Galactic Cosmic Rays Near the Interstellar Interface
A Whitepaper Submitted to the NASA Heliophysics Vision 2050 Workshop


AAG: Office of Space Research and Technology, Academy of Athens, Athens, Greece; APL: Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; BU: Boston University, Boston, MA, USA; CIT: California Institute of Technology, Pasadena, CA, USA; MIT: Massachusetts Institute of Technology, Cambridge, MA, USA; UAH: University of Alabama, Huntsville, AL, USA; UAZ: University of Arizona, Tucson, AZ, USA

INTRODUCTION

At one time cosmic ray experiments reached the required altitude in the wicker basket of a hydrogen balloon, drifting with the wind thousands of meters above the Austrian countryside (Hess, 1912). In present day, analogous experiments reach their “high” vantage point of 150 AU from the Sun aboard the Voyager 1 (V1) spacecraft, immersed in the interstellar wind of the local interstellar medium (LISM), the frontier region connecting our heliosphere with the rest of the Milky Way galaxy (Krimigis et al., 2013; Stone et al., 2013; Cummings et al., 2016; Rankin et al., 2019; Hill et al., 2020). Since 2012, V1 has been in the LISM, beyond the heliopause (HP), measuring galactic cosmic rays (GCRs)—high energy particles accelerated elsewhere in the galaxy, probably in energetic events such as supernovae. The LISM in the vicinity of V1 is sometimes called the very local interstellar medium (VLISM) as it is barely beyond the heliosphere, if at all; in fact, some formulations name the inner heliosheath as the region between the solar wind termination shock (TS) and HP and the outer heliosheath as the region beyond the HP out to the heliospheric bow shock or bow wave, equating our terms, heliosheath (HS) and VLISM, with the inner and outer heliosheath, respectively. The heliospheric boundaries and regions are defined in Figure 1.

The VLISM—which was also entered in 2018 by Voyager 2 (V2), as reported in 2019 by Burlaga et al., Gurnett et al., Krimigis et al., Richardson et al., and Stone et al.—is not at all isolated from the effects of the Sun; it is in fact actively perturbed by solar activity, and so, dynamically, the VLISM is very much a part of the heliosphere. Yet in other ways it is also not quite a part of the heliosphere, at least the heliosphere as we have known it through several decades of in situ observation. This fascinating interface between the heliosphere and interstellar space, the VLISM, is a place, as we currently understand it, awash in the plasma, suprathermal particles, gas, and dust born in distant stars and galactic clouds, not the familiar products of the Sun. It is a place that is magnetically connected to the galaxy’s magnetic field, not directly to the Sun along the spiraling Parker field (Parker, 1958), and where GCRs are the dominant mobile charged particles.

Figure 1. A depiction of the heliosphere defining the regions and boundaries therein along with the spacecraft trajectories of three active outer heliospheric/LISM mission, V1, V2, and NH. The example magnetic field lines are intended to illustrate the typical magnetic connectivity of the field in the VLISM to the rest of the interstellar medium rather than to the Parker field. The tan highlights in the SW and the HS indicate the dominant solar origin of the particles in those regions as compared to the blue highlights designating the interstellar origin of the particles in the VLISM and LISM. Galactic cosmic rays pervade the entirety of the heliosphere but are especially potent probes of the VLISM region.
particle, not ions and electrons accelerated in the solar wind or at the Sun. The LISM is new to us. And the GCR phenomena available for study from this new vantage point, for a few more years while Voyager observations continue, are ripe for an intensifying level of study.

**QUESTIONS**

The scientific questions stemming from GCR observations in the VLISM, along with ongoing—New Horizons (NH; Stern et al., 2018; Hill et al., 2020 and references therein)—and past measurements in the distant heliosphere and the heliosheath, vary from persistent, global problems to new, more limited puzzles. Past and continuing remote energetic neutral atom (ENA) measurements of this region, such as from Cassini (Krimigis et al., 2010) and the ongoing Interstellar Boundary Explorer (IBEX; McComas et al., 2009a)—and a new mission, the Interstellar Mapping and Acceleration Probe (IMAP; McComas et al., 2018), with a planned launch in 2024—provide a global view and have contributed importantly to understanding aspects of the VLISM (McComas et al., 2009b; Dialynas et al., 2017).

One of the longest-standing problems is that of GCR transport throughout the heliosphere (see, e.g., Florinski, Ferreira & Pogorelov, 2013 and references therein); but, here we focus on the outer heliosphere and beyond. This has been studied for decades, driven largely by a continual stream of new data from the Voyager missions and increasing sophistication in modeling, enabled by advancements in computational technology. A new piece of information on this subject comes from the observation that the spatial gradient of GCRs outside the HP at V1 is consistent with zero (Cummings et al., 2016), which is not what global modulation models predicted. Another area of investigation is seeking the ultimate source of the GCRs themselves, for which it is necessary to uncover their source spectra, as they exist in the unperturbed LISM, away from the influence of any stars, including our sun. What is needed is not just protons and electron spectra but elemental and isotopic composition, the later useful for understanding the age of GCRs (Ptuskin & Soutoul, 1998). Spectral measurements from V1 (Cummings et al., 2016) get us closer to determining this key fact about GCRs, but will not get us all the way there. These are problems that can be addressed with continued theoretical work but also with more observational input, such as incorporating NH and V2 data and (when broadening our horizon to contemplate the next thirty years of exploration) new, high-resolution measurements from a mission to interstellar space.

Conversely, a fresh problem that was entirely unexpected is the puzzle of the episodic anisotropy episodes observed in GCRs in the VLISM (Krimigis et al., 2013), behavior quite unlike the nearly isotropic GCRs observed everywhere else, to that point. There have been explanations put forward—perhaps particle trapping associated with shocks plays a key role (Kota & Jokipii, 2017; Zhang & Pogorelov, 2020)—but this is an open question (Rankin et al., 2019; Hill et al., 2020) that requires a deeper analysis of existing observations, concentrated theoretical and modeling scrutiny and, as above, ultimately new observations. The V1 and
V2 traversals of the heliosheath from 2003 to 2018 have uncovered a large, unexpected dependence of particle intensities, including GCRs, on the proximity to the heliomagnetic sector zone (Hill et al., 2014). This robust observational feature has yet to be explained. Problems like these are benefiting from the close, coherent, and focused collaboration between theorist, experimentalists, and modelers made possible by science centers, such as Heliospheric SHIELD (http://sites.bu.edu/shield-drive/research/; M. Opher, PI).

A line of inquiry that is not new but which gathers increasing facility to probe the global heliosphere (due to new observations from NH along with new data as V1 and V2 transitioned into new regions), is that of solar disturbances, such as traveling shocks, contributing to GCR intensity variations and how these disturbances change as they propagate across the heliosphere (Figure 2). There has been recent progress on this (Hill et al., 2020) examining from 1 AU to the VLSM, but there remains a sizable opportunity to gain additional understanding, especially involving detailed case studies and statistical data analysis of the GCR intensities and associated low-energy phenomena and the global simulations needed to tie together the disparate observations. The continuation of Solar-related phenomena in the VLSIM calls out for new observations to investigate the influence of the Sun on the rest of the galaxy.

GCRs play a role in broader investigations of the heliosphere. As alluded to above the understanding of the global heliosphere must include GCRs to be complete. Studies that rely on the partial pressures—for example to investigate the width of the heliosheath, concerning which the difference between observations and theory cannot be reconciled (Krimigis et al., 2010)—need to include the GCR contribution. An understanding of the unusual GCR behavior in the VLSM is likely a sensitive probe of the interstellar magnetic field, which in turn connects to the question of the shape of the heliosphere, because the configuration of field lines draped around the heliopause is expected to depend on the particular heliospheric shape. (Opher et al., 2017). So, for purposes ranging from understanding the details of solar transients, to the shape of the heliosphere, to probing supernovae throughout the galaxy, Galactic Cosmic Rays, after over a century of study, remain of vital scientific interest and the prospects for continued, deepening knowledge punctuated by occasional discoveries is very good.

ACKNOWLEDGEMENTS

We would like to acknowledge useful, recent discussions among the members of the Heliospheric SHIELD DRIVE Science Center (M. Opher, PI) and the Interstellar Probe study (R.L. McNutt, Jr., Lead), as well as long term discourse among the science team members of the Voyager Interstellar Mission (E.C. Stone, PS) and New Horizons Kuiper Belt Extended Mission (S.A. Stern, PI; Stern et al., 2018).

REFERENCES


Dialynas, K. et al. (2017) Nat. Astron. 1, 0105, doi: 10.1038/s41550-017-0115


McComas, D.J. et al. (2009b) Science 326, 999, doi:10.1126/science.1180906


