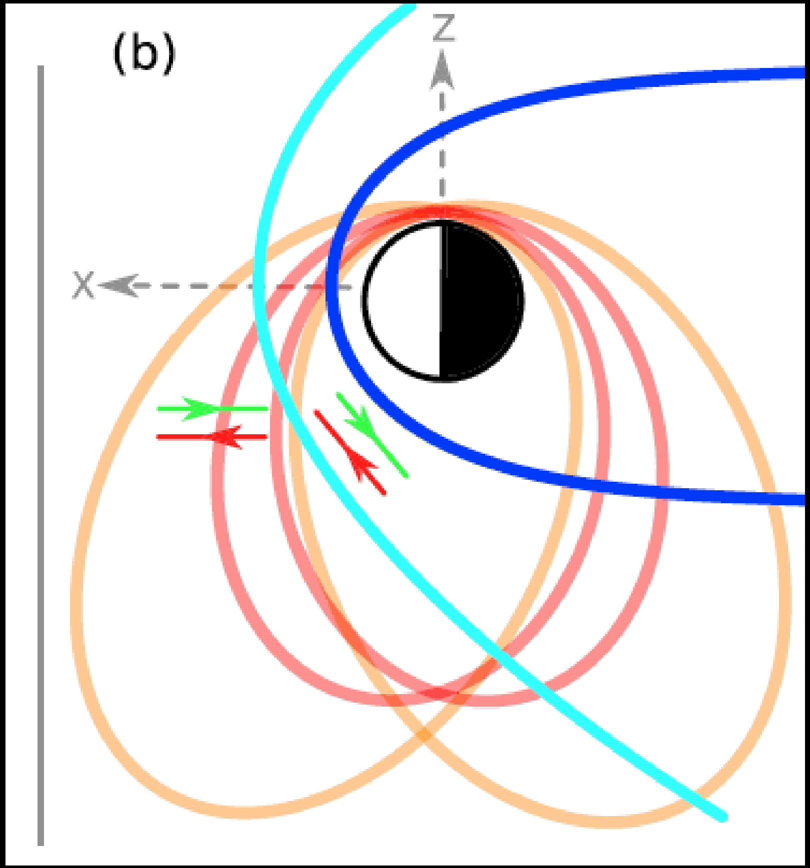






Under Radial IMF, the Martian Magnetosphere May Degenerate (upper, Zhang et al., 2024) or Not (bottom, Lin et al., 2025)

The <u>LACK</u> of Real-Time Monitor

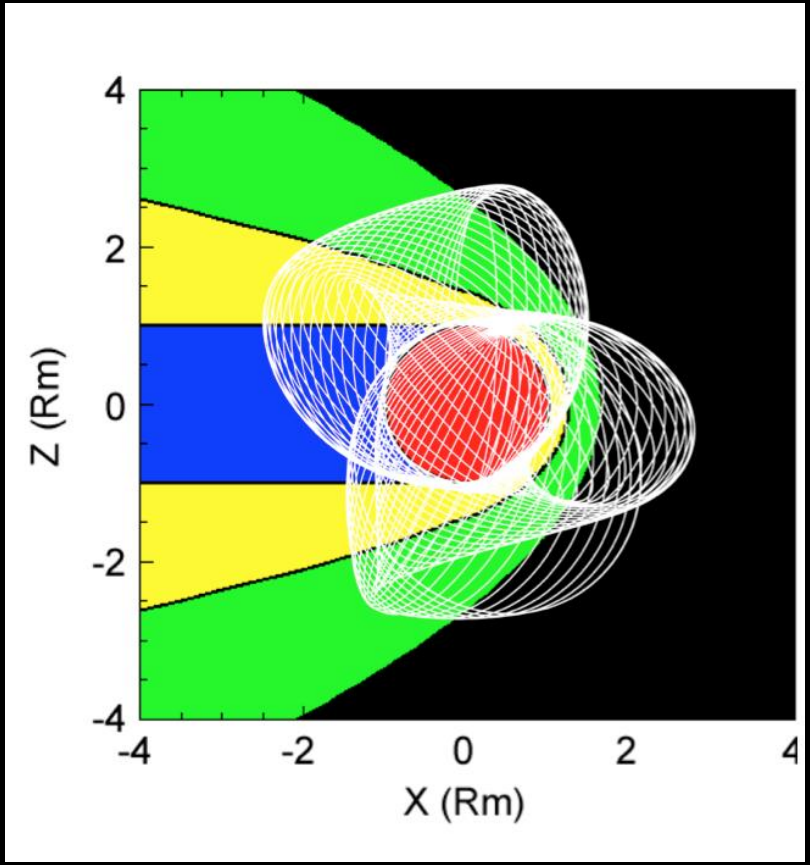


NASA-MESSENGER's Orbit

For Planetary Observation:

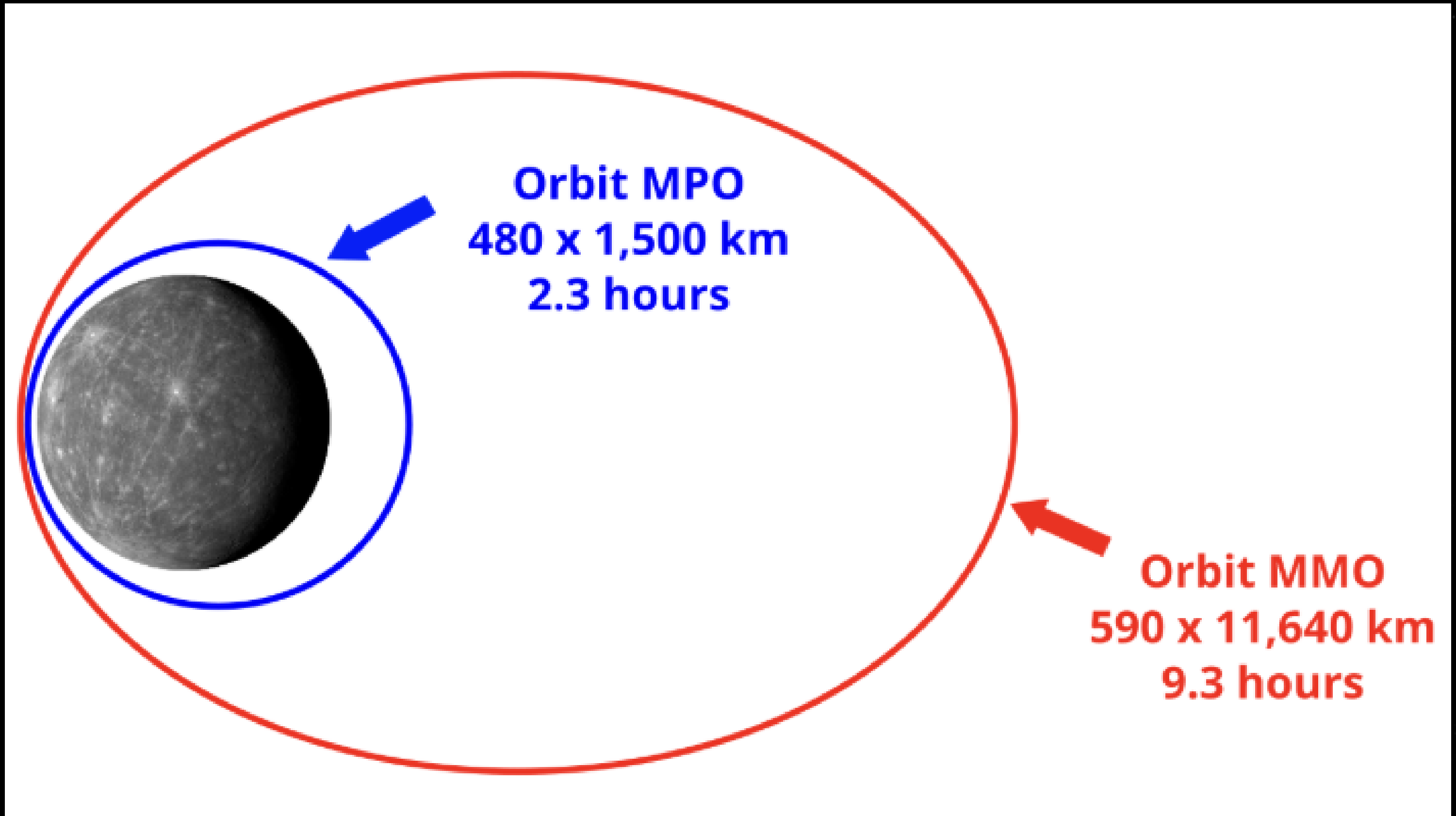
1. No Upstream Monitor at L1
2. No Spacecraft Constantly stay at Upstream
3. Even no orbiter in the upstream [e.g., Uranus, Neptune]

<u>Limited, the most recent upstream IMF for downstream study</u>

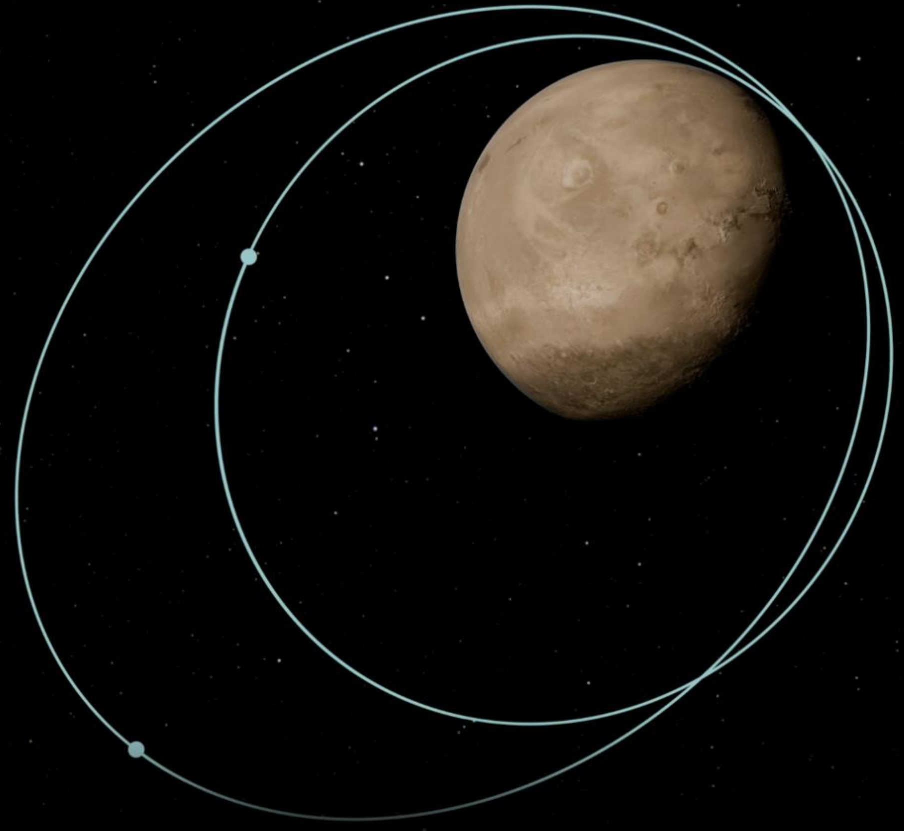


NASA-MAVEN's Orbit

The LACK of Real-Time Monitor



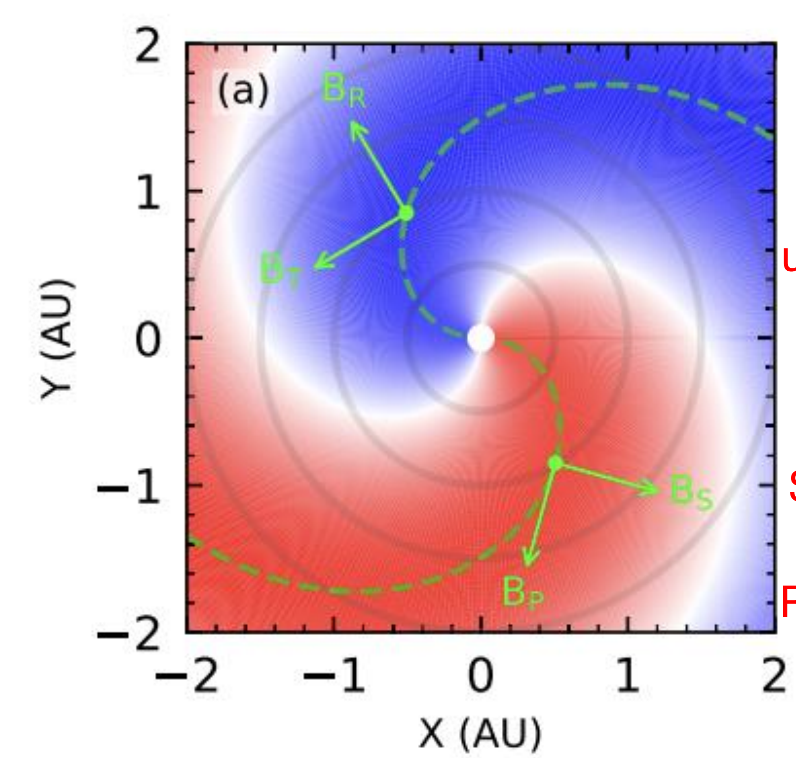
ESA-JAXA Joint
BepiColombo Mission
to Mercury



NASA-ESCAPADE
Mission to Mars

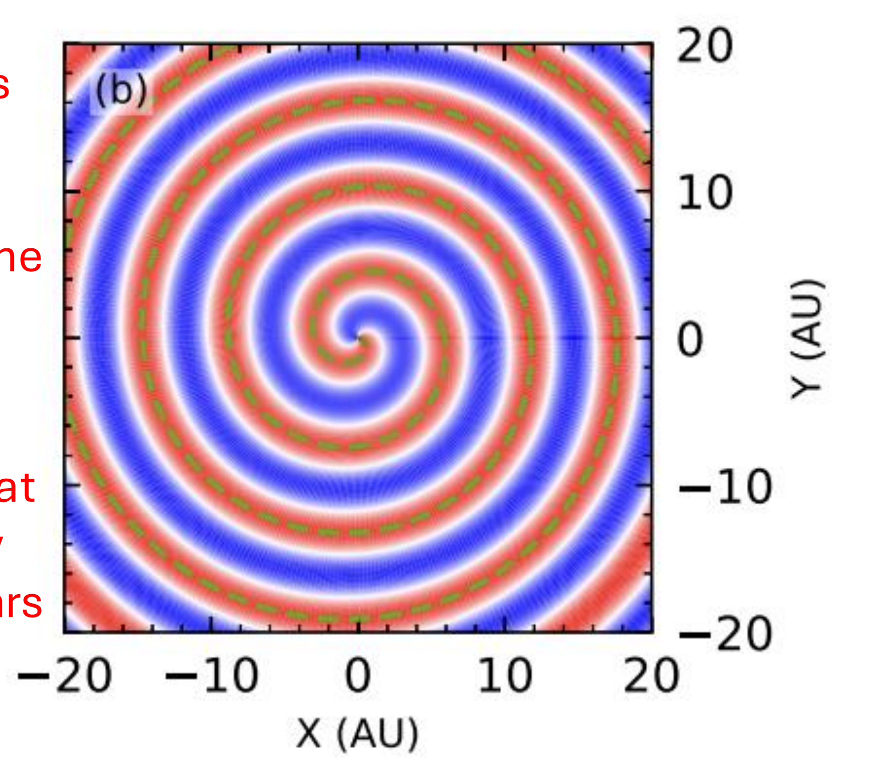
Twin-Satellite is
required & on their way

Parker Spiral Model: <u>0th-ORDER</u>



Parker Model is great, but still limited in understanding the worst (best) cases, e.g.,

Southward IMF at Earth/Mercury
Radial IMF at Mars



- $B_r = B_{r0}\left(\frac{r_0}{r}\right)^2$
- $B_\theta = 0$
- $B_\phi = B_{r0}\left[\frac{\Omega_0 (r - r_0)\sin\theta}{V_{sw}}\right]\left(\frac{r_0}{r}\right)^2$

r_0: Source Surface Radius (Typically, 2.5 Rs)
Ω_0: Solar Spin Rate

Parker Spiral Angle	-> 0 deg (±R) at 0.1 AU
	-> 45 deg (between R & T) at 1 AU
	-> 90 deg (±T) at > 10 AU
Intensity	-> $1/r^2$ < 1 AU
	-> $1/r^1$ > 1 AU

Science Objectives

1. Static Properties

How Often Does IMF deviate from Parker Model

e.g., Occurrence of Southward/Radial IMF?

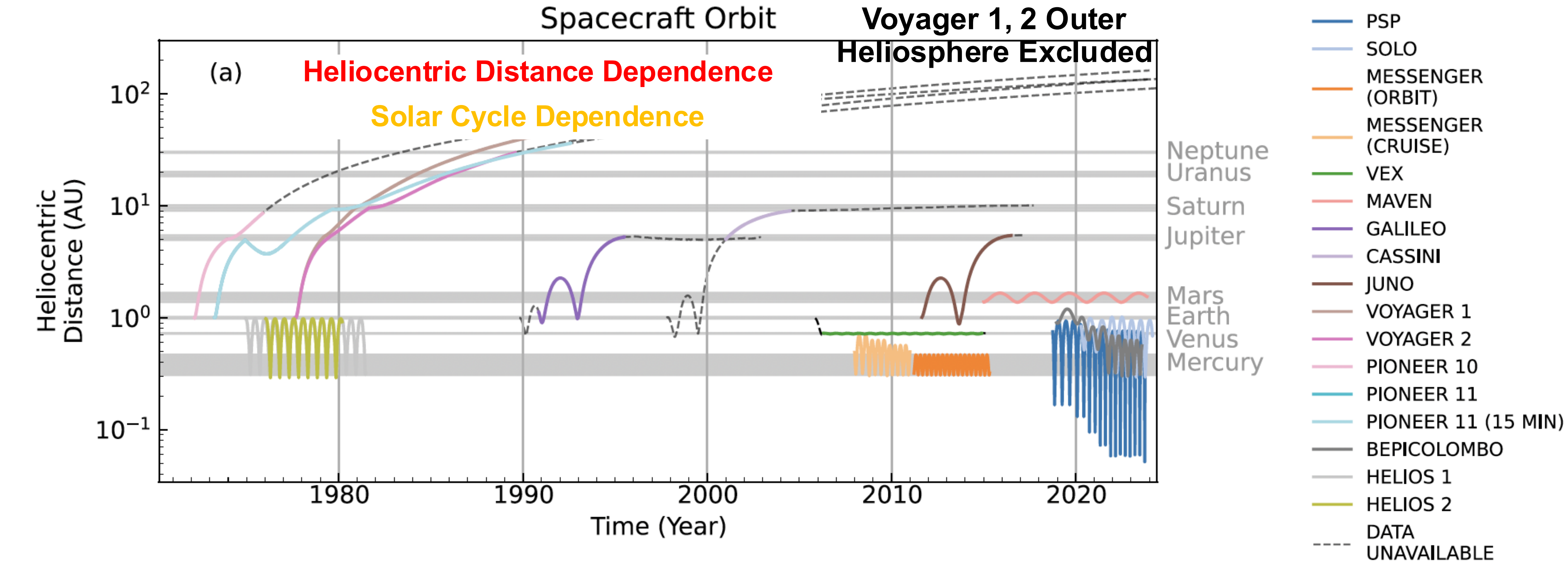
2. Temporal Variation

How Long Can IMF sustain a Steady Condition

e.g., Is 60 mins earlier observation a good reference?

Central Strategy: MULTI-Spacecraft

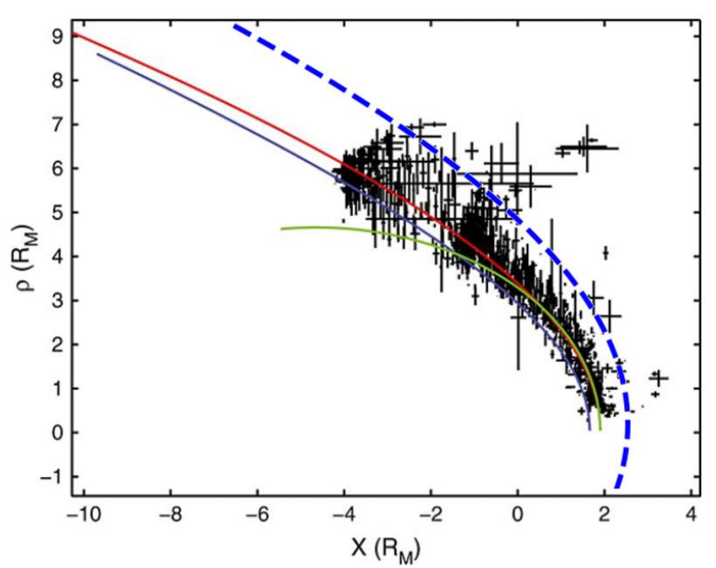
From 0.1 to 30 AU (Mercury to Neptune)



All Data are Down-sampled to 1 min cadence & Quality Checked

EXCLUSION of Downstream Data

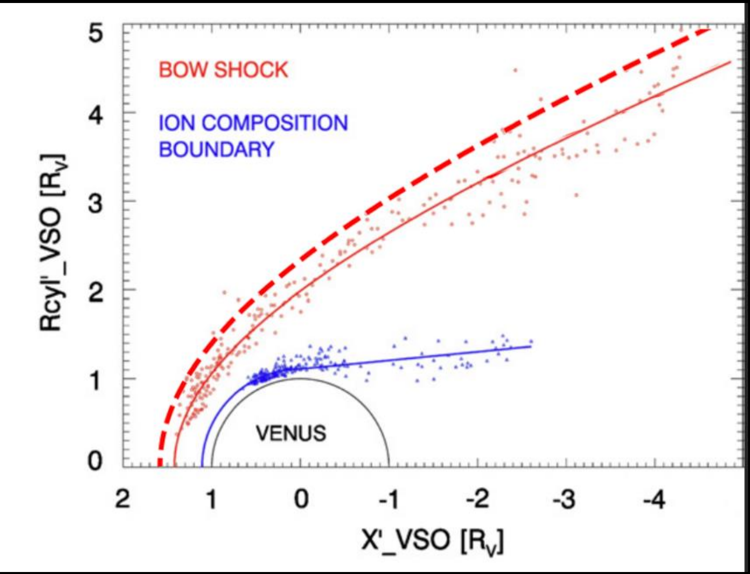
We remove the data inside the enlarged averaged bow shocks



Mercury Bow Shock

- - - 1.5 * Model

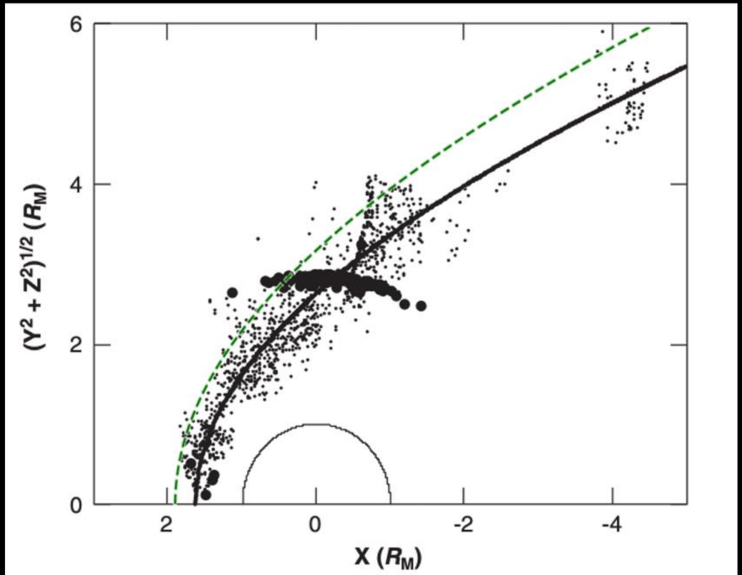
Winslow et al., 2013



Venus Bow Shock

- - - 1.25 * Model

Martinecz et al., 2008

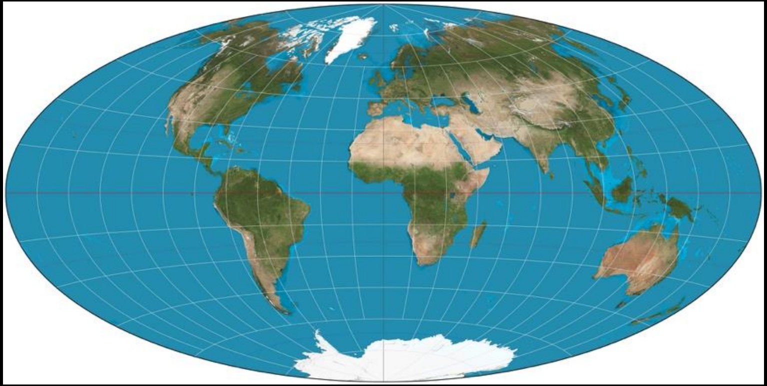


Mars Bow Shock

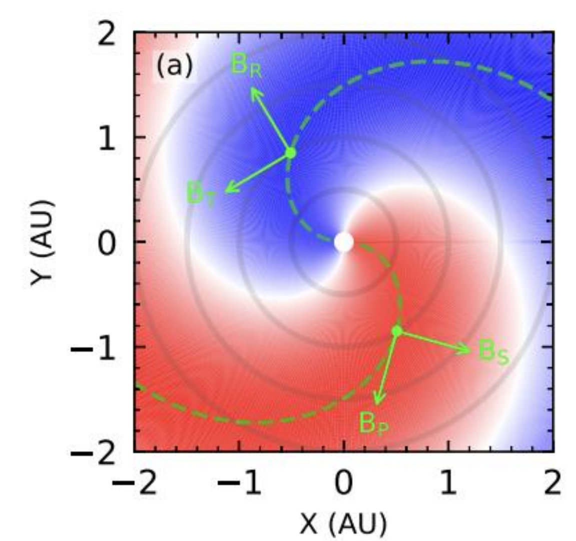
- - - 1.25 * Model

Trotignon et al., 2006

ANGULAR & INTENSITY Distribution in RTN Coordinates



Aitoff Projection



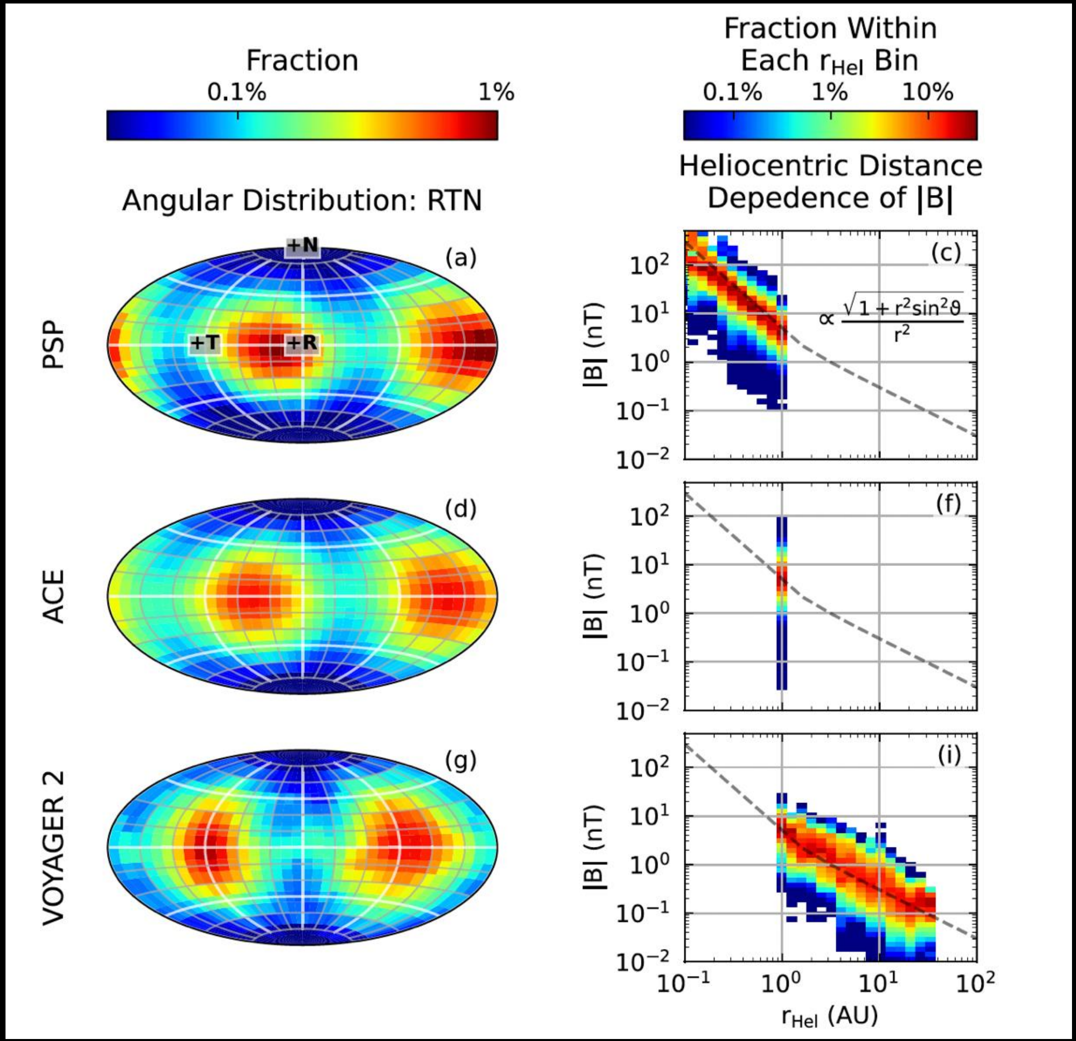
~0.3 au, $\pm$R

1 au between R and T

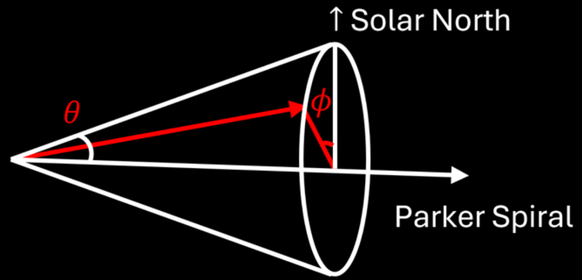
Parker Spiral provide a Great baseline & most Probable Situation

>10 au, $\pm$T

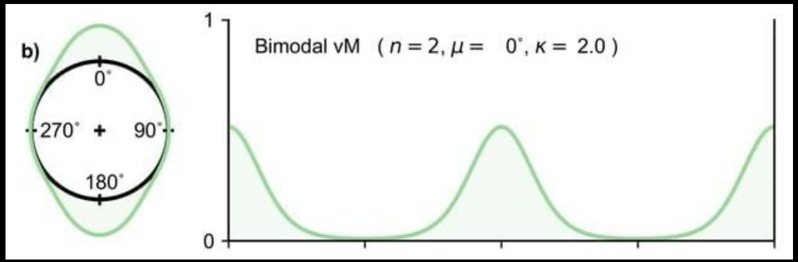
Coordinate Transform RTN to PSN



ANGULAR & INTENSITY Distributions in PSN Coordinates



Bi-Modal Von-mises Distribution

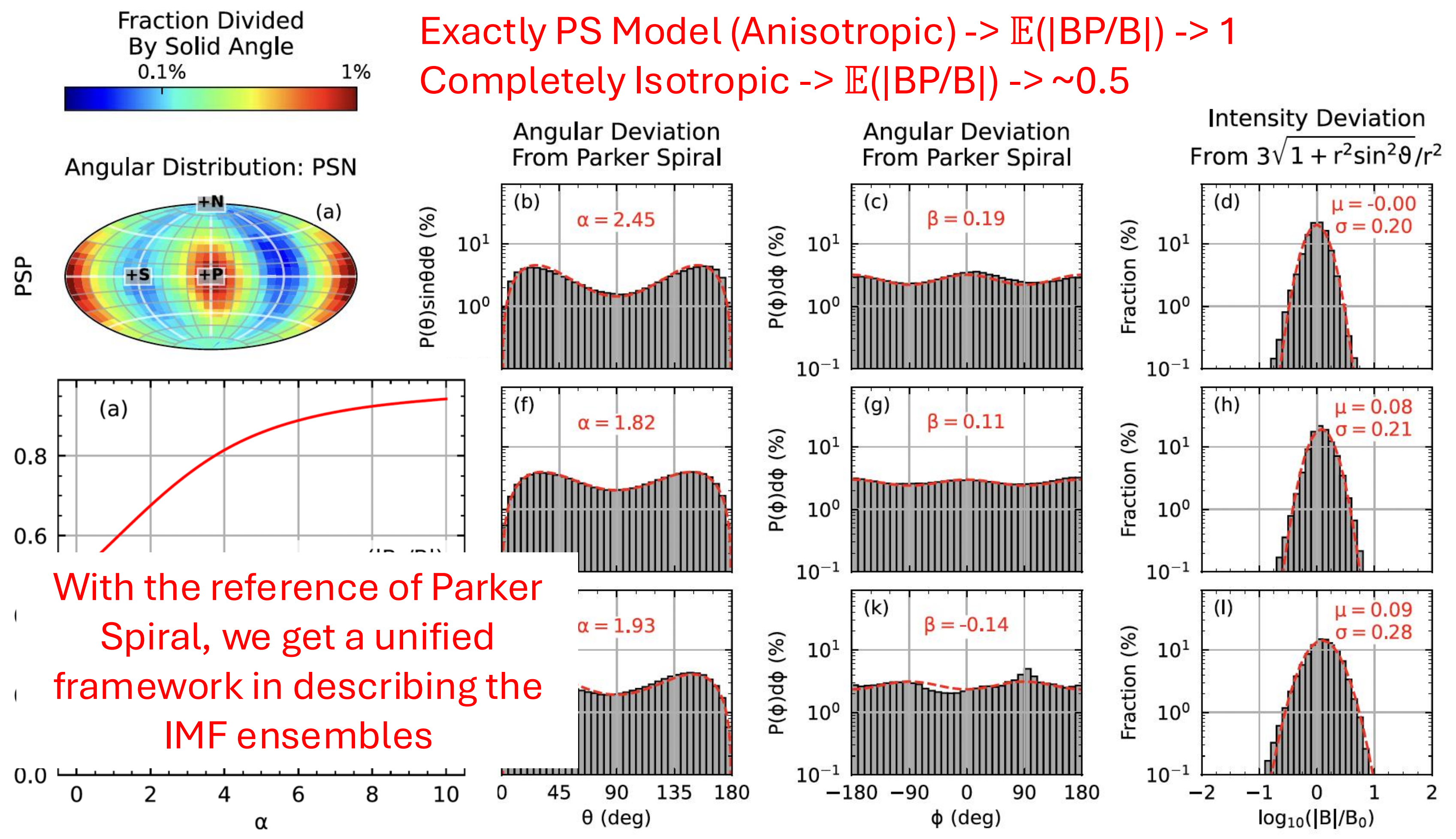


Technical Conclusion 1
An empirical, analytic distribution

Deviation from PS:

- $P(\theta) \propto \exp(\alpha \cos^2 \theta)$
  - Von-mises Distribution
- $P(\phi) \propto \exp(\beta \sin^2 \phi)$
- $P(B/B_0)$ follows log-normal
  - B_0: Parker Model Value

Exactly PS Model (Anisotropic) -> $\mathbb{E}(|BP/B|)$ -> 1
Completely Isotropic -> $\mathbb{E}(|BP/B|)$ -> ~0.5



With the reference of Parker Spiral, we get a unified framework in describing the IMF ensembles

How to determine these model parameters?
⇒ Moment Estimation

Solar Phase & Heliocentric Distance DEPENDENCE

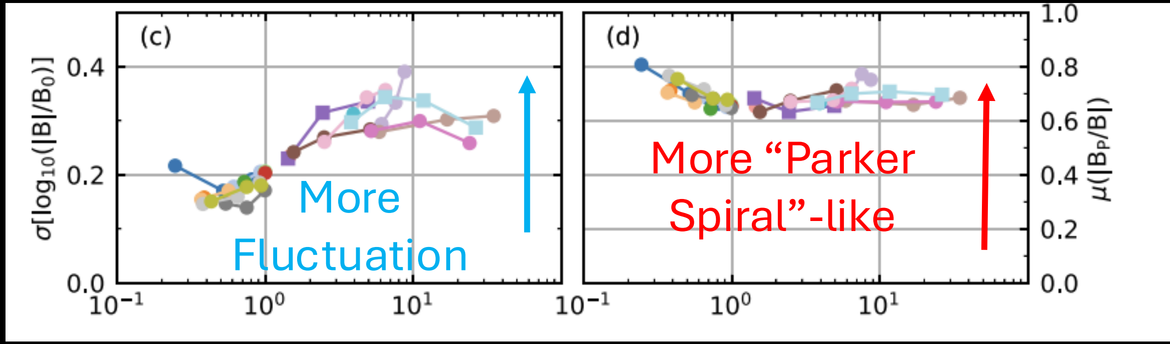
log|B| Distribution Width:

Outer > Inner Heliosphere

⇓

Exactly PS Model-> |BP/B| -> 1

Completely Isotropic -> |BP/B| -> ~0.5

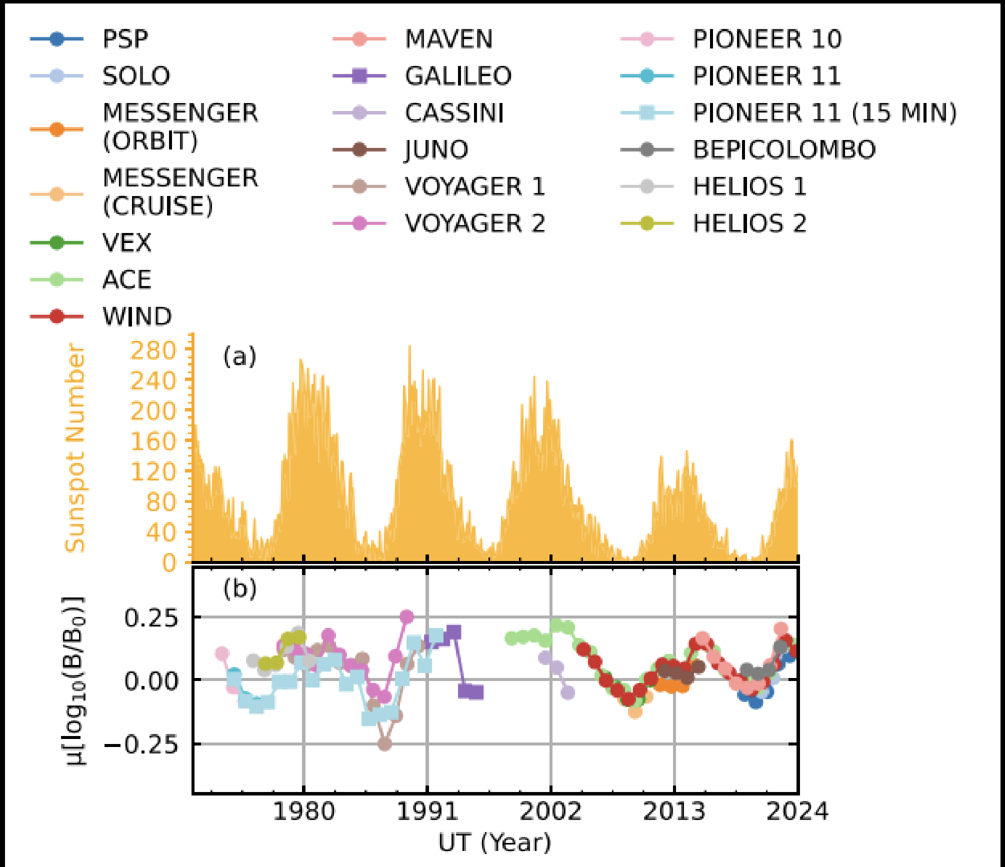


⇑

Angular Concentration on the Parker Spiral:

Inner > Outer Heliosphere

11 year-Modulation of Solar Open Magnetic Flux unveiled by the mean of $\log(B/B_0)$ ⇒

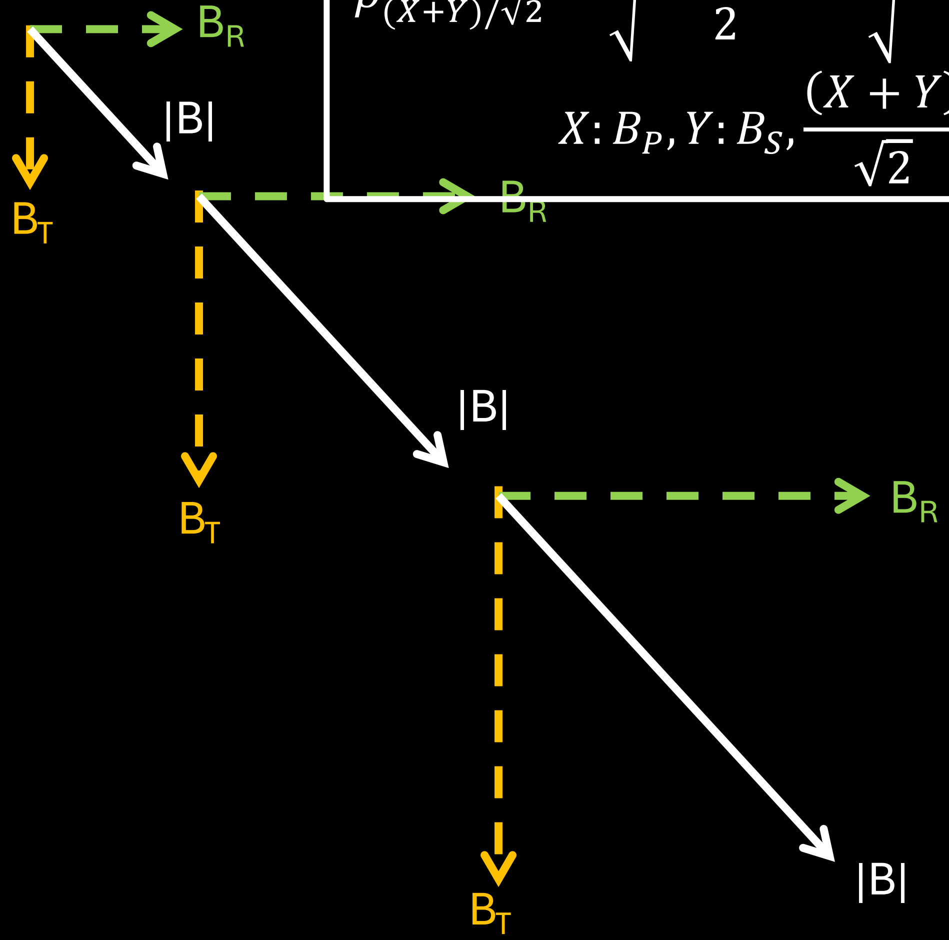


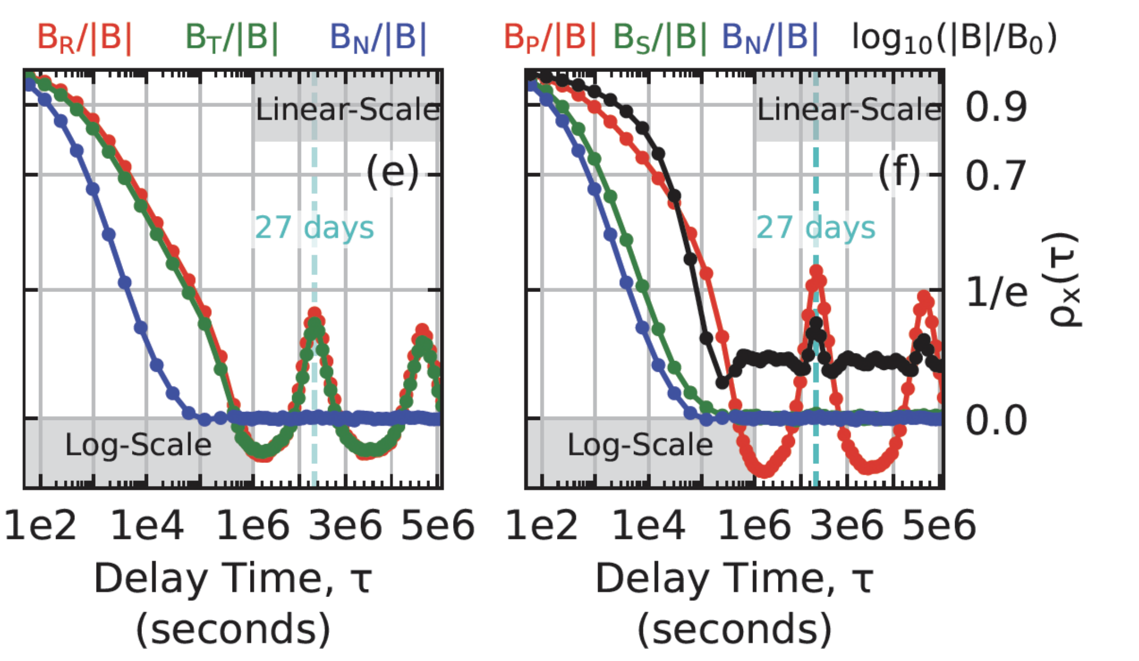
Auto-Correlation Function (ACF)

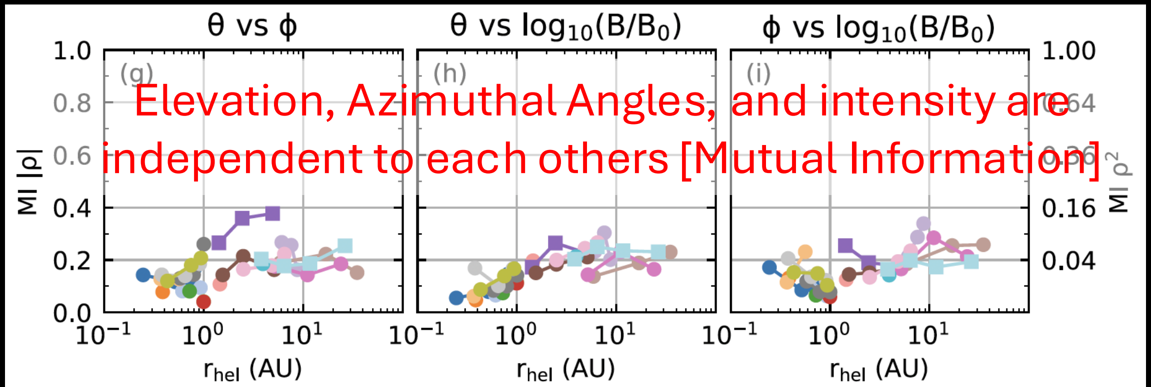
How to evaluate the situation of interest?

$$\rho_{(X+Y)/\sqrt{2}} = \sqrt{\frac{\rho_X^2 + \rho_Y^2}{2}} = \sqrt{\frac{0.42^2 + 0.0^2}{2}} \approx 0.3$$

$$X: B_P, Y: B_S, \frac{(X+Y)}{\sqrt{2}} = B_R$$



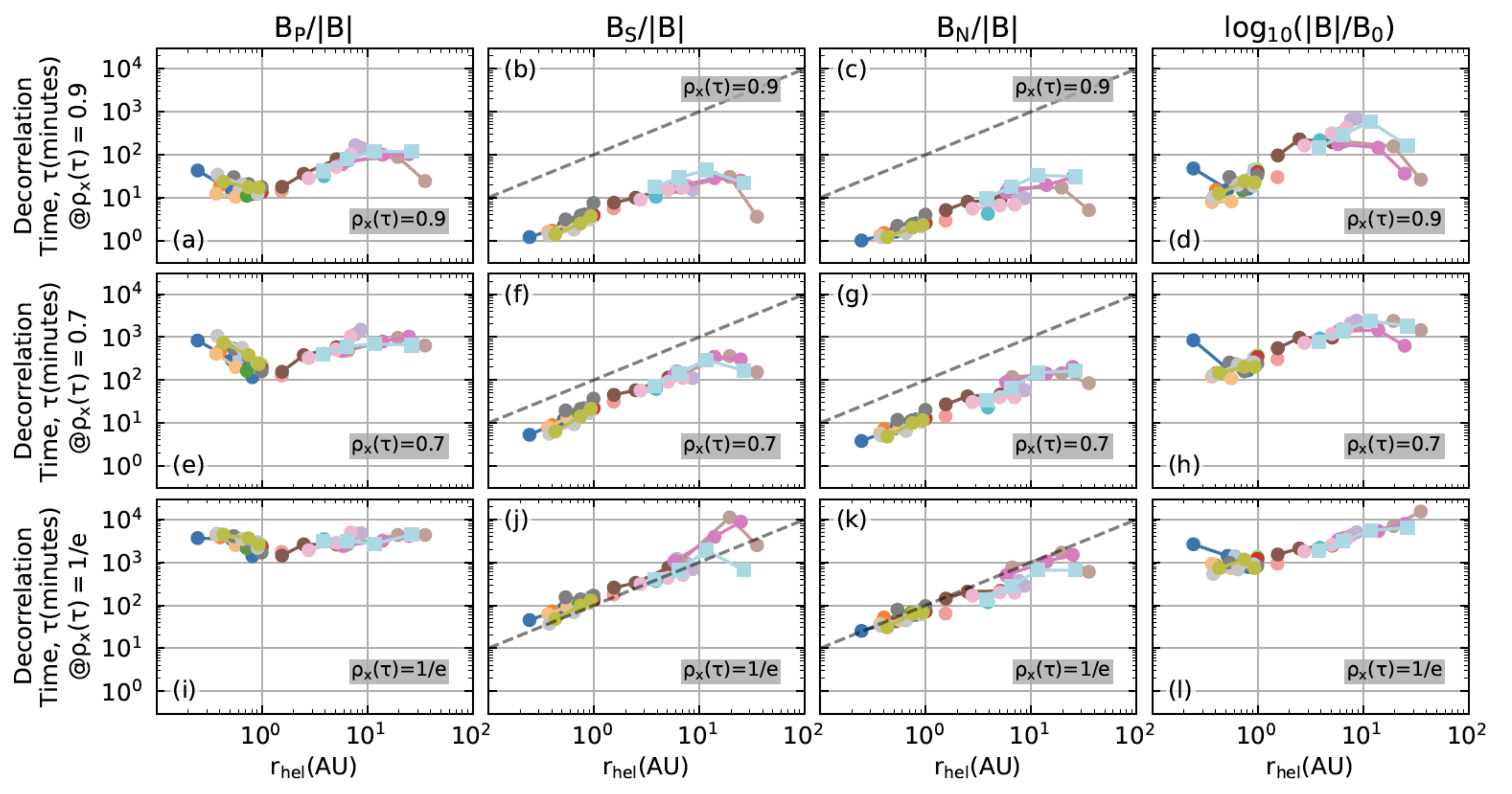




Elevation, Azimuthal Angles, and intensity are independent to each others [Mutual Information]

Heliocentric Distance Dependence

How long does the auto-correlation function decay to 0.9, 0.7 or 1/e

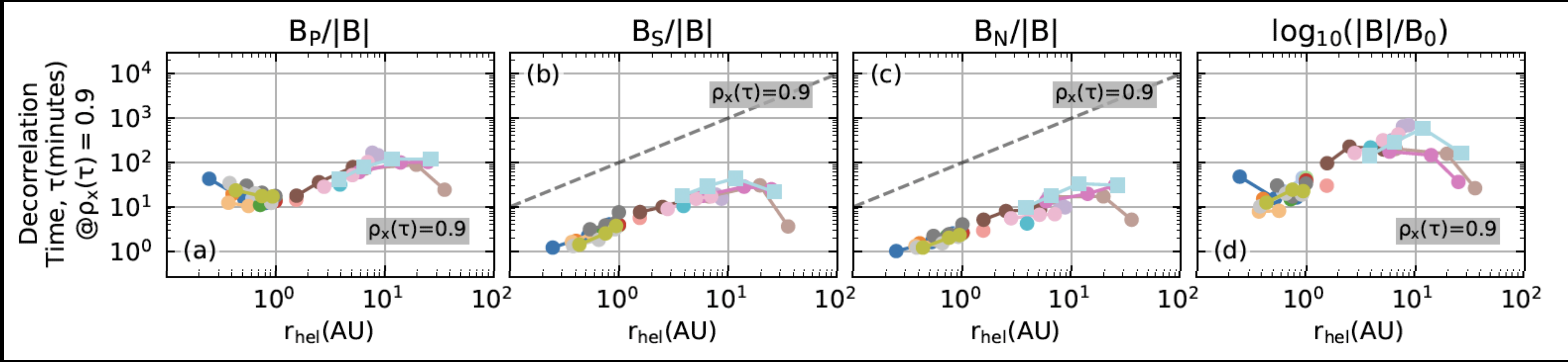


In Outer Heliosphere, magnetic field is more stable

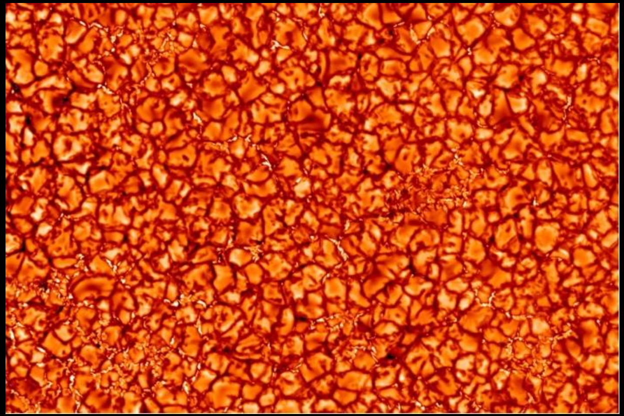
⇒ Feel "Safer" to use the non-Real Time IMF

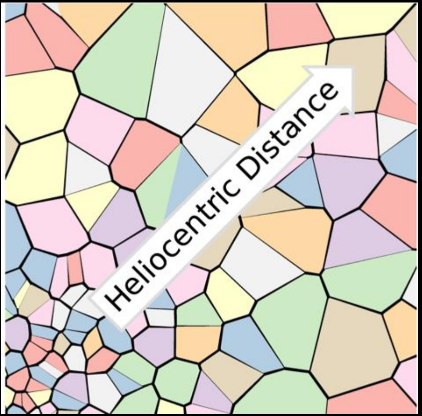
But… for a giant planet, spacecraft's orbital period can be super long…(even longer than 27 days)

Technical Conclusion 2
Take a threshold for ACF, we can see how long the



Trace Back to Solar Surface: Supergranulation (Borovsky et al., 2008) Radial Expansion (This Study)





Science Conclusion
Flux Tube Expansion as Radially Propagation

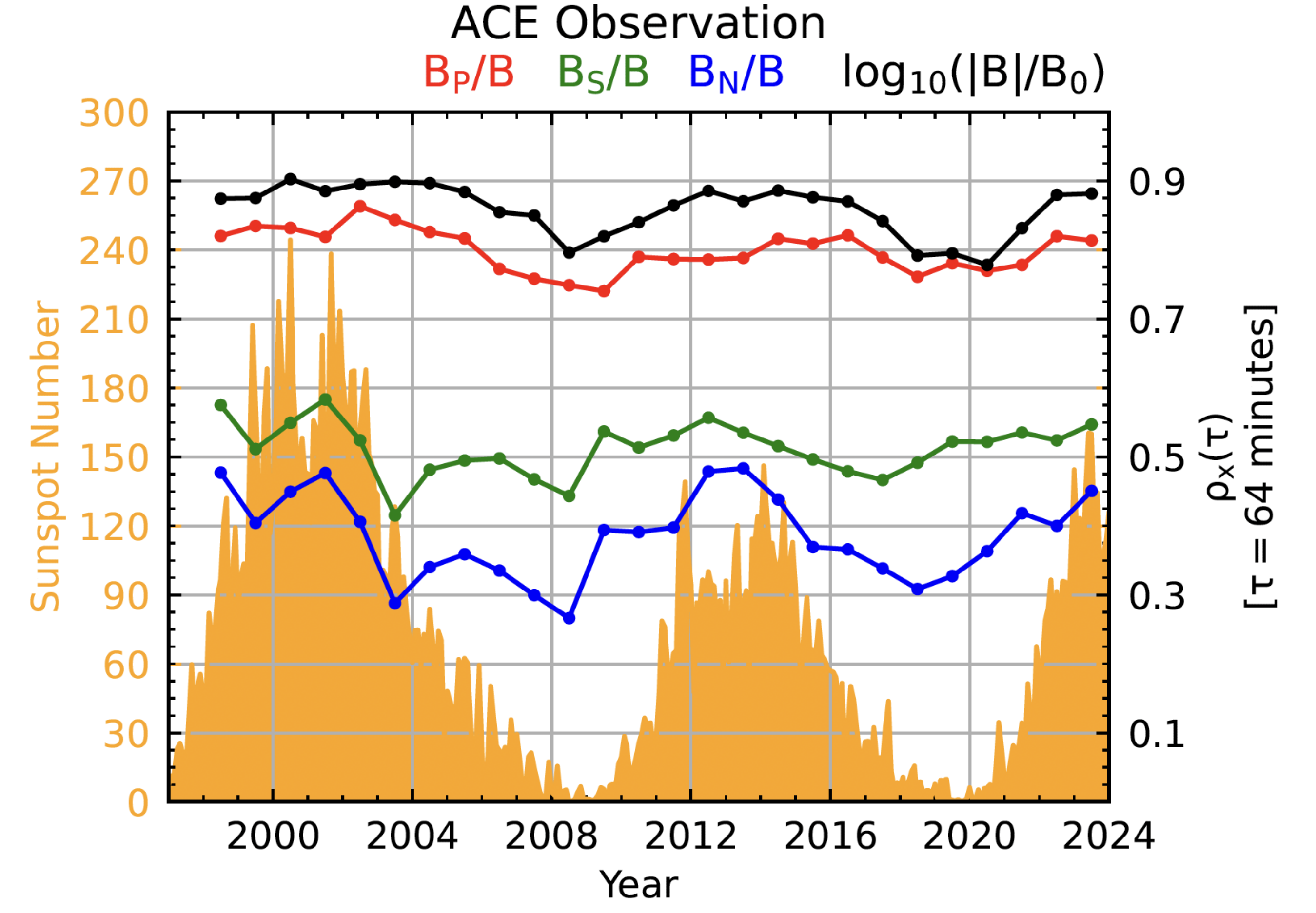
Reference
Jiutong Zhao *et al* 2025 *ApJ* **980** 89; **DOI** 10.3847/1538-4357/ad9b28
Jiutong Zhao *et al* 2025 *ApJ* **987** 93; **DOI** 10.3847/1538-4357/add72f

Table 1

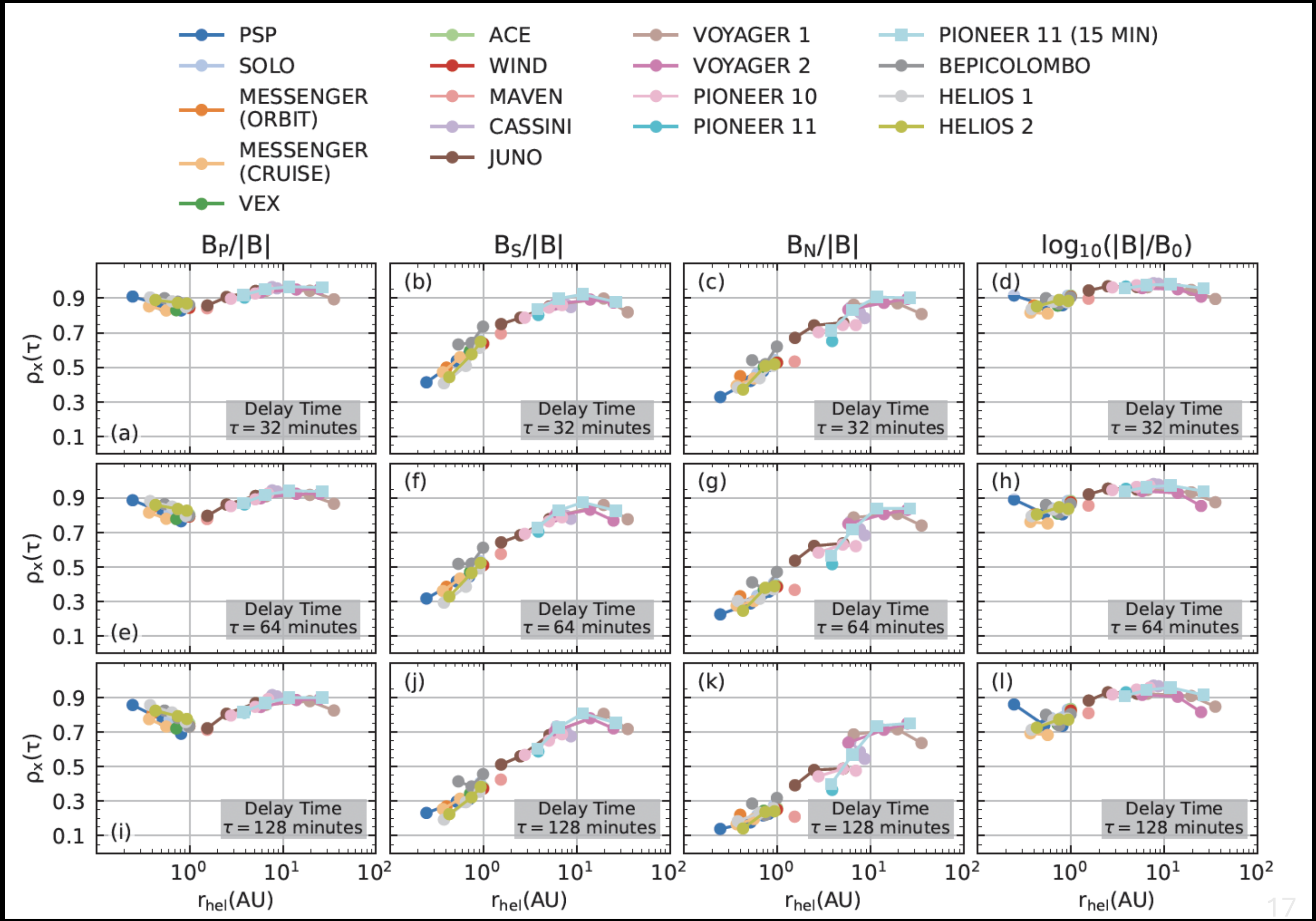
Planetary Bow Shock Sizes and the Correlation Coefficients between the Midpoint Estimations and the Real Observations of the IMF

Planet ($r_{\rm hel}$ Range)	$R_{\rm BS}(R_P)$	$T_{\rm orb}$ (day)	Spacecraft	$B_P/\lvert B\rvert$	$B_S/\lvert B\rvert$	$B_N/\lvert B\rvert$	$\log_{10}(\lvert B\rvert/B_0)$
				Pearson R: $x(t)$ $v.s.$ $x'_{T_{\rm orb}/2}(t)$			
Mercury (0.31–0.46 au)	1.90[a]	0.10	SolO	0.85	0.54	0.43	0.77
Venus (0.57–0.86 au)	2.44[b]	0.14	SolO	0.83	0.49	0.37	0.75
Earth (0.9–1.1 au)	14.6[c]	1.28	ACE	0.62	0.10	0.03	0.45
Mars (1.2–1.8 au)	1.63[d]	0.10	VOYAGER1	0.93	0.84	0.82	0.91
Jupiter (4.2–6.2 au)	84.0[e]	34.22	VOYAGER1	0.11	0.18	0.10	0.12
Saturn (7.6–11 au)	26.1[f]	8.71	VOYAGER1	0.24	0.25	0.17	0.34
Uranus (15–23 au)	30.0[g]	7.52	VOYAGER1	0.28	0.26	0.19	0.37
Neptune (27–33 au)	34.9[h]	8.23	VOYAGER1	0.27	0.26	0.18	0.36

Solar Cycle Dependence



Heliocentric Distance Dependence



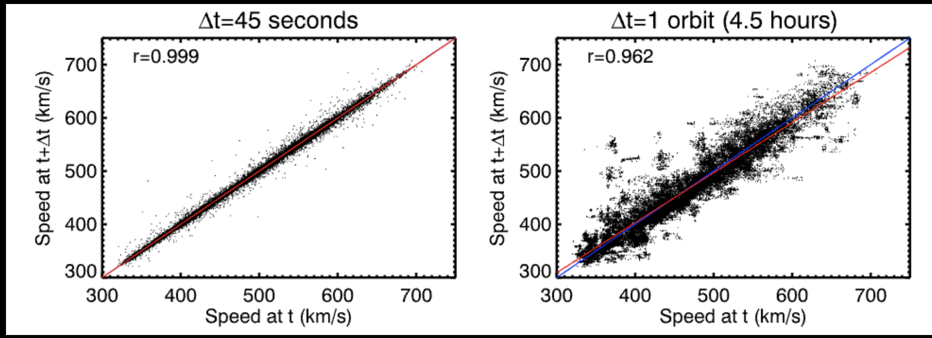
Temporal Variation / Stationary / Stability of IMF

Objectives

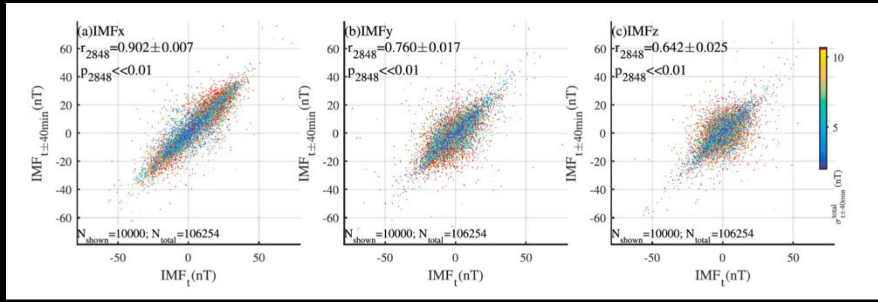
- Get Upstream IMF condition by using single-spacecraft inside the magnetosphere
- E.g., Mercury substorm, Mars Ion Escape

A Simple Prediction:

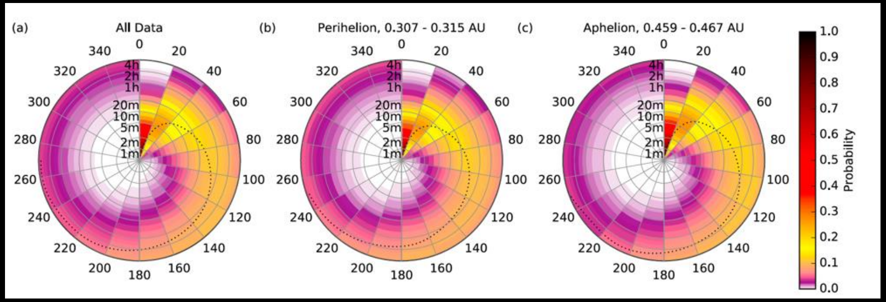
- IMF observed at the nearest time



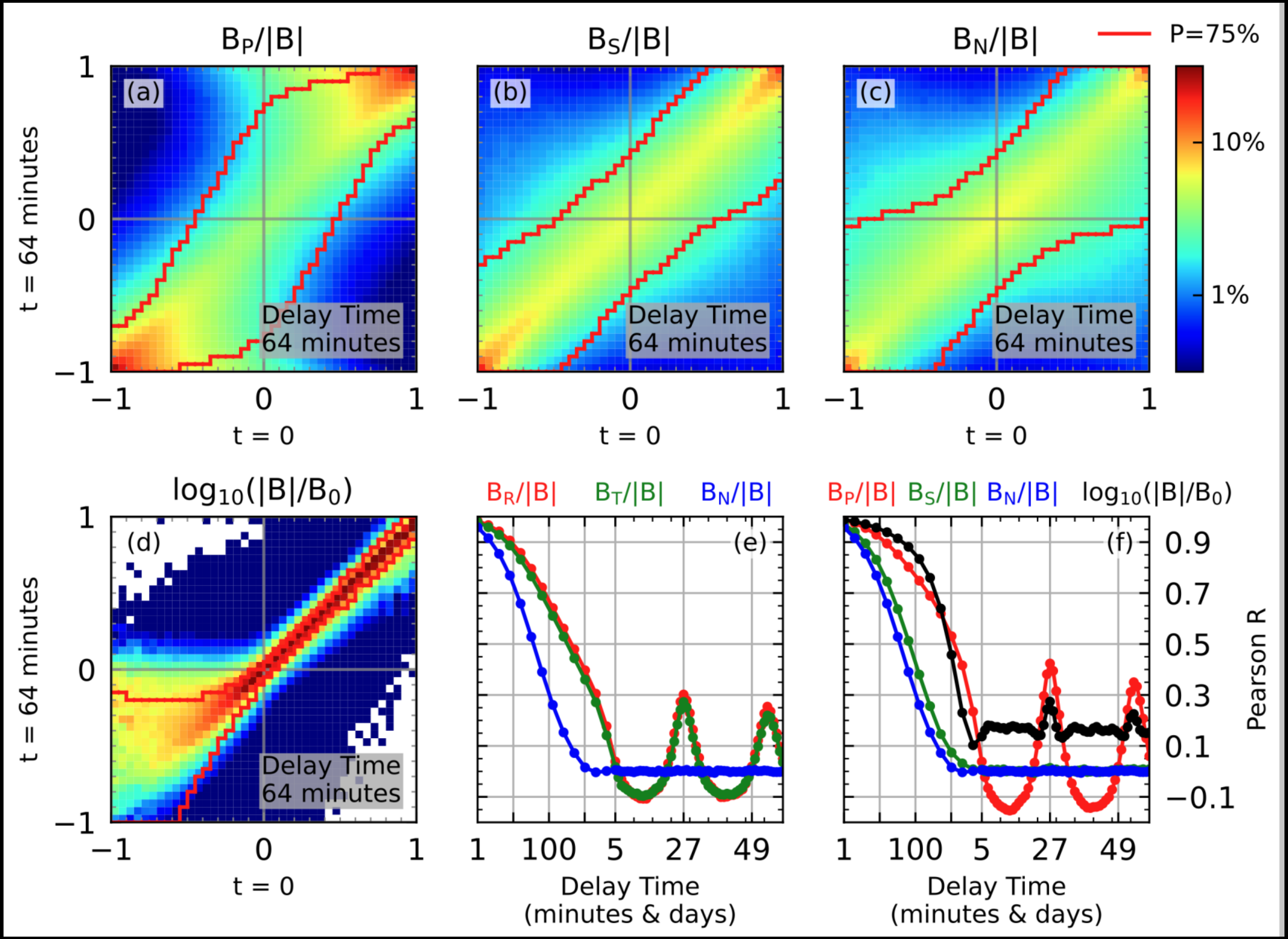
[Marquette et al., 2018]



$\Delta T = 40$ Minutes
[He et al., 2017 JGR]



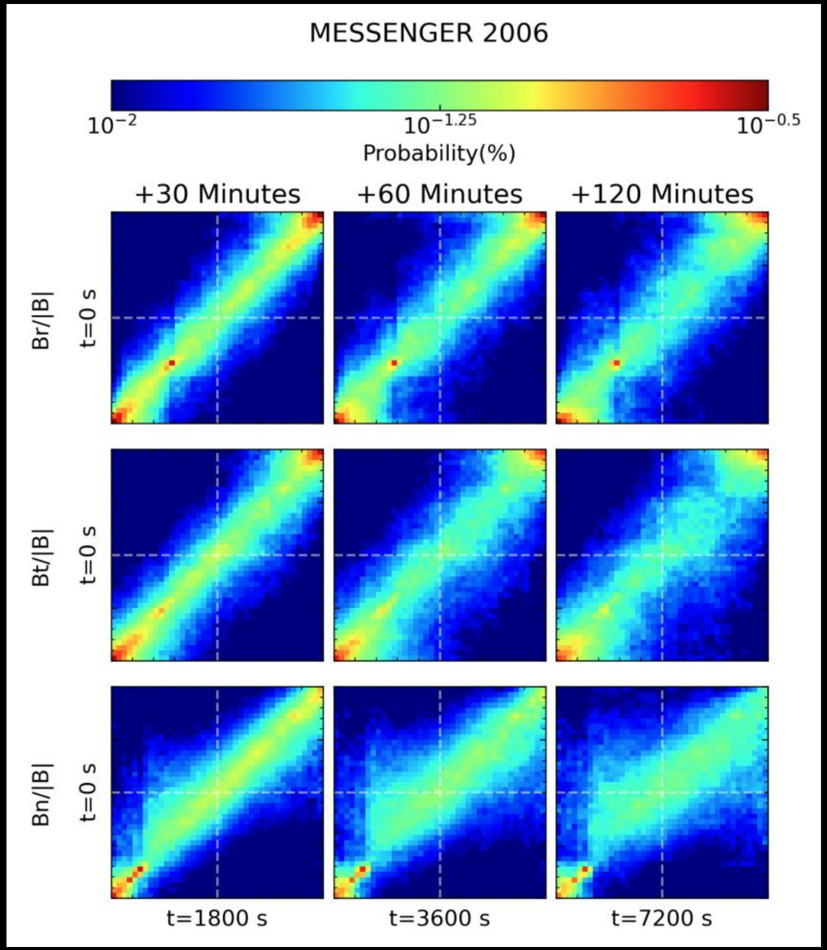
The azimuthal axis shows the amount by which clock angle has changed in degrees.
ΔT vs ΔClock Angle
[James et al., 2017]



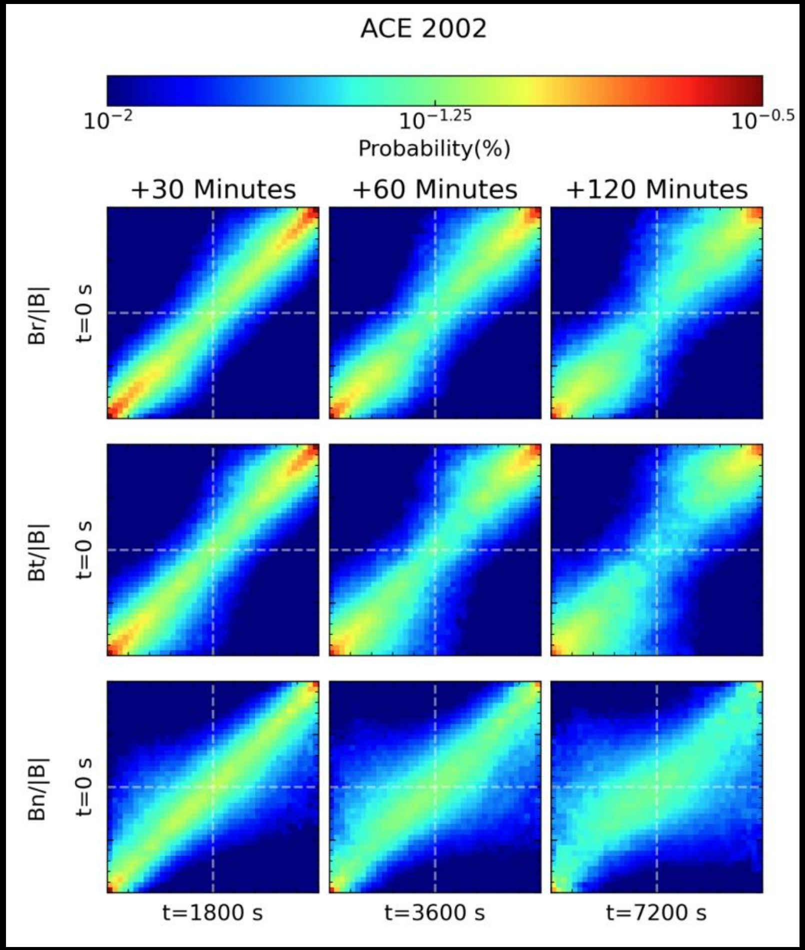
$B_P/|B|$
$B_S/|B|$
$B_N/|B|$
P=75%
10%
1%
(a)
(b)
(c)
(d)
(e)
(f)
Delay Time
64 minutes
t = 64 minutes
t = 0
$\log_{10}(|B|/B_0)$
$B_R/|B|$ $B_T/|B|$ $B_N/|B|$
$B_P/|B|$ $B_S/|B|$ $B_N/|B|$ $\log_{10}(|B|/B_0)$
Pearson R
Delay Time (minutes & days)

Heliocentric Distance Dependence

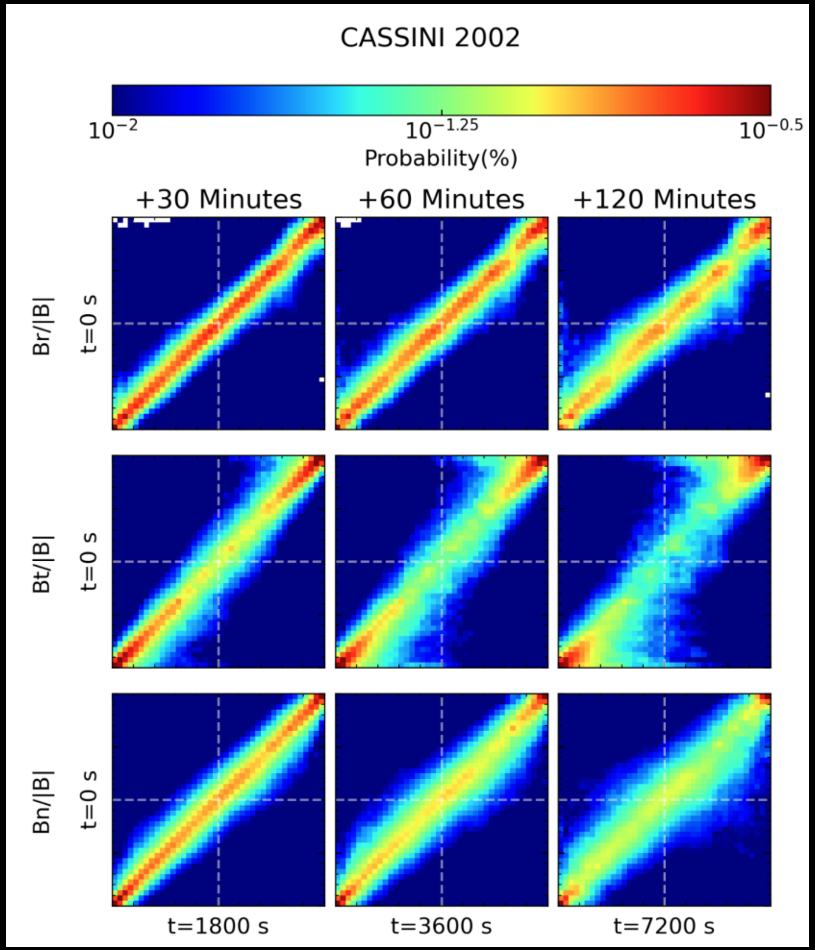
Window = Cadence: 16s



0.60-1.06 AU



1 AU



6.8-8.0 AU