Proposal to ISSI for a Team to Address the Physics of the Very Local Interstellar Medium and its Interaction with the Heliosphere

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1. Executive Summary

We propose an international team to study the physics of the very local interstellar medium (VLISM) in the context of a variety of recent observations. These include *in-situ* measurements of the VLISM by Voyager 1, remote observations of energetic neutrals from the Interstellar Boundary Explorer (IBEX), and the anisotropy of high-energy galactic cosmic rays (GCRs) from Earth-based air shower detectors, revealing structure related to the VLISM, in addition to recent theoretical and modeling studies related to these observations. The goal is to bring experts together in each of these areas to discuss how they inform us of the nature of the VLISM, and particularly of the nature of interstellar turbulence which affects the transport of high-energy charged particles, such as GCRs. This will also maximize the science return from the relevant spacecraft missions.

We have assembled an international team of experts on the fundamental physics and observations of the VLISM, to work collectively on the problem of understanding what these new observations, taken as a whole, tell us about the heliosphere and VLISM, and the interstellar turbulence spectrum. We will have two separate meetings at ISSI each with duration of 4-5 days. We have commitments to participate on the team from:

- ***David Burgess*** (UK) Simulations and theory of shocks and instabilities relevant to the LISM
- ***Maciej Bzowski*** (Poland) Theory, simulations, and observations of the LISM; IBEX observations
- ***Iver Cairns*** (Australia) Theory and simulations of waves, shocks, and instabilities in the LISM.
- ***Alan Cummings***, (USA) representing the Voyager mission, observations of galactic cosmic rays
- ***Vladimir Florinski***, (USA) simulations, theory, and observations of the heliosphere and cosmic-ray transport, and turbulent magnetic fields
- ***Gwenael Giacinti***, (Germany) simulations, theory, and observations of TeV-PeV cosmic-ray anisotropies and their relation to interstellar turbulence
- ***Joe Giacalone***, (USA) theory and simulations of particle transport in turbulent magnetic fields
- ***Vladislav Izmodenov***, (RUS) simulations of the heliosphere and interactions with the VLISM
- ***Lan Jian,*** (USA) Voyager observations of magnetic fields in the LISM
- ***J. R. Jokipii***, (USA) theory of turbulence, interstellar medium, cosmic-ray transport
- ***Martin Pohl***, (Germany) theory, simulations, and observations of galactic cosmic rays
- ***Eric Zirnstein***, (USA) IBEX observations of the LISM.

The team comes from six different countries and has representatives from relevant spacecraft missions (IBEX and Voyager) and experts on the relevant data sets. It includes a broad selection of theorists and modelers with strong backgrounds in the physics of the VLISM. Our team also has three junior scientists (Giacinti, Jian, Zirnstein), as well as some senior and mid-career scientists.

This proposed team is timely because it has only recently been recognized that the interaction of VLISM with the heliosphere produces effects that inform us of local scales in the much-larger-scale turbulent plasma of interstellar space. Moreover, the heliosphere produces effects on the VLISM that have been observed which are not well understood. This is discussed in detail below.

2. Scientific Rationale

The interstellar medium is observed to be turbulent on scales from hundreds of kilometers to parsecs. Shown in Figure 1 is the spectrum of fluctuations in the interstellar electron density as determined from interstellar scintillations and other techniques. Its power-law nature, with a slope very close to the Kolmogorov value of -11/3 (-5/3 for the energy spectrum) suggests strongly an energy cascade from parsec scales to the smallest scales observed. This has been called 'the great power law in the sky'. These observations utilize the effect of the turbulence on electromagnetic radiation on lines of sight extending tens to hundreds to thousands of parsecs. The fluctuations in electron density are accompanied by magnetic-field fluctuations whose spectrum reflects the cascading properties of the various MHD wave modes that can be found in space. The small-scale magnetic-field structure of the VLISM influences the propagation of galactic cosmic rays (GCRs) as they are deflected by magnetic-field irregularities, leaving their imprint in the arrival distribution of cosmic rays at Earth.

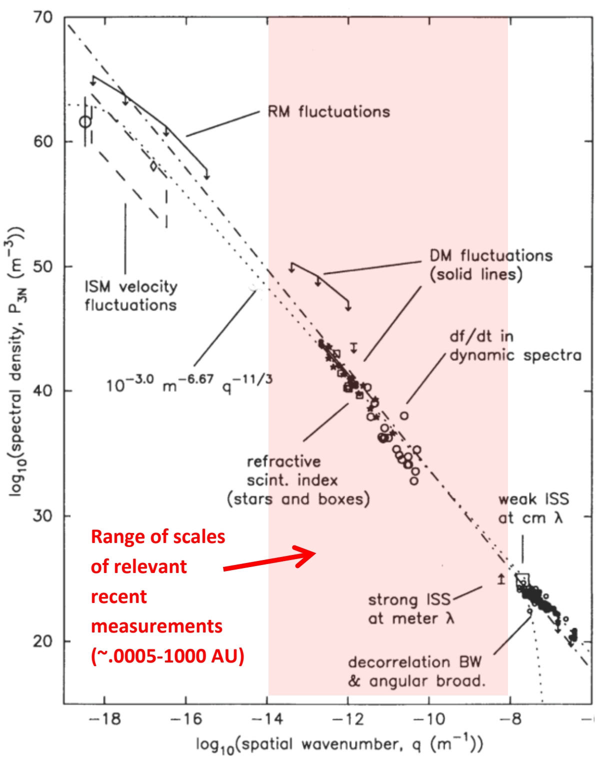

Figure 1: *The Observed spectrum of interstellar density fluctuations (Armstrong et al., 1995)*

Until recently, the existence of this spectrum in the immediate vicinity of the heliosphere was not confirmed. However, recent Voyager and IBEX spacecraft observations have opened the possibility of closing this gap. Voyager 1, most likely currently in interstellar space, is likely providing the first direct measurements of the small-scale end of this spectrum (Burlaga et al., 2015). These ongoing observations, as well as those of IBEX, SoHO, and others, and Earth-based cosmic-ray air-shower detectors also open the exciting possibility of using the effects on heliospheric scales to provide new information on the turbulence. In Figure 1 we have indicated the range of scales which correspond to those relevant to the interaction of the turbulence with the heliosphere.

Figure 2 shows a sample of recent studies relating heliospheric observations to the structure of the VLISM. The unexpected discovery of the IBEX Ribbon (McComas et al., 2009), an emission of energetic neutral atoms coming from the distant heliosphere and interstellar space, provides a new probe of the VLISM. For one, the width of the ribbon is likely related to a combination of the "draping" of interstellar magnetic field (ISMF) as it nears the heliosphere (e.g. Heerikhuisen et al., 2010; Zirnstein et al., 2016) and the turbulent component of the ISMF (Giacalone & Jokipii, 2015; Jokipii et al., 2010), or self-excited fluctuations produced by pickup ions (Schwadron & McComas, 2013; Isenberg, 2014). The small-scale structure in the ribbon (seen in the insert) is likely also related to interstellar turbulence. Also, the source region of ribbon-producing particles depends on energy. By examining the properties of the ribbon at different energies, one can infer the direction of the local ISMF (Zirnstein et al., 2016). It has also been proposed that the ribbon source is far from the heliosphere

(Grzedzielski et al., 2010), providing information on the interstellar medium over scales of a few thousand AU. Giacinti & Sigl (2012) have shown that the small-angular-scale anisotropies observed in TeV cosmic rays may be convincingly interpreted as a response of the cosmic rays to turbulent fluctuations in the interstellar magnetic field over approximately one parsec (the scattering mean free path of cosmic rays). More recently, Schwadron et al. (2014) related the dipolar TeV cosmic-ray anisotropy to the very local magnetic field and the IBEX ribbon.

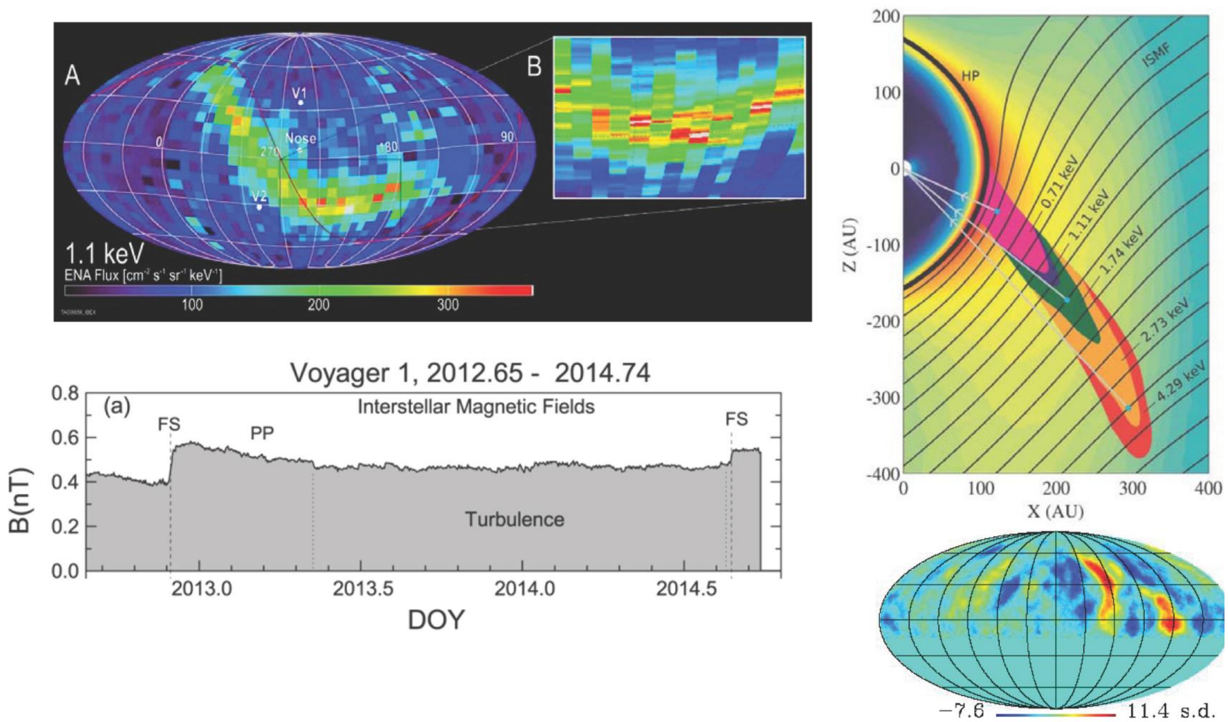

Figure 2: *The top left figure shows the well-known IBEX ribbon, with an insert showing structure likely related to local interstellar turbulence. The upper right image results from a calculation of the IBEX ribbon indicating how energetic neutral atoms of different energies, combined with a model of the "draped" interstellar magnetic field near the heliosphere, can be used to infer the direction of the local interstellar magnetic field. The lower-right figure shows structure in the anisotropy of TeV cosmic rays, also related to turbulence in the local interstellar medium. The lower-left figure shows Voyager 1 measurements of the magnetic field possibly indicating interstellar turbulence; two transient structures caused by disturbance from the heliosphere are also seen in this figure.*

In addition to the effects of interstellar turbulence on observations in the VLISM, the heliosphere affects the VLISM, changing some observed phenomena. For instance, Voyager 1 has observed three transient shock-like structures in interplanetary space. One of these disturbances is possibly related to the plasma-wave emission seen by Voyager 1 that convinced the science team that it was in interstellar space because the associated plasma density is comparable to that expected of the interstellar gas (Gurnett et al., 2013). These structures are interesting in their own right. They appear to be similar to shocks seen in the heliosphere, but seem to be thicker – that is, the magnetic-field magnitude increases gradually over scales which are much longer than the typical thickness of collisionless shocks (Burlaga et al., 2013). The association of these transient events with GCRs has also been noted (Jokipii & Kota, 2014), providing information regarding the transport of cosmic rays in the VLISM. Also, it may be that the flow pattern of the VLISM past the heliosphere distorts the interstellar turbulence discussed above. This effect would affect the discussion in Burlaga et al. (2015). These and other physical processes related to disturbances propagating out from the Sun into the VLISM provide further, important insights into the physics of the VLISM.

The observations discussed above provide previously unavailable information concerning the nature of turbulence near the heliosphere, and influence of the Sun and heliosphere on the local interstellar medium. Previous observations used fluctuations in various radiations over much larger distances (10-1000 pc) or more, so these recent observations may be an indication that the general interstellar turbulence is also present very near to the heliosphere. The proposed team meetings will involve focused discussions and collaborations which will make it possible to address and possibly answer a number of previously inaccessible questions, which include:

1. Is interstellar turbulence present locally, just beyond the heliopause?
2. Are the interstellar variations seen near Earth and by Voyager 1 in the outer heliosphere consistent with the general level of interstellar turbulence seen on larger scales?
3. What is the nature of the transient events seen by Voyager 1 and how do these transients from the Sun affect the VLISM and alter the intensity of galactic cosmic rays?
4. How does the heliosphere affect the plasma and magnetic field in the local interstellar medium?
5. To what extent does the reported interstellar turbulence affect the interaction of the interstellar medium with the heliosphere?
6. Do the new observations of the VLISM affect our understanding of the transport of GCRs in interstellar space and within the heliosphere? Do they help us understand the relatively weak amplitude of the GCR dipole anisotropy at both TeV and PeV energies (the so-called “CR anisotropy problem”)?

Value added to ISSI: The proposed topic relates to the topic of the very first ISSI workshop (and subsequent volume) on the interaction of VLISM with the heliosphere. Thus, our topic has a long history at ISSI. Moreover, the fact that our project is at the crossroads of several fields (heliosphere, interstellar medium, and high-energy galactic cosmic rays) makes our project very interdisciplinary. Also, any publications resulting from discussions at our team meetings will acknowledge ISSI support.

3. Meeting Schedule, Discussion Points, Expected Outputs

We will schedule two separate four or five-day meetings to be held at ISSI beginning as soon as practicable after proposal approval and extending over a period of 12-18 months. We will use the first meeting to define a minimum of 3 specific collaborations amongst the various team members, from which we will expect at least three joint publications. We will place considerable emphasis on nurturing these collaborations and on publishing results. For example, we will have occasional tag-up meetings via Skype, for example, between the two face-to-face meetings to report on progress. This will be managed by the team coordinators. The second face-to-face meeting will be used to report on the output from these collaborations and plans for publications. The only facilities required are a meeting room at ISSI with internet access and a projection system. We ask for the standard financial support, which includes living expenses while in Bern for each of the participants and travel support for the team conveners. ISSI is the ideal venue for this study for a number of reasons, it provides an environment conducive to studying these issues, it facilitates the attendance of European investigators, and ISSI has a history of enabling such studies.

In addition to creating specific collaborations amongst the team members, much of the first meeting will be devoted to discussion of spacecraft observations such as Voyager 1 and IBEX, Earth-based air-shower observations of TeV-PeV cosmic rays, and their interpretation in the context of the physics of the VLISM. This includes the most-recent observations and their capabilities for making more measurements in the VLISM. We will also discuss results of recent modeling and theory of relevant physical processes in the VLISM.

Possibilities include:

- Discussions of the latest models of GCR anisotropies and energy spectra and how comparisons between these and observations relate to the properties of the VLISM.
- We will discuss the magnetic field in the VLISM observed by Voyager 1 in the context of whether it is consistent with our expectations of VLISM turbulence. Moreover, we will discuss predictions for future observations. Do these observations constrain, for example, the coherence scale of interstellar magnetic-field turbulence? How? How does this turbulence affect the heliosphere?
- Since Voyager 1 does not have a functioning plasma instrument, does our increased knowledge of the VLISM through the combination of various observations discussed above provide predictions about the density and flow-velocity fluctuations in the VLISM that can be tested by Voyager 2, which has a functioning plasma instrument that will measure the plasma in the VLISM, when it crosses the heliopause?
- We will also discuss our current understanding of GCR transport in interstellar space in the context of the new observations of the VLISM.
- We will also discuss the importance of the transients, of heliospheric origin, that have been observed by Voyager in interstellar space. How common are they? What is their nature?

The schedule of the second team meeting will be decided after the end of the first meeting.

4. References

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