



Solar Magnetic Switchbacks Produced by Magnetized Coulomb Scattering between Galactic Cosmic Rays and Solar Radiation

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ABSTRACT

Magnetic switchbacks contribute significantly to coronal heating and the acceleration of the solar wind. In this study, they are considered a weakly collisional plasma phenomenon influenced by the magnetic-field configuration rather than a process arising solely from electrostatic Coulomb collisions. The proposed mechanism involves magnetic scattering associated with interactions between low-energy Galactic Cosmic Rays (GCRs; 3–30 MeV/nuc) and solar radiation. These interactions are considered to become more pronounced during periods of enhanced solar activity, including the release of Solar Energetic Particles (SEPs). Within this framework, highly modulated GCRs interacting weakly with solar radiation are proposed to generate magnetic switchbacks through a form of anti-Stokes Raman-like scattering. This process transfers energy within the magnetized plasma, thereby contributing to plasma heating and solar-wind acceleration. The interaction is nonlinear and non-isotropic, with the external magnetic field modifying charged-particle dynamics and producing characteristic S-shaped trajectories. In the presence of a strong magnetic field, Coulomb scattering can be substantially modified because cyclotron motion (gyromotion) interacts with the Coulomb potential. Consequently, charged particles may follow complex, S-shaped, or non-monotonic trajectories rather than the simple hyperbolic paths associated with conventional unmagnetized Coulomb scattering. The proposed mechanism provides the basis for examining the possible role of magnetized Coulomb scattering in the formation of solar magnetic switchbacks.

Keywords: magnetic switchbacks; Galactic Cosmic Rays; Coulomb scattering; magnetized plasma; solar wind; coronal heating; anti-Stokes scattering.

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INTRODUCTION

Scattering processes play a fundamental role in astrophysical plasmas by governing interactions between electromagnetic radiation and charged particles, as well as interactions among the charged particles themselves. These processes influence

radiation transport, energy transfer, plasma heating, and particle acceleration in environments ranging from stellar atmospheres and accretion disks to the solar corona, solar wind, and interstellar medium (Chandler, 2010; Rankin et al., 2022). Depending on the energy of the interacting particles, the properties of the surrounding plasma, and the strength and

configuration of the magnetic field, several scattering mechanisms may operate simultaneously. These include Thomson, Compton, inverse Compton, resonant, Coulomb, wave particle, and Raman scattering. In strongly magnetized and weakly collisional plasmas, particle trajectories and energy-transfer processes can be significantly modified by magnetic-field geometry, plasma turbulence, and resonant wave particle interactions (Bandyopadhyay & McComas, 2021; Rivera et al., 2024). The principal interaction components, physical mechanisms, and representative astrophysical applications of these scattering processes are summarized in Table 1.

Table 1. Major scattering processes in astrophysical plasmas, including their interaction components, physical mechanisms, and representative astrophysical contexts.

Scattering Type	Interaction Components	Physical Mechanism	Astrophysical Context
Thomson Scattering	Low-energy photon + electron	Elastic scattering of radiation by free electrons	Stellar atmospheres, accretion disks
Compton Scattering	High-energy photon + electron	Inelastic scattering involving energy transfer between the photon and electron	X-ray binary sources, active galactic nuclei
Inverse Compton Scattering	Photon + relativistic electron	A high-energy electron transfers energy to a low-energy photon	Cosmic-ray interactions, jets in active galaxies
Resonant Scattering	Photons + bound atomic electrons	Photon absorption followed by immediate re-emission	Solar corona, galaxy clusters, stellar winds
Coulomb Scattering	Charged particle + charged particle	Electrostatic interaction (binary)	Plasma heating, thermalization, diffusion
Wave-Particle Interaction	Particle + turbulent waves	Resonance between particle gyromotion and turbulent magnetic fields	Diffusive Shock Acceleration (DSA), cosmic rays
Raman Scattering	Electromagnetic wave + plasma waves	Inelastic interaction in which an electromagnetic wave decays into a scattered wave and a plasma wave	High-radio-brightness systems, such as pulsars and quasars

Four principal factors influence the nature and efficiency of scattering in astrophysical plasmas. First, optical depth determines whether scattering occurs predominantly as a single interaction or through multiple scattering events and diffusion. Second, plasma temperature affects the particle velocity distribution and consequently influences phenomena such as Doppler broadening of scattered radiation. Third, density and plasma non-ideality become important in dense environments, where collective effects and Debye screening modify the effective interaction potentials. Fourth, the magnetic field can substantially alter charged-particle trajectories and promote resonant interactions with high-energy particles (Chandler, 2010; Maher et al., 2006). These considerations are particularly important in the solar environment, where magnetized plasma, energetic particles, electromagnetic radiation, and turbulent magnetic fields interact over a wide range of spatial and temporal scales. Observations from the Parker Solar Probe and Solar Orbiter have demonstrated the prevalence of magnetic switchbacks and large-amplitude magnetic fluctuations in the near-Sun solar wind (Huang et al., 2023; Telloni et al., 2022). In addition, observations and theoretical studies indicate that energetic-particle interactions and turbulent plasma processes contribute significantly to solar-wind heating and acceleration (Rankin et al., 2022; Rivera et al., 2024).

HIGHER RATES OF GALACTIC COSMIC RAYS ARE REACHING THE SUN THAN THEORETICAL MODELS PREDICT

Contrary to the simplified view of the Sun as a perfect shield, valuable data indicate that the solar modulation of Galactic Cosmic Rays (GCRs) is complex, allowing a substantial residual flux of high-energy particles to penetrate the inner Solar System, even during periods of high solar activity.

Recent observations, particularly during the 2020s, indicate that GCRs are reaching the inner Solar System at higher rates than traditional theoretical models predicted. This increased flux suggests that the ability of the solar magnetic field to shield the Solar System a process known as solar modulation is less effective than previously thought. While solar modulation reduces GCR intensity by roughly 15–20%, mainly at lower energies (<30 GeV/nucleon), it acts more like a leaky barrier than a complete shield. Realistically, the heliosphere acts more like a protective membrane than an impenetrable solid barrier, with its effectiveness varying over time. Data obtained from NASA's Voyager 1 and Voyager 2 missions have shown that the heliosphere is not a uniform or perfect bubble but rather a dynamic and irregular structure. Specifically, data from Voyager 2 indicate that the heliopause, the outer boundary of the heliosphere, contains leaks or porous regions that allow more GCRs to penetrate into the Solar System. Moreover, the heliosheath is not smooth but contains magnetic bubbles formed through the interaction of the solar magnetic field, which is carried by the solar wind, with the interstellar medium. This interaction creates a frothy structure that allows cosmic particles, particularly highly energetic particles, to pass through. Additionally, neutral interstellar atoms, such as hydrogen, do not experience the electromagnetic effects of the solar wind, allowing them to pass directly through the heliopause and enter the inner Solar System. Obviously, GCRs play a more crucial role in the functioning of the Sun than current mainstream models assume. In the Solar System, the Sun acts as the primary scattering center and modulator of Galactic Cosmic Rays. Data from AMS-02 (Alpha Magnetic Spectrometer) show that the intensity of GCRs is strongly affected by solar modulation,

which is magnetic-rigidity-dependent and primarily influences particles with lower rigidities.

Studies indicate that the spectra of primary cosmic rays, such as helium, carbon, and oxygen, become essentially identical above rigidities of approximately 60 GV, demonstrating that solar-modulation effects caused by interactions with magnetic fields in the solar wind are significant below approximately 60 GV (Lara et al., 2024).

However, despite this modulation, a large proportion of GCRs are deflected at the interface between the heliosphere and the interstellar medium, with further modulation occurring through the heliospheric magnetic field (HMF) in the inner Solar System. GCRs with very high energies that is, non-modulated Galactic Cosmic Rays can reach the solar surface. It should also be noted that GCRs striking the Sun have higher energies than those reaching the Earth (Thomas et al., 2014; Rankin et al., 2022).

These non-modulated GCRs interact with the solar surface, particularly the photosphere, through high-energy nuclear collisions, producing subatomic particles and emitting high-energy gamma radiation, often exceeding 100 GeV and occasionally reaching TeV levels, primarily during solar minimum.

Thus, although GCRs are generally more energetic in terms of energy per particle than average solar particles, the modulation process causes incoming GCRs at 1 AU to be less energetic than they would otherwise be, often reducing their energies below those of SEPs (Giacalone et al., 2022).

However, modulation is effective mainly at lower energies (<10 GeV); higher-energy cosmic rays can penetrate the solar atmosphere and reach the photosphere and lower layers (John et al., 2026).

Inelastic nuclear collisions between GCRs and solar material are a key process for generating high-energy secondary particles, notably gamma rays, neutrinos, and neutrons. However, as already stated, while solar magnetic fields “modulate” or deflect low-energy cosmic rays, high-energy, unmodulated protons and heavier nuclei, such as helium, can penetrate the corona and collide with photospheric matter.

In this respect, it is worth mentioning that the Sun's high-energy gamma-ray emissions are also correlated with the rates of GCRs reaching the polar regions and the solar surface. Very-high-energy gamma radiation from the Sun has been detected at energies extending to approximately 1 TeV. Such high-energy gamma-ray observations have been reported using the High-Altitude Water Cherenkov (HAWC) Observatory and high-energy gamma-ray observations associated with space-based instruments (HAWC Collaboration, 2023; Abdalla, 2025).

This emission is significantly brighter than predicted, indicating complex interactions between solar magnetic fields and cosmic rays. These high-energy gamma rays were detected during periods of relative calm in the solar cycle, particularly around solar minimum, rather than exclusively during intense solar-flare activity (Linden et al., 2018; Glenn, 2019).

Moreover, observational data show that during solar minimum, gamma-ray emission rates are higher in the polar regions. In contrast, during solar maximum, they are higher in the equatorial regions, except during the polar-reversal period.

Basically, observations from NASA's Fermi Gamma-ray Space Telescope show that gamma-ray emission from the Sun is strongly correlated with the reversal of the solar magnetic field, which occurs around the peak of solar maximum (Arsioli & Orlando, 2024).

Specifically, empirical data show that gamma-ray emission increases during polar reversals, with the highest concentration observed at the poles when the Sun's magnetic field reverses. The observation makes perfect sense no mystery exists the polar fields become exceptionally weak during the reversal process, often reaching near-zero strength during its final stage. Weaker polar magnetic fields imply a higher rate of GCRs reaching the polar regions.

Consequently, a higher rate of gamma-ray emission would be produced. Apparently, Galactic Cosmic Rays are a crucial factor in the magnetic scattering and collisions occurring within the solar body, including direct collisions responsible for the emission of high-energy gamma rays and highly energetic neutrinos. High-energy solar neutrinos, in the TeV range and above, are secondary particles produced through cosmic-ray interactions, and recent research indicates that they are produced both in the solar atmosphere (corona) and through interactions within the solar surface (photosphere/disk).

THE PHENOMENON OF MAGNETIC SWITCHBACKS

Although magnetic switchbacks were sporadically observed by Helios 1 and 2 in the 1970s, the NASA-ESA Ulysses mission in the 1990s was the first to explore the Sun's polar regions and identify them in the solar wind (Toth et al., 2023). Moreover, the Solar Orbiter spacecraft provided the first direct images linking a switchback to an active region on the solar surface, while the Parker Solar Probe (PSP) revealed them as enormous vortex structures more than 2.6 solar radii above the solar surface and has frequently passed through them within 3.8 million miles of the main solar body (Huang et al., 2023; Telloni et al., 2022).

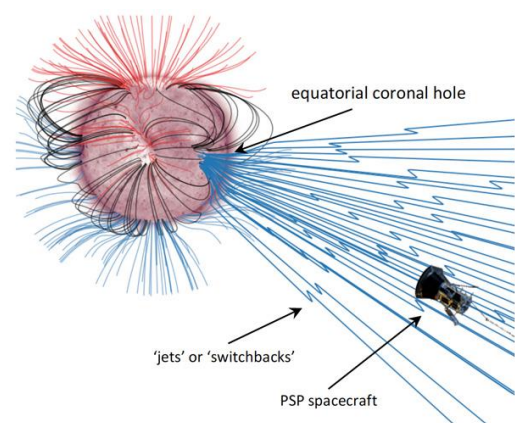


Fig. 1. Graphic by UC Berkeley; spacecraft image courtesy of NASA/Johns Hopkins APL.

These magnetic features are violent, massive structures, approximately the diameter of the Earth, and are highly prevalent in the solar wind, especially in the inner heliosphere

(Badman et al., 2026). They appear in large patches, mostly concentrated near the solar surface, and this is one of the main reasons for the rapid heating immediately above the relatively cool surface, where the plasma temperature rapidly rises to approximately 1 million K (Soni et al., 2024).

In other words, magnetic switchbacks are embedded in the young solar wind, causing rapid acceleration to supersonic speeds and a sudden increase in temperature to approximately 1 million K.

Studies using PSP data have confirmed that these magnetic structures are far more frequent and pervasive close to the Sun (within 0.3 AU) than at larger distances (Badman et al., 2026; Bandyopadhyay & McComas, 2021).

It can also be argued that these structures are highly numerous in the solar wind during solar minimum, as observed by the Ulysses spacecraft, because the rate of GCRs reaching the Sun at the polar regions is higher during this period than during solar maximum (HAWC Collaboration, 2024).

ANALYSING THE COMPLEX SCATTERING PROCESS THAT GENERATES MAGNETIC SWITCHBACKS

While Raman scattering is generally discussed in the context of laser spectroscopy (photon-phonon interaction), it is, in reality, a fundamental physical process that can occur when natural, high-intensity light sources interact with excited matter. The Sun is an extremely high-intensity, broad-spectrum light source, and GCRs are in an excited state as high-energy, fully ionized atomic nuclei. In fact, GCRs are not excited in the conventional atomic sense, in which electrons orbit a nucleus at a higher energy level; rather, they are fully stripped nuclei travelling at near-light speed, meaning that their atomic structure has been completely broken down by extreme acceleration mechanisms.

However, the anti-Stokes component of Raman scattering is typically weak under equilibrium conditions because it relies on scattering from already excited vibrational states. Under non-equilibrium conditions, such as those found in astrophysical plasmas, this component can be significantly enhanced, particularly in the presence of strong magnetic fields. Moreover, the interaction of GCRs with magnetized plasma can heat the local medium, excite electron plasma waves, and increase the population of high-energy electrons, thereby providing the necessary excited state for anti-Stokes scattering.

Thus, the conditions required for this type of scattering do exist: cosmic particles have high internal vibrational energy, and solar radiation provides the intense photon flux needed to initiate this inelastic scattering. Accordingly, anti-Stokes scattering, in which particles gain energy from turbulent fields (waves) in the plasma, can be considered one of the astrophysical scattering processes. In other words, a form of anti-Stokes Raman-like scattering can theoretically occur and does occur between Galactic Cosmic Rays (GCRs) and charged particles in the Sun. In plasma physics, this analogous process is known as inelastic scattering or resonant wave-particle interaction rather than conventional optical Raman scattering.

As GCRs travel through the heliosphere, they encounter magnetic-field fluctuations and electromagnetic waves (magnetohydrodynamic waves) embedded in the solar wind. When GCRs interact with these plasma waves, inelastic scattering occurs. If a GCR particle gains energy from the fluctuating magnetic field of the solar wind, the process is analogous to anti-Stokes scattering, in which the scattered wave has more energy than the incident wave. Conversely, Stokes scattering (energy loss) also occurs, contributing to the modulation and deceleration of GCRs.

These physical processes are better described as resonant wave-particle interactions, in which particles scatter from plasma turbulence. They are key components of solar modulation, in which the heliospheric magnetic field acts as a barrier, causing high-energy GCRs to lose energy while lower-energy GCRs are deflected and undergo changes in energy, resulting in a localized gain in kinetic or potential energy.

Definitely, anti-Stokes scattering is a key inelastic process in turbulent plasma, in which waves or particles absorb energy from background turbulent fields, causing the scattered emission to gain energy and frequency (a blue shift). It is crucial in astrophysical environments, such as fast-radio-burst propagation and magnetar winds, as an energy-transfer mechanism between wave modes and particles.

Therefore, this type of scattering is not only a realistic physical process but is also crucial in astrophysical plasmas. It causes energy to be transferred from turbulent fields (waves) back to particles, leading to particle acceleration or an upshift in particle frequencies. Thus, in this type of inelastic scattering, the incident energy interacts with an excited medium, resulting in scattered waves with higher energy than the incident waves; in plasma, this often corresponds to the transfer of energy from large-amplitude turbulent fields (waves) to particles. Observations, particularly by the ESA Proba-3/ASPIICS mission, have confirmed that blue-shifted outflows (jets) in the solar wind move three to four times faster than previously expected in the inner corona.

These outflows, which originate from coronal holes and active-region boundaries, represent the "progenitors" of the fast solar wind and accelerate as they move through the Sun's upper atmosphere.

SUBSTANTIAL ENERGY TRANSFER IN WEAKLY COLLISIONAL PLASMA

Despite the low frequency of binary Coulomb collisions in weakly collisional plasmas, substantial energy transfer can occur through collective interaction mechanisms, such as wave-particle or wave-wave interactions, rather than through simple binary collisions. These collective behaviours mean that the total energy transfer in weakly collisional plasmas can be much larger than predicted by simple collisional transport, allowing significant energy conversion over large spatial scales.

This process is crucial for converting large amounts of magnetic or bulk-flow energy into thermal particle energy. Therefore, although binary collisions are infrequent, weak collisions (Coulomb collisions) can trigger instabilities that generate plasma waves, such as Langmuir waves. These waves

can, in turn, accelerate electrons or dissipate energy, creating a high-energy non-thermal particle tail.

Kinetic dissipation of turbulence is a critical mechanism in weakly collisional plasmas, such as the solar wind, magneto sheath, and astrophysical jets, where it acts as a primary process for transferring turbulent magnetic energy into thermal energy. However, magnetic switchbacks are instrumental in transporting energy to and from the Sun.

More importantly, they contribute enormously to the heating of the solar corona and to the acceleration and heating of the solar wind (Rivera et al., 2024).

Nonetheless, the magnetic-scattering component of Coulomb collisions specifically, when considering the interaction of charged particles with magnetic textures or magnetic fields is inherently inelastic at high energies because of the energy exchange associated with the excitation of internal degrees of freedom and the non-conservative nature of the scattering.

The scattering process is governed by magnetic guiding-center motion, with perpendicular and parallel energies relative to the magnetic-field line, typically described in cylindrical coordinates. The motion of a charged particle q in a magnetic field and a Coulomb potential can be described by the following relations:

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (1)$$

$$H = \frac{(P - qA)^2}{2m} + V(r) \quad (2)$$

$$V(r) = \sum \frac{qQ}{4\pi\epsilon_0 r} \quad (3)$$

where P is the canonical momentum, A is the vector potential, and $V(r)$ is the Coulomb potential. When the ion gyrofrequency is much larger than the collision frequency, the scattering is modelled by analyzing changes in the particle's velocity components relative to the magnetic field (pitch-angle scattering):

$$\Omega_i = \frac{eB}{m_i} \quad (4)$$

The scattering angle χ between the initial and final velocity vectors is calculated using the relative speed between the colliding species:

$$g = |\mathbf{V}_\alpha - \mathbf{V}_\beta| \quad (5)$$

The magnetized cross-section incorporates the impact parameter B_i relative to the line on which the charge is located, leading to a modified Rutherford-scattering formula that accounts for gyromotion. Nevertheless, in intense fields, the Hamiltonian is solved in cylindrical coordinates, with the magnetic field acting as the dominant factor and the Coulomb interaction treated as a perturbation.

The energy is decomposed into parallel ($E_{\parallel}$) and perpendicular ($E_{\perp}$, associated with Landau levels) components, and the outgoing scattering angle Ψ is derived from the guiding-centre trajectory. In magnetised Rutherford scattering, this is given by an inverse trigonometric function

depending on the impact parameter B_i and the Landau radius b_0 :

$$\Psi = C - \arcsin\left(\frac{B_i^2}{r} + b_0\sqrt{b_0}\right) \quad (6)$$

The scattering frequency exhibits strong oscillatory behavior with increasing particle energy. This results from the quantized Landau levels and S-shaped paths, in contrast to the smooth, monotonic behavior of unmagnetized Coulomb collisions. This means that particles are confined to discrete energy levels, and scattering transitions occur between these levels, particularly in strong magnetic fields. However, for particles restricted to the lowest Landau level ($L = 0$), only backward scattering contributes significantly to the collision frequency, resulting in a unique S-shaped path when viewed in the guiding-centre frame. In other words, the S-shaped trajectory occurs because the magnetic field limits transverse motion (gyro-orbits), while the Coulomb force provides longitudinal acceleration/deceleration, forcing a transition between different field lines or guiding-centre paths.

Specifically, the S-shaped trajectory arises when the particle experiences a magnetic force ($q\mathbf{V} \times \mathbf{B}$) that forces it to bend in one direction, while electric repulsion, proportional to $1/r^2$, bends it in the other direction.

Because inelastic scattering is a process in which an incident particle collides with a target, a portion of its kinetic energy is transferred to the target system (Elsevier, n.d.; Chandler, 2010), implying that the corona gains energy and that collisions increase. Temperature is a measure of the average kinetic energy of particles; faster-moving particles correspond to a higher temperature.

Magnetic scattering and Coulomb collisions in a plasma act as a drag force (friction) on charged particles, and this force generally decreases with increasing particle velocity. For velocities above the thermal velocity of the plasma, the force decreases with increasing electron velocity, approximately according to:

$$F \propto v^{-3} \quad (7)$$

When a strong electric field exceeds a critical value, electrons that have gained enough energy to reduce their collision frequency enter a runaway state in which the accelerating electric force exceeds the frictional drag force. This state occurs when the electric field is high or when the electron energy increases to a point at which collisions become infrequent. In other words, runaway electrons are electrons in a plasma or ionized gas subjected to an electric field that experience an acceleration force greater than the frictional drag force from collisions, causing them to accelerate continuously to ultra-high velocities (Houghton, 1975).

The runaway electrons are modelled by kinetic equations, primarily by balancing the acceleration force from an electric field:

$$E_c = \left(\frac{n_e e^3 \ln \Lambda}{4\pi \epsilon_0^2 m_e c^2}\right) \times const \quad (8)$$

The momentum-space dynamics are governed by the Boltzmann kinetic equation, and the threshold at which acceleration exceeds the maximum frictional force is defined approximately as:

$$E_c \approx \left(\frac{n_e e^3 \ln \Lambda}{4\pi \epsilon_0^2 m_e c^2} \right) \quad (9)$$

where n_e is the plasma density, e is the elementary charge, $\ln \Lambda$ is the Coulomb logarithm, and $m_e c^2$ is the electron rest-energy term. The acceleration of an electron in an electric field E along the magnetic field is often simplified as:

$$\frac{dE}{dx} = eE - F(e) \quad (10)$$

where $F(e)$ is the frictional deceleration force. The exponential multiplication of electrons through knock-on collisions, known as the Runaway Electron Avalanche (REA), is often expressed as:

$$\gamma_{RA} \approx \frac{(eE - F_d)}{m_e c \ln \Lambda} \quad (11)$$

where E is the electric field and F_d is the friction at high velocity. Because anti-Stokes scattering in plasma is highly temperature-dependent since it relies on the population of excited states, which increases with temperature when an incident Galactic Cosmic Ray interacts with a charged solar particle that is already in an excited energy state, the particle absorbs energy (Maher et al., 2006). This increases the energy of the scattered particle, leading to a higher frequency and a shift toward the blue end of the spectrum. The energy-balance equation for inelastic scattering, specifically anti-Stokes scattering, is:

$$E_f = E_i + \Delta E_{matter} \quad (12)$$

where the final and initial energies can be written as:

$$E_f = h\nu_f \quad (13)$$

$$E_i = h\nu_i \quad (14)$$

and ΔE_{matter} is the energy gained from the material. In terms of frequency:

$$\nu_f = \nu_i + \frac{\Delta E_{matter}}{h} \quad (15)$$

Since $\Delta E_{matter} > 0$, the final frequency ν_f is greater than the initial frequency ν_i , resulting in a blueshift. In terms of wavelength:

$$\frac{1}{\lambda_f} = \frac{1}{\lambda_i} + \frac{\Delta E_{matter}}{hc} \quad (16)$$

Because wavelength and frequency are related by:

$$\lambda = \frac{c}{\nu} \quad (17)$$

an increase in frequency ($\nu_f > \nu_i$) results in a decrease in wavelength ($\lambda_f < \lambda_i$). It should be remembered that magnetic switchbacks are often associated with strong, blue-shifted plasma up flows originating near active regions in the solar atmosphere, as shown by spectroscopic data.

These up flows are characteristic of plasma accelerating away from the Sun. The acceleration and movement of these structures are linked to Type III radio bursts detected by the Parker Solar Probe and are strongly associated with velocity spikes and enhanced plasma flow (Badman et al., 2026; Bourouaine et al., 2022).

These velocity spikes and the overall structures move faster than the surrounding, quieter solar wind, producing a blue-shifted signature relative to the ambient coronal plasma. In fact, recent results from the European Space Agency's Proba-3 mission, published in April 2026, confirmed that blue-shifted outflows (plasma blobs/jets) in the inner solar corona move three to four and sometimes up to five times faster than previously expected, often reaching speeds of 250–500 km/s compared with the predicted 100 km/s. The velocity spike δV is related to the speed of the magnetic wave as follows:

$$V_{m.wave} = \frac{B}{\sqrt{4\pi\rho}} \quad (18)$$

$$\delta V \approx \frac{\delta B}{\sqrt{4\pi\rho'}} \quad (19)$$

Inside the switchback, the plasma gains kinetic energy from the change in shape of the magnetic field, leading to localized acceleration. This blue-shifting effect is illustrated in Fig. 2.

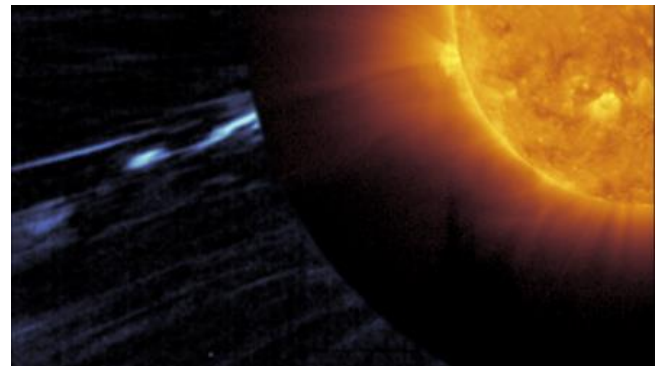


Fig. 2. Blue-shifted signatures. Credit: Work performed by ATG under contract for ESA, based on data from ESA & NASA/Solar Orbiter/EUI & Metis Teams and Telloni et al. (2022); Zank et al. (2020).

THE SCATTERING PROCESS OF EXPLODING DOUBLE LAYERS (EDLS) IN THE SUN

All energetic events on the Sun are primarily and fundamentally driven by magnetic interactions (collisions and scattering processes). These processes are fundamental to energy transfer, heating, and the structural dynamics of the solar atmosphere. They involve complex interactions between plasma particles and the Sun's magnetic field, extending from the dense photosphere to the tenuous, extremely hot corona. In fact, the hypothetical process of magnetic reconnection has to be considered as Exploding Double Layers (EDLs).

EDLs are electrical features that can occur in plasma systems, including those interacting with liquids (plasma-liquid interfaces). They are highly dynamic, non-stationary structures in plasma and, unlike stable double layers, rapidly evolve, explode, and collapse, releasing bursts of high-energy particles.

These structures act as a strong localized electric field an area of charge separation with a positive and a negative layer that drives significant electrical current and acts as a localized, high-energy load in a plasma system. It can be shown that EDLs produce highly accelerated beams of both electrons and ions, which can lead to further scattering when they interact with the surrounding plasma. Different types of electromagnetic radiation in space are emitted through the mechanism of EDLs.

However, the concept of magnetic reconnection is unrealistic because magnetic-field lines are not physical entities; they are only a mathematical visualization or aid. Thus, how can magnetic-field lines reconnect if they do not exist physically? Lines of magnetic force are no more physical entities than the contours on a geographer's map or the isobars on a weather chart. One might just as well speak of contour reconnection as an explanation for a volcanic eruption as consider magnetic reconnection to be an explanation for energy outbursts of various kinds. Obviously, the basic aim behind the notion of magnetic-field lines is to describe the magnetic field mathematically as a vector field. It is the only way to represent the information contained within a vector field. In this mathematical visualization, the density of field lines where the lines bunch together indicates the regions of strongest magnetic field; however, field lines do not start or stop anywhere, but always form closed loops, and the direction of the field is indicated by drawing arrowheads along the lines. Lines of force can just as easily be considered to exist between the drawn lines as along the lines themselves. In the real world, however, magnetic fields are best visualized by dropping iron filings onto a surface near a strong magnetic material, such as a bar magnet. Each filing behaves like a tiny magnet with north and south poles, and the filings remain separated because like poles repel each other. The flaws in the conventional theory of magnetic reconnection are also evident in the equations describing this hypothetical process. They assume a very slow discharge of energy lasting for years; however, solar flares can be observed to discharge in minutes, with far more energy than the theoretical model assumes.

Moreover, whenever this phenomenon occurs, regions of electron-depleted space are associated with it, and a two-layer flow of particles is formed that accelerates those electron-depleted atoms, with propagation velocities reaching up to 700 m/s. Clearly, this energetic phenomenon meets all the characteristics of an EDL rather than the elegant hypothetical theory of magnetic reconnection. EDLs are highly unstable plasma structures that often form in the narrow, high-voltage interface between a plasma and a liquid surface, or other conducting surfaces. Plasma does not directly touch a liquid surface; instead, a sheath (a space-charge layer) always forms to separate the hot plasma from the cold, dense liquid. Because of differences in energy levels, strong electric fields develop. In particular, the plasma sheath near a liquid

frequently behaves as a double layer a region containing a thin positive space-charge layer adjacent to a negative layer. The sudden explosion accelerates ions out of the liquid region and electrons into it, forming high-energy plasma beams. This process can be simulated by electrical-wire explosions over water, which create intense plasma jets and shock waves when the wire is transformed into plasma. Furthermore, EDLs are not restricted to plasma-liquid interfaces; they are a broader nonlinear phenomenon that occurs whenever strong potential structures in plasma become unstable, often because of high current density or rapid expansion.

These layers can form in homogeneous plasmas, between plasma regions of different densities or temperatures, and in laser-produced plasmas. In pure plasmas, such as gas-phase plasmas, double layers (DLs) are generally narrower and more compact than those found in more complex environments such as liquid-plasma interfaces. They are characterized by a strong potential jump, effectively separating plasma regions with different properties such as density, temperature, or energy distribution and accelerating ions and electrons in opposite directions. Double Layers (DLs) convert electrical potential energy into the kinetic energy of ions and electrons, and strong DLs can accelerate particles to relativistic energies, as in cosmic phenomena or laboratory discharges.

Four particle populations are typical within a strong DL: (1) streaming electrons, (2) streaming ions, (3) trapped/reflected electrons downstream, and (4) trapped/reflected ions upstream.

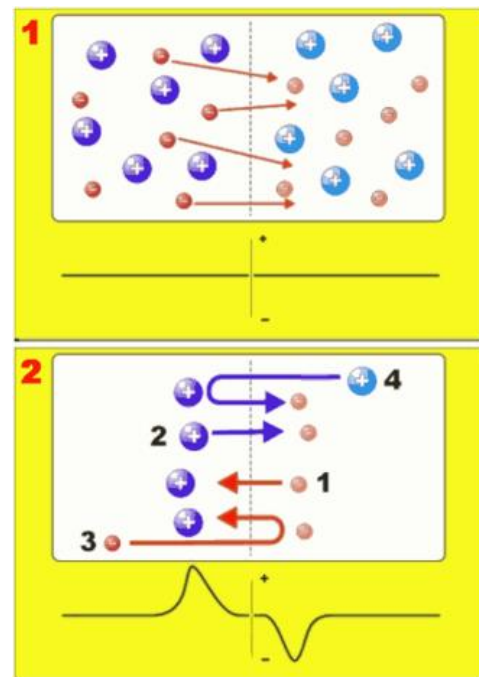


Fig. 3. Double-layer formation. Formation of a double layer requires electrons to move between two adjacent regions (Diagram 1, top), causing charge separation. An electrostatic potential imbalance may result (Diagram 2, bottom).

In summary, as the current driven through the double layer increases or the plasma density changes, the electron drift velocity may exceed the threshold for instabilities.

Excessive current forces a high concentration of space charge (ions and electrons) to build up within the narrow layer. This layer behaves like a capacitor that stores energy.

When the charge concentration becomes too great, the layer becomes unstable, and the confined charge is released, often causing the layer to move abruptly, vanish, or rapidly expand. This release of stored energy results in a sharp, large spike in the potential drop across the layer, often accelerating particles to high energies. The region of the double layer can rapidly expand in the form of a plasma jet, with a mushroom-cloud-like appearance similar to that often observed in underwater explosions.

Nonetheless, high-resolution solar observations demonstrate that the process of EDLs or what is known as magnetic reconnection is not limited to high-altitude flares but is a frequently occurring process in the photosphere and low chromosphere, manifesting through phenomena such as Ellerman bombs, UV bursts, and chromospheric jets.

Recent high-resolution observations, for example from the Swedish 1-m Solar Telescope (SST) and Solar Orbiter's EUVI, have shown that small-scale 'reconnection' is constantly occurring, with estimates suggesting that hundreds of thousands of Ellerman bombs (EBs) are present at any time. In our view, these observations reveal important empirical facts about the Sun, but the details cannot be provided in this article.

MAGNETIC SWITCHBACKS OBSERVED WITHIN EARTH'S MAGNETOSHEATH

In August 2025, NASA's Magnetospheric Multiscale (MMS) mission detected magnetic switchbacks within Earth's magnetosheath, the turbulent region between the magnetosphere and the interplanetary magnetic field. The magnetosheath is characterized by extremely high temperatures, often reaching millions of degrees (1.5-2.5 million K).

Typically, the temperature ranges between 100 eV and 1 keV (roughly 1 million to more than 10 million K), depending on the planet and solar-wind conditions. It should be noted that, based on the second law of thermodynamics, the maximum temperature of a planetary magnetosheath cannot exceed the temperature of the solar corona. The solar wind, which forms the magnetosheath, originates from the solar corona. The second law of thermodynamics implies that, in steady-state scenarios, heat cannot naturally flow from a lower-temperature source to a higher-temperature destination.

However, as in the case of the solar corona, magnetic switchbacks are the leading mechanism responsible for the high temperature of the magnetosheath, although other magnetic processes also contribute in several ways. EDLs are one of the fundamental processes, as in the case of the Martian magnetosheath.

In addition, filamentary currents, magnetic dips (holes), and vortical flows in the turbulent magnetosheath act as scattering centers for ions (Chaston & Travnicek, 2021). These structures convert magnetic energy into particle kinetic energy through chaotic orbits, thereby heating ions and producing high-energy tails in the particle-energy distribution. A non-thermal particle tail is a high-energy population of particles in a plasma that

deviates from the standard Maxwellian velocity distribution, often appearing as a power-law distribution.

These populations, which are frequently observed in solar flares and astrophysical systems, indicate that particles have been accelerated by processes such as magnetic turbulence. Additionally, numerous instabilities, such as mirror modes and whistler waves, develop because of the high temperature anisotropy behind the bow shock (Guo et al., 2025):

$$T_{\perp} > T_{\parallel} \quad (20)$$

These waves scatter particles, with whistler waves in particular playing a crucial role in heating electrons in the quasi-parallel magnetosheath. The bow shock compresses the solar wind, and the resulting turbulent environment particularly in the quasi-parallel magneto sheath exhibits chaotic variations in magnetic field and density, further contributing to particle heating (Behar et al., 2024; Zhang et al., 2013).

Thus, despite the fact that the magnetic scattering of Coulomb collisions is the major factor in the high temperature of Earth's magnetosheath, other complex scattering processes occur in the transition region between the bow shock and the magnetopause, where the solar-wind plasma is compressed, heated, and decelerated. These processes are characterized by intense, kinetic-scale, broadband electromagnetic fluctuations that efficiently scatter ions and electrons.

This is consistent with the identical processes occurring in the highly magnetized plasma environment of the Sun (the solar corona), a region that constantly experiences both local and large-scale compressive events. Turbulent dissipation in the corona, which is driven mainly by external Galactic Cosmic Rays rather than by solar activity, also contributes to its heating.

The heliosphere is subject to a continuous and immense bombardment of ultra-fast Galactic Cosmic Rays, and the rate of this bombardment is the main factor in its contraction and expansion (Rankin et al., 2022). However, as in the case of the magnetosheath, magnetic scattering of Coulomb collisions is the critical process in the solar corona and depends on modulated Galactic Cosmic Rays. On the other hand, unmodulated cosmic rays play the leading role in other energetic events, such as the production of high-energy gamma rays.

In essence, Galactic Cosmic Rays are the driving force behind the most important dynamic phenomena of the Sun, including coronal heating, particle acceleration, and the triggering of solar eruptions. In fact, solar observations show that even when eruptions appear to start on the surface, they are often triggered by processes occurring higher in the Sun's atmosphere.

This is a clear indication of the important role of external magnetic fields in the mechanism of solar eruptions.

Solar eruptions, including solar flares and Coronal Mass Ejections (CMEs), are explosive events that primarily originate in the solar corona directly above active regions (ARs). These magnetically intense and complex regions on the solar surface serve as centers for magnetic interactions between external and local magnetic fields, leading to such explosive energetic events. In other words, a stronger external

field is required to interact with a local field, with the external field forcing the local field to change its configuration and release its stored energy in the process.

Thus, based on our evaluation, the assertion that the magnetic fields embedded in the solar wind are stronger than those embedded in all GCRs cannot be considered a scientifically valid concept. This is because a highly energetic charged particle, such as an electron or proton, generates its own magnetic field as a consequence of its motion, according to the Biot-Savart law. Specifically, a moving charged particle produces both electric and magnetic fields, and when it moves at extremely high speeds, its surrounding fields are intensified. The intensity, or strength, of the magnetic field produced by a moving charged particle is directly proportional to its velocity. There is no reason why GCRs would be an exception to this fundamental rule of electromagnetism. It would therefore be expected that the magnetic fields embedded in high-energy GCRs would be stronger than those embedded in the solar wind.

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CONCLUSION

Although mainstream consensus asserts that magnetic switchbacks result from magnetic reconnection between open and closed magnetic-field lines, this widely accepted notion lacks real scientific substance and decisive empirical evidence. Essentially, the hypothetical concept of magnetic reconnection violates not only Alfvén's theorem, commonly known as the frozen-in flux theorem, but also the most basic feature of magnetism.

This is because a charged particle carries the magnetic force with it as it moves. Consequently, the magnetic force cannot break its continuity because it is an inseparable property of matter. Hence, an objective evaluation of observational data, based on the standard experimental laws of physics, shows that magnetic switchbacks are caused by a weakly collisional process. They are the result of magnetic scattering arising from Coulomb collisions between modulated Galactic Cosmic Rays and solar radiation.

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