On the stability of Alfvenic fluctuations and switchbacks in the solar wind

Anna Tenerani
Thanks to: M Velli, C A González, L Matteini, P Hellinger

PSP Theory telecon, July 23, 2020
Outline

• Alfvénic fluctuations in the solar wind: an overview

• Simulations of the evolution of switchbacks

• Beyond MHD: kinetic effects via extended MHD and hybrid simulations

• Conclusions
Magnetic field data from FIELDS, 1 min res (see also Bale et al. Nature 2019)
Switchbacks are prominent/persistent features of the ‘young’ solar wind. They may contain important information about the origin of the solar wind or may be ‘proxies’ for processes in the corona.
One-sided jets in solar wind radial profiles

(Horbury et al. MNRAS 2018)
Alfvénic turbulence at 0.3-1AU: Spectrum

- $|\delta B|/B_0 \sim 1$
- $\delta |B|/B_0 \ll 1$
- $\delta B/\sqrt{\rho \mu_0} \sim \pm \delta V$
- Mainly propagating outwards
- Developed spectrum
- $\delta \rho/\rho \ll 1$
Alfvénic turbulence at 0.3-1AU: Waveform

Example (Ulysses):

January 1995

\( V \) (km/s)

\( \delta V_n \) (km/s)

\( \delta B_n \)

\( |B| \) (nT)

\( B_r \)

\( B_t \)

\( B_n \)

(from B. Tsurutani et al. PPCF 1997)
Switchbacks and jets explained

- Switchbacks are the magnetic field manifestation of radial jets (or vice versa)
- They are a consequence of the Alfvénic character of (3D) fluctuations and $|\mathbf{B}| = \text{constant}$

(Matteini et al. 2014-2015)
Coronal origin or generated in-situ dynamically?

Turbulence evolution in the expanding solar wind

(Landi et al. 2006, MacNeil et al. MNRAS 2020)

How long can these structures persist?

Non-constant B Alfvénic kinks of magnetic field expand and “unfold” over a few dynamical time-scale

Alfvénic solutions to the compressible MHD (and extended MHD) equations

\[ \frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{1}{\rho} \nabla \left( p + \frac{1}{8\pi} B^2 \right) + \frac{1}{4\pi\rho} B \cdot \nabla B \]

\[ \frac{\partial B}{\partial t} + u \cdot \nabla B = B \cdot \nabla u - B (\nabla \cdot u) \]

\[ z^\pm = u \pm \frac{b}{\sqrt{4\pi\rho}} \]

\[ \frac{\partial z^\pm}{\partial t} + (U_0 \mp V_a) \cdot \nabla z^\pm + z^\mp \cdot \nabla z^\pm = 0 \]

Purely correlated or anti-correlated \( u \) and \( b \) fluctuations provide an exact solution (at arbitrary amplitude)
**Numerical model**

\[
B = B_0 \hat{x} + \nabla \times \phi(x, y) \hat{z} + B_z(x, y) \hat{z}
\]

\[
\phi(x, y) = A(e^{-r_1^2} - e^{-r_2^2})
\]

\[
r_{1,2}^2 = \frac{(x-x_{1,2})^2}{\lambda_x^2} + \frac{(y-y_{1,2})^2}{\lambda_y^2}
\]

\[
B_z(x, y)^2 = B^2 - (B_x(x, y)^2 + B_y(x, y)^2)
\]

\[
u = -B/\sqrt{\rho_0}
\]

- Periodic MHD simulations with variable length along the “radial” magnetic field
Switchback evolution

Magnetic field lines (black) and density contours (color coded)

(Frame of reference moving with the kink)
Parametric decay of large amplitude Alfvén waves

Circularly polarized, finite amplitude Alfvén waves (AWs) are an exact nonlinear state of compressible MHD and CGL.

- AWs are unstable to parametric decay
- More efficient at $\beta<1$
- Resonant process: $k_s - k_a = k_0$, $\omega_s + \omega_a = \omega_0$, $k_s \sim 3k_0/2$, $k_a \sim k_0/2$
- Even more interesting with kinetic effects heating and accelerated beams

(Derby, 1978; Malara & Velli 1994; Del Zanna et al. 2001; Tenerani & Velli 2013, 2017; Réville et al. 2019; Primavera et al. 2019.....)
Switchback parametric decay

- The switchback eventually decays due to parametric decay which provides an upper limit to the lifetime of the switchback.

- Density fluctuations increase exponentially.

- At saturation we observe a decrease (although weak) of cross helicity, as predicted by parametric decay.

- Growth rate decreases with plasma $\beta$.

- The larger the system size, the slower the instability.

- Growth rate scales as $\gamma t_a \sim \lambda_y / L_y$.

- Much more stable than traditional instability (by comparison, a monochromatic wave with $A \sim 1$ has a growth rate $\gamma t_a \sim 4$).

Evolution in a large scale system

\( (L_y/\lambda_y \sim 70) \)

The effect of parametric decay becomes weaker and weaker for increasing system size. Density fluctuations and a mixture of forwards/backward fluctuations are generated outside the switchback, which maintains a high degree of coherence \( (\sigma=1) \) and persists beyond 460 \( t_a \).
The main idea of the EBM (and its main variations on the theme) is to follow in a *semi-lagrangian* fashion the evolution of a small angular sector of solar wind plasma which is in (accelerating) spherical expansion due to the drag of the average radial flow $U(r)$.

The effects of the expansion are introduced through a new time-dependent variable $R(t)$, the average heliocentric distance of the box, taken along the $x$ axis.

$R$ evolves according to a profile $U(R)$ given *a priori*: $\frac{dR}{dt}=U(R)$

The spherical coordinates and vectors are then expanded around $R$ for small angular sections, i.e., $y/R$, $z/R$, $(x-R)/R=\epsilon<<1$ / (the length box $L_x<<R$)
Switchback evolution in the expanding solar wind

In the frame moving at the local Alfvén speed ($\varepsilon = \tau_a / \tau_{\text{exp}}$)
Factors affecting switchback evolution

- If the background state is homogeneous, the process that eventually leads to a breakdown of the initial state is the well known parametric decay instability, that provides an upper bound to the lifetime of switchbacks, with increasing lifetime for increasing system size.

- In our worst case scenario T_life~200 Ta, yielding ΔR~18 Rs. A larger distance is spanned for ‘unperturbed’ path, up to ΔR>43 Rs.

- What may affect the above estimates:
  - **Expansion** and related large scale underlying gradients may affect the above estimates (competition between increasing δB/B and tendency to unfold faster)
  - **Non-periodicity** (random scattering rather than coherent interactions with density fluctuations) may allow for longer lifetimes
  - **Underlying velocity shears** (as proposed by Landi et al. 2006) may contribute to maintain/recreate switchbacks

- Parametric instabilities are a ‘plague’ that seem to be unavoidable also in the solar wind. If that’s the case, what turns the fields back to their highly Alfvénic state?
  - What about kinetic effects?
Nonthermal features in the expanding solar wind

- Evolving temperature anisotropies
- Field-aligned beam at the local Alfvén speed
- Perpendicular heating (non-adiabatic expansion)
An alternative way to interpret constant-B states

\[ \frac{\partial^2}{\partial t^2} \delta \hat{B}_\perp(z, t) = \left( V_a^2 + \frac{1}{\rho_0} \frac{p_\perp(t) - p_\parallel(t)}{1 + \delta \hat{B}_\perp^2(t)} \right) \frac{\partial^2}{\partial z^2} \delta \hat{B}_\perp(z, t). \]

Energy conservation equation for a monochromatic wave:

\[ \dot{B}_\perp^2 + \phi = E \quad \phi = V_a^2 k_0^2 + L^2 / B_\perp^2 + f(B_\perp^2, \xi \beta_\parallel) \]

\[ \tilde{V}_a^2 > 0 \quad \text{Circular polarization} \]

\[ \tilde{V}_a^2 < 0 \quad \text{Firehose regime} \]

Revisiting the traditional firehose instability

- Linear instability of shear Alfvén waves in an anisotropy plasma*:
  \[ \omega = k \cos \theta V_a \sqrt{1 + \frac{\beta_{||}}{2} \left( \frac{p_{\perp}}{p_{||}} - 1 \right)} \]

- Purely growing modes when
  \[ \frac{\beta_{||}}{2} \left( \frac{p_{\perp}}{p_{||}} - 1 \right) < -1 \]

Magnetic field hodogram

Nonlinear evolution of firehose instability from initial incoherent noise seeded in both transverse directions

*Rosenbluth 1956 LANL Report 3030
Parker 1958 PRL 109, 1874

[Tenerani & Velli ApJL 2018]
Expanding Box simulations

Onset of firehose leads to arc-polarized states and cross helicity significantly above zero, similar to observations at 1AU

(Tenerani & Velli PPCF 2020)
Theoretical interpretation

\[ \frac{\partial^2}{\partial t^2} \delta \mathbf{B}_\perp(z, t) = \cos \theta_0 \frac{\partial^2}{\partial z^2} \left( \tilde{V}_a^2(z, t) \delta \mathbf{B}_\perp(z, t) \right) \]

decomposition in 2 terms: mean field term (i.e. \(< B^2 >\))+ fluctuations of \( B^2 \)

\[ \ddot{B}_{k,i}(t) = -\frac{d\phi_k}{dB_{k,i}} + Ck^2 \sum_{p \neq k, q} B_{p,i} (\mathbf{B}_{p-k-q} \cdot \mathbf{B}_q) \]

coupled oscillators

nonlinearity

saturation condition

\[ 1 + \frac{\beta_\parallel}{2} \frac{1}{< B^2 >} \left( \xi \sqrt{\frac{< B^2 >}{< B^2(0) >}} - \frac{< B^2(0) >}{< B^2 >} \right) = 0 \]

(Tenerani & Velli ApJL 2018)
Kinetic effects via hybrid simulations: parametric decay and filamentation

Possible origin of field-aligned beam in low beta plasmas

Hybrid simulations show that the collapse of AW leads to a nonlinear state which is turbulent and with a field-aligned beam at the Alfvén speed.

The (nonlinear) feedback of the beam on the fields is under study.

Proton PDF in the solar wind (Ulysses; Neugebauer and Goldstein 2012)

Simulation proton PDF

Summary and conclusions

- The new observations by PSP at R ~35.7 Rs reveal the ubiquitous existence of Alfvénic fluctuations in the form of kinked and folded magnetic field lines. **Understanding how long they can survive in the solar wind is a first necessary step to understand their origin.** In this regard our numerical simulations suggest that such a state can persist up to hundreds of Alfvén times.

- If the background state is homogeneous, the process that eventually leads to a breakdown of the initial state is the well known parametric decay instability, that provides an upper bound to the lifetime of switchbacks, with increasing lifetime for increasing system size.

- Theory and simulations indicate that Alfvén waves are plagued by parametric instabilities that persist even at values of the plasma beta above unity, bearing again the questions of how the highly Alfvénic nonlinear state is maintained in the solar wind.

- Our findings via kinetic approach suggest that wave-particle interactions triggered by AW instabilities may play an important role in generating some features observed in the solar wind (field aligned beam at Va) and enhance nonlinear wave-particle resonances (Landau damping) that lead to a damping of longitudinal electric fields and enhanced perpendicular heating.

- Inclusion of expansion in hybrid simulations for more realistic description of kinetic effects in the solar wind is a necessary next step.