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Magnetic Fields in Interplanetary Space

A weak magnetic field pulled out from the sun has considerable influence on interplanetary processes.

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During the past decade there has been increasing evidence that the space around the sun is occupied by a weak magnetic field, pulled out from the sun by continually emitted clouds of ionized gas. The field is of very low magnitude, only 5 to 10 gammas (1 gamma = 10^{-5} gauss). Its general configuration appears to be a spiral with the sun as a hub, where field lines extend perhaps 100 astronomical units (1 A.U. = 1.495×10^{8} km) from the sun. Early experimental evidence for the presence of such a field was indirect. Some properties of magnetic fields in space surrounding the earth could be inferred from their effects on charged particles. Hence, studies of fluctuations in the cosmic radiation—energetic protons bombarding the earth—indicated the gross structure of the interplanetary field. Theoretical work on the expansion of ionized gas (plasma) from the sun and the transport of solar magnetic fields by this gas suggested the origin of the field. Early satellite measurements indicated that an interplanetary field existed, but they were ambiguous concerning the direction and magnitude of this field. Only very recently have reliable vector (direction and magnitude) measurements of the interplanetary field been obtained.

Although the field is very weak and its energy density (in ergs per cubic centimeter) is much lower than that of the advancing solar plasma that carries it along, its influence on several interplanetary and planetary processes is profound. The field influences the behavior of the solar plasma itself. It constrains the individual protons and electrons of the plasma to move collectively, thus causing the solar plasma to behave as a fluid rather than as an assembly of independently moving particles. The fluid flow around the earth and its magnetic field and the resulting interactions have been discussed by Hines (*1*). It is thought that these interactions would be quite different in the absence of an interplanetary field.

We can see that high-energy charged particles from the sun, solar cosmic rays, and particles of even higher energy from outside the solar system (galactic cosmic rays) can be affected by this very weak magnetic field when we consider that the small force exerted on the particles by the field acts over distances of 1 astronomical unit or more. This force is always perpendicular to the direction of particle velocity and to the field direction. It bends the particle trajectories into circular arcs; low-energy particles are deflected more than high-energy particles. Enhancement of the interplanetary field following large eruptions of plasma during solar flares is thought to cause the abrupt decreases in cosmic radiation called Forbush decreases. A gradual enhancement of the interplanetary field during the more active portion of the sun's 11-year sunspot cycle is thought to cause a gradual decrease in the intensity of cosmic radiation. In this article I discuss the development of the concept of an interplanetary magnetic field, the evidence of its existence, and the effects of this field.

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Growth of the Interplanetary Magnetic Field Concept

Until recently, interplanetary space was assumed to be devoid of matter and of magnetic field. The earth's magnetic field, of the order of 1 gauss at the earth's surface, decreases as the inverse cube of the radial distance from the center of the earth and thus drops to a magnitude of less than 1 gamma within a few hundred thousand kilometers of the earth's surface. Some of the other planets have magnetic fields, but their fields should also decrease to 1 gamma within a few hundred thousand kilometers. An observed shift in the frequencies of certain lines of the sun's spectrum was attributed to the presence of magnetic fields near the sun (*2*). A general solar field, with the configuration of a magnetic dipole (similar to that of a small bar magnet), was inferred from the spectral measurements and from the configuration of the solar corona during eclipses. Visible streamers of coronal gas appear to follow dipole-like lines of force emanating from the sun's polar regions. The magnitude of this field is of the order of 1 gauss at the sun's surface. More localized fields, associated with active solar regions, appear to be higher by one or two orders of magnitude than the 1-gauss dipole field. The strength of the dipole field should decrease by the inverse cube of the distance from the sun's center and will be below 1 gamma within 100 solar radii (one solar radius = 7.0×10^{5} km). The stronger local fields decrease more rapidly, and thus at the distance of the earth's orbit (1 A.U.) solar fields should be well below 1 gamma. A large-scale magnetic field aligned with the spiral arms of our galaxy has been proposed. This field (of the order of 1 gamma) could extend through the empty interplanetary space.

Chapman and Ferraro (*3*) in the early 1930's realized that the increase in the magnitude of the earth's magnetic field in the initial phase of a magnetic storm could be attributed to compression of the earth's field by plasma from the sun. It had been observed that magnetic storms on the earth followed eruptions on the sun by 1 or 2 days, and from this delay the plasma velocity was determined to be approximately 1000 kilometers per second. Chapman and Ferraro envisioned this solar plasma as being emitted in isolated clouds from active regions on the sun's surface at the time of solar flares; they did not envision continuous emission of plasma from the sun's surface. The magnetic field of the sun did not enter into the theory, and the plasma compressing the earth's magnetic field was assumed to be free of magnetic field.

Alfven (*4*) proposed that a moving ionized gas could carry a magnetic field along with it, and it was he who first enunciated clearly the concept of the "frozen-in" magnetic field. This concept is based on the fact that a highly ionized plasma also has a high electrical conductivity. According to Alfven, a magnetic field initially established somehow in a highly conductive plasma prevents motion of the plasma perpendicular to the lines of the magnetic field. During such motion the field would deflect protons in one direction and electrons in the opposite direction. The strong electrical currents produced by the deflections of protons and electrons would maintain the magnetic field and prevent it from changing. This can be considered an example of the general law of Lenz: In case of a change in a magnetic system, that thing happens which tends to oppose the change. In the case described, either the motion is stopped when the field is strong enough, or the field is carried along with the plasma if the plasma energy is strong enough. If we imagine tubes of magnetic flux initially threading the plasma, each segment of plasma, according to the frozen-field concept, is destined to remain on the same magnetic flux tube. Conversely, a given body of plasma will carry along a magnetic field embedded in it so that the field lines always remain associated with the same group of particles.

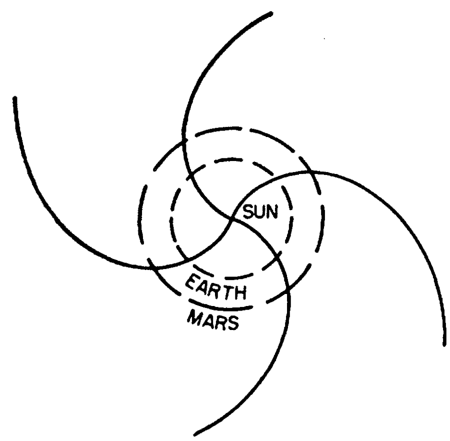

Fig. 1. Spiral interplanetary magnetic field. The view is from the north ecliptic pole, looking down on the ecliptic plane. The sun's rotation, in a counterclockwise direction, causes the plasma radially ejected from a point fixed on the sun's surface to form a spiral in space, much like the stream of water from a rotating garden hose. The magnetic field, attached to the same point on the sun's surface, is pulled by the moving plasma into the spiral shape. [E. N. Parker, *J. Geophys. Res.* **64**, 1675 (1959)]

The next step in the unfolding of the interplanetary field concept came from the work of Biermann (*5*) on deflection of comet tails away from the sun. Biermann reasoned that this deflection could not be caused by sunlight alone but must be due to particles from the sun, traveling radially outward. Chapman (*6*) advanced the idea that the atmosphere of the sun is not confined to a volume extending several solar radii out from the sun's surface but may extend to the orbit of the earth. He had in mind, however, a static atmosphere at a high temperature, 10^5 degrees Kelvin.

Parker (*7*) combined several of these ideas and established the general features of a continually expanding plasma (the solar wind) streaming radially outward from the sun's surface and pulling with it the magnetic field of the sun, to the earth and beyond. According to Parker, and to such observations of the solar corona as existed, the region out to a distance of several solar radii is populated by a hot (10^6 deg K), relatively dense (3×10^7 particles per cubic centimeter) plasma of protons and electrons. Parker proceeded to show that the atmosphere of the sun could not exist in static equilibrium with the estimated galactic gas pressure, even at very great distances from the sun. Thus, a static solar atmosphere extending to the orbit of the earth, as suggested by Chapman, was not an attractive hypothesis. Biermann's work indicated a plasma streaming outward from the sun, so Parker sought to establish a model for a continually expanding solar atmosphere. The energy flux of the solar plasma at great distances from the sun could be estimated from the work of Biermann; the estimate gave velocities of the order of 1000 km/sec with particle densities of the order of 100 per cubic centimeter at the orbit of the earth. The coronal temperature would not be sufficient, however, to provide escape velocity for individual hydrogen ions. Escape velocity for the sun is of the order of 500 km/sec, while the thermal velocity corresponding to the assumed coronal temperature is only 160 km/sec. Starting with the equation of motion of the coronal gas (including the gravitational attraction of the sun and coronal heating effects) and the equation of continuity (the same amount of gas must flow through each of a series of concentric spherical shells about the sun), Parker was able to show that the velocity of the gas continues to increase to several hundred kilometers per second as the gas travels outward. The velocity attained depended on the coronal temperature assumed. After heating effects from the corona had ceased, the velocity remained constant as distance from the sun increased. The expansion and increasing velocity of the gas, were, therefore, the direct result of maintaining the coronal temperature at a steady value. Assuming a coronal temperature of 10^6 deg K, Parker showed that a streaming velocity of 500 km/sec was attained at 30×10^6 km and that this velocity remained constant thereafter. Since heating of the solar corona by by electromagnetic radiation or by acoustical waves propagating upward from the solar surface was thought to be inefficient, he suggested, as a mechanism, hydromagnetic waves propagating from the sun's surface.

Parker then turned his attention to the effects on the sun's magnetic field of the streaming solar plasma. He assumed that the average field in the corona must be dipole in nature and that the outward-streaming solar gas commenced its expansion with solar magnetic field lines firmly imbedded within it. He reasoned that, according to the frozen-in field concept, the sun's field must be pulled out from the sun by the radially moving plasma. Although the plasma would continue moving radially outward at great distances from the sun, the field lines, anchored firmly to the moving plasma and just as firmly to the surface of the rotating sun, would be stretched into spirals, as shown in Fig. 1. The angle (Θ) which the spiral field line makes with a radial line from the sun at a point in space near the plane of the ecliptic is given by:

$$\tan \Theta = \frac{\omega R}{V}$$

where ω is the angular velocity of the sun, R is the radial distance to the field line, and V is the plasma velocity. From this relationship Parker noted that at a distance of approximately 2.5 astronomical units, for plasma with a velocity of 1000 km/sec, the field line would make an angle of 45° with the radius vector. In Parker's words, "The radial configuration will be as universal as Biermann's outward gas motion which is responsible for it." He noted that the 11-year modulation of galactic cosmic radiation could be caused by the magnetic fields carried outward by the solar wind. He envisioned a broad disordered shell of interplanetary magnetic field at a distance of many astronomical units. The intensity of this shell would be enhanced at the peak of the 11-year cycle of solar activity, and the shell would become more effective in deflecting galactic cosmic-ray protons.

Parker's model of the steady solar wind is appropriate for the quiet sun. The sun's surface is known, however, to be active. Active regions—groups of sunspots—move across the visible face of the sun as the sun rotates; sometimes the same group of sunspots will be apparent for several solar rotations. At times there are eruptions, from the sun's surface, of great bodies of gas; this is particularly apparent when an eruption occurs on the limb of the sun, where it may be photographed against the darkness of space. Of course the activity of the sun and production of local clouds of ionized gas were known long before the steady emission of the solar wind was suggested. Parker recognized that the proposed steady expansion of gas and smooth, spiral magnetic fields were idealized views of the actual situation.

Another model that emphasizes the active solar regions and is complementary to Parker's in some respects has been presented by Gold (*8*). According to Gold's model, plasma is spewed forth from an active region on the sun's surface at the time of a solar flare. Strong magnetic fields are observed to be associated with active regions. The violently expanding gas cloud pulls the magnetic field of the active region outward from the sun's surface, while the ends of the lines of force remain anchored to the sun. The model shown in Fig. 2 differs from Parker's in that the field is tied to a local active region on the sun. The expanding gas cloud pulls the field out into loops, which resemble a bottle. If the bottle expands toward the earth it causes, a day or two later, the onset of a magnetic storm at the earth's surface, as was first noted by Chapman and Ferraro. Gold recognized the presence of interplanetary gas prior to a flare in noting that the advancing gas cloud must have a very sharp leading edge. This he inferred from the sudden rise (within 1 or 2 minutes) of the geomagnetic field at the beginning of magnetic storms. If the gas were expanding into a vacuum, then thermal diffusion would broaden the leading edge of the gas cloud, so that compression of the earth's magnetic field would take place over several hours.

The magnetic bottle model was used to explain two phenomena, the Forbush decrease of galactic cosmic radiation and the wide range of arrival times of high-energy charged particles from a solar flare. According to Gold, the Forbush decrease, a decrease of a few percent in the cosmic radiation measured at the surface of the earth, could be explained by the shielding effect of the magnetic bottle. The magnetic fields of the bottle would deflect incoming charged particles and thus exclude some galactic cosmic rays from the interior of the bottle. The onset of the Forbush decrease would signal the envelopment of the earth by a magnetic bottle. From the observation that the onset time of Forbush decreases was an hour or two, Gold was able to deduce the magnitude of the magnetic fields forming the bottle; he predicted

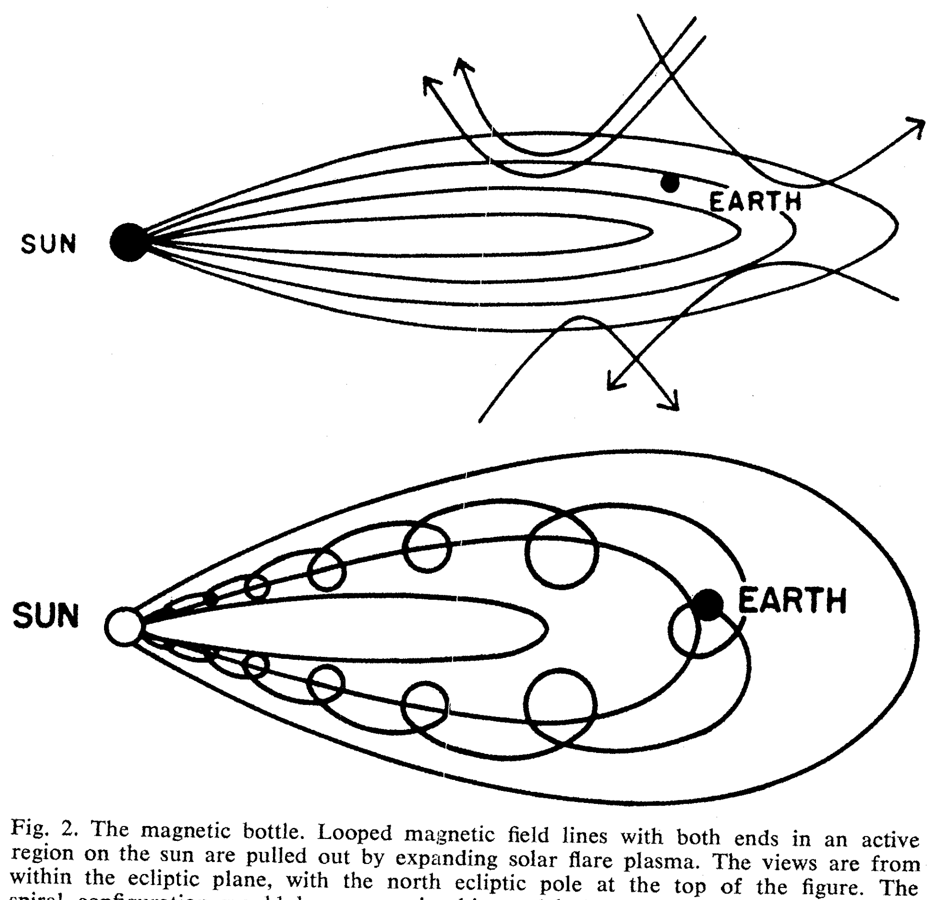

Fig. 2. The magnetic bottle. Looped magnetic field lines with both ends in an active region on the sun are pulled out by expanding solar flare plasma. The views are from within the ecliptic plane, with the north ecliptic pole at the top of the figure. The spiral configuration would be present in this model, but it is not apparent in these views. (Top) Charged particles, of low energy, coming from outside the bottle are reflected by the magnetic field. (Bottom) Charged particles inside the bottle are trapped by the magnetic field and travel along the field lines in helical paths. [T. Gold (*8*)]

values of the order of 1 to 10 gammas.

Increases in the cosmic radiation sometimes are observed within several hours after the beginning of a solar flare. The particles responsible are assumed to be protons from the sun with energies of the order of 1 billion electron volts (*9*). These particles should reach the earth much more rapidly than the lower-energy (1000-electron-volt) particles comprising the solar plasma. The trajectories of the particles are determined by the magnetic fields between the sun and the earth, however, and the wide range of arrival times of solar cosmic rays after the occurrence of the parent flare suggests a variety of interplanetary magnetic field conditions. In addition to excluding the galactic cosmic rays, a magnetic bottle would tend to confine any particles generated within the bottle. The arrival of particles of cosmic-ray energy is sometimes observed for several hours after the flare, particles of higher energy arriving first, those of lower energy arriving later and from all directions. If a bottle from a previous flare contained the earth, then flare particles injected into the bottle would have easy access to the earth, spiraling along the magnetic lines of force. If the particles were injected into a bottle not near the earth, then the low-energy ones could not reach the earth until the bottle had expanded to envelop the earth. Higher-energy particles could escape the bottle, however, and arrive directly. Gold also noted that very low-energy particles which fail to reach the earth's surface at low latitudes sometimes arrive in the polar regions and produce enhanced ionization in the ionosphere, 50 kilometers above the earth, for several days after a flare (*10*). These observations support the view that particles emitted from the solar flare, particularly those of lower energies (100 Mev), are trapped in the magnetic-field pattern expanding from the flare.

Gold's magnetic bottle and Parker's quiet-time spiral field may both exist. Gold has suggested that any interplanetary field existing before the flare would be pushed aside by the expanding bottle. Parker (*11*) has presented a modification of the spiral field at the time of a flare. This model, shown in Fig. 3, assumes that after a flare plasma is emitted from the corona with a velocity greater than that of the quiet solar wind. A "blast wave" is formed between the two regions, where the slower plasma and its field lines are compressed. An important difference remains: the blast wave is generated in the corona, due to enhanced coronal heating related to the flare; the bottle originates at the surface of the sun and pulls out local magnetic fields associated with an active region.

Evidence for Interplanetary Magnetic Fields

Perhaps the most convincing evidence for an interplanetary magnetic field stretching from the sun in a spiral pattern comes from the work of McCracken (*12*, *13*). This evidence is obtained from measurements by neutron monitors at ground level. A neutron detector surrounded by suitable shielding responds principally to neutrons produced indirectly by protons of the primary cosmic radiation. During the International Geophysical Year standardized neutron monitors were established at several locations on the earth's surface to provide reliable and precise measurements of long-term variations in the cosmic radiation. Although the galactic cosmic radiation shows little fluctuation, changes of the order of a few percent may be observed with detectors of sufficient sensitivity. Some features of the cosmic ray fluctuations had been explained in a general manner by the magnetic bottle model. It had previously been noted that solar cosmic rays were observed more frequently from flares that occurred in the western hemisphere of the sun than from those in the eastern hemisphere. McCracken attempted to use the neutron-monitor data to determine more about the nature of the interplanetary field.

Protons that arrive at the top of the earth's atmosphere have been deflected from their original arrival directions by the earth's magnetic field. Particles of lower energy are deflected more than those of higher energy. McCracken was able to show that a given neutron monitor detected only those protons, in a certain energy range, which arrived outside the earth's magnetic field in a relatively narrow cone of directions. He called this cone the asymptotic direction of approach. He calculated the asymptotic direction of approach for each monitor by tracing the path of a charged particle in the reverse direction —that is, from the neutron monitor, back through the earth's magnetic field, into the interplanetary medium. The asymptotic direction of approach

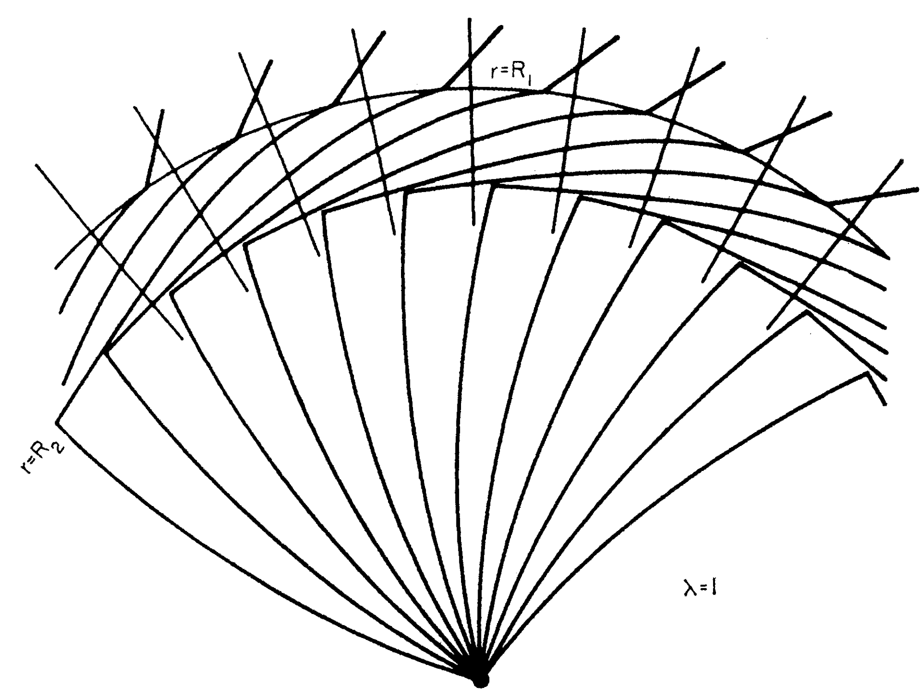

Fig. 3. Blast wave model. The view is again from the north ecliptic pole. Beyond $r = R_1$ lie the quiet solar wind and the spiral field. At distances of less than R_2 exists the post-flare plasma, traveling at a higher velocity; the field lines are more nearly radial because of the higher velocity. Between these two regions the plasma and the field lines are compressed, and thus the angle between the field lines and the radial direction is larger. [E. N. Parker, *Natl. Bur. Std. U.S. J. Res.* **65D**, 537 (1961)]

for a certain monitor could be specified in geographic latitude and longitude. Thus, because of the geomagnetic field, the neutron monitor becomes a directional detector of solar cosmic-ray protons, pointing toward a known direction in the sky. The cone of directions sweeps a path around the celestial sphere each day as the earth rotates. The asymptotic directions of several neutron monitors may be similar in latitude but different in longitude, so that, if charged particles are incident from a certain direction in space, one neutron monitor will see them at a certain time of day and another neutron monitor, further to the west, will see them later in the same day. McCracken proceeded to use the data from the neutron monitors in determining the direction of arrival of solar cosmic rays. He found, in an analysis of three events in 1960, that solar protons which arrived early during the solar flare event arrived from directions definitely to the west of the sun's direction in space. Figure 4 is a chart, in geographic latitude and longitude, of the asymptotic directions of approach for several neutron monitors and the relative counting rates observed at these monitors in the interval 1045 to 1100 hours, Universal Time, during the solar flare of 4 May 1960. Also shown are the direction of the sun and the mean direction of arrival of cosmic rays, deduced from consideration of the various counting rates observed. The mean direction of arrival on 4 May is approximately 55° to the west of the sun.

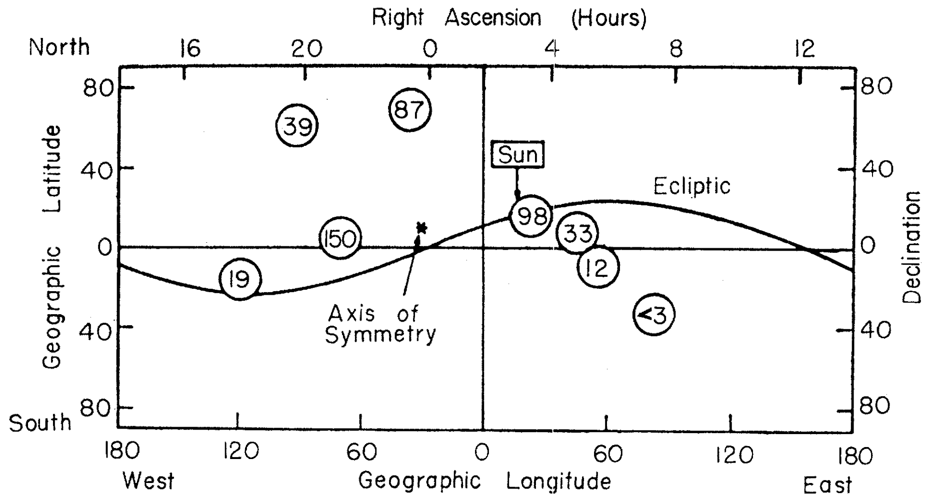

Fig. 4. Asymptotic directions of arrival. The arrival directions (in geographical coordinates) of solar cosmic ray protons during the solar proton event of 4 May 1960 are shown, as observed by several neutron monitors. Within the circles denoting arrival directions are values for the increases (in percentages) of the quiet-time neutron flux, as observed at each monitor. The direction of the sun and the mean arrival direction (axis of symmetry) of the solar cosmic rays are shown. The arrival directions in celestial coordinates may be determined from the right ascension and declination scales on the figure. [K. G. McCracken (*13*)]

From analysis of the solar cosmic-ray events in 1960, and other reported events, McCracken arrived at the following conclusions. An active sunspot region produces a spiral interplanetary magnetic-field pattern with lines of force extending from the active region to the earth's orbit. When the active region is near the western limb of the sun, the spiral lines of force connect the sun with the earth; when the region is in the eastern hemisphere or near the central meridian, the lines do not connect the sunspot to the earth. At the earth's orbit the field lines are inclined approximately 50 degrees relative to the earth-sun line and lie approximately in the plane of the ecliptic. There are small irregularities in the field lines, and these cause some isotropy in the arrival of the solar particles, so that even initially some particles are seen far from the mean direction of arrival. Later in the event, particles are seen at all neutron monitors, indicating complete isotropy. If the lines connecting the sun to the earth were perfectly smooth, then the particles would arrive in a sharply collimated beam.

Apparently the magnetic fields extending from the active region trap solar cosmic rays and retain them for several days, since the cosmic-ray increases are sometimes observed to last that long. If the field lines are not directly connected to the earth, then solar protons may reach the earth only by diffusing slowly out of the magnetic trapping region. This accounts for the observed slow rise times for cosmic-ray increases observed after flares are seen on the eastern hemisphere of the sun. A magnetic region that could trap solar cosmic rays could exclude galactic cosmic rays and cause a Forbush decrease.

McCracken pointed out that a magnetic field region proceeding toward the earth, but still some distance away, can shield the earth from galactic cosmic rays approaching from the direction of the sun, or from west of the sun. Thus, a small Forbush decrease could be produced somewhat in advance of the magnetic storm that indicates arrival of the plasma from the flare. An early Forbush decrease of this type was observed before the event of 22 October 1957. Trapping of solar protons within the magnetic region implies reflection of the particles by some feature of the magnetic field at the outer edge of the region, as well as reflection of the particles from the converging lines of force near the sun. During one of the flare events of 1960, particles were observed coming in a relatively narrow beam from the direction opposite to the sun. This suggests propagation along a reasonably direct path, with reflection accomplished by some smooth feature of the field beyond the earth's orbit. Scattering of the particles from disordered magnetic fields would result in particles arriving from many directions.

The interplanetary magnetic field required by the solar proton observations is not to be compared directly with Parker's quiet-time spiral model. Instead, a configuration appropriate for times of solar activity is needed. Gold's magnetic-bottle model and Parker's "blast wave" model are available. McCracken concludes that either of these models is consistent with the solar proton observations. Trapping in the magnetic bottle is provided by particles spiraling outward along a line of force and continuing along the same line as it loops back to the sun. The kink in the magnetic line of force caused by the outward-moving blast wave in Parker's model can provide particle reflection. Some limitations are placed on this kink, however. According to McCracken the direction of the line of force in the kink must change by a large angle, as great as 70°, in order to cause reflection of the solar protons.

Measurement of Interplanetary Field by Space Probe

The Russian space probe Lunik 2 apparently first observed the solar wind by detecting low-energy electrons at great distances from the earth; magnetometers carried by this probe were of low sensitivity, and only an upper limit—50 to 100 gammas—could be estimated for the interplanetary field (*14*). Pioneer 1, a U.S. space probe, provided the first measurements of what appeared to be the interplanetary magnetic field. The magnetometer carried on Pioneer 1 was essentially a coil of wire rotating in space because of the spin of the satellite. Through rotation of the coil in the ambient magnetic field a sinusoidal voltage is generated, and the amplitude of this voltage is a measure of the component of the magnetic field perpendicular to the spin axis of the satellite. The total field magnitude and the direction could not be determined from the measurements. Pioneer 1 was launched almost directly along the line from the sun to the earth, as shown in Fig. 5, and provided measurements out to a distance of 14 earth radii (R_E) (*15*). When the component of the magnetic field measured by Pioneer 1 was compared with the value predicted by extrapolation of the ground-level field there was reasonably good agreement for distance between 4 and 7 R_E. At distance between 10 and 13.5 R_E the field was considerably higher than that predicted, and large fluctuations in the magnitude appeared. Near 13.5 R_E there was a rather abrupt decrease in the magnitude of the measured component, and beyond this distance the field magnitude remained near 5 gammas. The abrupt decrease was initially interpreted by the experimenters as indication of the boundary of the earth's magnetic field compressed by the solar wind. The fluctuating measurements between 10 and 13.5 R_E were interpreted as hydromagnetic disturbances propagating inward from the field boundary. The magnitude of the field for distances beyond 13.5 R_E was in agreement with that expected for the interplanetary field.

The Pioneer 5 space probe, launched in 1960, provided measurements out to several million kilometers from the earth (*16*). The magnetometer carried by this probe was similar in design to the Pioneer 1 magnetometer. Data were obtained for 55 days in several 20-minute intervals each day. Because of the orientation of the spacecraft the field component measured was approximately perpendicular to the earth-sun line. Again, the field component measured near 8 R_E was in general agree-

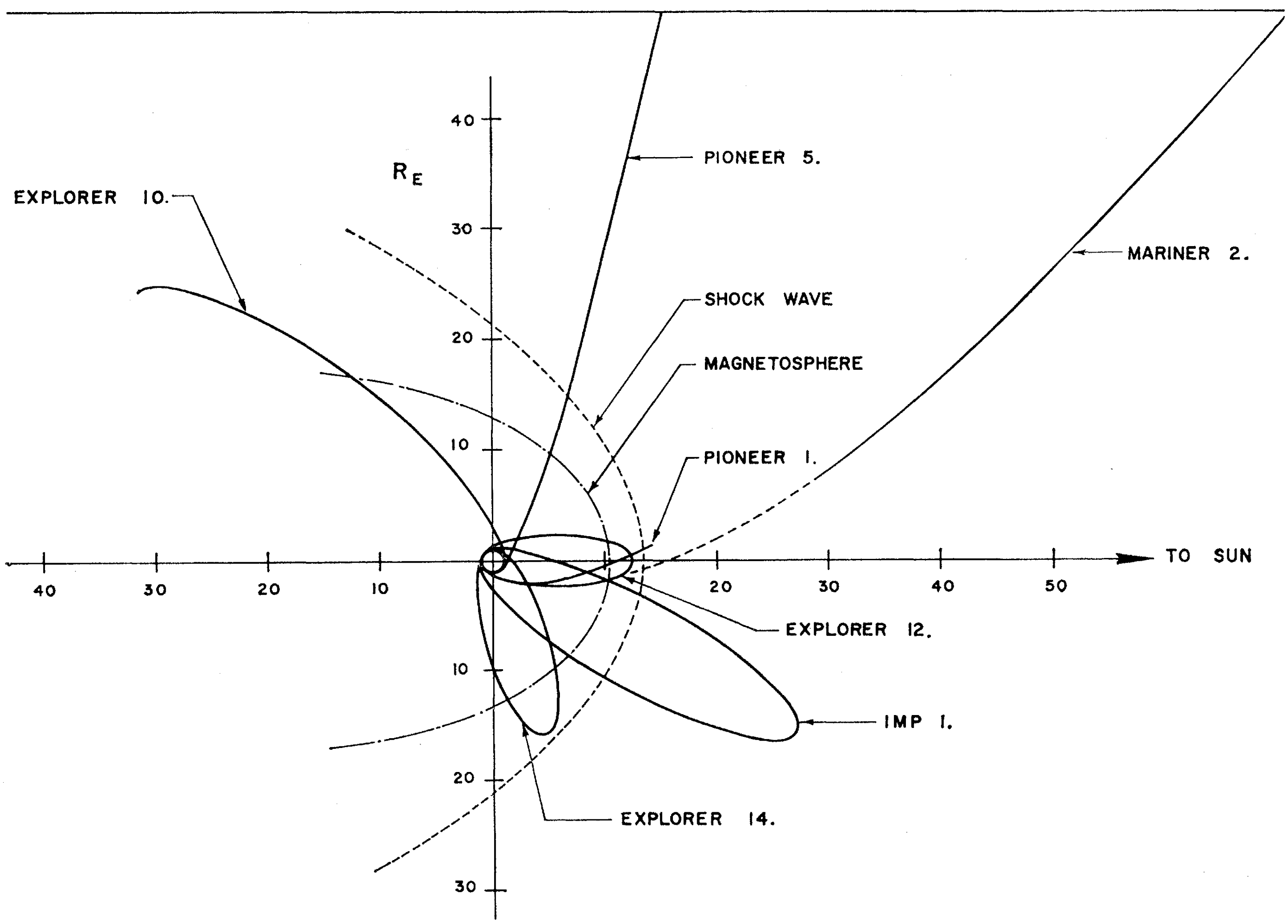

Fig. 5. Orbits of spacecraft carrying magnetic experiments. This is a view from the earth's north pole of the approximate projections of satellite orbits into the equatorial plane. The initial elliptical orbits of the long-lived satellites are shown. These orbits progress, in a clockwise direction, about 1 degree per day relative to the earth-sun line, due to revolution of the earth around the sun. The approximate traces of the magnetosphere boundary and the shock front are shown. The distance scales are in earth radii.

ment with the predicted field, and the component measured between 12 and 20 R_E was higher than had been predicted, with large fluctuations. Beyond 25 R_E the field was, in general, of low magnitude—of the order of 2 to 3 gammas.

The direction of the field component was originally interpreted as being, on the average, nearly perpendicular to the ecliptic plane. Since the models of the interplanetary field and the solar proton evidence presented by McCracken indicate an interplanetary field lying in the ecliptic, this evidence for a component perpendicular to the eclipitic was disturbing. A magnetic storm occurred while Pioneer 5 was in operation, providing the first opportunity to observe, in space, the magnetic field of the plasma cloud that would produce a storm on earth. During the storm the field magnitude at the satellite rose to 40 gammas, and a Forbush decrease was observed at the probe as well as on earth.

Explorer 10 was launched in 1961 along the 9 p.m. local time meridian, approximately 135° from the earth-sun line (*17*). The record of this satellite showed evidence that the satellite penetrated the geomagnetic boundary several times (beyond 22 R_E) during its passage outward to 40 R_E (see Figs. 6 and 7). When the satellite was inside the magnetosphere (that region about the earth which is dominated by the earth's magnetic field), the field measured was relatively smooth, although considerably distorted in direction and of higher magnitude than the predicted field. When the satellite moved outside the boundary (the magnetopause) a sudden abrupt transition in magnitude and direction of the measured field occurred, accompanied by the appearance of plasma. The magnitude of the field outside the magnetosphere was relatively high, between 10 and 20 gammas, and the fluctuations in magnitude and direction were large. Several different average field directions were observed when the satellite was outside the magnetosphere, but none of these appeared to correspond to the spiral interplanetary field. The frequent transitions from inside to outside the magnetosphere suggested that the satellite was skirting along the boundary of the geomagnetic field and that the transitions were

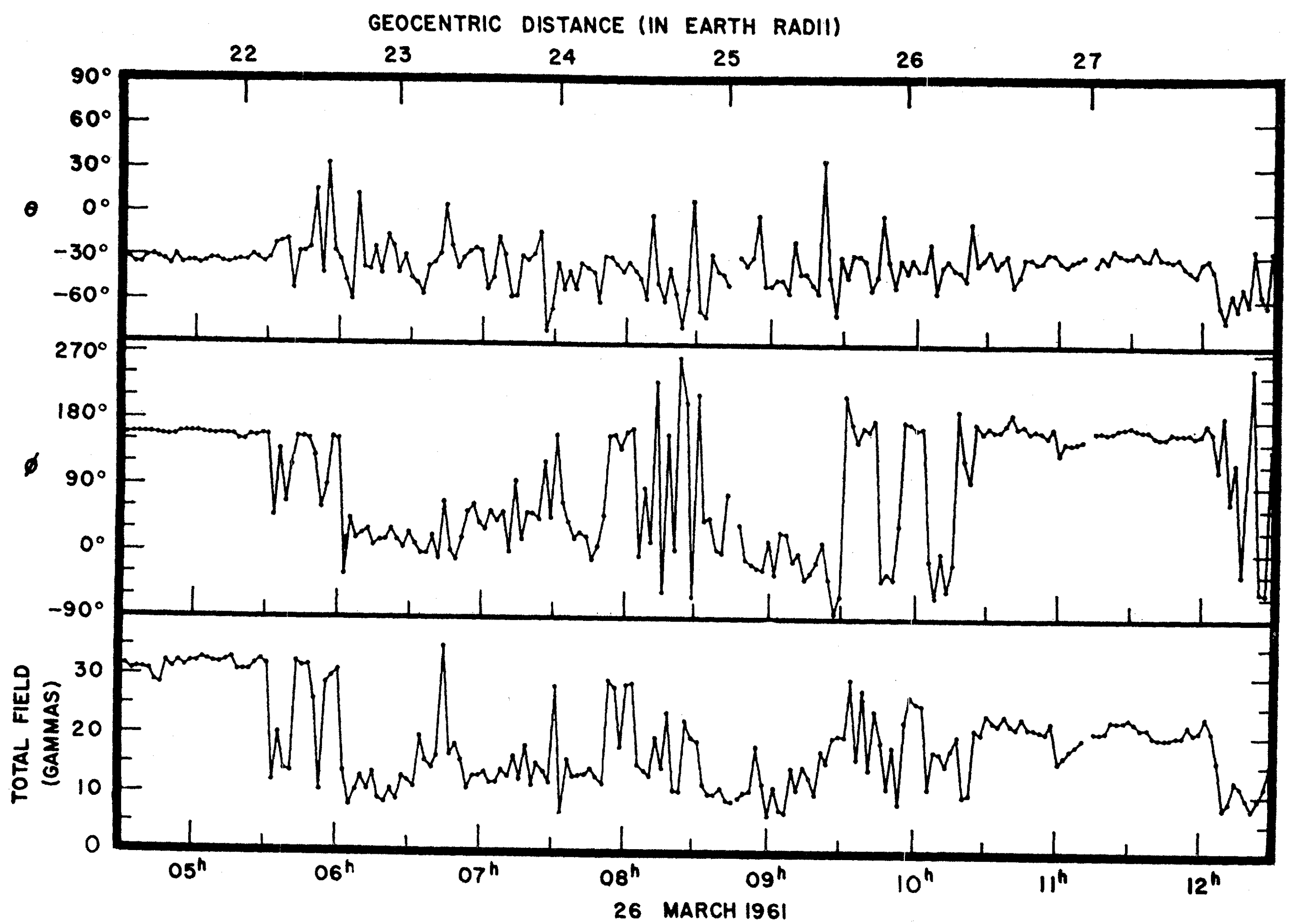

Fig. 6. A portion of the magnetic-field record from Explorer 10. Plotted here are total field magnitude, in gammas, and field direction, in the solar ecliptic angles Θ and ϕ (described for Fig. 7). The portion shown covers 7 hours of flight while the satellite traveled more than 5 R_E (from 22 to 27 R_E). When the satellite was closer to the earth than 22 R_E the direction and magnitude were relatively smooth (similar to the segment shown for distances less than 22 R_E) and the magnitude was decreasing as the inverse cube of geocentric distance. For distances beyond 27 R_E to the end of measurement, near 40 R_E, the record resembles the record shown in this figure. First penetration of the geomagnetic boundary occurred slightly beyond 22 R_E. Near 23 R_E, with $\phi = 0°$, $\Theta = -30°$, the field points back toward the sun but below the ecliptic plane. Note that between 26.5 and 27.5 R_E the magnitude and direction become relatively steady and the direction angles are close to those observed prior to 22 R_E. This suggests that the satellite is again inside the magnetosphere, and the absence of plasma in the interval confirms this view. [J. P. Heppner, N. F. Ness, C. S. Scearce, T. L. Skillman (*17*)]

caused when the boundary moved back and forth past the satellite.

Explorer 12, launched in 1961, initially penetrated the magnetopause near the earth-sun line (*18*). The boundary was observed at distances from 8 to 13 R_E. Penetration of the boundary was usually indicated by a rapid decrease in field magnitude and by change in direction. The field just outside the boundary was frequently observed to be opposite in direction to the geomagnetic field inside. The significance of this finding with regard to the nature of the magnetosphere has been discussed by Hines (*1*). It has been suggested by Dungey (*19*) that an interplanetary field antiparallel to the earth's field at the boundary would allow connection of the two magnetic-field regions and would lead to a boundary open to the interplanetary medium. Explorer 14, a year later, provided similar observations on the dawn side of the magnetosphere. The observations of Explorers 10, 12, and 14 beyond the magnetosphere boundary were not in agreement with the predicted spiral field of 1 to 10 gammas. It was apparent that the magnetic field directly outside the magnetopause was not the true interplanetary magnetic field, and that the plasma flow and the magnetic field carried along with the plasma were influenced considerably by the presence of the geomagnetic boundary.

Several workers have suggested that a shock front forms in the plasma flow around the magnetosphere, similar to that formed in the supersonic flow of an ordinary gas around an obstacle (*20*). It has been proposed that the velocities of propagation of hydromagnetic waves within the plasma (in analogy to sound velocity in a gas) are lower than the velocity of the plasma, so that the flow is, in a sense, "supersonic." One essential in the formation of an ordinary shock front in fluid flow is that the mean free path—the average distance between collisions of gas molecules—be smaller than the diameter of the obstacle. If this condition is not met, then the molecules act as individual particles and not collectively as a fluid. Since the solar-wind gas is very tenuous, the collision mean free path is large, approximately 1 astronomical unit—larger by several orders of magnitude than the diameter of the magnetosphere. A "collision-free" shock front had been proposed earlier, by Gold, for the case where a fast cloud of solar plasma overtakes a slow cloud. Gold assumed that the interplanetary magnetic field constrains the particles to move collectively. With this assumption, the radius of the circle described by a proton in the interplanetary magnetic field (the Larmor radius) replaces the mean free path of a gas flow with collisions. The plasma flow around the magnetosphere may be treated as a fluid flow, since the proton Larmor radius is much smaller than the magnetosphere. The arguments for the formation of such a shock front, however, have been based largely on analogy, and no detailed theoretical treatment of the formation of a "collision-free" shock front is available.

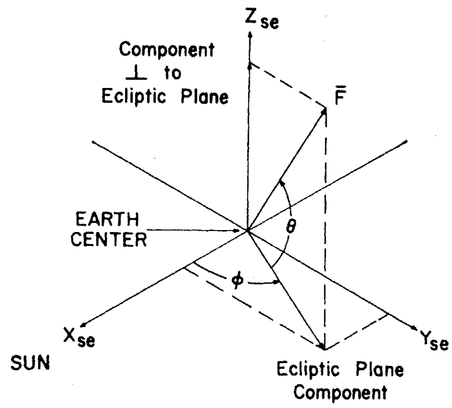

Fig. 7. Solar ecliptic coordinates. The *X* axis points from earth to sun; the *Z* axis points to the north ecliptic pole; the *Y* axis lies in the ecliptic plane. The angle ϕ is measured from the earth-sun line to the projection of the magnetic field vector in the ecliptic plane. It may vary from 0° to 360°. The angle Θ is measured between the magnetic field vector and its projection in the ecliptic plane. It varies from 0° to 90° when the field vector is above the ecliptic plane. It varies from 0° to −90° when the field vector is below the ecliptic plane.

The observations of the Explorer satellites and, in retrospect, of Pioneers 1 and 5, between 10 and 20 R_E indicated a transition region beyond the magnetopause where the interplanetary field differed in magnitude and direction from that predicted. Several earth radii upstream from the magnetopause, a second boundary, perhaps detected by Pioneer 1 at 13.5 R_E, could be expected, and beyond that, the undisturbed interplanetary field. Only Pioneer 1 and Pioneer 5 traveled far enough from the earth to observe the true interplanetary field. Even then the ambiguity arising from the fact that only one component of the field was measured made satisfactory comparison with the models of the interplanetary field impossible. Pioneer 5 measurements, indicating a 3-gamma field at an angle of 60° to 90° relative to the ecliptic plane, appeared to be in disagreement with the predictions, by Parker and Gold, of spiral fields lying in the plane of the ecliptic.

The Mariner 2 spacecraft, traveling from the earth to Venus in the period August to December 1962, carried a plasma detector and a magnetometer that measured all three components of the magnetic field-vector. The plasma measurements obtained by this satellite conclusively confirmed the existence of the solar wind (*21*). The period was one of moderate solar activity. There was always a measurable flow of plasma, streaming radially from the sun. The plasma velocity varied from 300 to 800 kilometers per second, and the density varied from 0.2 particle to 70 particles per cubic centimeter. Sudden increases in velocity were followed by increases in fluctuations of the magnetic field on the earth's surface. Major peaks in velocity showed a tendency to recur after 27 days, the period of solar rotation. This suggested long-lived plasma beams, associated with active regions on the sun, sweeping through space as the sun rotated. At the start of an increase in plasma velocity the plasma density rose to a peak value, then the density decreased, while the velocity remained high.

Unfortunately, magnetic materials within the spacecraft produced a field of the order of 100 gammas at the magnetometer location (*22*). This magnetic field changed significantly between the time of preflight calibration of the magnetometer and the beginning of measurement in space. The spacecraft was rotating during the first few days after launch. Since the spacecraft field rotated with the spacecraft and the interplanetary field could be considered stationary (during a rotation), experimenters were able to determine the magnitude of the magnetic field produced by the spacecraft in the direction perpendicular to the spin axis. The component along the direction of the spin axis could not be measured by this method. After the rotation had been stopped this axis of the spacecraft was kept pointing toward the sun. Field changes in this direction, the radial direction from the sun, could be observed, but the mean value was unknown. The radial component could be pointing toward the sun or away from it. The opportunity to measure the direction of the interplanetary magnetic field was lost, due to experimental difficulties. Still the experimenters were able to show that the average value of the field component perpendicular to the ecliptic plane was nearly zero, when observations over several days were considered. This demonstrated that the interplanetary magnetic field did, indeed, lie close to the ecliptic plane, in agreement with the models of Parker and Gold, and with the indirect evidence of McCracken.

Evidence for a collisionless shock front deep in space has recently been presented by Mariner 2 experimenters (*23*). The identification hinges on the abruptness of a change in both plasma and interplanetary field. The distance, within the moving plasma, in which the changes occur is much smaller than the collision mean free path of plasma protons but larger than the gyroradius of protons in the interplanetary field.

Recent Direct Measurements

The Interplanetary Monitoring Platform, IMP 1, was launched in late 1963, carrying several plasma experiments, as well as a complete magnetic experiment (*24*, *25*). The magnetic experiment consisted of a rubidium-vapor magnetometer, which provides a precise measurement of the magnitude of the field, and two flux-gate magnetometers, each measuring a single component of the magnetic field, mounted at an angle to the spin axis of the satellite. Since the satellite was spinning, the two flux-gate magnetometers yielded, during each rotation, measurements of both magnitude and direction of the field. The rubidium-vapor magnetometer was subjected to a sequence of applied, known magnetic fields so that the direction of the interplanetary field could be inferred. The redundancy provided by two independent magnetometer systems gave promise of reliable measurements. The magnetic field produced by the spacecraft was kept to a very low value, less than 1 gamma, as determined in preflight measurements and confirmed by analysis of in-flight data. The care taken by experimenters and spacecraft engineers in preparing and installing this experiment should serve as a guide for future experiments. The satellite was launched during a period of low solar activity, so the observations are to be compared principally with the quiet-time model of Parker.

The total magnitude of the interplanetary field was observed to be remarkably steady. Variation between 4 and 7 gammas, with occasional decreases to 1 gamma and occasional increases to 10 gammas, is noted. The average direction of the field is consistent with the spiral structure predicted by Parker. The angle between the field and the earth-sun line is about 45°, on the average, and the field points slightly below the ecliptic plane. The direction of the field is observed to reverse on a time scale of several hours, and occasionally in intervals as short as 5 to 20 minutes, changing from 135° to 315° relative to the earth-sun line, in terms of solar-ecliptic coordinates (see Fig. 8). The frequent reversals of the magnetic field suggest that the spiral interplanetary field is filamentary in nature, the fields of adjoining filaments having opposite directions. The magnetopause, the transition region, and a second boundary beyond were repeatedly observed. The plasma experiments confirmed the interplanetary measurements of Mariner 2 and revealed a plasma in the transition region that was incident from all directions (isotropic). The transition in plasma and field properties at the second boundary was consistent with the shock front predicted. The proposed collision-free shock front now appears to rest on quite a firm observational foundation. The relatively steady, low-intensity field in interplanetary space may be typical of quiet conditions near solar minimum. At times of large storms, or during solar maximum, the field may become stronger and more variable. It will be interesting to see if the field pointing below the ecliptic persists throughout a year of observations, as the satellite is carried around the sun, and if the field remains below the ecliptic throughout the solar cycle.

Summary

The brief period between the conception of the interplanetary magnetic field and conclusive proof of its existence has been an exciting one. Imaginative theoretical developments and careful experimental verification have both been essential to rapid progress. From

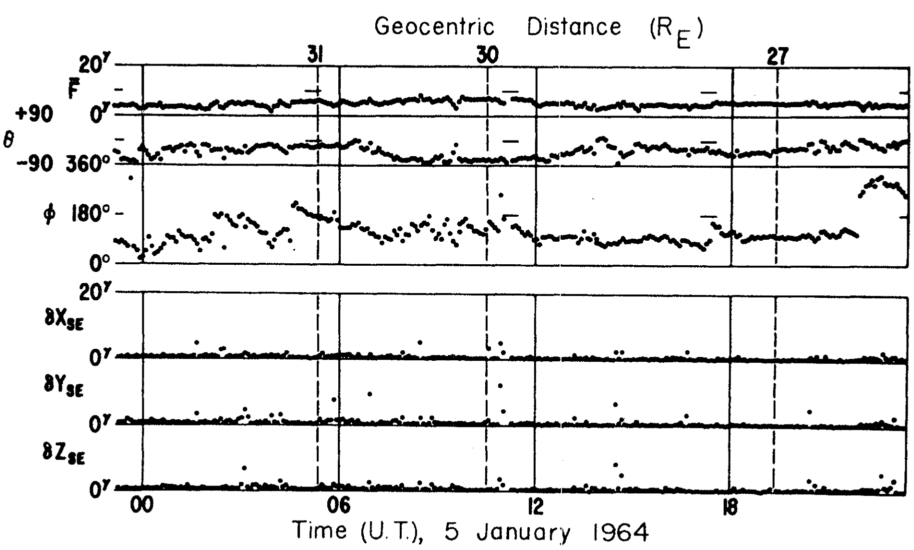

Fig. 8. A portion of the magnetic field record of the Interplanetary Monitoring Platform, IMP-1. During this 24-hour interval (5 January 1964) the satellite traveled outward toward apogee near 31 R_E. The time scale, at the bottom of the figure, is in hours, Universal Time; the distance scale, at the top, is in earth radii. The top record shows total field **magnitude,** $\bar{F}$, in gammas. Below this, in the order mentioned, are records showing variation of the solar ecliptic angle θ (−90° to 0° to +90°) and of the angle ϕ (0° to 360°), and the variance of the magnetic field (*27*) in each of the solar ecliptic components *X*, *Y*, and *Z*. Note that the variance beyond 20 R_E is low, a few gammas, indicating a steady field. Beyond 20 R_E, in the undisturbed interplanetary medium, the field magnitude varies between 2 and 8 gammas, the angle θ varies between +10° and −90°, and the angle ϕ varies between 0° and 210°. Note the sudden large changes in ϕ. Near 1500 hours the field is steady for an hour or so, with magnitude near 5 gammas, with θ near −45°, and with ϕ near 180°, pointing away from the sun. Near 1800 hours the magnitude and θ are unchanged but ϕ is near 90°; the field is perpendicular to the earth-sun line. The boundary of the magnetosphere appears at 13 R_E, where the magnitude drops and the direction changes abruptly; the shock front is near 20 R_E, where the field magnitude decreases and the direction and magnitude become more steady. Note the decrease in variance at this point. [N. F. Ness, C. S. Scearce, T. B. Seek (*25*)]

the various lines of evidence described here it is clear that an interplanetary magnetic field is always present, drawn out from the sun by the radially streaming solar wind. The field is stretched into a spiral pattern by the sun's rotation. The field appears to consist of relatively narrow filaments, the fields of adjacent filaments having opposite directions. At the earth's orbit the field points slightly below the ecliptic plane. The magnitude of the field is steady and near 5 gammas in quiet times, but it may rise to higher values at times of higher solar activity. A collision-free shock front is formed in the plasma flow around the earth. In the transition region between the shock front and the magnetopause the magnitude of the field is somewhat higher than it is in the interplanetary region, and large fluctuations in magnitude and direction are common. A shock front has also been observed in space between a slowly moving body of plasma and a faster, overtaking plasma stream.

Beyond the earth's orbit the solar plasma must continue to expand with the same velocity, carrying the interplanetary field with it (*26*). The angle between the spiral field lines and the radial direction from the sun continues to decrease until, at great distances, the field is perpendicular to the direction of plasma flow. The energy density of the plasma decreases with plasma number density as the inverse square of the radial distance until ultimately, between 10 and 100 astronomical units, the energy density of the plasma approaches that of the galactic medium. Instabilities produce a disordered outer region of plasma and field. Direct experimental investigation awaits a deep space probe capable of reaching and operating at a distance of 100 astronomical units.

The weak interplanetary field exerts considerable influence on the cosmic-ray protons. Study of these particles has been a particularly valuable tool in determining the large-scale properties of the interplanetary field. Precise measurement of the magnitude and direction of the field at a point in space and study of small-scale fluctuations can be accomplished only by means of a spacecraft magnetometer. The two methods are complementary, and both will be used in further study of the interplanetary field during the increasing solar activity of the next 5 years.

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27. The variance, a measure of the fluctuation of field measurements in each 12-measurement average, is defined by Ness (*25*) as:

$$\delta X_{se} = \left[\frac{1}{N} \sum_{i=1}^{N} (X_{se}^{i} - \overline{X}_{se})^2 \right]^{\frac{1}{2}}$$

where N is 12, X_{se}^{i} is an individual measurement of the component X_{se}, and $\overline{X}_{se}$ is the average of 12 measurements.

Biosynthesis of Alkaloids

New and unexpected routes to the pyridine and piperidine rings have been discovered.

Edward Leete

Some organic compounds, particularly the α-amino acids and carbohydrates such as glucose and ribose, are found in all plants, and it seems probable that these ubiquitous compounds are formed by essentially the same metabolic reactions in all plants. However certain plants contain compounds known as alkaloids which to our knowledge appear to have no biological role in the plants which produce them. About 3000 different alkaloids have been isolated from about 4000 plant species (*1*). Some typical alkaloids are illustrated in Fig. 1. Until recently the chemical investigation of plants has been a rather random process, and I consider that tens of thousands of new alkaloids remain to be discovered in the vast plant kingdom. Alkaloids may be defined as naturally occurring organic compounds containing nitrogen, which is usually located in a heterocyclic ring. The nitrogen in alkaloids is present as an amino group, and this group causes solutions of alkaloids in water to be basic. Many nitrogen-containing compounds (such as nocardamine, gliotoxin) which are produced by microorganisms could be regarded as alkaloids, although one seldom finds such compounds discussed in treatises on alkaloids. The same alkaloid is sometimes found in quite unrelated species. Thus the fungus *Claviceps* produces a group of compounds known as the ergot alkaloids which are derivatives of lysergic acid. Lysergic acid derivatives have also been isolated from the