NikoUArxive_astron_20260823_792622

The Solar Magnetic Switchbacks are Magnetic Scattering of Coulomb Collisions between Galactic Cosmic Rays and Solar Radiation

(1) Jamal S. Shrair, PhD: Electronic engineer & independent astrophysics researcher. Email: Jamalshrair@yahoo.com
(2) John Turner, Physicist: Formerly employed in the energy sector, worked for Alstom, General Electric and Framatome. Email: johnlilburneturner@proton.me

Abstract

The process of magnetic switchbacks contributes greatly to coronal heating and the acceleration of solar wind. It is a weakly collisional plasma process influenced by magnetic field configuration, rather than a result of purely electrostatic Coulomb collisions. This magnetic process is a consequence of magnetic scattering, in which low-energy galactic cosmic rays (3-30 MeV/nuc) interact with solar radiation, and this interaction is more pronounced during periods of heightened solar activity, including the release of Energetic Solar Particles (**SEPs**). Essentially, when highly modulated Galactic Cosmic Rays (**GCRs**) collide weakly with the solar radiation, magnetic switchbacks are formed, resulting in a form of anti-Stokes Raman scattering that increases the temperature of a magnetised plasma and accelerates the solar wind. It is unconventional Raman scattering of a highly magnetised plasma involving nonlinear, non-isotropic interactions in which an external magnetic field modifies charged-particle dynamics, producing an optical S-shaped signature. In the presence of a strong magnetic field, Coulomb collisions are significantly altered, forcing them into complex, S-shaped or non-monotonic trajectories rather than the simple hyperbolic paths observed in conventional Coulomb scattering. That is because the magnetic field induces cyclotron motion (gyromotion) which interacts with the Coulomb potential, causing the heavily charged particle to spiral or curve, intersect its asymptotic line, and create a unique S-shape before completing its scattering.

Scattering Processes in Astrophysical Plasma

Scattering processes in astrophysical plasmas involve interactions between radiation (photons) and charged particles (electrons and ions), or between the particles themselves. These processes are crucial for understanding radiation transfer, energy transport, and particle acceleration in cosmic environments like stellar atmospheres, accretion disks, and the interstellar medium.

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: energy transfer between photon and electron	X-ray binary sources, Active Galactic Nuclei
Inverse Compton	Photon + relativistic electron	High-energy electron transfers energy to 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	Particle + turbulent waves	Resonance between particle gyro-motion and turbulent magnetic fields	Diffusive Shock Acceleration (DSA), cosmic rays
Raman Scattering	EM wave + plasma waves	Inelastic interaction: EM wave decays into scattered wave +plasma wave	High-radio-brightness systems (pulsars/quasars)

Note that there are four factors impacting scattering: First, **Optical Depth**, which determines if scattering is single or multiple (diffusion). Second, **Plasma Temperature**, which affects the velocity distribution and, thus, the Doppler broadening of scattered radiation. Third, **Density/Non-Ideality**, because in dense environments, collective effects are important, and Debye screening modifies interaction potentials. Fourth, **Magnetic Field**, which causes resonant scattering of high-energy particles.

NikoUArxive_astron_20260823_792622

Higher rates of galactic cosmic rays are reaching the Sun than theoretical models are predicting

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 activity. Recent observations, particularly in 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 solar magnetic field's ability to shield the solar system—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 as a leaky barrier than a total shield.

Realistically, the heliosphere acts more like a protective membrane than an impenetrable solid barrier, with its efficiency changing over time. Data received from NASA's Voyager 1 and 2 missions have shown that the heliosphere is not a uniform or perfect bubble, but rather a dynamic, irregular structure. Specifically, data from Voyager 2 indicates that the heliopause, the outer boundary of the heliosphere, has leaks - porous holes - that allow more GCRs to penetrate into our solar system. Moreover, the heliosheath is not smooth but rather full of magnetic bubbles that are formed as a result of the interaction of the solar magnetic field (which is carried by the solar wind) with the interstellar medium, creating a frothy structure that allows cosmic particles - especially the highly energetic ones- to pass through. Additionally, neutral interstellar atoms (such as hydrogen) do not feel the electromagnetic effects of the solar wind, allowing them to pass directly through the heliopause and into 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 (GCRs). The AMS-02 (Alpha Magnetic Spectrometer) data show that the intensity of Galactic Cosmic Rays (GCRs) is strongly affected by solar modulation, which is magnetic rigidity-dependent and primarily impacts particles with lower rigidities. Studies indicate that the spectra of primary cosmic rays, such as helium, carbon, and oxygen, are identical above rigidities of 60 GV, demonstrating that solar modulation effects—caused by the interaction with magnetic fields in the solar wind—are significant below ~60 GV (18). But, in spite of this, a large portion of GCRs are deflected at the interface between the heliosphere and the interstellar medium, with further modulation by the heliospheric magnetic field (HMF) in the inner solar system, those with a very high energy (non-modulated galactic cosmic rays) can reach the solar surface, keeping in mind that GCRs which strike the Sun have higher energy than those that reach the

NikoUArxive_astron_20260823_792622

Earth (9), (10). Those non-modulated GCRs interact with the solar surface—specifically 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, while GCRs are generally more energetic (higher energy per particle) than average solar particles, the modulation process makes incoming GCRs at 1 AU less energetic than they would be without it, often putting their energy lower than SEPs (11). But the modulation is only effective at lower energies (< 10 GeV); the higher-energy cosmic rays can easily penetrate the solar atmosphere, reaching down to the photosphere and lower layers (12). Inelastic nuclear collisions between galactic cosmic rays (GCRs) and solar material are a key process that generates high-energy secondary particles, notably gamma rays, neutrinos, and neutrons. However, as already stated, while solar magnetic fields "modulate" (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 that reach the polar regions and the solar surface. Very high-energy gamma radiation from the Sun has been detected, reaching up to ~1 trillion electron volts (1 TeV). The detection was made by the High-Altitude Water Cherenkov Observatory (HAWC) and NASA's Fermi Gamma-ray Space Telescope (13), (14). This emission is significantly brighter than predicted, indicating complex solar magnetic fields and cosmic ray interactions. These high-energy rays were detected during a period of relative calm in the solar cycle (solar minimum), rather than during intense solar flares or activity. (15), (16). Moreover, observational data show that during the solar minimum, gamma-ray emission rates are higher in the polar regions. In contrast, at the 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 during the peak of the solar maximum (17). 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 inverts. The observation makes perfect sense–no mystery exists–the polar fields become exceptionally weak during the reversal process, often reaching near-zero strength during the final stage of the reversal. Weaker polar magnetic fields imply a higher rate of GCRs reaching the polar regions. Consequently, a higher rate of gamma-ray emissions would be produced.

Apparently, galactic cosmic rays are a crucial factor in the magnetic scattering and collisions that occur in the solar body, including direct collisions which are responsible for the emission of high-energy gamma rays and highly energetic neutrinos. High-energy solar neutrinos (TeV range and above) are secondary particles produced by cosmic ray interactions, and recent research indicates they are produced both in the solar atmosphere (corona) and by interactions within the solar surface (photosphere/disk).

NikoUArxive_astron_20260823_792622

The Phenomenon of Magnetic Switchbacks

Although magnetic switchbacks were sporadically spotted by Helios 1 and 2 in the 1970s, the NASA-ESA Ulysses mission in the 1990s was the first to explore the Sun's poles and identify them in the solar wind (1). 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) showed them as enormous vortex structures over 2.6 solar radii above the solar surface, and it has frequently passed through them within 3.8 million miles from the main solar body (2),(3).

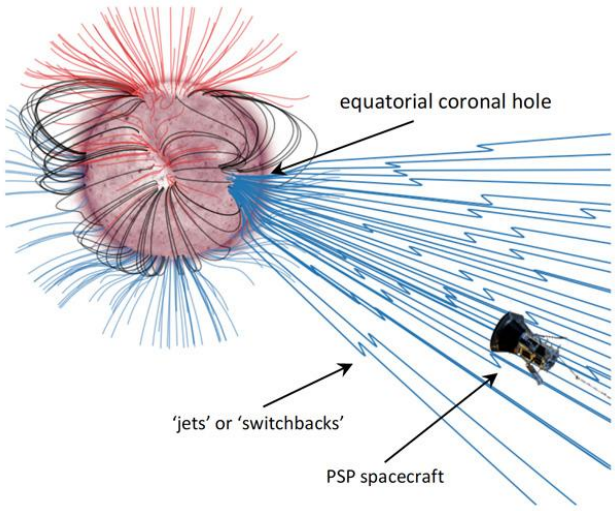


Fig. 1: Graphic by UC Berkeley; spacecraft image courtesy of NASA/Johns Hopkins APL

These magnetic features are violent, massive structures, approximately the diameter of the Earth and highly prevalent in the solar wind, especially in the inner heliosphere (4). They appear in large patches, mostly concentrated near the solar surface, and this is one of the main reasons for the rapid heating just above the relatively cool surface, where the plasma temperature rises rapidly to 1 million Kelvin (5). That is to say, the magnetic switchbacks are embedded in the young solar wind, causing rapid acceleration to supersonic speeds and a sudden increase in temperature up to 1 million Kelvin. Studies using data from the PSP have confirmed that these magnetic structures are far more frequent and pervasive close to the Sun (within 0.3 AU) than at larger distances (6), (7). And it can be argued that the reason these structures are highly numerous in the solar wind during the solar minimum, as observed by the Ulysses spacecraft, is that the rate of CGRs reaching the sun at the polar regions is higher during this period than during the solar maximum (8).

Analysing the Complex Scattering Process that Generates Magnetic Switchbacks

While Raman scattering is generally discussed in the context of laser spectroscopy (photon-phonon interaction), in reality it is a fundamental physical process that can occur with natural, high-intensity light sources interacting with excited matter. The Sun is an extremely high-intensity, broad-spectrum light source, and GCRs are in an excited state (high-energy, fully ionised atomic nuclei). In fact, GCRs are not just excited in the conventional atomic sense (electrons orbiting a nucleus in a higher energy level), but they are fully stripped nuclei travelling

NikoUArxive_astron_20260823_792622

at near light-speed, meaning their atomic structure has been completely broken down by extreme acceleration mechanisms. However, the anti-Stokes component in Raman scattering is typically weak under equilibrium conditions, because it relies on scattering from already excited vibrational states. But in 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 the magnetized plasma can heat the local medium, exciting electron plasma waves and increase the population of high-energy electrons, which provides the necessary excited state for anti-Stokes scattering. Thus, the conditions for his type of scattering do exist, cosmic particles have high internal vibrational energy, and solar radiation provides the intense flux of photons needed to initiate this inelastic scattering. Thus, the anti-Stokes scattering where particles gain energy from turbulent fields (waves) in the plasma can be considered as one of the astrophysical scattering processes. In other words, a form of anti-Stokes Raman-like scattering can theoretically occur—and it does occur—between Galactic Cosmic Rays (GCRs) and the charged particles of the Sun. In plasma physics, this analogous process is known as inelastic scattering or resonant wave-particle interaction rather than conventional optical Raman scattering.

Anyhow, as GCRs travel through the heliosphere, they encounter magnetic field fluctuations and electromagnetic waves (magnetohydrodynamic waves) embedded in the solar wind. When the GCRs interact with these plasma waves, inelastic scattering occurs, and if a GCR particle gains energy from the fluctuating magnetic field of the solar wind, it is analogous to anti-Stokes scattering (where 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 off 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 change their energy (resulting in a localised gain in kinetic or potential energy).

Definitely, anti-Stokes scattering is a key inelastic process in turbulent plasma where waves or particles absorb energy from background turbulent fields, causing the scattered emission to gain energy and frequency (blue-shifted). 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 also crucial in astrophysical plasmas. It causes energy to be transferred from turbulent fields (waves) back into particles, leading to particle acceleration or an upshift in particle frequencies. So, basically, in this type of inelastic scattering, the incident energy interacts with an excited medium, resulting in scattered waves having higher energy than the incident waves, and 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 are moving up to three-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, accelerating as they move through the Sun's upper atmosphere.

NikoUArxive_astron_20260823_792622

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 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, while binary collisions are infrequent, weak collisions (Coulomb collisions) can trigger instabilities that generate plasma waves (e.g., 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, magnetosheath, and astrophysical jets), where it acts as the primary process for transferring turbulent magnetic energy to 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, to the acceleration and heating of the solar wind (19).

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 due to the energy exchange associated with excitation of internal degrees of freedom and the non-conservative nature of the scattering. The scattering process is governed by magnetic guiding centre motion, with (⊥) and (||) energies to the magnetic field line, typically described in cylindrical coordinates. The motion of a charged particle (q) in a magnetic field B = ∇ x A and a Coulomb potential is described by the Hamiltonian: H = $\frac{(\boldsymbol{P}-\boldsymbol{qA})^{\boldsymbol{2}}}{\boldsymbol{2m}}$ + V (r) where P is the canonical momentum, A is the vector potential and (V(r))= ΣqQ/4$\pi\epsilon_0$r).

When the ion gyrofrequency (Ω_i = e B / m_i) is much larger than the collision frequency (ν_{ii}), the scattering is modelled by analysing changes in the particle's velocity components relative to the magnetic field (pitch-angle scattering). The scattering angle χ between the initial and final velocity vectors is calculated using the relative speed g = $|V_\propto - V_\beta|$ between colliding species. The magnetised 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 the 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 ($E_{\|}$) 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, however, this is given by an inverse trigonometric function depending on the impact parameter (B_i) and the Landau radius (b_0): Ψ= C – arcsin ($\frac{{B_i}^2}{r} + b_0\sqrt{b_0}$).

NikoUArxive_astron_20260823_792622

The scattering frequency exhibits strong oscillatory behaviour in response to increasing particle energy. This results from the quantised Landau levels and S-shaped paths, in contrast to the smooth, monotonic behaviour of unmagnetised Coulomb collisions. This means that particles are confined to discrete energy levels, and scattering transitions occur between these levels, particularly in strong magnetic fields. Yet, for particles restricted to the lowest Landau level (L = 0), only backwards scattering contributes significantly to the collision frequency, resulting in a unique S-shaped path when viewed in the guiding-centre frame. That is to say, 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 (qV X B) that forces it to bend one way, while the electric repulsion ($\sim 1/r^2$) bends it the other way.

Since the inelastic scattering is a process where an incident particle collides with a target, a portion of its kinetic energy will be transferred to the target system (20), (21), implying that the corona will gain energy, and the collisions will increase. Temperature is a measure of the average kinetic energy of particles (faster-moving particles correspond to a higher temperature). Note that 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, this force decreases with increasing electron velocity (approximately equal to v^{-3}).

But when a strong electric field exceeds a critical value, electrons that have gained enough energy to reduce their collision frequency will enter a runaway state, where the accelerating electric force exceeds the frictional drag force. This state occurs when the electric field is high, or when electron energy increases to a point where collisions become infrequent. In other words, the runaway electrons are electrons in a plasma or an ionised gas subjected to an electric field, which experience an acceleration force greater than the frictional drag force from collisions, causing them to accelerate continuously to ultra-high velocities (22). The runaway electrons are modelled by kinetic equations, primarily balancing the acceleration force from an electric field:

$E_c = \frac{n_e\, e^3\, In\, \Lambda}{4\pi\, e_0^2 m_e c^2}$ X const. The momentum-space dynamics are governed by the Boltzmann kinetic equation, and the threshold at which the acceleration exceeds the maximum friction force, defined as

$E_c \approx \frac{n_e\, e^3\, In\, \Lambda}{4\pi\, e_0^2 m_e c^2}$ where n_e is plasma density, e is the charge, InΛ is the Coulomb logarithm, and $m_e\, c^2$ is the mass energy equation (relationship between electromagnetic field energy and mass). The acceleration of an electron in an electric field E along the magnetic field is often simplified to $\frac{dE}{dx} =$ eE− F(e) where (Fe) is the frictional deceleration force. The exponential multiplication of electrons via knock-on collisions (The Runaway Electron Avalanche - REA) is

NikoUArxive_astron_20260823_792622

often expressed as $\gamma_{RA} \approx \frac{eE-Fd}{m_e c\, In\, \Lambda}$ where E is the field, F_d is the friction at high velocity.

Due to the fact that anti-Stokes scattering in plasma is highly temperature-dependent—because it relies on the population of excited states, which increases with temperature—when an incident galactic cosmic particle interacts with a charged solar particle which is already in an excited energy state, the particle absorbs energy (23). This increases the scattered particle's energy, 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): $E_f = E_i + \Delta E_{matter}$, where: $E_f = hv_f$ is the final energy of the scattered particle (h is Planck's constant, v_f is final frequency), $E_i = hv_i$ is the initial energy of the incident particle and ΔE_{matter} is the energy gained from the material. In terms of frequency (v): $v_f = v_i + \frac{\Delta E_{matter}}{h}$.

Since $\Delta E_{matter} > 0$, the final frequency v_f is greater than the initial frequency v_i, resulting in a blueshift. In terms of wavelength (λ) $\frac{1}{\lambda_f} = \frac{1}{\lambda_i} + \frac{\Delta E_{matter}}{hc}$. Because $\lambda = c/v$, an increase in frequency ($v_f > v_i$) results in a decrease in wavelength ($\lambda_f < \lambda_i$).

It should be remembered that the magnetic switchbacks are often associated with strong, blue-shifted plasma upflows that originate near active regions in the solar atmosphere Spectroscopic Data. These upflows are characteristic of plasma accelerating away from the Sun. The acceleration and movement of these structures are linked to the Type III radio bursts detected by the Parker Solar Probe. They are strongly associated with velocity spikes and enhanced plasma flow ((24), (25). These velocity spikes and the overall structure move faster than the surrounding, quieter solar wind, resulting in 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 are indeed moving three to four (and sometimes up to five) times faster than previously expected, often reaching speeds of 250–500 km/s compared to the predicted 100 km/s. The velocity spike δV is related to the speed of the magnetic wave, $V_{m.wave} = \frac{B}{\sqrt{4\pi\rho}}$: $\delta V \approx \frac{\delta B}{\sqrt{4\pi\rho}}$, and inside the switchback, the plasma gains kinetic energy from the magnetic field's change in shape, leading to localised acceleration. This blue-shifting effect is illustrated in Fig. 2 below.

NikoUArxive_astron_20260823_792622

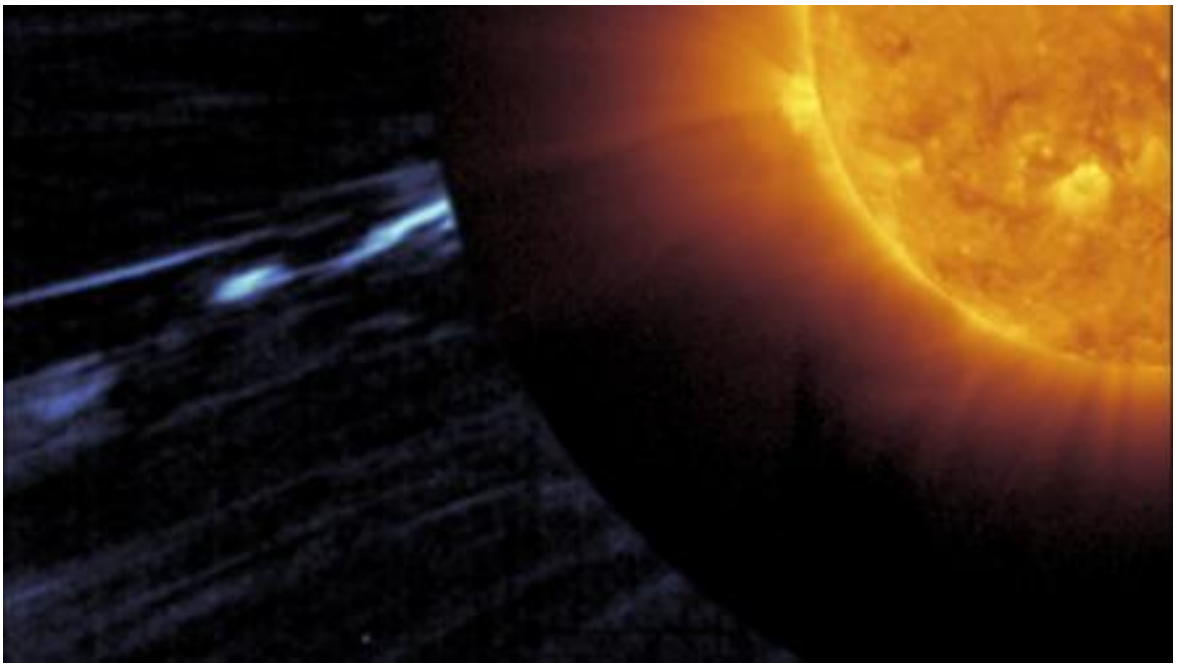


Fig. 2: Blue-shifted signatures. [Credit: Work performed by ATG under contract for ESA, based on data from ESA & NASA/Solar Orbiter/EUI & Metis Teams and D. Telloni et al. (2022); Zank et al. (2020).]

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 the energy transfer, heating, and structural dynamics of the solar atmosphere. They involve the complex interaction between plasma particles and the Sun's magnetic field, spanning from the dense photosphere to the tenuous, extremely hot corona. Actually, the hypothetical process of magnetic reconnection has to be considered as an Exploding Double Layers (EDLs). They are an electrical feature that can occur in plasma systems, including those interacting with liquids (plasma-liquid interfaces). EDLs 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 upon interacting with the surrounding plasma. Different types of electromagnetic radiation in space are emitted by 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 visualisation or aid. So, how can magnetic field lines reconnect if they do not exist at all? Lines of magnetic force are not physical entities, any more than are the contours of a geographer’s map, or the isobars of a weatherman’s chart. One might just as well talk about a contour reconnection as being the explanation of a volcanic eruption, as to consider magnetic reconnection to be an explanation of energy outbursts of

NikoUArxive_astron_20260823_792622

various sorts. 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. With this mathematical visualisation, the density of field lines (where field lines bunch together) indicates the strongest magnetic field regions, but the field lines do not start or stop anywhere; they always form closed loops and the direction of the field is indicated by drawing arrowheads along the lines. The lines of force can easily be considered or thought of as between those lines, as in any of the lines themselves. In the real world, however, magnetic fields are best seen by dropping iron filings onto a surface near a strong magnetic material, such as a bar magnet. It can be seen that each filing behaves like a tiny magnet with north and south poles. The filings are separated from each other because like poles repel.

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, but as can be observed, solar flares discharge in minutes with far more energy than the theoretical model assumes. Moreover, whenever this phenomenon takes place, there are regions of electron-depleted space associated with it, and a two-layer flow of particles is formed that speeds those electron-depleted atoms, where the propagation velocities can reach up to 700m/sec. Clearly, this energetic phenomenon meets all the characteristics of 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 touch a liquid surface directly, and a sheath (a space-charge layer) always forms to separate the hot plasma from the cold, dense liquid. Due to the differences in energy levels, strong electric fields develop. Namely, the plasma sheath near a liquid frequently behaves as a double layer—a region with a thin, positive space-charge layer and an adjacent 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 turns to plasma.

Furthermore, it is important to realise that the 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 due to high current density or rapid expansion. These layers can form in homogeneous plasmas, between plasma regions of different densities/temperatures, and in laser-produced plasmas. Note that in pure (e.g., gas-phase) plasmas, double layers (DLs) are generally narrower and more compact compared to those found in more complex environments like the liquid-plasma interface.

They are characterised 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 kinetic energy of ions and electrons, and strong DLs can accelerate particles to relativistic energies, such 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.

NikoUArxive_astron_20260823_792622

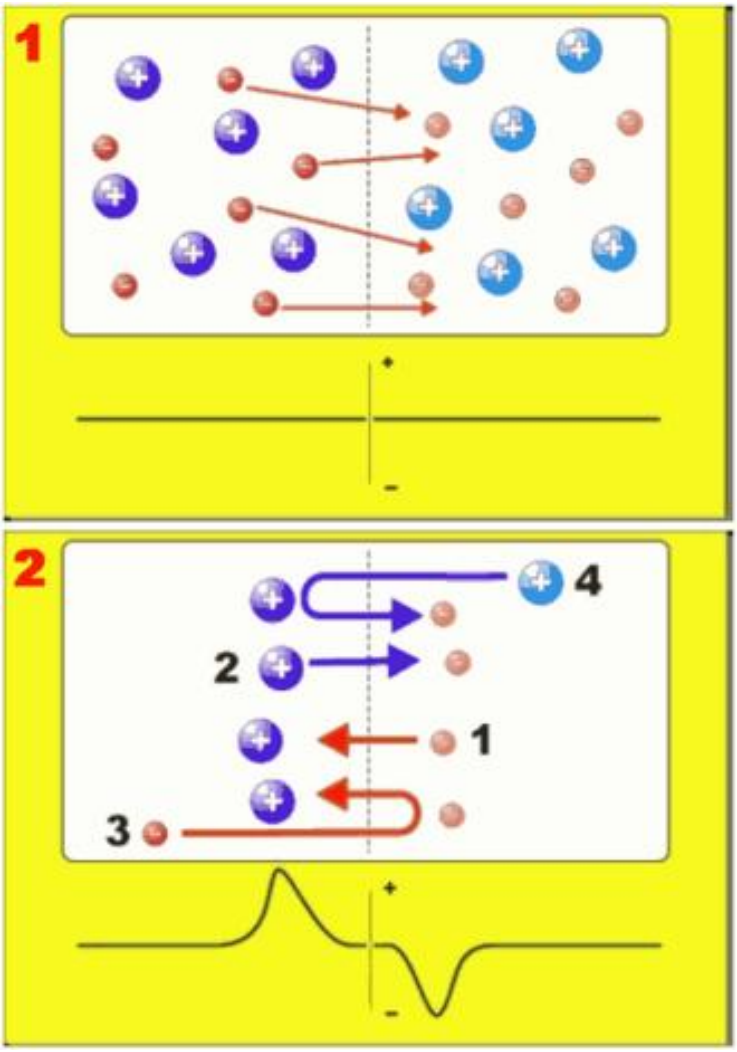


Fig. 3: Double layer formation. Formation of a double layer requires electrons to move between two adjacent regions (Diagram 1, top) causing a charge separation. An electrostatic potential imbalance may result (Diagram 2, bottom). Double layer (plasma physics)- Wikipedia

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. The 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 storing energy. And, 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 (mushroom cloud-like, as 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 like Ellerman bombs, UV bursts, and chromospheric jets. Recent, high-resolution observations (e.g., from the Swedish 1-m Solar Telescope (SST) and Solar Orbiter's EUI) 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 characterised by extremely high temperatures, often reaching millions of degrees **(1.5-2.5 million Kelvin)**. Typically, the temperature ranges between **100 eV** and **1 keV (roughly 1 million** to over **10 million Kelvin)**, depending on the planet and solar wind conditions. Note 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 magnetosheath's high temperature, but other magnetic processes also contribute in several ways. EDLs are one of the fundamental processes, as in the case of the Martian magnetosheath. Also, filamentary currents, magnetic dips (holes), and vortical flows in the turbulent magnetosheath act as scattering centres for ions (26). These structures convert magnetic energy into particle kinetic energy via chaotic orbits, thereby heating ions and producing high-energy tails in the particle energy distribution. Note that 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 shape. These populations, frequently observed in solar flares and astrophysical systems, indicate that particles have been accelerated by processes such as magnetic turbulence. Additionally, numerous instabilities (e.g., mirror modes, whistler waves) develop due to the high temperature anisotropy ($T_{\perp} > T_{\parallel}$) behind the bow shock (27).

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 magnetosheath—exhibits chaotic variations in magnetic field and density, further contributing to particle heating (28), (29). So, in spite of 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 characterised by intense kinetic-scale, broadband electromagnetic fluctuations that efficiently scatter ions and electrons.

This aligns with the identical processes occurring in the highly magnetised plasma environment of the Sun (the solar corona), a region constantly experiencing both local and large-scale compressive events. The turbulent dissipation in the corona, which is driven mainly by external

NikoUArxive_astron_20260823_792622

NikoUArxive_astron_20260823_792622

galactic cosmic rays—not by solar activity—is also contributing to its heating. The heliosphere is subject to a continuous and immense bombardment of ultra-fast galactic cosmic rays, where the rate of bombardment is the main factor in its contraction and expansion (30). 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, the 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 up in the Sun's atmosphere. That is a clear indication for 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 primarily originating in the solar corona directly above the active regions (ARs). These magnetically intense, complex regions on the solar surface serve as centers for magnetic interaction between the external magnetic fields and local ones, leading to those explosive energetic events. In other words, a stronger, external field is required to interact with a local field, where the external one forces the local field to change its configuration and releases 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 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 an electric and a magnetic field, 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 [See footnote[1] below].

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

[1] Fortunately, the Sun resides in a relatively quiet, low-density region of the Milky Way, and that is the reason why the rate of highly energetic galactic cosmic rays reaching it is very low. Otherwise, it would be in high-risk situations involving partial or complete explosions.

of magnetic reconnection violates not only Alfvén's theorem, commonly known as the frozen-in flux theorem, but also violates the most basic feature of magnetism. That is because a charged particle carries the magnetic force with it when it moves. Consequently, the magnetic force cannot break its continuity, since 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 weakly collisional process. They are the result of magnetic scattering arising from Coulomb collisions between modulated galactic cosmic rays and solar radiation.

NikoUArxive_astron_20260823_792622

References

(1) Formation of Magnetic Switchbacks Observed by Parker Solar Probe, [2301.02572] Formation of Magnetic Switchbacks Observed by Parker Solar Probe

(2) Observation of the Structure and Origin of Switchbacks: Parker Solar Probe Observations, The Structure and Origin of Switchbacks: Parker Solar Probe Observations - IOPscience

(3) Magnetic Switchback in the Solar Corona, Observation of a Magnetic Switchback in the Solar Corona - IOPscience

(4) Properties of Magnetic Switchbacks in the Near-Sun Solar Wind, [2601.04165] Properties of Magnetic Switchbacks in the Near-Sun Solar Wind

(5) Switchback Patches Evolve into Microstreams via Magnetic Relaxation, Switchback Patches Evolve into Microstreams via Magnetic Relaxation - IOPscience

(6) Properties of Magnetic Switchbacks in the Near-Sun Solar Wind, Properties of Magnetic Switchbacks in the Near-Sun Solar Wind | Space Science Reviews | Springer Nature Link

(7) Geometry of Magnetic Fluctuations near the Sun from PSP, 2110.14756

(8) Exploring the Coronal Magnetic Field with Galactic Cosmic Rays: The Sun Shadow Observed by HAWC, Exploring the Coronal Magnetic Field with Galactic Cosmic Rays: The Sun Shadow Observed by HAWC - IOPscience

(9) Galactic Cosmic Ray Modulation near the Heliospheric Current Sheet, Galactic Cosmic Ray Modulation near the Heliospheric Current Sheet | Solar Physics | Springer Nature Link

(10) Galactic Cosmic Rays Throughout the Heliosphere and in the Very Local Interstellar Medium, Galactic Cosmic Rays Throughout the Heliosphere and in the Very Local Interstellar Medium - PMC

(11) Anomalous Cosmic Rays and Heliospheric Energetic Particles, Anomalous Cosmic Rays and Heliospheric Energetic Particles - PMC

(12) Addressing the Impact of Solar Modulation Systematic Uncertainties on Cosmic-Ray Propagation Models, Addressing the Impact of Solar Modulation Systematic Uncertainties on Cosmic-Ray Propagation Models

(13) Discovery of Gamma Rays from the Quiescent Sun with HAWC | Phys. Rev. Lett.

(14) Multi-TeV Gamma Rays from GRB 221009A: Challenges for Emission Mechanisms, EBL Opacity, and Fundamental Physics, Multi-TeV Gamma Rays from GRB 221009A: Challenges for Emission Mechanisms, EBL Opacity, and Fundamental Physics

(15) Evidence for a New Component of High-Energy Solar Gamma-Ray Production, Evidence for a New Component of High-Energy Solar Gamma-Ray Production | Phys. Rev. Lett.

(16) Mysterious High Energy Gamma Rays Might Help Explain What Drives Solar Cycles, [1901.10574] Mysterious High Energy Gamma Rays Might Help Explain What Drives Solar Cycles

(17) Yet Another Sunshine Mystery: Unexpected Asymmetry in GeV Emission from the Solar Disk, Yet Another Sunshine Mystery: Unexpected Asymmetry in GeV Emission from the Solar Disk - IOPscience

(18) Interaction of Cosmic Rays With Magnetic Flux Ropes, Interaction of Cosmic Rays With Magnetic Flux Ropes - Lara - 2024 - Journal of Geophysical Research: Space Physics - Wiley Online Library

(19) In situ observations of large-amplitude Alfvén waves heating and accelerating the solar wind In situ observations of large-amplitude Alfvén waves heating and accelerating the solar wind | Science

NikoUArxive_astron_20260823_792622

(20) Scattered Particle- an overview | ScienceDirect Topics
(21) Chapter 5: Elastic and Inelastic Scattering: Energy Transfer in Collisions https://doi.org/10.1039/BK9780854041589-00116
(22) Electron runaway in turbulent astrophysical plasmas, Electron runaway in turbulent astrophysical plasmas - ScienceDirect
(23) Temperature dependent anti-Stokes/Stokes ratios under Surface Enhanced Raman Scattering (SERS) conditions, [physics/0511074] Temperature dependent anti-Stokes/Stokes ratios under Surface Enhanced Raman Scattering (SERS) conditions
(24) Properties of Magnetic Switchbacks in the Near-Sun Solar Wind, [2601.04165] Properties of Magnetic Switchbacks in the Near-Sun Solar Wind
(25) Features of Magnetic Field Switchbacks in Relation to the Local-field Geometry of Large-amplitude Alfvénic Oscillations: Wind and PSP Observations, Features of Magnetic Field Switchbacks in Relation to the Local-field Geometry of Large-amplitude Alfvénic Oscillations: Wind and PSP Observations - IOPscience
(26) Ion Scattering and Energization in Filamentary Structures Through Earth's Magnetosheath Ion Scattering and Energization in Filamentary Structures Through Earth's Magnetosheath | Semantic Scholar
(27) Excitation of Mirror Mode Waves and Whistler Waves in Space Plasmas, Excitation of Mirror Mode Waves and Whistler Waves in Space Plasmas- Guo- 2025- Journal of Geophysical Research: Space Physics- Wiley Online Library
(28) Impact of solar wind turbulence on a planetary bow shock, Impact of solar wind turbulence on a planetary bow shock
(29) Spontaneous hot flow anomalies at quasi-parallel shocks: 1. Observations, Spontaneous hot flow anomalies at quasi-parallel shocks: 1. Observations - Zhang - 2013 - Journal of Geophysical Research: Space Physics - Wiley Online Library
(30) Galactic Cosmic Rays Throughout the Heliosphere and in the Very Local Interstellar Medium, Galactic Cosmic Rays Throughout the Heliosphere and in the Very Local Interstellar Medium- PMC