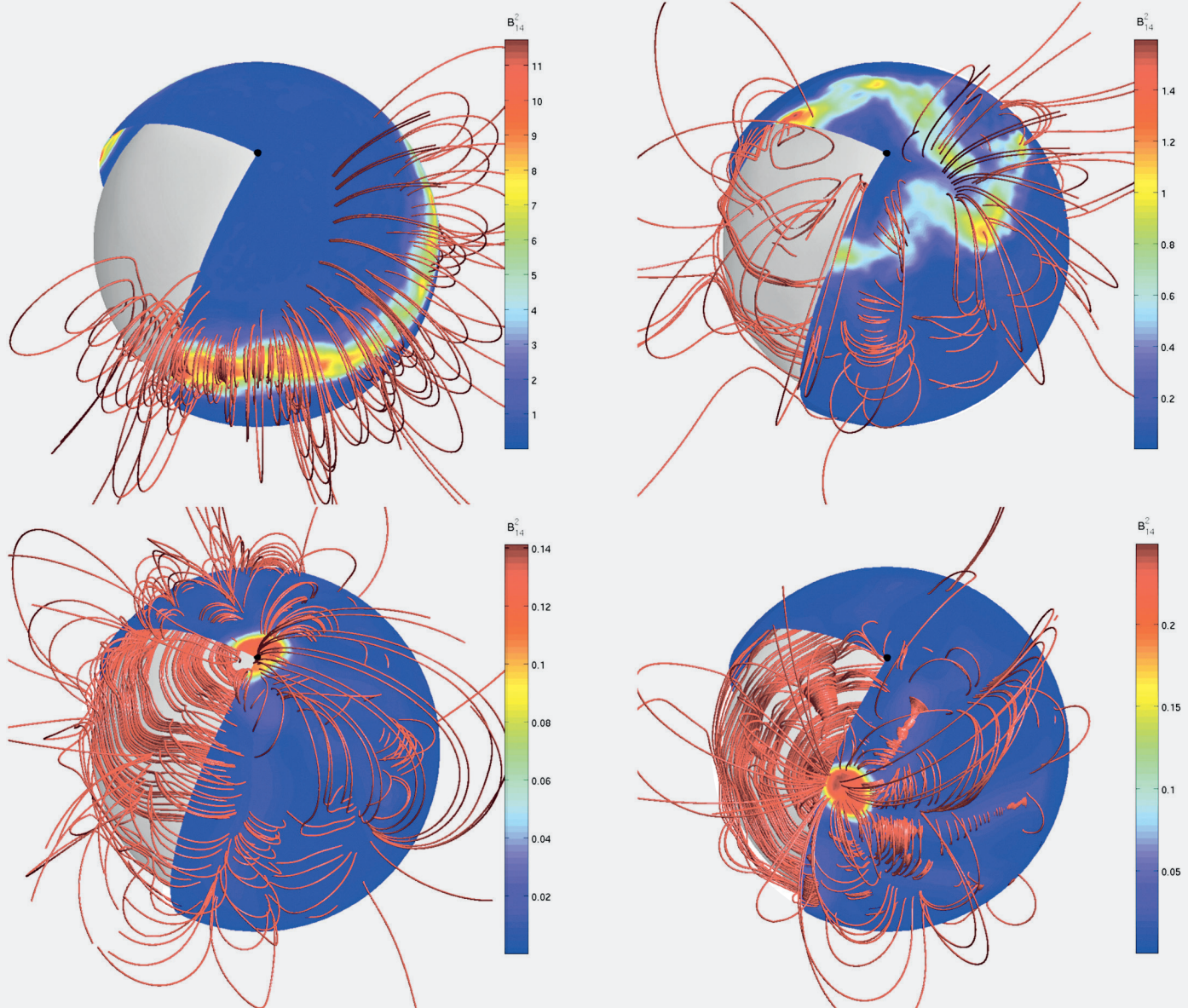


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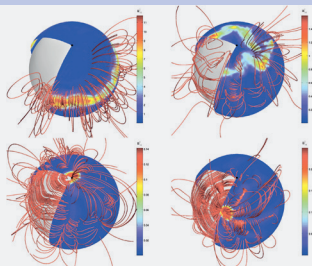
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Cover Image:

Magnetic field structure following Hall-MHD evolution in the crust with increasing toroidal magnetic field component energy: top left $E_{\text{tor}}/E_{\text{tot}} = 0.5$, top right $E_{\text{tor}}/E_{\text{tot}} = 0.9$, bottom left $E_{\text{tor}}/E_{\text{tot}} = 0.99$, bottom right $E_{\text{tor}}/E_{\text{tot}} = 0.99$ and the axes of the dipole and toroidal field form an angle of 45° . Adapted from Konstantinos N. Gourgouliatos and Rainer Hollerbach. "Magnetic Axis Drift and Magnetic Spot Formation in Neutron Stars with Toroidal Fields". *ApJ*, 852(1):21, January 2018.

Message from the President



It is my pleasure to introduce the 2026 issue of *Hipparchos*, the annual newsletter of the Hellenic Astronomical Society. As in previous years, this issue presents a collection of articles covering a broad range of topics in astronomy, astrophysics, and space science. We are particularly pleased to include four feature articles: Strong MHD Turbulence and Coherent Structures as Cosmic Particle Accelerators by Loukas Vlahos; The Multiple Pathways of Neutron Star Magnetic Field Evolution by K. N. Gourgoulitos; Determinism, Randomness and Theories of Everything by George Contopoulos; and SPEARHEAD: Reconstruction, Physics, and Interpretation of High-Energy Particle Populations in the Heliosphere by Athanasios Papaioannou. On behalf of the Society, I would like to express my sincere thanks to all the authors for their contributions to this issue.

On 26 June 2026, the Society will hold its annual General Assembly, while the biennial elections for the Governing Council, President, and Auditing Committee will also take place electronically on the same day. This provides an opportunity to reflect on the many activities and achievements of the past two years and to thank all those who have contributed to them. Among the highlights of this period was the 17th Hellenic Astronomical Society Conference, hosted by the University of Patras from 30 June to 2 July 2025. The conference attracted strong participation from the Greek and international astronomical communities and featured a number of distinguished invited speakers, including Nobel Laureate Didier Queloz. During the conference, the Society also presented the 2025 Harlaftis Prize for the best PhD

thesis in Astronomy and Astrophysics to Sofia Savvidou, recognizing an outstanding contribution by an early-career researcher. In addition, the Society continued its support of the Greek astronomical community through travel grants for PhD students, contributions to educational and outreach activities, and the promotion of astronomy-related events across the country. As the current term of office draws to a close, I would like to express my gratitude to all members of the Governing Council for their dedication and hard work. I would particularly like to thank the outgoing members of the Council—Dr. John Antoniadis, Dr. George Balasis (Vice-President), Dr. Athanasios Papaioannou (Treasurer), and Prof. Maria Petropoulou (Secretary)—for their invaluable contributions to the Society's activities during the past four years. During the General Assembly on 26 June, we will also present the Society's new website, which will provide a modernized and more dynamic platform for communication with our members and the broader public.

The period 2025–2026 has also been marked by significant developments in astronomical infrastructure in Greece. In September 2025, Skinakas Observatory in Crete began scientific operations with a 1-m optical telescope, while a 1.2-m class telescope dedicated to spectroscopic observations is scheduled for commissioning in summer 2026. At the same time, the ARGOS Pathfinder radio array, consisting initially of five dishes at the FORTH campus in Heraklion, is expected to enter operation, opening new opportunities in radio astronomy and multi-messenger astrophysics. In parallel, the National Observatory of Athens

has expanded its role in both astronomy and space science. During 2025, the Kryoneri and Helmos observatories successfully participated in long-distance optical communication experiments with NASA's *Psyche* mission, demonstrating advanced laser communication technologies. New infrastructure is also being deployed at both sites, including an 80-cm telescope at Kryoneri and upgrades to the Aristarchos telescope at Helmos. These developments will support not only astronomical research but also next-generation space optical communications and secure data-transmission technologies.

Looking ahead, I would also like to remind our members of the 6th Hellenic Astronomical Society Summer School, which will take place from 24 to 28 August 2026 at the National and Kapodistrian University of Athens. This year's school, devoted to Multimessenger Astronomy, will bring together leading researchers from Greece and abroad to introduce graduate students and early-career scientists to one of the most rapidly developing fields of modern astrophysics. We look forward to welcoming participants from across Greece and beyond.

It has been a privilege to serve the Society during the past two years and to witness the continued growth and achievements of our community. I thank all members for their support, engagement, and commitment to advancing astronomy and space science in Greece. I hope you enjoy this issue of *Hipparchos*, and I look forward to meeting many of you at our upcoming events and activities.

Despina Hatzidimitriou
President of Hel.A.S.

Strong MHD Turbulence and Coherent Structures as Cosmic Particle Accelerators

by Loukas Vlahos

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Abstract

Magnetohydrodynamic turbulence is an ubiquitous dynamical state of astrophysical plasmas and serves as a key mechanism for redistributing energy, dissipating it, and transforming it into various particle populations. Nonetheless, discussions of turbulence still typically focus on cascades, power spectra, and scale-to-scale energy transfer, while its capacity to generate localized regions of intense energization is comparatively underplayed. In this forward-looking review, intended for a wide astrophysical audience, I contend that any physically complete description of turbulent plasma heating and particle acceleration must place the self-consistent formation of coherent structures—such as current sheets, vortices, magnetic flux ropes, shocklets, and confined reconnection regions—at its core.

Viewed in this way, strong turbulence provides a unifying framework that links large-scale plasma dynamics to the generation of suprathermal particles and non-thermal energy distributions in the solar atmosphere, the solar wind, shock environments, and a wide range of other cosmic plasmas. Rather than attempting an exhaustive survey of the literature, this article offers a selective and physically organized synthesis of the field, emphasizing the mechanisms, regimes, and open problems most relevant to the development of predictive theories of particle acceleration in turbulent plasmas. It also identifies the principal conceptual and computational challenges that must be overcome if the next generation of models is to connect multiscale plasma dynamics with observable energetic-particle signatures.

Keywords: MHD turbulence, coherent structure formation, energetic particles, high energy astrophysics, cosmic rays

1. INTRODUCTION

In astrophysics, turbulence is commonly described within the classical framework of the Reynolds number, the transfer of energy across spatial scales, and the Kolmogorov picture of hydrodynamic turbulence. Although these concepts remain foundational, most astrophysical plasmas are magnetized, only weakly collisional, and far from thermodynamic equilibrium. Under such conditions, the coupling between velocity and magnetic fields fundamentally alters the dynamics. Magnetohydrodynamic (MHD) turbulence is therefore not simply a magnetic extension of ordinary fluid turbulence, but a richer multiscale process shaped by magnetic tension, anisotropy, intermittency, magnetic field-line topology, and reconnection (W. H. Matthaeus & M. Velli 2011; W. H. Matthaeus 2021; L. Vlahos & H. Isliker 2023).

As turbulence develops, the plasma self-organizes into localized coherent structures. Within these regions, gradients steepen, electric fields intensify, dissipation becomes concentrated, and particles undergo trapping, scattering, and repeated episodes of acceleration. These structures therefore provide the physical link between large-scale turbulent dynamics and the small-scale processes responsible for plasma heating, the formation of suprathermal particle populations, and the emergence of non-thermal energy distributions.

This viewpoint also changes how particle acceleration in astrophysical plasmas should be interpreted. Mechanisms that are often studied separately—stochastic acceleration, shock acceleration, reconnection-driven acceleration, and wave-particle interactions—may in fact operate simultaneously within the same intermittent turbulent environment. From this perspective, strong MHD turbulence offers a unifying framework in which these apparently distinct energization channels arise as interconnected consequences of multiscale energy transfer in a spatially structured electromagnetic field.

SCOPE AND PERSPECTIVE: This article is not intended to be a comprehensive review. Rather, it presents a forward-looking and concise overview with a pedagogical emphasis, aimed at astrophysicists who are not specialists in turbulence. The focus is on how coherent structures emerge, how they modify electric fields, how these processes transfer energy across scales, and how they influence particle acceleration in a broad range of magnetized plasma environments.

The presentation is organized as follows. I begin by outlining the transition from ordinary fluid turbulence to MHD turbulence, emphasizing the features most relevant to particle energization. The next section examines the emergence of coherent structures in strongly turbulent MHD regimes and discusses their statistical properties. I then explore how such coherent structures manifest themselves in laboratory, space, and astrophysical plasmas. Finally, I review numerical approaches—including MHD simulations, test-particle methods, and kinetic techniques—and discuss future prospects for the development of reduced, physics-informed neural models of turbulent particle acceleration.

2. FROM HYDRODYNAMIC TO MAGNETOHYDRODYNAMIC TURBULENCE

A standard way to introduce turbulence is through the competition between nonlinear advection and dissipation. In an ordinary fluid, this balance is measured by the Reynolds number,

$$Re = \frac{uL}{\nu} \quad (1)$$

where u is a characteristic flow speed, L is a representative large length scale, and ν is the kinematic viscosity.

When $Re \gg 1$, nonlinear advection dominates over viscous diffusion, the flow becomes unstable, and eddies develop over a broad hierarchy of scales. In this regime, energy injected at large scales

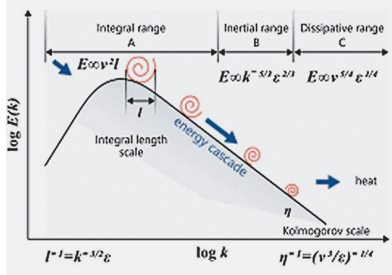


Figure 1: Energy introduced at large scales is gradually transferred to progressively smaller scales until it reaches the dissipation range, where it is converted into heat. (https://2021.help.altair.com/2021/hwsolvers/acusolve/topics/acusolve/training_manual/turb_scales_energy_cascade_r.htm)

is progressively transferred to smaller scales until it reaches the dissipative range, where it is ultimately converted into heat (Fig. 1). This cascade picture, established by Kolmogorov, remains one of the basic organizing principles of turbulence theory (A. N. Kolmogorov 1941a,b).

Within the inertial range of fully developed hydrodynamic turbulence, the mean energy flux per unit mass, ϵ , is approximately constant across scales. For an eddy of size ℓ and characteristic velocity u_ℓ , the turnover time is $\tau_\ell \sim \ell/u_\ell$, while the energy transfer rate is

$$\Pi_\ell \sim \frac{u_\ell^2}{\tau_\ell} \sim \frac{u_\ell^3}{\ell}. \quad (2)$$

By identifying $\Pi_\ell \sim \epsilon$, one retrieves the Kolmogorov scaling

$$u_\ell \sim (\epsilon \ell)^{1/3}, \quad (3)$$

which leads to the well-known energy spectrum

$$E(k) \sim \frac{u_\ell^2}{k} \propto \epsilon^{2/3} k^{-5/3}, \quad (4)$$

where $k \sim 1/\ell$ denotes the wavenumber. Although idealized, this framework captures the essential point that turbulence is intrinsically multiscale, with nonlinear interactions transporting energy across scales in an approximately self-similar way.

Astrophysical plasmas, however, are rarely well described as neutral fluids. In most space and astrophysical environments, magnetic fields are dynamically important, and the appropriate macroscopic description is MHD. The dynamics are then controlled not only by inertia, pressure gradients, and viscous stresses, but also by magnetic pressure, magnetic tension, and the evolution of the magnetic field itself. The MHD mo-

mentum and induction equations may be written as (T. J. M. Boyd & J. J. Sandereson 1969; N. A. Krall & A. W. Trivelpiece 1973)

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla \left(P + \frac{B^2}{8\pi} \right) + \frac{(\mathbf{B} \cdot \nabla) \mathbf{B}}{4\pi} + \nu \rho \nabla^2 \mathbf{u} + \mathbf{F}, \quad (5)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \quad (6)$$

here, P denotes the particle pressure, ρ the plasma mass density, $\mathbf{u}$ the bulk flow velocity, $\mathbf{B}$ the magnetic field, ν the kinematic viscosity, $\mathbf{F}$ the gravitational force, and η the magnetic diffusivity. The induction equation highlights a key feature of plasma dynamics: the magnetic field does not behave as a passive tracer. Instead, it is transported, stretched, and diffused by the flow while exerting a back-reaction on the plasma via the Lorentz force.

The corresponding control parameter for magnetic evolution is the magnetic Reynolds number,

$$R_m = \frac{uL}{\eta}, \quad (7)$$

which measures the competition between inductive transport and magnetic diffusion. In typical astrophysical plasmas, both Re and R_m are extremely large, implying that velocity and magnetic fluctuations evolve nonlinearly over an enormous range of scales. Under these conditions, the cascade becomes intrinsically coupled: kinetic and magnetic energies interact continuously, producing anisotropy, intermittency, and strong spatial inhomogeneity. This already represents a major departure from the simplest hydrodynamic picture.

A further distinction concerns the nature of the cascade itself. In magnetized plasmas, turbulent fluctuations can propagate as Alfvénic disturbances, are shaped by the local magnetic geometry, and often cascade anisotropically with respect to the mean or local magnetic field. Just as importantly, nonlinear MHD dynamics do not merely generate a background of random fluctuations; they also produce sharp gradients and complex magnetic topology. MHD turbulence, therefore, acts not only as a cascade process but also as an efficient generator of structure.

This point is central to particle energization. The quantity that enters directly into the dynamics of charged particles

is the electric field, which in MHD is given by

$$\mathbf{E} = -\frac{\mathbf{u} \times \mathbf{B}}{c} + \eta \mathbf{J}, \quad (8)$$

with

$$\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}. \quad (9)$$

The electric field thus depends directly on the very quantities that become intensely intermittent in strong turbulence: the velocity, the magnetic field, and the current density. When the plasma enters a state characterized by large magnetic fluctuations and numerous coherent structures, the electromagnetic conditions experienced by particles become highly nonuniform in both space and time. Under these circumstances, adiabatic invariants are likely to be violated, giving rise to irreversible processes. Consequently, it is reasonable to anticipate that transport and acceleration are controlled not only by broadband fluctuations, but also by repeated encounters with localized structures where electric fields are intensified, and dissipation is concentrated (L. Vlahos et al. 2004).

For the purposes of this review, this is the essential conceptual step. Hydrodynamic turbulence shows how nonlinear systems redistribute energy across scales. MHD turbulence adds a further level of complexity by coupling this transfer to magnetic topology, intermittent current structures, and spatially localized electric fields. It is precisely this combination that makes strong MHD turbulence so relevant to astrophysical plasmas: it provides not only a means of redistributing energy, but a genuinely dynamical environment in which plasma heating, reconnection, and particle acceleration can be understood within a unified multiscale framework.

3. THE EMERGENCE OF COHERENT STRUCTURES IN STRONG MHD TURBULENCE

Intermittency is one of the defining signatures of strong turbulence. In a turbulent plasma, dynamical activity is distributed unevenly: extended regions may remain relatively quiet, whereas only a limited fraction of the volume contains sharp gradients, intense currents, enhanced vorticity, and strong electric fields. In this way, intermittency links the large-scale transfer of energy across scales to the localized regions where

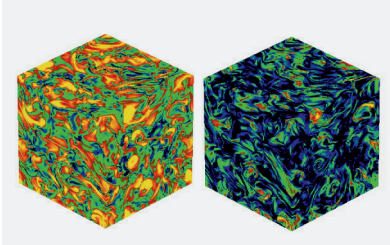


Figure 2: Visualization of the turbulent magnetic field strength $|B|$ (left) and electric field strength $|E|$ (right) across the simulation domain. Regions of high intensity are shown in yellow (light), whereas low-intensity regions are shown in blue (dark) (P. Dmitruk et al. 2003).

that energy is ultimately converted into heat or non-thermal particle energy. Several studies (P. Dmitruk et al. 2003; P. Dmitruk et al. 2004; K. Arzner et al. 2006) investigated decaying turbulence in simulations that started with both kinetic and magnetic perturbations, considering configurations both with and without an imposed magnetic field, as well as setups featuring a strong guide field (C. Dong et al. 2022).

After several Alfvén crossing times, τ_A ($\tau_A = L/v_A$, with v_A denoting the Alfvén speed (F. F. Chen 2016)), the system reaches a fully developed turbulent state spanning a broad range of spatial scales (see Fig. 2). In this regime, coherent structures associated with intense, spatially localized electric fields naturally arise from the nonlinear interaction of kinetic and magnetic fluctuations. In strongly magnetized plasmas, where $B^2/4\pi > P$, the turbulent cascade becomes increasingly anisotropic and intermittent. Such conditions favor the formation of thin current sheets, magnetic filaments, vortices, and localized

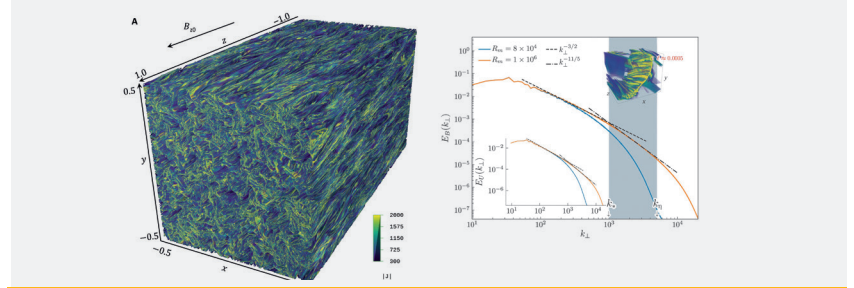


Figure 3: (Left) Volume rendering of the current density $|J|$ over the full domain at a time when turbulence is fully developed. Numerous current sheets are visible in the plane perpendicular to the mean magnetic field B_{z0} . (Right) Spectra of the magnetic and kinetic energies associated with the perpendicular field components, $E_B(k_\perp)$ and $E_U(k_\perp)$, showing a standard inertial range with a slope $-3/2$ and a reconnection-driven (or tearing-mediated) subinertial range with a slope $-11/5$ for large R_m (orange curves) (C. Dong et al. 2022).

reconnection sites (see Fig. 3) (C. Dong et al. 2022).

Under such conditions, coherent structures are not uniformly distributed throughout space but instead appear in localized clusters. This patchy and highly inhomogeneous organization is consistent with a fractal or multifractal description, in which coherent structures occupy the plasma through a hierarchy of interconnected scales rather than as isolated entities with a single characteristic size (C. Y. Tu & E. Marsch 1995; H. Isliker et al. 2019). Three-dimensional MHD simulations further show that both current and vorticity structures follow clear scaling laws in their spatial distributions, supporting the view that the topology of coherent structures is fundamentally fractal and self-similar over a wide range of scales (V. M. Uritsky et al. 2010).

V. Zhdankin et al. (2013) analyzed fully developed MHD turbulence and provided a statistical characterization of the current sheets that arise spontaneously in their simulations. Their main result is that the characteristic properties of

these structures follow powerlaw distributions. This is important because it shows that, in addition to the wave-like fluctuations cascading toward smaller scales, coherent structures in turbulent MHD also exhibit robust scale-free behavior (see Fig. 4).

It should also be emphasized that, in strongly turbulent regimes, coherent structures may arise either through the fragmentation of a large-scale current sheet (M. Onofri et al. 2006; F. Guo et al. 2021; Y. Wang et al. 2025) (see Fig. 5(Left)) or through the development of turbulence in the vicinity of a shock (see Fig. 6) (Y. Matsumoto et al. 2015; D. Caprioli & A. Spitkovsky 2014). The corresponding energy spectra that characterize this turbulent state are likewise shown in Fig. 5 (Right).

We may therefore conclude that many nonlinear plasma configurations long

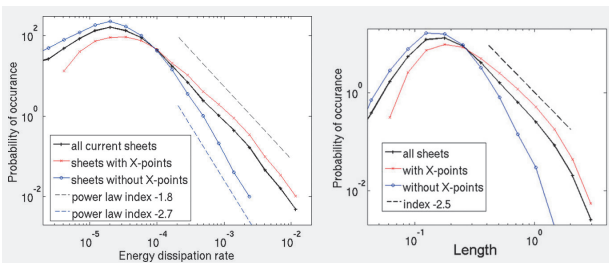


Figure 4: (Left) Probability distribution of the Ohmic energy dissipation rate in current sheets. The distribution for the full ensemble of current sheets (black) displays a power-law tail with an index of roughly -1.8 . Also shown are the distributions for two subsets of current sheets: those containing X-points (red) and those without X-points (blue), the latter exhibiting a power-law index of approximately -2.7 . (Right) Probability distributions for all geometric scales of the current sheets. For the full set of current sheets (black), the distributions of the length ℓ and width ξ display power-law tails with exponents close to -2.5 (V. Zhdankin et al. 2013).

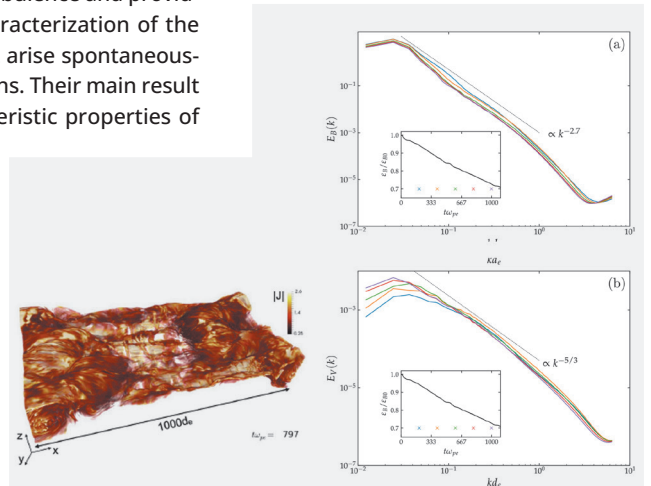


Figure 5: (Left) Turbulence generated by the fragmentation of a large-scale current sheet. (Right) Magnetic and kinetic energy spectra as functions of wavenumber at several times. The insets also show the temporal evolution of the system's total magnetic energy. For scales larger than the kinetic scale, the magnetic energy spectra follow an approximate power law with a slope of about -2.7 , whereas the kinetic energy spectra are generally consistent with a $-5/3$ slope (F. Guo et al. 2021).

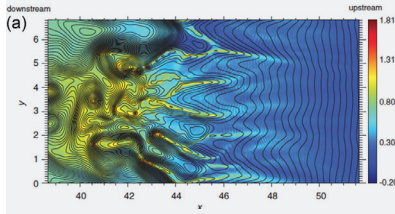


Figure 6: As time progresses, the evolution of a shock formed near the center of a turbulent medium produces an environment that becomes strongly turbulent (Y. Matsumoto et al. 2015).

suggested as sites of particle energization—such as large-scale current sheet or turbulent shocks—can, within only a few Alfvén times, transform into a similar multiscale environment filled with numerous coherent structures that exhibit characteristic power-law statistics.

From the analysis presented in this section, several conclusions can be drawn:

- A defining property of strongly turbulent MHD flows is the spontaneous formation of coherent structures with characteristic power-law statistics.
- In regimes where the fluid pressure greatly exceeds the magnetic pressure, these structures largely resemble those found in conventional hydrodynamic turbulence.
- By contrast, when magnetic pressure dominates, coherent structures acquire distinct properties, and the emergence of current filaments, together with their mutual interactions, becomes a principal process shaping the evolution of the cascade.

4. SELECTED LABORATORY, SPACE, AND ASTROPHYSICAL ENVIRONMENTS

In laboratory, heliospheric, magnetospheric, and astrophysical settings, turbulence can be driven by a wide variety of physical processes—including pressure gradients, convection, shear, shocks, magnetic buoyancy, rotation, and gravity—yet it often evolves toward a qualitatively similar state: a multiscale, intermittent regime populated by coherent structures. The examples discussed below are therefore not intended to be exhaustive. Rather, they are selected to illustrate characteristic environments in which the progression from turbulent driving to structure formation is especially transparent.

4.1. Laboratory plasmas: edge turbulence in tokamaks

In tokamaks, edge turbulence arises naturally from the strong density, temperature, and pressure gradients that form near the separatrix and across the scrape-off layer. In this boundary region, the combined influence of unfavorable magnetic curvature, finite collisionality, and parallel losses along open field lines destabilizes the plasma through drift-wave, interchange, and ballooning-like modes. Nonlinear coupling among these instabilities, mediated by fluctuating $\mathbf{E} \times \mathbf{B}$ advection, generates broadband turbulence, intermittent cross-field transport, and filamentary coherent structures commonly known as blobs (Fig. 7).

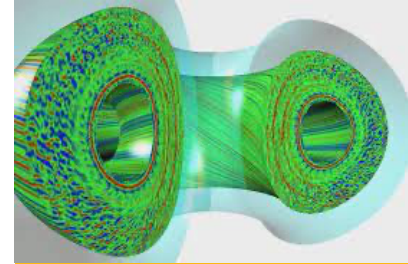


Figure 7: Visualization of microturbulence data generated by the Gyrokinetic Toroidal Code (GTC) (Princeton Plasma Physics Laboratory 2005).

4.2. MHD turbulence in the heliosphere

Solar convection zone.—The solar convection zone is a strongly stratified and highly turbulent region in which convective motions over a broad range of scales continuously stretch, shear, fragment, and amplify magnetic fields. Differential rotation, together with dynamo action, generates large-scale toroidal magnetic configurations, some of which become buoyantly unstable and reorganize into coherent magnetic flux tubes (Fig. 8). The subsequent ascent of these tubes is shaped by turbulent buffeting, drag, rotation, and magnetic twist (Fig. 9Left); taken together, these effects determine whether the tubes preserve their coherence and ultimately emerge at the solar surface as active regions. Turbulence in the convection zone thus plays a dual role: it generates magnetic intermittency while also allowing selected magnetic structures to survive as rising, organized flux systems.

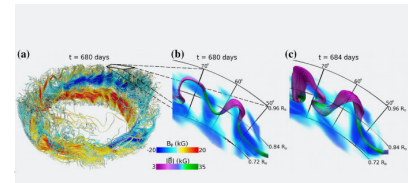


Figure 8: Within the convection zone, turbulent motions generate organized magnetic structures known as flux tubes, which rise toward the solar surface and eventually form active regions in the solar atmosphere (Y. Fan 2009).

Solar atmosphere. —The solar atmosphere, extending from the photosphere to the corona, behaves as a continuously driven magnetized system in which footpoint motions, emerging magnetic flux, propagating waves, and reconnection events inject fluctuations over a wide range of spatial and temporal scales (Fig. 9Right). As these perturbations propagate upward into layers where the density decreases sharply and the magnetic field becomes increasingly structured, partial wave reflection and non-linear interactions promote Alfvénic turbulence, while field-line braiding and current-sheet formation localize dissipation in space and time (Fig. 9Right).

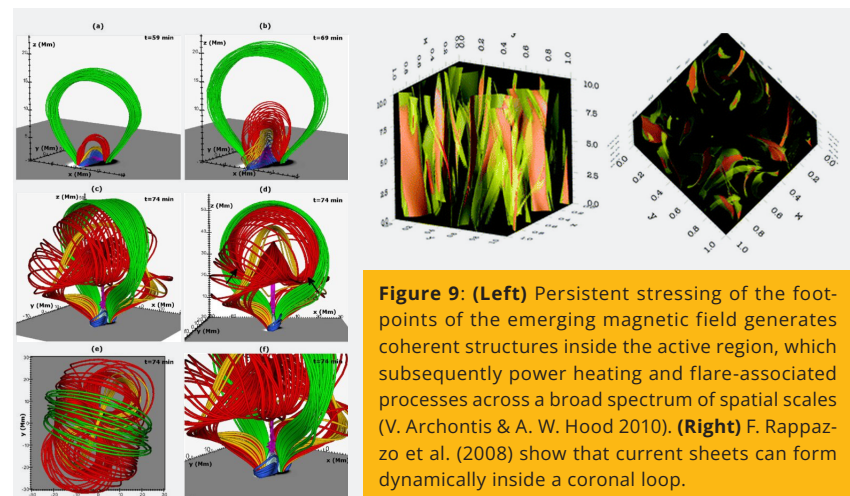


Figure 9: (Left) Persistent stressing of the footpoints of the emerging magnetic field generates coherent structures inside the active region, which subsequently power heating and flare-associated processes across a broad spectrum of spatial scales (V. Archontis & A. W. Hood 2010). **(Right)** F. Rappazzo et al. (2008) show that current sheets can form dynamically inside a coronal loop.

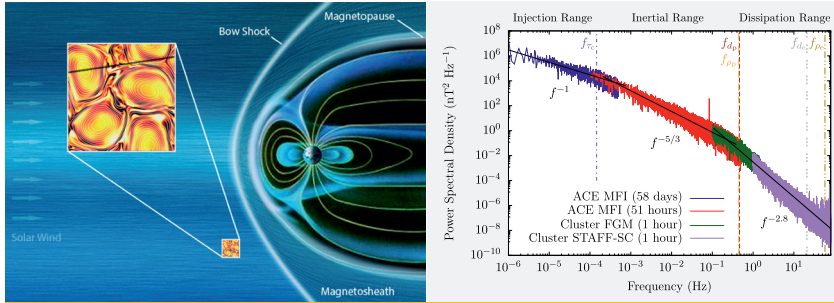


Figure 10: (Left) Turbulence in the solar wind. **(Right)** Power spectral density of magnetic field fluctuations in the solar wind. The black lines show power-law fits with slopes of -1 , $-5/3$, and -2.8 , corresponding to the injection, inertial, and dissipation ranges, respectively (D. Verscharen et al. 2019).

Solar wind. —The solar wind provides the most accessible natural laboratory for the study of MHD turbulence, carrying from the Sun a broad spectrum of fluctuations that evolve as the flow expands through interplanetary space. On large scales, especially within high-speed streams, these fluctuations are often strongly Alfvénic.

With increasing heliocentric distance, however, they develop stronger anisotropy and intermittency, accompanied by a cascade that transfers energy down to ion and electron kinetic scales (Fig. 10). Closer to the Sun, reflection-driven interactions between outward- and inward-propagating Alfvénic wave packets are thought to be particularly important, linking coronal dynamics to solar-wind heating and acceleration, as well as to the formation of coherent structures such as current sheets and flux ropes.

Bow shock and magnetosheath. —At Earth's bow shock, the supersonic solar wind is abruptly slowed, compressed, and heated, creating a downstream magnetosheath filled with waves, discontinuities, and turbulent fluctuations. Rather than simply transmitting upstream turbulence unchanged, the shock transforms it through compression, unstable particle distributions, temperature anisotropies, and localized flow patterns, producing a highly intermittent plasma environment in which coherent structures and localized dissipation are widespread (Fig. 11). The magnetosheath therefore serves as an especially important transition region, linking large-scale shock-driven processes to reconnection, heating, and kinetic-scale dissipation.

Earth's magnetotail. —Earth's magnetotail is a driven and highly dynamic plasma environment in which energy supplied by the solar wind is first stored

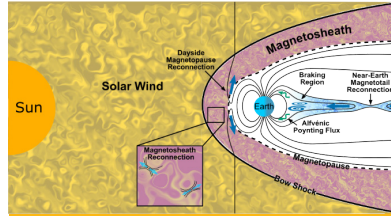


Figure 11: Diagram illustrating turbulent regions in near-Earth space together with the locations of large-scale reconnection events across the system. Turbulence can both interact with these global reconnection processes and generate additional, smaller-scale reconnection events within the turbulent areas (J. E. Stawarz et al. 2024).

in elongated magnetic field lines and later released explosively through reconnection, bursty bulk flows, and current-sheet disruptions. These processes generate multiscale fluctuations in the magnetic field and plasma velocity within the plasma sheet, where vortical motions, filamentary current systems, and intermittent reconnection jets naturally produce a turbulent MHD state. The magnetotail is therefore not only a site of global magnetic reconfiguration, but also a region where turbulence, coherent structures, and reconnection are tightly interconnected.

4.3. Selected astrophysical systems

Star formation. —Star formation occurs within cold, magnetized molecular clouds, whose evolution is governed by highly compressible, often supersonic turbulence.

On large scales, this turbulence can oppose or reshape gravitational collapse, whereas on smaller scales it generates shocks, converging flows, and filamentary networks that lead to the formation of prestellar cores. Turbulence is therefore not a secondary complication superimposed on gravity, but a central process regulating fragmentation, star-

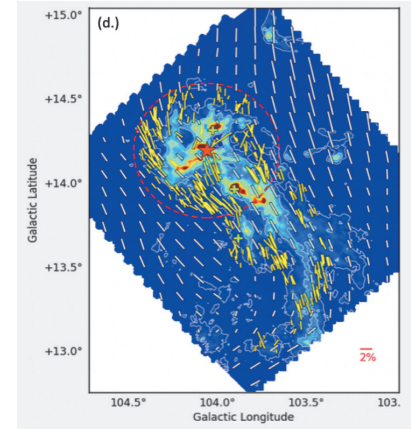


Figure 12: Magnetic-field structure in the bright-rim cloud complex L1172/1174. The background image traces the morphology of the cloud, while the short line segments indicate the projected magnetic-field orientation inferred from polarimetric measurements. The field exhibits a coherent, large-scale configuration, with localized bends and irregularities in denser regions, suggesting an interaction between the cloud structure, compressive processes, and magnetic-field topology during star formation (A. Soam et al. 2024).

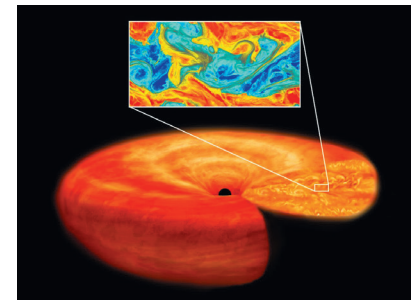


Figure 13: Artistic image of accretion disk turbulence. The inset is the magnetic field fluctuations computed by the simulation of Kawazura et al., *Science Advances*, 2024.

formation efficiency, and the spatial clustering of young stellar populations (see Fig. 12).

Accretion disks and the vicinity of black holes. — Accretion disks around compact objects are intrinsically turbulent because microscopic viscosity alone is far too weak to account for the outward transport of angular momentum required for accretion.

In sufficiently ionized disks, even relatively weak magnetic fields destabilize the shear flow through the magnetorotational instability, rapidly producing MHD turbulence that taps the free energy of orbital motion and converts it into stresses, dissipation, and enhanced accretion. In the vicinity of black holes, this turbulent plasma also interacts with

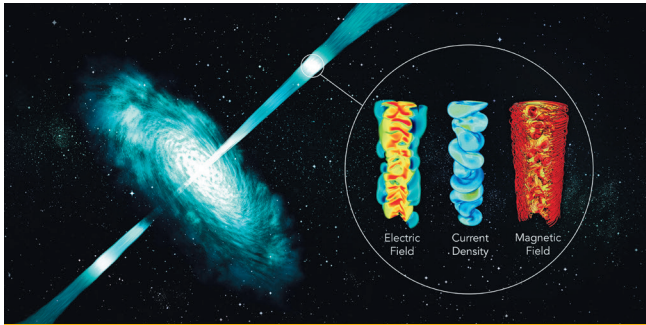


Figure 14: Artist's illustration of an astrophysical jet, with an inset displaying the jet's internal electromagnetic structure. The presence of irregular electric fields, localized current filaments, and a twisted (helical) magnetic field configuration indicates that relativistic jets provide favorable conditions for magnetic-energy dissipation, turbulent energy transport, and the acceleration of non-thermal particles (E. P. Alves et al. 2018).

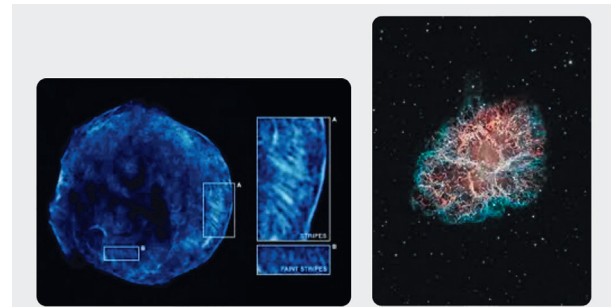


Figure 15: (Left) Young supernova remnant displaying narrow striped patterns and filamentary structures associated with turbulence driven by shocks and amplified magnetic fields. (NASA/CXC/Rutgers/K. Erikson) **(Right)** Supernova remnant showing an intricate network of luminous filaments formed by the nonlinear interaction between the outward-moving shock front and the surrounding plasma. These structures highlight the intermittent character of supernova remnants and their role as natural laboratories for the study of particle acceleration. (NASA, ESA and Allison Loll/Jeff Hester (Arizona State University))

large-scale magnetic fields, coupling the internal disk dynamics to the launching of relativistic jets and the production of high-energy emission. Turbulence in accretion flows is therefore more than a transport mechanism; it is a central process linking disk structure, variability, magnetic-energy release, and outflow formation (See Fig. 13).

Astrophysical jets.—Astrophysical jets, spanning systems from young stellar objects to active galactic nuclei and gamma-ray bursts, are highly collimated outflows whose evolution is strongly influenced by magnetized turbulence. After their launch, these jets propagate through stratified and inhomogeneous environments where shear, entrainment, current-driven instabilities, and internal shocks produce multiscale structure and turbulent mixing. This turbulence influences both jet stability and radiative output by enhancing magnetic dissipation, driving particle acceleration, and mediating the interaction with the surrounding medium. It is therefore essential not only for the persistence and collimation of jets, but also for their efficiency as sources of non-thermal radiation (see Fig. 14).

Supernova remnants.—When a massive star ends its life in a supernova explosion, the blast wave drives an expanding remnant whose strong shocks sweep through the surrounding medium, creating a turbulent, magnetized shell (see Fig. 15Left). Turbulence develops both upstream and downstream of the shock, driven by shock corrugation, fluid instabilities, and the amplification of magnetic irreg-

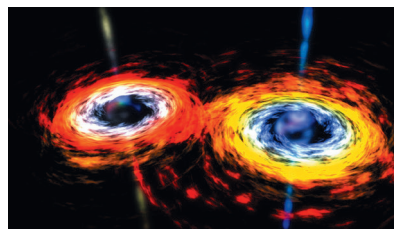


Figure 16: Artist's illustration of a pair of black holes in orbit, surrounded by bright accretion flows. Gas orbiting each compact object forms hot, chaotic accretion disks, while part of the infalling plasma is ejected as narrow relativistic jets aligned with the spin axes. These systems provide an extreme setting for angular-momentum transport, magnetic-energy dissipation, and the acceleration of high-energy particles. (NASA, D. Berry and M. McClare)

ularities by cosmic rays. The result is a highly inhomogeneous and intermittent environment, widely regarded as one of the primary sites of Galactic cosmic-ray acceleration (see Fig. 15Right). Supernova remnants therefore provide a particularly clear example of how shocks, turbulence, and magnetic-field amplification work together to convert explosion energy into heat, radiation, and non-thermal particles.

Black-hole mergers and multimessenger environments.—Mergers of compact objects have opened the era of multimessenger astronomy by connecting gravitational-wave detections with the electromagnetic response of the surrounding plasma and magnetic fields.

In gas-rich environments, turbulence in circumbinary material, remnant accretion disks, or magnetized plasma following the merger can regulate angular-momentum transport, magnetic-field am-

plification, energy dissipation, and the possible formation of transient jets. Although these environments remain less well characterized than the cases discussed above, they may be especially important because the presence and nature of turbulence could determine whether a given merger is observed solely through gravitational waves or also through an electromagnetic counterpart (see Fig. 16).

Although the systems discussed in this section are driven by very different physical mechanisms, they display a common phenomenology: turbulence generates multiscale coherent structures that regulate transport, dissipation, and, in many cases, particle energization. The recurrence of this behavior in laboratory, heliospheric, magnetospheric, and astrophysical plasmas supports the view that strong turbulence is ubiquitous in the universe and should be regarded as a dynamical state that naturally gives rise to structure.

5. TURBULENCE-INDUCED COHERENT STRUCTURES AS PARTICLE ACCELERATORS

In strongly turbulent media, charged particles interact continuously with multiscale electromagnetic fluctuations as well as with coherent structures generated by the turbulent cascade, such as current sheets, vortices, shocks, contracting magnetic islands, and localized reconnection regions (E. Fermi 1949, 1954; H. Isliker et al. 2017; M. Lemoine 2021).

These interactions collectively produce a combination of stochastic energization, systematic acceleration, particle trapping and escape, and complex transport in both configuration and energy space (B. Teaca et al. 2014; H. Isliker et al. 2017; M. Lemoine 2021; O. Pezzi et al. 2022).

5.1. Cosmic rays and non-thermal particles in the heliosphere

Cosmic rays constitute the non-thermal component of astrophysical plasmas and provide one of the clearest indications that efficient particle acceleration operates far from thermal equilibrium. Their nearly ubiquitous power-law energy spectrum points to robust acceleration processes active across a wide variety of cosmic environments, while the almost isotropic flux measured at Earth reflects the dominant role of magnetic scattering during propagation through interstellar and heliospheric magnetic fields. At the same time, small but measurable deviations from isotropy persist, especially at the highest energies, indicating that acceleration and transport remain closely coupled (see Fig. 17). Supernova-remnant shocks are still widely regarded as the primary mechanism responsible for producing Galactic cosmic rays up to at least the knee (A. M. Hillas 2005; K. M. Schure et al. 2012). Yet cosmic rays are far more than passive tracers of explosive activity. Through

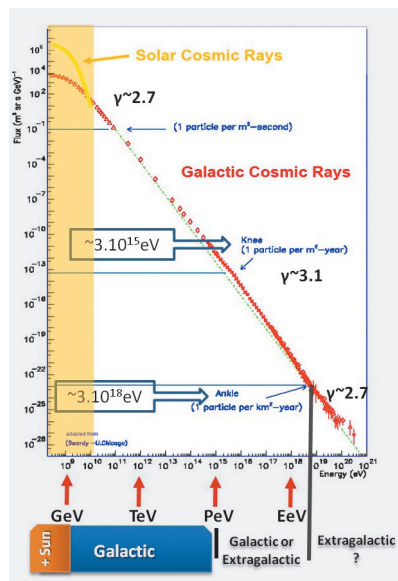


Figure 17: Measured all-particle cosmic-ray energy spectrum, highlighting the solar contribution at low energies and the principal spectral features of the Galactic and extragalactic components, in particular the knee at about 3×10^{15} eV and the ankle near 3×10^{18} eV (P. D. Group 2024).

pressure feedback, ionization, plasma heating, and the conditions under which they are produced, they actively modify the dynamics of their surroundings. They therefore represent a major channel through which turbulent and explosive plasma flows transfer and redistribute energy over a broad range of scales. The heliosphere provides a particularly instructive example of this broader picture. In the low corona, impulsive magnetic-energy release, magnetic reconnection, and turbulent dissipation accelerate both electrons and ions, while CME-driven shocks produce gradual solar energetic-particle events (see Fig. 18Left). As the solar wind expands outward, additional energization occurs through wave-particle interactions, turbulent scattering, magnetic islands, and reconnection within heliospheric current sheets and stream-interaction regions. Taken together, these processes sustain suprathermal particle populations and supply seed particles for subsequent shock acceleration (D. V.

Reames 1999; L. Vlahos et al. 2019; T. D. Phan et al. 2022). Particle energization at the Sun and throughout the solar wind should therefore be viewed as a tightly coupled multiscale process linking coronal dynamics, turbulence, reconnection, and shocks (see Fig. 18Right).

The broader conclusion is that particle heating and non-thermal acceleration in the heliosphere are not distinct phenomena, but different manifestations of the same turbulent hierarchy that also characterizes many of the energetic systems discussed earlier.

5.2. From Fermi acceleration to coherent-structure acceleration

The modern discussion of particle acceleration begins with Fermi's seminal proposal that repeated interactions between fast particles and moving magnetic irregularities can produce net energization (E. Fermi 1949). In its original form, this stochastic process is second-order in the ratio V/c , where V is the speed of the scattering centers, and is therefore relatively

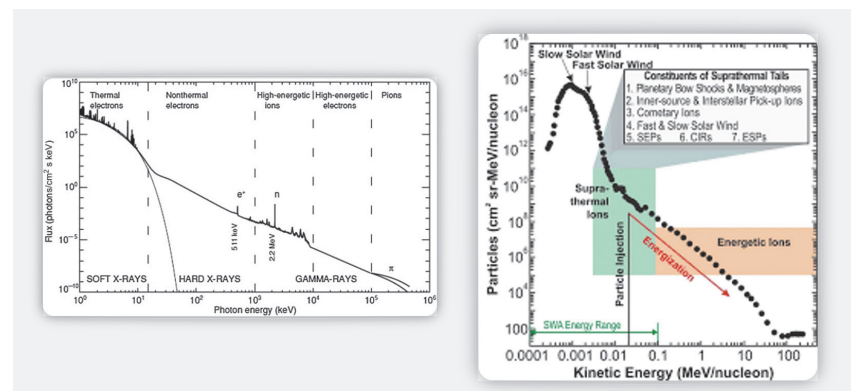


Figure 18: (Left) Broadband photon spectrum of a major solar flare, showing the transition from thermal soft X-ray emission to non-thermal hard X-rays and gamma rays produced by accelerated electrons and ions, as well as by nuclear interactions and pion decay (R. P. Lin et al. 2003). (Right) Energy spectrum of heliospheric ions extending from the solar-wind peak through the suprathermal tail into the energetic-particle regime. The shaded transition region marks the injection window, where seed particles are supplied for further acceleration by shocks and turbulent structures in the heliosphere (R. A. Mewaldt et al. 2001).

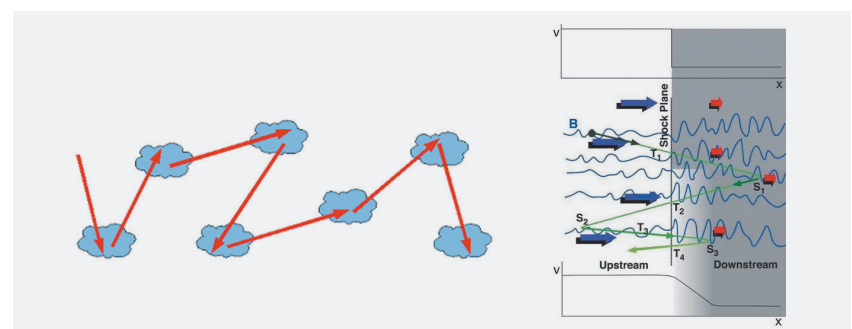


Figure 19: (Left) Stochastic (second-order) Fermi acceleration results from random interactions with moving magnetic irregularities or scattering centers. (Right) First-order Fermi acceleration occurs at a shock front, where repeated crossings produce a systematic increase in particle energy.

inefficient (see Fig. 19Left). Fermi soon recognized that converging flows, and especially shock fronts, provide a much more efficient first-order mechanism (E. Fermi 1954) (see Fig. 19Right). This insight led to the theory of diffusive shock acceleration, which remains one of the corner-stones of high-energy astrophysics (M. S. Longair 2011).

Several years after Fermi first introduced these ideas, reconnecting current sheets were identified as another fundamental and persistently active acceleration site, especially in heliospheric and magnetospheric environments, where they were associated with solar flares and Earth's magnetotail (C. de Jager 1986; Y. E. Litvinenko & B. V. Somov 1993; Y. E. Litvinenko & I. J. D. Craig 1996; Y. E. Litvinenko 1996) (see Fig. 20). Stochastic Fermi acceleration, shock acceleration, and acceleration in reconnecting current sheets have therefore come to be regarded as the standard mechanisms responsible for producing non-thermal particles in space and astrophysical plasmas.

The perspective adopted here does not replace these mechanisms. Rather, it embeds them within a broader turbulent framework. In strongly turbulent plasmas, different coherent structures coexist and interact with particles along their trajectories. Since Ohm's law is

$$\mathbf{E} = -\frac{\mathbf{u} \times \mathbf{B}}{c} + \eta \mathbf{J}, \quad (10)$$

the fluctuating velocity field naturally produces stochastic energization through the $-\mathbf{u} \times \mathbf{B}/c$ term, while intense localized current structures generate coherent electric-field components through $\eta \mathbf{J}$ that are responsible for first-order acceleration (see H. Isliker & L. Vlahos (2025); M. Lemoine (2025) for details). Strong turbulence therefore couples heating and acceleration in a persistent way, naturally producing particle distributions with a heated core and a suprathermal or non-thermal tail (Kappa distribution).

5.3. MHD turbulence and test particles

A widely used approach evolves the turbulent plasma using the MHD equations and then follows charged particles as test particles in the resulting electromagnetic fields (M. Onofri et al. 2006; R. Turkmani et al. 2005; H. Isliker et al. 2019; B. Teaca et al. 2014; M. Lemoine 2021). In this framework, particle

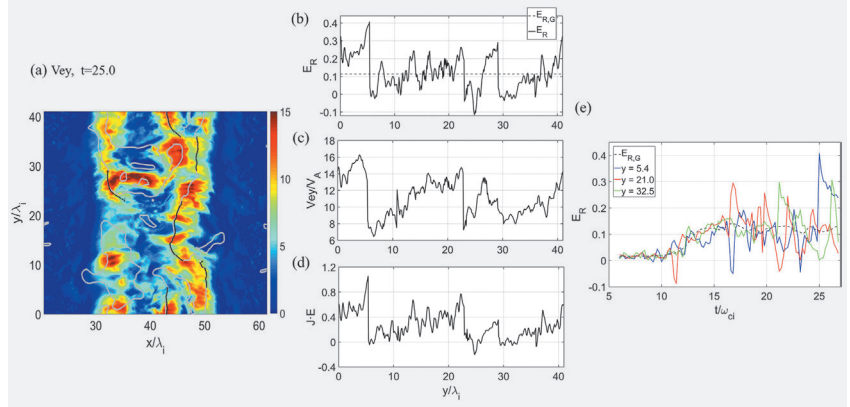


Figure 20: (a) Evolving turbulent current sheet. (b)–(d) Spatial profiles of (b) E_R , (c) V_{ey} , and (d) $J \cdot E$ along the most active x-line, with the dashed curve indicating the global reconnection rate. (e) Temporal evolution of E_R (Y.-N. Liu et al. 2024). Particle motion in the evolving turbulent electric fields leads to heating and acceleration within the current sheet. (Liu et al. 2024)

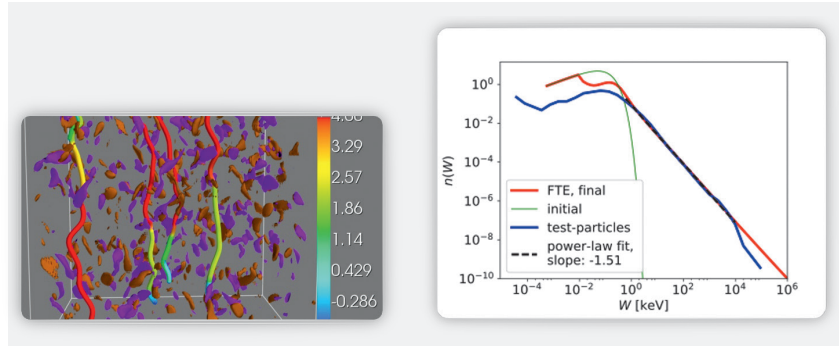


Figure 21: Representative results from test-particle calculations in strongly turbulent electromagnetic fields, illustrating particle transport and energization in an environment dominated by spontaneously emerging coherent structures. (Isliker et al. 2017)

feedback on the fields is neglected, an assumption that remains valid as long as the energy density of the accelerated particles is small compared with the magnetic and bulk-flow energy densities. A particle of charge q and mass m obeys the relativistic Lorentz force,

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}, \quad \frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right), \quad \mathbf{p} = \gamma m \mathbf{v}, \quad (11)$$

with energy evolution

$$\frac{d}{dt}(\gamma mc^2) = q \mathbf{v} \cdot \mathbf{E}. \quad (12)$$

Equation (12) makes the central point explicit: a particle's energy can change only through the electric field. The magnetic field redirects particle motion, controls trapping and confinement, and organizes transport, but it does not itself do work.

In ideal MHD, the electric field in the fluid frame is perpendicular to the magnetic field. Particles can nevertheless be energized through drifts in strongly non-uniform fields, as well as through compressive and time-dependent processes and the contraction of flux ropes, where

strong inductive electric fields arise (M. Lemoine 2023). Test-particle simulations are therefore especially useful because they retain the multiscale structure and intermittency of turbulent MHD fields while allowing direct examination of particle orbits, trapping, escape, and energy change.

H. Isliker et al. (2017) analyzed particle transport in strongly developed turbulence, where the random spatial distribution of spontaneously emerging coherent structures dominates the energy gain (Fig. 21).

At the ensemble level, the particle distribution function is often described by a Fokker–Planck equation,

$$\frac{\partial P(W, t)}{\partial t} = -\frac{\partial [F(W)P(W, t)]}{\partial W} + \frac{\partial^2 [D(W)P(W, t)]}{\partial W^2} - \frac{P(W, t)}{t_{esc}(W)}, \quad (13)$$

where $F(W)$ and $D(W)$ describe systematic and stochastic energy changes, respectively, and $t_{esc}(W)$ denotes the escape time from a bounded system (R. Schlickeiser 2003). This framework is appropriate when particles undergo many

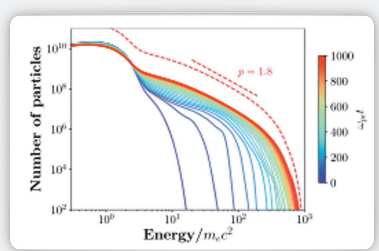


Figure 22: Particle energy spectra at different times during a representative PIC simulation. At late times, the spectrum develops a clear non-thermal tail with a spectral index of $p = 1.8$ F. Guo et al. (2021).

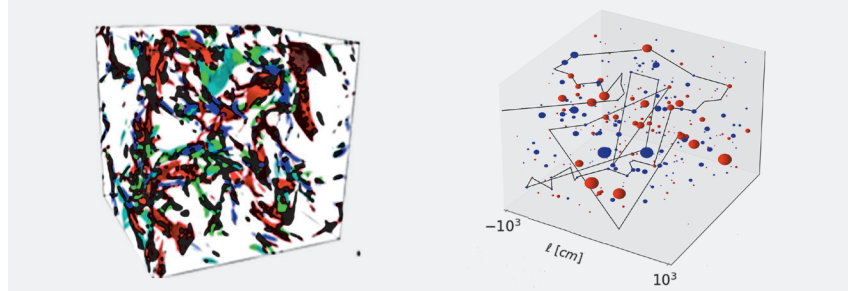


Figure 23: (Left) A range of coherent structures within a three-dimensional turbulent plasma (T. Richard et al. 2022). (Right) Schematic depiction of coherent current structures in a magnified portion of the turbulent region. As particles move through this volume, they interact with these structures in both stochastic and systematic ways (N. Sioulas et al. 2022).

small, weakly correlated interactions. By contrast, in strongly intermittent turbulence, broad distributions of both waiting times and energy increments may emerge—especially when coherent structures control the dynamics—so that conventional diffusive transport may need to be generalized to fractional or event-driven formalisms (H. Isliker & L. Vlahos 2025; F. Effenberger et al. 2025). The strength of the test-particle method lies in its intermediate character. It preserves the multiscale structure of turbulent fields and shows that random scattering and systematic energy gain can operate simultaneously. Its limitation is equally clear: once energetic particles begin to affect the global dynamics appreciably, or when kinetic-scale physics becomes essential, a fully kinetic description is required.

5.4. Particle-in-cell simulations

Particle-in-cell (PIC) simulations provide the fully kinetic framework required in regimes where microscopic plasma processes cannot be neglected (J. M. Dawson 1983; P. L. Pritchett 2003; C. K. Birdsall & A. B. Langdon 1991; R. W. Hockney & J. W. Eastwood 1988). In the PIC method, ions and electrons are represented by computational macro-particles whose trajectories are advanced self-consistently in electromagnetic fields defined on a discrete grid, while those fields are updated through Maxwell's equations using the charge and current carried by the particles. The main advantage of PIC lies in its ability to resolve kinetic phenomena absent from MHD and test-particle approaches: charge separation, plasma oscillations, kinetic instabilities, electron and ion diffusion regions, non-Maxwellian velocity distributions, and the self-consistent feedback of particles on the electromagnetic fields. This is crucial for studies of

particle acceleration and heating because reconnection layers, shock injection, and the most intense dissipation regions are often governed by kinetic-scale physics.

A major practical limitation is the separation of scales. To resolve kinetic physics, a PIC simulation must capture characteristic plasma scales such as the Debye length, the plasma frequency, and the skin depth (P. A. Sturrock 1994). This requirement is computationally demanding for astrophysical systems whose macroscopic dimensions exceed kinetic scales by many orders of magnitude. To alleviate computational difficulties associated with scale separation, PIC simulations often use mass ratios intentionally set below their physical values. PIC, therefore, cannot yet simulate an entire turbulent corona, jet, or magnetotail with a realistic scale hierarchy. It should instead be viewed as a local microscope that reveals the elementary kinetic processes operating inside the dissipative structures produced by larger-scale turbulence.

L. Comisso & L. Sironi (2019) explored strong turbulence and particle acceleration using PIC simulations, and F. Guo et al. (2021) studied the temporal evolution of a reconnecting current sheet (see Fig. 22).

MHD and test-particle approaches indicate where energization regions are expected to appear and characterize how particles move through a turbulent multiscale environment. PIC simulations, in turn, reveal the dynamics within those regions once fluid descriptions become invalid. A complete theory of turbulent particle acceleration must incorporate both perspectives.

5.5. A Network of Scatterers

Coherent structures determine the specific sites where intermittent, event-driven

particle energization takes place. This viewpoint suggests that energization is more naturally described as a sequence of discrete events than as a smooth, continuous diffusion process in a uniform background (see Fig. 23Left). Particles spend most of their time in a relatively quiescent medium and gain the bulk of their energy during brief encounters with current sheets, shocks, flux ropes, or similar structures. When such structures are arranged in a fractal or multi-fractal manner, the resulting distributions of encounter distances, waiting times, and energy increments can naturally produce anomalous transport. N. Sioulas et al. (2022) investigated this scenario in a highly turbulent, unbounded medium by representing coherent structures as a network of scatterers, each endowed with its own stochastic or systematic energization properties. In this framework, the key elements are the statistical distributions of free-path lengths and waiting times, along with the associated random energy increments (see Fig. 23Right). When waiting times are negligible and spatial displacements exhibit fractal characteristics, the particle distribution evolves into a heated core accompanied by a power-law tail (see Fig. 24).

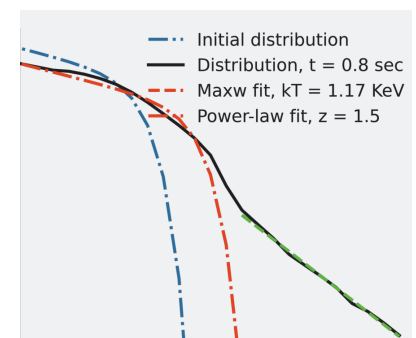


Figure 24: Steady-state kinetic-energy distribution showing the coexistence of a heated Maxwellian-like core and a power-law tail (N. Sioulas et al. 2022).

This is precisely the parameter regime in which reduced statistical descriptions and physics-informed surrogate models may become particularly useful. The aim of future Physics-Informed Neural Network (PINN) strategies is not to replace first-principles plasma physics, but to be guided by MHD and test-particle results while “learning” the effective statistical behavior of energization events, waiting times, acceleration timescales, and escape times. In this way, they provide a promising means of restoring the missing feedback between large-scale turbulence and kinetic particle transport that is not captured by the conventional test-particle approximation.

5.6. Toward reduced models and physics-informed surrogates

One promising direction is the development of physics-informed surrogate models. In this context, the goal of a PINN-based or related framework is not to reproduce the full hierarchy of plasma dynamics through a purely data-driven fit. Rather, it is to infer reduced transport closures from simulation data while remaining consistent with physical constraints. The most appropriate targets are therefore not the full particle distribution function itself, but effective quantities such as systematic and stochastic energization coefficients, escape times, waiting-time distributions, or event-conditioned kernels (neural operators) that characterize particle interactions with coherent structures. The motivation for such reduced models follows directly from the structure-centered picture advanced in this review. In a strongly turbulent plasma, particles do not gain energy uniformly throughout the volume. Instead, they spend much of their time in a comparatively quiet background and receive most of their

energization during short encounters with current sheets, shocks, flux ropes, or other coherent structures. A useful coarse-grained description should therefore focus on the statistics of discrete energization events rather than assume spatially smooth diffusion from the outset.

A practical strategy would thus be to combine MHD simulations and test-particle calculations within an event-resolved framework. The MHD simulation provides the evolving electromagnetic fields together with a catalog of coherent structures. Test-particle trajectories then supply information on where and when particles encounter these structures, how long they remain trapped, and how much energy they gain or lose during each interaction. From these data, one may infer the distributions of energy increments, waiting times, and free-path lengths, as well as the distributions of acceleration and escape times in a finite turbulent domain. Within this setting, physics-informed surrogates may serve as reduced-closure models. Their role would be to learn, from simulation data and explicit transport constraints, which effective description is appropriate under given conditions: a standard diffusive closure, a fractional transport model, or a more general event-based statistical description. This should still be viewed as a developing strategy rather than an established predictive framework. Its usefulness will depend critically on the quality of the structure diagnostics, the definition of the events, and the physical constraints built into the surrogate. The value of such an approach, if successful, would be modest but important. It could provide a principled way to connect large-scale turbulence, coherent-structure statistics, and reduced kinetic

transport without requiring a fully kinetic simulation of the entire astrophysical system. In that sense, physics-informed surrogates may eventually provide part of the missing bridge between multi-scale MHD turbulence and non-thermal particle evolution.

6. SUMMARY

This article puts forward a proposition: strong MHD turbulence constitutes a dynamical state that generates structure. In this picture, plasma heating, suprathermal tails, and non-thermal particle acceleration emerge naturally and self-consistently. MHD turbulence is thus not just compatible with cosmic particle acceleration—it provides one of its most natural environments.

A particularly important implication of the coherent-structure-based picture advanced here is that it may unify two of nature’s most striking scale-free laws: the Kolmogorov spectrum of turbulence and the power-law energy distributions of high-energy particles and cosmic rays.

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The Multiple Pathways of Neutron Star Magnetic Field Evolution

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Abstract

Neutron stars host some of the strongest magnetic fields in the Universe. Without their magnetic fields, neutron stars would have been significantly dimmer, observable only due to cooling and would have lacked most non-thermal emission mechanisms. Their magnetic fields mediate radiative processes by accelerating charges and producing radio and high-energy emission in the magnetosphere. In their interior, magnetic field decay provides the essential reservoir for thermal radiation via Ohmic heating, while in strongly magnetised sources, the magnetic field is sufficiently strong to make the crust yield and twist the magnetospheric field, releasing large amounts of energy in the form of bursts and flares. Magnetic field decay and generation of Ohmic heating, crust yielding and magnetospheric twist, indicate that the magnetic field is in a dynamically evolving state. The lack of a long-lived convective zone inside the neutron star requires that mechanisms other than the well-known dynamo are responsible for magnetic field evolution. Here, I will discuss magnetic field evolution processes that take place in a neutron star after its formation, focusing on their crusts where the magnetic field evolves primarily due to the Hall effect and Ohmic decay and the core where ambipolar diffusion and superconductivity operate. Particular focus will be given on effects that modify the standard evolution, such as plastic flows and crust-core coupled evolution. Finally, the impact of magnetic field evolution on the observable properties of neutron stars, their outbursting and flaring activity, their evolution across the $P-\dot{P}$ diagram and the quiescent emission of magnetars will be discussed.

1. Introduction

Neutron stars are the outcome of stellar evolution of stars whose masses are in the range of $8-25M_{\odot}$, though the exact details depend on rotation, metallicity and mass loss during stellar evolution [1]. They form during a supernova explosion, when the core of a massive star collapses into a proto-neutron star which then cools and deleptonises into a neutron star within about a minute. In the regions where the density exceeds $4 \times 10^{11} \text{ g cm}^{-3}$, neutrons drip out of the atomic nuclei, however, they do not undergo β -decay because they are in β equilibrium with the surrounding matter and are stabilized by degeneracy effects. Neutron star masses are typically $1.4M_{\odot}$ with observed values up to $\sim 2.1M_{\odot}$ [2] while their radii are approximately $10-13 \text{ km}$ [3]. Thus, their average densities are of the order of the nuclear saturation density $2.8 \times 10^{14} \text{ g cm}^{-3}$ [4] and there are regions where this density is even exceeded.

The existence of neutron stars was proposed shortly after the discovery of neutron by Chadwick in 1932 [5] by Baade and Zwicky and were linked to supernovae [6]. The basic properties of their equilibrium structure were worked out by Tolman, Oppenheimer and Volkoff [7, 8] who solved for the hydrostatic equilibrium in general relativity for dense matter. However, their observational confirmation remained elusive until 1967 when the first neutron star was observed as a pulsating radio source (pulsar) by Bell and Hewish [9] and was later identified as a rapidly rotating, magnetised neutron star. As of now, more than 4300 neutron stars have been discovered [10], with the vast majority being bright in the radio part of the electromagnetic spectrum, being rotation-powered radio pulsars.

The combined effect of rotation and magnetism leads to the acceleration of charges which are responsible for coherent radio emission [11]. Moreover,

the observation of a positive period derivative, demonstrating that the rotation becomes slower, provides an order of magnitude estimate for the magnetic field strength, by attributing the entire decrease of the kinetic energy to magnetic dipole emission [12, 13], through the following expression:

$$B_{dip} = 3.2 \times 10^{19} (P \dot{P})^{1/2} \text{ G}, \quad (1)$$

where B_{dip} is the magnetic dipole field, P is the neutron star period measured in seconds and $\dot{P}$ is the neutron star period derivative. Similarly, the lengthening of the period due to spin-down provides an estimate of the pulsar age through the characteristic age:

$$\tau_c = \frac{P}{2\dot{P}}. \quad (2)$$

The presence of a strong magnetic field and rapid rotation came to no surprise, as mere conservation of a fraction of the magnetic flux and angular momentum of the progenitor star leads to a rapidly rotating object due to its small radius. Moreover, differential rotation and dynamo action during the proto-neutron star phase may amplify the seed magnetic field [14, 15]. Measurements of period and period derivative show different trends in the observational manifestations of neutron stars in the $P-\dot{P}$ diagram, Figure 1. This diversity has motivated a unification effort to relate their properties to their age and evolving magnetic field [16].

Magnetars, originally identified as anomalous X-ray pulsars (AXPs), which are neutron stars whose X-ray emission is higher than their spin-down power, and soft gamma-ray repeaters (SGRs) which are sources exhibiting recurrent bursts in soft gamma-rays, have exceptionally strong magnetic fields [18]. Their magnetic field typically exceeds the Quantum Electrodynamics (QED) limit, or Schwinger limit $4.4 \times 10^{13} \text{ G}$. On the contrary, there are several sources whose magnetic field is in the range of the Schwinger field, yet their behaviour is that of normal pulsars and final-

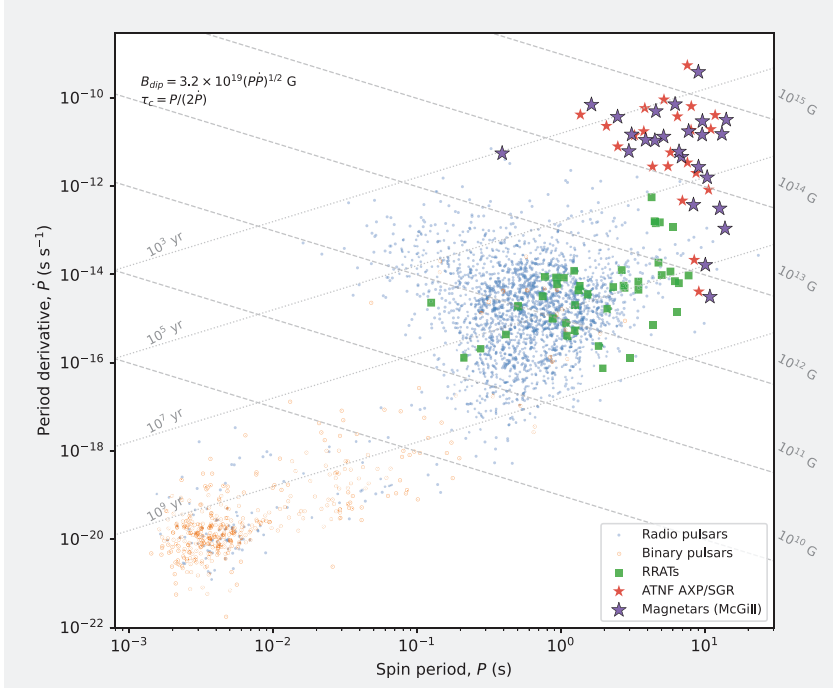


Figure 1: The P - $\dot{P}$ diagram of neutron stars showing pulsar populations and magnetars, with lines of constant magnetic field and characteristic age, data from the ATNF catalogue [10] and McGill magnetar catalogue [17].

ly there are sources transitioning from pulsar to magnetar behaviour and vice-versa. These effects collectively indicate that the magnetic field should undergo an evolutionary process more complex than simple magnetic field decay. Finally, recent observations have revealed magnetic activity in slowly spinning and presumably old sources [19]: such effects may be related to core magnetic field evolution providing magnetic flux from the interior. These results challenge the simple magnetic dipole braking picture with a constant magnetic field, and motivate the study of more complex, evolving magnetic field configurations.

2. Magnetic field evolution

The mechanism driving magnetic field evolution depends on the microphysics of the part of the neutron star we are focusing on and the strength of the magnetic field itself. Moving from the surface to the interior of a neutron star we encounter a thin liquid envelope, also known as the ocean, composed of ions and electrons and a typical depth of a few meters to a few tens of meters depending on the star's temperature. Then, there is the solid crust: its outer part is an ion crystal lattice with an electron fluid, which transitions to the inner crust at neutron drip density ($4 \times 10^{11} \text{ g cm}^{-3}$),

where the neutron fraction increases sharply, while a smaller number of electrons remains present to ensure charge neutrality. The system transitions to the core at approximately the nuclear saturation density $2.8 \times 10^{14} \text{ g cm}^{-3}$. In the core, there are abundant neutrons in superfluid state, a smaller number of protons, possibly superconducting, while more exotic particles could be present especially at the inner core.

2.1 Crustal magnetic field

The abundance of free electrons in the crust allows the electron-MHD approximation, as the mechanical strength of the lattice allows it to maintain its structure. This single fluid approximation, also known as Hall-MHD, can be derived through Ohm's law

$$\mathbf{E} = -\frac{\mathbf{v} \times \mathbf{B}}{c} + \frac{\mathbf{j}}{\sigma},$$

where $\mathbf{E}$ is the electric field, $\mathbf{v}$ the electron velocity, c the speed of light, $\mathbf{j}$ the electric current density and σ the electric conductivity. Next, we relate the fluid velocity to the electric current which is carried entirely by electrons $\mathbf{j} = -en_e \mathbf{v}$, where e is the elementary charge n_e the electron number density. This expression is combined with Ampère's law

$$\mathbf{j} = \frac{c}{4\pi} \nabla \times \mathbf{B}.$$

and eventually leads to the form below for Faraday's law of induction:

$$\frac{\partial \mathbf{B}}{\partial t} = -\frac{c}{4\pi} \nabla \times \left[\frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{en_e} + \frac{c}{\sigma} \nabla \times \mathbf{B} \right]. \quad (3)$$

The above equation details the main magnetic field evolution mechanisms in neutron star crusts [20]. The first term in the right-hand side describes the advection of the magnetic field due to the Hall effect; the second one is the Ohmic decay related to its diffusion. The Hall term dominates for magnetic field strengths of 10^{13} G and above leading to evolution timescales in the order of kyrs, while for weaker fields Ohmic decay is dominant. The Hall term is conservative, and its non-linear form is reminiscent of the vorticity equation that leads to turbulent cascade. The Ohmic term, on the contrary, leads to magnetic field decay and generation of heat. While not directly dissipating magnetic energy into heat, the Hall term accelerates dissipation by the formation of smaller structures through, either instability or cascade [21, 22, 23, 24, 25].

The impact of Hall-MHD evolution in the crustal field has been studied in detail, in the context of magnetar fields [26, 27] and magnetothermal evolution [16]. It has been found that a magnetic field, that would have been stable under the usual MHD requirements (i.e., a twisted torus geometry) suffers instabilities, which then fragment the field of the star into smaller scales generating multipoles, Figure 2, [28, 29]. There, the field is amplified locally, through the redistribution of existing magnetic flux, while the overall magnetic field energy decays. The fragmentation of the field in small regions may power hotspots where electric currents are stronger and dissipate rapidly. As the magnetic field extends beyond the surface of the star and closes in the near magnetosphere, it generates magnetic arcades that are responsible for absorption features that have been observed in magnetars [30] and have provided independent estimates of the magnetic field strength, suggesting that it lies indeed, in the range of $10^{14} - 10^{15} \text{ G}$. These large field strengths arise naturally through Hall-driven instabilities. The characteristic length scale of the instability is comparable to the scale height of the crust which is also similar to that of the hot spot emitting regions in magnetars [31].

The presence of such strong magnetic fields, however, challenges the assumption of an undeformed crust, that was used in the derivation of the Hall-MHD equation (3). Magnetic fields of 10^{14} G at the surface of the crust and above 10^{15} G deeper in, Figure 3, produce stresses that deform the crust beyond its elastic limit. In this case the crust may yield [32, 33] initiating a plastic flow, or leading to localized failure, sometimes modelled as brittle cracking [34]. Both phenomena have been explored within the context of magnetar outburst and flares [35, 36, 37, 38], providing distinct predictions. Plastic flows slow down Hall evolution locally, as the crust ions are displaced so that they annul the magnetic stress. However, as the crust is likely to fail only in regions where deformation is beyond the elastic limit, the rest of the crustal field will continue to evolve under Hall-MHD. Therefore, the combined effect will generate complex and twisted structures, Figure 4.

The interplay between thermal and magnetic field evolution in strongly magnetised neutron stars has important observable implications: magnetars have thermal components which are due to magnetic field decay, thus while the presence of currents and the overall Ohmic losses is a proxy for thermal luminosity and the temperature, a detailed study involving the full magnetothermal cycle is essential. The main effects that involve both the temperature and the magnetic field are the following: Ohmic heat is produced by the magnetic field decay; heat is transported preferably along magnetic field by electrons; changes in temperature affect electric and thermal conductivity and heat capacity; and finally sharp thermal gradients power a thermoelectric electromotive force [39]. These effects have been studied both in axisymmetry and in 3-D providing a unification of the neutron star observational incarnations and the role of the magnetic field [40, 41, 42]. In this context, magnetothermal evolution provides the essential heat required to power neutron star thermal emission and successfully reproduces quiescent magnetar light curves [43].

2.2 Core magnetic field

The state of the core magnetic field requires a deep dive in the behaviour of electromagnetic fields beyond classical electromagnetism. Two main effects have been identified to play a crit-

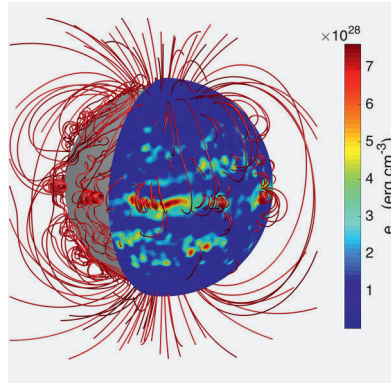


Figure 2: The structure of the magnetic field in the crust of a neutron star after 15 kyr of Hall-MHD evolution. The initial conditions correspond to a sheared dipole with $\ell = 2$ toroidal field. The field lines are plotted in red and the magnetic field energy density is shown in colour. Adapted from [29].

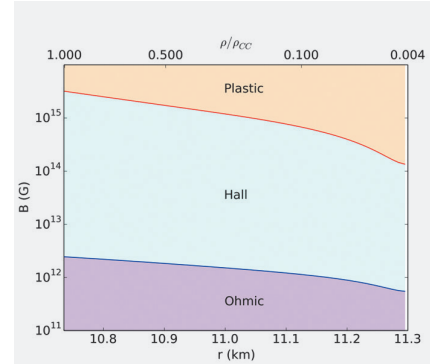


Figure 3: The regions in the parameter space of crust density/depth and magnetic field where the Hall effect, Ohmic dissipation and plastic flow dominate. The density is given in units of the density at the crust-core interface. Adapted from [38].

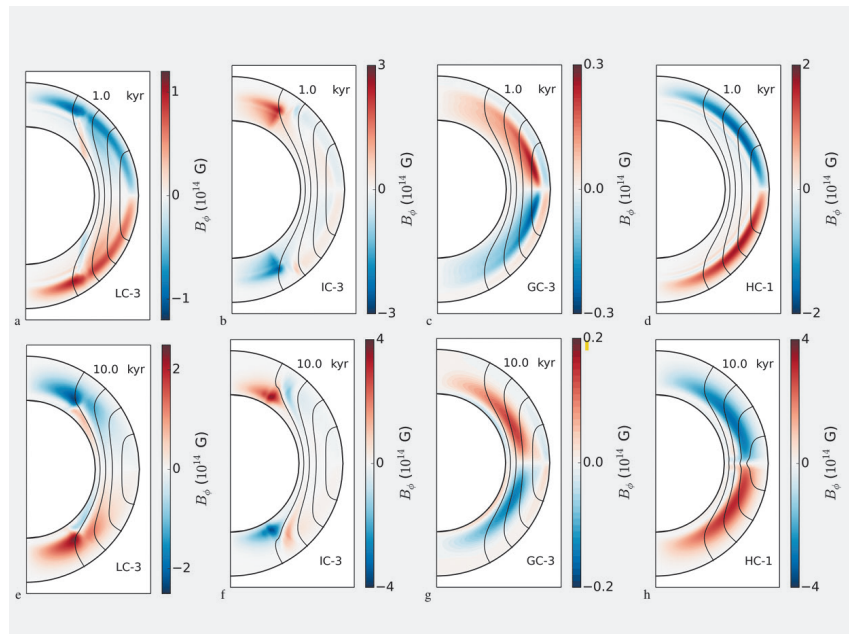


Figure 4: Axisymmetric evolution with plastic flow showing snapshots at 1kyr (top row) and 10kyrs (bottom row) of evolution. The first column (panels a and e) shows the runs where the crust fails and flows plastically only locally, the second column (panels b and f) shows the runs where a larger area is affected by the plastic flow, the third row (panels c and g) shows runs where plastic flow extends to the entire crust and the last column (columns d and h) shows the runs where only the Hall effect operates for comparison. Adapted from [38].

ical role in the magnetic field evolution there: ambipolar diffusion and superconductivity.

Ambipolar diffusion occurs due to the relative motion between the charged components, consisting of protons and electrons, and the abundant neutrons in the core. It is driven by the Lorentz force acting on the charged particles, while collisions with neutrons, mediated primarily by strong nuclear interactions, provide a drag force. In addition, weak interactions act to restore β equi-

librium. Combining these effects, one obtains a modified version of Ohm's law. The ambipolar diffusion term can be derived under a set of simplifying assumptions appropriate for neutron star cores composed of non-superconducting neutron-proton-electron matter [20]. Here, charged particles (protons and electrons) are tightly coupled electromagnetically and are approximated as a single fluid. Neutrons, which constitute the dominant mass component, interact with the charged fluid through

collisional coupling, primarily via proton–neutron scattering, characterized by a drag timescale τ_{pn} . Deviations from beta equilibrium are quantified by the chemical potential imbalance

$$\Delta\mu = \mu_p + \mu_e - \mu_n.$$

Weak interactions act to restore equilibrium with the corresponding timescales depending on the temperature.

Under these assumptions, the magnetic field evolution due to ambipolar diffusion can be written through a magnetic field induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\frac{x_n^2 \tau_{pn}}{m_p^*} \left((\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla(\Delta\mu) \times \mathbf{B} \right) \right], \quad (4)$$

where x_n is the neutron fraction, n_c is the charged particle number density, and m_p^* is the effective proton mass. The chemical potential imbalance $\Delta\mu$ is governed by the interplay between magnetic forces and weak interactions restoring β equilibrium. In this limit, deviations from chemical equilibrium are sustained by the Lorentz force per unit volume,

$$\mathbf{f}_{\text{mag}} = (\nabla \times \mathbf{B}) \times \mathbf{B} / 4\pi,$$

and relaxed by weak interactions characterized by a reaction rate λ . The chemical imbalance then satisfies

$$\Delta^2(\Delta\mu) - \frac{m_p^* \lambda}{x_n^2 n_c \tau_{pn}} \Delta\mu = \nabla \cdot \left(\frac{\mathbf{f}_{\text{mag}}}{n_c} \right). \quad (5)$$

This equation shows that the spatial structure of $\Delta\mu$ is determined by the competition between the Lorentz force and weak interaction processes. In the limit of high temperatures (i.e., $T > 10^9\text{K}$) chemical imbalance is restored rapidly, thus only equation (4) needs to be solved, whereas for cooler cores, which is the case for most older neutron stars, the system of coupled partial differential equations needs to be addressed. The presence of a cubic term on the magnetic field and multiple vector derivatives lead to complex evolutionary patterns. The ambipolar diffusion velocity can be decomposed to a solenoidal and an irrotational component. The solenoidal component evolution is faster and controlled by the drag, whereas the irrotational is slower and balanced by weak interactions.

Numerous computational studies have addressed the question of mag-

netic field evolution under various assumptions. While there is no definite picture for the end point of evolution, ambipolar diffusion tends to reduce Lorentz forces and drive the system toward force balanced configurations [44, 45, 46, 47], while some other works starting from more complex initial conditions tend to relax a twisted torus Grad-Shafranov equilibrium [48]. Finally, if the crustal field is connected to the core, and allowed to evolve simultaneously due to the Hall effect, there is interaction between the two parts of the field disrupting the initial north-south symmetry of the field, as the Hall effect does not preserve the symmetry of the initial magnetic field due to the one-fluid approximation (electrons only) whereas ambipolar diffusion does [49].

The discussion of ambipolar diffusion assumes that the protons are in a normal state; however, the temperatures and densities in neutron star cores favour superconducting protons and superfluid neutrons [50]. Depending on the microphysical assumptions, several approaches have been proposed. In one approach, the fluxtube array is treated as a macroscopic fluid, leading to modified induction equations that resemble ambipolar diffusion but with different transport coefficients [51]. In another more microscopic picture, the evolution is governed by the forces acting on individual fluxtubes, including pinning to neutron vortices and interactions with the surrounding medium [52, 53]. These processes can significantly alter

the timescales and morphology of magnetic field evolution compared to the normal-matter case, generally leading to slower evolution and a stronger coupling between rotational and magnetic dynamics [53].

A critical question is whether superconductivity expels the core magnetic field. In typical terrestrial laboratory conditions, the Meissner effect leads to immediate expulsion of the magnetic flux from type-I superconductors, however the physical dimensions and the intensity of the magnetic field of neutron stars make this assumption questionable. It has been suggested that the timescale for magnetic field expulsion from the core may be in the range of Gyrs [54]. However, results from magnetothermal evolution models are consistent with strong currents concentrated near the base of the crust indicative of magnetic fields that do not penetrate deeply into the core [16, 43]. A resolution to this tension may be related to a partial or even total disconnection of the crustal and the core field. In this case superconductivity initiates from a thin shell located at the outer core. Magnetic flux is then pushed out from this shell, leading to a magnetic field that resides in the core and is substantially disconnected from the external field, while the magnetic field that reaches the crust and the surface of the star extends beyond this shell [55]. Given that strong magnetic fields lead to the collapse of superconductivity, the core and crustal field may be linked through holes, Figure 5.

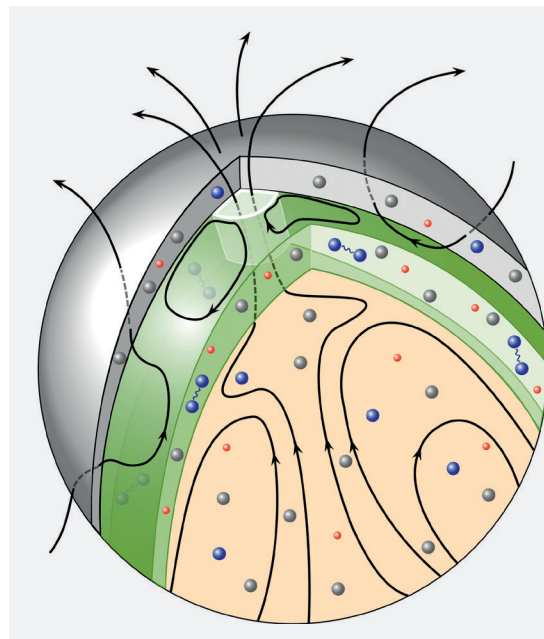


Figure 5: A neutron star cut showing the field disconnection through a superconducting layer (green). Neutron, protons and electrons are depicted as gray, indigo, and red spheres. The external field may be linked to the central through holes shown here in the pole, if the magnetic field expulsion is incomplete. Adapted from [55].

3. Insights from the models

The description of magnetic field evolution in the crusts of neutron stars has enabled us to link observations with theory following the seminal work of Goldreich and Reisenegger who set the framework more than 30 years ago [20]. The first axisymmetric studies identified the key aspects of initial evolution out of equilibrium, magnetic field decay and end points of the magnetic field evolution in the form of the Hall attractor in axisymmetric systems [21, 27, 56, 57]. Once 3-D codes have been developed a new array of features have appeared. Mainly, the interplay between instabilities and cascade has been understood: the former push initially axisymmetric configurations out of equilibrium which then generate smaller scale features [28, 37, 43, 57]. The dominant modes of the instabilities set the length-scale of the features and are affected by the relative strength of the toroidal and poloidal components of the magnetic field, Figure 6, while shorter wavelength features accelerate magnetic field decay [31]. Depending on the initial strength of the magnetic field, the evolutionary tracks of pulsars in the period-period derivative diagram pass through the magnetar or the radio pulsar region, before the magnetic field decay becomes faster than the spin-down rate, thus dropping towards lower $\dot{P}$ while only changing mildly the period, Figure 7.

An additional effect arising from Hall-MHD evolution in the crust is the lack of north-south symmetry of the field: a magnetic field with a twisted-torus geometry will push the toroidal field towards one of the poles. Higher multipoles may have higher curvature and pair creation near the surface, while the dipolar field remains in the radio pulsar range. These multipolar loops have been invoked to explain absorption features in the thermal spectra of magnetars [30] and also to locations where magnetospheric particles are accelerated and bombard the crust: this process provides an alternative model for crustal heating through the exterior and magnetic field untwisting instead of purely internal heating [59]. Finally, there have been recent observational results supporting the idea of crust slippage happening during outburst phases in magnetars. There, the evolution of light curves shows that the peaks evolve

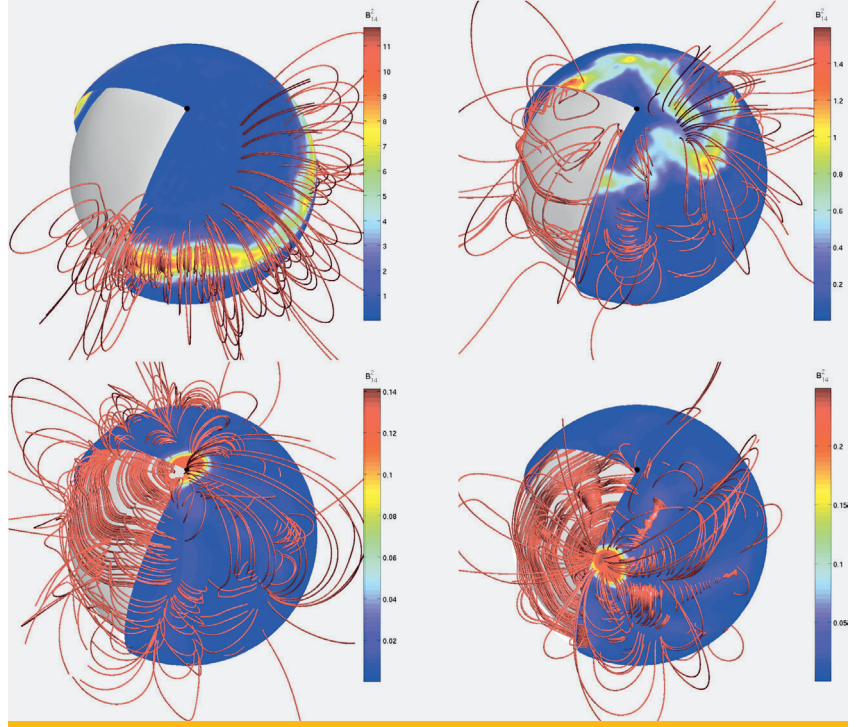


Figure 6: Magnetic field structure following Hall-MHD evolution in the crust with increasing toroidal magnetic field component energy: top left $E_{\text{tor}}/E_{\text{tot}} = 0.5$, top right $E_{\text{tor}}/E_{\text{tot}} = 0.9$, bottom left $E_{\text{tor}}/E_{\text{tot}} = 0.99$, bottom right $E_{\text{tor}}/E_{\text{tot}} = 0.99$ and the axes of the dipole and toroidal field form an angle of 45° . Adapted from [58].

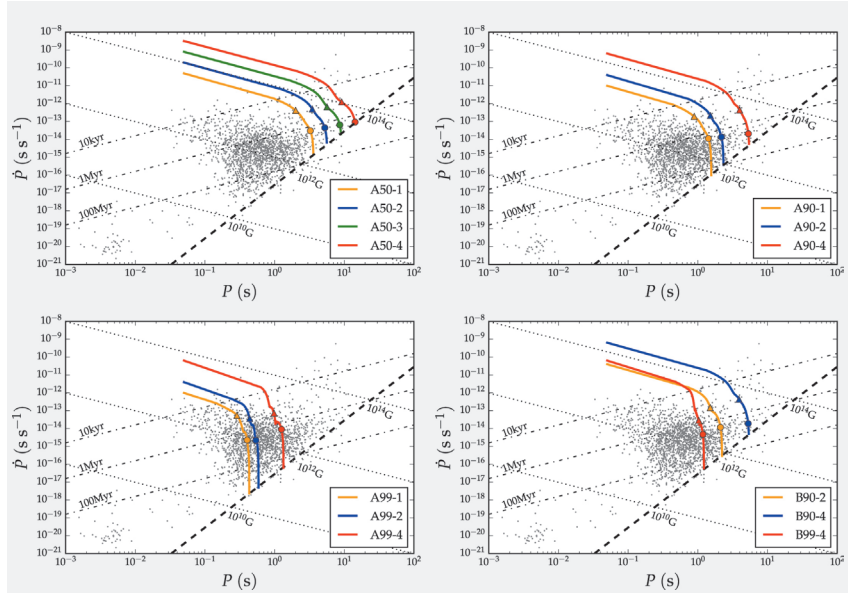


Figure 7: Tracks of neutron stars in the period-period derivative diagram, for sources with evolving magnetic fields and varying toroidal to total magnetic field energy ratio. Adapted from [58].

and merge indicating that parts of the crust are flowing [60].

The core field is more enigmatic and there have been fewer direct observational links with magnetic field evolution. The evolution of the magnetic field in the core is expected to proceed on much longer timescales than in the crust, governed by processes such as

ambipolar diffusion and the dynamics of superconducting fluxtubes, and is therefore more difficult to constrain observationally. Recent theoretical work has suggested that strong internal fields may give rise to enhanced magnetar activity, in which a substantial fraction of the magnetic energy is stored in the core and can power extreme activity be-

yond that of standard magnetars [61]. At the same time, theoretical models incorporating proton superconductivity provide a consistent framework for interpreting several observational phenomena, including neutron star cooling [62] and long-term magnetic field evolution [63]. While these effects offer indirect evidence for superconductivity in the core, they remain model-dependent and do not yet constitute definitive proof.

4. Prospects and open questions

The great progress of magnetic field evolution modelling efforts has opened new horizons and research areas. There are open questions related to microphysics implemented in the simulations, numerical approaches and connection to observations.

Regarding the crustal magnetic field, the Hall–Ohmic evolution has been studied thoroughly; nevertheless, the question of the appropriate physical mechanisms that need to be included in modelling efforts remains open. For instance, the role of additional processes such as plastic flows, thermoelectric (battery) terms, and the coupling to the magnetosphere is still under active investiga-

tion. These effects have already been incorporated in axisymmetric studies, yet, full 3-D models focus on the standard Hall–MHD. They modify the standard picture by altering the transport of magnetic energy, the formation of small-scale structures, and the localisation of dissipation. Moreover, uncertainties in the microphysics of the crust, including the electrical and thermal conductivities, impurity content, and the presence of nuclear pasta phases in the inner crust, introduce further complexity in predicting the long-term evolution of the magnetic field.

The coupling between the crust and the core remains one of the major open problems, as the exchange of magnetic flux across the crust-core interface can significantly impact the global magnetic evolution of the star. Similarly, the coupling between the crust and the magnetosphere is still missing from most studies, despite some initial efforts in axisymmetric models [64]. For magnetars, another open issue is whether the standard Hall–Ohmic prescription remains sufficient when the magnetic field exceeds the QED critical field, $B_{\text{QED}} = 4.4 \times 10^{13}$ G. At the level of crustal magnetic field evolution, the classical induction equation is usually still adopt-

ed, since Hall drift and Ohmic decay are controlled primarily by the charged-particle transport properties of the crust. However, fields above B_{QED} can modify the microphysics, radiative transfer, opacity, pair creation, and magnetospheric currents, so additional QED and magnetospheric effects may be required when connecting the internal evolution to observable emission.

Apart from further physical questions, such as the exact location of the boundary between the crust and the magnetosphere and the role of the ocean in dissipation, heat transfer and electrical conductivity, there are strong numerical challenges. The timescales of magnetic field evolution in the core, crust and magnetosphere differ vastly: from Gyrs in the core, to years and kyrs in the crust down to a fraction of a second in the relativistic magnetosphere. These scales make direct numerical simulation of a neutron star magnetic field impossible, requiring instead a piecewise approach in which equilibrium solutions are used for some regions while dynamical evolution is solved in others. Addressing these issues is essential for building a comprehensive and predictive model of neutron star magnetic field evolution and linking it directly to observations.

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Determinism, Randomness and Theories of Everything

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Abstract

We consider the role of determinism and randomness in determining the laws of physics. These laws have many applications but they are only approximate. In the quantum domain we have a number of approaches: the standard (Copenhagen) approach, the many worlds approach, the Feynman (histories) approach and the de Broglie-Bohm approach. The last approach is deterministic and it explains the phenomena of order and chaos in microphysics. Then we consider the multiverse and the theories of everything. In recent years many people have adopted the views of string and superstring theory. The superstring theory consists of 5 variants that are expected to express an unknown M theory. Hawking's last book supports the M theory as the only feasible Theory of Everything despite the fact that it has over than 10^{500} different realizations. There are also other theories like the loop quantum theory and the twistor theory of Penrose. Limitations of every Theory of Everything are due to the theorems of Gödel and Turing.

1. Introduction

Determinism is the view that all physical phenomena are governed by physical laws. The laws are expressed usually in mathematical form. Such are the Hamiltonian equations of motion of particles

$$\frac{dq}{dt} = \frac{\partial H}{\partial p} \quad \frac{dp}{dt} = -\frac{\partial H}{\partial q}, \quad (1)$$

where the Hamiltonian is a function of the positions q and the momenta p , and possibly also of the time t , or partial differential equations like the Schrödinger equation of Quantum Mechanics

$$\frac{-\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi = i\hbar \frac{\partial \Psi}{\partial t}, \quad (2)$$

where V is the potential, $\hbar$ is the reduced Planck constant and Ψ is the wavefunction (see §6) that is related to the probability P of finding a particle at a certain region through the Born relation $P = |\Psi|^2$.

The known physical laws have been established experimentally and describe approximately the effects of the main forces of nature (gravitation, electromagnetism, weak and strong nuclear forces). Although the known physical laws may not be applicable in some extreme cases, it is believed that more refined forms of these laws should explain all physical phenomena.

However, in recent years there have been attacks on determinism. The first attack was a claim that there are no strict laws but that all physical phenomena can be explained by probabilities (e.g. [1]). The second attack was made by the theory of the multiverse according to which there is a practically infinite number of universes with different physical laws. Thus the physical laws are random [2].

In the present paper, we review the problem of determinism versus randomness. We discuss first the exact physical laws and the laws based on probabilities, with particular emphasis on the various versions of Quantum Mechanics. Then, we consider the multiverse and the efforts to find a Theory of Everything, that should explain all physical phenomena.

2. Physical laws

One of the most important developments of physics was the mathematical description of some basic physical laws and the discovery of their universality. Our observations of the stars and the galaxies up to billions of light years away show the same chemical elements of matter and the same laws governing the processes of this matter. Both the

forms of the laws of electromagnetism and gravitation and the constants entering in these laws are the same. The laws of the strong and weak nuclear forces seem to be the same as well.

It is remarkable that the proportions of the various chemical elements are found to be the same when the light started billions of years ago, just after the beginning of the expansion of the Universe. Furthermore, the whole Universe is filled with the same background radiation corresponding to a temperature of 2.7° Kelvin, which comes to us from all directions with very small variations. It was also shown that the Universe is expanding with the same velocity and acceleration in all directions. In the past, there have been a number of efforts to find a change of the constants of nature over time, but these efforts failed and presently most researchers accept the universality of the physical laws in space and time.

3. Randomness and laws of the large numbers

Random phenomena are observed continuously around us. If we play dice or roulette, we consider that all the results are equally probable and this is the characteristic of randomness. The probabilities are either based on a theory, as in the case of the Quantum Mechanics (see Section 6), or they are found experimentally. E.g. in the case of a uniform die the probability of a particular number is $1/6$. This value is provided by throwing a large number of dice. Similar statistical results are found in a large number of molecules of a gas, or of a fluid and in other collections of bodies. After defining the equiprobability of the basic phenomena (like the throwing of one die) the probabilities of complex phenomena are found mathematically. Thus we have the "laws of large numbers" that are the basic elements of the physics of fluids and thermodynamics. E.g., the density of the air in a room is constant, the local pressure on the walls is con-

stant and the temperature is constant. If we introduce a bunch of molecules in an empty room, the density, the pressure and the temperature in various points of the room change for some time. But then they tend to become equal all over the room. Any hot point tends to drop its temperature and an ice cube tends to melt. These phenomena are described by laws about the entropy of the system, which tends to increase.

The laws of thermodynamics are statistical. They are derived from the randomness of the motion of the elements of a system. There is a very small probability that the system will decrease its entropy after a long time (Poincaré recurrence time). E.g. the molecules of the air in a room may be concentrated in a small region after a very long time but later they will fill again the whole room. In fact, there are theorems that define the behaviour of the set of molecules and give estimates of the Poincaré recurrence time in every case. In any case, the basic form of the “large number laws” remains the same.

4. Limits of the laws

The extreme form of determinism was claimed by P.S. Laplace in the 19th century. Laplace stated that “An intelligence knowing all the forces acting in the Nature at a given instant, as well as the momentary positions of all things in the Universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes.”

If this view is correct then the laws that govern various types of phenomena (like gravitation, electromagnetism etc.) determine every detail of the future and of the past of the whole world. However, the known physical laws have certain limits:

- (a) The Newton law of gravity

$$F \propto 1/r^2$$

is not applicable near a black hole. In this case a much better theory of gravitation was provided by Einstein, the general theory of relativity. This does not mean that Newton's law is useless. In most problems of Celestial Mechanics the Newtonian theory gives very good approximations and it is used in most

calculations. Only in the case of the perihelion of Mercury and in similar cases relativistic corrections are necessary.

There are limits of applicability even within the Newtonian theory. The theory cannot handle properly the cases of collisions. When a point particle collides with another particle, the gravitational force goes to infinity and the particle is reflected. But if we have a collision of 3 particles, then the orbits near it are chaotic. Therefore one cannot predict the outcome of this collision. There are also problems of 4 or 5 bodies that lead to infinite velocities after a finite time [3]. In these cases, the Newtonian theory cannot be applied.

The predictions of the General Theory of Relativity that the Universe is expanding was verified by Hubble. Einstein considered a repulsive force due to a cosmological constant that counteracts the attraction of gravity and keeps the Universe static. But such a Universe is unstable. In fact our Universe is expanding. However, the form of the cosmological constant is not yet completely established. Near the Big Bang it is believed that there was a period of inflation as it was stated by Kazanas in 1980 [4] and Guth in 1981 [5]. The radius of the Universe increased by a factor of order 10^{100} . After this period we had a normal expansion with velocities proportional to the distance. But in the last billions of years we have an accelerated expansion [6]. Thus the applicability of general relativity is limited and there is no generally accepted theory explaining all the effects of gravitation, especially close to the Big Bang.

- (b) A different set of laws refers to quantum domain, as it will be discussed below (Section 6).

- (c) Beyond the quantum theory there are a number of theories of the elementary particles that refer to the weak and strong nuclear forces and further theories trying to unify the laws of physics that we will discuss in later sections. These theories are still in development and no final theory exists today.

5. Chaos versus randomness

Chaos refers to very irregular orbits, and various definitions of chaos have been given in the past (see e.g. Wikipedia). However, the most consistent definition refers to deterministic systems. In such systems chaos refers to “sensitive dependence on initial conditions”. Namely, two orbits with nearby initial conditions deviate later considerably (e.g. exponentially). A measure of the deviations is the “finite time Lyapunov characteristic number” [7]:

$$\chi = \frac{1}{t} \ln \left(\frac{\xi}{\xi_0} \right) \quad (3)$$

where ξ_0 and ξ are the infinitesimal deviations at times 0 and t . The limit of χ when $t \rightarrow \infty$ is the “Lyapunov Characteristic Number” (LCN), or Lyapunov exponent.

A necessary requirement for the definition of chaos is that the system is compact, i.e. it has no escapes (in a non-compact system we speak about ‘chaotic scattering’). If the LCN is positive for some initial conditions, the system is called chaotic, while if $\text{LCN} = 0$ for all the orbits, the system is called ordered. In general, a system has both ordered and chaotic orbits. The cases where we have only ordered or only chaotic orbits are exceptional. On the other hand, a random system has an infinite LCN. But even if a deterministic system has infinite LCN it is different from a random system.

E.g. in the standard map

$$\begin{aligned} x' &= x + y', \\ y' &= y + \frac{K}{2\pi} \sin(2\pi x) \end{aligned} \quad (4)$$

the distribution of the helicity angles Φ (the angles formed by the deviation ξ with the x-axis) is different from the random case. In fact, for $K = 3$ the spectrum has four maxima, and when $K \rightarrow \infty$ these tend to two fixed values ([7], Fig. 1). But in the random case, the spectrum is flat

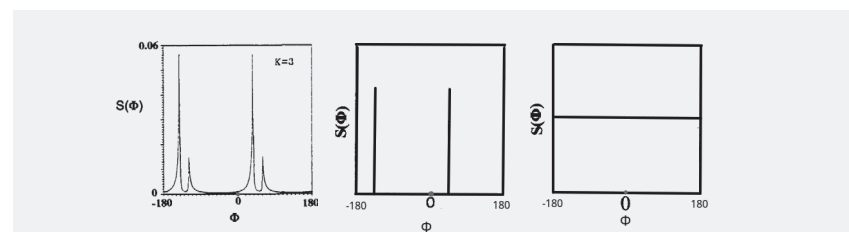


Figure 1: The spectra of the helicity angles a) when $K = 3$, b) when $K \rightarrow \infty$ and c) in a random case.

because all the directions of ξ are equally probable. We conclude that chaos is different from randomness as regards the distribution of the values of some quantities after many iterations.

A strange consequence of the determinism of the successive points in chaotic systems is the following: It is known that near an equilibrium point (or a stable periodic orbit) there are closed invariant curves (or surfaces) where the orbits are ordered (KAM theorem, [8, 9, 10]) described by asymptotic series. But these series are divergent, and between any two such curves, or surfaces, there are small chaotic domains. However, in the neighbourhood of an unstable point (or unstable periodic orbit) the KAM curves (or surfaces) are given by convergent series, as it was shown by Moser[11] and Giorgilli [12].

In particular, the successive points of the hyperbolic Hénon map ([13])

$$\begin{aligned}x' &= \cosh(k)x + \sinh(k)\left(y - \frac{x^2}{\sqrt{2}}\right) \\ y' &= \sinh(k)x + \cosh(k)\left(y - \frac{x^2}{\sqrt{2}}\right) \pmod{1} \quad (5)\end{aligned}$$

close to the unstable point (0, 0) can be given by series which are convergent. E.g. if we take an initial point along the unstable asymptotic curve of the origin (0, 0) the successive points are concentrated around the origin and appear to be randomly distributed [14] (Figs. 2a,b). Nevertheless the positions are given with great accuracy by the series expansions. This result is remarkable because it applies around an unstable equilibrium (0, 0) where chaos is generated, while near the stable equilibria the corresponding series diverge and give only approximate solutions up to a short time.

6. Determinism and randomness in Quantum Mechanics

The basic law of Quantum Mechanics is provided by Schrödinger's equation (eq. 2). This is a linear equation for the wavefunction Ψ . However, there are various interpretations of the wavefunction.

(a) In the original (Copenhagen) interpretation (Bohr, Born, Heisenberg, von Neuman, etc.), the probability density of finding a particle at a certain position is given by Born's rule $P = |\Psi|^2$. But

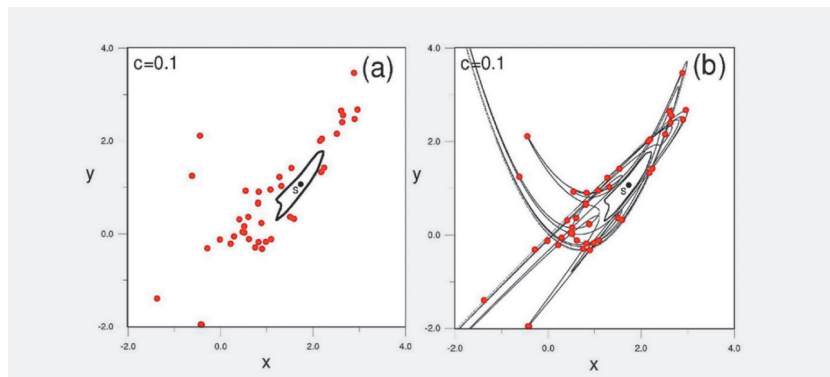


Figure 2: a) The successive iterates of a point near the origin have a chaotic distribution. b) However, all these points are along the unstable asymptotic curve of the unstable point (0, 0) and can be given by convergent series.

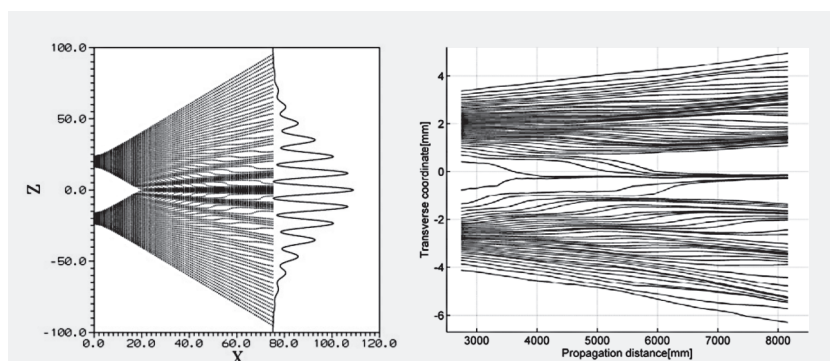


Figure 3: a) The orbits of particles in the two-slit experiment form interference patterns. b) The experiments of Kocsis et al [21] are consistent with the Bohmian orbits.

no orbits of particles are considered. In fact, the Heisenberg uncertainty equation $\Delta x \cdot \Delta p \geq \hbar$ does not allow to establish an accurate orbit, which requires at every moment both the position x and the momentum $p = mv$ of the particle. Only when a measurement is made one can find the position of the particle. E.g. in the case of the two-slit experiment (Fig. 3) we find an interference pattern consisting of particles, but we cannot state whether a particular particle has passed through one or the other slit. The measurement is made by a classical (large scale) detector (e.g. a photographic plate) and the result is due to a reduction (or collapse) of the wavefunction.

Therefore, this interpretation of Quantum Mechanics is probabilistic as regards the microphysics. But the microphysics may have large scale consequences as in the case of the Schrödinger cat. A cat in a box may be alive or dead, depending on a microscopic effect due to e.g. a cosmic ray, but we cannot say in what state she is until we open

the box and see if she is alive or dead. The measurement process has been studied in detail by Penrose [15], who tried to explain the differences between the various results of the measurements as due to gravitational effects. But this theory is incomplete and no generally accepted theory of the collapse effect exists at the present time.

b) A different interpretation of Quantum Mechanics is the "many worlds theory" of Everett [16]. In this view there is no collapse of the wavefunction, but all the processes are described by the same Schrödinger equation applied to different worlds. In one world the Schrödinger cat is alive, and in another world she is dead. Both worlds are equally real. This view implies that there are infinite parallel worlds.

c) The 'histories approach' of Feynman [17] considers an infinity of paths (histories) of particles that lead to the observed results. However, the probability of every path is an exponential of the form $P \propto e^Q$, where Q is the classical action of each path (or history). The to-

tal effect of all the paths is the 'path integral' from a point A (in the space $(\vec{x}, t)$) to a point B and this is equal to the outcome of the solution of the Schrödinger equation. This view is of course probabilistic, but it does not mean that real particles follow all the possible paths (histories) from A to B. It is rather a mathematical method of solving Schrödinger's equation.

d) The 'pilot wave' approach of de Broglie [18] and Bohm [19] (or ontological approach) is completely deterministic. Every particle is assumed to have a definite orbit, whether it is observed, or not. Its orbit is given by the Bohmian equations of motion

$$m \frac{d\vec{r}}{dt} = \hbar \nabla \ln \left(\frac{\nabla \Psi}{\Psi} \right) \quad (6)$$

and it is 'guided' by the wavefunction Ψ which is a solution of Schrödinger's equation. E.g. in the two-slit experiment the orbits are not straight lines beyond the two slits, but have oscillations (Fig. 3a) that lead to the interference patterns that are observed. It has been shown that in general the de Broglie-Bohm theory gives the same results as the Copenhagen theory. However there are some cases where the Bohmian and the Copenhagen theories give different results. These cases refer to experiments that depend on the time [20]. Therefore an experiment with great accuracy in time is required.

At present there are experiments [21] (Fig. 3b) that support the type of orbits provided by Bohm's equations of motion. These experiments are weak observations of the positions of particles at various distances beyond the two slits. 'Weak' means "not exact" (because then the uncertainty in the momentum due to Heisenberg's relation would make the momenta completely uncertain) but with uncertainties Δx that would allow a rough estimate of the velocities. Thus if we consider many orbits at the same times we can have an average position at every distance beyond the two slits. Then if we join these average positions we find orbits consistent with the Bohmian theory. This result is a strong indication (but not a proof) that the Bohmian orbits are correct.

The Bohmian theory is non-local. Thus they are not affected by the theorem of Bell [22] that excludes local theories of hidden variables. The Bell inequality was established by the experiments of

Aspect et al. [23] that have shown the effects of quantum theory at rather large distances. However, these experiments do not affect Bohm's theory which is inherently non-local. In fact Bell was one of the main supporters of the Bohmian theory.

The Bohmian equations provide a distinction between ordered and chaotic orbits and establish the existence of chaos in Quantum Mechanics. Chaos is introduced by the approaches of particles to the nodal points N , i.e. the points where the wavefunction is zero (both its real and its imaginary parts are zero). Close to a nodal point there is an unstable equilibrium point, called X -point, in the flow of particles (in the frame of reference of the nodal point N). Moving particles approaching the X -point are deviated along opposite directions thus chaos is generated. However the Born distribution contains, in general, both ordered and chaotic orbits. The chaotic orbits are ergodic, i.e. they have the same distribution of points after a long time. But the ordered orbits are not ergodic. Then, if we consider an initial distribution with $P_0 \neq |\Psi_0|^2$, we cannot reach the Born distribution unless we have the correct proportion of ordered trajectories.

People supporting the Copenhagen approach of Quantum Mechanics do not consider quantum chaos in the same way as in classical physics (where chaos is defined in terms of orbits). Instead they consider the quantum behaviour of systems that are classically ordered (integrable) or chaotic. But if a classical system is integrable then the corresponding Bohmian quantum system has in general both ordered and chaotic trajectories. Chaos is dominant, in general, in the quantum case, and the Bohmian approach can describe its origin in detail [24]. Furthermore there are also some cases where the quantum system is ordered, while the corresponding classical one is chaotic.

(b) Further approaches:

There are several further interpretations of Quantum Mechanics that have not a wide support. Only one approach, due to Dirac [25], that has combined Quantum Mechanics with Special relativity is established as a basic field theory of Quantum Mechanics. Furthermore various efforts have been made to include nonlinearity in extensions of the Schrödinger equation. But these ef-

forts have not provided a generally accepted theory.

7. Multiverse

Several years ago it was noticed that the physical laws are particularly appropriate for the existence of life. If they were changed, even a little, life would not have appeared on the Earth, and we would not exist at all. This remark was emphasized by Carter and Longair [26] who called it the 'anthropic principle'. An example is the existence of carbon which is the basic element of life. Carbon is formed by the action of the weak nuclear force. If this force would have been different by more than 1%, no carbon would be formed. Similar astonishing coincidences refer to many other laws of physics.

A discussion of the anthropic principle was presented in detail by Barrow and Tipler [27]. The main variations of this principle are the weak and the strong anthropic principle. The weak anthropic principle simply describes the forms of the physical laws and the values of the constants of nature that allow the appearance of life. The strong anthropic principle states that these laws and constants indicate the existence of a design. In both cases the basic question is why the physical laws and the constants of Nature have the observed form and canonical values. One possible answer to this question is that there are many different universes (practically infinite in number) and every universe has a random set of laws. Even if we consider the universes that have the same basic forces as our Universe (gravitation, electromagnetism, weak and strong nuclear forces) the amplitudes of the forces can have any possible values. Most of these universes are hostile to every possible form of life. Only in exceptional cases, like our Universe, the physical laws and constants allowed the appearance of life. But still the habitable universes may be infinite in number. They are similar to the rational numbers which are infinite although their measure is zero.

An extreme form of these considerations was formulated by Tegmark [2]. Tegmark considered universes of different levels beyond our Universe. Level I universes have the same physical laws but different initial conditions. Level II universes have different physical constants and different dimensions. Level III universes are the infinite quantum

worlds of the Everett formulation of Quantum Mechanics. And level IV universes have any imaginable form of difficult laws.

Of course one can imagine various scenarios of the multiverse. But the question is: do these other universes exist in reality? The distances of the external universes are supposed to be well beyond the “cosmic horizon” of our Universe (the distance of photons moving with the expansion of the Universe with velocities approaching the velocity of light at about 45×10^9 light years away (the distance covered by these photons since the Big-Bang up to now)). Some people think of distances 1000 times larger than our cosmic horizon or even $10^{1000000}$ times larger [28]. Therefore these external universes are so far away that no connection with them can exist even with signals at the velocity of light. No connection can be expected in the future, even in times much longer than the prospective life span of every universe. Nevertheless, if we consider an infinite space of the multiverse we can find all possible universes we can think of. But unless there is some observational test of them, one cannot consider them as physical theories. They are rather mathematical constructions and science fiction.

8. Theories of Everything

Many people have tried to find a theory that unifies the various forces of Nature. Einstein, after the success of his general theory of relativity that connects gravitation with the distribution of matter, tried to unify gravitation with electromagnetism [29]. However, this theory failed and no one considers it any more. Another Theory of Everything was proposed by the famous English astronomer Eddington [30] who called it ‘Fundamental Theory’ but it failed. The main effort of the physicists was to unify Quantum Mechanics with general relativity. Dirac [25] had already extended Quantum Mechanics in a form compatible with special relativity. However the unification with general relativity remains an open problem up to now.

A success of the unification efforts was realized around 1960 when Salam [31] and Weinberg [32] connected the electromagnetic forces with the weak nuclear forces. These two forces are united at high energies of the order of 100 GeV. The common force is called ‘elec-

troweak’. The corresponding particles (W^+ , W^- and Z^0) were found experimentally with masses around 80 and 91 GeV. This success encouraged people to try to unify also the strong nuclear force by finding a Grand Unified Theory (GUT). Although no generally accepted GUT has been found up to now, it is hoped that such a theory will be found in the future. On the other hand, the study of the strong nuclear forces led to the discovery of the quarks which form the basic components of the particles forming the atomic nuclei (protons and neutrons) and have mass about 1 GeV. These particles consist of three quarks [32]. There are also particles consisting of two quarks (mesons). The force between the quarks is the strong force, and the corresponding particles of that force are called ‘gluons’.

The electroweak theory, together with the theory of quarks and gluons forms the so-called ‘standard model’ that has been extremely successful up to now. Its most recent success was the discovery of the Higgs boson in 2012. This is the particle corresponding to a new field, the Higgs field [33], that generates the mass of the elementary particles beyond the photon. The Higgs boson has a mass of 125 GeV and it completes in some way the standard model.

However, the electroweak and the strong forces are not united in the standard model. In fact a prediction of various GUTs is that the proton (the most stable nuclear particle) should disintegrate into leptons (electrons and neutrinos) after a very long time of the order of 10^{32} years. But if this estimate is correct, some protons should disintegrate at a much shorter time. Such disintegrations have not been observed, but maybe the disintegration time is longer. On the other hand, another unification has been established, the unification between matter and antimatter. In fact, every particle of matter has a corresponding antiparticle. The proton corresponds to an antiproton, the electron corresponds to a positron, and so on. Such antiparticles were observed in the cosmic rays and are produced in the large accelerators.

But all these unifications did not apply to gravity. The gravitational force is extremely weak (10^{36} times weaker than the electromagnetic force). But as the large bodies of Astronomy (planets, stars, galaxies, etc.) are electrically neutral, they are attracted by gravitation

which is governed by the general theory of relativity. This has been verified by many observations and detailed experiments.

Many people have tried to unify Gravity with Quantum Mechanics by considering models of ‘Quantum Gravity’. In particular, they consider a possible particle that transfers the gravitational force. This particle is called ‘graviton’ but it has not been observed up to now.

A new theory that claims to be a successful Theory of Everything is the String Theory, and more recently the Superstring Theory.

The String Theory assumes that the elementary particles are not points but strings of microscopic lengths, close to the Planck length (10^{-23} cm) that undergo particular oscillations. The history of the String Theory is well described in the book of Smolin ‘The trouble with physics’ [34]. This is a nice theory with many interesting developments. The basic theory was expressed in 5 forms. It has 10 dimensions, 4 of them the usual spacetime, and 6 dimensions compactified around lines, with extremely small thickness. Then Witten [35] found some relations between the 5 versions of the String Theory and suggested that all of them are expressions of a unique theory of 11 dimensions that he called the M theory (M meaning mysterious or magic or membrane). This is the Superstring Theory. It contains various types of membranes and multiplicities of higher dimensions. Seven dimensions are supposed to be compactified in various ways. An estimate gives that there are 10^{500} ways of compactification, that influence the laws of the elementary particles beyond the standard model. Thus we have a set of 10^{500} universes with different laws.

The M theory is supposed to unify the forces of Nature, including Gravity. The basic element of this theory is ‘supersymmetry’. This is a theory that unifies the particles of integer spin, that are called ‘bosons’ (photons, W^+ , W^- etc.) with the particles of half integer spin, that are called ‘fermions’ (electrons, positrons, neutrinos, quarks). For each known boson there is a corresponding fermionic superparticle, and for each known fermion there is corresponding bosonic superparticle. The names of the superparticles have either an ending ‘ino’ (e.g. photino from photon, gravitino from graviton etc.) or an ‘s’ at their beginning (e.g. selectron from electron, squark from quark, etc.).

The masses of the superparticles are supposed to be several hundreds of GeV. However, no indication for such particles has been found up to now, although the new accelerator LHC of CERN has reached an energy of 13600 GeV. If no supersymmetric particles are found with this accelerator, then the supersymmetric theory will be in a very difficult position.

Many efforts have been made by the theoretical physicists to find the M theory (thousands of papers) but without success. The main drawback of this theory is that it has so many versions (at least 10^{500}) that no one can have an idea which version is more likely to be real. Nevertheless, the M theory still attracts the interest of many people.

One strong proponent of this theory was Hawking [36]. Hawking had developed previously a supergravity theory called N8 [37] and claimed that probably, this theory will provide the end of theoretical physics.

In 1996 Hawking attacked the String Theory [38] saying that this theory 'had been oversold', i.e. it was advertised beyond its value. But in his last book [36] in 2010 he claims that the M theory is the only acceptable Theory of Everything. His attitude is really strange. He does not care whether the M theory is a unique theory, or a set of different string theories. He does not even care that the number of realizations of the M theory is 10^{500} . Instead, he uses the multiplicity of the theory in order to introduce a new notion of reality. According to him, reality is not unique but 'model dependent'. He claims that 'a well-constructed model creates a reality of its own'.

Hawking writes [36]: 'According to the idea of a model-dependent reality introduced in Chapter 3, our brains interpret the input from our sensory organs by making a model of the outside world...'. He gives some examples and concludes: 'The mental concepts are the only reality we can know'. This attitude is exactly the attitude of solipsism, a theory support-

ed in the early 18th century by Berkeley (1710). This theory is never considered as a serious philosophical idea. But Hawking considers that the 'M theory is the only candidate for a complete theory of the Universe... there is no other consistent model'.

This claim is simply wrong. In fact, there are presently several other theoretical approaches that try to formulate a Theory of Everything. Among them is the Twistor Theory of Penrose [39] and the 'Loop Quantum Gravity' that was introduced by Ashtekar [40].

The Twistor Theory of Penrose is an effort to introduce a new form of spacetime that affects all the theories of Nature. This theory has been actively studied in recent years [41].

The Loop Quantum Gravity has been developed successfully by Rovelli and Smolin [42] and several other people. It unifies gravity with the other forces of Nature, without introducing any more dimensions beyond the usual 4 dimensions of spacetime.

Hawking's final conclusion is that "M theory is the unified theory Einstein was hoping to find." But the 10^{500} theories of Hawking are very far from a unified theory that Einstein wanted. Furthermore, there is no experiment that supports the String Theory and its generalization, the M theory. As Smolin [34] says: 'String theory has not made any new precise and falsifiable predictions that should check its validity'. For these reasons the book of Hawking has been severely criticized by Penrose [43] and others. In particular, Woit [44] has written a book with the title 'Not even wrong' which states that "the superstring theory is not really a theory but rather a set of reasons for hoping that a theory exists".

9. Limitations of the Theories of Everything

A basic problem of all candidate Theories of Everything is whether they can, in principle, cover all physical phenom-

ena. However, there is a basic theorem of Gödel that limits all physical theories. Gödel's theorem [45] states that any system of mathematical axioms (that include the usual Algebra) cannot answer all mathematical problems. One basic mathematical problem is the lack of a proof of the consistency of the system: It is impossible to prove that one cannot ever derive two opposite statements by following two series of statements based on the same set of axioms. Furthermore, there are true statements outside the system that cannot be proved by using the axioms of the system. A detailed explanation of Gödel's theorem was given by Hofstadter [46]. An important application of Gödel's theorem was provided by Turing [47] in the case of computers. Turing proved that there is no algorithm that can decide whether any given computer program will or will not attain a solution and stop. This is the so called 'halting problem'. If a computer works for a long time one does not know whether it will find later a solution and stop, or whether it will work forever without finding a solution. These theorems have direct counterparts in physics. One cannot prove that any given problem will have a solution within a given theory that claims to be a Theory of Everything. There will be always problems that cannot be solved by this theory, and true statements outside this theory. This means that a complete Theory of Everything does not probably exist. Only approximations that cover many physical phenomena are expected to be found.

Nevertheless, the search for a Theory of Everything continues and will continue in the future. Despite the claims of some established physicists that they have found a final theory, many people continue the search for theories that reveal the deepest secrets of Nature. And I believe that this search will never stop.

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SPEARHEAD: Reconstruction, Physics, and Interpretation of High-Energy Particle Populations in the Heliosphere

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Abstract

The SPEARHEAD (SPECification, Analysis & Re-calibration of High Energy pArticle Data) project constitutes a major effort within the Horizon Europe framework to advance the observation and physical understanding of high-energy particles in the heliosphere. Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs) are fundamental probes of plasma processes in solar eruptions and interplanetary space, yet their measurement at high energies remains limited by instrumental constraints and complex transport effects. SPEARHEAD addresses these limitations through the development of physics-based reconstruction techniques, cross-calibrated multi-instrument datasets, and integrated modelling approaches. This review synthesizes the project's progression from methodological development to the currently ongoing scientific exploitation, emphasizing the physical interpretation of high-energy particle acceleration, release, and transport. Attention is given to the role of CME-driven shocks, magnetic connectivity, and heliospheric structures in shaping particle populations. The implications of SPEARHEAD for space weather forecasting and heliophysics are discussed, highlighting future directions.

Keywords: Sun: particle emission · Sun: solar flares · Sun: coronal mass ejections-CMEs · solar-terrestrial relations · interplanetary structures · Galactic Cosmi Rays · Forbush decreases · space weather

1. Introduction

High-energy particles in the heliosphere constitute one of the most dynamic and informative components of the space environment (Anastasiadis et al., 2019; Papaioannou et al., 2025a). Solar Energetic Particles (SEPs), accelerated during eruptive solar events, and Galactic Cosmic Rays (GCRs), originating from astrophysical sources beyond the heliosphere, provide complementary probes of plasma processes across a wide range of spatial and temporal scales (Vainio et al., 2009). Their interaction with spacecraft systems, planetary environments, and human activities in space makes them not only a subject of fundamental scientific interest but also a key driver of space weather effects (Whitman et al., 2023; Kasapis et al., 2026).

Despite decades of observational and theoretical work, major uncertainties remain in our understanding of how these particles are accelerated to high energies, how they escape their source regions, and how they propagate through the heliosphere. A central limitation has been the incomplete coverage of high-energy particle measurements, particularly above 100 MeV for ions and above 1 MeV for electrons. Many spaceborne instruments were not designed to operate efficiently in these regimes, leading to fragmented datasets and inconsistencies between different missions. At the same time, the physical processes governing particle behavior—ranging from shock acceleration to turbulent transport—are inherently complex and strongly coupled (Strauss and Effenberger, 2017).

The **SPEARHEAD** project (*SPECification, Analysis & Re-calibration of High Energy pArticle Data*) [<https://spearhead-he.eu/>] was conceived to address these challenges through a coordinated, multi-institutional effort. Funded under the Horizon Europe programme, **SPEARHEAD** brings together a consortium

of eight partners from across Europe, including research institutes, universities, and space science centers with expertise spanning instrumentation, data analysis, modelling, and space weather applications. The collaboration is led by the National Observatory of Athens and includes contributors from the University of Turku (Finland), the Christian-Albrechts-Universitat zu Kiel (Germany), the University of Oulu (Finland), the University Paul Sabatier, Toulouse III (France), the Istituto Nazionale di Astrofisica (Italy), the Hvar Observatory (Croatia) and SPARC (Greece), the combination of which brings together strong backgrounds in heliophysics, cosmic ray physics, and computational modelling. This distributed expertise enables SPEARHEAD to tackle the problem of high-energy particle measurements in a comprehensive and interdisciplinary manner. Figure 1 shows the logo of the project.



Figure 1: The SPEARHEAD logo.

At the core of SPEARHEAD lies a set of three fundamental scientific questions that reflect the main stages of particle evolution in the heliosphere. The **first question** addresses the mechanisms by which ions and electrons are accelerated to the highest energies during solar eruptions. The **second** focuses on the processes governing the release of these particles from their acceleration sites in the solar corona, including

1. <https://spearhead-he.eu/partners/>

the role of magnetic connectivity and temporal evolution. The **third** concerns the transport of high-energy particles through the interplanetary medium, the magnetosphere, and the atmosphere, where scattering, diffusion, and large-scale structures shape their observed properties.

To address these scientific challenges, SPEARHEAD is built upon a set of complementary technical objectives that bridge the gap between raw observations and physical interpretation. A primary goal is the development of advanced analysis tools capable of extracting high-energy particle fluxes from instruments that were not originally designed for such measurements. This involves the determination of detailed instrument response functions and the reconstruction of particle fluxes as a function of time and energy (Kühl et al., 2017). In parallel, the project aims to process and cross-calibrate a large number of datasets from different spacecraft and ground-based detectors (i.e. mainly neutron monitors), producing harmonized and publicly accessible data products. A further objective is the validation of these reconstructed datasets against direct measurements from spectrometers (from the *Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics* – **PAMELA**; Adriani et al., 2011) and the *Alpha Magnetic Spectrometer* – **AMS-02**; Aguilar et al., 2021), ensuring their reliability and scientific usability.

The structure of SPEARHEAD reflects this dual focus on methodology and science. Work packages dedicated to instrument modelling and calibration provide the foundation for the generation of high-quality datasets, while subsequent work packages focus on the analysis of SEP and GCR events, the modelling of solar and heliospheric structures, and the development of user-oriented applications. This layered approach allows the project to progress from data reconstruction to physical interpretation and ultimately toward predictive capabilities. In this context, SPEARHEAD can be viewed as an effort to unify previously disparate elements of heliospheric research. By combining multi-instrument observations, advanced modelling techniques, and a strong emphasis on cross-calibration and validation, the project seeks to establish a coherent framework for the study of high-energy particles. The following sections build upon

this foundation, tracing the evolution of SPEARHEAD from its methodological beginnings to its current phase of scientific exploitation, with a particular focus on the physical insights gained into particle acceleration, release, and transport.

II. From Instrument Response to Physical Fluxes: Bridging Observation and Physics

A key innovation of SPEARHEAD lies in its ability to extract physically meaningful particle fluxes from instruments that were not originally designed for high-energy measurements. This is achieved through GEANT4-based simulations that model the interaction of particles with detector materials and geometries. At a physical level, the challenge can be understood as an inverse problem. Detectors measure count rates, which depend on both the incident particle flux and the detector response function. The response function itself is energy-dependent and often highly non-linear. SPEARHEAD addresses this by simulating particle interactions within the detector, accounting for processes such as energy loss, scattering, and secondary particle production (Hörlöck et al., 2026). For this purpose, an open access tool, G4VM, has been developed and released via Github (<https://spearhead-he.eu/tools/>).

Figure 2 illustrates how simulated detector responses are used to convert meas-

ured count rates into energy-dependent particle fluxes. This approach allows the reconstruction of fluxes at energies extending well beyond the nominal sensitivity of the instruments. Importantly, it enables the inclusion of a wide range of spacecraft—spanning different heliocentric distances—in a unified dataset. This multi-spacecraft perspective is essential for studying spatial variations in particle populations. From a physics standpoint, this reconstruction is not merely a technical step; it directly impacts the interpretation of particle spectra. The shape of the energy spectrum contains information about the acceleration mechanism, while temporal variations reflect both injection and transport processes. Without accurate reconstruction, these physical signatures would remain obscured.

III. Cross-Calibration and the Emergence of Coherent Heliospheric Datasets

The next critical step is the cross-calibration of datasets from different instruments. In the absence of calibration, differences in detector response, background noise, and observational conditions can lead to inconsistencies that mask physical trends. SPEARHEAD addresses this by comparing overlapping observations and deriving scaling relationships that bring datasets into agreement. This process effectively creates a common reference frame for particle

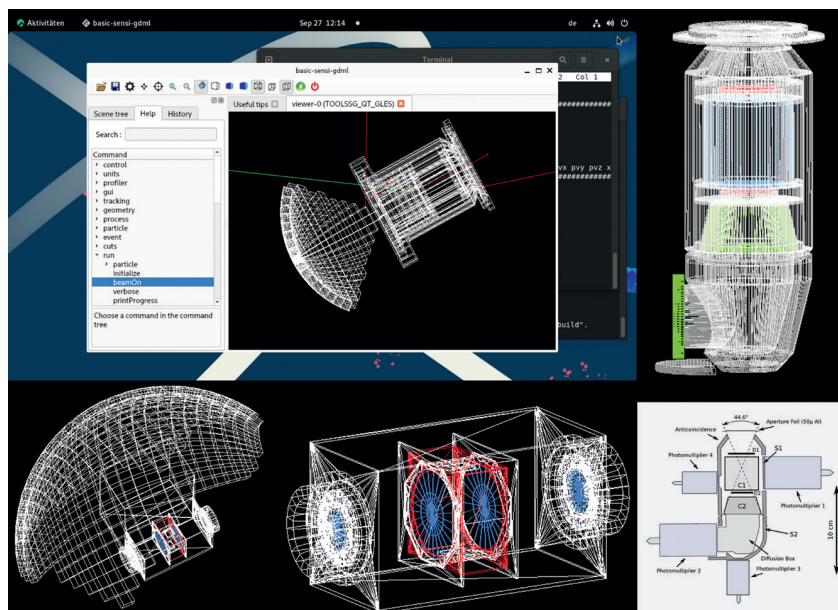


Figure 2: Instrument response and flux reconstruction using the G4VM. GEANT4 model of SOHO/EPHIN (top left panel); Solar Orbiter/HET (bottom left and middle panels), Ulysses/KET (top right) and the corresponding sketch of KET (bottom right).

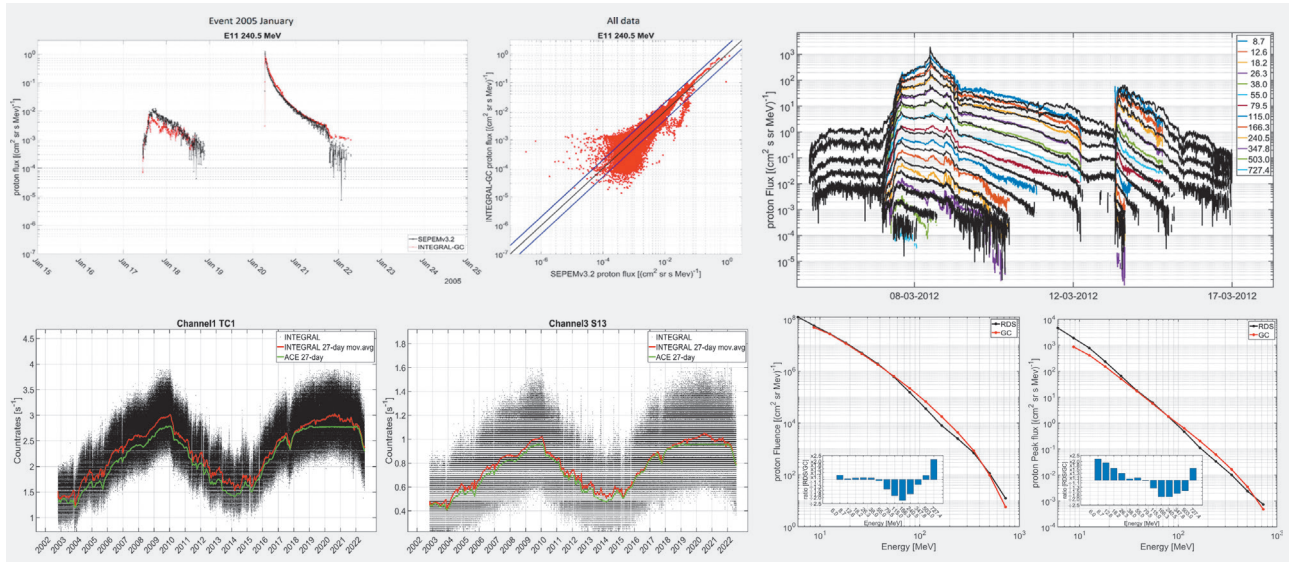


Figure 3: Cross-calibration and dataset harmonization for the Standard Radiation Environment Monitor (SREM) units onboard INTEGRAL and Planck missions.

measurements across missions. Figure 3 shows the convergence of independently measured fluxes after calibration, demonstrating improved consistency (Aminalragia-Giamini et al., 2018). From a physical perspective, cross-calibration is essential for identifying global phenomena. For example, the longitudinal spread of SEPs, or the radial evolution of GCR modulation, can only be studied if measurements from different locations are directly comparable. The harmonized datasets produced by SPEARHEAD thus enable a new class of studies that were previously difficult or even impossible to execute.

IV. Shedding light on SPEARHEAD's Scientific Questions

a. Particle Acceleration: Shock Physics, Spectral Formation, and Constraints from SPEARHEAD

The acceleration of particles to relativistic energies in the heliosphere is a fundamental problem in space plasma physics, and one that lies at the core of SPEARHEAD's scientific objectives. Observational and theoretical studies over the past decades have converged on the idea that CME-driven shocks are the dominant accelerators of high-energy SEPs, particularly for gradual events (Kouloumvakos et al., 2024). However, the detailed physics of how particles are injected, accelerated, and evolve spectrally remains an active area of research. Within this context, SPEARHEAD

provides a significant advance by combining reconstructed high-energy particle spectra with detailed modelling of shock properties, enabling a more direct confrontation between theory and observation. The key physical mechanism underpinning shock acceleration is diffusive shock acceleration (DSA), in which particles gain energy through repeated crossings of a shock front. In this process, particles scatter off magnetic fluctuations in the upstream and downstream regions, effectively sampling converging plasma flows and gaining energy in a stochastic but systematic manner (Afanasiev et al., 2015; Vlahos et al., 2019). The efficiency of DSA depends sensitively on several parameters. One of the most important is the shock Mach number, which determines the compression ratio and thus the spectral slope of the accelerated particles. Stronger shocks generally produce harder (flatter) energy spectra, while weaker shocks yield steeper spectra. SPEARHEAD's ability to reconstruct particle fluxes over extended energy ranges allows for detailed measurements of spectral indices, providing direct constraints on shock strength and evolution (Jarry et al., 2024).

Another critical parameter is the shock geometry, defined by the angle between the shock normal and the upstream magnetic field. In quasi-parallel shocks, where this angle is small, particles can more easily scatter back upstream and re-cross the shock, enhancing acceleration efficiency. In quasi-perpendicular shocks, on the other hand, particle re-

flection and injection are more limited, although drift acceleration mechanisms may still contribute (Tylka et al., 2005). SPEARHEAD's integration of particle data with 3D reconstructions of CME-driven shocks enables, in a systematic way, the correlation of observed particle properties with local shock geometry (Kouloumvakos et al., 2019). Figure 4 illustrates the spatial structure of a CME-driven shock, including derived quantities such as shock speed, Alfvén Mach number, and magnetic connectivity to different observers for the SEP event on 11 May 2024 (i.e. Ground Level Enhancement – GLE74).

A further key aspect of particle acceleration concerns the injection problem, namely how particles are initially energized to enter the DSA process. Thermal particles in the solar wind typically lack sufficient energy to cross the shock multiple times, implying the need for a pre-accelerated seed population (Rouillard et al., 2011; Reames, 2021). SPEARHEAD's high-energy datasets provide important constraints on this issue by revealing the presence of suprathermal particle populations and their evolution during SEP events. These observations suggest that the efficiency of acceleration is strongly influenced by the availability and properties of seed particles, which may originate from previous events or from the ambient solar wind. In addition to DSA, SPEARHEAD results also highlight the importance of time-dependent effects in particle acceleration. CME-driven shocks are not stationary structures; they evolve as

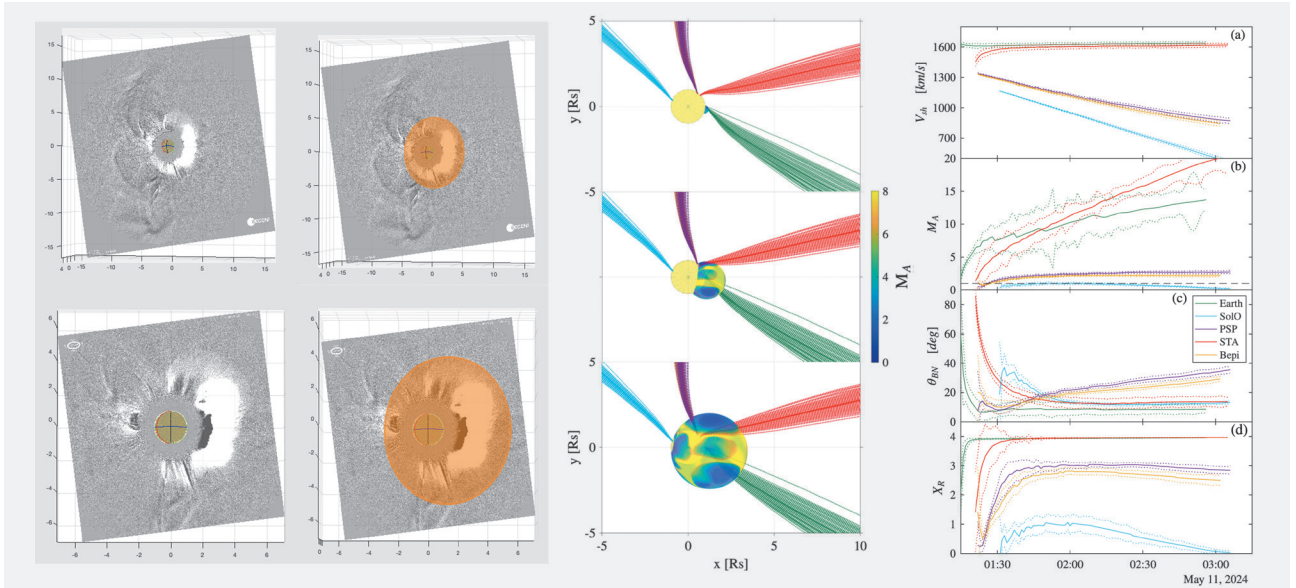


Figure 4: 3D reconstruction of the CME-driven shock and derived parameters for GLE74 (taken by Rouillard et al., 2026)

they propagate through the corona and heliosphere, changing their speed, geometry, and interaction with the ambient medium. As a result, the acceleration process itself is inherently dynamic, leading to time-dependent particle spectra and intensities. This is reflected in the observed evolution of SEP events, where spectral hardening or softening can occur over the course of the event (Figure 5; Rouillard et al., 2026).

Another important consideration is the maximum energy attainable by particles, which is limited by factors such as the size and lifetime of the acceleration region, as well as the level of magnetic turbulence. SPEARHEAD's reconstruction of particle fluxes at energies exceeding 100 MeV provides valuable constraints on these limits, particularly in extreme events such as Ground Level Enhancements (GLEs; Papaioannou,

2023). In these cases, the combination of strong shocks, favorable magnetic connectivity, and efficient injection can lead to the production of relativistic particles detectable at Earth (Plainaki et al., 2010; Mishev et al., 2018; Papaioannou et al. 2022; 2025b). Finally, the integration of particle data with solar observations enables a more comprehensive understanding of the relationship between flares, CMEs, and shocks (Papaioannou et al., 2016; 2026). While flares are often associated with impulsive acceleration processes, CMEs and their shocks are generally responsible for the sustained acceleration observed in gradual SEP events. SPEARHEAD's multi-instrument datasets allow for the disentangling of these contributions, providing evidence that, in many cases, the highest-energy particles are predominantly associated with shock accelera-

tion rather than flare processes (Jarry et al., 2026a).

In summary, SPEARHEAD significantly advances the study of particle acceleration by providing high-quality observational constraints on the key physical parameters governing the process. By linking reconstructed particle spectra with detailed shock modelling, the project enables a more quantitative and physically grounded interpretation of SEP events. This represents a crucial step toward resolving long-standing questions about the origin of high-energy particles in the heliosphere.

b. Particle Release: Magnetic Connectivity, Injection, and Timing Diagnostics

The release of energetic particles from their acceleration sites into the heliosphere represents one of the most challenging aspects of SEP physics, as it involves the interplay between acceleration efficiency, magnetic topology, and temporal evolution of solar eruptive structures. While acceleration processes may occur efficiently at CME-driven shocks or flare sites, the observability of SEPs depends critically on whether magnetic field lines provide a connection between the source region and the observer (see Fig.2 of Papaioannou et al., 2025a). In this context, SPEARHEAD significantly advances the study of particle release by combining high-resolution particle flux reconstructions with detailed modelling of coronal and heliospheric magnetic structures. The calibrated datasets produced within the

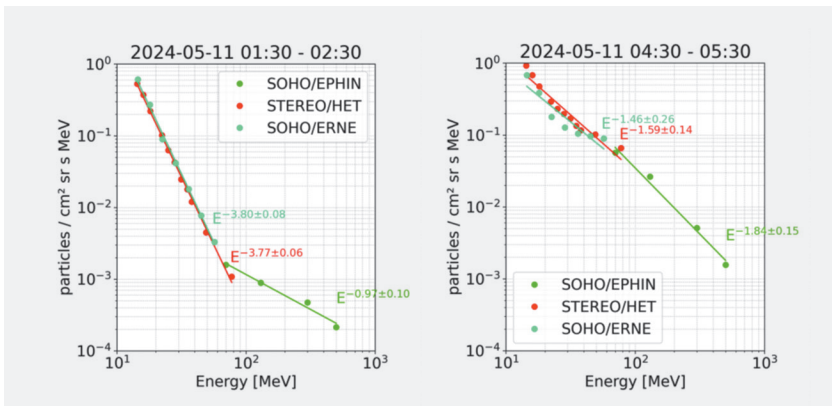


Figure 5: Hourly evolution of proton energy spectra measured by SOHO/EPHIN (dark green), STEREO/HET (red), and SOHO/ERNE (light green) prior and during GLE74 (taken by Rouillard et al., 2026)

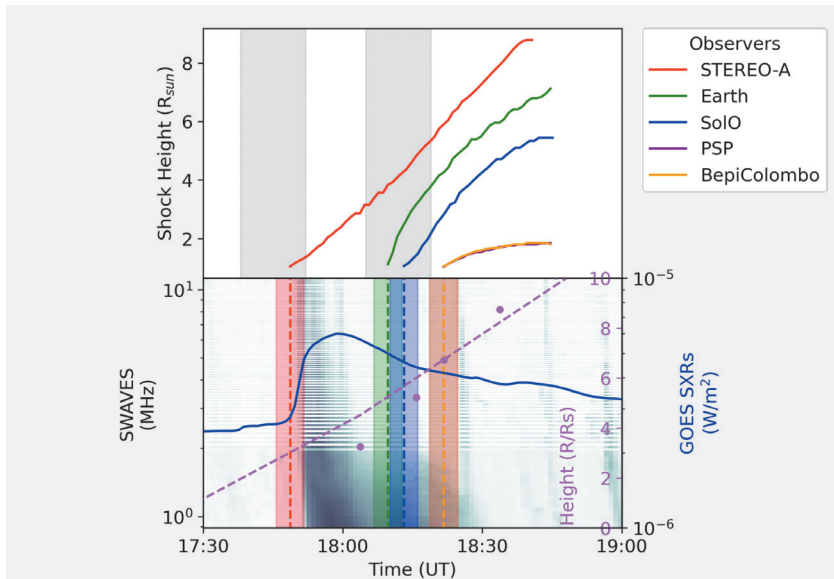


Figure 6: Reconstructed shock heights from CME modeling are shown for STEREO-A (red), Earth (green), Solar Orbiter (blue), Parker Solar Probe (magenta), and BepiColombo (yellow). Gray shading shows VDA results for STEREO-A and Earth (top). The soft X-ray (SXR) profile (blue, right axis) indicates the C-class flare, and the CME height-time profile from SOHO/LASCO (magenta) is overlaid on the SWAVES radio data spectrum. Dashed red/green lines mark shock-field line intersections, with ± 3 min uncertainty (bottom) (Jarry et al., 2026b).

project allow for precise determination of SEP onset times across multiple energies and spacecraft, enabling the application of timing diagnostics such as Velocity Dispersion Analysis (VDA) and Time-Shift Analysis (TSA) (Kolymbiris et al., 2023). These techniques exploit the energy-dependent arrival times of particles to infer both the release time near the Sun and the effective path length traveled along the interplanetary magnetic field. From a physical perspective, the interpretation of these timing signatures is non-trivial. The classical assumption of scatter-free propagation often

leads to inconsistencies, such as unrealistically long path lengths or delayed release times. SPEARHEAD results, benefiting from improved data quality, reinforce the view that particle release is not instantaneous but rather extended in time, reflecting the evolution of the acceleration region—particularly the expanding CME-driven shock. Moreover, the role of magnetic connectivity emerges as a key factor. The Parker spiral configuration of the heliospheric magnetic field implies that observers are preferentially connected to western solar longitudes. However, SPEARHEAD’s multi-

spacecraft datasets demonstrate that SEPs are frequently observed over wide longitudinal ranges, suggesting the importance of cross-field transport and evolving magnetic connectivity. In particular, the lateral expansion of CME shocks can progressively connect to different field lines, effectively “sweeping” across the heliosphere and injecting particles over extended regions (Jarry et al., 2026b).

Another important aspect concerns the injection threshold problem in shock acceleration. Only particles above a certain energy can participate in diffusive shock acceleration, and this threshold depends on the shock geometry and upstream turbulence. SPEARHEAD’s ability to reconstruct high-energy particle spectra provides constraints on these injection processes, offering insights into the seed populations required for efficient acceleration (see Figure 6).

c. Particle Transport: Diffusion, Turbulence, and Heliospheric Structuring

Once released, energetic particles propagate through a highly structured and turbulent heliospheric medium. Their transport is governed by the focused transport equation, which describes the evolution of the particle distribution function under the combined effects of diffusion, convection, adiabatic deceleration, and magnetic focusing (see e.g. Lavasa et al., 2026). A key parameter in this framework is the diffusion tensor, which encapsulates both parallel and perpendicular transport. Parallel diffusion, along magnetic field lines, is relatively well understood and depends on the level of magnetic turbulence and the particle rigidity. Perpendicular diffusion, however, remains more uncertain and is thought to arise from a combination of field line random walk and particle scattering. SPEARHEAD’s multi-spacecraft observations provide crucial constraints on these processes, particularly in events where particles are detected over wide longitudinal separations (Figure 7).

The project’s extensive catalogue of Forbush Decreases (Dumbovic et al., 2025) offers a complementary perspective on particle transport. FDs are characterized by sudden reductions in GCR intensity, typically associated with the passage of interplanetary CMEs (ICMEs) and their associated shock-sheath regions (Papaioannou et al., 2020).

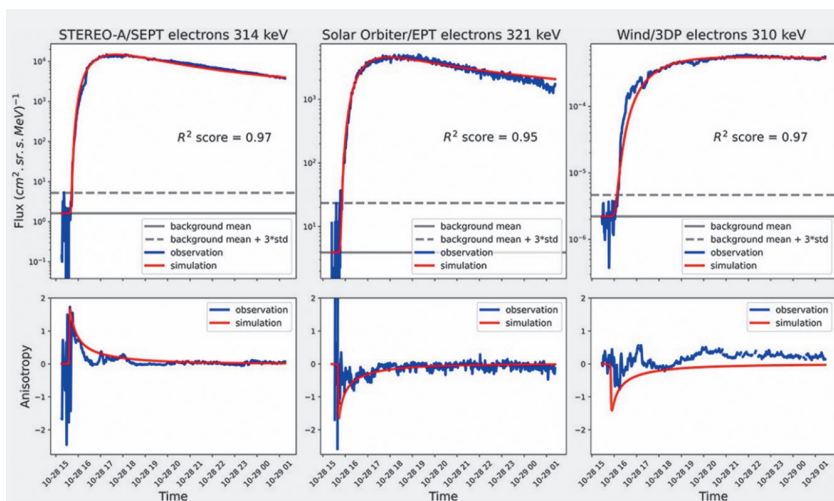


Figure 7: Inverse solution to particle flux (top) and anisotropy (bottom) of three observers (left: STEREO-A/SEPT, middle: Solar Orbiter/EPT, right: Wind/3DP) for ~ 314 keV electrons (taken by Lavasa et al., 2026).

Physically, these decreases are interpreted as the result of reduced diffusion coefficients and enhanced magnetic field strengths within the ICME, which inhibit the penetration of cosmic rays. SPEARHEAD's identification of a large number of FD events across different heliocentric distances enables systematic studies of their spatial and temporal evolution, in line with Belov et al., 2023. These studies reveal that the magnitude and recovery time of FDs depend on both the global structure of the ICME and the rigidity of the particles. Higher-energy particles, with larger gyroradii, are less affected by magnetic barriers, leading to energy-dependent modulation patterns (Figure 8) (Benella et al., 2025; Dumbovic et al., 2026). Furthermore, the interaction between SEPs and pre-existing heliospheric structures introduces additional complexity. For example, particles propagating through an ICME may experience enhanced scattering or even trapping, leading to prolonged event durations (see Figure 9) (Papaioannou et al., 2025b; Rouillard et al., 2026). SPEARHEAD's integrated datasets, combining SEP and FD observations, provide a unique opportunity to study such interactions in detail.

V. Integration and Scientific Exploitation: Toward a Unified Physical Picture

The transition to scientific exploitation within SPEARHEAD represents more than a procedural milestone; it reflects the emergence of a coherent physical framework that integrates particle acceleration, release, and transport into a unified interpretation. In this phase, the project leverages its validated response functions and calibrated datasets to perform both statistical analyses and detailed case studies. The combination of large-scale catalogues with high-resolution event analysis allows for the identification of general trends while preserving sensitivity to event-specific characteristics (Köberle et al., 2025; Jarry et al., 2026a; Papaioannou et al., 2026). A particularly important development is the coupling of particle datasets with solar and heliospheric modelling. By incorporating 3D reconstructions of CME-driven shocks and magnetic flux ropes, SPEARHEAD enables direct mapping between observed particle properties and the evolving physical conditions in the

solar corona and interplanetary space. This approach bridges the traditional gap between remote sensing observations (e.g., coronagraphs) and in-situ particle measurements. A key outcome

of this integration phase is the development of a dedicated interface for accessing SPEARHEAD datasets and event catalogues (Figure 10). This interface enables streamlined exploration, visual-

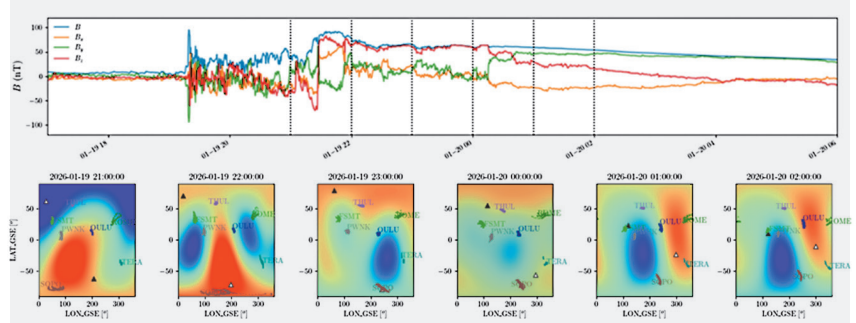


Figure 8: Top panel: magnetic field measurements from ACE of the ICME passage. Vertical lines indicate the time steps at which the FD model is optimized. Bottom panel: time variation of first and second anisotropy obtained from NM data during different ICME phases. The colormap is defined in the range [-4, 4]%. Triangles indicate the parallel (filled) and antiparallel (empty) directions to the interplanetary magnetic field (Dumbovic et al., 2026).

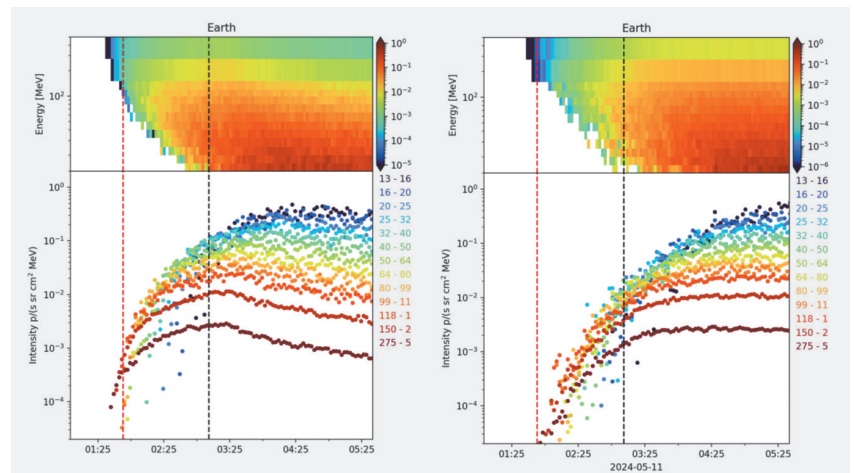


Figure 9: Top panel presents the derived spectrum of SEP measurements, while the bottom panel the relevant derived SEP time profiles, from the SEP acceleration and transport modelling chain. Panel on the left-hand side assumes a Parker spiral geometry, whereas panel on the right-hand side assumes propagation of particles within a flux rope. (taken by Rouillard et al., 2026).

HomeAboutResultsPartnersMeetingsNewsE.A.C.Contact												
Event-Group ID	SEP Onset Time	SXR Peak Time	SXR Class	CME Start	CME Speed	Spacecraft	GLE	Actions				
SPH-SEP-001	1997-09-24T03:50:00	1997-09-24T02:48:00	M8.5	1997-09-24T03:38:00	532	SOHO	-	Particle Observations	Solar Associations			
SPH-SEP-002	1997-11-04T06:25:00	1997-11-04T05:58:00	X3.0	1997-11-04T06:10:00	785	SOHO	-	Particle Observations	Solar Associations			
SPH-SEP-003	1997-11-06T12:20:00	1997-11-06T11:55:00	X13.5	1997-11-06T12:10:00	1556	SOHO	GLE55	Particle Observations	Solar Associations			
SPH-SEP-004	1998-04-20T11:05:00	1998-04-20T10:21:00	M2.1	1998-04-20T10:07:00	1863	SOHO	-	Particle Observations	Solar Associations			
SPH-SEP-005	1998-05-02T13:55:00	1998-05-02T13:42:00	X1.7	1998-05-02T14:06:00	938	SOHO	GLE56	Particle Observations	Solar Associations			
GLE Name		Fluence		Peak Intensity		Observer						
GLE56		17200		10		CALG						
SPH-SEP-006	1998-05-06T08:15:00	1998-05-06T08:09:00	X4.0	1998-05-06T08:29:00	1099	SOHO	GLE57	Particle Observations	Solar Associations			
SPH-SEP-007	1998-05-09T04:50:00	1998-05-09T03:40:00	X1.1	1998-05-09T03:35:00	2331	SOHO	-	Particle Observations	Solar Associations			
SPH-SEP-008	1998-10-18T22:40:00	-	-	-	-	SOHO	-	Particle Observations	Solar Associations			
SPH-SEP-009	1998-11-14T06:00:00	1998-11-14T05:18:00	C2.5	-	-	SOHO	-	Particle Observations	Solar Associations			
SPH-SEP-010	1998-11-22T07:05:00	1998-11-22T06:42:00	X5.9	-	-	SOHO	-	Particle Observations	Solar Associations			
Catalogue ID	Instrument	Energy (Species)	BS Start	BS End	BS Mean	Onset Time	End Time	Peak Flux	Peak Time	Fluence	Fluence Start	Fluence End
SPH-SEP-SOHO-010	SOHO/ERNE	>100 MeV (protons)	-	-	684.54	1998-11-22T07:05:00	-	-	-	-	-	-
SPH-SEP-SOHO-010	SOHO/EPH	>100 MeV (protons)	-	-	3.60e-4	1998-11-22T07:05:00	1998-11-22T09:25:57	4.50e-4 (±0.076)	-	1.60 (±0.076)	-	-
SPH-SEP-011	1998-11-24T03:50:00	1998-11-24T02:20:00	X1.7	1998-11-24T02:30:00	1798	SOHO	-	Particle Observations	Solar Associations			

Figure 10: Screenshot of the interactive web-interface to the SPEARHEAD E>100 MeV SOHO/ERNE catalogue.

ization, and retrieval of both SEP and FD events, effectively linking the reconstructed particle datasets with their associated solar and heliospheric context (https://spearhead-he.eu/catalogues_data/). By combining catalogue information with analysis tools within a unified environment, SPEARHEAD facilitates both detailed case studies and large-scale statistical analyses, significantly enhancing the usability and scientific exploitation of its results (see Jarry et al., 2026a; Papaioannou et al., 2026). Another key aspect of this integration is the development of user-oriented analysis environments, such as the JupyterHub platform and the SPEARHEAD Github (<https://github.com/spearhead-he>). These tools not only facilitate internal analysis but also promote reproducibility and community engagement. Importantly, they allow users to apply SPEARHEAD methodologies to new datasets, extending the project's impact beyond its original scope. In addition to data products and analysis tools, SPEARHEAD places strong emphasis on knowledge transfer and capacity building within the scientific community. This is reflected in the development and dissemination of educational material, including a dedicated MSc-level course (<https://spearhead-he.eu/msc-course/>) and the organization of training activities such as the SPEARHEAD School. These initiatives provide structured access to the methodologies, datasets, and scientific context developed within the project, enabling early-career researchers and external users to engage directly with high-energy particle analysis techniques. By combining theoretical background with hands-on use of the project's tools and catalogues, these educational efforts contribute to the long-term sustainability and broader impact of SPEARHEAD.

VI. Discussion and Outlook: Open Questions and Emerging Directions

While SPEARHEAD has made substantial progress in both methodology and scientific interpretation – so far, it also highlights several key challenges that remain unresolved in the field of high-energy particle physics. One of the most significant open questions concerns the relative contributions of different acceleration mechanisms. While CME-driven shocks are widely re-

garded as the primary source of high-energy SEPs, flare-related processes may also play a role, particularly in impulsive events. Disentangling these contributions requires detailed spectral and compositional analysis, as well as precise timing information—areas where SPEARHEAD provides valuable new capabilities.

Another challenge lies in the complexity of particle transport, particularly in relation to perpendicular diffusion and large-scale magnetic structures. The wide longitudinal spread of SEP events observed in SPEARHEAD datasets suggests that cross-field transport is more efficient than previously thought, but the underlying mechanisms remain poorly understood (Lavasa et al., 2026). Addressing this issue will require a combination of observational constraints and advanced numerical simulations. The role of seed particle populations is also a critical factor in determining acceleration efficiency. Pre-accelerated particles, possibly originating from previous events or from the ambient solar wind, can significantly enhance the production of high-energy SEPs (Lee et al., 2012). SPEARHEAD's ability to reconstruct particle spectra over extended energy ranges provides new opportunities to study these seed populations. Looking forward, the integration of machine learning and data-driven approaches represents a promising avenue for future research. The large, harmonized datasets produced by SPEARHEAD are ideally suited for such techniques, which can identify complex patterns and correlations that may not be apparent through traditional analysis (Papaioannou et al., 2018). However, the success of these approaches will depend on maintaining a strong connection to physical models, ensuring that predictions remain interpretable and scientifically meaningful (Lavasa et al., 2021).

VII. Conclusions

SPEARHEAD has demonstrated that substantial progress in heliospheric physics can be achieved through the combined advancement of data reconstruction techniques, coordinated multi-instrument analysis, and physically grounded interpretation. By addressing longstanding limitations in the measurement of high-energy particles, the project has significantly improved the ob-

servational basis upon which our understanding of SEPs and GCRs is built. A central achievement of SPEARHEAD lies in the **systematic provision of high-quality, cross-calibrated datasets**, derived from space-borne and ground-based instruments. Through the development and validation of detailed instrument response functions, the project has enabled the reconstruction of particle fluxes at energies that were previously inaccessible or poorly constrained. In particular, *the main contributions of SPEARHEAD can be summarized as follows:*

- **Provision of harmonized datasets**
 - Reconstruction of high-energy particle fluxes across multiple missions
 - Cross-calibration ensuring consistency between instruments and platforms
 - Extension of usable energy ranges beyond nominal detector capabilities
- **Development of comprehensive event catalogues**
 - Catalogues of SEP events (including >100 MeV proton events and relativistic electrons: 1 MeV, >5 MeV)
 - Extensive identification of Forbush Decreases across the heliosphere
 - Integration of particle data with solar and heliospheric context
- **Implementation of open-access tools and infrastructure**
 - Publicly available analysis tools and software environments (e.g., JupyterHub, GitHub)
 - Long-term data archiving and accessibility (e.g., Zenodo repositories)
 - Support for reproducibility and community-driven research
- **Advancement of scientific understanding**
 - Improved constraints on particle acceleration at CME-driven shocks
 - Better characterization of particle release processes and magnetic connectivity
 - Enhanced understanding of particle transport, diffusion, and heliospheric modulation
- **Progress toward space weather applications**
 - Integration of datasets and mod-

els into early-stage forecasting tools

- Contribution to radiation environment specification
- Foundations for predictive capabilities in SEP event evolution

- **Educational and training activities**

- Development of a dedicated MSc course based on SPEARHEAD methodologies
- Organization of the SPEARHEAD School and Workshops
- Dissemination of training material supporting capacity building and community engagement

Beyond these individual achievements, SPEARHEAD has contributed to bridging the gap between **descriptive and predictive heliophysics**. By integrat-

ing datasets, catalogues, and modelling approaches into a unified framework, the project provides the basis for future tools capable of forecasting high-energy particle environments—an essential requirement for upcoming space missions and technological resilience. At this stage of the project, SPEARHEAD remains actively under implementation, with current efforts extending through:

- Continued exploitation of its datasets and catalogues for statistical and case-study analyses
- Expansion of its methodologies to future missions and new observational platforms
- Integration with advanced modelling and machine learning approaches
- Ongoing support of open science and collaborative research

In this sense, SPEARHEAD represents not only a major step forward in our current understanding of high-energy particles in the heliosphere, but also a foundational platform for the next generation of heliophysics research and space weather forecasting.

Acknowledgements

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6th Hel.A.S. Astrophysics Summer School

Aug 24-28, 2026

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- Machine learning and deep learning applications

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- Matteo Cerruti (APC University Paris Cite, France)
- Maria Gerontidou (National and Kapodistrian University of Athens, Greece)
- Nikolaos Karnesis (National Observatory of Athens, Greece)
- Foteini Oikonomou (Norwegian University of Science and Technology, Norway)
- Maria Petropoulou (National and Kapodistrian University of Athens, Greece)
- Niharika Sravan (Drexel University, USA)
- Katerina Tzamarioudaki (NCSR Demokritos, Greece)
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Tidal Disruption Events and Nuclear Transients in Crete vol. 2 - 24-28 Aug 2026

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- Accretion disk and outflow formation
- Multiwavelength/multimessenger emission and polarization
- Radio outflows and jets
- Variable AGN, Bowen flares, and Ambiguous Nuclear Transients
- Host galaxy environments, population studies, and event rates
- Repeating TDEs and Quasi-Periodic Eruptions

Invited Speakers:

- Luca Broggi
- Joheen Chakraborty
- Anna Franckowiak
- Adelle Goodwin
- Itai Linial
- Andrew Mummery
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- Dimitris Langis
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21-25 Sep 2026



Rationale

Star formation is governed in large part by the interplay of gravity, turbulence, magnetic fields, and stellar feedback. Over the past decade, new surveys and analysis techniques have revealed these processes with unprecedented clarity in the local kiloparsec of the Milky Way, where stellar nurseries can be studied down to sub-parsec scales. The time is now ripe to connect this wealth of local knowledge to the broader galactic context.

The goal of **Star Formation Fields** (Crete IV) is to bring together interstellar medium (ISM) and star formation researchers working on recent large-scale surveys and simulations that integrate the main multiple physical fields governing large-scale (from pc to kpc) star formation. A key objective is to bridge the local ISM and its star formation fields with the extragalactic context. By doing so, we aim to advance a unified picture of how star formation operates across environments, from molecular clouds in our Galactic neighborhood to star-forming regions in nearby galaxies.

The conference will be limited to about 100 participants to foster intensive discussion and collaborative problem solving. With no traditional poster sessions, participants will have the opportunity to present electronic posters on the web, complemented by short oral highlights, ensuring that every contribution is visible.

The venue, the historic Neratze Mosque in Rethymno, Crete, a building that has hosted different worldviews throughout its centuries-long history, will provide an inspiring setting that encourages the exchange of ideas and creative collaboration.

Topics

Star Formation Fields will bring together experts in ISM and star formation. Given the limited time available, the meet-

ing will focus mainly on scales from pc to kpc. In particular, we will address:

- Fields as forces: the role of gravitational, velocity, and magnetic fields in shaping the ISM and regulating star formation.
- Fields as regions: key nearby star-forming environments such as Scorpius–Centaurus and Orion, alongside star formation complexes in nearby galaxies.
- Fields as methods: new approaches such as Information Field Theory, Bayesian inference, and 3D tomographic maps of gas density in the local kiloparsec, enabling reconstruction of ISM structures and flows.
- Bridging scales: place the detailed view of the local Milky Way within the comparative framework of external galaxies.

Scientific organizing committee

- João Alves (co-chair)
- Raphael Skalidis (co-chair)
- Josefa Großschedl
- Alvaro Hacar
- Emily Hunt
- Sebastian Hutschenreuter
- Stefan Meingast
- Núria Miret-Roig
- Martin Piecka
- Kostas Tassis
- Catherine Zucker

Local organizing committee

- Raphael Skalidis
- Konstantinos Christidis
- Eleftheria Tsenteliero
- Konstantinos Droudakis

September 21-25, 2026
Neratze Mosque
Rethymno, island of Crete,
Greece

<https://star-formation-fields.univie.ac.at/>

Back issues of Hipparchos

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