MOMENTS IN THE LIFE OF A SCIENTIST

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Physics in space

At the end of the 1950s the appearance on the scene of new accelerators, capable of producing strong and controlled beams of high-energy particles, deprived cosmic rays of the monopoly over the study of high-energy nuclear interactions and of the elementary particles born of these interactions. Many other interesting aspects of cosmic-ray physics still remained to be explored. Among these were temporal intensity changes related to solar activity or due to other causes, high-energy extensive showers, etc. But these did not suffice to fill the vacuum left by the transfer of high-energy nuclear physics to accelerators.

As luck would have it, while the scope of cosmic-ray research was shrinking, the advance of space-flight technology was opening a rich, new field of scientific inquiry. Cosmic-ray physicists were in a privileged position to take advantage of this opportunity because of some kinship between cosmic-ray and space research with regard to both objectives and experimental tools. It is no wonder that these scientists should have been responsible for most of the early achievements of space science. My own contribution to this science was motivated by an interest in two subjects: the exploration of outer space and a search for celestial X-ray sources located outside the solar system.

Interplanetary space

Space activity in the United States, spurred by the success of Soviet space technology, was then in rapid expansion. In January 1958, barely four months after the launching of *Sputnik*, the first American satellite, *Explorer I*, went into orbit. With the detection of the Van Allen belt, this satellite started a long series of discoveries.

In the meantime the Federal government was proceeding to completely reorganize the space program by assigning the control over all space activities of a non-military nature to a new agency, the *National Aeronautics and Space Administration* (NASA). For its part the National Academy of Sciences created a committee, the *Space Science Board*, whose assignment was to stimulate and coordinate scientific activity in space. Initially the Board, under the chairmanship of Lloyd Berkner, included sixteen scientists, chosen from among the experts in one or another of the disciplines which were expected to substantially advance from observations in outer space. I was asked to join the Board, even though I was, in a way, a foreigner in the group. Or perhaps this was just the reason why I had been invited, my task being to discover possible gaps in the program developed by the experts.

Each Board member was asked to form a subcommittee. Three eminent scientists and close friends of mine – the biologist Salvador Luria, the physicist Philip Morrison, and the astrophysicist Thomas Gold – agreed to join my subcommittee. The subcommittee held its first meeting in September 1958. One of the conclusions reached at this meeting was the desirability of initiating a program aimed at the exploration of the physical conditions of interplanetary space.

As a matter of fact, it was hard to understand why this exploration should not have been included in the early program of NASA. Actually for several years observations from Earth had suggested that the space surrounding our planet is not entirely devoid of matter, as had been supposed in the past but contains a dilute *plasma*, i.e., an ionized gas consisting, presumably, of electrons and protons. Thus, already in 1930, Sidney Chapman and Vincenzo Ferraro in England had advanced the hypothesis that magnetic storms are produced by streams of ionized particles coming from the Sun and directed toward the Earth. More recently, in 1950, Ludwig Bierman in Germany had shown that the tails of type 1 comets (those formed by electrons and ionized molecules) could not be produced by the pressure of solar light (as had been assumed until then), and had suggested that the agent responsible for the formation of the tails was a fast stream of ionized gas originating from the Sun. In addition to these (and other more questionable) pieces of evidence derived from observations, theoretical considerations also supported the view that the space around the Earth contains a plasma in motion. According to a theory developed by

Eugene Parker, a physicist at the University of Chicago, the solar corona is not in a state of stationary equilibrium but expands steadily outward thus producing a plasma wind in interplanetary space, which Parker called the *solar wind.*

However, while there was general agreement about the presence of a plasma in interplanetary space, the views concerning the properties of this plasma were widely divergent. The estimates of the plasma density ranged from one to one thousand electrons and protons per cubic centimeter. Some believed that the plasma was nearly stationary, others that it was flowing with a speed of 1000 kilometers per second. Perhaps the plasma was distributed more or less evenly in space; perhaps it was condensed into clouds.

For us in the cosmic-ray group the problem of a plasma in interplanetary space was nothing new. For some time, we had been concerned with this problem because of the possibility suggested by some scientists that certain temporal changes of cosmic-ray intensity might be due to clouds of magnetized plasma ejected by the Sun into the surrounding space. I well remember the help we received from Philip Morrison and Thomas Gold in our attempts to bring the problem into focus. Therefore, having dutifully reported to the Space Science Board the recommendations of my subcommittee, I felt motivated to initiate a study of interplanetary plasma with my own group at MIT. Thus was born a research program which continues to this day and has been one of the major research activities of the Institute.

The first to join this new venture was Herbert Bridge who would later become one of the leaders in the science of interplanetary plasma. Others followed: Frank Scherb, Edwin Lyon, Alan Lazarus, Constance Dilworth-Occhialini, Alberto Bonetti, and Alberto Egidi.

Our plan called for an experiment to be performed in outer space by means of a plasma probe carried aloft by a satellite. In designing the probe, several requirements had to be kept in mind. In the first place, since one of our purposes was to study the motion of the plasma, the probe must record the protons and ignore the electrons, because in a fast-moving plasma made of protons and electrons, the protons form a beam of particles all moving in almost the same direction, which is the direction of motion of the plasma itself, whereas the electrons, on account of their high thermal agitation,

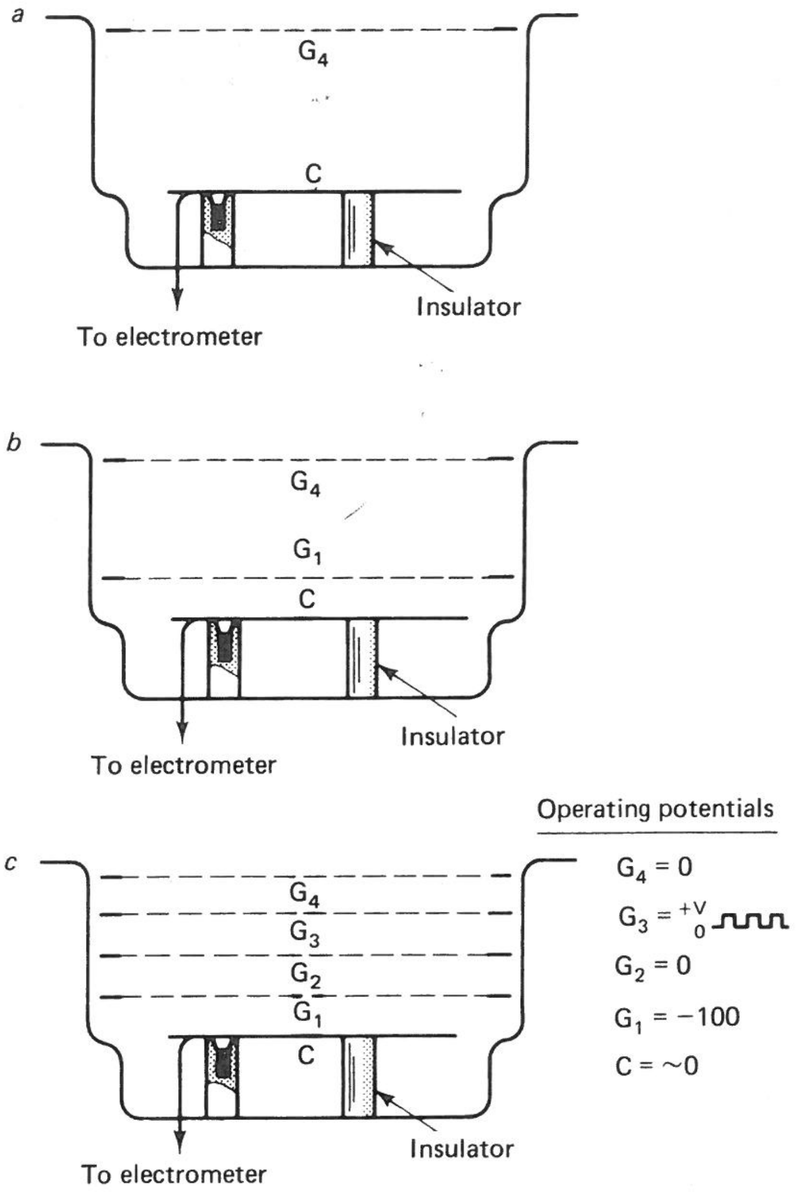

Fig. 6.1. Steps in the development of the MIT plasma probe.

move more or less at random and therefore cannot provide any information on the bulk motion of the plasma. Second, because of the very large uncertainty concerning the properties of the plasma, a large dynamic range was an essential property of the measuring instrument. Finally, we wanted our probe to be of solid design, simple in its construction and fully reliable in its operations. With these requirements in mind, we planned our probe starting from the model of a classical, well-tested instrument, the *Faraday cup*. We would build this cup (see Fig. 6.1*a*) by placing a plate C (the collector), behind a grid, G_2, that covers a hole in the skin of the satellite. The grid would be kept at the potential of the satellite's skin (to be called *zero potential*) while the collector would be brought to a negative potential. When a plasma stream entered the chamber through the grid, the protons would reach the collector, while the electrons would be repelled by it. Thus in the collector circuit there would appear an electric current of an intensity proportional to the proton flux.

However, we were aware that measurements taken with an instrument of this design would be subject to a serious source of error, because the strong solar radiation impinging upon the collector would eject electrons which, moving toward the grid, would produce in the collector circuit an electric current of the same sign as that produced by the protons moving in the opposite direction. We could remove this inconvenience by placing, in front of the collector, a second grid, G_1, kept at a negative potential relative to the collector (see Fig. 6.1*b*). This grid, by repelling the photoelectrons emitted by this electrode toward the collector, would stop the *direct* photoelectric current created by these electrons. While doing so, however, it would generate a *reverse* photoelectric current due to the solar radiation reflected toward it by the collector. We soon realized that it was not possible to entirely suppress the photoelectric disturbances by adding more grids, because each new grid would have been a new source of photoelectrons. Clearly, we had to contrive some entirely different method of making the response of our probe insensitive to the photoelectric effect.

It was not an easy problem. But finally we found a satisfactory solution, which consisted of *modulating* the proton flux *selectively*, i.e., without, at the same time, *modulating* the photoelectric current. The modulation was achieved by a third grid (the *modulating grid* G_3 in Fig. 68.1*c*), whose electric potential oscillates rapidly between zero and some positive voltage (the *modulating voltage*). The modulating grid will cut off the flow of protons with energies below a certain value which, for normal incidences, equals the value of the modulating voltage (if this voltage is measured in volts, and the energy is electron volts). The modulation of the proton flow will produce in the detector circuit an alternating current of an intensity proportional to the modulated part of the proton flux. Photoelectric currents, not subject to modulation, will not affect the measurements.

We were concerned about the possibility of disturbances arising from a capacity coupling between the modulating grid and the collector. Actually, on the face of it, we did not see how it would be possible to record millivolt signals in the vicinity of an electrode where voltage fluctuations of hundreds or thousands of volts were taking place. Thus I did some figuring and found that while, in fact, a single grid between the modulating grid and the collector (such as the grid G_1 already included in the design of the probe) would not suffice to entirely shield the collector, two grids would afford perfectly adequate protection. On the basis of this result, we decided to insert still another grid (G_2) directly behind the modulating grid.

Having completed the conceptual design of the probe, we proceeded to construct a model of the instrument, which we then submitted to a number of tests. For this purpose, we placed the probe in a vacuum chamber and exposed it to beams of protons of different energies, incident at different angles with respect to the normal to the cup. We used a modulating frequency of 1400 cycles per second. For each energy of the protons and for each angle of incidence, we measured the alternating current in the collector circuits, with values of the modulating voltage ranging from 5 to 2300 volts. The results were in perfect agreement with the expectations. The minimum observable current turned out to be of about 2×10^{-11} amperes, corresponding (for protons at normal incidence) to a flux density of $4 \times 16^{6}/\text{cm}^2/\text{s}$. The maximum detectable flux density (a limit set by the saturation of an electronic amplifier in the collector circuit) was about 2×10^{10} protons cm^2/s.

Our tests confirmed the expectation that the probe would have the capability of measuring the energy spectrum of the plasma protons, a property that derived from the fact that the intensity of the alternating current in the detector circuit was a measure of the number of protons in that part of the energy spectrum which extends up to the energy of the protons subject to modulation by the applied modulating voltage. We also verified that no spurious signals occurred because of a residual coupling between the modulating grid and the collector. Most importantly, we verified that photoelectric currents produced by intense ultraviolet radiation did not in the least affect the alternating current in the collector circuit. These tests made us confident that we entirely understood the behavior of our probe in all of its details, and that there would not have been any ambiguity in the interpretation of its results. Having reached this stage of our work we were ready and anxious to fly.

While our work was in progress, other scientists were engaged in programs directed, like ours, to the exploration of physical conditions in interplanetary space. The only team which had already done some direct observations in space was a group of Soviet scientists, under the leadership of Konstantin Gringauz. From 1959 to 1961 they flew their detectors on four satellites, the first three directed at the Moon, the fourth at Venus. As implied in the name *charged particle traps*, these detectors were not designed specifically as plasma probes, but were to be used to measure fluxes of charged particles (electrons or protons) in outer space, and actually many of the results of the Soviet scientists referred to the electron population in the general proximity of the Earth. Like our probes, the Soviet traps were modified Faraday cups. But, as the Russian scientists were aware, their design did not provide adequate protection against photoelectric interference, nor did it afford the possibility of significant measurements of the proton energies, the two important features that modulation had provided for our probe. The Soviet observations of greatest interest to us were obtained by the traps aboard *Lunik III* during its flight to the Moon. From a geocentric distance of about 255 000 kilometers and up to impact on the lunar surface, the traps recorded a flux of charged particles, presumably protons. The authors correctly claimed that their experiment had provided the first evidence for the presence of a stream of charged particles in interplanetary space. However they could only state that the energy of the particles was greater than 15 electron volts, and that the direction of their motion was consistent with the assumption that they came from the Sun.

In the USA two other groups besides ours were making preparations for experiments on interplanetary plasma. The first was a group working at the Jet Propulsion Laboratory (JPL) under the direction of Conway Snyder and Marcia Neugebauer; the second was a group working at the Ames Laboratory of NASA, under the direction of Michael Bader. In their final design, the instruments developed by these two groups were based on the deflection of a stream of charged particles in the electric field between two curved plates held at different electric potentials. Despite the friendly personal relations between the members of the three groups, it was inevitable that when the time came to fly our instruments, a keen competition would develop for the privilege of being the first to do so. We felt that we deserved this privilege. I had been the first to alert NASA, through the Space Science Board, about the importance of plasma measurements in interplanetary space; with a series of lectures at various institutions I had done my best to bring the problem to the attention of the scientific community in the United States. Moreover our group had already developed and fully tested an original, most reliable plasma probe, capable of precise measurements.

Eventually, after several ups and downs, it looked as if our way was clear to an early flight. It so happened that, for some reason, NASA had changed the mission of one of its satellites, *Explorer X*, from a flight to the Moon to an orbit around the Earth. James Heppner, a physicist working at the Goddard Space Flight Center of NASA, obtained the use of *Explorer X* for a study of the geomagnetic field in the space around the Earth. Clearly, simultaneous measurements of plasma and of magnetic field were essential for a complete description of the hydromagnetic conditions in outer space. Thus our request to fly our plasma probe on the same satellite was accepted. But our worries were not yet over. For we learned that a plasma probe, developed by another laboratory, might fly before ours on a different satellite. At this point (we are now in the spring of 1960) I wrote a long letter to Homer Newell, Deputy Director of Space Science at NASA which read, in part: 'The interest in a program of plasma measurements that we have succeeded in generating has not been sufficient to ensure adequate support to this program, but might well have been sufficient to freeze us out of it.' These were harsh words, explained, if not justified, by my strong concern over the fate of our experiment. I seem to have felt that I was not being fair to NASA and, in particular, to Homer Newell (our best friend at NASA Headquarters) for I ended the letter with the words: 'I realize that I have disposed of in less than three lines of our debt of gratitude to NASA, while I have filled more than two pages of criticism. This, I am afraid, is the incurable ingratitude of human nature.' I do not know whether this letter had any effect. Be this as it may, on March 21, 1961, *Explorer X*, carrying our plasma probe and Heppner's magnetometers, was launched into a very elongated elliptical orbit, which reached an apogee of 46.6 earth radii, in a direction about 33° from the anti-solar direction.

The magnetic field detectors included a rubidium vapor magnetometer and two flux gate magnetometers. Our plasma probe was mounted on the side of the satellite, looking in a direction perpendicular to the satellite's axis (see Fig. 6.2). An aspect sensor, provided by the Goddard Space Flight Center, was used to indicate the instantaneous orientation of the satellite.

During the flight, the spacecraft was spin-stabilized and spun around its axis with a rotation period of 548 milliseconds. It was anticipated that, if the plasma had a sufficiently high bulk velocity relative to the satellite, the proton flux detected by the probe would be modulated by the satellite's rotation, reaching a maximum when the direction of the normal to the cup came closest to the plasma velocity vector. The sharpness of the maximum would provide a measure of the degree of collimation of the proton beam. Solar cells were not yet available. Thus our satellite was powered by chemical batteries which provided reliable operation of the probe for about sixty hours, during which time the satellite almost reached the apogee.

The International Conference on Cosmic Rays and the Earth Storm, held in Kyoto in September 1961, provided the opportunity of acquainting the scientific community with our *Explorer X* experiment and of presenting some preliminary results. The most significant finding was the existence of two sharply separate regions around the Earth. In the first region (nearer to the Earth) the plasma probe did not give any signal that could be ascribed to an interplanetary plasma (while the magnetometers recorded a fairly regular magnetic field). In the second region (farther from the Earth) the plasma probe recorded a substantial, although variable, proton flux, while the magnetometers recorded a somewhat weaker, irregular magnetic field. The proton flux was strongly modulated by the rotation of the satellite, the maximum intensity being observed when the angle formed by the normal to the cup with the Sun's

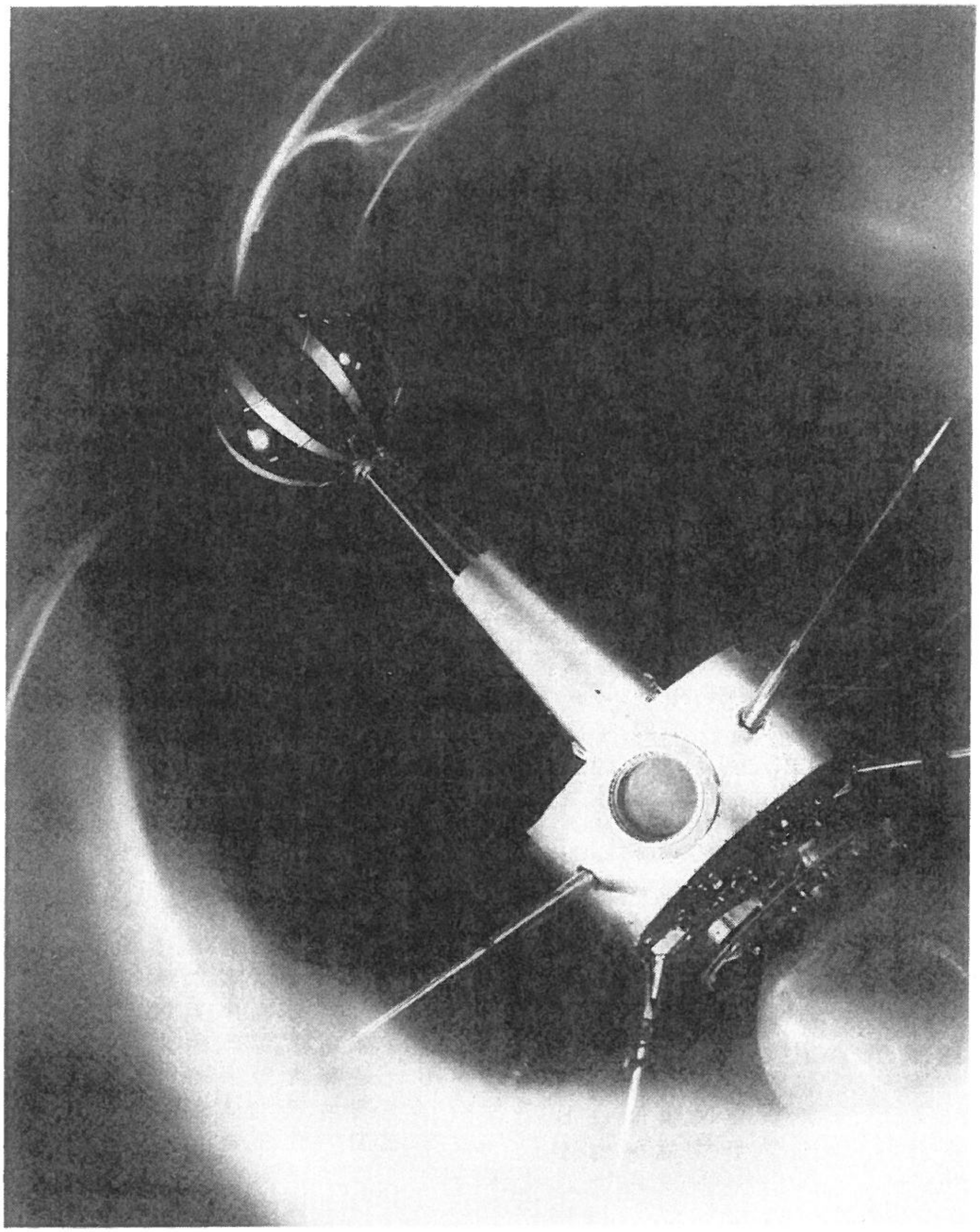

Fig. 6.2. The MIT plasma probe mounted on the side of *Explorer X*.

direction went through a minimum (see Fig. 6.3). The average energy spectrum of the protons peaked around 500 electron volts. The typical density was in the range of 6 to 20 particles per cubic centimeter. *Explorer X*, travelling in a direction away from the Sun, crossed the boundary between the two regions at a distance on the order of twenty Earth's radii.

In the months following the Kyoto meeting, we carried out a

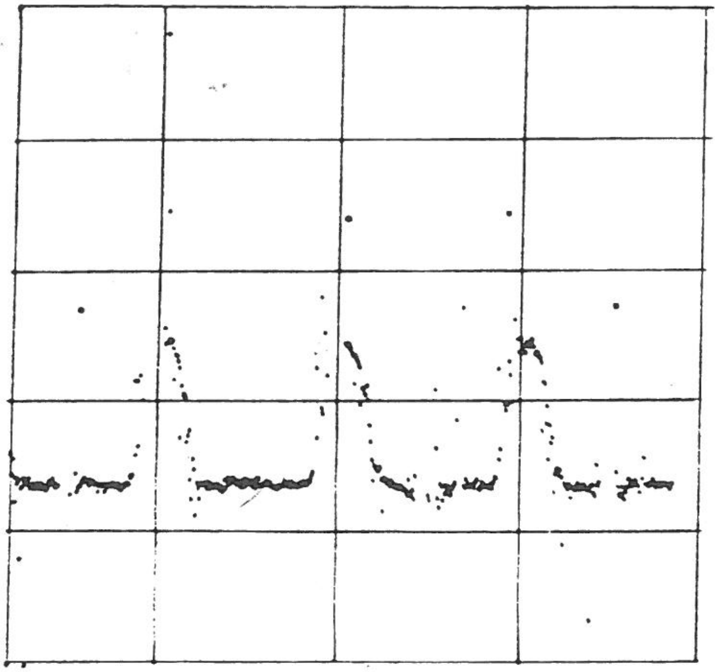

Fig. 6.3. Modulation of the plasma flux due to the rotation of the satellite. Vertical lines show the azimuth of the Sun. From an article by A. Bonetti, H. Bridge, A. Lazarus, E. Lyons, G. Rossi & F. Scherb in *Space Research*, III, 543 (1963).

detailed and critical analysis of our plasma measurements. We compared them with the simultaneous measurements of the magnetic field and examined the consequences that could be drawn from the experimental data. At the Third International Space Science Symposium held in Washington in the spring of 1962, members of our group described the experimental procedure and the final results of our work. In a speech summarizing our conclusions I said:

> Behind the Earth (i.e., downstream with respect to the plasma wind) there exists a region which is effectively shielded from the wind by the Earth's magnetic field. The boundaries of this region, which we may call '*geomagnetic cavity*', appear to be quite sharp. Beyond them, a plasma flow is observed, whose protons have a mean kinetic energy of about 400 ev, indicating for the plasma a bulk velocity of about 300 km per sec. The proton flux fluctuates around a mean value on the order 3×10^8 particles per cm^2 per sec, indicating a plasma density on the

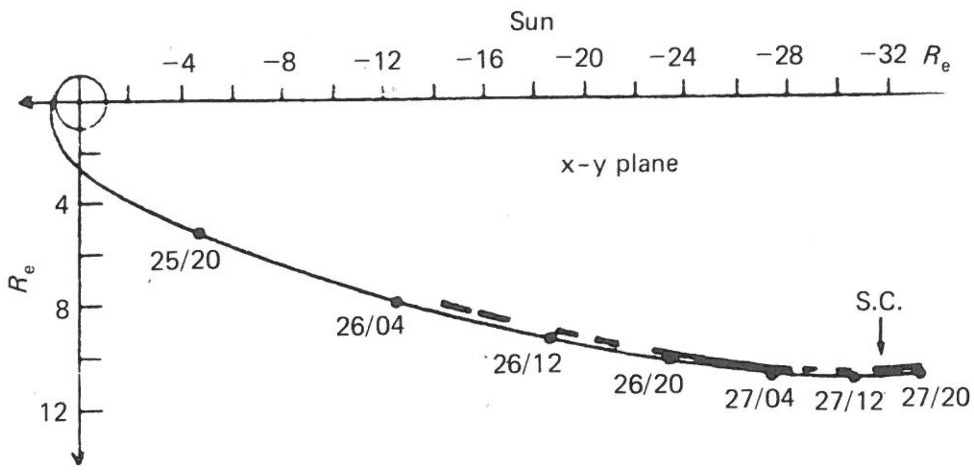

Fig. 6.4. Projection on the plane of the ecliptic of the trajectory of *Explorer X*. Heavy lines show the sections of the trajectory where plasma was observed. From a paper by A. Bonetti, H. Bridge, A. Lazarus, E. Lyons, B. Rossi & F. Scherb in *Space Research*, **III**, 542 (1963).

> order of 10 protons and electrons per cm^3. The direction of the plasma wind lies within a 'window' of about 20° × 60° aperture, which includes the Sun. An appreciable energy spread is observed, which may be explained by the assumption that the moving plasma has a 'temperature' between 10^5 and 10^6 degrees Kelvin. Explorer X crossed the boundary of the geomagnetic cavity at a distance of about 22 Earth radii from the center of the Earth. However, on several occasions during the rest of the flight, the plasma current disappeared and then reappeared again. A tentative interpretation of this effect is that the satellite was flying close to the boundary of the geomagnetic cavity and that this boundary was not fixed in space but was moving back and forth, perhaps as a consequence of variations in the speed or in the density of the plasma wind.

Figure 6.4 shows a projection of the *Explorer X* trajectory on the ecliptic plane. The heavy segments indicate the sections of the trajectory where substantial fluxes of protons were detected.

Comparing the velocity of the plasma flow with the velocities of plasma waves, we found that the plasma wind was supersonic. Therefore we concluded that:

> The picture emerging from *Explorer X* data is that of a

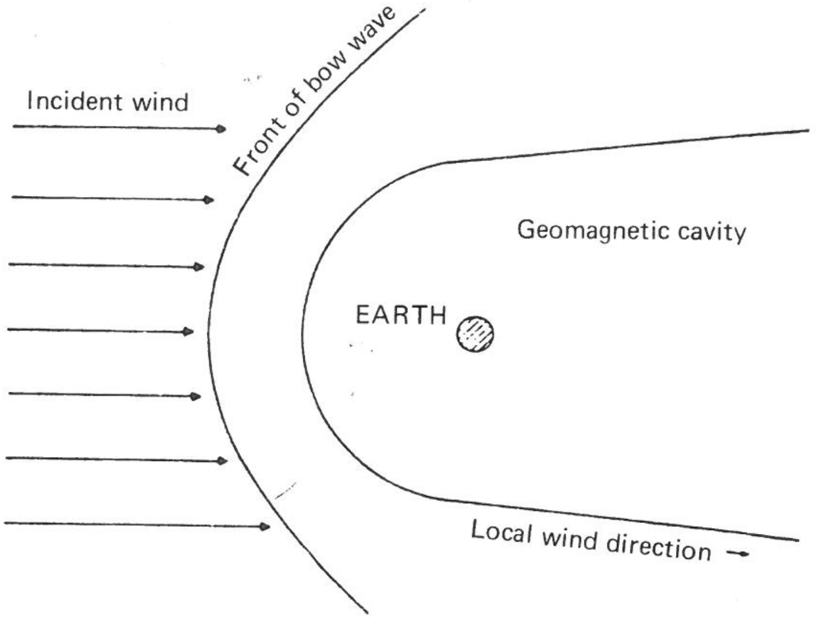

Fig. 6.5. Schematic picture of the geomagnetic cavity and the bow wave. From an article by A. Bonetti, H. Bridge, A. Lazarus, B. Rossi & F. Scherb in *Journal of Geophysical Research*, 68, 401 (1963).

> supersonic flow of plasma around an obstacle represented by the Earth's magnetic field. Under these circumstances one should expect the formation of a 'bow wave', pointing towards the direction of the oncoming wind and enveloping the geomagnetic cavity.

A schematic illustration of the above conclusions appears in Figure 6.5.

We were aware of the possibility that *Explorer X*, while outside the magnetic cavity, might have remained inside the bow wave, and that the properties of the plasma might have been modified by the transversal of this surface. However, we took the view that, whatever interaction with the Earth's magnetic field might have occurred, it could not have increased the wind's velocity; thus from the supersonic character of the observed plasma flow, it was safe to conclude that the plasma flow in free space was also supersonic. (Actually, the observed velocity could not have been very different from that of the wind in free space because *Explorer X* was flying along the tail of the geomagnetic cavity, which was nearly parallel to the plasma flow.)

In the years that followed the flight of *Explorer X*, the study of the interplanetary plasma and of its interactions with the various bodies of the solar system has become one of the most active branches of space research. Observations were carried out at greater and greater distances from the Earth, with flights to the Moon, then to Mars, Venus, Mercury, Saturn, Uranus, and Neptune. The MIT group, under the leadership of Herbert Bridge, and with the active participation of other experimental and theoretical physicists, foremost among them Stan Olbert, has kept at the forefront of these research activities. The modulated plasma probe, originally developed for the *Explorer X* experiment is still being used, having proven to be the most effective detector for many kinds of plasma measurements.

X-ray astronomy

In 1959, when I first began to think about the experimental program which was to become the forerunner of X-ray astronomy, the Sun was the only known celestial source of X-rays. It is a comparatively weak source, which can be detected easily from the Earth because of its proximity. For over ten years, solar X-rays had been studied extensively by scientists at the Naval Research Laboratory (NRL), under the leadership of Herbert Friedman. Astronomers had known that it would be very desirable to extend their observations of more distant celestial objects into the X-ray range of the spectrum, but they had been deterred from doing so by the foreseeable extreme weakness of the X-ray signals reaching the Earth from these objects.

Because of the strong absorption of X-rays in air, extraterrestrial X-rays can be detected only from above the atmospheric blanket. For their observations of solar X-rays the NRL team had used detectors carried aloft by the rockets that were then available. Now the more powerful rockets and the satellites, products of the developing space technology, had made it possible to hold the detecting instruments outside the atmosphere for much longer periods of time than could have been done before, a prime requirement for the detection of much weaker X-ray sources.

I felt induced to exploit this capability of space vehicles in an attempt at observing X-ray sources located outside the solar system.