Picture of Outer Heliosphere Develops with New Data

PAGES 499, 502–503

In August and September 1977, Voyagers 1 and 2 were launched to embark on the most extensive tour ever undertaken by a spacecraft. The Voyager spacecraft visited a number of previously unexplored planets and provided unique insight into these unknown worlds. In 1989, the Voyager spacecraft started an even bigger adventure into a new frontier that is, according to specialists in this field, very close to completion. Voyager is supposed to leave the space that is carved out by the supersonic solar wind of the Sun and begin exploring the region where the heliosphere interfaces with the interstellar medium. When this occurs, the Voyager spacecraft will be part of the history of humankind once again. They will be the first spacecraft to leave the region of space dominated by the Sun!

This piece discusses a part of a meeting held to discuss results from the flotilla of heliospheric spacecraft that are currently operating; specifically, that part concerned with "interstellar neutrals, pickup ions, and anomalous cosmic rays." This emphasized the outer heliosphere and its boundary regions.

The "holy grail" of this area of research is to observe the spheroid termination shock (TS) of the solar wind, which is located beyond the Voyager spacecraft's current position but affects the particle environment in the heliosphere, including the inner heliosphere near Earth. Its existence follows theoretically from the fact that the solar wind is supersonic and should undergo a shock transition before interfacing with the interstellar gas. This is illustrated in Figure 1 using a current state-of-the-art simulation of the flow patterns and boundaries, especially the TS, in the outer heliosphere [*Zank*, 1999]. The TS is a very effective accelerator of particles, and it is the source of the anomalous cosmic rays that are penetrating to Earth. The area between the TS and the unperturbed interstellar gas directly affects the intensity of cosmic rays entering the heliosphere.

Other means of remote measurement, such as radio waves, stellar absorption features, and neutral atoms coming in from the region of interaction of the solar wind with the interstellar gas also provide constraints on the geometrical structure and physical properties of the heliospheric space beyond Pluto. Of particular interest are the contrasts between galactic cosmic rays that come from elsewhere in the galaxy and the anomalous cosmic rays, which are accelerated to energies in excess of GeV (10^9 eV) at the termination shock. Such comparisons are telling us a great deal about the nature and location of the termination shock.

The scientific questions relating to this exciting area of research were debated in a number of talks and discussions dealing with the outer boundaries of the solar system, and, more generally, the space beyond the planets. Most of the experimental investigations rely on results from NASA missions such as Voyagers 1 and 2, the Advanced Composition Explorer (ACE) near Earth, and Ulysses on its trajectory to high heliospheric latitudes. In addition, data from Sampex, SOHO, Wind, IMP8, and Pioneer prove to be crucial as we try to answer many of these questions.

Where is the Termination Shock?

Stone [2001] recently summarized the experimental constraints on the location of TS. Based on a number of different approaches, the best estimate of the heliocentric distance of the termination shock at its nose was found to be $r_{TS} = 90 \pm 10$ AU. Very likely, the TS is within 110 AU. For reference, Figure 2 shows an estimated shock location using an MHD model and the Voyager heliocentric radius. The large-scale properties of the solar wind directly affect the TS location. At solar minimum, the TS typically moves 10–20 AU farther from the Sun because of increased solar wind bulk pressure. Figure 2 illustrates that there is a good chance to "catch" the TS before solar minimum, hopefully before 2006.

What is the Nature of the Termination Shock?

The lack of understanding of the physics of the termination shock has been a major reason for the difficulty of accurate prediction of its location. It is clear from basic fluid physics that a termination shock must exist. Furthermore, anomalous cosmic rays are a witness to the existence of a strong accelerator of particles. However, it is precisely this acceleration process that could change the nature of the TS. If the TS were not affected by accelerated particles, the shock would very likely be strong due to the high Mach number of the infalling solar wind. If the internal pressure of the accelerated particles becomes large, these fast particles manage to slow down the solar wind before it hits the TS, therefore producing

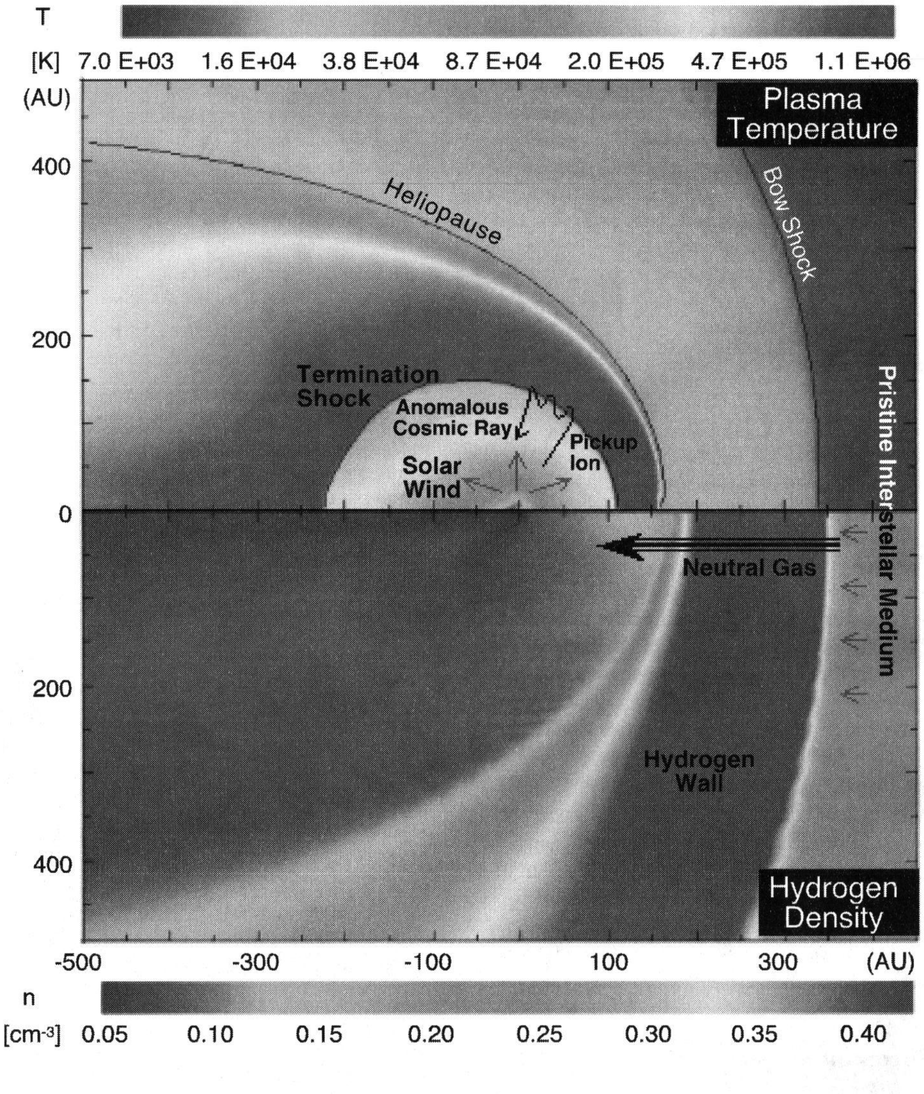

Fig. 1. A state-of-the-art simulation of the innermost heliospheric boundary, the termination shock, is shown. In this region, the solar wind speed drops to subsonic values. From a numerical simulation by Zank *[1999]. Original color image appears at the back of this volume.*

a weaker shock. So far, there is no evidence from Voyager data that such a foreshock region exists that would slow down the solar wind. This question will be resolved when Voyager crosses this shock. Local, in situ measurements of the magnetic field will be available, although the instrument was not designed to work in the extremely rarefied wind at large distances from the Sun.

What are the Sources of Energetic Particles Accelerated at the Termination Shock?

In their seminal paper, *Fisk et al.* [1974] predicted that the anomalous cosmic ray (ACR) component should be singly charged. They predicted that ionizing interstellar gas particles in the heliosphere, their convection with the solar wind as so-called pickup ions, and their acceleration at the TS would produce the anomalous component. This is in sharp contrast to galactic cosmic rays that are typically highly charged and have a different source. Even though this idea has been proven to be correct in principle, based mostly on data from the Sampex mission, the situation turned out to be more complex. Most importantly, there are ACR components that are not associated with interstellar gas.

Elements with low first ionization potential, such as Si and Mg, are almost fully ionized in the local interstellar medium and should not penetrate the heliosphere. However, there are ACR observations of such elements, which suggests another source for these accelerated particles. One possible candidate is neutrals in the heliosphere that result from the solar wind interacting with planetary objects and near-solar dust.

Acceleration Processes for Source Particles

Shocks are efficient particle accelerators for particle energies above ~1MeV/nuc. Shocks are therefore thought to be the most dominant sources of high-energy particles throughout the heliosphere and the galaxy. A major conundrum is the fact that shock acceleration by itself is not able to accelerate low-energy particles and inject them above the threshold of ~MeV/nuc.

Recent observation from ACE, Ulysses, and Voyager [*Gloeckler et al.*, 2000; *Krimigis et al.*, 2000] have revealed that the dominant acceleration mechanisms <MeV/nuc may be very different in nature and not associated with shocks. Solar wind and pickup ion particle distributions undergo significant heating at increasing heliospheric distance. This heating may be statistical in nature, but it is currently not understood. Figure 3 shows pickup ion distributions observed by SWICS-Ulysses. This acceleration mechanism produces high-energy tails, and these energetic particles are subsequently accelerated by the termination shock. This interaction process may have applications for many problems in magnetospheric, solar, and heliospheric physics, and the study of shock acceleration in the interstellar medium.

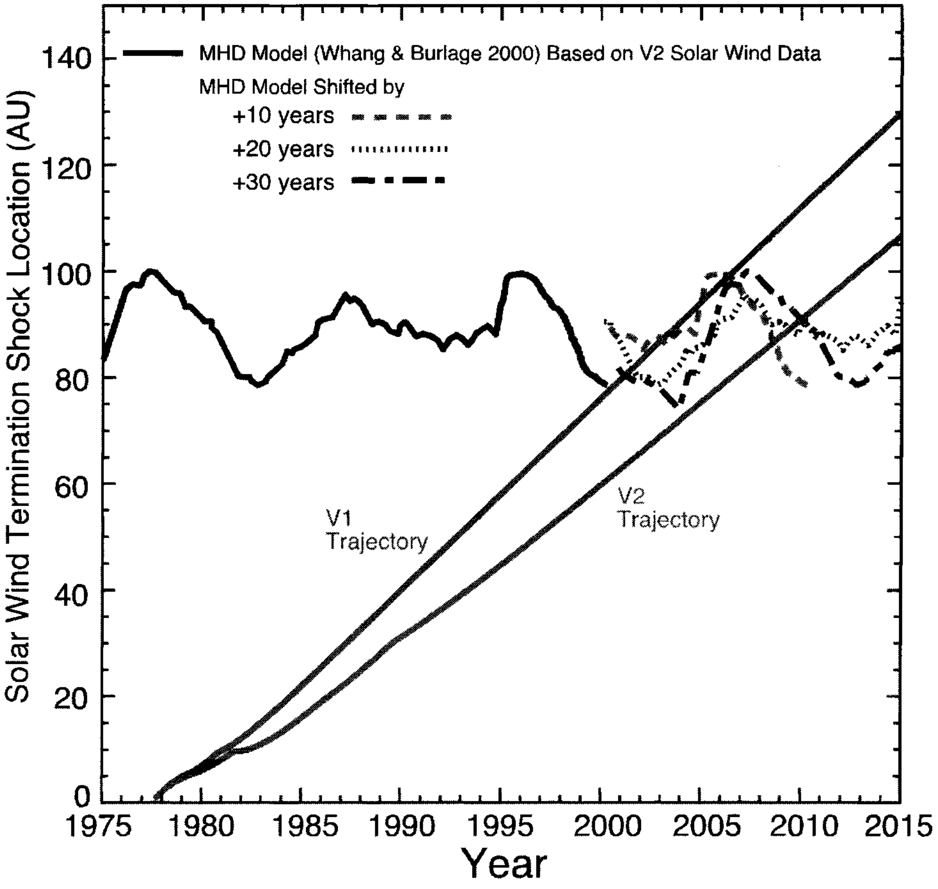

Fig. 2. The location of the termination shock is shown, as modeled by Whang and Burlaga [2000] based on Voyager 2 plasma data. To illustrate the possible range of shock distances in the years ahead, the predicted location from the prior solar cycle (solid blue line) has been shifted by 10, 20, and 30 years to visualize the variability of this boundary over three solar cycles. Voyager 1 is expected to cross the termination shock around 2003–2005, depending on the solar wind properties in the heliosphere during the next solar activity minimum. After Stone [2001]. Original color image appears at the back of this volume.

It was evident from the discussions and presentations at the October 2001 meeting that there is excellent agreement between theory and observation in these studies. A number of the talks focused on large-scale numerical simulations, but there were also numerous data studies from two generations of Voyager scientists. Researchers are confident that the near future will provide answers to many of the outstanding questions. There was also a sense of urgency during these discussions. At a time when quick success is advocated and budget pressures are real, lengthy investigations such as Voyager and Ulysses face funding difficulties.

Within 5 years, we should learn the position and nature of the termination shock, and we will learn about its ability to accelerate energetic particles. The steady progress of the Voyager spacecraft, combined with new remote sensing data from the inner heliosphere and new theoretical developments, should both resolve these important issues and reveal important aspects of the interaction of the solar system and its heliosphere with our local interstellar environment.

These results likely will lead to new investigations that will make use of instrumentation that was not available when the Voyager spacecraft were launched. Such new techniques allow remote sensing of the heliospheric boundary and may enable an investigation in the future that penetrates far beyond where Voyager has gone: the Interstellar Probe.

Acknowledgments

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References

Fisk, L. A., B. Kozlovsky, and R. Ramaty, An interpretation of the observed oxygen and nitrogen enhancements in low-energy cosmic rays, *Astrophys. J., 190*, L35, 1974.

Gloeckler, G., L. A. Fisk, T. H. Zurbuchen, and N. A. Schwadron, Sources, injection and acceleration of heliospheric ion populations, in *Acceleration and Transport of Energetic Particles in the Heliosphere*, edited by R. A. Mewaldt, T. H. Zurbuchen, and A. C. Cummings, AIP Conf. Proc. 158, 221, 2000.

Krimigis, S. M., R. B. Decker, D. C. Hamilton, and G. Gloeckler, Observations of pick-up ions in the outer heliosphere by Voyagers 1 and 2, in *Acceleration and Transport of Energetic Particles in the Heliosphere*, edited by R. A. Mewaldt, T. H. Zurbuchen, and A. C. Cummings, AIP Conf. Proc. 158, 333, 2000.

Stone, E. C., News from the edge of interstellar space, *Science, 293*, 55, 2001.

Whang, Y. C., and L. F. Burlaga, Anticipated Voyager crossing of the termination shock, *Geophys. Res. Lett., 27*, 1607, 2000.

Zank, G., Interaction of the solar wind with the local interstellar medium: A theoretical perspective, *Space Sci. Rev., 89*, 413, 1999.

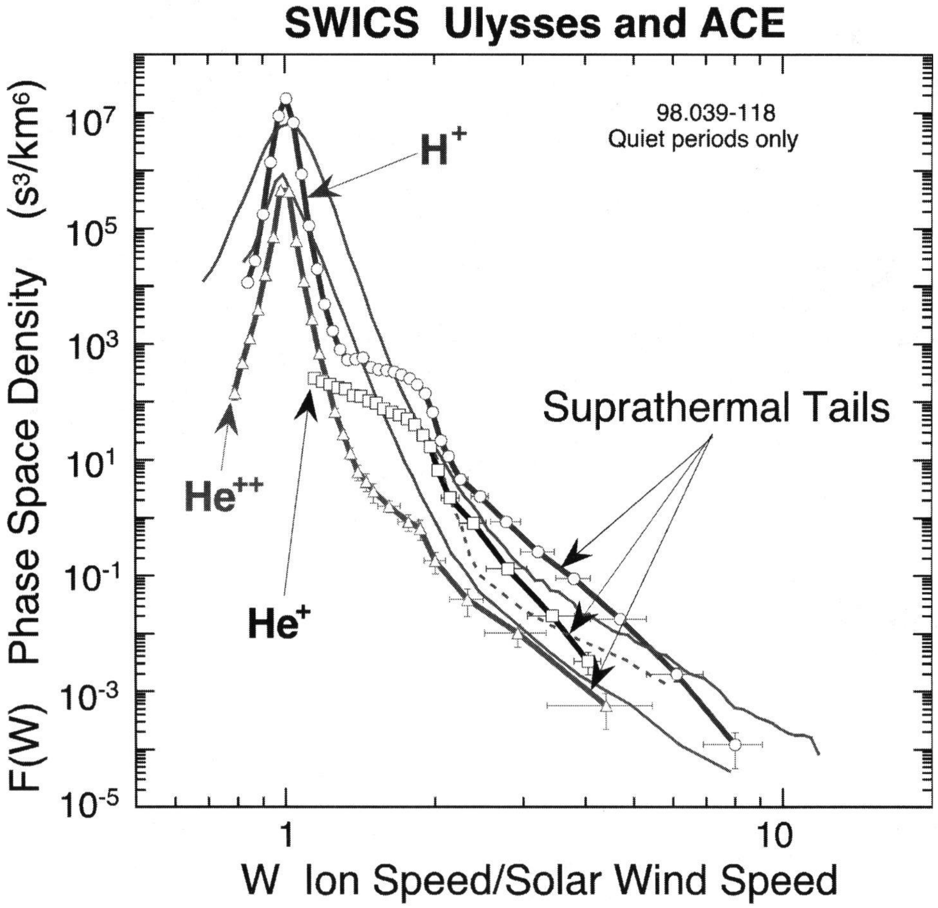
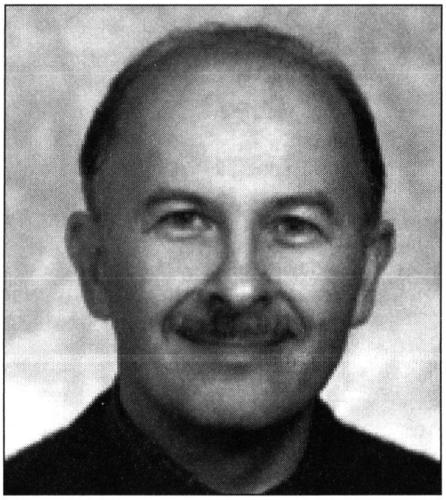


Fig. 3. Speed distributions of H^+, He^+, and He^{2+} observed in the quiet low-latitude solar wind is shown during approximate alignment of ACE and Ulysses. The ACE H^+ and He^{2+} data are shown by thin gray lines, scaled by 29.2 to account for the R^2 difference from ACE to Ulysses that was at approximately 5.4 AU during this period. These ACE data are compared to the Ulysses measurements of H^+, He^+ from solar wind and pickup ions and solar wind He^{2+}. All distributions show significant suprathermal tails that increase with heliocentric distance. These tails are likely created in the solar wind, without direct association with shocks. After Gloeckler et al. *[2000]. Original color image appears at the back of this volume.*

ABOUT AGU

Aykut A. Barka (1952–2002)

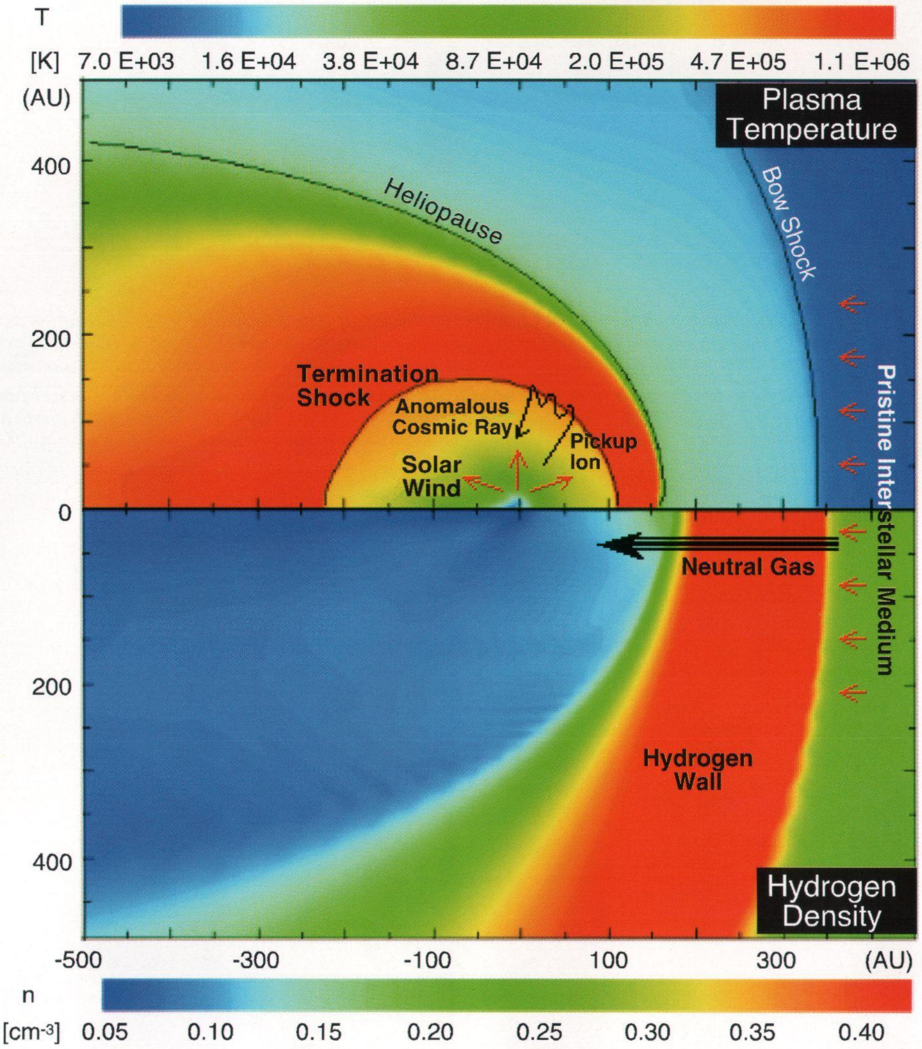
PAGES 499–500



Aykut Barka, a scientist respected throughout the world for the quality and depth of his research, died on 1 February 2002 from injuries suffered in a car accident five weeks earlier. Barka embodied the highest calling of science in service to the public. He was known for his unstinting integrity; his humor, openness, and selflessness; his plain talk to the Turkish public; and his tireless efforts to convince the Turkish government to confront the potential for an earthquake disaster in one of the most vulnerable countries in the world. Barka had been an AGU member (Seismology) since 1990.

An identical twin, Barka was born in Istanbul on 7 January 1952. He received a Ph.D. in 1981 from Bristol University in England, studying under the late Paul Hancock. Barka was a senior geologist for the Turkish Geological Survey (MTA) until 1985, a research scientist at the Massachusetts Institute of Technology from 1986 to 1990, professor at the Kandilli Observatory of Bosphorus University from 1990 to 1991, and later, professor at Istanbul Technical University. From 1983 to 1984, he was a visiting scientist at the Geological Survey of Japan. In 1985, he was a visiting professor at the University of Bristol, and in 1998 he was a visiting professor at the Institut de Physique du Globe de Paris. He also was a frequent visitor to the U.S. Geological Survey in Menlo Park.

Barka made deep and lasting contributions to the study of active faulting, drawing upon the tools of geomorphology, paleoseismology, and space geodesy. In a series of papers with R. Armijo, E. Altunel, S. Wesnousky, K. Kadinsky-Cade, and N. Toksöz, Barka studied the neotectonics and paleoseismology of the north and east Anatolian fault systems, focusing on the complexities of this great transform fault at its eastern and western extremities. He showed how basins could be used to understand the interaction of branching fault strands. This work not only extended the precious record of large earthquakes back several thousand years, but also offered a comprehensive model of the fault-driven evolution of the Marmara



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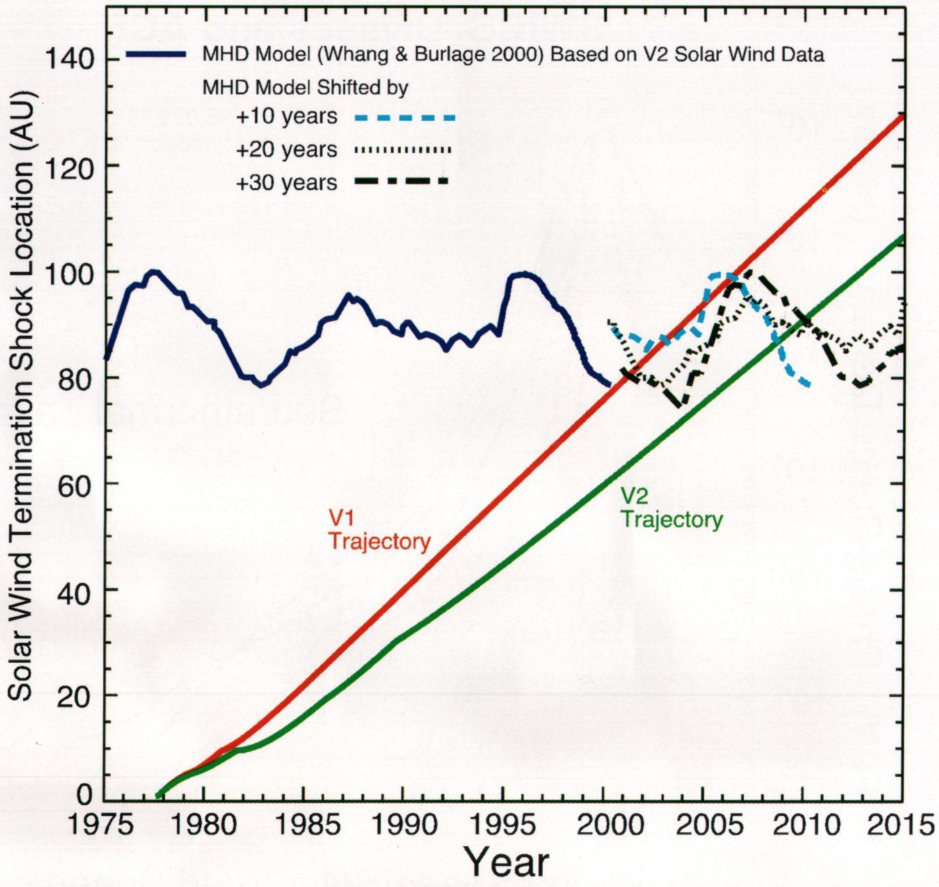

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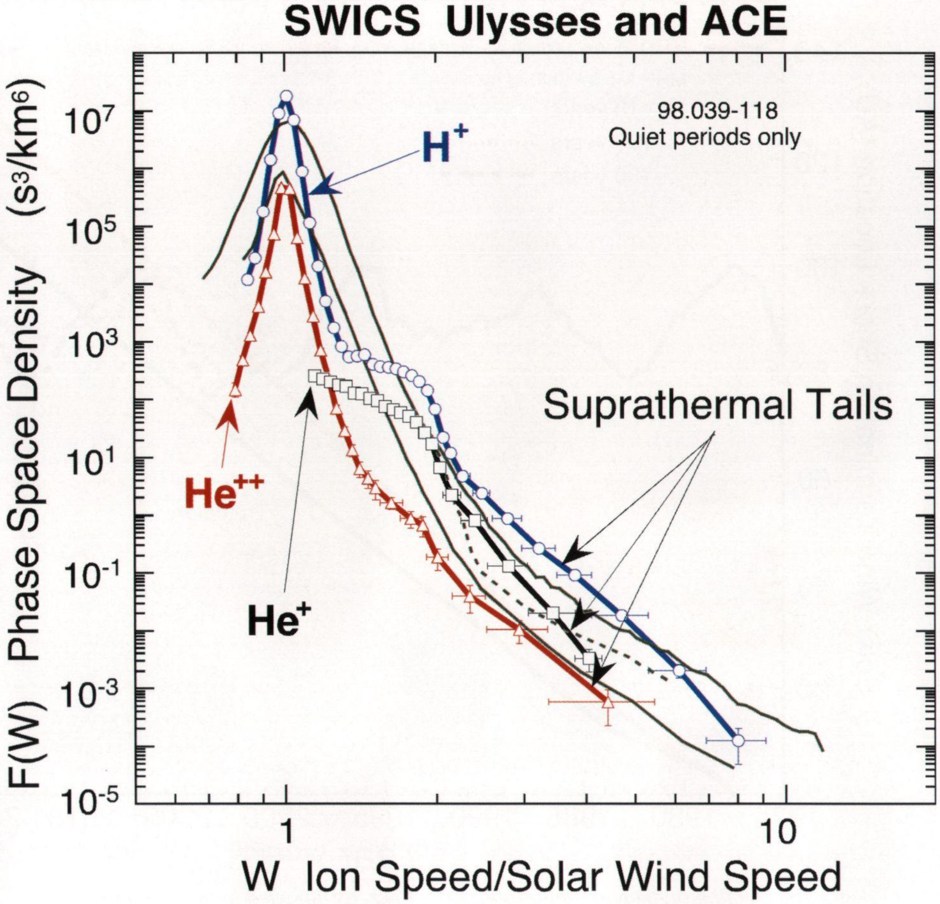

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