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COSMIC-RAY PICTURE OF THE HELIOSPHERE

Cosmic rays were discovered about 75 years ago. During the last quarter of a century, the study of the time variations of cosmic rays has progressed considerably and has been transformed into an investigation of cosmic rays over time and space. The study has served as a useful tool for probing the interplanetary medium, a dynamic and complex region reborn with a new name—the heliosphere. In situ observations by satellites and spacecraft have enlarged and enhanced our understanding of the heliosphere, so a clearer picture of this region of solar influence is gradually emerging.

INTRODUCTION

Over the millenia, humanity has worshipped, wondered about, and pondered the sun and its influence over our lives. During the past four centuries, the human perspective has been radically altered by the so-called Copernican revolution and subsequent contributions by men like Galileo and Newton. The view through the telescope (viz., the sunspots, the mountains on the moon, and the satellites of Jupiter) has changed our perception of the world we live in. Beginning in the early 1900s, a revolution in physics took place, leading to relativity and quantum mechanics. Another landmark was the discovery of cosmic rays, the study of which has become an astrophysical tool for probing the interplanetary medium. The next jump in the progress of physics and astronomy was the first launching of an artificial satellite (in 1957), which ushered in the space age. Since then, the study of solar system physics and solar-planetary relations has assumed a new importance. We have indeed begun to understand our solar system, which is but a microcosm of the macrocosm, the universe.

OUR SUN

Our focus is on the sun, its environment, and the connection between them. What can we say about them? Our sun is an average star, not too hot or cool and not too massive or light, but in between. It is indeed a sample of cosmic material. Technically speaking, it belongs to the spectral class G4 and lies on the main sequence in the Hertzsprung-Russell (H-R) diagram (a plot of luminosity versus spectral or, equivalently, temperature classification of stars). Our sun is a gaseous sphere and the only star near enough for us to study in sufficient detail to understand stellar phenomena (a study that includes disciplines such as atomic physics, nuclear physics, plasma physics, and magnetohydrodynamics). Furthermore, the planetary magnetospheres (the regions surrounding the planets where their magnetic fields dominate) serve as large-scale laboratories for the study of plasma processes.

The Active Magnetospheric Particle Tracer Explorers (AMPTE) program is the latest satellite venture of APL and is a first in the active study of plasma processes in nature. It is aimed at understanding the physical processes that control fundamental phenomena already recognized (the Van Allen radiation belts, the magnetosphere, and the interaction between the solar wind and the magnetosphere). It actively introduces tracer ions to study the plasma processes and is thus a departure from past passive investigations, which merely measured what is there.

THE HELIOSPHERE—THE REGION OF SOLAR INFLUENCE

Our sun influences and shapes the region of the interplanetary medium. Currently, we refer to that region as the heliosphere, within which physical conditions are established, modified, and governed by the sun. What is the morphology of the heliosphere? How does it evolve as a function of space and time? How far into the interstellar medium does its influence extend (where is the heliospheric boundary)? These are some of the important questions that are being examined. The answer to the last question is particularly important, since it provides an overview of all that happens within the region.

Figure 1 is an overview of the heliosphere. Some features, such as the bow shock, shock front, heliosheath, and heliopause, are reminiscent of the terrestrial magnetosphere, with which we are familiar. The spiral magnetic field (the so-called Archimedean spiral), the continuously expanding supersonic solar wind, and the subsequent turbulent flow are all features that have come to be identified with the region.

Our sun, like all other stars, is a dynamic body, constantly undergoing changes, the manifestations of which can be referred to as solar activity, which is a consequence of the interplay of three factors—the magnetic field, internal convection of heat, and differential rotation. This continuously changing solar activity provides the input to the heliosphere and thereby modifies and controls it.

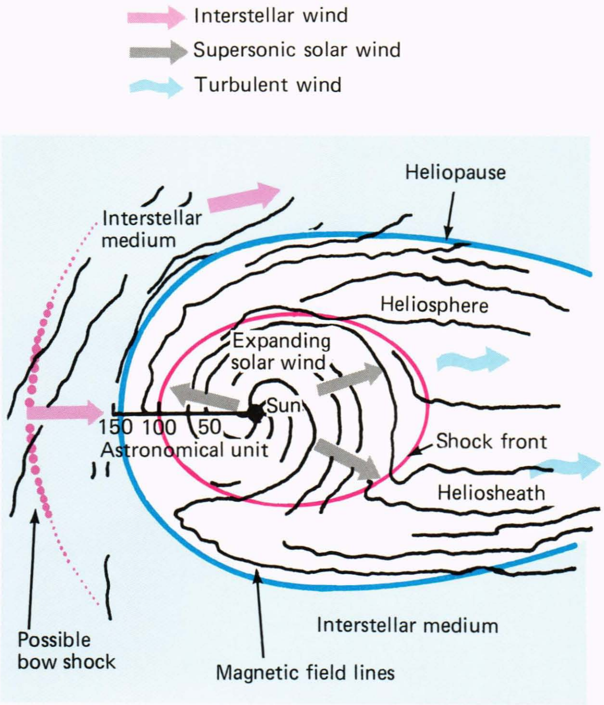


Figure 1—Conceptual overview of the heliosphere. The interplanetary medium with its sparse distribution of gas and solid particles, which composes the heliosphere (analogous to the magnetosphere), defines the region of domination of solar activity and thus of solar control and influence on diverse phenomena. Spherical symmetry has been assumed in the past but is now clearly invalid. The motion of the solar system in the interstellar medium is believed to generate a bow shock. The region between the boundary of the heliosphere (heliopause) and the bow shock contains the interstellar magnetic field (of perhaps 1×10^6 gauss). The continuous outflow of solar wind at supersonic speed becomes subsonic outside the heliopause. Within the region of the shock front, the magnetic field is along the so-called Archimedean spiral, while the plasma outflow is radial; outside the shock front, the magnetic fields are disordered and the plasma flow is visualized as turbulent. Outside the heliopause, one anticipates the stellar wind flow. The distance of the heliopause is not known. Estimates currently place it at least beyond 100 astronomical units and possibly as far as 150 astronomical units. Galactic cosmic rays are assumed to be incident isotropically on the heliopause. (Courtesy, L. J. Lanzerotti, AT&T Bell Laboratories.)

The near-geophysical environment of our terrestrial neighborhood has been quite carefully explored over the past two decades. Some of the essential details of the features of the innermost heliosphere (viz., within 1 astronomical unit, which is the distance between the earth and the sun) are also reasonably well understood. Some of the remaining questions will be answered by programs such as the Solar Polar Mission (now renamed the Ulysses Mission), in which APL is also involved.

It is common knowledge that solar gravity is insufficient to retain all the sun's matter; consequently, the hot solar corona (the uppermost layers of the sun) expands continuously into what is called the "solar wind." The insight into the physics of this expansion has been provided by a comparison to the expansion of a gas in a deLaval nozzle.[1] Gravity is equivalent to the constriction in the tube; with appropriate dimensions, the output can be a supersonic flow of gas. The solar wind constantly flows outward from the sun at supersonic speed averaging 350 to 450 kilometers per second. Sweeping through the heliosphere, it interacts with everything in its path; one consequence is the formation of a fascinating variety of planetary magnetospheres. The Jovian magnetosphere, for example, provides surprising departures from the terrestrial case. The hydrodynamic streaming of the plasma outflow from the sun[2] is the energy transport mechanism from it to the heliosphere. Since the solar wind permeates the entire heliosphere, it is appropriate to list in Table 1 its average characteristics at the radial distance of the earth, namely, 1 astronomical unit.

Table 1—Average characteristics of the solar wind.

Composition	Protons, electrons, and a few percent of alpha particles and heavier nuclei
Flux	500 × 10^6 particles per square centimeter per second
Velocity	300 to 450 kilometers per second*
Density	5 particles per cubic centimeter (range 1 to 20, generally of particles of each sign)
Thermal energy	10 electronvolts
Proton kinetic energy	1000 electronvolts
Electron kinetic energy	10 electronvolts
Magnetic field	5 × 10^{-5} gauss (range 3 to 15)

*We are not including values for high-speed streams, which are often as high as 600 to 800 kilometers per second and sometimes as high as 2000 kilometers per second.

Skylab observations in the X-ray wavelength region have established the existence of the solar feature known as "coronal holes"[3] (Fig. 2). The regions that are dark in contrast to their surrounding background give the impression of holes, hence the name. Coronal holes have been shown to be a source of high-speed streams. The magnetic field lines emerging from the holes are open field lines, extending far out into space. The Skylab discovery of this feature is indeed a landmark in solar physics. Figure 3 is a phenomenological model of the coronal magnetic structure and the associated magnetic sector and high-speed solar streams in interplanetary space.[4] This large-scale structure is an important feature that dominates the region, as will be discussed later. The coronal holes evolve from one solar rotation to another, as well as over a period of approximately 11 years, with an apparent inverse correlation with sunspot numbers. The solar polar

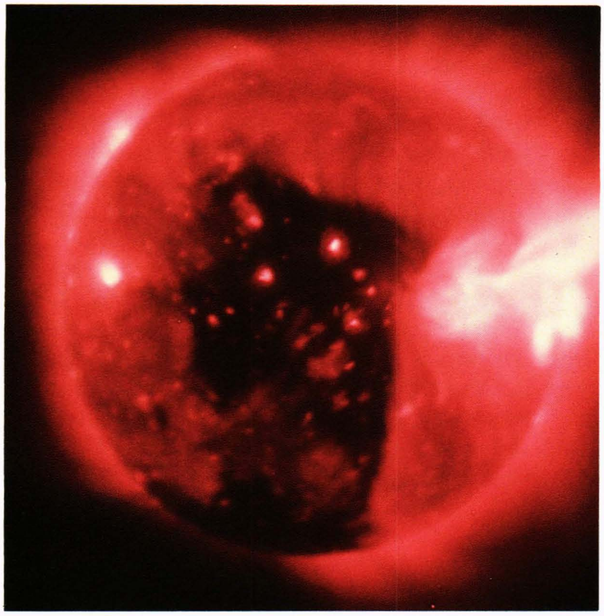


Figure 2—A coronal hole was demonstrated by Skylab observations of the solar corona, although even earlier, various data tended to suggest the existence of such holes. The operational definition[3] of coronal holes is "fairly large-scale, cool, low-density areas at both low latitudes and solar polar caps, encompassing weak, predominantly uni-polar magnetic fields which extend away from the sun as diverging open lines of force and which give rise to high-speed solar wind streams that cause geomagnetic storms." This picture of the coronal hole is in soft X-ray wavelengths (0.2 to 6 nanometers) and was taken by the American Science and Engineering X-ray telescope. In principle, one can observe it from X-ray to radio wavelengths. Specifically, we wish to refer to observations of the white light corona by ground-based detectors. Regions outside the contours of certain well-defined intensity levels clearly define the coronal hole. Coronal holes seem to avoid regions of high solar activity; coronal hole areas increase, as they extend to lower heliolatitudes with the progression of sunspot cycle toward sunspot minima and retract to small polar areas with the progression of sunspot cycle toward sunspot maxima. (Courtesy, American Science and Engineering.)

coronal holes shrink in size (to small areas in the polar region) during years of sunspot maxima, and expand and extend to lower heliolatitudes during years of sunspot minima. The impact of this, in terms of modulation of cosmic-ray intensity, will be discussed later. Various other phenomena such as solar flares and mass ejections also provide an input to the heliosphere. Charged particles, accelerated and ejected from solar flare regions (solar cosmic rays), will be dealt with later inasmuch as they contribute to cosmic-ray intensity variations. Figure 4 is a schematic drawing of particle acceleration and particle escape from the sun.

It is now appropriate to ask, "What is the role of cosmic rays in exploring heliospheric physics?" Studies using a world-wide network of ground-based detectors, commencing with the International Geophysical Year (July 1957 through December 1958) have enhanced our understanding of some aspects of the time variations of cosmic-ray intensity. However, studies of solar

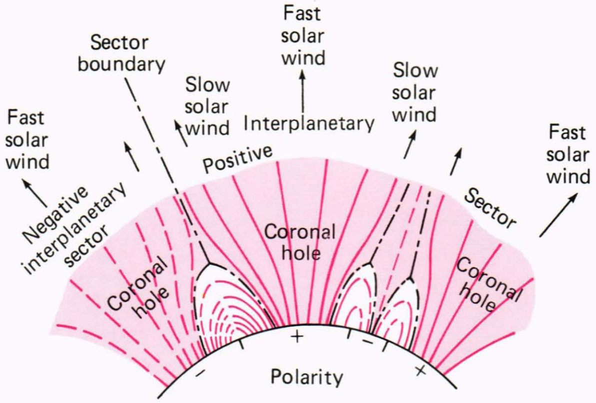


Figure 3—Phenomenological model of the large-scale coronal magnetic structure. Also shown are the associated magnetic sectors and high-speed streams in the heliosphere.[4] Each stream tends to have a single dominant magnetic polarity with changes in the large-scale polarity generally occurring at low speeds between the high-speed streams. Because this sector pattern is expected to be frozen into the flow, it serves as a vital clue in searches for solar origin of high-speed streams, which generally have speeds of 500 to 600 kilometers per second. The relationship between the interplanetary (heliospheric) stream sector structure and the large-scale coronal magnetic structure is shown.

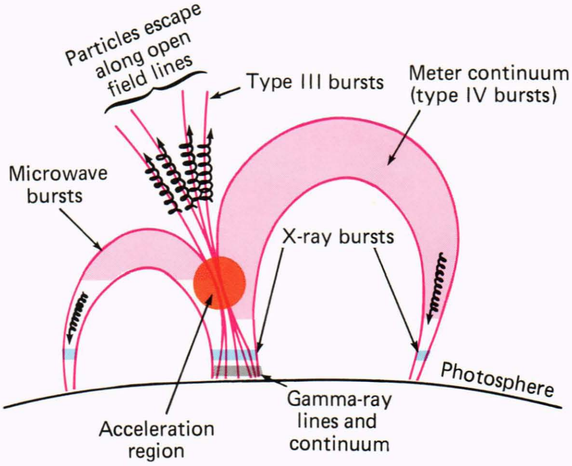


Figure 4—Particle acceleration and escape from the sun. This schematic representation of the interaction between two solar coronal magnetic "loops" describes one of the typical schemes for the solar flare acceleration of particles. It is surmised that electrons are accelerated at the interface of two coronal loops. Some of them are trapped within the loops and radiate at frequencies of microwave and meter wavelength; other electrons follow the open magnetic field lines and either produce associated radio bursts (so-called type III) or are directly detected in space. Still other electrons stream toward the chromosphere where they radiate hard X-ray photons from their interaction with the ions at the transition region or below. It has been recognized for some time that a shock is developed subsequent to the impulsive injection of electrons and ions, and that the shock accelerates the electrons and ions to even higher energies. The shock causes another type of radio burst (so-called type II), with gamma rays and high-energy neutrons also observed. Gamma-ray lines are the products of nuclear reactions between flare-accelerated protons and nuclei with the ambient solar atmosphere.

modulation of cosmic-ray intensity have received an impetus and become particularly rewarding with the advent of in situ observations by spaceborne instruments for solar and cosmic-ray observations on Skylab, Mariners, Pioneers, IMPs, and Voyagers, among others. Thus, continuous monitoring of cosmic-ray intensity over time as well as space has provided us with some insights into the physics of the heliosphere and into solar physics as well.

THE BEGINNINGS OF COSMIC-RAY PHYSICS

Cosmic rays are continuously bombarding the earth. The primary cosmic rays interact with our atmosphere and produce secondary rays. About 10 to 20 secondaries of these subatomic particles from afar strike each of us every second.

The discovery of cosmic rays and the development of the discipline provide a fascinating story. It began about 75 years ago with an observation of a residual ionization that persisted even when radiation detectors (such as the familiar gold-leaf electroscope) had been well insulated and surrounded by thick shielding. Soon it became obvious that unknown radiation was penetrating the shielded chamber and ionizing the air surrounding the electroscope. After Becquerel's discovery of natural radioactivity at the turn of the century, it was logical to attribute residual leakage of the electroscope to the presence of radioactive contamination in the air and surroundings. However, pioneering observations from balloon-borne detectors eventually demonstrated a pronounced increase in intensity of the penetrating radiation with an increase in altitude. In 1912, Victor F. Hess ascended to an altitude of 17,500 feet in his balloon-borne gondola with measuring instruments and proved the extraterrestrial nature of the unknown radiation. Its origin from the cosmos led to the adoption of the name "cosmic rays."

Meteorites give evidence that the intensity of cosmic rays has been fairly constant over a cosmological period of time. The evidence is left behind by cosmic rays that have bombarded the meteorites before these rock and metal fragments plunge into our atmosphere. The well-preserved nuclear effects produced by cosmic rays enable us to study the age of the meteorites.

Cosmic rays have been identified as electrically charged particles and not electromagnetic radiation, as originally assumed. The primaries impinging on the top of the atmosphere are atomic nuclei of elements. Protons (or hydrogen nuclei) are the most abundant, followed by alpha particles (or helium nuclei) in the approximate ratio of 10:1 (which is the same as their relative abundances observed throughout the universe). On the other hand, heavier nuclei, although relatively scarce (approximately 1 percent), are more plentiful in cosmic rays than elsewhere. However, nuclei heavier than those of iron are exceedingly rare in cosmic rays. There are also some electrons but only a few percent. Note that the primaries interact with the atmospheric constituents and hence do not penetrate very deeply. They transfer their energy to the secondaries, which are eventually observed at ground level. Figure 5 shows a well-known classical diagram of the principal modes by which the energy of a primary cosmic-ray particle incident on the top of the atmosphere is propagated through our atmosphere.

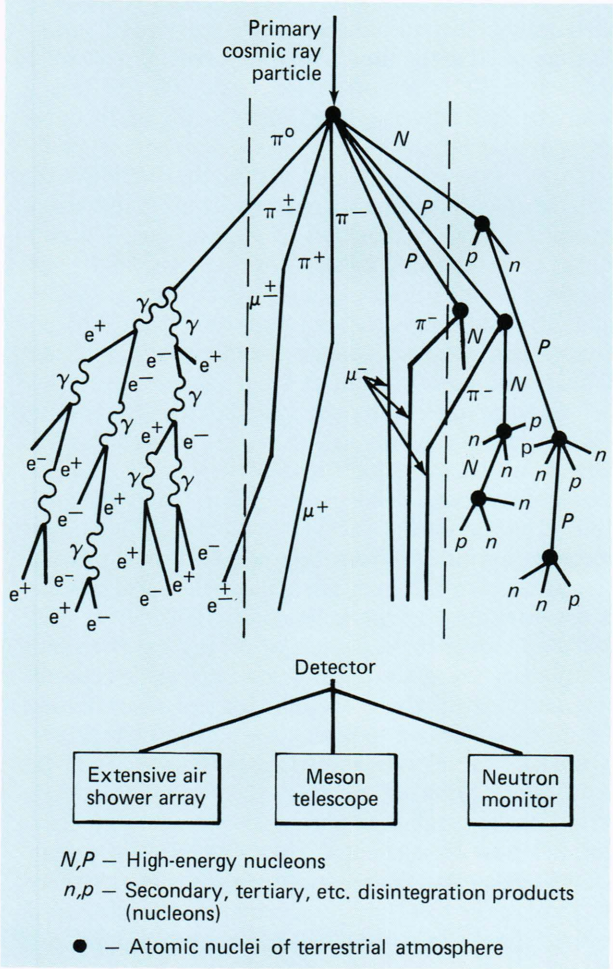


Figure 5—Propagation of the energy of a primary cosmic-ray charged particle through the atmosphere. The fate of a typical cosmic-ray particle (high-energy proton) when it strikes the top of our atmosphere is depicted schematically. Interactions start as soon as it encounters an appreciable amount of matter. There are three modes of transfer of energy of the incoming particle through the atmosphere to sea level and even below: (a) the nuclear-active or nucleonic component, (b) the hard or meson component, and (c) the soft or electromagnetic component. One of the three mechanisms of conversion of primary energy into a secondary component predominates, depending on the magnitude of the primary particle energy. High-energy protons and neutrons emitted as disintegrated products of interactions of the primaries with atmospheric atomic nuclei give rise to a nucleonic component, which then develops in a cascade process. At higher energies, π mesons are also emitted in addition to nucleons. Charged pions ($\pi^\pm$) turn into muons ($\mu^\pm$) that carry on the original charge. μ mesons are also unstable, but some survive the journey to earth. Neutral π mesons (π^0) decay into gamma rays, which, by a succession of electromagnetic processes, evolve into a great many particles extending over a large area. Some of the electrons resulting from the decay of μ mesons may possess enough energy to initiate showers.

The primary galactic cosmic rays extend in energy from 10^6 electronvolts to an upper limit of at least 1×10^{20} electronvolts. Whereas one particle of 1×10^9 electronvolts passes through an area of 1 square centimeter each second at the top of the atmosphere, only one particle of 1×10^{20} electronvolts strikes an area of 100 square kilometers in one year. In the interplanetary medium, approximately four cosmic-ray particles per second pass through an area of 1 square centimeter. There, the cosmic-ray energy density is about 1×10^{-12} erg per cubic centimeter and thus is comparable to the energy arriving at the earth in the form of starlight.

Cosmic rays are isotropic; that is, they arrive at the earth in essentially equal amounts from all directions (except for some cosmic rays of solar origin). The consensus of cosmic-ray physicists is that most of the cosmic rays are of galactic origin; hence they are called galactic cosmic rays, as distinguished from those of solar origin, known as solar cosmic rays. A certain heliospheric contribution of some cosmic rays up to 10^9 electronvolts cannot be excluded. But Hannes Alfvén[5] is still the only astrophysicist who claims that cosmic rays (except for those of very high energies) are all of solar and heliospheric origin. Hence the question of acceleration processes within the heliosphere becomes important from this point of view as well.

A number of different particle-acceleration processes are envisaged in the heliosphere; some have been observed, while the existence of others has been only postulated. Some kind of shock acceleration is anticipated as most likely to account for the observations. Figure 6 (not drawn to scale) is a schematic representation[6] of acceleration processes observed in the heliosphere, showing the most likely sites of acceleration. Shocks associated with each region of acceleration are bow shocks associated with planetary magnetospheres, solar-flare associated shocks (which travel outward in the heliosphere), coronal shocks, forward-reverse shocks in corotating interaction regions, and the solar wind terminal shock. The scale size of the shock and its configuration are believed to determine the maximum energy of the accelerated ions, while the duration of the intensity increase (observed at 1 astronomical unit) depends on the interplanetary propagation processes and the magnetic field configuration between the point of observation and the acceleration region.

When the heliospheric boundary is reached by a spacecraft and one can obtain a cosmic-ray spectrum outside the boundary, it will perhaps be possible to settle definitively the controversy of the origin of cosmic rays. We will show how the study of cosmic rays became a unique tool for investigating the heliosphere.

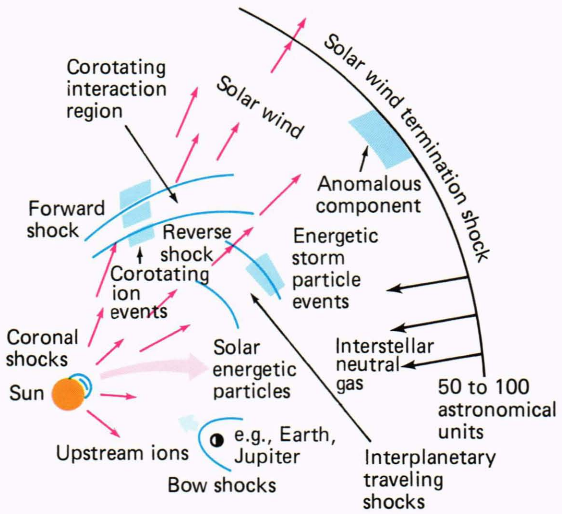


Figure 6—The diverse particle acceleration processes (observed or visualized) in the heliosphere. Some form of shock acceleration seems to be the most promising theory to account for the observations. The likely acceleration sites, as well as the energetic particle populations produced at these sites, are also shown. The acceleration region in each case is associated with shocks. The scale size of the shock and its configuration are believed to determine the maximum energy of the accelerated ions. The duration of the intensity increase observed at any place in the heliosphere (for example, at 1 astronomical unit) is dependent on the interplanetary propagation processes and the magnetic field configuration between the observing site and the acceleration region. The following briefly summarizes the details. Solar energetic particles (less than 0.1 to approximately 10 MeV per nucleon) undergo acceleration over days in the corona. The anomalous cosmic rays (approximately 1 to 30 MeV per nucleon) undergo acceleration possibly at the heliospheric boundary (or more probably in the galaxy) over a period of years. This component is present primarily during solar minima and possibly during alternate solar cycles. There is some question whether this is a heliospheric component. The corotating ion streams (approximately 0.2 to 10 MeV per nucleon) undergo acceleration, over days, in the forward-reverse shocks at distances greater than 2 astronomical units; again, this feature is observed primarily near solar minima. The energetic storm particles (approximately tens of thousands of electronvolts to a few million electronvolts) undergo acceleration, over hours to a day, in propagating shocks, whereas the shock spikes (approximately tens of thousands of electronvolts to a few million electronvolts) undergo acceleration, over minutes to hours, in the interplanetary shocks. Last, the diffuse upstream ions (or post-shock spikes, less than 10 keV to approximately 299 keV per charge) undergo acceleration, over hours, in the planetary bow shock (magnetosphere).

MORE ABOUT THE HELIOSPHERE

The heliosphere is not to be viewed as a passive medium immersed in energetic particles injected at its center (solar cosmic rays) or particles seeping in across its outer boundary (galactic cosmic rays). In fact, it is a dynamic region, modulating and modifying the two cosmic-ray components with its space- and time-dependent structures, and creating new energetic particles out of the supersonic solar wind at planetary bow shocks, at traveling shocks, at interaction regions between slow and fast solar streams, and at the solar wind termination shock. Heliospheric shock waves are transient phenomena and manifestations of the phenomenon of solar flares.

The global solar magnetic field is a key factor in the organization of the heliosphere. The magnetic field is drawn out of the sun by the material flow. When conductivity is infinite, there cannot be any relative motion between the two; this is what Alfvén initially named the "frozen-in" magnetic field. Changes in the heliospheric magnetic field with the solar cycle have been studied, and the concept of a warped heliospheric current sheet[7] organizing the interplanetary field has emerged.

Great changes occur in the structure of the heliospheric magnetic field during the course of the sunspot cycle. Near sunspot minima, the current sheet (the boundary between the magnetic field toward and away from the sun) is nearly equatorial with four small excursions away from the solar equatorial plane in each rotation. Since the ecliptic plane is tilted only 7° to the solar equator, even these small 10° to 15° excursions are large enough to affect the earth and produce the four-sector structure commonly observed in the interplanetary magnetic field. Near sunspot maxima, the structure becomes quite complex. The structure simplifies somewhat further with a decrease in activity to a situation indicating two sectors in the interplanetary magnetic field. Later, four sectors again emerge.

Figure 7 is a visualization of the current sheet, the evolution of which with increasing distance from the sun is not presently understood. In essence, the current sheet organizes the heliospheric magnetic field and, thus, the cosmic rays. A comparative study of diverse observations over a long period of time, over great distances, and on a vast range of scales has demonstrated that the heliosphere is a complex but highly organized and integrated system.

VARIATIONS OF COSMIC-RAY INTENSITY

Let us now turn our attention to cosmic rays and the role they have played in our understanding of the heliosphere. Because cosmic rays traverse the heliosphere, their intensity variations truly reflect the state of the heliosphere and changes within it; these, in turn, respond to the various solar phenomena, all of which contribute to the continuously evolving heliosphere. The solar inputs also leave their imprint on cosmic rays; thus a systematic study of cosmic-ray intensity variations in space and time enables us to monitor the heliosphere in all its vastness and complexity. We shall now specifically deal with some of these situations.

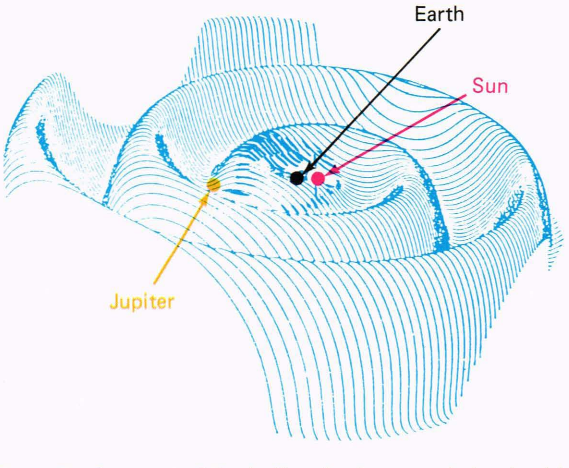


Figure 7—Concept of the heliospheric current sheet, which is visualized as being warped. The evolution of the sheet with distance from the sun is far from clear. Details are given in the text. (Courtesy, L. J. Lanzerotti, AT&T Bell Laboratories.)

The subject of solar modulation (modification) of cosmic-ray intensity is currently in a state of flux, as a consequence of the recognition of the three-dimensional nature of the heliosphere.[8] Note that the problems in the study of galactic cosmic-ray modulation are inverse to those in the investigation of solar particle propagation. In one case, we have particles streaming inward from the heliospheric boundary upon which the galactic cosmic rays are assumed to be incident, uniformly and isotropically (the same from all directions); however, the propagation conditions at the boundary and in the outer heliosphere are matters of conjecture. In the other case, we have particles streaming outward from the sun. Again, the propagation conditions in the outer solar corona are not that clear. The fundamental question is: "What is the mechanism of modulation?" The various factors involved are inward diffusion, outward convection by the solar wind, and other physical processes such as adiabatic deceleration of higher energy particles, particle drifts produced by the intensity gradient and curvature of the interplanetary magnetic field, and the role of solar produced interplanetary shocks. Whether the heliosphere is spherically symmetric is also a most relevant question.

SOLAR WIND SPEED AND LONG-TERM VARIATION OF COSMIC-RAY INTENSITY

The persistence of solar wind over time and space is well known. The correlation between solar wind speed and ΣK_p (an index of geomagnetic activity) over the short interval of five solar rotations emerged from the study of Mariner 2 data[9] (Fig. 8). (K_p ranges on a scale of 0 to 9 in steps of 3, from quiet to disturbed; it is a planetary index derived from the geomagnetic variations measured at a number of select stations. Eight 3-hourly values are available per day; the daily sum is denoted ΣK_p.) It is true that there is some scatter in the data; however, the general trend is quite clear. It was natural from the then-prevailing ideas of cosmic-ray modulation to look for a direct relationship between solar wind speed and cosmic-ray intensity. Figure 9 is a plot of the time series of cosmic-ray intensity from the Sulphur Mountain (Canada) neutron monitor and of solar wind speed.[10] The neutron monitor is a detector that records the nucleonic component of the cosmic-ray intensity (Fig. 5). Figure 10 is a crossplot of the same cosmic-ray intensity versus solar wind speed. It is clear from the figures that there is no good overall correlation between the two on a long-term basis. In retrospect, the lack of a simplistic, good correlation is not surprising. This will be discussed later, as will the role of high-speed streams.

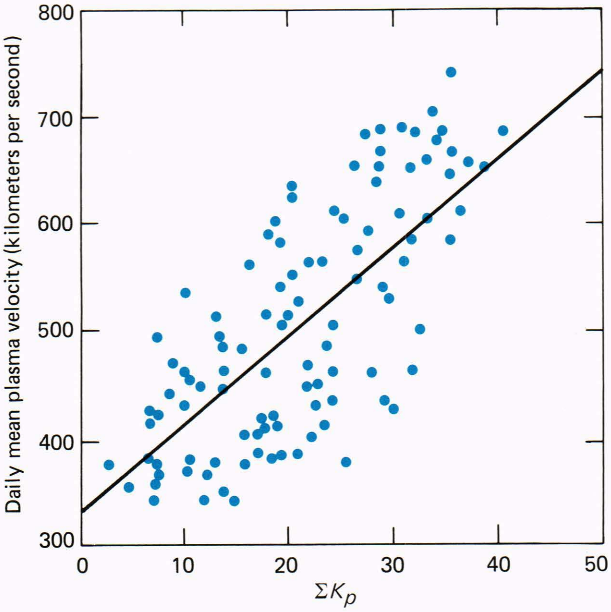


Figure 8—Solar wind speed versus the index of geomagnetic activity. Mariner 2 observations provided, for the first time, direct experimental evidence of the solar wind. The daily mean values of solar wind speed were plotted versus the daily mean values of the index of geomagnetic activity, ΣK_p. Individual 3-hourly values of K_p, range from 0 (quietest) to 9 (most disturbed) in steps of one third. The value of the index of geomagnetic activity ΣK_p (the sum of eight 3-hourly values) is derived by averaging the K values from a number of selected observatories in the world. Despite the scatter in the plot, there is a definitive correlation between solar wind speed and the index of geomagnetic activity.

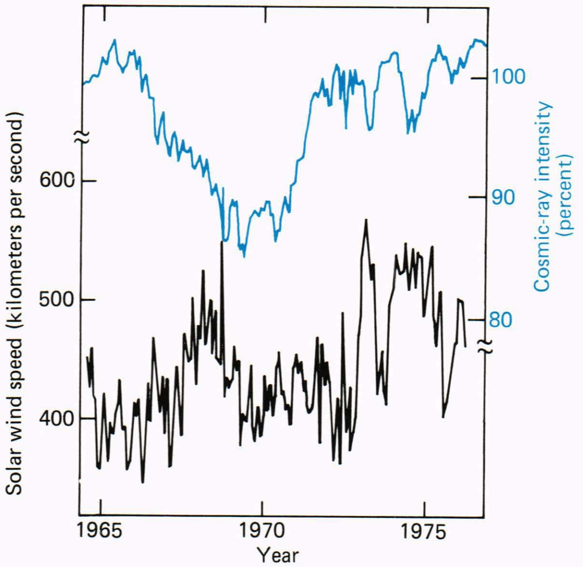


Figure 9—Time series of the cosmic-ray intensity registered by the cosmic-ray detector (neutron monitor) located on Sulphur Mountain and of the solar wind speed. There is no obvious long-term correlation between the two.

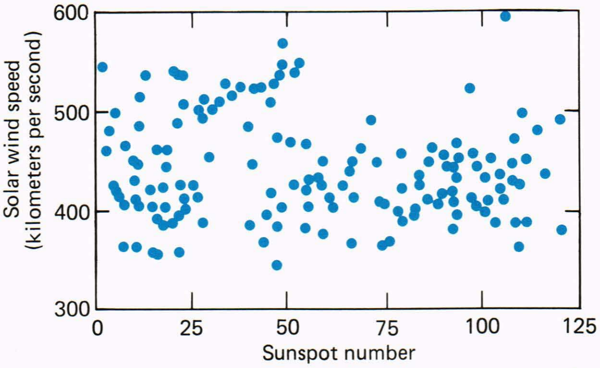


Figure 10—Cross plot of cosmic-ray intensity versus solar wind speed (the same values plotted in Fig. 9). It is clearly seen that the points are not aligned along a line; the data are widely scattered, indicating the poor correlation between the two parameters.

The Approximate 11-Year Cycle of Cosmic-Ray Intensity Variation: Heliospheric Boundary

An inverse correlation between cosmic-ray intensity and solar activity as represented by sunspot number was first pointed out by Scott E. Forbush[11] using data from his set of four widely separated ionization chambers. The approximately 11-year modulation by solar activity is shown in Fig. 11, which again provides data from the Sulphur Mountain neutron monitor.[12] Inset is the data of Forbush for an earlier sunspot cycle from one of his stations, Huancayo.

It is appropriate here to discuss the approximately 11-year cycle of solar modulation and Forbush decreases. In brief, the sun emits magnetized clouds with scattering centers of chaotic magnetic fields. At first, there are no cosmic rays within them; they enter (or rather, diffuse) into the plasma clouds. The centers of scattering that are convected outward from the sun tend to carry the cosmic-ray population with them. Eventually a quasi-steady state of outward convective flux equaling the net inward diffusive flux of cosmic rays is attained. This is given by the simple equation

$$D \frac{\partial n}{\partial r} = nv ,$$

where D is the macroscopic radial diffusion coefficient, n is the number density, r is the radius, and v is the solar wind velocity.

Earlier thinking (although questionable) visualized a spherically symmetric cosmic-ray-modulating region of radius r, alternately identified as the heliosphere. The quest had been to determine the distance of that boundary from the sun. An earlier conjecture predicted about 5 astronomical units. To pursue the problem further, let us look at Fig. 12, which shows the intensity-time profiles of the 27-day means of cosmic ray intensity recorded by the M-scintillator ($E \geq 35$ MeV (million electronvolts)) on the earth-orbiting satellite IMP-8, the Eβ05 detector ($E \geq 70$ MeV) on Voyagers 1 and 2, and Detector C ($E \geq 80$ MeV) on Pioneers 10 and 11, over the period from late 1977 to early 1983. The first three detectors were made by APL, and the last two were made by the University of Iowa. Sunspot numbers (representing solar activi-

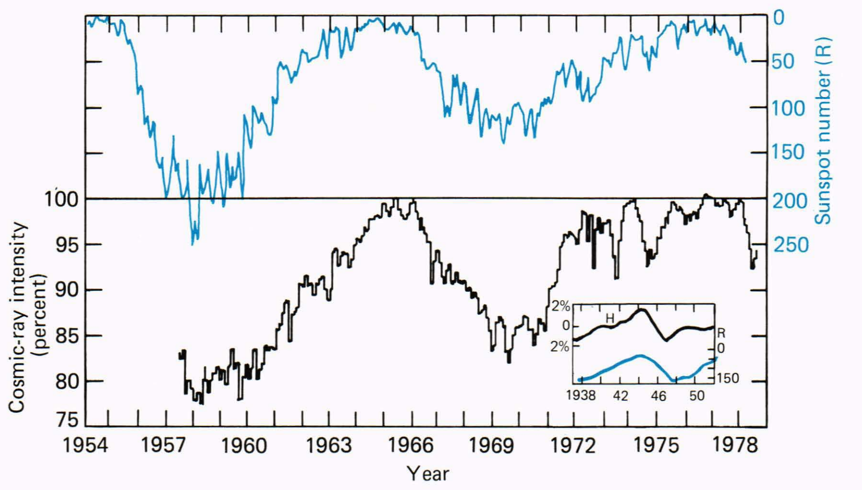


Figure 11—The monthly mean cosmic-ray intensity as measured by the Sulphur Mountain detector for the period mid-1957 to mid-1978, together with corresponding values of the sunspot number (the latter is plotted with values increasing downward to facilitate the comparison). The negative correlation between the two is clearly seen. This is also seen from the inset, which is for the earlier sunspot cycle; the data plotted are the sunspot number (R) and the cosmic-ray intensity as measured by the ion chamber operating at Huancayo (H), Peru, from the pioneering study of Scott Forbush.

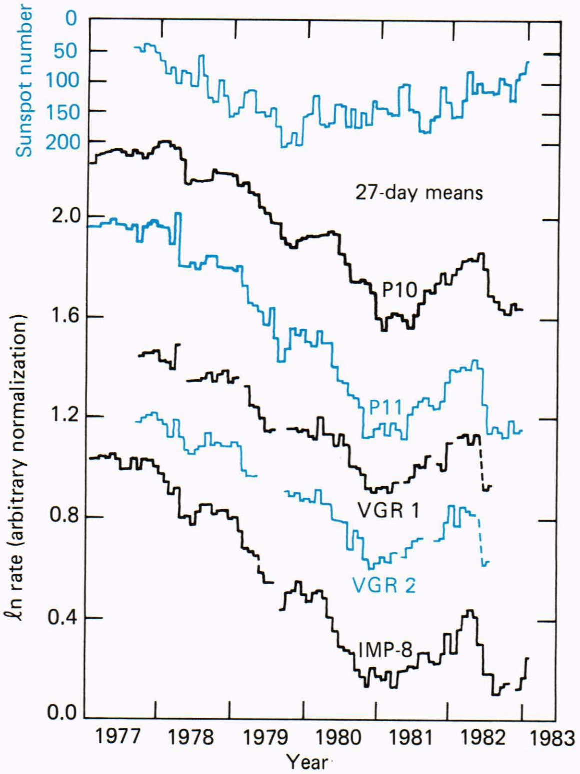


Figure 12—Twenty-seven-day means of sunspot number and cosmic-ray intensity as recorded by Pioneers 10 and 11 ($E \geq 80$ MeV), Voyagers 1 and 2 ($E \geq 70$ MeV), and IMP-8 ($E \geq 35$ MeV). Again, the sunspot number is plotted with values increasing downward to facilitate comparison. Note the long-term variation consisting of episodic decreases alternating with plateaus.

ty) are also plotted with their values increasing downward to better indicate the inverse correlation. Certain data such as flare increases, Forbush decreases, and planetary encounters have been deleted (details are being omitted for the sake of brevity) before the 27-day averages are computed, in order to make the data suitable for intercomparison.

It is interesting to note the similarity between the episodic decreases and the cosmic-ray minimum in the five detectors[13] situated at various radial distances in the heliosphere. Ground-based neutron monitors that register higher energy cosmic rays (not shown in Fig. 12) also reveal the same behavior. Any process invoked within the heliosphere that accounts for the solar cycle variation of cosmic-ray intensity has to incorporate the feature of plateaus (constant intensity) alternating with decreases. Furthermore, the lag of 9 to 15 months (depending on the solar cycle) between the time at which solar (sunspot) activity reaches a maximum and the time at which the cosmic-ray intensity reaches a minimum (as observed at 1 astronomical unit) also needs to be taken into consideration. Such a lag has been pointed out earlier by Forbush[11] from a study of his ground-based ion chamber data. Data from Voyagers and Pioneers, suitably corrected for cosmic-ray intensity gradient and for propagation effects of cosmic-ray features at solar wind speed,[13,14] also exhibit this lag. The conclusion from the studies can be posed as a question: "Does this represent a time-constant of the heliosphere?" With a rule-of-thumb interval of 4 days to cover 1 astronomical unit, the distance traveled by the solar wind in 9 to 15 months would be about 70 to 110 astronomical units. Does this therefore provide the evidence for the heliocentric distance of the heliospheric boundary?

The radial extent of the region of solar modulation of cosmic rays (or alternately, the boundary of the heliosphere) is a fundamental quantity that cosmic-ray physicists have been trying to determine ever since time-variation studies were initiated. The early conjecture of 5 astronomical units has proved to be a gross underestimate. Various observations that have a bearing on this subject will be discussed later.

The registration of the cosmic-ray minimum by Pioneer 10 (Fig. 12) in 1980-81 and of the secondary minimum in mid-1982, at which times the Pioneer 10 spacecraft had been at radial distances of about 25 astronomical units and 29 astronomical units, demonstrates clearly that the heliospheric boundary is beyond at least 30 astronomical units. Further comparable evidence is the observation of Forbush decreases[14] in the data recorded by Pioneer 10.

Note also that the two minima at Pioneer 10 (Fig. 12) are clearly seen to be later than those observed, for example, at IMP-8 (or, for that matter, at Voyagers 1 and 2 and Pioneer 11, although the delays are different). Two consequences follow: (a) the propagation of the cosmic-ray feature to spacecraft at greater radial distances from the sun is involved, and (b) the speeds of such propagation for specific cosmic-ray intensity features can be different. For example, in order to line up the two cosmic-ray intensity minima observed at Pioneer 10 (Fig. 12) with those at IMP-8, one needs to use average solar wind speeds of 500 and 800 kilometers per second, respectively, and correct the former data for the propagation delay. Further comments are reserved for a later section.

The Radial Gradient of Cosmic-Ray Intensity

The simultaneous observations of the cosmic-ray intensity by almost identical detectors on different spacecraft situated at varying radial distances enable us to calculate the so-called cosmic-ray intensity radial gradient, an important parameter for cosmic-ray-modulation studies. The integral radial gradient, g_r, has been computed,[13a] for example, from the data of Voyager 1 and the near-earth IMP-8, using the equation

$$g_r = \frac{ln(R_1/R_8)}{r_1 - r_8} ,$$

where R_1 and R_8 are the counting rates of the detectors onboard Voyager 1 and IMP-8, respectively, r_1 and r_8 are the heliocentric radial distances of the two detectors, respectively (r_8 here is 1 astronomical unit), and *ln* is the natural logarithm. Such gradient determinations in principle can be made between any two spacecraft. When one of them is near earth, we use the term integral radial gradient; otherwise, we use the term differential gradient.

Our determinations using data from Voyagers 1 and 2 and IMP-8 have provided a positive radial gradient of 2 to 4 percent per astronomical unit on the average, over a radial distance up to approximately 13 astronomical units from late 1977 to mid-1982. Van Allen and Randall obtain a mean value of +2.0 percent per astronomical unit for a radial range of 1 to 32 astronomical units during 1972-84.[14] Other determinations with independent sets of data provide values in general agreement with our determination. Despite some mild disagreements among various groups, a value of 2 to 3 percent per astronomical unit now appears to be reliable in the midst of the existing complex physical situation. The near-constancy of the integral radial gradient[14-18] during periods of intensity changes spanning over a solar cycle imposes severe constraints upon conventional modulation theories of cosmic-ray intensity.

The Heliolatitudinal Gradient

Until recently, heliospheric observations have been essentially restricted to the ecliptic plane; thus radial gradients have been emphasized. A unique opportunity for determining heliolatitudinal gradients over a long period using closely spaced spacecraft has become possible since 1981, using the APL detectors on the two Voyagers. Voyager 1, subsequent to its Saturn encounter, is proceeding to higher heliolatitudes. The study up to mid-1982 indicates that the data are consistent with either a helioradial gradient of approximately 1.8 percent per astronomical unit or, alternately, a heliolatitudinal gradient of 0.4 percent per degree.[14a] If we correct for the radial gradient, the heliolatitudinal gradient is for all practical purposes 0 percent per degree over a 16 degree heliolatitude separation from 8 to 13 astronomical units. In summary, the latitudinal gradient seems to be very much smaller than anticipated.

We have mentioned that galactic cosmic rays from outside the heliosphere enter and traverse inward. Nevertheless, we see that the modulation of cosmic-ray intensity proceeds outward from the "center" of the heliosphere. That is why we see the propagation delay in the specific cosmic-ray intensity features. For any intercomparison of data from various spacecraft situated at varying distances, we have therefore to "correct" the more distant spacecraft data for propagation delay as well as for the gradient.

Figure 13 illustrates this clearly. Curve A gives the 27-day means for the cosmic-ray intensity registered by Voyager 1, and Curve B gives the same, time-shifted for solar wind convection at 500 kilometers per second. Curve C is the same as Curve B, further corrected for a radial gradient of approximately 3 percent per astronomical unit, which is the average value we have

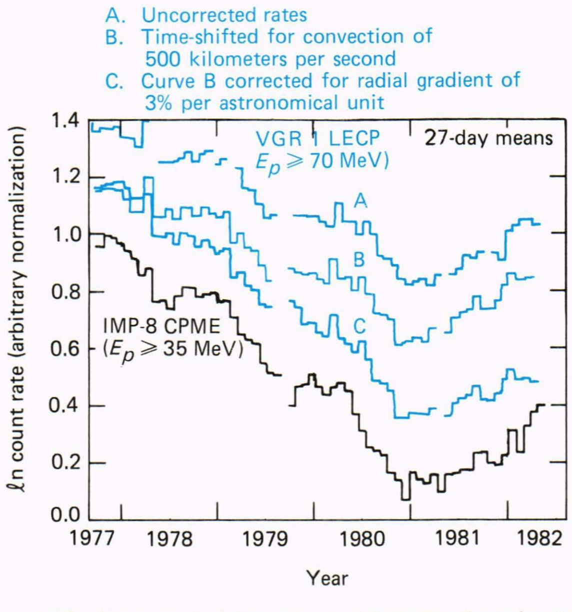


Figure 13—Voyager 1 observations with corrections for the propagation effects of cosmic-ray features and radial gradient. To compare the IMP-8 data with the Voyager data, the Voyager data have been corrected for the two effects mentioned in the text. The long-term changes of these two curves are strictly comparable.

determined. Note that Curve C is now strictly comparable to Curve D, which is the profile of the 27-day averages of cosmic-ray intensity registered by the earth-orbiting satellite IMP-8. The long-term decrease over the period from late 1977 to early 1982 observed by Voyager 1 after the corrections have been made is virtually the same as that of IMP-8, lending confidence in the two corrections.

DYNAMICS OF COSMIC-RAY MODULATION

We have seen that the large-scale cosmic-ray modulation effects propagate outward from the sun, with speeds of the order of the solar wind and of radial shocks in the heliosphere. There is now a general consensus among cosmic-ray physicists that the radius of the modulating region extends to at least 70 to 100 astronomical units. It is not clear if this boundary undergoes any great change with sunspot cycles, although it is not unreasonable to expect some sort of change with overall solar activity in the heliocentric distance of the boundary. The recovery from Forbush decreases appears to take a much longer time as the spacecraft are situated progressively farther out in the heliosphere.

Observations during the period of 1981-84 are extremely instructive. Some features have already been pointed out, including the second minimum in cosmic-ray intensity consequent to the series of large Forbush decreases in mid-1982. The differences in the recovery periods for detectors situated at various distances in the heliosphere seem to indicate that the level of modulation is determined to a large extent by the nearby characteristics of the interplanetary medium[19] within a few astronomical units of the location of the spacecraft. Thus there seems to be some question about the role of the overall global structure and topology of the heliosphere.

Forbush decreases in cosmic-ray intensity are one of the impressive short-term changes, an example of which is shown in Fig. 14. The onset of the decrease is quite sudden, and the minimum is reached within a few hours. But the recovery back to the original intensity level (or a new level) usually takes several days. We have already pointed out that the recovery of Forbush decreases as observed by detectors on board distant spacecraft takes a much longer time. We have also drawn attention to the series of Forbush decreases in mid-1982 that resulted in a second cosmic-ray minimum.

The question of whether (a) Forbush decreases are additionally superposed on the long-term approximately 11-year variation or (b) whether the long-term variation is the net result of a series of Forbush decreases has been debated for a long time. There is an apparent relationship between the magnitude and frequency of Forbush decreases and the approximately 11-year variations.

Figure 15 shows the significant result that the cosmic-ray intensity registered by a neutron monitor can be simulated by the cumulative effects of Forbush decreases.[19] The result thus emerges that the approximately 11-year variation can be simulated by the cumulative effects of the observed Forbush decreases.

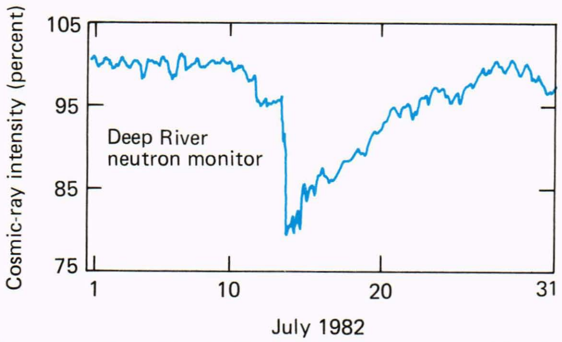


Figure 14—Example of a Forbush decrease, one of the transient changes in the intensity of cosmic rays that is often quite impressive. The decrease reaches the minimum value in a few hours and subsequently recovers over a period of several days. Sometimes, a second Forbush decrease occurs even before the recovery of the first one is complete. Often (but not always), a Forbush decrease occurs in the wake of a solar flare increase in cosmic-ray intensity and is associated with a geomagnetic storm. Forbush decreases are connected with either the interplanetary shock or with a plasma cloud containing magnetic fields that are not necessarily physically connected to the sun. (Data from monthly publication *Solar Geophysical Data—Comprehensive Reports*, NOAA, Boulder, Colo.)

SOLAR FLARE

Let us now consider another input into the heliosphere, the solar flare. The phenomenon of a solar flare is a dramatic and complex one in nature. The sudden release of a large amount of energy from the solar atmosphere in the form of photons, plasma, hard X rays, bursts of microwave radiation, and energetic particles (solar cosmic rays) traverses to the earth and beyond in the heliosphere. Flares also generate shock waves and geomagnetic storms. It is generally agreed that prior to a flare onset, the energy stored in a current-carrying magnetic field is in a metastable state and the sudden reconnection of this field releases its free energy, which accounts for all subsequent phenomena.

RELEASE OF ENERGETIC PARTICLES

The solar particles are accelerated, released. and propagated through the heliosphere. Satellite-borne detectors observe a large number of solar cosmic rays of low energy. Occasionally, when particles have energy in excess of 1×10^9 electronvolts, they are detected by ground-based cosmic-ray detectors. Figure 16 gives such an example;[20] the Sulphur Mountain neutron monitor registers a larger increase of cosmic-ray intensity since it detects particles that are subsequently absorbed in the additional atmosphere between Sulphur Mountain and Calgary. Otherwise, the outputs of the two detectors are identical. The intensity profiles of flare increases provide information about the heliosphere. It is relevant to note that a realistic picture of the interplanetary magnetic field was inferred

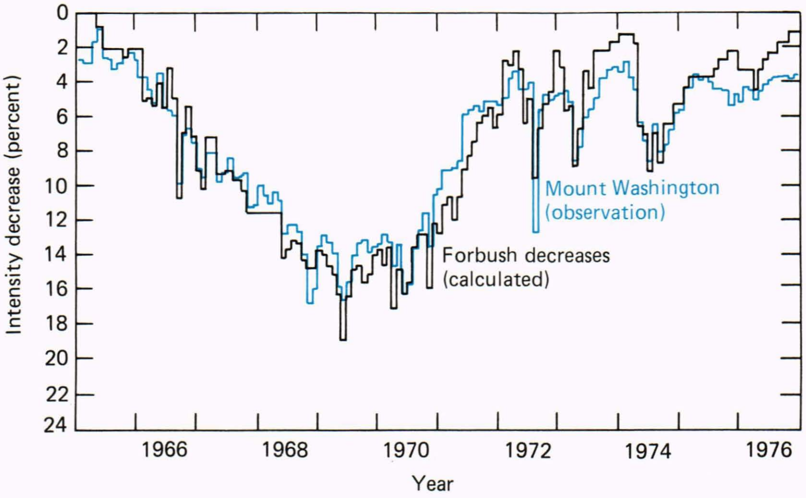


Figure 15—The approximately 11-year variation of cosmic-ray intensity and Forbush decreases. Attention should be given to the resurgence of the view that the long-term variation in cosmic-ray intensity is the result of the cumulative effects of Forbush decreases. The approximately 11-year variation in cosmic-ray intensity as observed by a neutron monitor is shown, together with a theoretically generated intensity variation using Forbush decrease as a suitable function. The good tracking between the two is quite impressive.

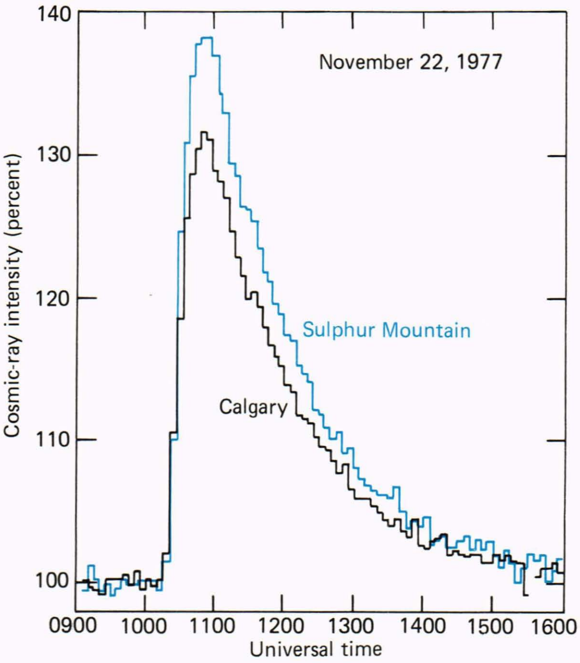


Figure 16—Solar flare increase of cosmic-ray intensity. It has already been pointed out that on a few occasions solar particles are accelerated to sufficient energies to be observed by earth-based detectors. This figure shows an example of the solar flare increase as observed by neutron monitors at the Calgary and Sulphur Mountain stations of the University of Calgary. The slightly greater increase recorded by the Sulphur Mountain detector arises because it is at a higher elevation than Calgary, so lower energy particles that are absorbed in the additional atmosphere over Calgary are registered at Sulphur Mountain. Typically, the increase occurs over a few minutes and the decay over several tens of minutes. In comparison with ground-based detectors, the satellite-borne instruments register many more solar events (which are, of course, low-energy particles). Observations by multiple spacecraft situated at different locations in the heliosphere enable us to understand the propagation of low-energy particles in the interplanetary medium.

from studies of solar flare increases observed on the ground long before man-made satellites were launched, and that provides another example of the vital role played by ground-based detectors in our understanding of the heliosphere.

Figure 17a is an example[21] of a flare increase observed by APL's detectors on the IMP-7 and IMP-8 satellites, both earth-orbiting. Their positions are shown in Fig. 17b. The plot in Fig. 17a shows hourly means of the intensity versus time profiles for the period July 2 to 8, 1974, for alpha particles and medium and heavy nuclei, with their energy ranges given in brackets. Also shown in Fig. 17a are major solar flares and their classification and heliographic coordinates. Both spacecraft reveal large variations in the recorded charge composition. Note the variations by as large as factors of 3 to 4 from one hour to the next; 3-hour averages (not shown here) reveal nearly a factor of 10 from peak to minimum values over the duration of an event. Comparisons of measurements from IMP-7 and IMP-8, separated by approximately 70 earth radii, show that the gross compositional variations are reproduced well at both satellites, although significant differences in composition and intensity occur over brief periods. The observations in the heliosphere thus clearly define the boundary conditions that any theory involving the acceleration, release, and propagation of solar energetic particles has to satisfy.

We have come a long way from ground-based observations. Simultaneous observations from spacecraft distributed in solar longitude and radial distance from the sun can be used to separate solar and interplanetary propagation processes. Measurements with deep space probes (such as the Pioneers and Voyagers) are of particular importance because they permit us to derive the average propagation characteristics of the heliosphere. Individual solar particle events differ considerably with respect to their magnitude, duration, structure, chemical composition, etc. Some are certainly related to the observer's location vis-a-vis the solar flare, but others are dependent on the solar conditions nearby. The injection of energetic particles from the sun into the heliosphere is a function of acceleration,

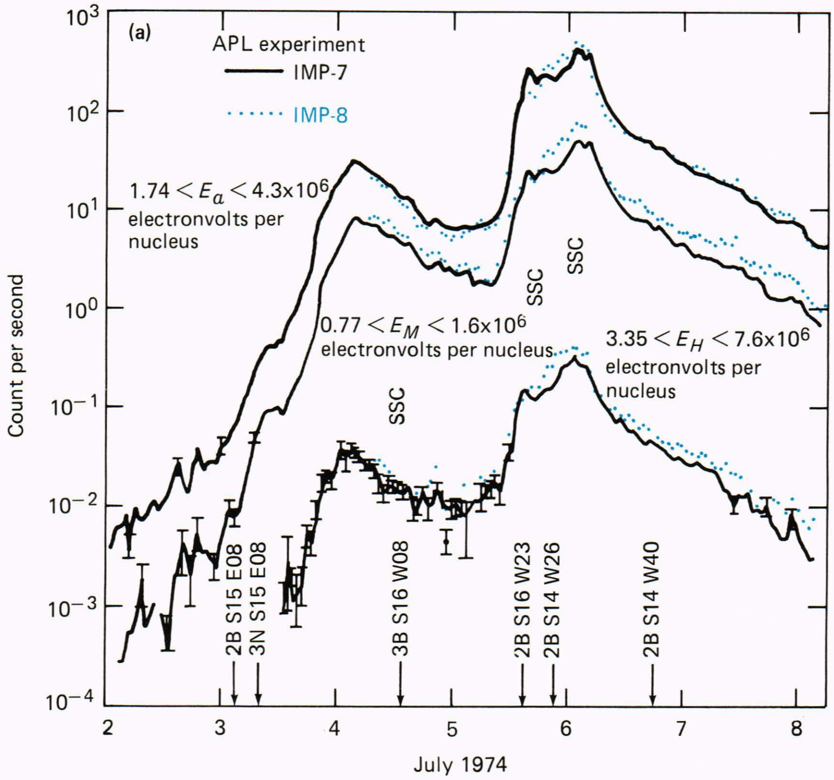
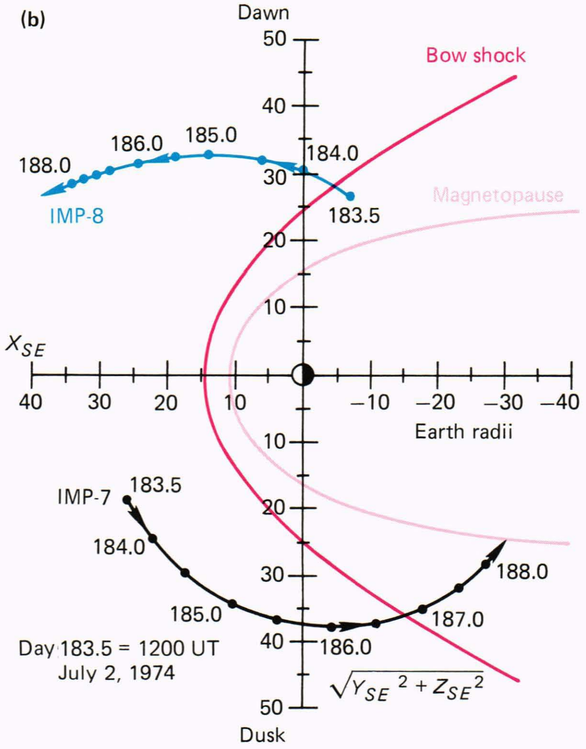


Figure 17—Solar flare increase. (a) As observed at satellites IMP-7 and IMP-8, whose positions are shown in (b) during the event. Note from the figure that IMP-7 is proceeding from upstream of the bow shock toward the magnetopause, while IMP-8 is proceeding from behind the bow shock on the earthward side into the upstream solar wind. The hourly averages plotted in (a) show the solar flare increase as registered by the detectors corresponding to alpha (α) particles and medium (M) and heavy (H) nuclei. This event (July 4, 1974) shows variations in charge composition by factors as large as 3 to 4 from one hour to the next. The two spacecraft are separated by approximately 70 earth radii. Significant differences in composition and intensity exist for brief periods, although gross compositional variations are reproduced well at both spacecraft. These observations provide particularly stringent conditions for theories of the acceleration, release, and propagation of solar energetic particles.



storage, propagation, and release; the differing variability in these factors accounts for the wide differences from one event to another. Furthermore, there are changes in the state of the heliosphere, e.g., its scattering efficiency varies with its position in space and with time, and for particles of different species and energy. Hence, for a given solar injection profile, qualitatively different propagation models may have to be considered. They could range from the so-called ordinary diffusion to almost scatter-free propagation. In summary, the information on solar acceleration and coronal propagation has to be derived from observations of the energy of solar particles because these contain effects of propagation in the dynamic heliosphere.

SOLAR-FLARE-ASSOCIATED SHOCK

X rays, ultraviolet radiation, and visible light propagate directly to the earth in about 8 minutes. Energetic protons, alpha particles, and electrons travel along the Archimedean spiral lines of the magnetic field in a range of tens of minutes to days, depending on the kinetic energy of the particle and the solar longitude of the flare site. But the ejected plasma and field are the slowest to travel; traveling at speeds of 500 to 1000 kilometers per second, they may take 2 to 3 days to reach the earth. Nevertheless, half of the flare energy (approximately 1×10^{30} to 1×10^{32}ergs) is associated with the ejected plasma and fields. Near periods of sunspot maxima, an average of about four to five such solar flare shock events per month are detected. The solar-flare-associated shock (and associated fast stream) produce a number of effects. We shall mention only the two that are relevant to us: (a) energization of ions and electrons to energies exceeding 1×10^6 electronvolts and several tens of thousands of electronvolts, respectively, and (b) substantial decreases in the ambient galactic cosmic-ray flux. This arises from particle interaction with shocks and compressed magnetic fields downstream.

Figure 18 is an illustration of a series of four Forbush decreases[22,23] associated with the passage of four interplanetary shocks, as observed on Voyager 1 and 2 and Pioneer 10. Forbush decreases associated with the passage of flare-associated shocks are well known. The cosmic rays in the path of high-speed solar streams are swept out by particle drifts in the magnetic field gradients or by reflection of the energetic particles by the compressed magnetic fields at and behind the shock. It is appropriate to point out that a quantitative shock-dependent three-dimensional model of Forbush decreases needs to be developed that is uniformly applicable to any part of the heliosphere. The inputs needed are multiple spacecraft observations of shocks and cosmic rays, providing the characteristics of the shock, the upstream plasma, and field and relative position of the observation with respect to the flare site.

SOLAR MAGNETIC LOOP

Another interesting example of input into the heliosphere is the observation[24] by the APL experiment on IMP-7 of energetic particles from solar flares injected into extended solar magnetic loop-like structures extending beyond the earth and anchored near regions with strong magnetic fields. From the development of angular distributions of energetic protons ($E_p > 0.3$ MeV and $E_p > 25$ MeV) and electrons ($E_e > 220$ MeV), the bouncing of energetic particles between two "magnetic mirrors" located on the sun has been inferred. Figure 19 is a schematic of a possible magnetic loop configuration of the interplanetary magnetic field during the event of November 5, 1974. That event and the one on September 7, 1973, have been investigated. In one, the spacecraft-detected particles were injected into an apparently pre-existing "magnetic loop" during the onset of a solar flare particle event. During the other event, IMP-7 entered a magnetic field regime in which the intensities of the energetic particles had already reached a characteristic angular distribution, implying a stably trapped population. Concepts such as solar magnetic bubbles in the heliosphere detached from the sun, magnetic clouds, and magnetic bottle configurations have also been explored by several scientists. (The magnetic clouds and bottle configurations have been associated, in some cases, with interplanetary shock waves.)

CORONAL HOLES AND HIGH-SPEED STREAMS

The three-dimensional nature of the heliosphere has also been put into proper perspective from yet another set of studies that originated after the Skylab observations of coronal holes and recognition of the

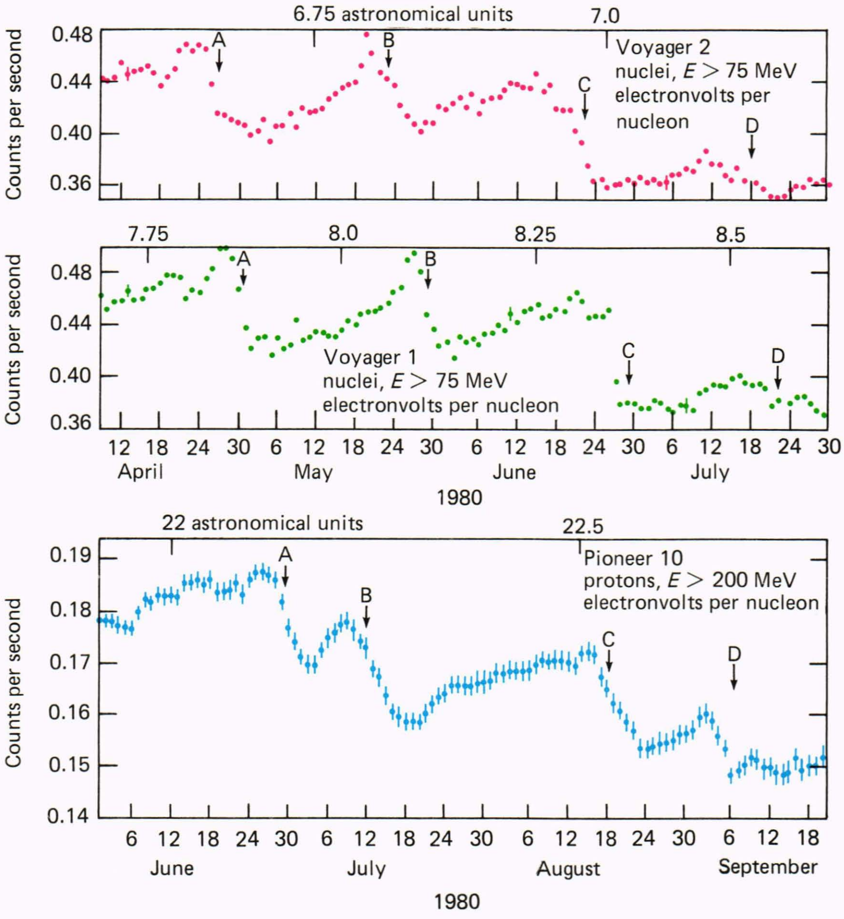


Figure 18—A series of Forbush decreases. This figure[22] shows the observation of four Forbush decreases associated with the passage of flare-associated interplanetary shocks as recorded by Voyagers 1 and 2 and Pioneer 10 when their locations in the heliosphere were at 8, 7, and 22 astronomical units, respectively. Note the decreases in cosmic-ray flux after each successive shock, effectively producing a long-term modulation effect. Reflection of the energetic particles by the compressed magnetic fields at and behind the shock or by particle drifts in the field gradients is considered to sweep out the cosmic rays in the path of the high-speed stream.

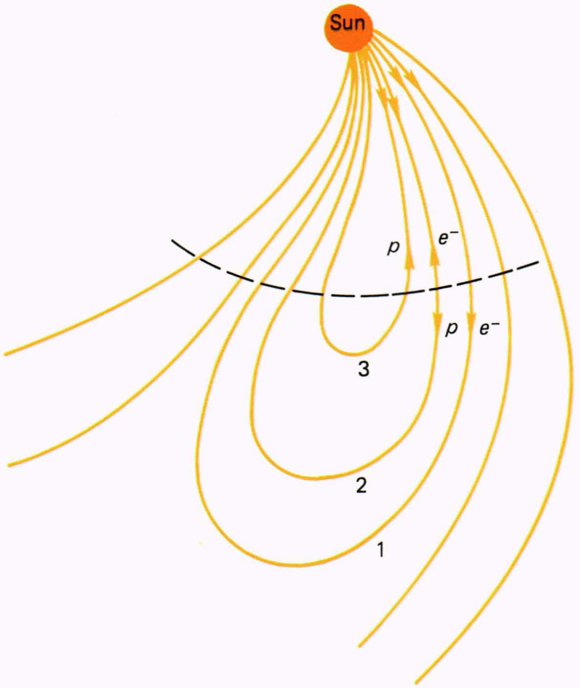


Figure 19—Schematic of a magnetic field loop, yet another example of solar input into the surrounding medium. Existing and extended magnetic loop structures (even beyond 1 astronomical unit) provide an easy path to energetic particles from solar flares. (The text gives details.)

associated high-speed streams.[4,26,27] Using the Skylab measurements of the areas of the solar polar coronal holes, it has been shown[28] that during nondisturbed periods, the north-south gradient of galactic cosmic rays as measured at 1 astronomical unit by the north- and south-looking neutron monitors at Thule and McMurdo (the North and South Polar stations, respectively) depends on the difference in the areas of the solar polar coronal holes. Higher cosmic-ray fluxes are observed from the polar direction into the smaller coronal hole area. The study was motivated by the idea that possible north-south asymmetries of cosmic-ray intensity at the earth can arise from the asymmetric equatorial extension to the ecliptic plane of the magnetic fields from the solar polar coronal holes.[28] A coronal hole, as pointed out earlier, consists of a region of open magnetic field lines from which plasma can apparently easily expand and contribute significantly to the high-speed solar wind.[4]

It is to be noted that these results pertain to an interval in the solar cycle (1973-74), during which the polar coronal structure was particularly evident and large solar flare disturbances were practically absent. The results imply that the high-speed solar wind streams originating from coronal holes inhibit the access of galactic cosmic rays to the solar system during sunspot minima conditions. It appears, therefore, that the galactic cosmic-ray modulation is disturbed by at least two processes. The first of these is the "solar-activity-center-dominated" effect operative in limited active regions that gives rise to Forbush-type decreases. The second is the result of large-scale solar polar coronal holes extending to lower heliolatitudes. The Skylab study of about five solar rotations in 1973-74 has been extended[29] to the two complete years 1973 and 1974 by using the white light data from the K-coronometer. Contour maps of white light coronal brightness were plotted as a function of solar latitude and Carrington longitude. These maps represent daily values of the polarization longitudes and are termed white areas. For the Skylab epoch of simultaneous observations, the low brightness regions in such maps have been found to correspond well to coronal holes observed by X-ray and extreme ultraviolet techniques.[3,4] Thus all regions with a brightness below a fixed low level are referred to as coronal holes. The results of the extended study support the limited period study using the Skylab data.

In summary, during sunspot maxima conditions the solar activity produces high-speed streams that produce successive Forbush-decrease-type particle modulations. Recall that Forbush decreases have a longer recovery time at larger radial distances, providing a mechanism for progressively depleting a high-latitude reservoir or galactic particles. During such sunspot maxima conditions, the coronal holes are small in area and concentrated near the poles. During solar minima conditions, the polar coronal holes are much larger, dominating a larger fraction of the solar disk and greatly influencing the heliospheric conditions in the ecliptic plane. However, the solar wind streams from these polar holes with their well-ordered magnetic structures produce only a minimal convection-type modulation of the galactic cosmic rays.

JOVIAN ELECTRONS

Earlier, we had referred to the possibility of cosmic rays of heliospheric origin. It is appropriate to refer to this feature in some detail for the sake of completeness. Figure 20 shows a plot of the counting rate of electrons[30] from the University of Chicago detector on Pioneer 10 during the period 1972 to 1976. It identifies Jupiter as a source of high-energy electrons that were earlier thought to be cosmic-ray electrons. It is well to bear in mind that upstream and downstream ions have been observed[30,31] by Voyagers at distances of up to approximately 800 and approximately 1200 earth radii, respectively. It has been suggested on the basis of the similarity of the composition of the upstream events to that of the Jovian magnetosheath and magnetosphere[32,33] that the upstream ions are definitely of Jovian origin and most likely leaking out of the Jovian magnetosphere. These ions could undergo subsequent acceleration to higher energies by interaction with the solar wind.[34] The role of Jupiter as a source of low-energy cosmic rays needs to be investigated.[35]

Figure 21 shows the counting rate of detector C ($E > 80$ MeV) on Pioneer 10, the data from the Sulphur Mountain neutron monitor, and the sunspot number. The trend line drawn for the top two curves clearly

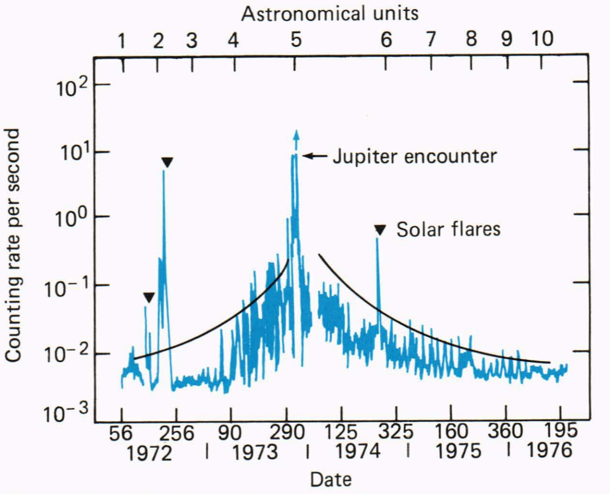


Figure 20—This intensity-time profile over the period 1972 to mid-1976 clearly demonstrates the role of Jupiter as a source of high-energy electrons. The peak in the Chicago detector on Pioneer 10 refers to electrons of energy 3 to 5 MeV.

illustrates again the presence of Jovian electrons in the data[36] of Pioneer 10.

CONCLUDING REMARKS

We have discussed in detail various aspects of the heliosphere and cosmic-ray intensity variations and have seen that the solar interaction with its environment (namely, the heliosphere) is complex and varied. One of the important questions that has repeatedly appeared in the discussion is "How far away is the heliospheric boundary?" Recent detection of a radio emission at 3 kilohertz in the outer heliosphere[37] by plasma wave receivers on Voyagers has been suggested as evidence of observation of the heliopause. The continuously evolving character of the outer heliosphere is closely connected to this question. The in situ observations of the Pioneer and Voyager satellites have contributed (and are still contributing) to our knowledge of the heliosphere at progressively greater distances and higher latitudes.

It is obvious that the high-speed streams, whether they come from solar active regions or coronal holes, their interaction with the slower streams, the corotating interaction regions, the possible interaction among shocks, and an understanding of complex large-scale flows from the sun need to be dealt with.[38] A synthesis of the interplanetary magnetic field data and plasma observations is vital, and the modulation of cosmic rays in the heliosphere needs to be addressed.

We have come a long way since the International Geophysical Year, up to which time the probing of the heliosphere was carried out only by ground-based equipment. We still have a long way to go before our understanding of the heliosphere becomes nearly complete. We started this article with a conceptual view of the heliosphere as we currently visualize it (Fig. 1). Only the future can tell how this picture will change.

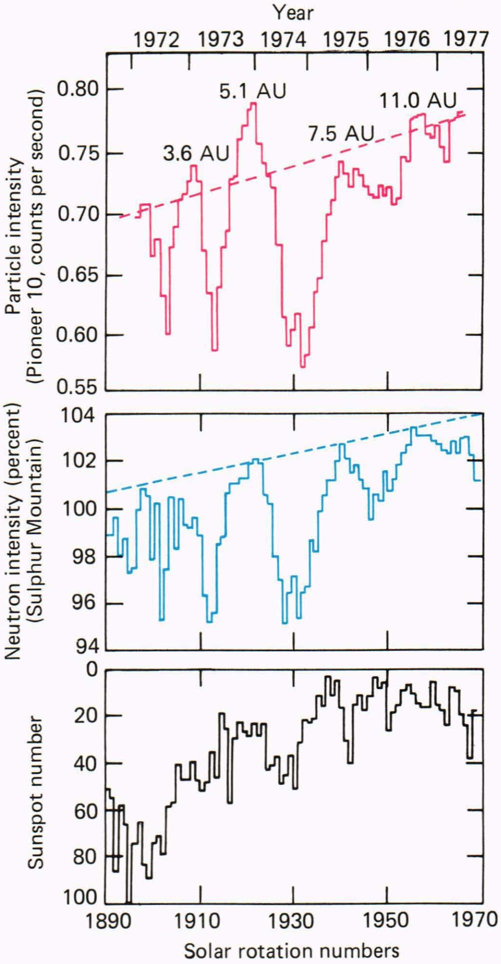


Figure 21—Observations of Jovian electrons by the Iowa detector on Pioneer 10, another example that shows the presence of Jovian electrons. Here a comparison of the 27-day means of galactic cosmic-ray intensity as registered by the neutron monitor on Sulphur Mountain with the intensity recorded by detector C on Pioneer 10 is made. Trend lines for a long period are drawn for both sets of data. Note clearly that at the Jupiter encounter, there is still an excess counting rate, as seen by the excess over the trend line.

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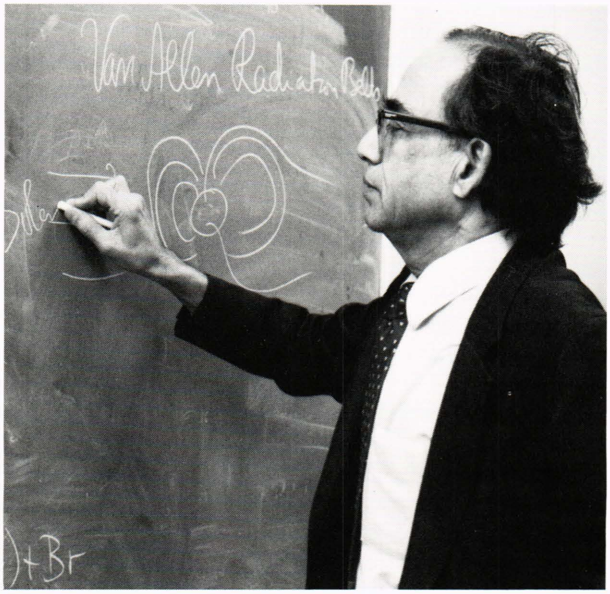

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