the same. Similarly, if the ideas of relativistic cosmology are correct, the temperature of the cosmic microwave background must be the same in all directions at the same distance and must scale as expected with redshift. All of this will be tested experimentally in future.

Astronomers and physicists are confident of the outcome, nearly certain that the fundamental concepts of cosmology and of Big Bang nucleosynthesis will once again be found to be consistent with observations. But perhaps present-day scientists are slightly less confident than their intellectual predecessors, Michelson and Morley, who set out to measure the velocity of the Earth with respect to the aether. □

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SOLAR SYSTEM

Heliosphere in a bottle

W. S. Kurth

WITH Pioneers 10 and 11 and Voyagers 1 and 2 now forming a veritable fleet of heliospheric probes, interest in the outermost reaches of the Sun's influence is mounting. When can we expect them to reach the regions where the solar wind's influence gives way to that of the local interstellar medium, and what will be seen there? These questions have led S. Minami to make the first laboratory simulations of the interaction[1].

First, the context of the problem. The solar wind, a stream of ionized solar gas with its associated magnetic field, flows radially outwards at supersonic velocities throughout the Solar System. Initially, it should expand more or less spherically, but must eventually collide with the local interstellar medium (ISM) through which the Solar System is moving. It is believed that the solar wind becomes subsonic at the termination shock, well inside the heliopause, yet beyond the current positions of the Voyager and Pioneer spacecraft. The shape of the heliopause — the boundary of the region of space dominated by the Sun's plasma — will depend on the relative velocities and, as a further complicating factor, on the interstellar magnetic field in our locality.

Some evidence of the interaction between the solar wind and ISM is already emerging, including low-frequency radio emissions possibly from the heliopause at distances of 116–177 astronomical units (1 AU is the distance from Earth to Sun)[2], and evidence for the termination shock in Voyager and Pioneer observations of the hydrogen Lyman-α lines[3].

But even if one or more of the probes directly samples the interface, models will be important in making sense of the observations and fitting them into a global picture. There have been numerous analytical and numerical simulations of this interaction, but all have suffered from the simplifying assumptions required to make the problem tractable. To be sure, Minami's laboratory simulations have their own limitations, but it is good to see that laboratory plasmas and theory can be used in complementary ways to fill in the gaps in our knowledge of the heliosphere.

In Minami's experiment, a barium plasma (representing the solar wind) expands into a flowing argon plasma with a variable magnetic field (representing the local ISM). Both flows are supersonic. The barium plasma is luminous, so a high-speed camera can take global images of the simulated heliosphere.

The primary purpose of the initial work is to investigate how sub- or super-Alfvénic flow of the local ISM alters the shape of the heliopause. The Alfvén velocity refers to the velocity of propagation of low-frequency magnetohydrodynamic waves in which the fluid provides the inertia and the magnetic field the restoring force. This velocity is proportional to the background magnetic field. The Alfvén Mach number is the ratio of the flow velocity to the Alfvén velocity; hence, Alfvén Mach numbers greater than 1 imply super-Alfvénic flow.

The shapes obtained for sub- and super-Alfvénic flow are rather different. In the two sub-Alfvénic cases that Minami looks at, the 'heliopause' develops a sharply pointed nose oriented into the ISM flow and an open tail streaming away from it (the exact direction of the tail depends on the angle of the interstellar field, and there is strong axial asymmetry if this is not parallel to the flow direction). The super-Alfvénic case (at low magnetic field) produces a parabolic shape to the nose, similar to that seen in many of the theoretical models. As we do not know all of the essential parameters of the interstellar wind, we cannot assume that the agreement implies that the flow is super-Alfvénic; rather, it suggests that the two independent methods of modelling the interface provide the same qualitative results and, therefore, at least partially validates the modelling approaches.

Minami estimates that the simulation implies distances to the heliopause in the range 200–400 AU, but he cautions that the scaling of distances in the experiment is more qualitative than quantitative.

This is evidently only the first in a series of experiments which can be done in the laboratory, and the work promises much more in the way of parametric studies of the interaction between solar wind and ISM. Its great advantage is the relative ease of varying important parameters such as the strength and orientation of the interstellar magnetic field to obtain even a qualitative understanding of their effect on the characteristics of the interaction. Analytical and numerical modelling has been limited in the ability to include such effects, particularly asymmetries.

A good example of numerical modelling appeared about the same time as Minami's laboratory work. In this model, Steinolfson and co-workers[4] use a gas dynamic model for the interaction without including the interstellar magnetic field. (Neither model includes the magnetic field of the solar wind.) In apparent agreement with Minami's super-Alfvénic result, the numerical model suggests a parabolically shaped nose, but the comparison cannot be taken further as the particular problem set up by Steinolfson *et al.* does not allow axial asymmetries. Again, the authors promise future work with additional effects included.

Modelling the heliosphere promises to continue with increasing intensity and fidelity as the deep-space probes approach and overtake the termination shock. The list of effects that various researchers urge should be incorporated is impressive: it includes the question of whether the shocked solar wind is compressible, the interplanetary magnetic field, resonant charge-exchange effects between interstellar hydrogen and the plasma, pickup of interstellar hydrogen in the solar wind, cosmic rays and the anomalous component of the cosmic-ray spectrum, the solar cycle, interstellar magnetic field strength and orientation, and a wide range of interactions at the heliopause which may or may not be analogous to effects at the Earth's magnetopause such as diffusion and reconnection. (See ref. 5 for a summary — although not an exhaustive review — of some of these modelling efforts.)

Given the sheer number of possible effects, Minami's type of experiment should be welcome to heliospheric physicists as a chance to compare the theoretical models to a real plasma system, as limited in its similarity to the actual heliosphere as it might be. □

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