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Solar Wind Interaction with the Local Interstellar Medium: Its Role in the Galactic Cosmic Ray Modulation

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The Sun moves through the local interstellar medium (LISM) and modifies its properties to heliocentric distances as large as 1 pc, especially if the effect of the heliosphere on the transport of multi-TeV Galactic cosmic ray (GCR) fluxes is concerned. The solar wind (SW) inside the heliosphere is affected by the penetrating LISM neutral atoms. Charge exchange between the LISM atoms and SW ions creates non-thermal, pickup ions and secondary neutral atoms, the latter propagating deeply into the LISM. Observational data from the IBEX, New Horizons, and Voyager spacecraft, as well as numerous air shower experiments, convincingly demonstrate that the heliosphere modulates Galactic Cosmic Rays (GCRs) up to extremely high energies. From the GCR transport perspective, it is important to understand the structure of the heliosphere, properties of the turbulent solar and LISM plasma, and distributions of magnetic field throughout the interaction region. We discuss observations and simulations that shed light onto the mutual influence of the SW and LISM. We also describe the physical phenomena that accompany the SW–LISM interaction, analyze the coupling of the heliospheric and interstellar magnetic field at the unstable surface of the heliopause, and discuss their effects on GCR modulation in the outer heliosheath. We propose a new model, which is implemented in a box of 12,000 au cubed, extends far into the heliotail region, and is necessary for the explanation of TeV GCR anisotropy measurements.

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1. The heliosphere in the local interstellar medium

The structure and dynamical evolution of the heliosphere, our home in the universe, is governed by a number of fundamental physical processes that define how plasma and magnetic fields of solar origin interact with the local interstellar medium (LISM). Our understanding of the processes occurring in the heliosphere has increased tremendously due to breakthrough observations performed by the fleet of NASA and ESA spacecraft over the past two decades.The solar plasma is accelerated near the Sun and creates a solar wind (SW), which is collisionless with respect to Coulomb collisions, so the possibility of its description by MHD equations is mostly based on the wave-particle interaction arguments (proton scattering on magnetic field fluctuations). The Sun moves through the LISM, which itself is affected by the presence of the heliosphere. The SW–LISM interaction creates the heliospheric termination shock (TS) and the heliopause (HP), both observed in situ by *Voyager* 1 (*V1*) and *Voyager* 2 (*V2*) spacecraft [2, 3] (see Fig. 1). The LISM plasma is only partially ionized, so charge exchange between ions and atoms plays a major role in the SW–LISM interaction at large heliocentric distances [4, 5]. As new populations of neutral atoms are born in the SW and LISM, some of them can propagate far upstream into the LISM and modify it to such extent that the existence of a bow shock cannot be confirmed knowing the properties of the unperturbed LISM only [6]. In addition, nonthermal (pickup) ions (PUIs) are created [7, 8]. They generate turbulence which heats up the thermal ions [9]. The heliosphere beyond the ionization cavity is dominated thermally by PUIs [10, 11]. According to [12], the inner heliosheath (IHS, the SW region between the TS and the HP) pressure contributed by energetic PUIs and anomalous cosmic rays (ACRs) far exceeds the pressure of the thermal background plasma and magnetic pressure.

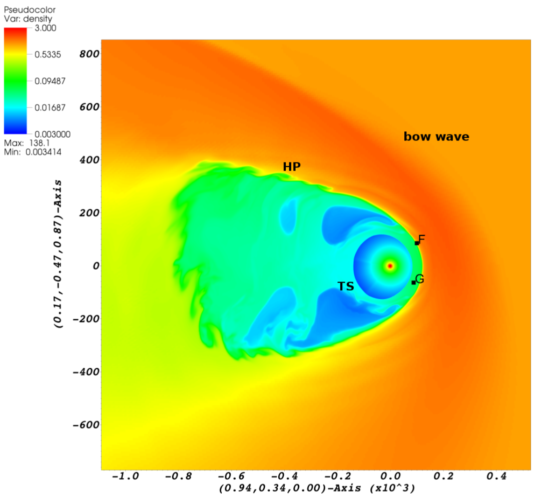

Figure 1: The picture of the SW–LISM interaction is shown through the plasma density distribution in the plane formed by the *V1* and *V2* trajectories [1]. Letters *F* and *G* show the spacecraft positions in 2015. While the HP crossing distance at *V1* is closely reproduced, we also predicted that *V2* may cross the HP at a similar distance.

The presence of the heliosphere modifies the properties of the LISM surrounding by two mechanisms: (1) the secondary neutral atoms born in the supersonic SW ahead and in the IHS can propagate far upstream into the LISM decelerating it and increasing its temperature; (2) a rarefaction wave is created around the HP because the LISM is not universally superfast magnetosonic at large heliocentric directions. Moreover, the heliosphere affects not only the LISM plasma, but also GCRs penetrating into it. These two factors motivated [13] to extend (as compared with [9], where only the deposition of the SW material was considered) the term Very Local Interstellar Medium (VLISM) to the LISM affected by the presence of the heliosphere, regardless of what physical processes are responsible for such modification and which physical quantities are affected. The space filled by the VLISM is sometimes called the outer heliosheath (OHS).

The *Voyager* interstellar mission started when V1 crossed the HP in August 2012 and V2

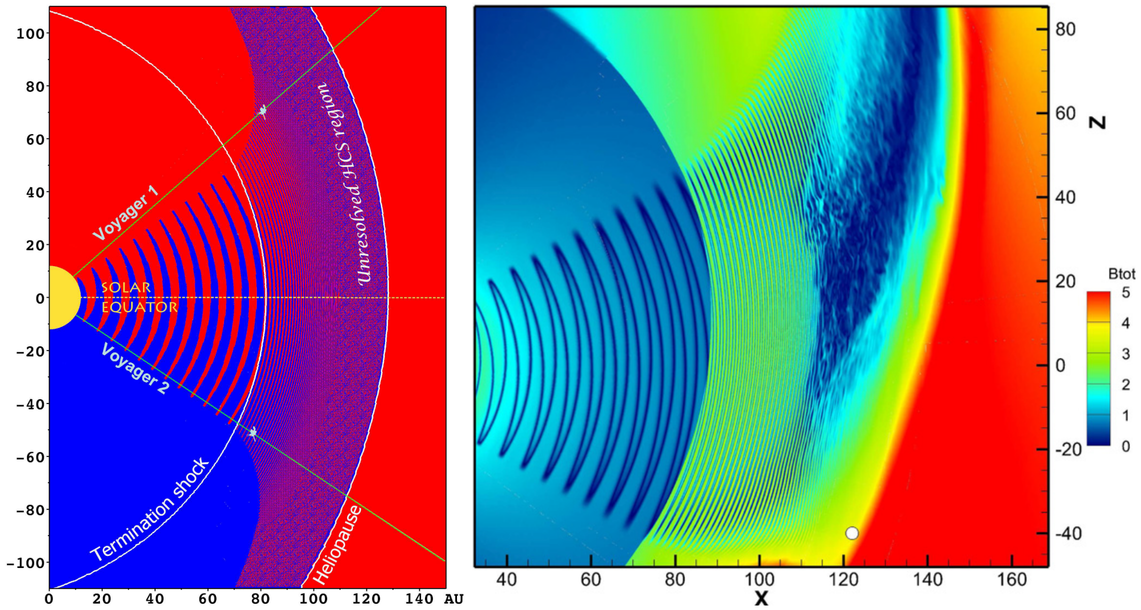

Figure 2: (*Left panel.*) HCS structure in the plane formed by the current V1 and V2 trajectories. The *Voyager* locations are given on 2010 July 1. The tilt of the Sun's magnetic axis to its rotation axis is 30°. (*Right panel.*) Transition to chaotic behavior in the IHS. Magnetic field strength distribution (in μG) is shown in the meridional plane defined by the Sun's rotation axis and the LISM velocity vector. The angle between the Sun's rotation and magnetic axes is 30°. The boundary conditions are from [14], but the solution is completely different.

joined it in November 2018. The *Voyager* spacecraft provide the heliospheric and astrophysics communities with the invaluable measurements of plasma and magnetic field in the LISM. It is remarkable how this data instigates new theoretical studies and lays out critical challenges for modeling and simulation, which have been been successful in the interpretation and explanation of a number of spacecraft observations [see, e.g., 15–21, and references therein].

2. Heliospheric models and their aspects important for GCR propagation.

Galactic cosmic rays can penetrate into the heliosphere and be measured in situ by spacecraft and air shower observatories. On the other hand, Voyagers were measuring GCR fluxes in the outer heliosphere and in the IHS. They are also the first spacecraft in the history of humankind that provide us with the CR properties in the VLISM.

There are a few important global features of the SW–LISM interaction that are particularly important for CR acceleration and transport. We briefly describe them below.

2.1 Heliospheric current sheet and solar cycle

The tilt of the Sun's magnetic axis to its rotation axis is a function of time. Since the polarity of the solar magnetic field changes to the opposite every solar cycle, the heliospheric current sheet (HCS) has a complicated shape even for a nominal solar cycle with a single, constant frequency (determined by the solar rotation) describing all time dependent processes [22] (see Fig. 2, left panel). The HCS surface in that simulation was tracked with the level set method, but it is impossible to resolve the sectors of opposite polarity throughout the IHS because their width is proportional to the SW speed. The panel on the right demonstrates that an increase in the space resolution, in reality, makes the distribution of magnetic field chaotic. This makes it problematic the application of the approach used in, e.g., [23], where the heliospheric magnetic field was assumed unipolar in the belief that the actual polarity can be entered a posteriori, by following the HCS surface. It has been shown in [6, 20] that the assumption of unipolar heliospheric magnetic field is not truly helpful in the resolution of the HCS challenge because it results in a considerable overestimation of magnetic pressure in the IHS, as compared with Voyager data, and therefore exaggerates its effect, ultimately leading to the heliotail being split into two branches and acquiring a “croissant” shape [24, and the followup papers]. The discussion of this phenomenon can be found in [1, 19].

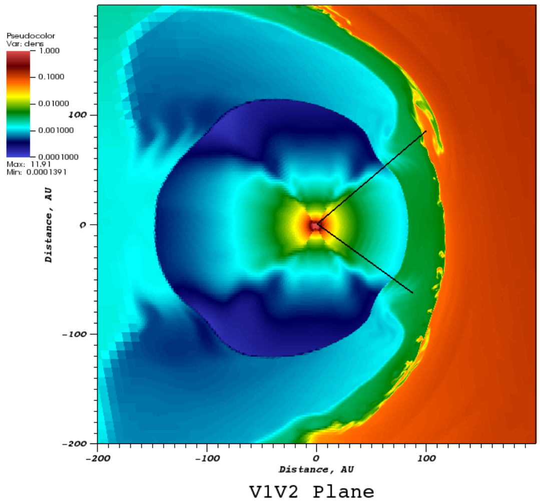

Figure 3: Plasma density in the plane formed by the Voyager 1 and and Voyager 2 trajectories shows instabilities of the heliopause and adjacent regions.

The current sheets can greatly affect the propagation of CRs through the heliosphere. For low-energy particles whose gyroradii are smaller than the size of the magnetic field sectors, particles can drift rapidly along the current sheet [e.g. 25]. For TeV CRs, their trajectories appear meandering rather than gyrating in the presence of opposite polarities of magnetic fields.

2.2 Heliopause instabilities

Of importance for GCR transport are instabilities of the heliopause. There are multiple mechanisms for that summarized in [6, 26]. Regardless of whether the instability is caused by the heliopause motion, Rayleigh–Taylor-type instability caused by charge exchange [27], as shown in Fig 3, a radially moving spacecraft would be crossing the regions of SW and LISM plasma consecutively. Thus, it would move through the plasma regions magnetically connected either to the Sun or remote LISM, which affects GCR fluxes.

It is interesting to note in this connection that the Rayleigh–Taylor instability in the heliotail described in [28] seems to be not physical, since it is instigated by the choice of initial conditions. In particular, neutral atoms are introduced into the computational region with the uniform distribution taken from the unperturbed LISM. This introduces extensive charge exchange, because the initial distribution of plasma corresponds to a simulation without atoms. As shown in [29], such artificial instability quickly decays with time.

2.3 Turbulence in the SW and VLISM

Turbulence in the IHS and VLISM is compressible, anisotropic, inhomogeneous, and extends over a broad range of scales [13, 30, 31]. Moreover, it coexists with coherent structures and nonlinear waves. Remarkably significant short- and long-term GCR modulation occurs in the IHS, which is not fully understood [32]. Figure 4 (left panels) shows magnetic field, plasma and GCR data in the IHS observed by V2. We computed the normalized power spectral density (PSD) of GCR count rates in the time interval 2013-2016 (right panel). To reconstruct the lower and higher frequency branches of the PSD we used the techniques described by [13, 30] with CRS data resampled at the resolution of 12 hours and 30 minutes. The power-law behavior of GCR power spectra shown here reflects the presence of turbulence. Different additional features are seen, e.g., spectral peaks and knees that set relevant time scales. At low frequencies, the spectra also include the effects of meso-scale structures in the energy injection regime of MHD IHS turbulence, such as the pressure pulses (possibly, shocks) observed by V2/PLS/MAG or large-scale dynamics that may be associated with the solar cycle. For example, the ∼ 25 and ∼ 50 day periodicities are clearly detected. Furthermore, a reference, the convected gyrofrequency ($f^C = V_{sw}/(2\pi r_c)$, where r_c is the gyroradius) of 20 and 540 MeV proton GCRs are $\sim 2.5 \times 10^{-6}$ Hz and $\sim 4.2 \times 10^{-7}$ Hz, respectively (using $B = 0.1$ nT, $V = 100$ km s^{-1}, while the gyrofrequencies are $\sim 1.5 \times 10^{-3}$ Hz and $\sim 9.6 \times 10^{-4}$ Hz), which also fall into the range of frequencies where a bulge in the PSD is observed.

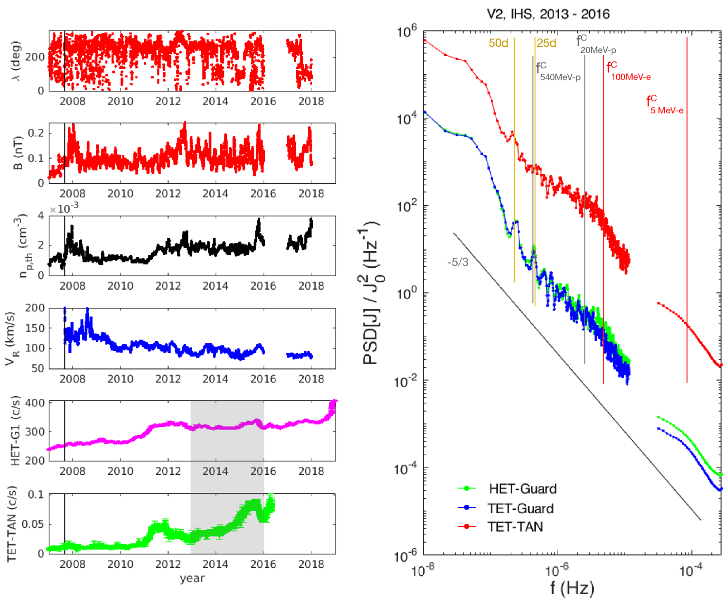

Figure 4: Voyager 2 observations of magnetic field, plasma, and GCSs in the IHS. (Left panels) From the top to the bottom, panels show the HMF azimuthal angle (λ); HMF strength; thermal proton density; radial velocity component; the omnidirectional GCR Guard rate measured by the HET telescope (> 20 MeV, proton-dominated), and the electron TAN rate (∼5 to ∼105 MeV). (Right panel) Power spectral density of the GCR Guard rates from HET and TET, and the GCR electron TAN rate in the IHS (2013-2016).

2.4 General structure of the SW–LISM interaction: bow shock and heliotail

The general topology of the heliopause is subject of theoretical discussions (see [19] and references therein). In contrast to a comet-like heliosphere, it was proposed in [33] that the heliotail can split into two branches. The solutions of the latter kind were further promoted in [34].

Neither of these papers took into account the solar cycle effects, as was done in [1, 19]. It is important to distinguish two physical phenomena: (1) the spiral heliospheric magnetic field is deflected tailwards on crossing the TS, which may result in the SW collimation, its density increasing inside the tornado-like magnetic field lines and (2) the above collimation makes the heliotail split into two branches. For this scenario to be realized, magnetic field should be strong enough, which is typically not so in the heliosheath, where magnetic pressure is considerably lower than the PUI pressure. It it is obvious from [1, 6, 20, 34], that this happens only of the HMF is assumed, contrary to the common knowledge, to be unipolar. This assumption makes the plasma beta in the heliosheath small enough to produce artifacts [1], see Fig. 5. In reality, magnetic pressure is almost 50 higher than it was observed by Voyagers. In addition, plasma density is substantially higher in the slow SW, as compared with the fast SW, and the boundary between them is a function of time, which makes the collimation impossible. Comet-like, long-tail solutions agree well with the anisotropy of TeV GCRs observed in a number of air shower experiments [35]. This requires computational grids extending to 12,000 au into the heliotail.

Non-stationary heliosphere gives rise to transient shock propagating upstream into the LISM and creates additional modulation to GCR fluxes [36].

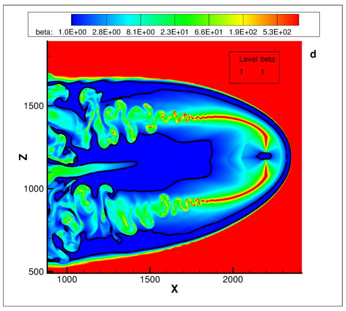

Figure 5: Distribution of plasma beta in the meridional plane (from [1]), in the assumption of unipolar HMF.

3. Summary

We described a few important physical processes affecting the transport of GCRs from the LISM into the heliosphere. One important issue is worth being emphasized: while it is clear that GCRs of moderate energy are affected by the presence of the heliosphere, even GCRs in the TeV-PeV energy range are affected. This means that any theoretical explanation of their behavior requires subtracting the heliospheric influence from air shower observations.

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