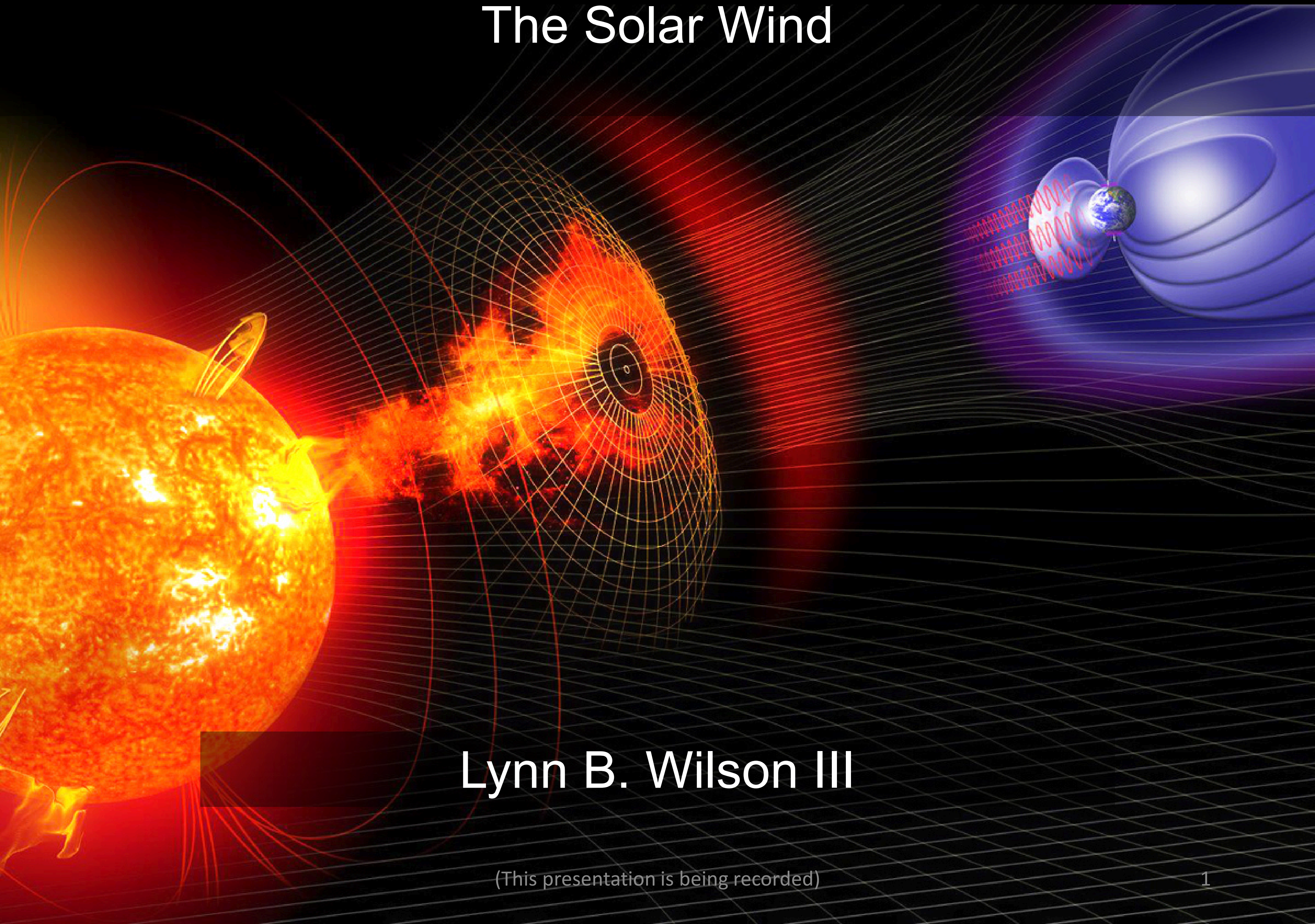
The Solar Wind



Lynn B. Wilson III

(This presentation is being recorded)

Summary

- Introduce jargon and basic concepts
- Introduce solar wind
  - Fast vs Slow
  - Interplanetary magnetic field orientation
- Discuss temperature-dependent solar wind properties
- Discuss solar wind transients
  - CIRs/SIRs
  - ICMEs
  - SEPs
- Briefly mention/introduce fluctuations
- Summary

Definitions and Jargon

Fluid: a substance that smoothly and continually deforms under shear stress

Note: The term fluid includes liquid, gas, and plasma states of matter

Neutral Medium: a substance dominated by the interactions of charge-neutral molecules, i.e., binary particle collisions mediate most interactions

Ionized Medium: a substance containing atoms of unbalanced charge

Note: Ionization ranges from weakly (e.g., fire) to fully (e.g., solar corona)

Plasma: an ionized gas that exhibits a collective behavior, due to long-range forces (i.e., electromagnetic) resulting in correlated motions, and has roughly equal positive and negative charged species within a shielding scale length called a Debye sphere

Definitions

$\varepsilon_o \equiv$ permittivity of free space [F m^{-1}]

$\mu_o \equiv$ permeability of free space [H m^{-1}]

$c \equiv$ speed of light in vacuum [m s^{-1}]

$e \equiv$ fundamental charge [C]

$k_B \equiv$ Boltzmann constant [J K^{-1}]

$m_s \equiv$ mass of species s [kg]

$q_s = Z_s\, e \equiv$ charge of species s [C]

$T_s \equiv$ temperature of species s [eV]

$n_s \equiv$ number density of species s [cm^{-3}]

Definitions

$\mathbf{B}_o\,(\mathbf{B}_o) \equiv$ quasi-static magnetic(electric) field 3-vector

$\omega_{ps} = \sqrt{\frac{n_s {q_s}^2}{m_s \varepsilon_o}} \equiv$ plasma frequency of species s [rad s^{-1}]

$\Omega_{cs} = \frac{q_s B_o}{m_s} \equiv$ cyclotron frequency of species s [rad s^{-1}]

$V_{Ts} = \sqrt{\frac{2 k_B T_s}{m_s}} \equiv$ thermal speed of a 1D Gaussian of species s [m s^{-1}]

$V_A = \frac{B_o}{\sqrt{\mu_o m_i n_i}} \equiv$ Alfvén speed [m s^{-1}]

$\beta_s = \frac{2 \mu_o n_s k_B T_s}{{B_o}^2} \equiv$ plasma beta of species s

Debye Length

$$\lambda_{De} = \sqrt{\frac{\varepsilon_o\ T_e}{e^2\ n_e}}$$

The Solar Wind

- The **solar wind is not in thermodynamic or even thermal equilibrium**
  - $T_s \neq T_{s'}$ and $T_\perp \neq T_{//}$
  - presence of finite heat fluxes
  - It is a non-equilibrium kinetic gas
  - Recent work has even shown evidence of inelastic collisions [*Wilson et al.*, 2019]
- The source(s) of the solar wind is still a subject of active study
  - Early work noticed differences between fast and slow wind (e.g., T_s is higher in fast wind)
    - **Fast vs slow** has been defined by proton speed but **can be defined by other parameters**
  - The sources are thought to strongly depend upon the magnetic field geometry of the solar corona
  - The winds are known to have different compositions
    - Observed ions include: H^{+}; $^{4}He^{2+}$; $^{3}He^{2+}$; $O^{6+,7+}$; $C^{4+,5+,6+}$; N^{+7}; Si^{+9}; Ne^{+8}; S^{+10}; $Fe^{+8\,-\,+17\text{(higher?)}}$; etc.
      [e.g., *Bame et al.*, 1968; *Bochsler et al.*, 1985; *Gloeckler et al.*, 1998; *Lepri et al.*, 2013]
    - Composition: depends on first ionization potential for slow but not fast

L.B. Wilson III et al., "The Statistical Properties of Solar Wind Temperature Parameters Near 1 au," *Astrophys. J. Suppl.* **236**(8), doi:10.3847/1538-4365/aab71c, 2018.
L.B. Wilson III et al., "Electron Energy Partition across Interplanetary Shocks: I. Methodology and Data Product," *Astrophys. J. Suppl.* **243**(8), doi:10.3847/1538-4365/ab22bd, 2019.

Solar Wind: Source and Types

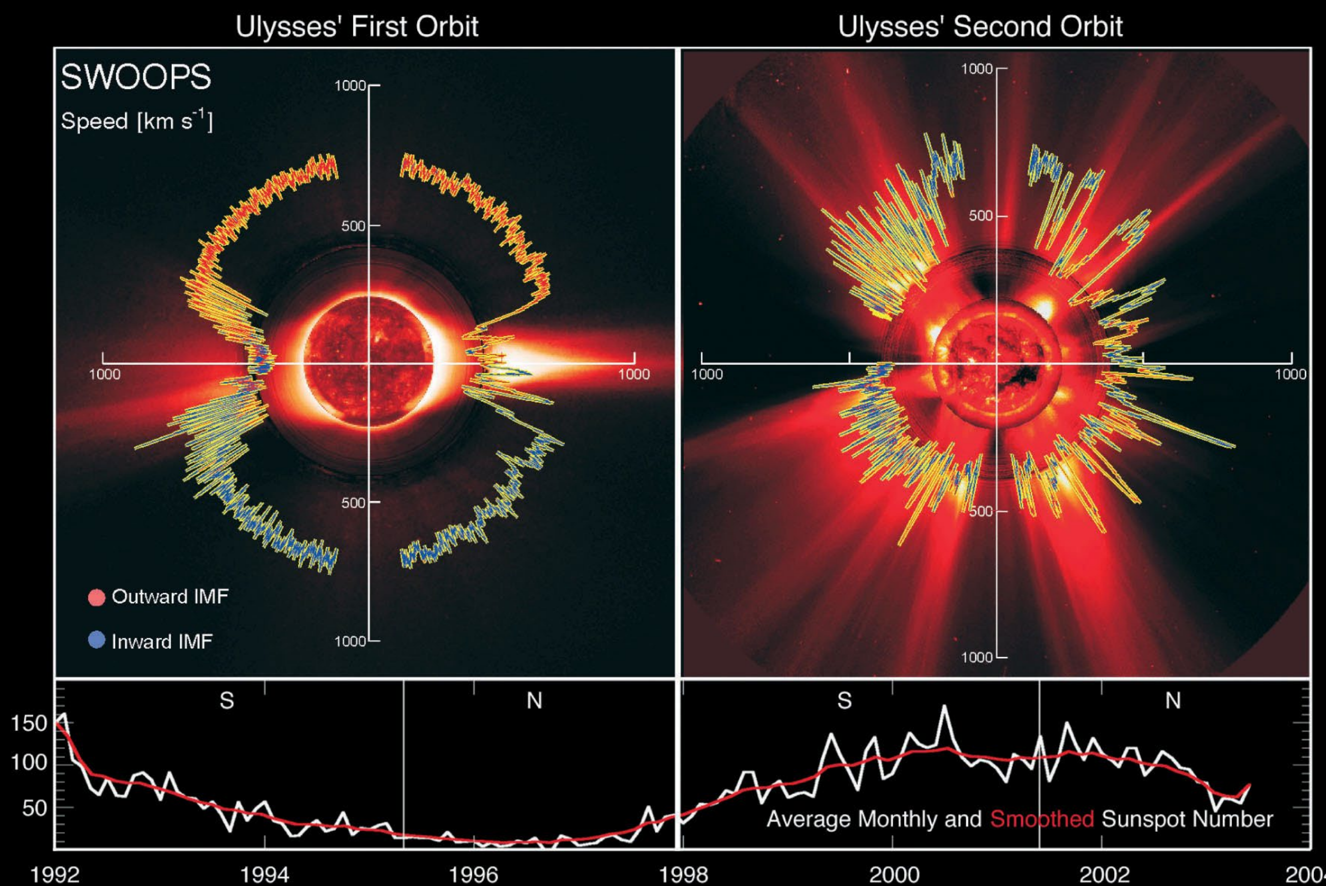


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Figure 2-1. Plots of solar wind speed as a function of heliographic latitude, illustrating the relation between the structure of the solar wind and coronal structure at solar minimum (left) and solar maximum (right). The baseline Solar Probe mission provides for two solar flybys, each at a different part of the solar cycle, so that measurements can be obtained at both the quiet and active phases of the cycle. (Ulysses SWOOPS solar wind data are superposed on composite solar images obtained with the SOHO EIT and LASCO C2 instruments and with the Mauna Loa K-coronameter [*McComas et al.*, 2003]).

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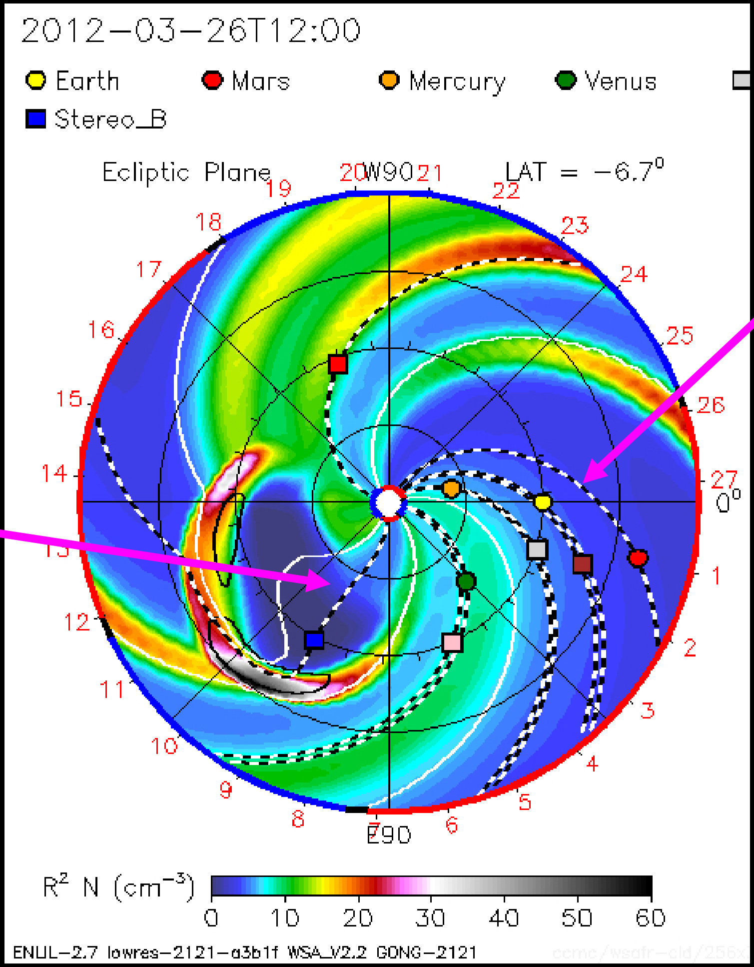
Solar Wind: Source and Types



radial field

Parker spiral field

Solar Wind: Fast vs Slow

- The study involved ~10 years of solar wind data observed by the *Wind* spacecraft [*Wilson et al.*, 2018]
- Additional constraints to those already imposed by *Wilson et al.* [2018]
  - $|(N_i – N_e)/N_e \times 100\%| < 30\%$
  - $j_{tot}/j_{therm} = |\Sigma_s (q_s\ n_s\ \mathbf{V}_s)/(e\ n_e\ V_{Te})| < 10\%$
- Fast Solar Wind (FSW) = $|V_p| > 500$ km/s
- Slow Solar Wind (SSW) = $|V_p| \leq 500$ km/s

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Percentile Ranges All vs Fast vs Slow: $X_{25\%}$ - $X_{75\%}(X_{med})$

Parameter	Fast Wind [$\lvert V_p \rvert > 500$ km/s]	Slow Wind [$\lvert V_p \rvert \leq 500$ km/s]	All wind
N_e [cm^{-3}]	3.75 – 6.51(4.52)	**6.37 – 13.8**(**9.28**)	5.71 – 13.0(8.57)
N_p [cm^{-3}]	3.19 – 5.70(4.04)	**5.66 – 12.4**(**8.28**)	5.05 – 11.7(7.61)
N_α [cm^{-3}]	0.14 – 0.26(0.18)	0.13 – 0.33(0.21)	0.13 – 0.32(0.21)
N_p/N_i [%]	90.3 – 93.3(91.8)	92.1 – 97.1(94.6)	91.7 – 96.9(94.1)
N_α/N_i [%]	**3.49 – 4.92**(**4.17**)	1.48 – 3.99(2.71)	1.64 – 4.19(2.97)

L.B. Wilson III et al., “The Statistical Properties of Solar Wind Temperature Parameters Near 1 au,” *Astrophys. J. Suppl.* **236**(8), doi:10.3847/1538-4365/aab71c, 2018.

Percentile Ranges All vs Fast vs Slow: $X_{25\%}$ - $X_{75\%}$(X_{med})

Parameter	Fast Wind [$|V_p| > 500$ km/s]	Slow Wind [$|V_p| \leq 500$ km/s]	All wind
$T_{e,tot}$ [eV]	**10.3 – 13.6**(**11.8**)	9.26 – 13.0(11.0)	9.41 – 13.1(11.1)
$T_{p,tot}$ [eV]	**17.8 – 33.2**(**24.4**)	4.47 – 12.4(7.54)	4.80 – 15.1(8.45)
$T_{\alpha,tot}$ [eV]	**19.4 – 92.8**(**55.6**)	5.31 – 31.6(11.5)	5.43 – 34.0(12.2)
$(T_{\perp}/T_{//})_e$	**1.11 – 1.35**(**1.22**)	1.00 – 1.10(1.04)	1.01 – 1.13(1.05)
$(T_{\perp}/T_{//})_p$	**0.66 – 1.03**(**0.82**)	0.59 – 0.95(0.76)	0.60 – 0.96(0.81)
$(T_{\perp}/T_{//})_\alpha$	**0.66 – 1.46**(**0.95**)	0.59 – 1.13(0.84)	0.60 – 1.14(0.84)

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Percentile Ranges All vs Fast vs Slow: $X_{25\%}$ - $X_{75\%}$(X_{med})

Parameter	Fast Wind [$\lvert V_p \rvert > 500$ km/s]	Slow Wind [$\lvert V_p \rvert \leq 500$ km/s]	All wind
$\beta_{e,tot}$ [N/A]	0.51 – 1.08(0.73)	**0.95 – 2.89(1.62)**	0.83 – 2.64(1.45)
$\beta_{p,tot}$ [N/A]	**0.92 – 2.12(1.41)**	0.64 – 1.86(1.13)	0.67 – 1.90(1.16)
$\beta_{\alpha,tot}$ [N/A]	**0.05 – 0.41(0.19)**	0.02 – 0.18(0.06)	0.02 – 0.19(0.07)

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Percentile Ranges All vs Fast vs Slow: $X_{25\%}$ - $X_{75\%}(X_{med})$

Parameter	Fast Wind [$\lvert V_p \rvert > 500$ km/s]	Slow Wind [$\lvert V_p \rvert \leq 500$ km/s]	All wind
$(T_e/T_p)_{tot}$	0.36 – 0.65(0.49)	**0.92 – 2.29**(**1.42**)	0.78 – 2.14(1.28)
$(T_e/T_\alpha)_{tot}$	0.12 – 0.45(0.19)	**0.35 – 1.83**(**0.87**)	0.32 – 1.78(0.82)
$(T_\alpha/T_p)_{tot}$	**2.28 – 4.75**(**3.72**)	1.38 – 3.52(1.96)	1.39 – 3.62(2.01)

L.B. Wilson III et al., "The Statistical Properties of Solar Wind Temperature Parameters Near 1 au," *Astrophys. J. Suppl.* **236**(8), doi:10.3847/1538-4365/aab71c, 2018.

Particle-particle Coulomb Collisions

$$\nu_{ss'} = \frac{C_{ss'}\ n_{s'}}{{V_{Tss'}}^3}\ \ln \Lambda_{ss'}$$

$$C_{ss'} = \frac{A_{ss'}\ e^4}{3\left(4\pi\varepsilon_o\right)^2\ {\mu_{ss'}}^2}$$

$$\Lambda_{ss'} \simeq \frac{\left(4\pi\varepsilon_o\right)\ \mu_{ss'}\ {V_{Tss'}}^2}{\sqrt{2}\ Z_s\ Z_{s'}\ e^2}\left[\left(\frac{\omega_{ps}}{V_{Ts,tot}}\right)^2 + \left(\frac{\omega_{ps'}}{V_{Ts',tot}}\right)^2\right]^{-1/2}$$

$$V_{Tss'} = \sqrt{{V_{Ts,tot}}^2 + {V_{Ts',tot}}^2}$$

$$\mu_{ss'} = \frac{m_s\ m_{s'}}{\left(m_s + m_{s'}\right)}$$

$$A_{ee} = 4\sqrt{2\pi}$$

$$A_{pp} = 4\sqrt{2\pi}$$

$$A_{\alpha\alpha} = 64\sqrt{2\pi}$$

$$A_{ep} = 2\sqrt{4\pi}$$

$$A_{e\alpha} = 8\sqrt{4\pi}$$

$$A_{p\alpha} = 8\sqrt{2\pi}$$

$${\lambda_{ss'}}^{mpf} = \frac{V_{Tss'}}{\nu_{ss'}}$$

$$\nu_{iaw} = \omega_{pe}\frac{\varepsilon_o\ \left|\delta E\right|^2}{2\ n_e\ k_B\ T_{e,tot}}$$

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Percentile Ranges All vs Fast vs Slow: $X_{25\%}$ - $X_{75\%}(X_{med})$

Parameter	Fast Wind [$\lvert V_p \rvert > 500$ km/s]	Slow Wind [$\lvert V_p \rvert \leq 500$ km/s]	All wind
ν_{iaw} [#/day]	41.8 – 64.4(52.8)	32.4 – 50.1(42.4)	33.0 – 52.2(41.6)
ν_{ee} [#/day]	0.29 – 0.49(0.37)	**0.49 – 1.40**(**0.79**)	0.43 – 1.30(0.70)
ν_{ep} [#/day]	0.13 – 0.22(0.16)	**0.21 – 0.63**(**0.35**)	0.19 – 0.58(0.31)
$\nu_{e\alpha}$ [#/day]	0.022 – 0.040(0.029)	0.022 – 0.058(0.035)	0.022 – 0.055(0.034)
ν_{pp} [#/day]	0.002 – 0.004(0.003)	**0.012 – 0.077**(**0.030**)	0.008 – 0.067(0.024)
$\nu_{\alpha\alpha}$ [#/day]	0.0002 – 0.003(0.0005)	**0.001 – 0.010**(**0.004**)	0.001 – 0.010(0.003)
$\nu_{p\alpha}$ [#/day]	0.0002 – 0.0004(0.0003)	**0.0006 – 0.002**(**0.001**)	0.0005 – 0.002(0.001)

ν_{iaw} assumes $\delta E \sim 0.1$ mV/m and waves always present

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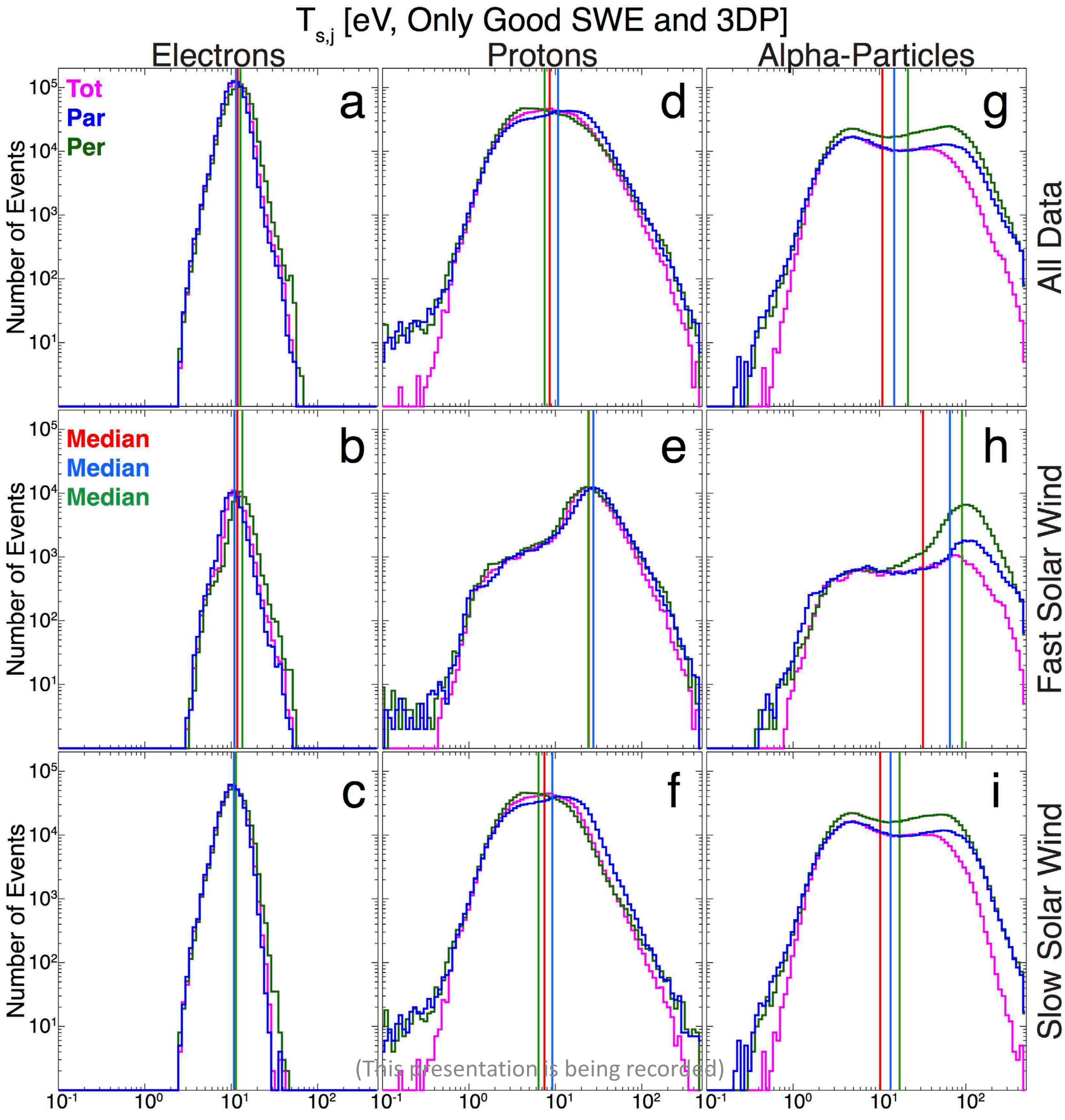

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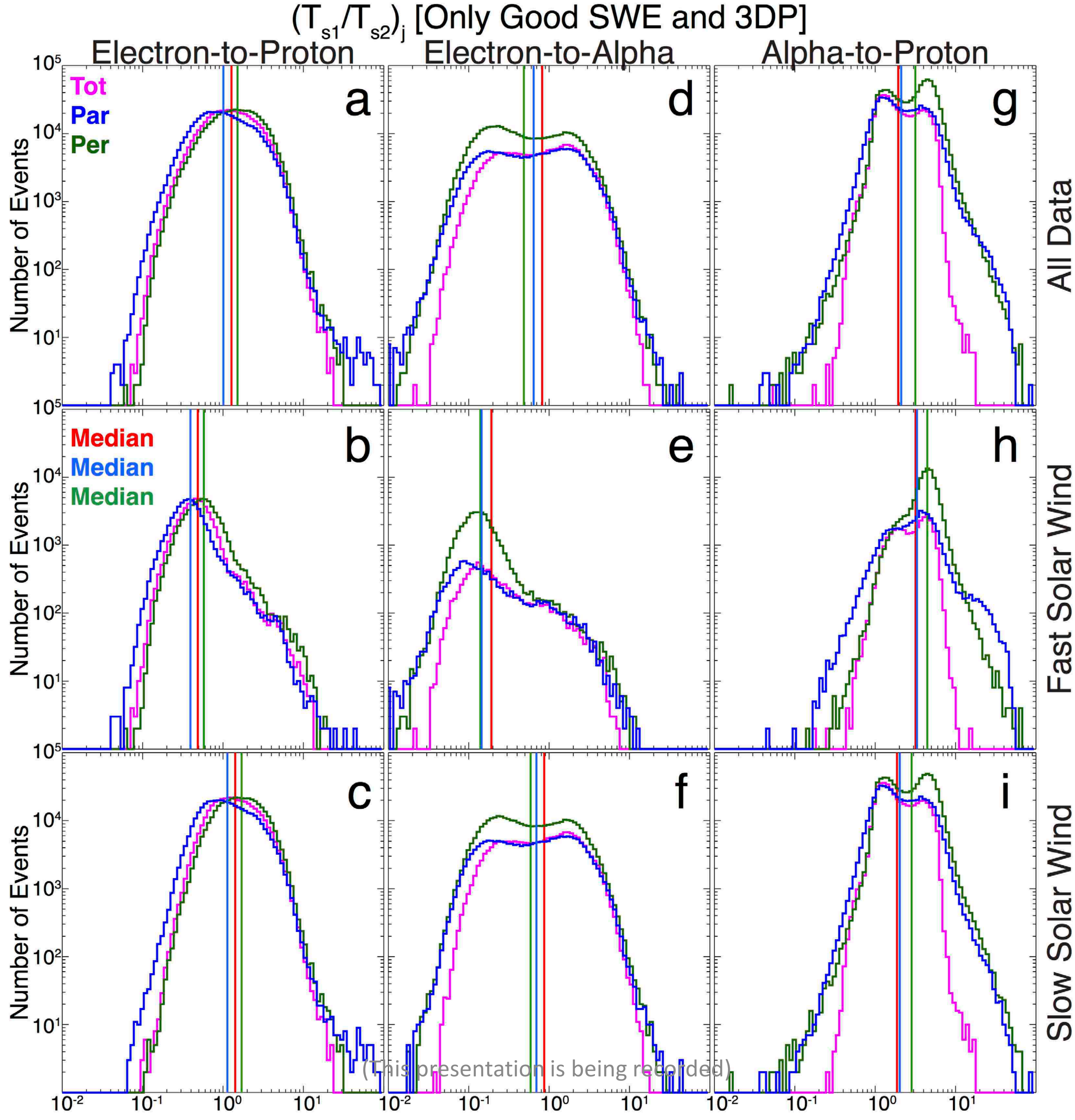

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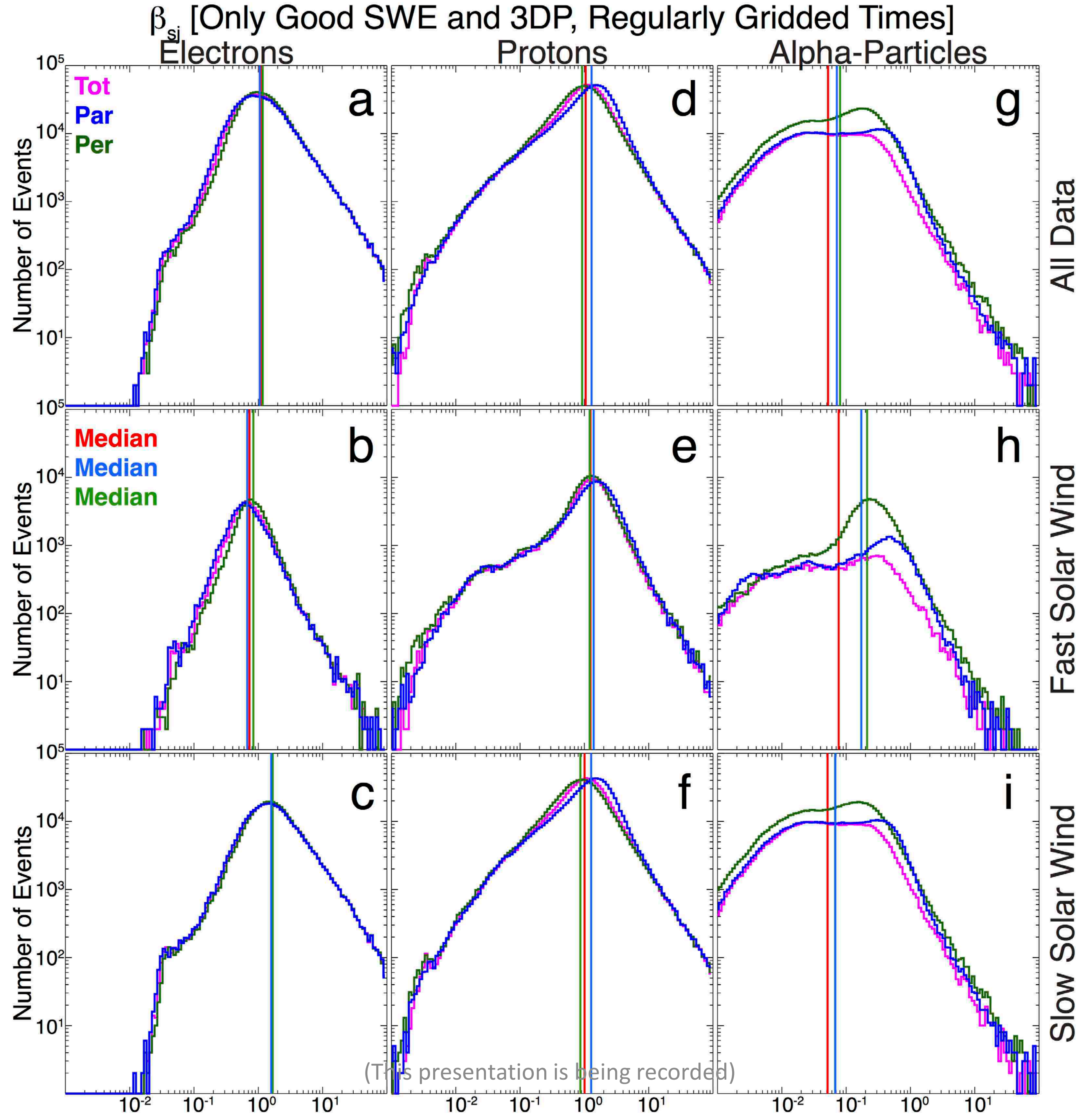

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Solar Wind Transients

- SIR = stream interaction region [*Jian et al.*, 2006; 2008; 2011]
- CIR = co-rotating interaction region
- CME = coronal mass ejection
  - ICME = interplanetary coronal mass ejection
  - MC = magnetic cloud [*Nieves-Chinchilla et al.*, 2018; *Li et al.*, 2018]
    - increase in $|\mathbf{B}_o|$
    - rotation in $\mathbf{B}_o$
    - decrease in T_p
  - Flux Rope = similar to magnetic cloud
- SEP = solar energetic particles
  [e.g., *Reames*, 2017; *Richardson et al.*, 2015]

L.K. Jian et al., “Properties of stream interactions at one AU during 1995 - 2004,” *Solar Phys.* **239**, pp. 337-392, doi:10.1007/s11207-006-0132-3, 2006.

L.K. Jian et al., “Stream Interactions and Interplanetary Coronal Mass Ejections at 0.72 AU,” *Solar Phys.* **249**, pp. 85-101, doi:10.1007/s11207-008-9161-4, 2008.

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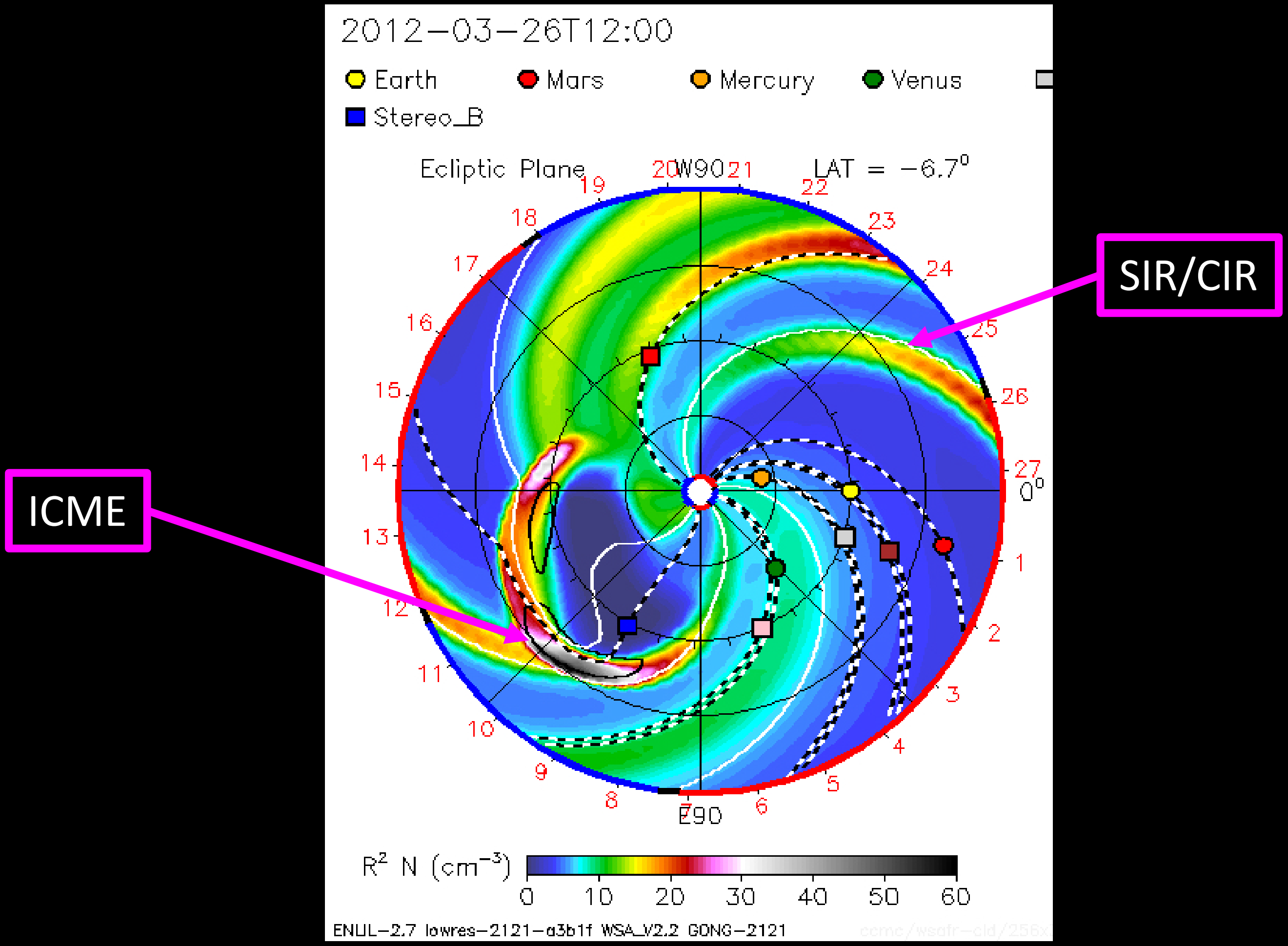
Y. Li et al., “Magnetic Clouds: Solar Cycle Dependence, Sources, and Geomagnetic Impacts,” *Solar Phys.* **293**(135), pp. 19, doi:10.1007/s11207-018-1356-8, 2018.

T. Nieves-Chinchilla et al., “Understanding the Internal Magnetic Field Configurations of ICMEs Using More than 20 Years of *Wind* Observations,” *Solar Phys.* **293**(25), pp. 31, doi:10.1007/s11207-018-1247-z, 2018.

D.V. Reames “Solar Energetic Particles,” *Lecture Notes Phys.* **932**, pp. 136, doi:10.1007/978-3-319-50871-9, 2017.

I.G. Richardson et al., “The Properties of Solar Energetic Particle Event-Associated Coronal Mass Ejections Reported in Different CME Catalogs,” *Solar Phys.* **290**, pp. 1741-1759, doi:10.1007/s11207-015-0701-4, 2017.

Solar Wind: Source and Types



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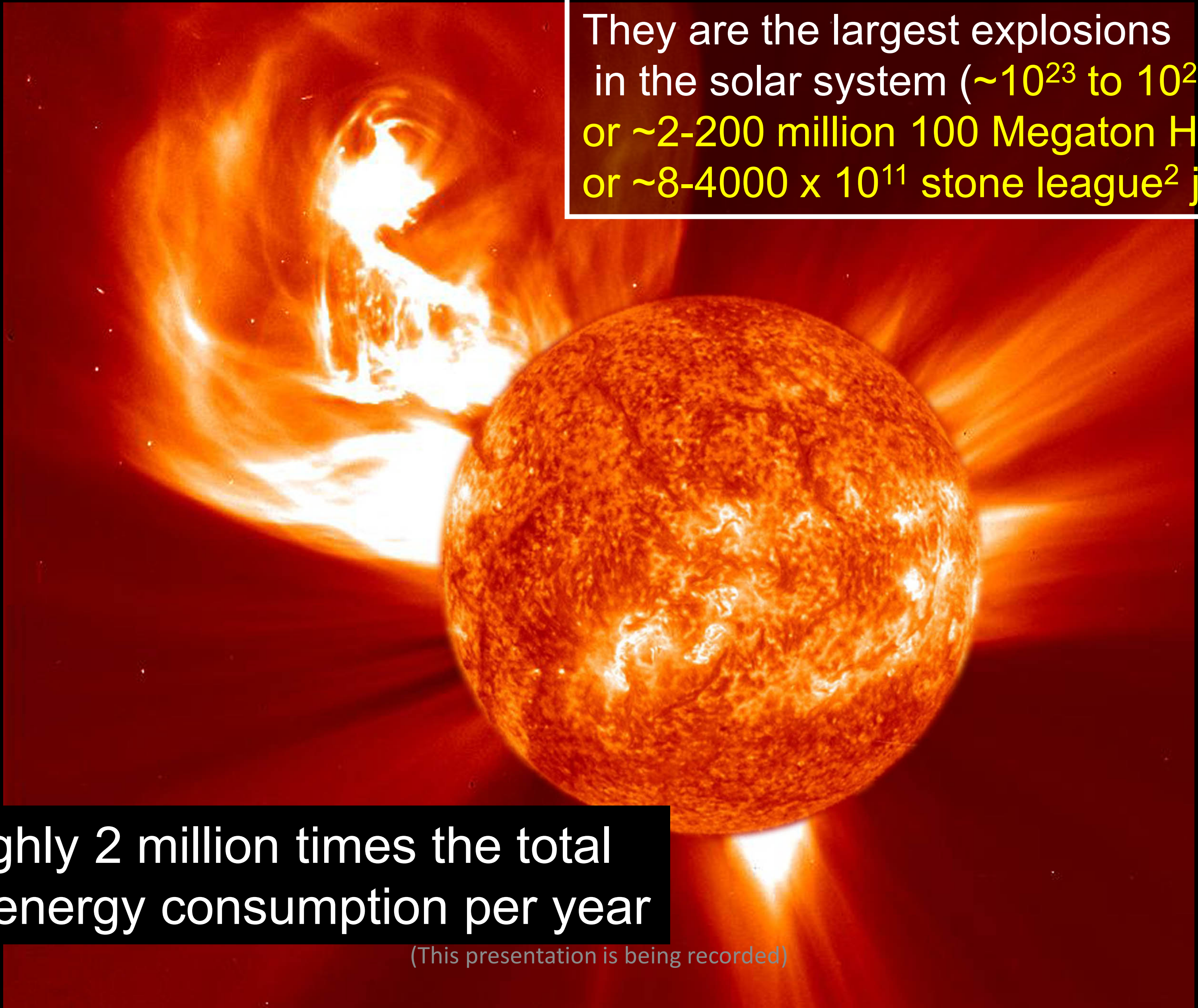
Coronal Mass Ejections (CMEs)

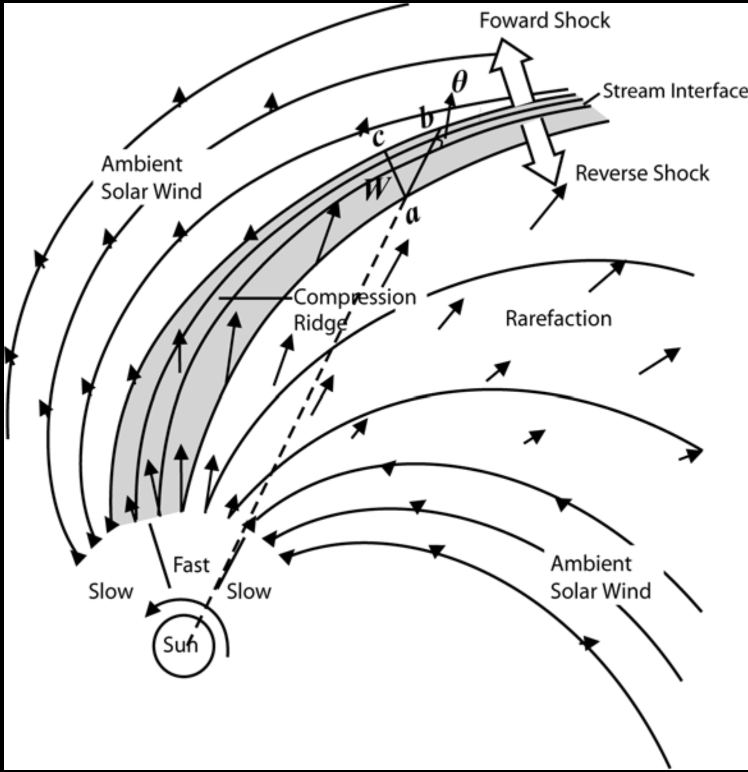


They are the largest explosions in the solar system ($\sim 10^{23}$ to 10^{26} J or ~2-200 million 100 Megaton H-bombs or $\sim 8\text{-}4000 \times 10^{11}$ stone league^2 jiffy^{-2}).

Roughly 2 million times the total world energy consumption per year

Fast/Slow Streams (SIRs and CIRs)

- SIR = stream interaction region [*Jian et al.*, 2006; 2008; 2011]
  - develops due to a faster flowing region overtaking a slower one
  - a subset are CIR = co-rotating interaction regions
    - require lifetime to surpass more than one solar rotation
- CIRs/SIRs form shocks
- They also drive geomagnetic storms [e.g., *Borovsky & Denton*, 2006]



J.E. Borovsky & M.H. Denton "Differences between CME-driven and CIR-driven storms," *J. Geophys. Res.* **111**, pp. A07S08, doi:10.1029/2005JA011447, 2006.
L.K. Jian et al., "Properties of stream interactions at one AU during 1995 - 2004," *Solar Phys.* **239**, pp. 337-392, doi:10.1007/s11207-006-0132-3, 2006.
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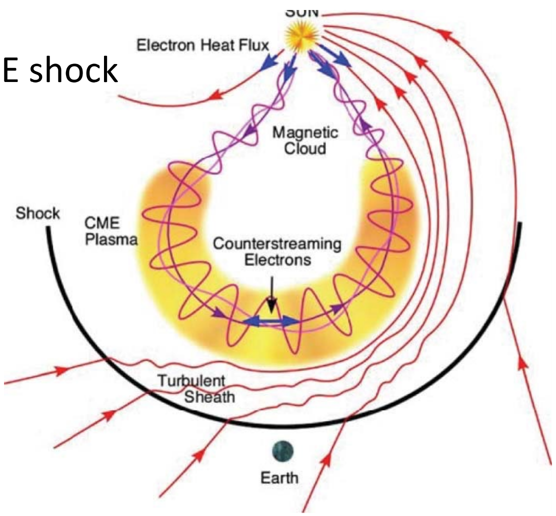
Solar Flares

They are massive localized enhancements in UV and x-ray emissions (~10^{20} to 10^{25} J or ~10^{4} to 10^{9} 50 Megaton H-bombs or combusting ~10^{12}–10^{17} gallons of gas).

Types of Collisionless Shock Waves

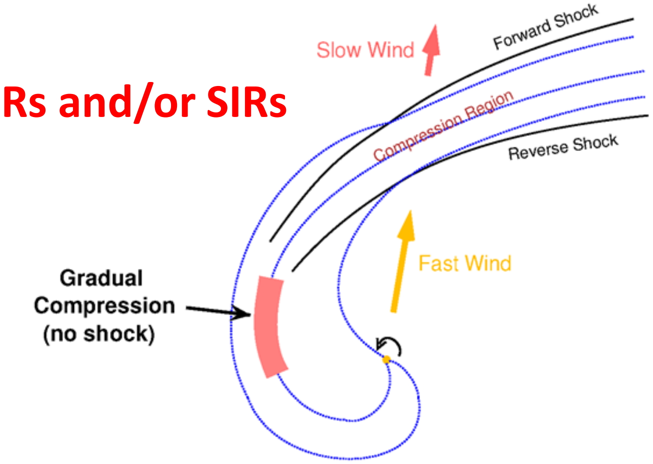
Heliospheric Shocks

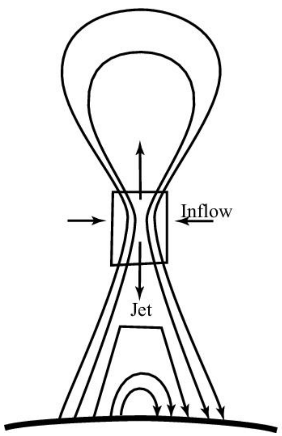
E shock

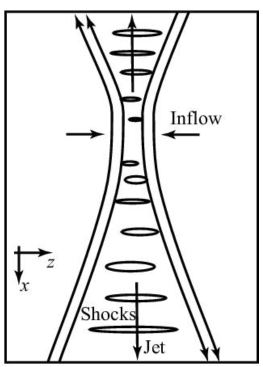


tion regions

CIRs and/or SIRs







Energetic Particles (SEPs, ESPs, etc.)

- solar energetic particles (SEPs)
  [e.g., *Reames*, 2017; *Richardson et al.*, 2015]
  - gradual
    - likely due to ICME shocks
    - transport effects critical (e.g., diffusion during propagation)
    - long duration and broader spectra
    - smaller nonthermal abundance variations than impulsive
  - impulsive
    - shorter duration onset and decay than gradual
    - ~1000 fold increase in ^{3}He/^{4}He abundance ratio
    - if interplanetary transient associated, then it is usually smaller, slower, and very narrow ICMEs
    - not (usually?) associated with γ-ray lines in low corona
    - never observe the elements Li, Be, or B
- when ICME width ≥100^o suprathermal H^+ intensities increase by 10^3

D.V. Reames "Solar Energetic Particles," *Lecture Notes Phys.* **932**, pp. 136, doi:10.1007/978-3-319-50871-9, 2017.
I.G. Richardson et al., "The Properties of Solar Energetic Particle Event-Associated Coronal Mass Ejections Reported in Different CME Catalogs," *Solar Phys.* **290**, pp. 1741-1759, doi:10.1007/s11207-015-0701-4, 2017.

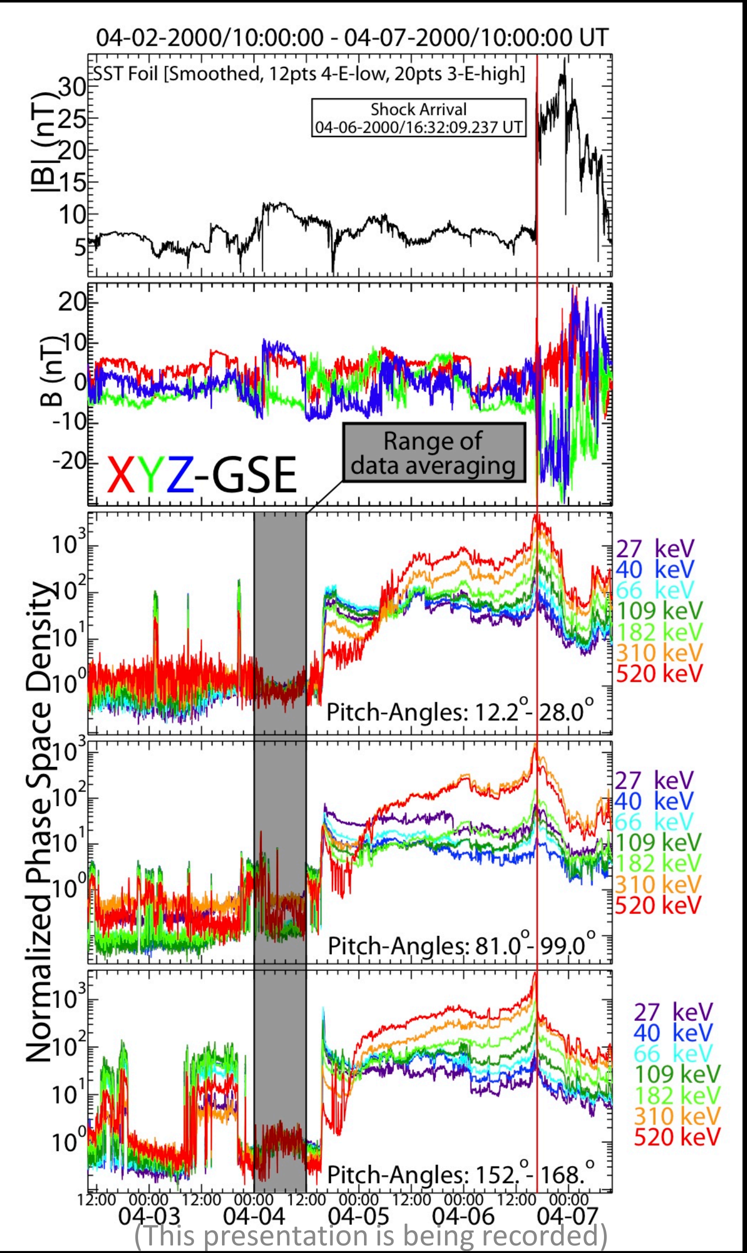
Particle Energization: Electrons

1 nT = 10 μG

Parallel

Perpendicular

Anti-parallel



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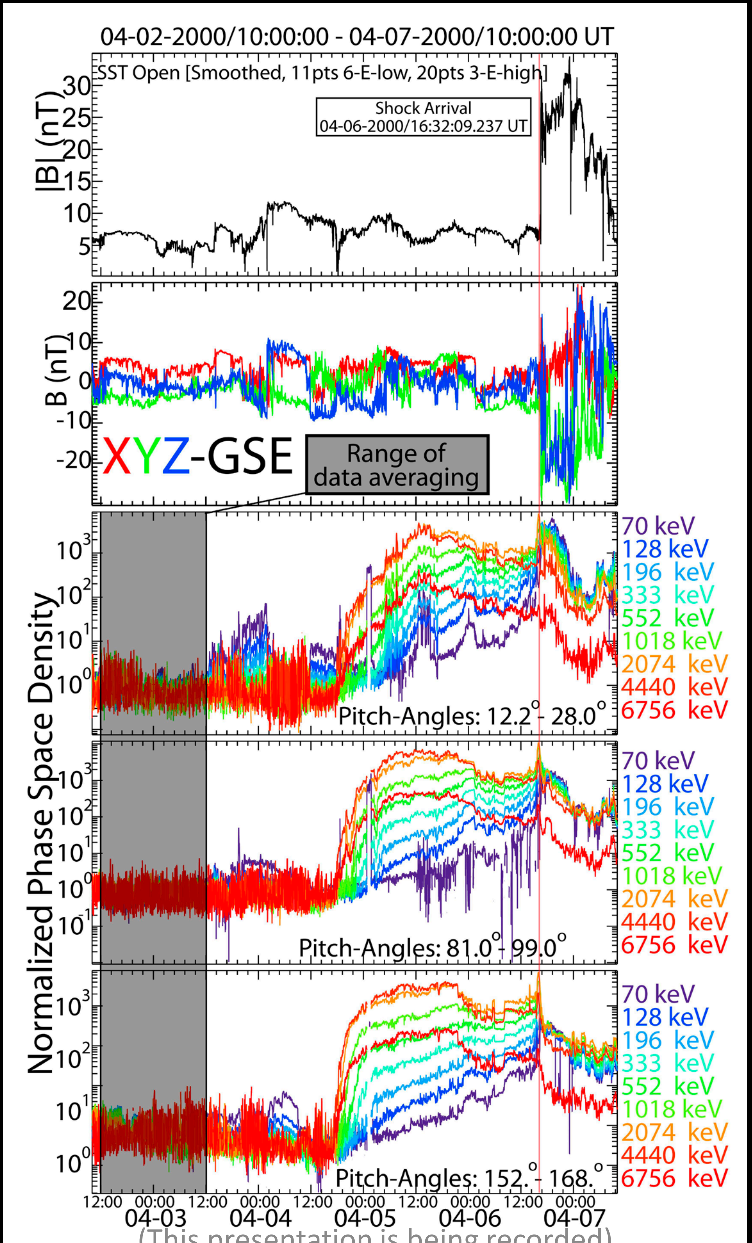

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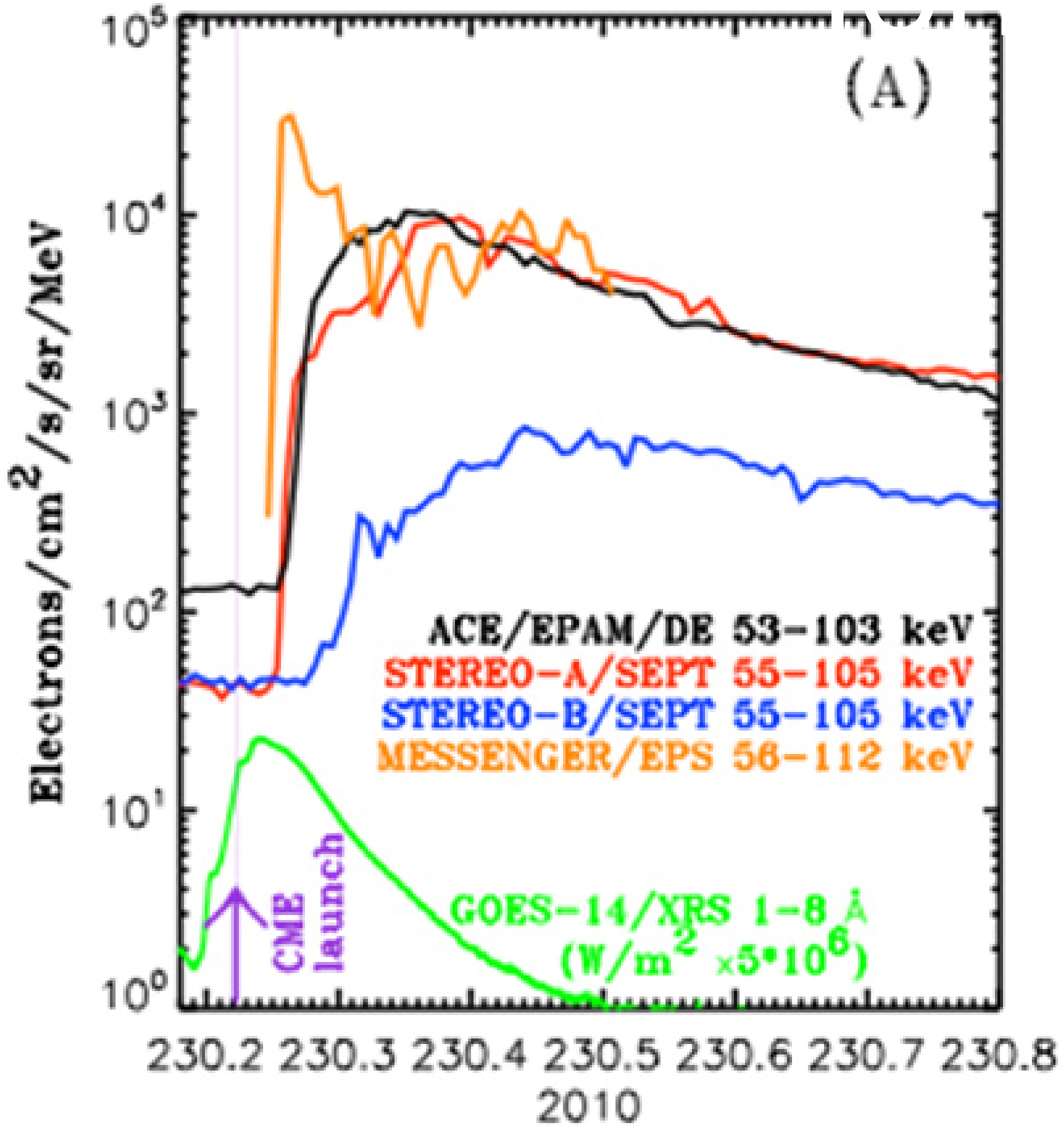
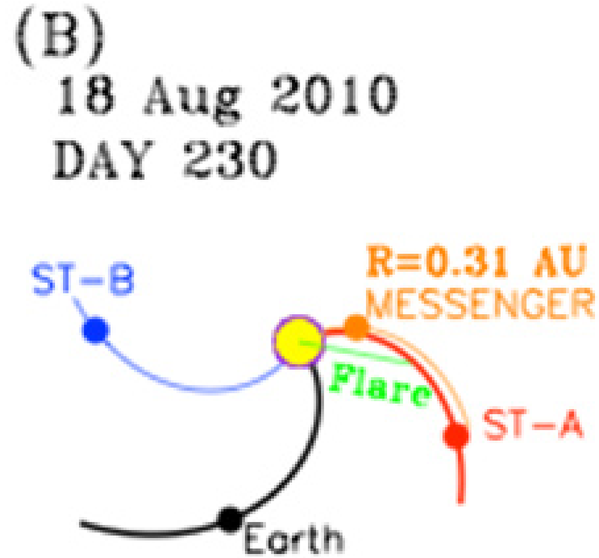
Puzzle: Longitudinal Dist. Ions

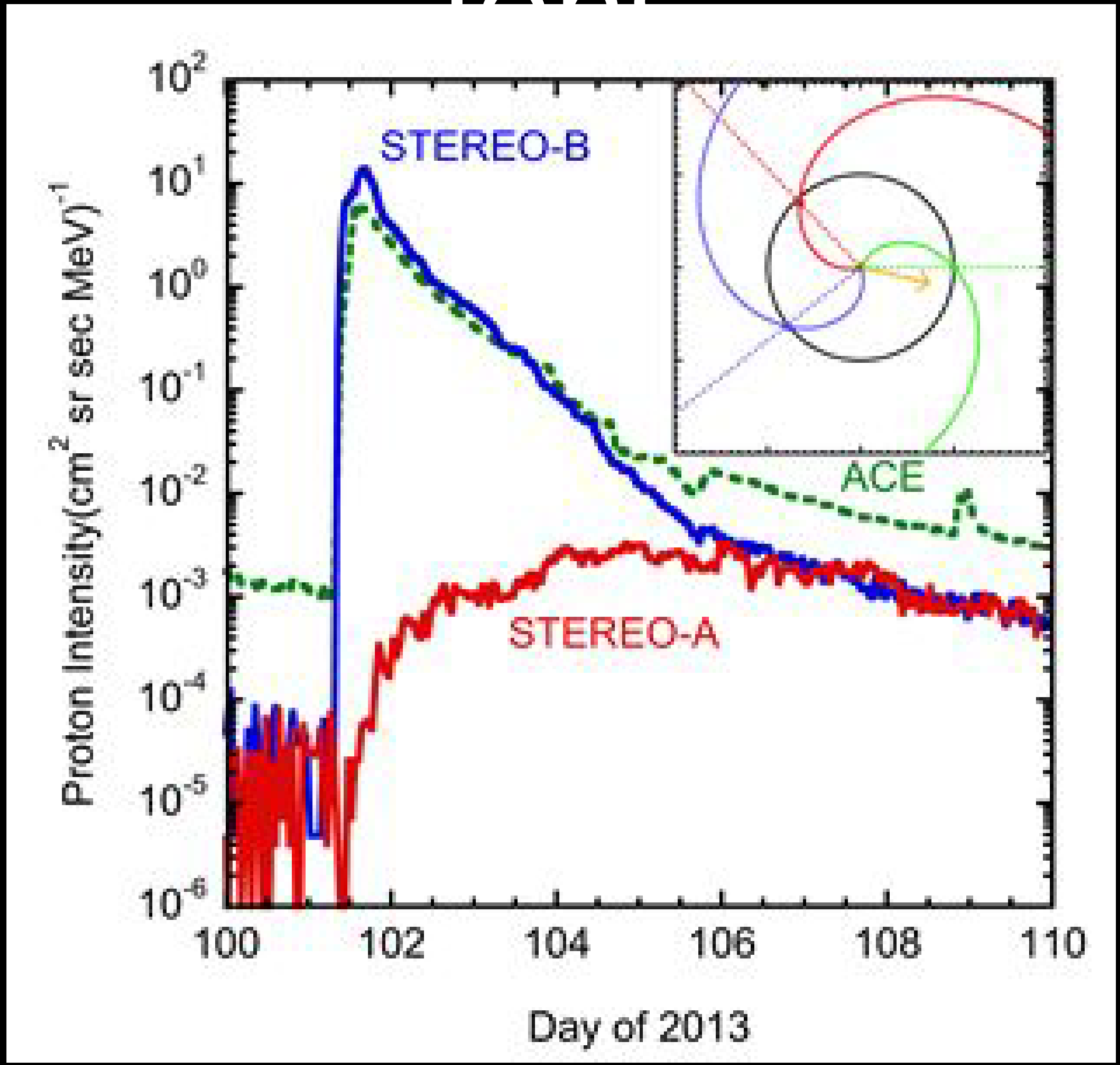




(A) 10-minute averages of the ~55-100 keV electron intensities measured by ACE, STEREO-A, STEREO-B, and MESSENGER during the electron event on 18 August 2010. The arrow indicates the time of the CME launch associated with the origin of the event, and the green trace shows the soft X-ray emission of the associated flare.
(B) Spacecraft location and nominal magnetic field connection to the Sun on 18 August 2010.

http://www.srl.caltech.edu/ACE/ACENews/ACENews139.html

Puzzle: Longitudinal Dist. Ions



http://www.srl.caltech.edu/ACE/ACENews/ACENews170.html

(This presentation is being recorded)

Solar Wind Fluctuations

- ICW = ion cyclotron wave [*Jian et al.*, 2009; 2014; *Wicks et al.*, 2016]
  - PCW = proton cyclotron wave
  - Sometimes called Alfvén/ion cyclotron waves
  - left-hand polarized, EM, mostly transverse with $\theta_{kB} \sim 0^o$
- KAW = kinetic Alfven wave
  [e.g., *Gershman et al.*, 2017; *Krauss-Varban et al.*, 1994; *Verscharen et al.*, 2019b]
  - both left- and right-hand polarized (depending on β and θ_{kB}), EM, wide range θ_{kB}
- Magnetosonic-whistlers or fast modes or electromagnetic lower hybrid waves
  - right-hand polarized, EM, δB in phase with δn, typically $\theta_{kB} \sim 20^o$-60^o
    [e.g., *Coroniti et al.*, 1982; *Verscharen et al.*, 2019a; *Wilson III et al.*, 2013]
- EM Turbulence [e.g., *Verscharen et al.*, 2019b]
- Lots more fluctuations at higher frequencies and smaller scales...

F.V. Coroniti, et al., "Whistler mode turbulence in the disturbed solar wind," *J. Geophys. Res.* **87**(A8), pp. 6029-6044, doi:10.1029/JA087iA08p06029, 1982.
D.J. Gershman, et al., "Wave-particle energy exchange directly observed in a kinetic Alfvén-branch wave," *Nature Comm.* **8**, pp. 10, doi:10.1038/ncomms14719, 2017.
L.K. Jian, et al., "Ion cyclotron waves in the solar wind observed by STEREO near 1 AU," *Astrophys. J.* **709**, pp. L105-L109, doi:10.1088/0004-637X/701/L105, 2009.
L.K. Jian, et al., "Electromagnetic waves near the proton cyclotron frequency: STEREO observations," *Astrophys. J.* **786**(123), pp. 18, doi:10.1088/0004-637X/786/2/123, 2014.
D. Krauss-Varban, et al., "Mode properties of low-frequency waves: Kinetic theory versus Hall-MHD," *J. Geophys. Res.* **99**(A4), pp. 5987-6009, doi:10.1029/93JA03202, 1994.
D. Verscharen, et al. "Self-induced scattering of strahl electrons in the solar wind," *Astrophys. J.* **886**(136), pp. 11, doi:10.3847/1538-4357/ab4c30, 2019a.
D. Verscharen, et al. "The multi-scale nature of the solar wind," Living Rev. Sol. Phys. 16(5), pp. 136, doi:10.1007/s41116-019-0021-0, 2019b.
R.T. Wicks, et al., "A proton-cyclotron wave storm generated by unstable proton distribution functions in the solar wind," *Astrophys. J.* **819**(6), pp. 9, doi:10.3847/0004-637X/819/1/6, 2016.
L.B. Wilson III, et al., "Electromagnetic waves and electron anisotropies downstream of supercritical interplanetary shocks," *J. Geophys. Res.* **118**(1), pp. 5-16, doi:10.1029/2012JA018167, 2013.

Summary

- The solar wind is not in thermodynamic or even thermal equilibrium
- The solar wind is commonly split into fast and slow
  - fast is hotter, larger temperature anisotropies, and more tenuous
  - slow is more collisional, but still collision rates are very small [typically ≤ 1 per day]
- ICMEs vs CIRs/SIRs
  - ICMEs generate larger Dst but smaller relativistic electron enhancements and sometimes: ground induced currents, reformation of radiation belts, SEPs
  - CIRs/SIRs have weaker Dst but more severe relativistic electron enhancements, but do not cause a reformation of radiation belts or ground induced currents (inference on SEPs is less clear... at least to me)
- Solar Energetic Particles: Gradual vs Impulsive
  - Gradual: almost all associated with ICME, long durations and broad spatial extent, and smaller abundance variations than impulsive
  - Impulsive: often blamed on solar flares but rarely if ever see g-ray emissions in low corona, no evidence of nuclear processes (i.e., don't see Li, Be, B, or ^{2}H or ^{3}H), ~1000 fold increase in ^{3}He/^{4}He abundance ratio (^{3}He not a nuclear reaction product), and sometimes associated with smaller, slower, and very narrow ICMEs

Extras
(no particular order)

Values vs Solar Min: $X_{avg} \pm X_{\sigma/N^{(1/2)}}$

Parameter	20/21 (~1976)	21/22 (~1986)	22/23 (~1996)	23/24 (~'08-'09)
V_{sw} [km s^{-1}]	449 ± 6	459 ± 7	422 ± 4	388 ± 4
B_o [nT]	5.56 ± 0.12	5.78 ± 0.14	5.16 ± 0.08	4.02 ± 0.08
N_p [cm^{-3}]	8.2 ± 0.3	8.5 ± 0.3	8.0 ± 0.2	5.5 ± 0.2
$T_{p,tot}$ [eV]	10.8 ± 0.4	9.4 ± 0.4	7.2 ± 0.3	5.5 ± 0.2
β_{tot} [N/A]	3.8 ± 0.2	3.4 ± 0.2	3.5 ± 0.1	4.1 ± 0.3
P_{dyn} [nPa]	2.81 ± 0.07	2.97 ± 0.07	2.44 ± 0.04	1.40 ± 0.03

L.K. Jian et al., "Comparing Solar Minimum 23/24 with Historical Solar Wind Records at 1 AU," *Solar Phys.* **274**, pp. 321-344, doi:10.1007/s11207-011-9737-2, 2011.

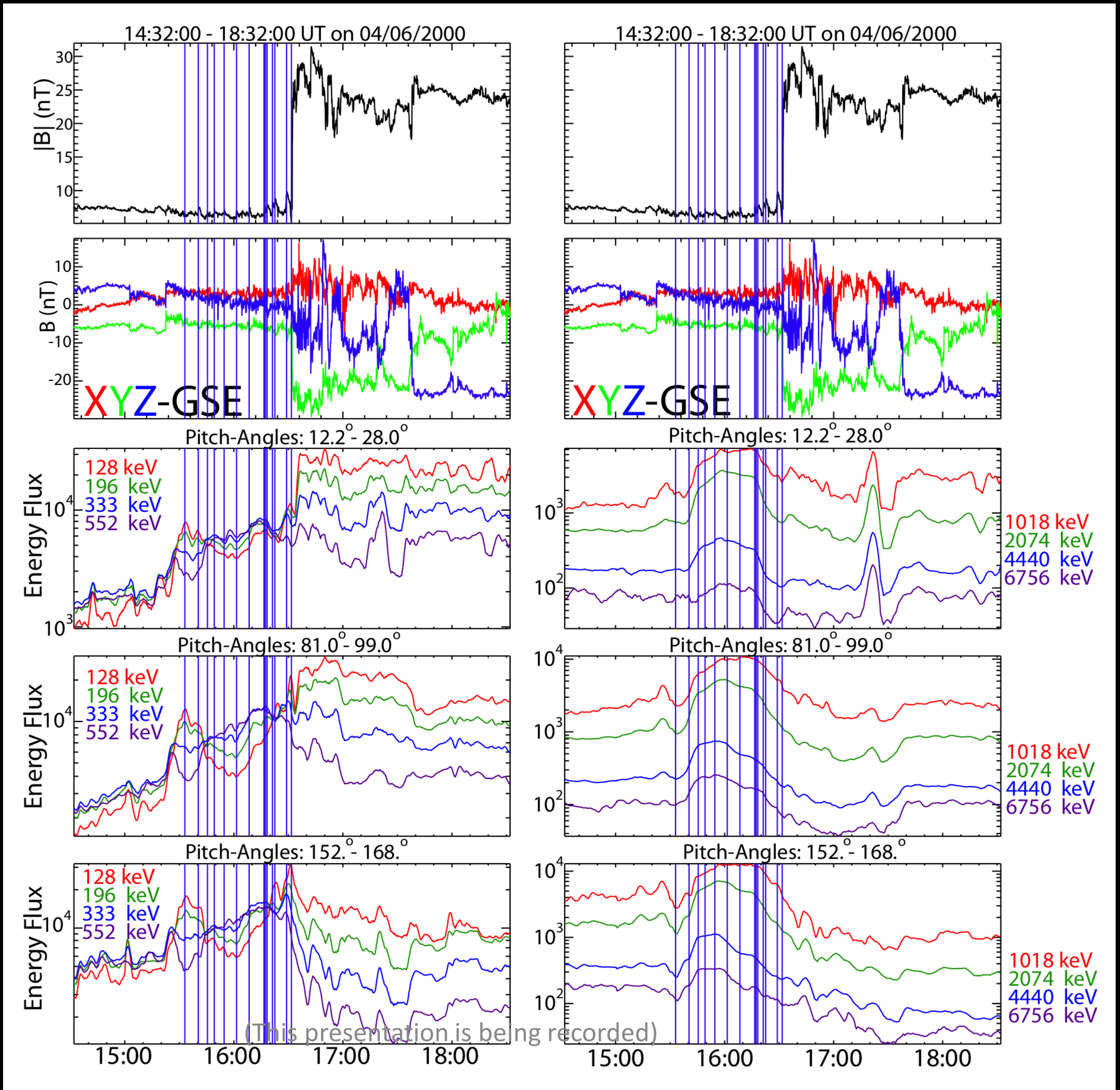
Particle Energization: Ions

1 nT = 10 μG

Parallel

Perpendicular

Anti-parallel



(This presentation is being recorded)

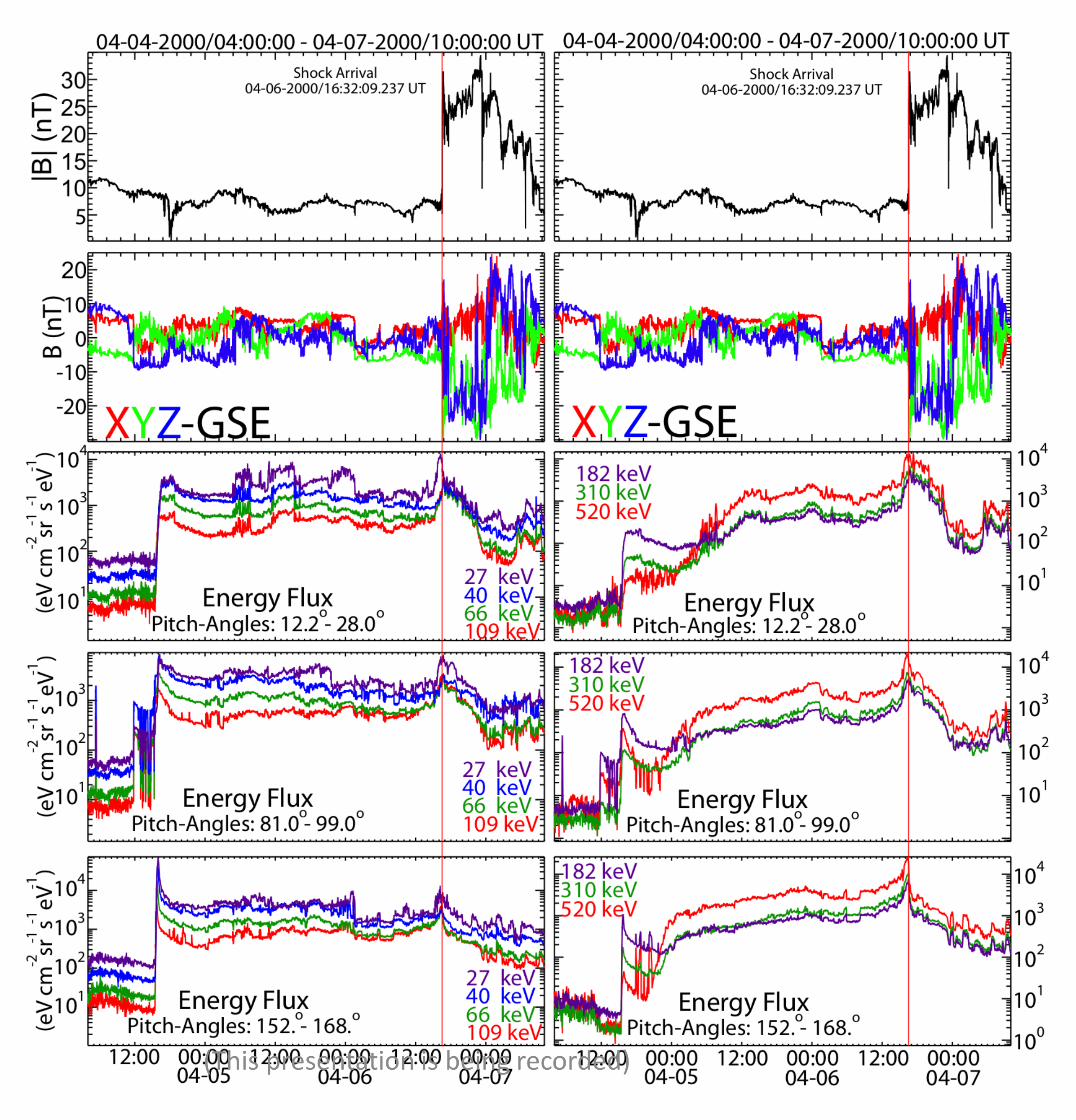
Particle Energization: Electrons

1 nT = 10 μG

Parallel

Perpendicular

Anti-parallel



(This presentation is being recorded)

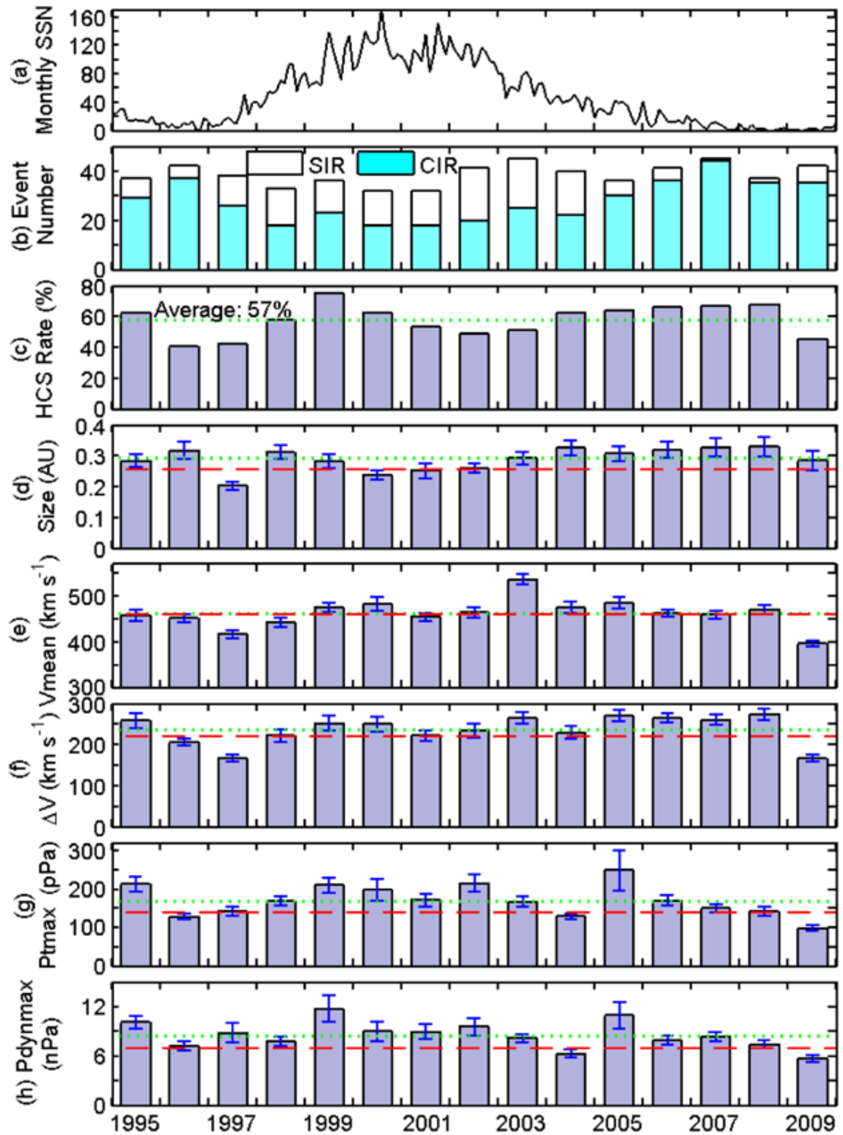
SIRs at Solar Min: $X_{avg} \pm X_{\sigma/N^{(1/2)}}$

Parameter	22/23 (~1996)	23/24 (~'08-'09)
V_{max} [km s^{-1}]	554 ± 12	525 ± 15
V_{min} [km s^{-1}]	349 ± 6	320 ± 5
V_{avg} [km s^{-1}]	451 ± 8	423 ± 9
B_{max} [nT]	12.8 ± 0.4	12.0 ± 0.6
$P_{dyn,max}$ [nPa]	7.2 ± 0.5	6.2 ± 0.6
# of SIRs	42	41
# with shocks	7 (17%)	16 (39%)

L.K. Jian et al., "Comparing Solar Minimum 23/24 with Historical Solar Wind Records at 1 AU," *Solar Phys.* **274**, pp. 321-344, doi:10.1007/s11207-011-9737-2, 2011.

SIRs binned by year

Figure 8 The variations of the annual average SIR properties from 1995 to 2009. From top to bottom: (a) monthly SSN from NOAA, (b) SIR (white) and CIR (cyan) event number, (c) HCS association rate, (d) size, (e) mean solar wind speed of a SIR, (f) speed increase over a SIR, (g) maximum total pressure, (h) maximum dynamic pressure. The error bar indicates the probable error of the mean. The red dashed line denotes the median value over all the SIRs of the 15 years, while the green dotted line for the 15-year average value. Extended after Jian *et al.* (2006a).



L.K. Jian et al., “Comparing Solar Minimum 23/24 with Historical Solar Wind Records at 1 AU,” *Solar Phys.* **274**, pp. 321-344, doi:10.1007/s11207-011-9737-2, 2011.

(This presentation is being recorded)

ICMEs at Solar Min: $X_{avg} \pm X_{\sigma/N^{\wedge}(1/2)}$

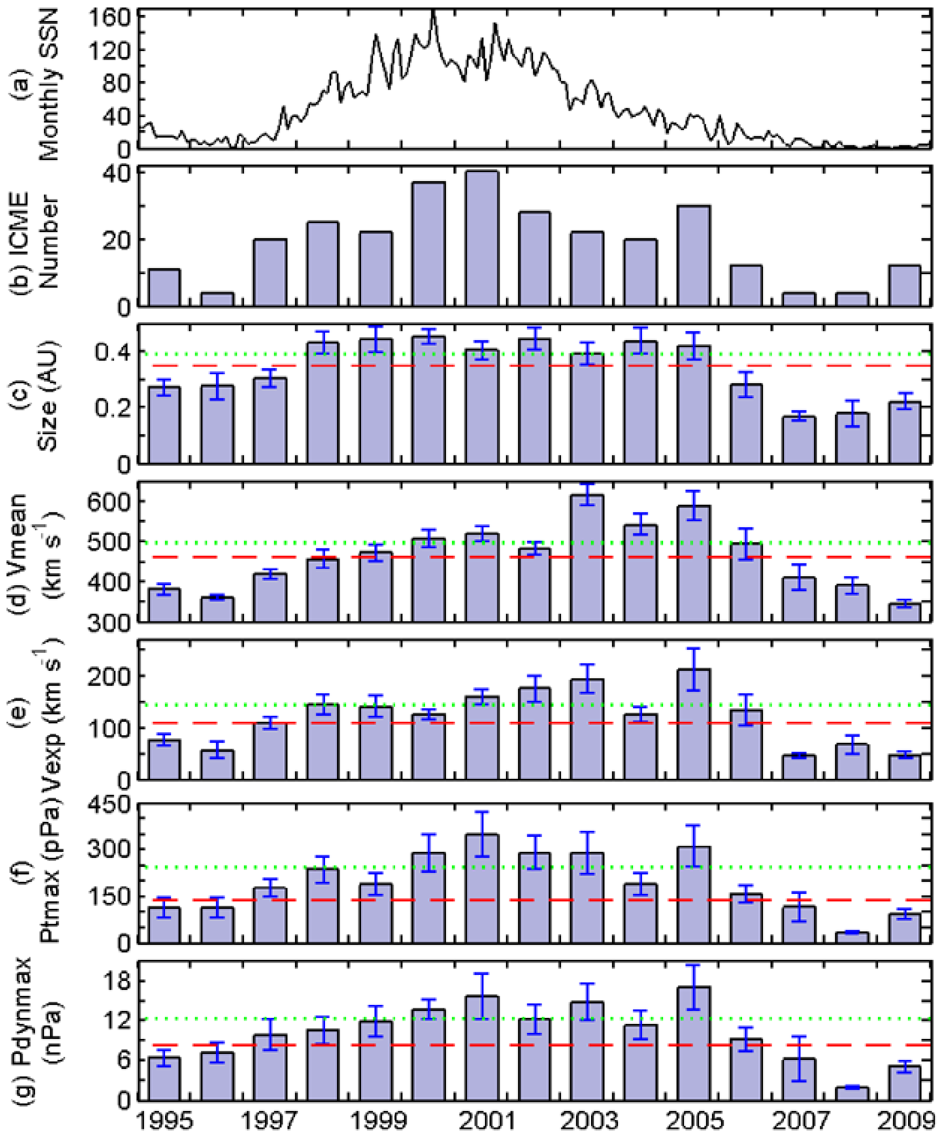
Parameter	22/23 (~1996)	23/24 (~'08-'09)
V_{max} [km s^{-1}]	388 ± 12	413 ± 14
V_{min} [km s^{-1}]	331 ± 7	346 ± 9
V_{avg} [km s^{-1}]	360 ± 6	379 ± 11
B_{max} [nT]	13.0 ± 1.7	10.1 ± 1.4
$P_{dyn,max}$ [nPa]	7.2 ± 1.5	4.4 ± 1.0
# of SIRs	4	8
# with shocks	0%	25%

L.K. Jian et al., "Comparing Solar Minimum 23/24 with Historical Solar Wind Records at 1 AU," *Solar Phys.* **274**, pp. 321-344, doi:10.1007/s11207-011-9737-2, 2011.

(This presentation is being recorded)

ICMEs binned by year

Figure 10 The variations of the annual average ICME properties from 1995 to 2009. From top to bottom: (a) monthly SSN from NOAA, (b) ICME number, (c) size approximated by the product of duration and mean speed, (d) mean solar wind speed of an ICME, (e) expansion speed of an ICME, (f) maximum total pressure, (g) maximum dynamic pressure. The error bar indicates the probable error of the mean. The red dashed line denotes the median value over all the ICMEs of the 15 years, while the green dotted line indicates the 15-year average value. Extended after Jian *et al.* (2006b).



L.K. Jian et al., “Comparing Solar Minimum 23/24 with Historical Solar Wind Records at 1 AU,” *Solar Phys.* **274**, pp. 321-344, doi:10.1007/s11207-011-9737-2, 2011.

(This presentation is being recorded)

Density Stats: Fast Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
N_e [cm^{-3}]	0.61	76.8	5.83	4.52	3.75	6.51
N_p [cm^{-3}]	0.53	69.9	5.07	4.04	3.19	5.70
N_α [cm^{-3}]	0.007	4.76	0.25	0.18	0.14	0.26

Density Stats: Slow Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
N_e [cm^{-3}]	0.34	104	11.0	9.28	6.37	13.8
N_p [cm^{-3}]	0.35	96.2	9.84	8.28	5.66	12.4
N_α [cm^{-3}]	0.005	7.91	0.27	0.21	0.13	0.33

*Note that uncertainties in particle density range from ~5% to 20%, depending on parameters and instrument limitations
It is also worth noting that the binning procedure and different cadences can affect these ratios.

Temperature Stats: Fast Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
$T_{e,tot}$ [eV]	3.16	53.9	12.2	11.8	10.3	13.6
$T_{p,tot}$ [eV]	0.68	375	27.7	24.4	17.8	33.2
$T_{\alpha,tot}$ [eV]	0.98	965	67.2	55.6	19.4	92.8

Temperature Stats: Slow Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
$T_{e,tot}$ [eV]	2.43	52.7	11.3	11.0	9.26	13.0
$T_{p,tot}$ [eV]	0.53	200	9.46	7.54	4.47	12.4
$T_{\alpha,tot}$ [eV]	0.65	370	22.9	11.5	5.31	31.6

*Note that uncertainties in particle density range from ~5% to 20%, depending on parameters and instrument limitations
It is also worth noting that the binning procedure and different cadences can affect these ratios.

Temperature Anisotropy: Fast Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
$(T_\perp/T_{//})_e$	0.71	2.65	1.25	1.22	1.11	1.35
$(T_\perp/T_{//})_p$	0.02	241	0.91	0.82	0.66	1.03
$(T_\perp/T_{//})_\alpha$	0.01	71.1	1.25	0.95	0.66	1.46

Temperature Anisotropy : Slow Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
$(T_\perp/T_{//})_e$	0.66	2.35	1.06	1.04	1.00	1.10
$(T_\perp/T_{//})_p$	0.001	279	0.80	0.76	0.59	0.95
$(T_\perp/T_{//})_\alpha$	0.004	401	0.96	0.84	0.59	1.13

*Note that uncertainties in particle density range from ~5% to 20%, depending on parameters and instrument limitations
It is also worth noting that the binning procedure and different cadences can affect these ratios.

Temperature Ratio Stats: Fast Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
$(T_e/T_p)_{tot}$	0.08	17.3	0.62	0.49	0.36	0.65
$(T_e/T_\alpha)_{tot}$	0.02	9.51	0.46	0.19	0.12	0.45
$(T_\alpha/T_p)_{tot}$	0.52	9.25	3.59	3.73	2.28	4.75

Temperature Ratio Stats: Slow Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
$(T_e/T_p)_{tot}$	0.10	25.3	1.79	1.42	0.92	2.29
$(T_e/T_\alpha)_{tot}$	0.04	22.9	1.28	0.87	0.35	1.83
$(T_\alpha/T_p)_{tot}$	0.34	18.4	2.52	1.95	1.38	3.52

*Note that uncertainties in particle density range from ~5% to 20%, depending on parameters and instrument limitations
It is also worth noting that the binning procedure and different cadences can affect these ratios.

Beta Stats: Fast Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
$\beta_{e,tot}$ [N/A]	0.02	681	1.05	0.73	0.51	1.08
$\beta_{p,tot}$ [N/A]	0.003	913	2.02	1.41	0.92	2.12
$\beta_{\alpha,tot}$ [N/A]	0.0004	111	0.40	0.19	0.05	0.41

Beta Stats: Slow Solar Wind

Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
$\beta_{e,tot}$ [N/A]	0.01	4330	3.37	1.62	0.95	2.89
$\beta_{p,tot}$ [N/A]	0.003	2530	1.97	1.13	0.64	1.86
$\beta_{\alpha,tot}$ [N/A]	0.0002	112	0.17	0.06	0.02	0.18

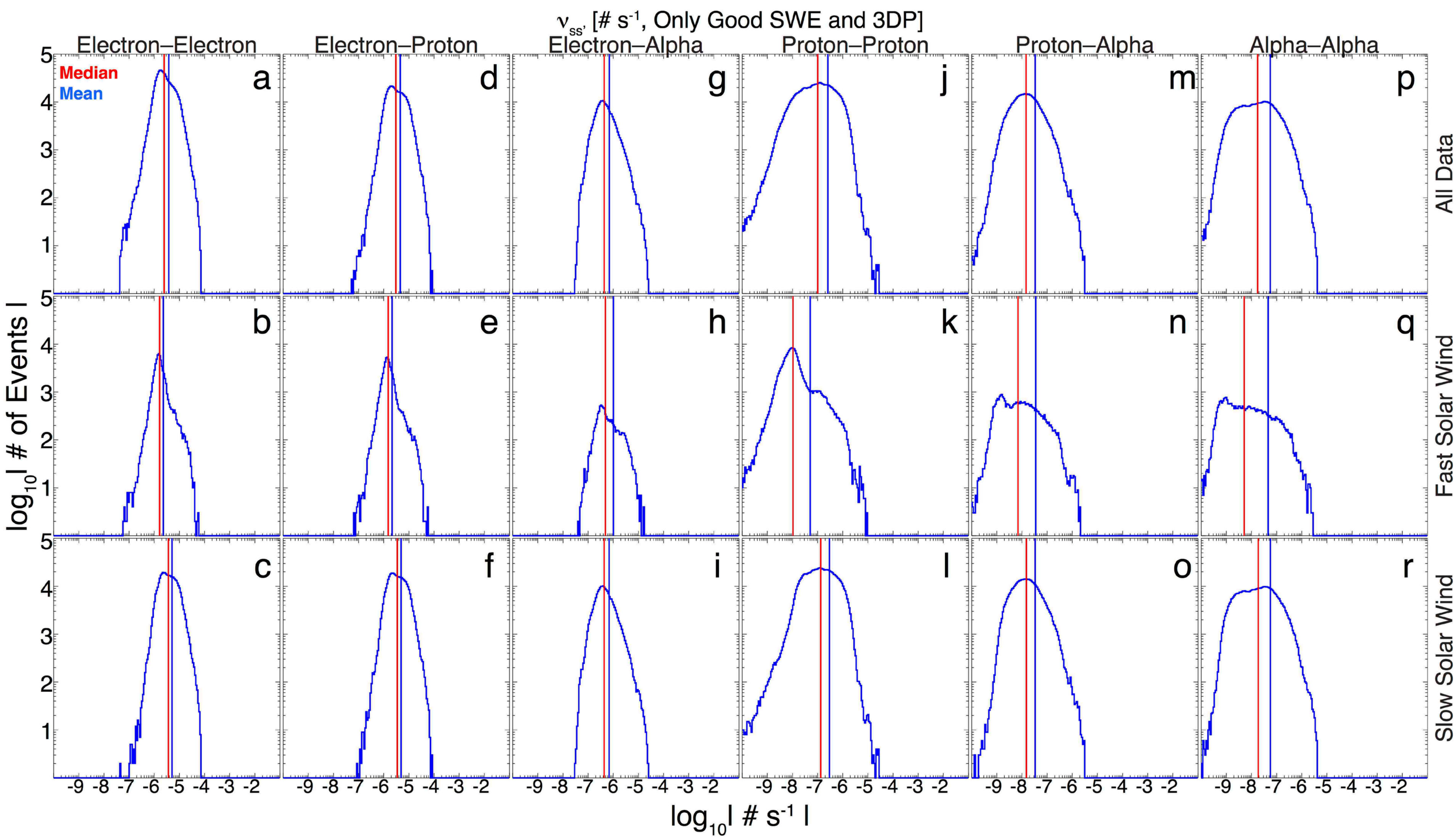
*Note that uncertainties in particle density range from ~5% to 20%, depending on parameters and instrument limitations
It is also worth noting that the binning procedure and different cadences can affect these ratios.

Particle-particle Coulomb Collisions

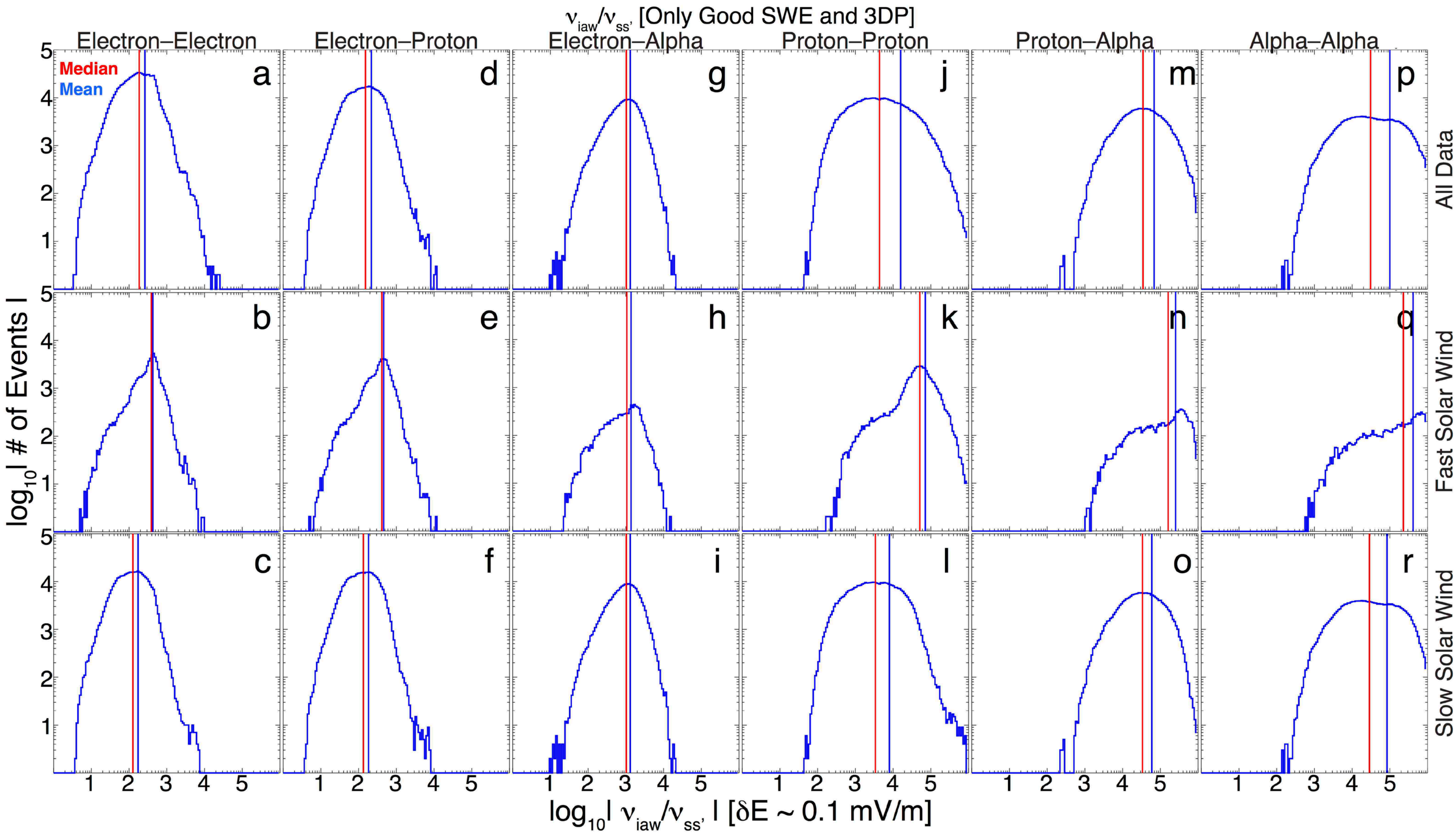
Parameter	X_{min}	X_{max}	X_{mean}	X_{median}	$X_{25\%}$	$X_{75\%}$
ν_{ee} [# day^{-1}]	0.01	23.5	1.01	0.70	0.43	1.30
ν_{pp} [# day^{-1}]	0.00004	1.56	0.05	0.02	0.008	0.07
$\nu_{\alpha\alpha}$ [# day^{-1}]	0.000006	0.47	0.009	0.003	0.001	0.01
ν_{ep} [# day^{-1}]	0.005	10.4	0.45	0.31	0.19	0.58
$\nu_{e\alpha}$ [# day^{-1}]	0.0008	4.86	0.05	0.07	0.02	0.06
$\nu_{p\alpha}$ [# day^{-1}]	0.000003	0.11	0.002	0.001	0.0005	0.002
ν_{iaw} [# day^{-1}]	5.72	232	4.39	4.16	3.30	52.2

$$\nu_{iaw} = \omega_{pe} \frac{\varepsilon_o \, |\delta E|^2}{2 \, n_e \, k_B \, T_{e,tot}}$$

Assuming $\delta E \sim 0.1$ mV/m



ν_ss, [# s^-1, Only Good SWE and 3DP]
Electron–Electron
Electron–Proton
Electron–Alpha
Proton–Proton
Proton–Alpha
Alpha–Alpha
Median
Mean
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p
q
r
All Data
Fast Solar Wind
Slow Solar Wind
log10| # of Events |
log10| # s^-1 |



$\nu_{iaw}/\nu_{ss'}$ [Only Good SWE and 3DP]
Electron–Electron
Electron–Proton
Electron–Alpha
Proton–Proton
Proton–Alpha
Alpha–Alpha
Median
Mean
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p
q
r
All Data
Fast Solar Wind
Slow Solar Wind
$\log_{10}$| # of Events |
$\log_{10}| \nu_{iaw}/\nu_{ss'} |$ [$\delta E \sim 0.1$ mV/m]