Geoeffective interplanetary conditions near Earth due to stream interaction regions

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Roadmap

• Context and Causes: CHs → SIRs

• Properties of SIRs near 1 au

• Consequences of SIRs on geospace

• Consequences of SIRs on GCRs

• Comparison between SIRs and ICMEs

• Summary and conclusions
The next SCOSTEP scientific program [2020-2024]
PRESTO: PREdictability of the variable Solar-Terrestrial cOupling
Key solar wind parameters for geoeffectiveness level near Earth

- interplanetary magnetic field
- solar wind speed
- solar wind density
- level of fluctuations/turbulence
- Alfven Mach number

- dawn-dusk electric field
- dynamic pressure
Coronal Holes:

- $B_{\text{open}}$
- The source of fast wind
- The cause of fast/slow wind interaction

Shaded area represents reduced mass density and low T regions (EUV & SXR Images of $T_{\text{cor}} \approx 10^6 K$)
Radial solar mass flux combined with solar rotation: spiral shape

An effect similar to a rotating garden sprinkler

Compression in front
Fast solar wind from coronal hole
Rarefaction at the rear
Stream Interaction Region (SIR): Region of interaction between fast/slow solar wind.
Coronal hole impact on solar wind near Earth: SIR

- Increase of $|B|$
- Change of $\mathbf{B}$ direction
- Increase of density (compression)
- Almost linear change of $|V|$
- Increase of $T$ (heating due to the compression)
Co-Rotating Interaction Regions (CIRs):
For long-lived CHs, high-speed solar wind streams is repeated after each solar rotation.

Due to the solar rotation, when CH are present during long periods of time, SIRs are repeated every ~ 27 days. Then, it is called CIRs.

Skylab Soft-X observations of CH (dark region).
• When fast/slow streams are present, the development of shocks is expected. Not near the Sun, but near 1 au or beyond
• Deflection is also expected, e.g., due to the warping of the heliospheric current sheet

Adapted from Gosling, Hundhausen and Barne (1976)
Superposed epoch analysis of SIRs

- 23 events – 5 min res
- Taking the interface as the common reference time for SEA
- Figure from review of Richardson [2018]
SIRs producing Geomagnetic Storms

- Adapted from Richardson [2018]

Example of SIRs triggering an intense geom storm (Dst<\(-100\text{nT}\))
Associated with Bz<0
Oct/2015: Impact of a SIR on the ionospheric vertical Total Electron Content (vTEC)

Double kick due to the two ranges of IP Bz<0

vTEC decreases (~ 20 TECu) during the main phase of the geom storm.
Negative ionospheric storm.

vTEC increases (~ 25 TECu) during the more intense geom perturbation
Positive ionospheric storm.

vTEC estimated using RAMSAC data over north of Argentina (Tucuman province). Dashed lines are reference values for quiet days. Solid line is the vTEC estimate from GPS stations.

[Molina+, 2020]
Oct/2015: Impact of a SIR on the ionosphere (FoF2 analysis)

vTEC decreases (~ 20 TECu) during the main phase of the geom storm.
Negative ionospheric storm

vTEC increases (~ 25 TECu) during the more intense geom perturbation
Positive ionospheric storm

FoF2 from an ionosonde over north of Argentina (data provided by Tucumán Space Weather Center). Dashed lines are reference values (quiet days). Solid line is estimated from ionosonde.
SIRs produce Forbush Decreases (FDs)

Data and Method:
- Catalogue from Jian+,06
- ACE (MAG/SWEPAM) for IP (64 sec)
- McMurdo NM for GCRs (1 hour)
- Normalized SEA: 2 reference times
- 300 time bins (before, during, after)

Main results:
- Parabolic shape of B at SIR
- Linear increase of V at SIR
- Bump of np nearer the SIR front
- Max of Tp nearer the SIR back
- Typical FD of ~ 0.5 %, with an initial increase (possible precursor of SIR arrival)

[From Gutierrez+24]
No significant effect on velocity (as for the case of ICMEs)

- Slow SIRs
- Medium SIRs
- Fast SIRs

**V < 450 km/s**
- Same parabolic shape

**450 km/s < V < 550 km/s**
- Shifted linear increase of V

**V > 550 km/s**
- Small np bump for fast (no time to develop)
- Similar profile of Tp
- Similar shape but larger dispersion for fast cases
Main geoeffective structures: ICMEs & SIRs

Both can produce: IP shocks, acceleration of particles, modulation of GCRs, enhancement of geomagnetic and ionospheric activity, etc.
Comparison effects of SIRs/ICMEs on GCRs

FD structure is different

For ICMEs:
• Two phases (sheath/ejecta)
• Min of FD near the ejecta front, with a strong recovery after the min
• Change of slope at the end of the ejecta

For SIRs:
• Decrease starts after the beginning of the SIR
• Continuous evolution at the end of SIR
• Slow recovery after SIR

[From Gutierrez+24]
Compare effects of SIRs/ICMEs on GCRs

For ICMEs:
- Strong dependence with V & B

For SIRs:
- Almost no dependence with V nor B

[From Gutierrez+24]
Evolution of MCs (subset of ICMEs) in the calm typical solar wind

SW Environment $\mathbf{P} = \mathbf{P}_0 (D/D_0)^{-np}$

Empirically (statistical analysis): $np = 2.91 \pm 0.31$

From theoretical modeling Démoulin & Dasso [’09]

$S = S_0 (D/D_0)^\zeta$, with $\zeta \approx np/4$

From theoretical modeling & statistical observations [Demoulin+08]:

$$\zeta = \frac{\Delta V_x}{\Delta t} \frac{D}{V_c^2}$$

$$S(D) = S_0 (D/D_0)^\zeta$$

If $dS/dt = \Delta V$

(when local ~ global)

$np = 2.91 \pm 0.31$

$\zeta_{\text{expected}} = 0.73 \pm 0.08$

$\zeta_{\text{observed}} = 1.1 \pm 0.6$

Non Perturbed MCs.
MC overtaken by a fast SW stream

Interpretation:
- temporal evolution of the interaction
- beginning compression
- later on over expansion (because of over pressure SW)

It strongly affects the MC outbound!

\[ V_x = 5 V_c \frac{D}{\Delta t - V_c^2} \]
(inner heliosphere (2 Helios spacecraft))

\[ \zeta = \frac{\Delta V_x}{\Delta t} \frac{D}{V_c^2} \]

- non overtaken MCs: \( \zeta \approx 0.9 \)
- overtaken MCs

Solar distance

\[ [\text{Gulisano}+09] \]
Summary and Conclusions

• Key IP properties for coupling IP with Earth: $B_s$, $V$, $n_p$

• We revised properties of SIRs, showing that SIRs can:
  - Create shocks
  - Drive geomagnetic storms
  - Drive ionospheric storms
  - Influence transport of GCRs

• Some physical processes at SIRs are similar to ICMEs overtaken by a fast stream

• In general, SIRs are less geoeffective than ICMEs. But in some cases, SIRs can be as important as ICMEs.

Thank you very much for your attention!
END
Additional Slides
Ionospheric storm
Figure 5  Ionograms acquired at 05:10 UT for three consecutive days (6, 7, and 8 October 2015) at Tucumán.
TURBULENCE & DIFFUSION
Splitting slow and fast solar wind at 1 au

Slow wind: $\lambda_{||} > \lambda_{\perp}$ consistent with ‘more’ like-2D fluctuations

Fast wind: $\lambda_{||} < \lambda_{\perp}$ consistent with ‘more’ like-1D (slab fluctuations)

Fig. 1.—Level contours for $R_{st}(r)$. Left, slow solar wind ($V_{sw} < 400$ km s$^{-1}$); right, fast solar wind ($V_{sw} > 500$ km s$^{-1}$). (See text.) Levels are at 1200, 1400, 1600, and 1800 km$^2$ s$^{-2}$.

[Dasso et al., ApJL, 2005] [188 citas en Scopus]
Splitting slow and fast solar wind at 1 au

- From single S/C: Several thousand samples of ISEE-3 data

![Diagram](image.png)

Quasi-2D
Matthaeus+, JGR’90
Quasi-slab
Evolución de la turbulencia en el viento solar

Splitting slow and fast solar wind at 1 au

Slow wind: $\lambda_\parallel > \lambda_\perp$ consistent with ‘more’ like-2D fluctuations

Fast wind: $\lambda_\parallel < \lambda_\perp$ consistent with ‘more’ like-1D (slab fluctuations)

Confirmado por Ruiz+JGR, 2011, a partir de observaciones a diferentes $D$
Solar Energetic Particles (SEPs) can:
- Travel along B connected to SW & magnetosphere
- Enter into de polar caps
- Reach low altitudes

Topology of IMF is crucial for propagation of energetic particles

ICMEs: $D > 1.2$ UA

Parker spiral: $D \sim 1.2$ AU

Interplanetary magnetic field lines

Masson et al., A&A 2012

Ranges of all GLEs events from Jul 2000 to Dec 2006

Length travelled by energetic particles from injection and arrival time of particles with different energies

Velocity dispersion analysis (13-130 MeVs + NMs \sim GeV)
LAMP GROUP
Space Weather activities of LAMP (RWC of ISES) are growing

Energetic particles from space, Argentine space agency (CONAE) [Lanabere & Dasso, 2018]

Operative SWx website (spanish): spaceweather.at.fcen.uba.ar
[Lanabere+, QV30926, R20 & dev of services]

Construction of two cosmic rays detectors:
fast ADQ system (~10 nsec) with amplification of more than $10^6$ times the energy of observed photons

Instalation of the first SWx Laboratory at an Argentina Antarctic. Jan-March, 2019
LAMP: Center for Space Weather monitoring (UBA-CONICET)

http://www.spaceweather.com/
spaceweather.at.fcen.uba.ar
Our group (LAMP) deployed in 2019 a Space Weather Laboratory at the Argentinean Antarctic Marambio base. Different instruments installed: GCR WCD detector (similar to surface Auger, it is a node of LAGO Collab), telemetry system, meteorological station, magnetometer, GPS receiver for time stamp of data, etc.
ICME-ICME INTERACTION (2^{ND} FASTER AS IN SIRS)
Changes on the level of geo-effectiveness associated with ICME-ICME interaction

Not only interaction at the moment of observations or even the total interchange of momentum need to be considered. Also the story of the interaction is very important!!!

• **Arrival**: deflection, changes on speed & size

• **Magnetic structure shape**: Compression/expansion, reconnection, passage of shock through ICME-1, deformation

• **Possible erosion**: depending on relative orientation

• **Double kick**: pre-kick to the magnetosphere by the ICME1, and knockout by the ICME2 (2-steps)
MC overtaken by another MC

[McDowell+ 2009]

Presence of 2 structures consistent with IPS analysis [Bisi et al., 2010]

\[ f = a \sqrt{n} = bD^{-1} \]

Wind Waves
TNR receiver

**ICME**

- \( B(nT) \)
- \( T_p \)
- \( V(Km/s) \)

**MC overtaken by another MC**

<table>
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<th>Time after (Hs)</th>
<th>MAY 15, 2005 UT</th>
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<tr>
<td>0</td>
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<tr>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
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</tbody>
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**MC1**

**MC2**

*ICME*

- \( T_{exp} \)
- \( B(nT) \)
- \( T_p \)
- \( V(Km/s) \)

**MC2**

**MC1**

- Interaction region at \( D \sim 0.5 \) AU

- MC1 alone (MC2 well behind)

- MC1 + MC2

**Dst peak** = -263 nT

[not possible to forecast it from assuming two single non-interacting ICMEs]
In general (because ICME-1 is slower) ICME-1 is weaker (good correlation between V, B, R from single events)

Then, ICME-1 is more affected by ICME-2 than the inverse (more similar to a car-truck collision than to a car-car collision)

Interactions between magnetized fluid structures (as ICMEs) are different than interactions between solid objects!

After the collision, ICME-1 (car ahead truck) can be observed as smaller and stronger (B) than expected! [the truck does not permit the typical expected expansion]
Compression of the first MC

- MC1 is compressed by the 2nd shock and it cannot over-expand due to the presence of MC2 at its back (Lugaz et al., ApJ, 2005; Xiong et al., JGR, 2006-2009).
- Influence of reconnection and relative orientations (Lugaz et al., 2013).

Cortesey from Noe Lugaz