Local Electric Currents are the dominant source of B(t) at spacecraft

0) The Solar Wind originates in the Photosphere, as \( \sim 10^7 \) Electric "Lightning" Jets.  --> UM09.03

1) Satellite B(t) data shows Pervasive Random Fluctuations
   --- Spectrum is random as \( f^{-1} \) above \( 10^4 \mu\text{Hz} \) (\( \tau < 100. \text{sec} \))
   --- "DC" values (\( f < 10.\mu\text{Hz}, \tau > 1. \text{day} \)) are "Mean of random walks"

2) "Dynamical Arcs" are prevalent in the data:
   --- Appear as Non-random Spectral Energy \( 10^1 < f < 10^3 \mu\text{Hz} \)
   --- Well-modelled by Polarized Neutral Plasma Flows
   --- Similar to PSP "Switchbacks" seen at 0.1 AU

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The Core is described as a highly collisional, fully ionized fluid of baryons and electrons, with a central temperature $T \sim 1350\, eV = 1.6 \times 10^7$ Kelvin.

Fusion energy diffuses out to $R_{\text{sun}}$ as a Photon Flux of magnitude $64\, \text{MW/m}^2$.

A plasma Recombination Sheath forms where the temperature drops below $1\, eV$; here, no model exists.

A weakly-ionized Photosphere $\sim 2\, \text{Mm}$ thick (yellow) covers the interior plasma. Here, the description must change from a collisional fluid to collision-less particles.

The Corona is a very low density, collisionless plasma, with empirical energy of about $100\, eV$ per particle.

The proton/electron Solar Wind is an energetic, pervasive, persistent, low-density flux $\Gamma$ of particles.
(1) Spectrum of Magnetic Fluctuations: ACE MAG @ 1.AU
16 sec data, 1998.0 -> 2019.4

1) Pervasive Random Fluctuations
--- Spectrum is random as $f^{-1}$ above $10^4$ µHz
($\tau < 100. \text{ sec}$)
--- "DC" values ($f < 10. \text{ µHz}$, $\tau > 1. \text{ day}$)
scale as "Mean of random walks"
[ $\pm$ magnitude of $f_1$ is distance above/below $10^{-2}$ ]

2) "Dynamical Arcs" are prevalent in the data:
--- Determine Spectral Energy $10^1 < f < 10^3$ µHz
--- Modelled by "Double Filament" radial Currents
--- Similar to PSP "Switchbacks" seen at 0.1 AU
Magnetic Fluctuations Levels are Determined by the Local Solar Wind Flux $\Gamma_w$

\[
B_{\text{rms}}^2 \propto \Gamma_w^{1.5} \quad n_w \sim r^{-2} \quad V_w \sim \text{const}
\]

\[
\Rightarrow \frac{B_{\text{rms}}^2}{n_w} \propto \sqrt{n_w} \quad \text{Statistical?}
\]

The measured magnetic fluctuations are created by the local electrical-currents of the Solar Wind, including any global currents from global charge separation.

Moreover, major Solar surface events cause spacecraft detections of enhanced fluctuations after the SW particle radial propagation time, unrelated to "rooted spiral magnetic field" lengths.

The $B_{\text{rms}}^2 \propto r^{-3}$ scaling is widely observed, and interpreted as hydro-magnetic fluctuations.

Here, we note that the magnetic energy per particle scales as the square-root of particle number, consistent with statistical fluctuations.
"Dynamical Arcs", Constant Magnitude temporal "arcs" in (B₀,B₂), (B₀,Bᵣ), or (Bᵣ,B₂).

At left, a \{B₀,B₂\} constant magnitude Arc appears in 6.7 hours MAG temporal data, unrelated to the sign of \(Bᵣ\) (red/blue). Other pairs \{B₂,Bᵣ\} and \{B₀,Bᵣ\} show no Arc during this time, but are equally prevalent in general. Below are 4 Arcs of 1.3 hrs duration, selected for their "clean" appearance.

Below left is a 0.2 hr segment from PSP data showing similar behavior, albeit at 20x larger field magnitudes.
Dynamical Arcs appear in all pairs of \{B_r, B_\theta, B_z\}, with similar rates of occurrence.

Here a moderately selective computer filter counts 137,000 Arcs (+/- 10%) with periods T~0.5hr, giving a rate of 18/day.

Averaging over multiple Dynamical Arcs contributes to the spectral region of $10 < f < 1000 \mu$Hz, where field magnitudes fall off more slowly than the "random" $f^{-1}$. 

Note: This moderately selective "arc-detector" finds 11,000 "arcs" in randomized data (~8% false-positive).
Solar Granulation:
L ~ 1. Mm
t ~ 500 sec

$v_\theta$ = 0.4 Mm/s
(but nothing is flowing in $\theta$)

"Neutral" Flow of $\{e^-\}$

$n_w$ ~ $10^{6.8}$ [##/m$^3$]

$\Gamma_w$ ~ $10^{12.5}$ [##/s.m$^2$]
~ $10^{24.5}$ [##/s.(Mm)$^2$]

Suppose $\delta n = (n_+ - n_-)$

from Filamentation, Dynamics, Current Pinch

Then

$B \approx 5$ nT implies:

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$r_0$</th>
<th>$\tau = \frac{v_w}{r_0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-3}$</td>
<td>$10^1$ Mm</td>
<td>20 sec</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>$10^3$ Mm</td>
<td>0.5 hour</td>
</tr>
</tbody>
</table>

Spacecraft measurements establish that the Solar Wind e-/p+ particle flux is basically radial, and global charge conservations requires that it is basically charge-neutral.

However, small deviations from charge neutrality ($\alpha \sim 10^{-5}$ here) can create currents which create the 5.nT magnetic field magnitudes observed at 1.AU.

Here, the spatial scale of $r_0 \sim 10^3$ Mm is suggested by the 0.5 hr time scale for major B-field magnitude changes.

The "challenge" is to characterize propagating structures of low-collisionality globally-neutral flows, with weak electric currents generating self-consistent Electric and Magnetic fields.
A simple "geometric" calculation of magnetic fields shows that Dynamical Arcs in pairs of \( (B_r, B_0, B_z) \) will arise from radially propagating charge separations.

Here, 200.\text{Mm} long filaments of +/- charge, separated by 5.\text{Mm}, propagate radially past the spacecraft with \( v_r = 0.5\text{Mm/s} \).

The currents are modelled by hundreds of particles, each "fuzzy" over 10.\text{Mm}.

The broad Dynamical Arc signature is obtained when the total charge is Zero; but not when only one sign of current is included.