Exploratory Journey out of the Ecliptic Plane

Major advances are to be expected from the first direct measurements at high solar latitudes.

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Figure 1 shows how nonuniform the solar atmosphere generally is. Moreover, the coronal streams that are seen stretching out to engulf the earth change their structure from hour to hour. Yet in spite of all the effort that has gone into space research, we have never managed to explore the solar environment beyond the narrow and totally unrepresentative strip traced out by the earth's orbit.

An exploratory journey out of the ecliptic to higher solar latitudes is essential if we are to understand the astrophysics of the nearest star—our sun—and explain how its behavior so dramatically affects the earth.

Our ignorance falls into three categories and arises largely because the earth, and all spacecraft so far flown or planned, never depart more than 7° from the solar equatorial plane.

1) We sample only a tiny fraction, within a narrow angular strip, of the radiation emitted by the sun. The sun continuously ejects a gusty supersonic plasma flow, called the solar wind (*1*), which fills interplanetary space and entwines the earth and planets with solar magnetic field lines dragged along with it (*2*). At times of localized eruptions the sun emits, in addition, penetrating nuclear particles having energies of millions of electron volts (*3*). These are accompanied by enormous blast waves in the plasma and frequently by ultraviolet, x-, and even potentially lethal gamma-ray bursts (*4*). The effects at the earth show up as the brilliant auroral lights, magnetic storms big enough to upset national electricity grids, and ionospheric disturbances that distort our radio communications (*5*). The large-scale structure of the solar wind may produce similar terrestrial effects, and there is now very convincing evidence—although the physical mechanism is not understood—that the earth's global weather is markedly affected too (*6*).

The performance of the sun and its variability are truly awesome. Normally the auroral lights, marking the latitude to which the solar wind has managed to penetrate the earth's shielding magnetic field, are seen around the polar circles, but we know of cases when auroras appeared close to the equator—for example, on 25 September 1909 and 14 to 15 May 1921 at Jakarta, Singapore, and Samoa (*7*). The ferocity with which the sun must have behaved in order to squeeze the earth's field in to these latitudes is difficult to comprehend. It could be that at such dramatic times the active sunspot belt, normally limited to solar latitudes between about 40° and 10° (*8*), had moved a bit lower, and the earth experienced the full radial plasma blast which it normally misses by staying within 7° of the solar equatorial plane. Just as an underwater swimmer might locate dirty patches by looking toward the light, so by looking through the solar wind toward cosmic radio stars we can get some crude idea of the structure in the wind. Indeed, it is very inhomogeneous and shows marked variations with solar latitude. Above about 40° solar latitude things appear calmer but the flow could be much faster (*9*). The variations with latitude are linked with the fundamental mystery of the 11-year sunspot cycle.

It is clear that our ability to sample the solar radiation is extremely limited and that what we do see is totally unrepresentative of what might be found at other latitudes. Our space efforts in this field thus far are equivalent to trying to map the earth's magnetosphere with a single spacecraft fixed in a circular equatorial orbit just below the radiation belts.

2) We do not know the structure or size of the heliosphere carved out by the solar wind, so we cannot tell how it affects galactic cosmic radiation on its way to the earth. Since, except around the earth, we have a poor idea of the radiations and field emitted by the sun, we are obstructed in our studies of the sun as a star. Astrophysics loses out again because, for the same reasons, we are unable to establish the nature of the true primary interstellar cosmic-ray spectrum. If we could travel to high solar latitudes we could get to understand the interplanetary cavity that hinders the radiation reaching the earth (*10*) and, at the same time, come closer to directly measuring the unmodulated cosmic radiation. We must make the journey because the modulating plasma and field parameter changes seen in the ecliptic plane during a solar cycle are totally inadequate to explain the cosmic ray changes seen over the same period.

3) Because we look at the sun from a fixed angle, we have a poor idea of the three-dimensional structure of many solar features. Two basic experimental problems arise in studying solar features: (i) We do not know the third dimension in most cases and therefore can only guess about the field configurations, absolute size, total energy, and so forth of objects such as the recently discovered coronal holes (*11*)—especially since these exist predominantly close to the solar poles. (ii) Our attempts to study the evolution of features are frustrated when every 13 days the center of interest disappears behind the western solar limb. A continuous bird's-eye view of the sun from polar latitudes would provide the third dimension and allow study of solar features from their moment of birth until they disappear or are dragged away into interplanetary space.

It is seen, then, that a journey out of the ecliptic is not just a crazy venture away from the plane of the planets toward "empty" space. There is ample evidence that there is much to be seen and gained if only we can get there. We stand today like the European sailor-explorer of the Middle Ages who was confident of reaching riches in the Indies if only he could find his way. Like him, we could well stumble on a new world during the journey.

Scientific Reasons for the Journey

The scientific considerations involved in a journey out of the ecliptic are described in more detail under six headings.

1) *Solar wind plasma.* The fact that all comet tails appeared to experience a slight push in a direction radially outward from the sun first led to the concept of a continuous solar wind (*12*). An essentially one-dimensional spherically symmetrical coronal expansion theory has been successful in ex-

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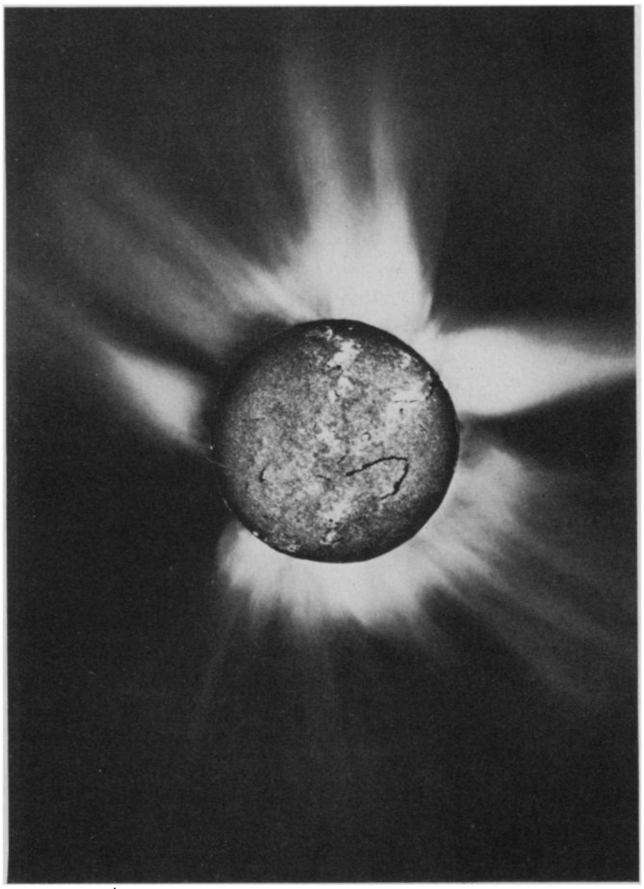


Fig. 1. Montage of an eclipse photograph of the solar corona and a photograph of the visible surface of the sun (out of eclipse, near the same time) in the light emitted by atomic hydrogen. [Courtesy of the Space Environment Laboratory, National Oceanic and Atmospheric Administration, Washington, D.C., and the High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado]

plaining the gross features (*13*) and plasma experiments in the ecliptic plane have confirmed the presence of a continuous outward plasma flow at speeds around 400 km/sec (*14*). However, there is a long way to go before we can understand the physics of the solar wind expansion and get to know the sun as a star. These studies require a knowledge of solar wind parameters over a wide range of solar latitudes, and just because the flow is nearly radial it is necessary to go out of the ecliptic to make the measurement.

Since the solar wind stretches out solar magnetic features to form the basic interplanetary field structure, we need to know the behavior of the wind at all solar latitudes in order to map the dynamic interplanetary cavity that surrounds the sun and so controls radiation reaching the earth. Cometary observations suggest an approximately radial wind at all positions (*15*) but we might expect velocities and flow characteristics above the active sunspot belt regions to be very different from those seen at latitudes above about 40°, or indeed near the equator (*9*) (Fig. 2). We are still uncertain whether the wind originates in small limited areas on the sun—for example, in the coronal holes (*11*)—and takes on its more continuous nature only at higher altitudes in the corona. Eclipse pictures of the corona suggest large changes in behavior between active region latitudes and the solar poles. Near the poles the plasma flow might be faster and essentially along magnetic field lines which are no longer wound into a tight Archimedes spiral by rotation. The absence of rotation there should change the interaction between fast and slow streams, fundamentally altering field-particle interactions (for example, Alfvén wave propagation characteristics).

Statistical surveys of plasma and magnetic field within our narrow 7° slice (*16*), the behavior of comet tail emissions (*17*), and radio star scintillation studies of plasma blobs (*9, 18*) all indicate significant latitudinal structure and suggest increasing flow velocities as higher latitudes are approached.

It is becoming clear that even within the narrow solar latitude slice we sample, the solar wind is not a nice steady plasma flow but is highly variable and consists of interacting fast and slow streams presumably originating in different places back at the sun (*1, 19*) (Fig. 3). Studies of the flow from different types of source regions (active regions, coronal holes, and so forth) and the variation of the effects of rotation with latitude should enable theorists to come closer to explaining, for example, thermal conductivity and field-particle interactions. One of the big mysteries of solar wind behavior is how helium varies so much in bulk velocity, temperature, and density compared to hydrogen (*1*).

It is also necessary to determine the three-dimensional shape of interplanetary shock fronts in the wind and to correlate wind discontinuities with solar latitude and surface features in order to see which discontinuities originate at the sun and which in interplanetary space.

We wish to know the total rate of loss of mass, energy, and angular momentum from the sun and the chemical composition of the material lost. Since the measurement in the ecliptic plane is certainly unrepresentative, measurements at other latitudes are required. It should then be possible to test the suggestion that the mass carried away from the sun is returned in the form of new comets. The total rate of loss of angular momentum has important implications for theories of star formation and evolution, solar system cosmogony, and the relativistic theory of gravitation.

2) *Interplanetary magnetic field.* The interplanetary field is carried into position by the solar wind. Near the earth in the ecliptic it follows the Archimedes spiral pattern and in polarity is directed either "toward" the sun or "away" from the sun (*20*). Typically the earth remains in a field sector where the polarity is toward the sun for about 7 days and then within a few hours finds itself transferred to a sector of opposite polarity, where it again stays for about a quarter of a solar rotation (*21*) (Fig. 4).

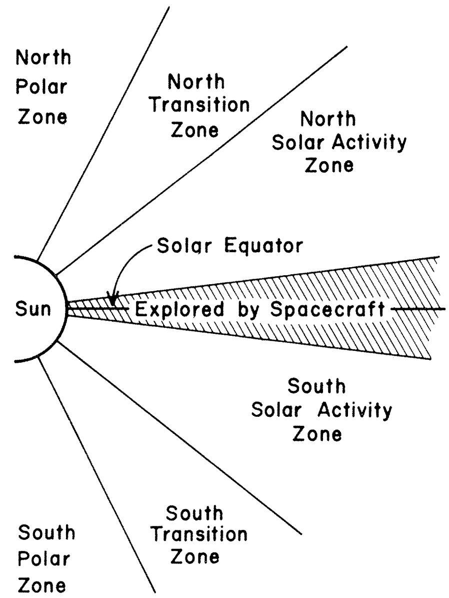
The sector structure is not understood, and the pattern we see in our 7° slice of solar latitude may be totally misleading. A section cut through another part of the three-dimensional field configuration surrounding the sun could look entirely different. (A fundamental plasma physics problem is explaining how the oppositely directed fields are maintained side by side in interplanetary space.) A basic objective of any mission out of the ecliptic must therefore be simply to find what the interplanetary field really looks like in three dimensions. We want to know at what latitudes the polar (dipolelike) field is prominent, in what features and over what volume in space the solar cycle variation shows, what happens when the solar background field reverses polarity, how the magnetic field fluctuations which so affect particle propagation vary with solar latitude during the solar cycle, and at what height in the corona the magnetic field begins to show the Archimedes spiral structure.

We might reasonably expect strongly

varying and tightly spiraled fields above active solar latitudes, but at latitudes higher than about 40° a smooth and more radial field could be anticipated as a result of faster plasma flow and reduced rotational effects. Statistical averaging over seasons, as the earth moves its 7° from the solar equator, already indicates that the average field polarity north of the solar equator is opposite to that south of it (*22, 23*) (Fig. 5). A basic experimental problem in an out-of-ecliptic mission will arise in separating true latitude variations from the large temporal fluctuations which call for long-term statistical averaging at each latitude.

3) *Solar particles.* We know that solar particles produced over a wide range of latitudes on the sun find their way through the continuously changing interplanetary magnetic field maze to reach the vicinity of the earth (*24*). We do not understand how and precisely where on the sun the particles originate, and since we do not know the three-dimensional nature of the magnetic field structure between the sun and the earth we can only guess about the propagation mechanisms. If the earth were sitting at a different solar latitude (for example, above the active belts) our concepts of solar particle events could be very different. By measuring plasma and fields out of the ecliptic we can get to know the regime through which the particles travel and, in turn, use the particles as tracers to help map this regime.

It is becoming clear that solar particles travel in three-dimensional snakelike magnetic field tubes carved out by solar wind streams and experience great difficulty in moving across field lines to neighboring field regimes (*25*). This fact can be used, together with a knowledge of solar wind history, to try and trace the particle propagation path back to its origin on the sun (*26*). One of the many problems arises in explaining the variable delays between solar flares and the arrival of particles near the earth. A simple explanation is that the flux tube in which the particles propagate most easily may have a very complicated three-dimensional shape and may even, with solar rotation, bypass the earth to the north or south of the ecliptic plane. There is also reason to believe that the particles may remain trapped for some time in closed magnetic field structures close to the sun before being released to travel along flux tubes in interplanetary space (*27*). Above about 40° in latitude it would be reasonable to expect to see the particles arrive without hindrance from the closed and spiral structures, if indeed particles are generated at these latitudes. The same event will look very different from one latitude to the next.



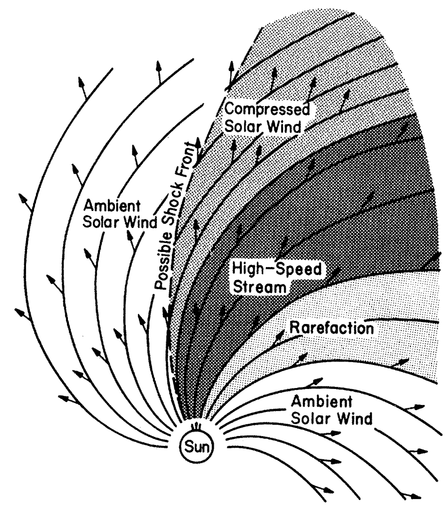
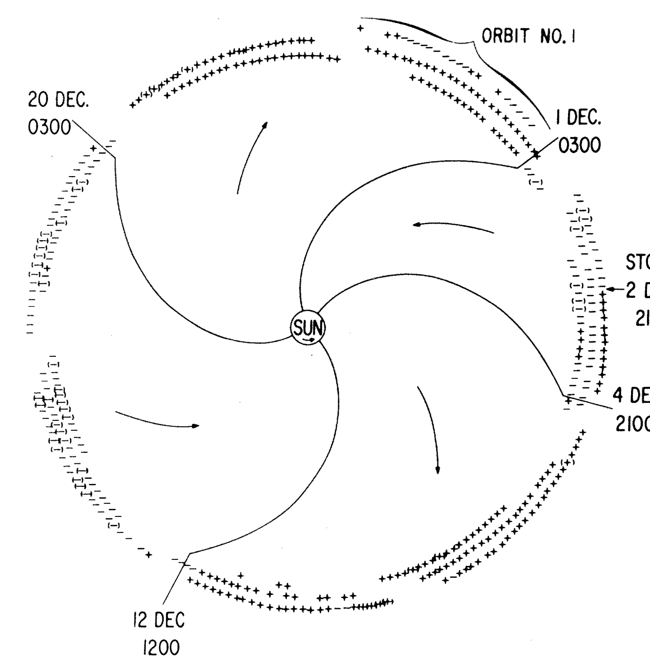


Fig. 2 (left). Schematic of distinct regions of polar latitude, where very different coronal behavior is expected. Close to the solar equator and over the poles there should be relative quiet. More violent phenomena will be witnessed above the sunspot belt, at latitudes between about 10° and 40°. [Courtesy of J. A. Simpson] Fig. 3 (right). The situation in interplanetary space when a high-speed stream in the solar wind "overtakes" plasma moving at more average velocities. [After Hundhausen (*1*)]

Fig. 4. Sector structure of the interplanetary magnetic field. There are typically, as on this occasion, four reversals of field polarity during one solar rotation (about 27 days). [After Wilcox and Ness (*21*)]



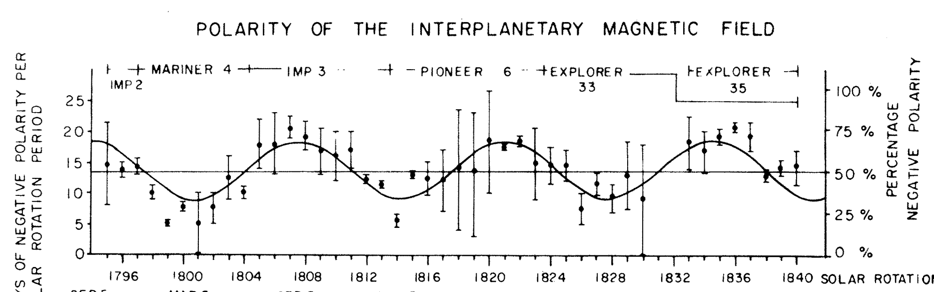


Fig. 5. In the course of a year the earth moves through a range of heliographic latitudes from about 7° north to 7° south. (The earth is on the solar equator each June and December.) Rosenberg and Coleman (*22*) show how the polarity of the interplanetary field observed near the earth varied accordingly in the years 1964 to 1968.

Study of solar events at various solar latitudes can therefore help explain where and how the particles originate. This would increase our understanding of the sun, which is our only readily accessible astrophysical object. The particles used as tracers can establish the structure of the interplanetary medium, yielding information on sector structure, where closed solar magnetic structures become spiral or radial, and the nature of the interface between colliding solar wind streams (which collide less at higher latitudes), and on a smaller scale they can permit study of solar wind discontinuities and Alfvén wave scattering of particles.

4) *Cosmic rays and astrophysics.* It has long been the aim of the cosmic-ray physicist to identify the origins of that radiation. However, the same interplanetary medium of plasma-borne magnetic fields which surrounds the sun and steers solar particles in three dimensions also obstructs the arrival of galactic particle radiation. In addition to exploring the nature of this obstructing cavity, a mission toward solar polar latitudes should provide an opportunity of directly measuring the local interstellar cosmic rays, which many believe arrive without hindrance along the supposedly radial solar polar field lines.

Knowledge of the interstellar spectral shape and particle composition would tell about the distribution of cosmic sources and the amount of matter traversed. The real primary electron spectrum combined with the galactic radio measurements would provide information on gas densities and magnetic fields in the galaxy. Recent exciting measurements have found enhanced nitrogen and oxygen components in the low-energy "turnup" of the modulated spectrum (*28*), which part of the spectrum had previously been assigned a solar origin. One interpretation is that neutral interstellar particles have penetrated the solar cavity, and have there been ionized and accelerated by the solar wind (*29*). This acceleration should be related to solar wind properties, so the hypothesis could be tested by measuring particle populations at different solar latitudes. There are also indications—for example, anticorrelation with solar activity—that the low-energy turnup may be of galactic origin (*28*). If this is so, the shape of the spectrum is a considerable mystery, and particle propagation at low energies must be quite unusual.

Measurements of the modulated "primary" spectrum made at the earth show a minimum intensity at around 20 Mev per nucleon and an increasing flux, perhaps of solar origin, below that energy (*3*) (Fig. 6). The spectral curve in these regions varies significantly with the 11-year solar cycle, and much work has gone into using the data thus generated to calculate a "true" primary spectrum, as would be seen outside the supposed modulating solar cavity. Recent spacecraft measurements show, however, that the plasma and magnetic parameters believed responsible for the modulation change so little in the ecliptic plane during a solar cycle that we are obliged to conclude that most of the modulation occurs far from the ecliptic (*30*). [The absence of a cosmic-ray gradient en route to Jupiter supports this (*31*).] The pertinent parameters or the cavity size and structure need to change dramatically in order to explain the cosmic-ray variations measured. Our ignorance of how the particles travel and how and where they are "modulated" is fairly complete, and it is difficult to see how the situation can be improved without direct exploratory measurements out of the ecliptic.

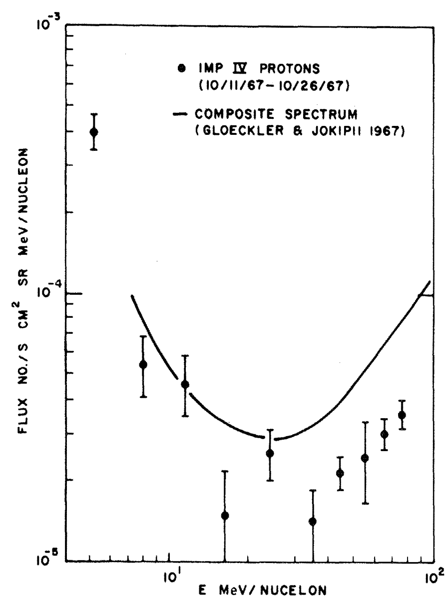


Fig. 6. Cosmic-ray fluxes plotted against energy during 1967. Below energies of about 20 Mev per nucleon the particles are thought to be mainly of solar origin. Above that energy they are probably of galactic origin. When the sun is less active than in 1967 more low-energy galactic particles (20 to 100 Mev per nucleon) can penetrate the heliosphere and the valley in the data curve fills up (*3*).

5) *The sun.* The study of radiation from distant exotic astrophysical objects is currently so popular that it seems surprising that more effort is not being made to widen our very narrow perspective of the one accessible star. Two fundamental problems arise in studying the sun from the position of the earth: (i) The shape and volume of many features cannot be determined because these are viewed from one angle only. Solar rotation may help if it can be assumed that a feature remains constant while it rotates to a different view angle, but the time constants of many phenomena are too short for this to be useful. (ii) Although following the development of a feature as it rotates across the sun can be useful, the study is of necessity interrupted every 13 days when the feature disappears beyond the western limb. Viewing the sun from high ecliptic latitudes would permit uninterrupted study of solar features as they evolve and would, in conjunction with near-earth measurements, allow the absolute size of solar features to be determined.

Spacecraft have made it possible to view the solar atmosphere at previously unattainable wavelengths, and the simultaneous examination of all heights in the solar atmosphere thus made possible has contributed greatly to our knowledge of the structure and dynamics of many solar features. At low solar altitudes closed magnetic loop structures dominate the plasma, but higher up coronal expansion takes control (*32*). Little is known about the transition region. Expansion—evidenced, for example, as streamers in eclipse pictures of the corona—remains radial up to about 10 solar radii, but somewhere beyond that point rotation presumably ceases to be rigid and the coronal streamers take on a "garden hose" configuration. It is of particular interest to follow the development of these features all the way into the solar wind, and continuous three-dimensional viewing would help enormously.

A relationship has been found between the long-lived coronal holes—recently discovered at all solar latitudes in soft x-ray and extreme ultraviolet images of the sun and found to exist mainly toward the solar poles (*11*)—and recurrent high-velocity streams in the solar wind. With simultaneous solar wind measurements and continuous viewing of the coronal holes from a vantage point directly above the solar poles this relationship could be examined in detail.

Another recent discovery is that of "coronal transients" (*33*)—large bubbles of gas moving out rather fast through the corona—which appear to be the source of a particular class of nonrecurrent high-velocity plasma streams (Fig. 7). Because of the fast development of these bubbles, solar rotation cannot be used to reconstruct their third dimension, and the determination of the masses and energies involved is therefore uncertain.

It seems clear that major progress can be made in understanding the sun as a star and in appreciating how its atmosphere—the heliosphere which engulfs the solar system—is formed, and performs, if only we can carry rather ordinary instruments out of the ecliptic to view the sun from another angle.

6) *Zodiacal light and interplanetary dust.* Zodiacal light is the light scattered

from dust in interplanetary space (*34*). If we could determine the spatial distribution and composition of this accessible interplanetary dust we might be able to identify its origins. As a consequence, we would be in a better position to understand the role of distant cosmic dust clouds in the genesis of other planetary systems, in stellar generation, and in molecule formation.

From near-earth measurements of zodiacal light we believe that the dust distribution is structured in rings from about 3 solar radii (closer to the sun the dust is vaporized) out to about 8 solar radii (*35*). Between the orbits of Mercury and the earth is a somewhat more homogeneous distribution of large particles. It would seem that most of the dust tends to be near the ecliptic plane (*36*) but there may be significant small deviations. For example, very recent observations suggest that the plane of symmetry of the inner zodiacal light coincides with the orbit of Venus rather than with the ecliptic (*37*).

Zodiacal light experimental measurements consist of determining, as a function of wavelength and polarization, the intensity of light scattered into a particular direction. The aim is to use these measurements to determine the distribution of dust particles in the solar system in terms of the chemical composition, size, shape, and orbital parameters of the particles. Since all these parameters are involved in determining the intensity and polarization seen at a particular wavelength, since many particles nonuniformly distributed in many positions may scatter light to produce an integrated "line of sight" measurement, and since from the earth it is not possible to vary the line of sight, it is hardly surprising that models of the interplanetary dust distribution are nonunique.

A major advance can be made when it becomes possible to look through the dust distribution from many directions. Measuring the zodiacal light from an out-of-ecliptic spacecraft would in many ways be analogous to studying a cloud by measuring light intensity in it as an airplane rose through it. At the moment we are stuck right in the cloud.

If it is also possible during the mission to measure in situ the size, mass, and velocity of individual dust particles, the distribution can be determined with even more certainty. Techniques are available to do this (*38*).

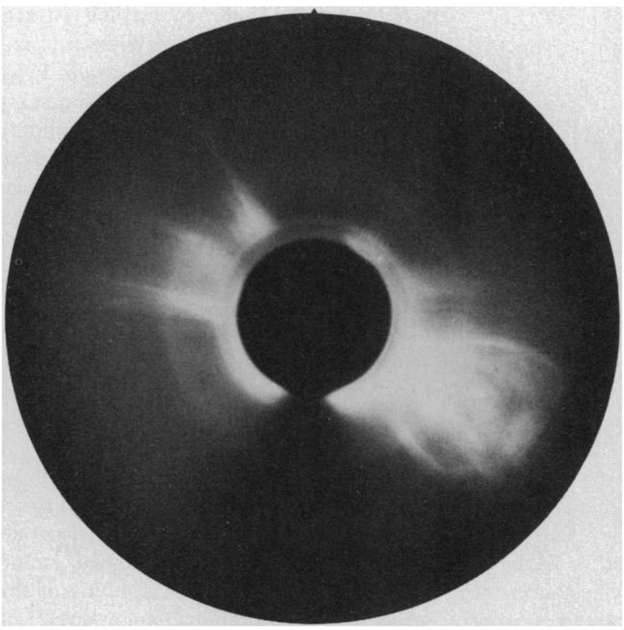
Two Ways out of the Ecliptic

Two ways of getting out of the ecliptic are being studied jointly by the National Aeronautics and Space Administration and the European Space Research Organisation. Each has some special advantages, but either would handsomely meet the scientific objectives.

1) In the solar electric propulsion method (*39*) a single spacecraft is injected into a circular orbit of radius 1 astronomical unit about the sun. The plane of the orbit is not far from the ecliptic plane, and its period about the sun is, not unnaturally, 1 year. At appropriate parts of the orbit ion thrusters are operated roughly perpendicular to the velocity vector, so that the spacecraft is gradually constrained to take up an orbit whose plane is inclined to the ecliptic. Each year the spacecraft scans a range of positive and negative solar latitudes, gradually increasing the range covered until, after about 4 years, latitudes around 55° have been reached.

This spacecraft can carry a relatively heavy payload and, being stabilized on three axes, is suitable for experiments directly viewing the sun. The payload can be tailored to specialize in interplanetary space and need not have the dynamic range necessary to handle vastly different environments or carry the shielding necessary to survive the Jovian radiation. Perhaps the most important advantage is that the spacecraft stays at a constant distance from the sun and scans relatively slowly and repeatedly through a limited range of solar latitudes. This permits sorting out variations with distance, latitude, and time; allows recalibration against known conditions each time the spacecraft crosses the ecliptic plane; and, in the end, makes possible the long-term statistical averaging so important in establishing background magnetic field configurations.

2) In the Jupiter swing-by method (*40*) two spacecraft are launched by one vehicle toward Jupiter in the now-standard way. Before Jupiter they separate. One enters the Jovian magnetosphere, swings by the



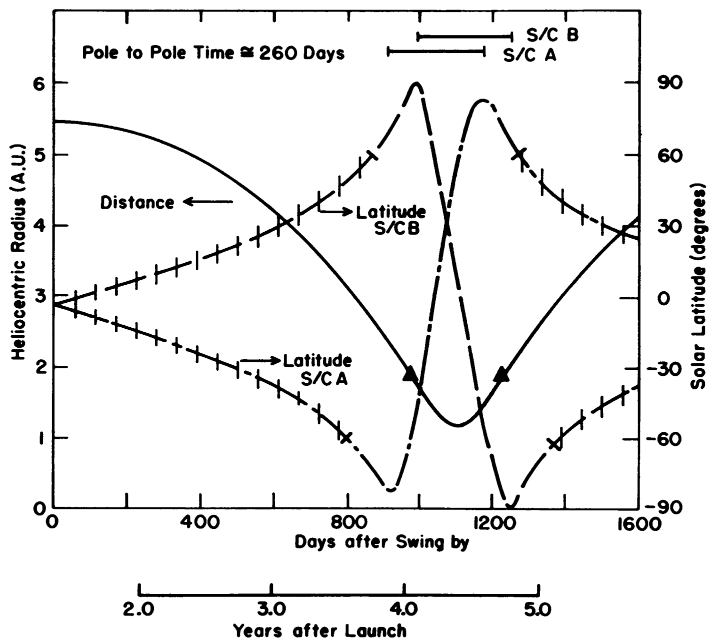


Fig. 7 (left). Coronal transient photographed from Skylab by the white light coronagraph of the High Altitude Observatory, Boulder, Colorado. Loop structures can be seen in material moving outward from the sun with an apparent velocity of about 450 km/sec. This event was observed for approximately half an hour (*33*). Fig. 8 (right). Progress of spacecraft A and B in the dual-spacecraft Jupiter swing-by mode of getting out of the ecliptic. When the spacecraft are over the solar poles each will be approximately 1.5 astronomical units from the sun. (One astronomical unit is the distance between the sun and the earth.) [Adapted by J. A. Simpson from data supplied by Ames Research Center, Moffett Field, California] planet, and exits through the northern magnetosphere, traveling through "north ecliptic interplanetary space" to pass over the north pole of the sun. The other is directed to use Jupiter for a pull that swings it into a similar path, but south of the ecliptic and then over the south pole of the sun. The progress of the mission in solar latitude is shown in Fig. 8. Each spacecraft is spin stabilized and carries about 30 kg of experiments. To take advantage of the almost unique opportunity to compare results from two spacecraft simultaneously operating in two different places, both spacecraft carry a standard "core" of experiments weighing about 17 kg. The remaining 13 kg in spacecraft A need not necessarily be the same as in spacecraft B.

The advantages of this method are that the use of two spacecraft permits the resolution of space and time ambiguities, it is possible to reach solar polar latitudes, the Jovian magnetosphere can be looked at on the way, and the spinning spacecraft render the measurement of particle anisotropies less complex technically.

Summary

Our narrow view of the sun and its surrounding atmosphere is quite inadequate if we are to understand the sun as a star and describe the behavior of its corona. Nor can measurements in the ecliptic plane enable us to determine the interstellar cosmic-ray intensity.

There is ample evidence that an exploratory journey out of the ecliptic to high solar latitudes would be highly rewarding. Rather simple experiments could lead to major advances in our understanding of solar wind physics, of cosmic-ray modulation, of the structure of the interplanetary magnetic field, of solar particle propagation, of interplanetary dust, and of the basic nature of the sun itself.

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Determination of Molecular Conformation in Solution

Applications of nuclear magnetic resonance to the topology of molecules in solution are reviewed.

M. Robert Willcott, III, and Raymond E. Davis

Immediately after the discovery of three signals in the proton nuclear magnetic resonance (NMR) spectrum of ethanol by three physicists (*1*), chemists appropriated the method as a tool for the deduction of detailed chemical structure. The complexity of the instrument, then and now, is offset by the facile interpretation of the experimental results in many instances. At present more than 2700 papers per year refer to NMR (*2*). Most of these accounts appear in chemical journals. Increasingly sophisticated NMR experiments are being developed through improvements in instrumentation. Each new method attracts specialists who generate new descriptions of the molecules under investigation. Typically, these new methods are not quickly assimilated into the chemical community due, in great part, to the time lag between understanding the experiment and obtaining funds for the purchase of new equipment (*3*).

Hinckley's recent description (*4*) of a convenient sample modification with paramagnetic ions has run counter to this trend. The additional cost of the experiment need not exceed $1, the required chemicals are readily available, and the experiment can be performed in two to four times the period normally used to obtain a single NMR spectrum. The most important feature of the Hinckley report is that the interpretation of the modified proton NMR signal frequencies in terms of the structure of the compound under investiga-

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