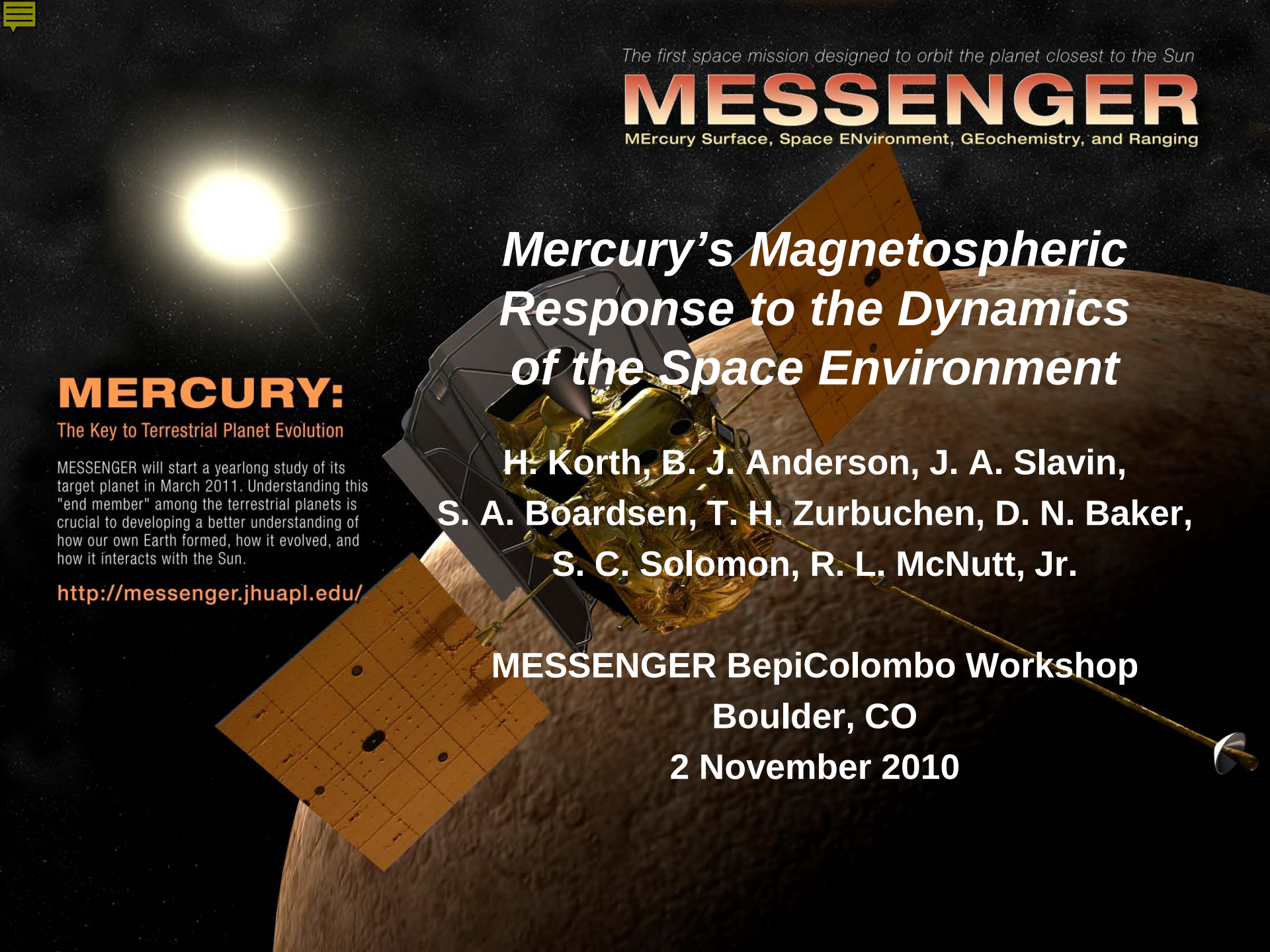


Mercury's Magnetospheric Response to the Dynamics of the Space Environment

H. Korth, B. J. Anderson, J. A. Slavin, S. A. Boardsen, T. H. Zurbuchen, D. N. Baker, S. C. Solomon, R. L. McNutt, Jr.

MESSENGER BepiColombo Workshop

Boulder, CO

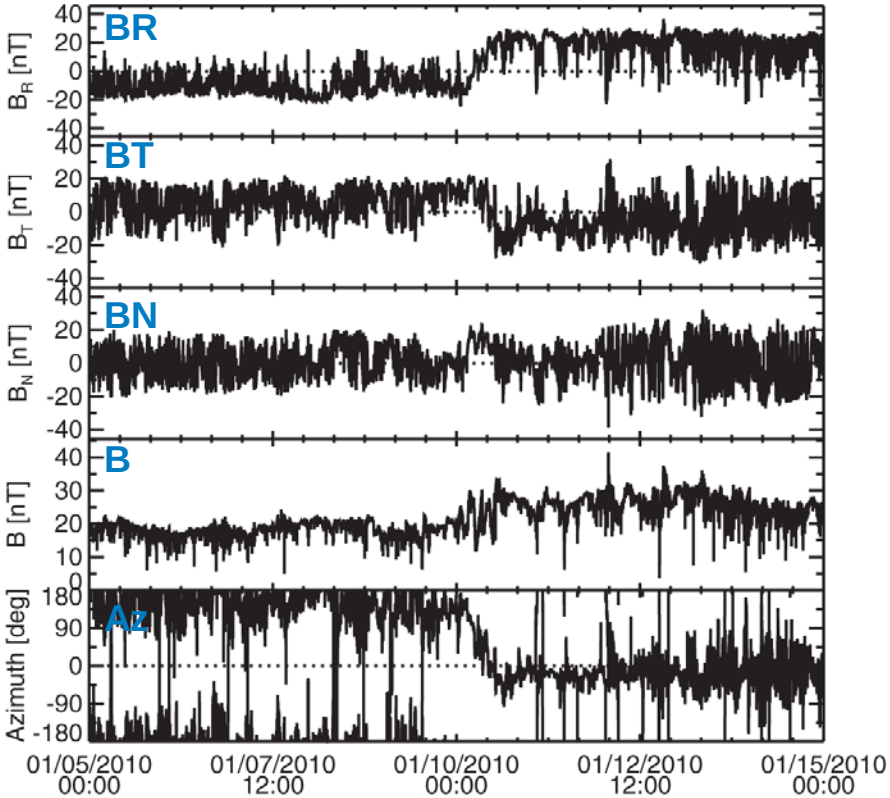
2 November 2010

MESSENGER
Motivation

- **Magnetospheric configuration and current systems are particularly sensitive to the interplanetary magnetic field (IMF) and its variability.**
- **Understanding Mercury's magnetic field depends critically on specifications of external current systems.**
- **Therefore the characteristic IMF variability in Mercury's orbital zone (0.31-0.47 AU) must be determined.**
- **Vector magnetic field measurements of the IMF in the inner heliosphere have been made by MESSENGER.**
- **MESSENGER observations allow for detailed studies of Mercury's space environment.**

MESSENGER
Magnetic Field Observations

MESSENGER (1-min Averages)



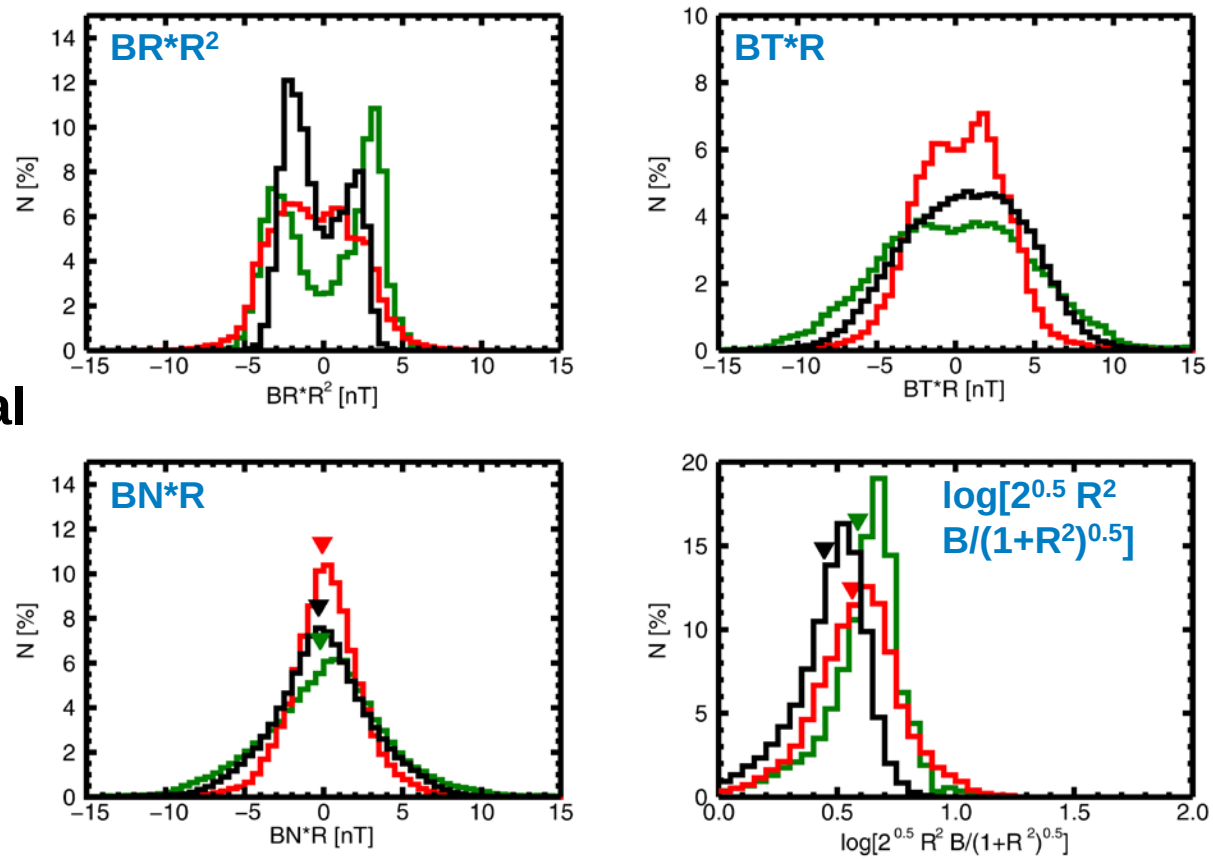
- **Field geometry consistent with Parker [1958] theory.**
- **BR, BT: Polarity changes indicate current sheet crossing.**
- **BN: Fluctuations about zero.**
- **Field magnitude: 20-30 nT.**
- **Field direction close to radial.**
- **Broad distribution in components and magnitude indicate high level of turbulence.**

- **ACE located 80°E of MESSENGER: Different solar source.**
- **Radial dependencies about BR~1/r^2, BT,BN~1/r as predicted by Parker.**
- **Systematic differences at 0.4 and 1 AU not captured by Parker model.**

MESSENGER
Scaled IMF Distributions

- Differences in IMF properties quantified from histogram distributions.
- Since August 2007, MESSENGER spent 268 days in Mercury's orbital zone.
- 1-minute averages scaled to 1 AU using Parker model.
- Reasonable agreement between distributions confirms zeroth-order validity of Parker model.

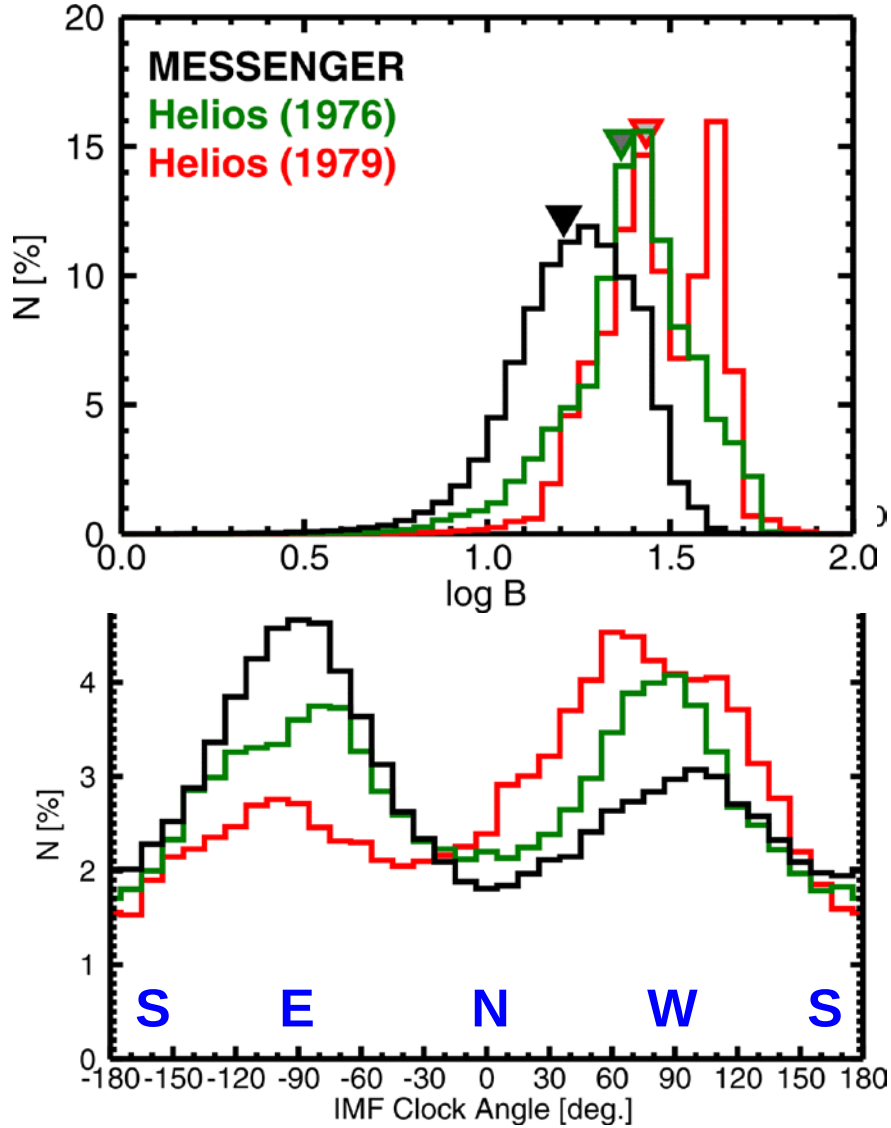
MESSENGER, ACE, Helios (1976)



- Differences due to observation geometry and dynamic evolution of the solar wind in the heliosphere.

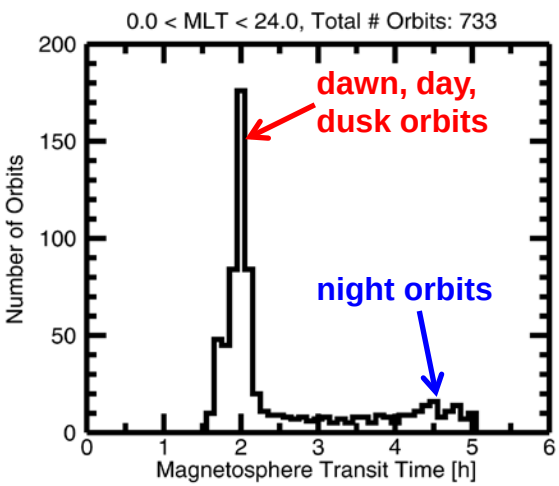
MESSENGER
IMF Distributions

- Mean IMF magnitude observed by MESSENGER was 16 nT.
- 30% lower than seen by Helios near solar minimum (23 nT).
- IMF Spiral and clock angles exhibit maxima in the Parker solar wind directions.
- Clock angle α=arctan(-BN/BT) controls solar wind-magnetosphere coupling geometry.
- The higher occurrence of eastward IMF in the MESSENGER data is due to an observational bias toward northern heliographic latitudes.

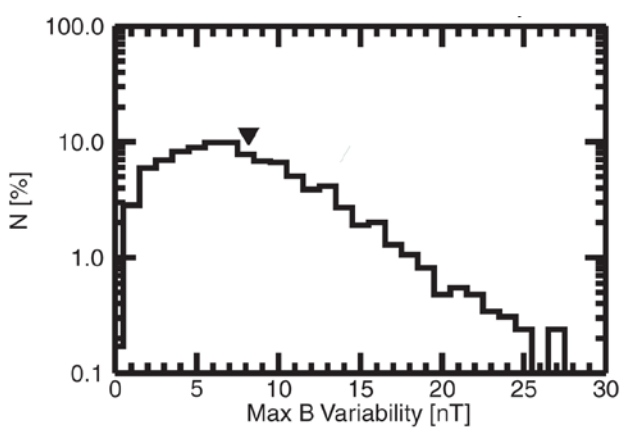


MESSENGER
Magnetospheric Response I

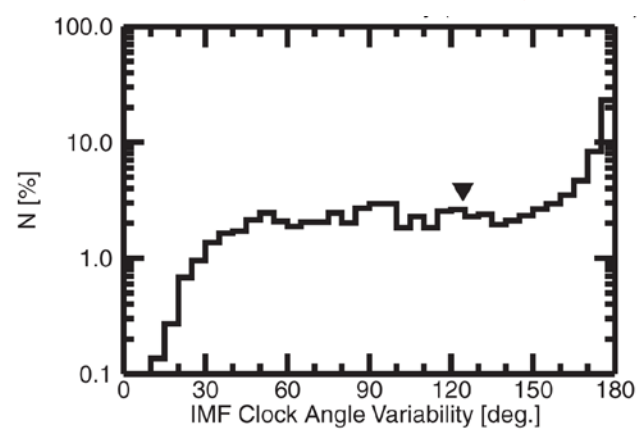
- **IMF intensity and direction control intensity and geometry of magnetospheric currents and generated external magnetic fields.**
- **IMF variability complicates inversion of planetary magnetic moment.**
- **Magnetosphere transit time can be estimated from time elapsed between inbound and outbound bow shock crossing.**
- **MESSENGER passes through Mercury's magnetosphere in 2-4 hours.**
- **Typical variability for dawn, day, and dusk orbits: δB=10 nT, $\delta\alpha$=130°.**



2-hour max δB



2-hour max $\delta\alpha$



MESSENGER
Magnetospheric Response II

- **Fraction of southward IMF reconnecting with planetary field and permeating the magnetosphere:**

$$|B_Z| = B\,\sin\left(\frac{\alpha}{2}\right)$$

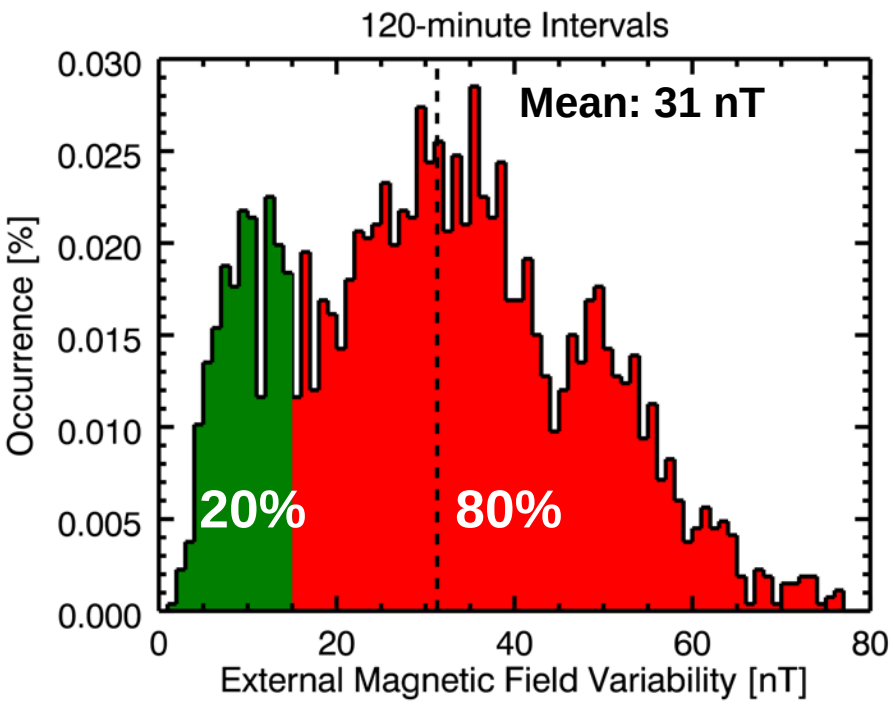
- **Magnetospheric magnetic field variability:**

$$\left|\delta B_Z\right| = \delta B\,\sin\left(\frac{\alpha}{2}\right) + B\,\delta\left[\sin\left(\frac{\alpha}{2}\right)\right]$$

- **Typical B=16 nT, $\delta\alpha$=130°, δB=10 nT gives maximum external magnetic field variability of 25 nT for southward IMF.**
- **Corresponds to 15-30% of the planetary field generated by a 250 nT R_M^3 dipole moment at 0.5 R_M altitude (75-150 nT).**
- **The effect of solar wind pressure variations on the external field variability is not considered in this estimate.**
- **Careful data selection required!**

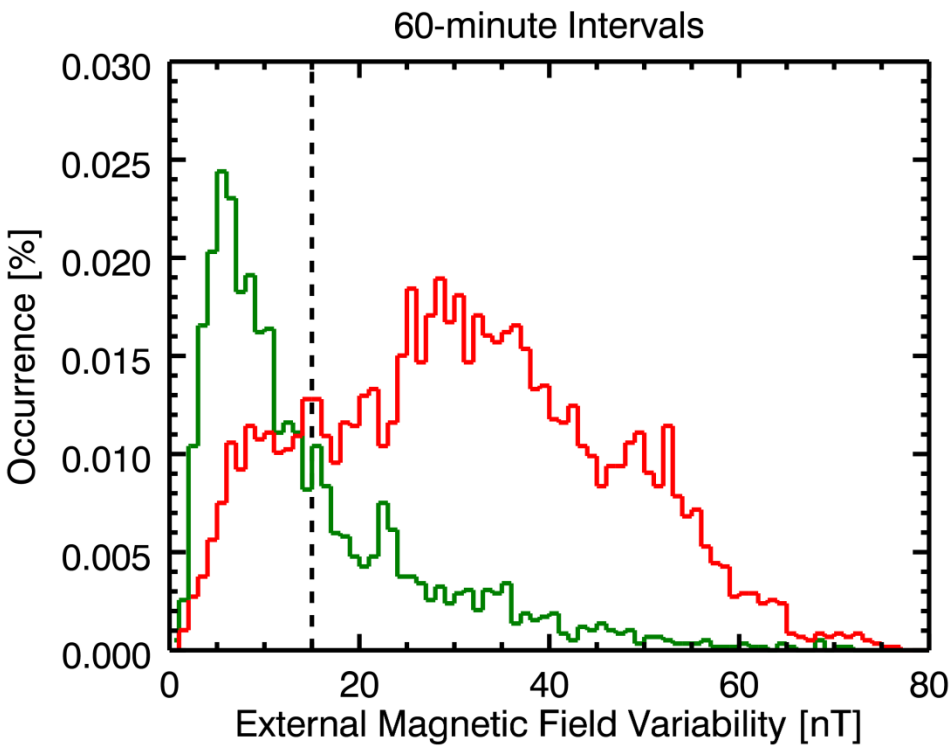
MESSENGER
Selection of Observations I

- **Recovery of planetary moment with ≤10% error requires similar uncertainties in the dipole field observations = 15 nT.**
- **Occurrence rate for stable conditions estimated from computing max. dB for 2-hour intervals from MESSENGER IMF observations.**
- **The mean external field variability is about 30 nT.**
- **Stable conditions persist over 2-hour periods 20% of all times.**
- **Complication: No Solar wind monitor available to identify these stable intervals.**
- **Alternative: Use observations prior to entry into magnetosphere to predict conditions during magnetosphere transition.**



MESSENGER
Selection of Observations II

- **Compare *B* variability in intervals $i_0=[t_0\text{-}1h,t_0]$ and $i_1=[t_0,t_0+1h]$ to estimate coherence.**
- **Stable conditions, $\delta B \leq 15$ nT:**
  - **70% of intervals stable in i_0 are also stable in i_1,**
  - **The probability that the magnetosphere is exposed to variable IMF conditions if stable conditions are encountered in the solar wind is 30%.**
- **Variable conditions, $\delta B > 15$ nT:**
  - **83% of intervals variable in i_0 are also variable in i_1,**
  - **Exclusion of data collected during intervals surrounded by variable IMF conditions results in a small, 17%, reduction of useful data.**

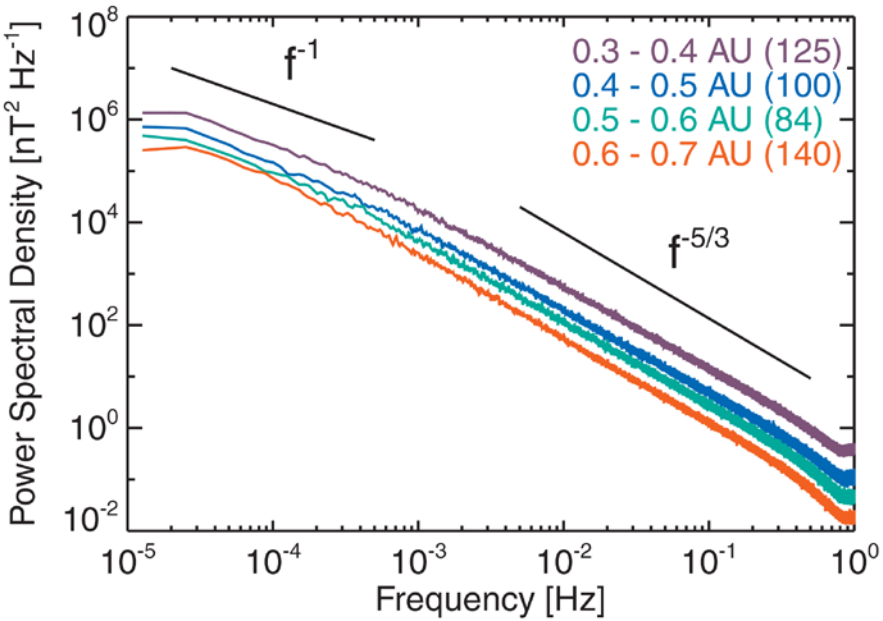


Magnetic field variability in i_1 for QUIET conditions in i_0.

Magnetic field variability in i_1 for ACTIVE conditions in i_0

MESSENGER
IMF Spectral Analysis I

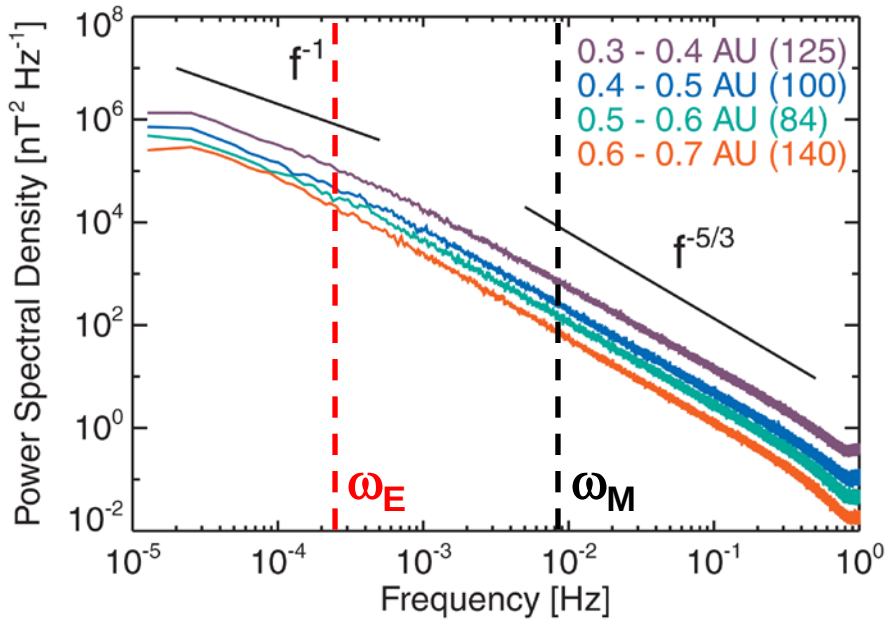
- **Spectral analysis is used to determine IMF characteristic variability.**
- **Data: 22-hour intervals of 2/s vector magnetic field samples.**
- **Frequency range: ~10^{-5} < f < 1 Hz.**
- **Total power = sum of power spectral densities of BR, BT, BN.**
- **Spectra binned by radial distance and averaged.**



- **Power spectral density over entire frequency range is well organized by radial distance.**

MESSENGER
IMF Spectral Analysis II

- **$f < 10^{-4}$ Hz: Spectral index SI≈-1; uncorrelated large-scale structures originating in the solar corona (Matthaeus, 1986).**
- **$10^{-4} < f < 10^{-1}$ Hz: SI ≈ -1.6; consistent with Kolmogoroff (1941) energy cascade: Turbulent mixing transfers energy to higher wave numbers.**
- **Magnetosphere constitutes low-pass filter to IMF fluctuations.**
- **Dungey cycle time τ:**
  Earth: τ_E = 1 hour,
  $\omega_E = 1/\tau_E = 2.8\times10^{-4}$ Hz.
  Mercury: τ_M = 2 minutes,
  $\omega_M = 1/\tau_M = 8.3\times10^{-3}$ Hz.



- **Mercury's Dungey timescale within frequency range dominated by turbulence.**
- **Implication: Turbulent IMF may more readily penetrate Mercury's magnetosphere.**

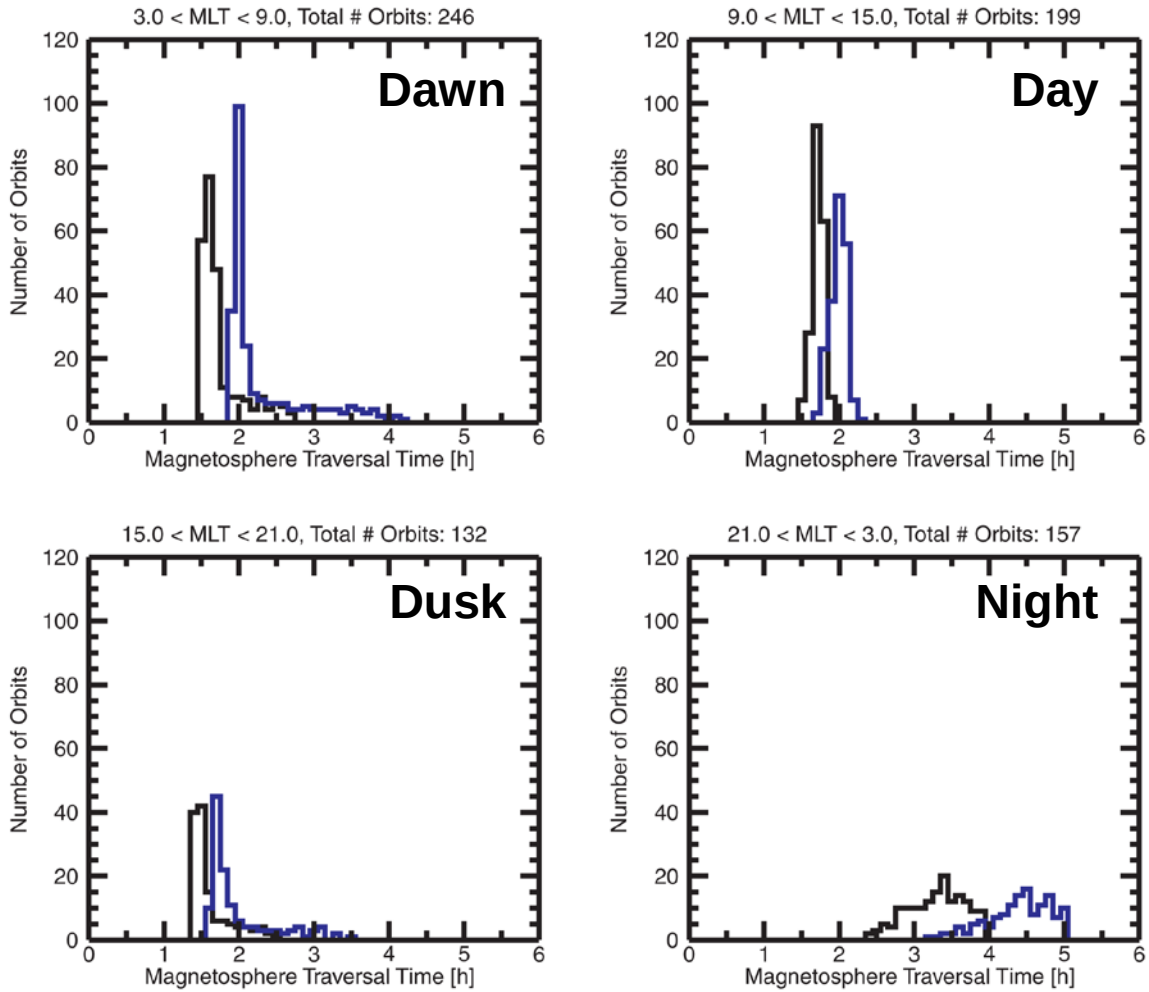
MESSENGER
Conclusions

- IMF geometry and dependence on heliocentric distance agree with predictions by Parker [1958] but observed dynamic evolution is not captured by this model.
- The IMF fluctuations permeate the magnetosphere so that significant variations in the external field are expected.
- Determination of Mercury's magnetic field thus requires a good quantitative understanding of IMF variability.
- The mean external field variability during a typical 2-hour magnetosphere transit is 30 nT.
- Mercury's Dungey timescale is within the frequency range dominated by turbulence; the turbulent IMF may more readily penetrate Mercury's magnetosphere.

Backup

MESSENGER
Magnetosphere Transit Time

- Magnetosphere transit time from predict trajectory.
- Slavin (2009) bow shock model: Parabolic fit to observed bow shock locations.
- Sibeck (1991) magneto-pause model scaled to Mercury.
- Orbits sorted by local time of ascending Node.
- Transition times: 4 hours for nightside orbits, 2 hours otherwise.



MESSENGER
IMF Spectral Analysis

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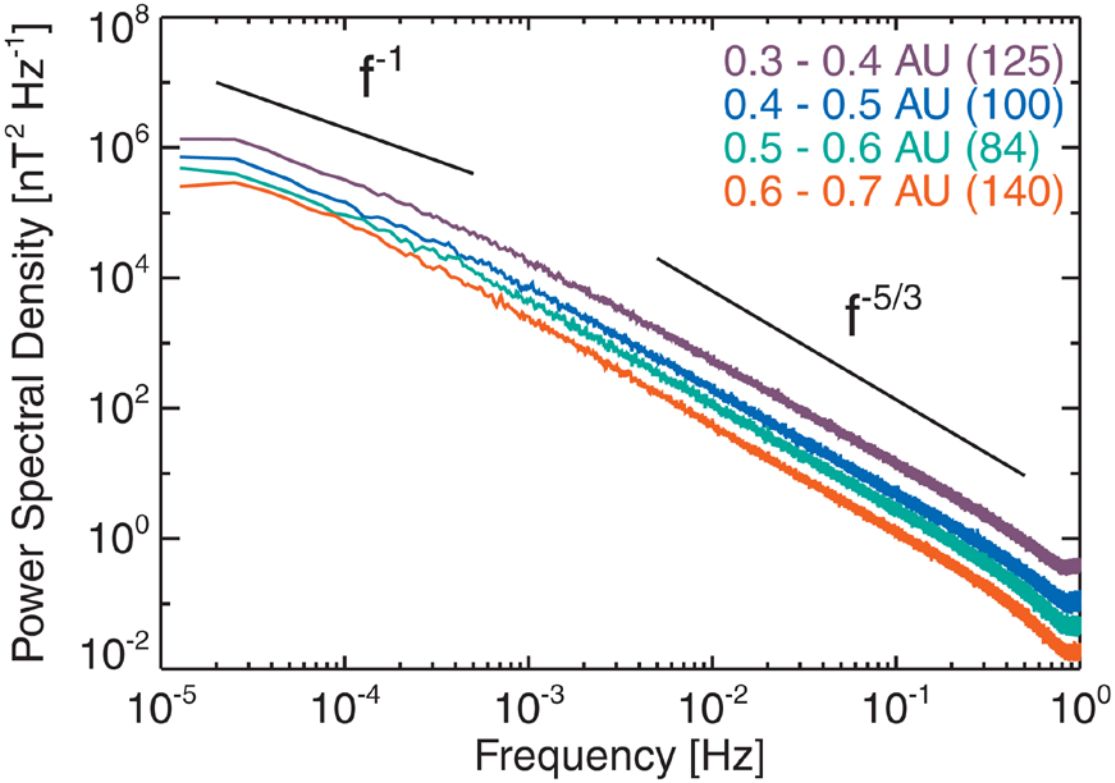
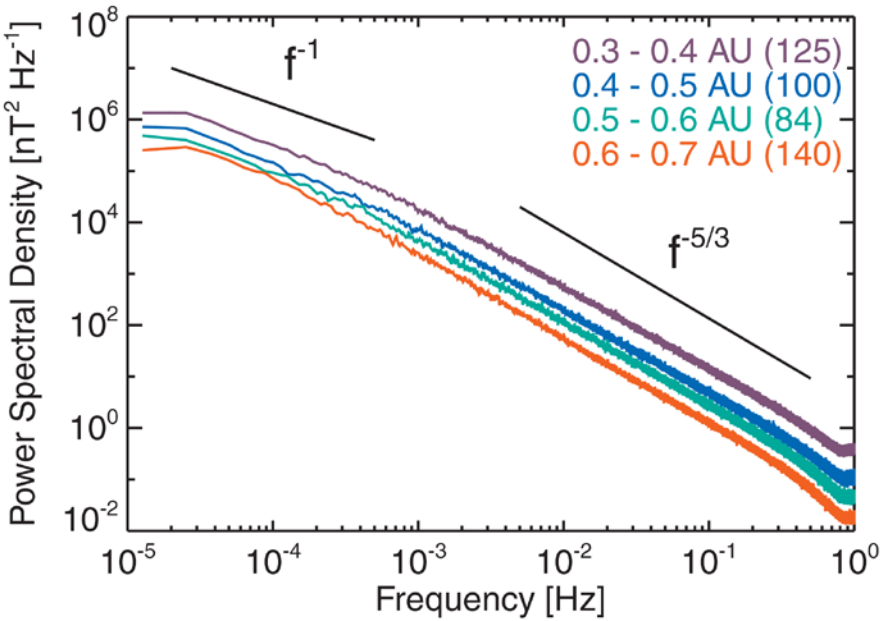


MESSENGER
IMF Spectral Analysis

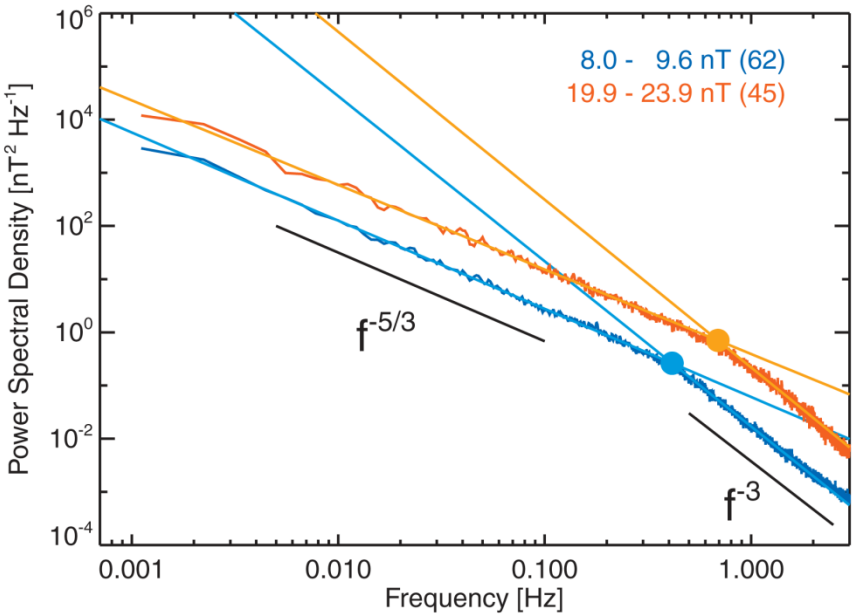
- **Power spectral density over entire frequency range is well organized by radial distance.**
- **f < 10^{-4} Hz: spectral index ≈-1; uncorrelated large-scale structures originating in the solar corona [Matthaeus and Goldstein, 1986].**
- **10^{-4} < f < 10^{-1} Hz: spectral index averages -1.6; consistent with prediction for a turbulent energy cascade [Kolmogoroff, 1941]: Turbulent mixing transfers energy to higher wave numbers in non-magnetic fluids.**

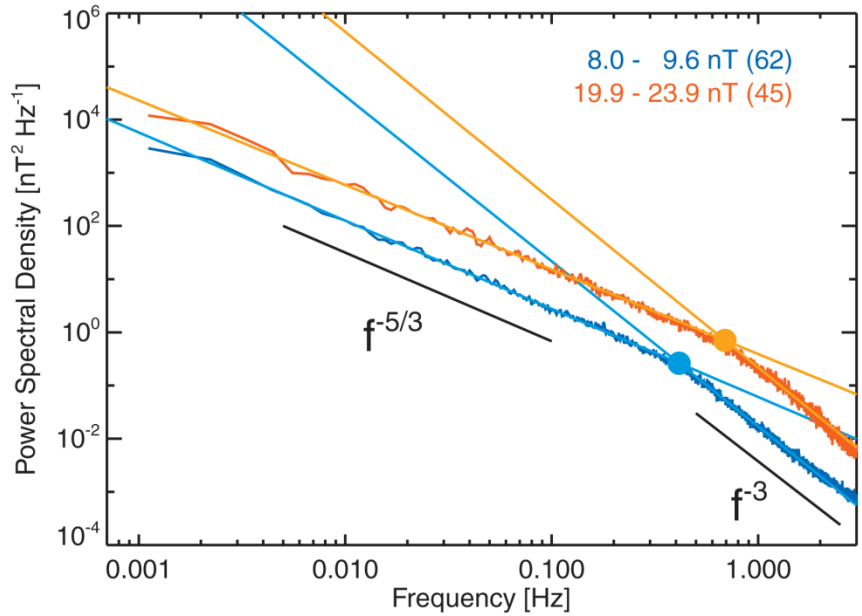
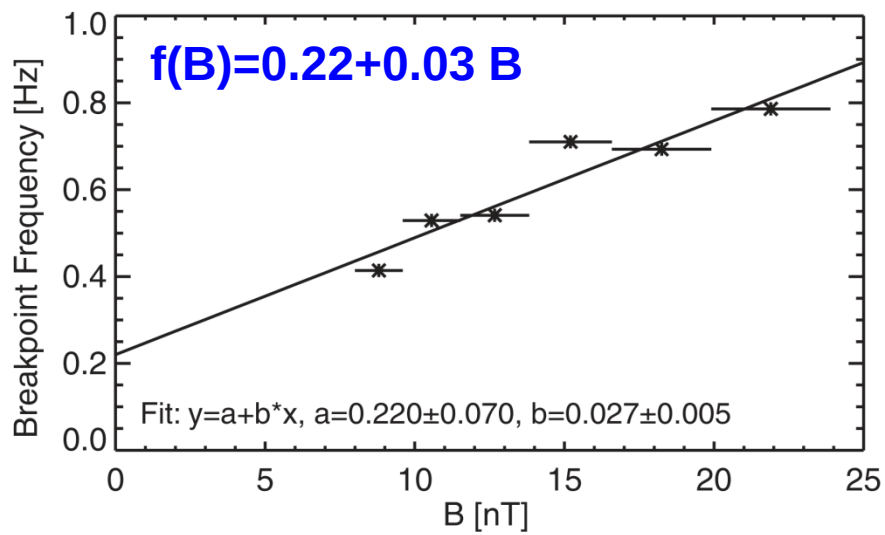


- **Steeper spectral slopes near 1-Hz Nyquist frequency: accurate analysis requires higher time resolution data.**

MESSENGER
IMF Spectral Analysis III

- Intervals of 20/s data averaging one hour per day since December 2009.
- f>1 Hz: steeper power laws are fit (spectral index [-3;-4]), consistent with previous observations.
- Possible explanation:
  - Dissipation (Proton cyclotron, Whistler-mode, Landau damping),
  - High-frequency energy cascade.
- Suggests transition controlled by local conditions, e.g., B magnitude.
- Average spectra sorted by magnetic field magnitude:
  - 6 bins covering 8-24 nT range,
  - Bin width=20% of minimum B.



MESSENGER
IMF Spectral Analysis III

- **Breakpoint frequency f_{BP}: Intersection of power-law fits in lower and higher frequency range:**
  - **Low f: $3 \cdot 10^{-3} < f < 10^{-1}$ Hz,**
  - **High f: 2-Hz-wide interval above f_{BP}.**
- **Observations: f_{BP} is well organized by IMF magnitude.**
- **Linear dependence of f_{BP} on field magnitude within uncertainty limits.**
- **Error bars given by width of magnetic field bins.**
- **Direct connection between lower frequency limit of dissipation range and ambient magnetic field strength.**