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43. I thank Dr. James F. Crow and especially Dr. Oliver Smithies for their help during the preparation of this manuscript. This article was written during the tenure of a postdoctoral fellowship from the Division of General Medical Sciences of the U.S. Public Health Service and was supported by grants from the National Science Foundation (C-14240) and the National Institutes of Health (GM-08217). The article is contribution No. 910 from the genetics department of the University of Wisconsin.

The Magnetopause: A New Frontier in Space

The interface of the sun's atmosphere and the earth's is the site of many phenomena of geophysical import.

C. O. Hines

Up until a decade ago it was widely believed by atmospheric scientists that the earth's atmosphere terminated, for all practical purposes, several hundred kilometers above ground level. Any atmospheric molecules that still remained at that height would be moving freely in ballistic orbits, without significant mutual interaction, and some of them would be spraying off from the earth's domain at speeds exceeding the escape velocity. This "exospheric" region provided the upper fringe of the atmosphere as it was then conceived; beyond lay interplanetary space, and whatever minor quantities of dust or particles it might contain.

In the same period few astronomers pictured the sun's atmosphere as extending far above the visible disk. Photographs taken during periods of eclipse had long since shown the existence of a hot "corona," rising on occasion to heights of a few solar radii above the photosphere, but there all trace of the gaseous envelope was lost (unless it made some contribution to the dust-dominated zodiacal light).

True, the sun was believed to eject at times, strong jets of highly ionized gas (or "plasma," in modern parlance) and these jets were taken by many to be the cause of geomagnetic and auroral storms. But their life was transitory, and their influence on low-lying layers of the earth's atmosphere was thought to be exerted only after deflection in the distant regions of the geomagnetic field and subsequent passage through the intervening void.

These views have undergone drastic change in recent years, to such an extent that a whole new picture must now be adopted. In this picture the neutral atoms of the terrestrial atmosphere still form an exosphere, as before, but their ionized counterparts extend to heights of several earth radii (R_E) and fully occupy the region of geomagnetic domination. The solar corona streams ever outward, in what has come to be called a "solar wind." It streams past the earth, confines the earth's magnetic field, and makes contact with the outermost plasma of the terrestrial atmosphere.

The region occupied by the terrestrial plasma, and dominated by the geomagnetic field, is now commonly called the "magnetosphere." Its boundary with the solar wind—the newly recognized frontier between the terrestrial and the solar atmospheres—is called by some the "magnetopause," in a somewhat inelegant analogy to the "tropopause" of lower levels. This article is concerned with the nature of the magnetopause, and with the processes it influences.

The Developing Picture

The decisive change of attitude came, insofar as the terrestrial atmosphere is concerned, with the work of Storey (*1*). He studied the characteristics of "whistlers"—radio signals that are generated by lightning flashes and that yield, on detection, a characteristic whistling or swishing tone which descends in pitch from high to low audio frequencies. It had been known that this characteristic behavior could be imposed on the initial noiselike emission by a dispersion of the various frequency components it contained, if the radio wave passed through the ionized gas of the upper atmosphere, but the path to be followed by the signal in its return to earth was difficult to chart. Storey concluded, on the basis of mathematical analysis, that the energy would tend to travel along the lines of the geomagnetic field; it would then rise from the region of its generation in one hemisphere, pass over the equator at some great height, and be guided back down toward the earth in the opposite hemisphere near the geomagnetically "conjugate point" (see Fig. 1, A–A′). In order for this explanation to hold, however, there must be appreciable amounts of ionization even at the highest point of the geomagnetic arch—some hundreds of electron-ion pairs per cubic centimeter at heights of 3 R_E; this is much more than had been proposed previously. With this conclusion, a new era in the exploration of the upper atmosphere began.

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The conclusion itself was supported by the suggestion that the heavier gases and ions, which would be confined to lower levels of the earth's atmosphere, were supplanted at greater heights by hydrogen atoms and proton-electron pairs. Extensive theories have been developed in support of this thesis (*2, 3*), an intermediate zone of helium predominance has been inferred (*4*), and, in recent years, the general conclusions have been substantiated by rocket and satellite data (*5*). The new techniques have also revealed the existence of trapped energetic particles—the Van Allen radiation belts—in the same regions, but these particles form only a minor fraction of the total particle population and have only an indirect bearing on this discussion.

The bulk of the ionized material behaves as a fluid, in the sense that its collective interactions are important. Collisions between charged particles remain frequent, for example, because of the large collisional cross-section contributed by Coulomb forces. An isotropic pressure is therefore maintained —no ion exosphere is formed—and the gradient of the pressure serves to offset the pull of gravity. On this basis it is possible to extrapolate the density profile to heights greater even than those explored by means of whistlers, and to infer concentrations in excess of 100 proton-electron pairs per cubic centimeter even at heights of 5 R_E and above (*3*).

Again, the ionization is strongly influenced by the presence of the geomagnetic field, and all its dynamical processes take place under magnetohydrodynamic (or "hydromagnetic") control as a result. Thus, the medium supports the propagation of hydromagnetic waves, while any large-scale motion it suffers is mapped throughout the magnetosphere in conformity with the "frozen-field" theorem: in a highly conducting plasma, all ionization connected by a tube of magnetic flux at one moment must move together, so as always to be connected by a tube of magnetic flux of constant flux content, as if the magnetic field lines and the ionization were frozen to one another (*6, 7*).

During the period of these new developments, a corresponding revolution was taking place in the assessment of the solar atmosphere. Siedentopf *et al.* (*8*) reported electron concentrations in the general vicinity of the earth, but outside the earth's atmosphere, as high as 600 per cubic centimeter, as determined from the zodiacal light, while Biermann (*9*) found it necessary to postulate a strong outflow of plasma from the sun to account for accelerations observed in the structure of comet tails. Thus emerged the concept of the solar wind or, as some would say (on the basis of more recent measurements and interpretations, which downgrade the inferred intensities), the "solar breeze."

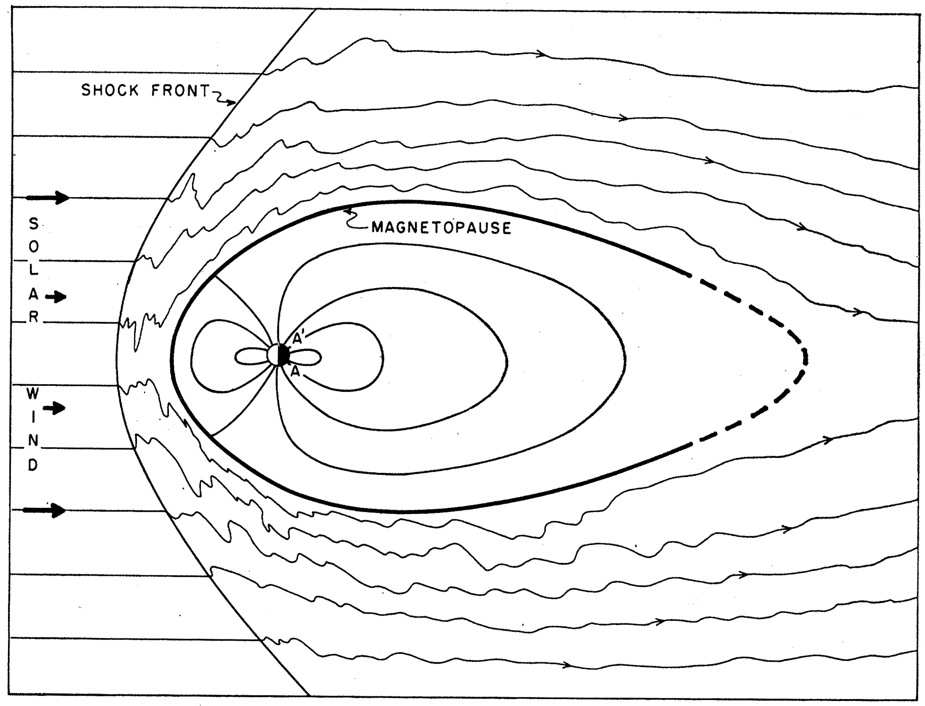

Fig. 1. The magnetopause, as it is often conceived today, in cross section through the noon-midnight meridional plane. The geomagnetic field (represented by lines such as AA′) is confined within, and the solar plasma flows round it (thin lines). The tail (broken line) may be fully closed, or sufficiently irregular and diffuse as to be undefined; the matter is one of current debate. The shock front illustrated is now inferred (see text). Insofar as possible the sketch is drawn to scale to match recent data. [After Johnson (*18*), Piddington (*19*), Axford (*25*), and Kellogg (*26*)]

As in the case of the terrestrial atmosphere, theories of this expanding solar plasma followed hard upon the observational conclusions (*10, 11*), and, with the development of space probes, direct detection of the positive-ion component of the plasma became possible. These direct measurements confirm recent indirect determinations and yield values for the unknown parameters of the solar-wind theory: the solar plasma near the earth contains concentrations of the order of 3 to 30 ion-electron pairs per cubic centimeter, the ions being predominantly protons (that is, hydrogen ions), and these stream outward from the sun at speeds of the order of 300 to 600 kilometers per second (*12–14*). Some irregularity of structure has been detected, but not as much as many would have guessed; it has been found more in the speed than in the density, but the observations to date have been made mainly during periods of low solar activity (*14*).

(If one wishes to compare the solar wind to ground-level winds, the following data may be of interest. Insofar as energy flux is concerned, the solar wind is equivalent to a surface wind moving at 10 centimeters per second; insofar as impact pressure is concerned, the solar wind is equivalent to a surface wind of about 10^{-2} centimeters per second. These speeds are of course low by any meteorological standards, but then we are not dealing with ordinary meteorological processes. An individual ion in the solar wind has a kinetic energy relative to the earth which exceeds that of an ordinary air molecule by a factor of 3.10^4 or more.)

The solar plasma streams unimpeded over most of its path, but it must be deflected or distorted in some fashion in the vicinity of the planets and of their moons. The interaction may occur by direct impact on the solid body, by collisional or charge-exchange processes with the molecules (if any) of its atmosphere, or by collective electrodynamic forces in the presence of a sufficiently strong magnetic field. It is the last of these interactions that is of immediate concern in the case of the earth, and that gives rise to the magnetopause interface.

The Concept of the Magnetopause

Although the concept of a permanent magnetopause is recent, the principles that underlie its formation were first considered many years ago, in connection with the transient problem, previously stated, in which a single jet of solar plasma was taken to be incident on the earth's domain at times of magnetic storms. The principles were investigated at considerable length in that context by Chapman and Ferraro (*15*). These authors showed that the leading edge of the jet would be subject to an induction electromotive force as a consequence of its motion in the geomagnetic field, and that strong electric currents would be established as a consequence, just as currents are produced by the motion of an armature in the magnetic field of an electric dynamo. In the case of the solar jet, the currents would give rise to a secondary magnetic field of just such a form as to cancel the geomagnetic field within the jet—within all but the surface layer, that is—and to increase the strength of the field between the jet and the earth. The part of the jet that impacted frontally on the geomagnetic field would be retarded in the process, but the remainder could sweep round the flanks and effectively envelop the field within a limited cavity.

This "Chapman-Ferraro cavity" or "geomagnetic cavity" is a feature of our picture today, although various extensions have introduced various refinements (*6, 16–18*). It is now commonly discussed, not in terms of surface currents, but in terms of the hydromagnetic frozen-field theorem: the incident solar plasma, if devoid of magnetic field initially, must remain field-free, and it can then sweep past the earth only by confining the geomagnetic field to some internal cavity. The form of the cavity most commonly adopted is depicted in Fig. 1, and its boundary provides the corresponding magnetopause.

Theoretical computations of the shape of the magnetopause are not easy to make, even with the simplest of assumptions, but there have been many attempts (*19, 20*). In these, for the most part, an individual-particle approach is adopted. A stream of incident, noninteracting particles from the sun is assumed, and their pressure on the magnetopause is taken to be balanced by a magnetic pressure from inside, subject to certain approximations, and an assumed specular reflection at the interface itself. The analysis is somewhat simpler if the incident particles are assumed to have a streaming velocity only, but in that case the cavity extends indefinitely downstream. If random "thermal" motions are added, to give the total pressure an isotropic component, theoretically the cavity can be made to close somewhat in the fashion illustrated in Fig. 1; but the true process of closure is almost certainly more complicated than such calculations would imply and Fig. 1 is drawn more by intuition than by computation.

Indeed, the whole system is probably much more complex than any of these analyses suggests. In his pioneering theoretical studies of the solar wind, Parker (*10*) was led to conclude that magnetic flux would be carried outward from the sun by the expanding plasma, and that the space beyond the geomagnetic domain could not then be considered field-free. This same situation had previously been postulated by Alfven (*21*), although he had a different geometry in mind, and it has since been confirmed observationally both by inference (*22*) and by direct measurement (*23*); a field of the order of 5.10^{-5} gauss is now believed to pervade interplanetary space in the vicinity of the earth. This introduces one major modification, and perhaps a second, in our picture of the magnetopause itself.

The first point to be made is that, with a field of this strength present, the incident solar plasma cannot be treated as an assemblage of noninteracting particles. It must behave, instead, like a fluid in any process whose spatial scales are as large as those of the magnetosphere—and as a hydromagnetic fluid, at that. It cannot propagate waves at speeds exceeding a certain characteristic value, the "hydromagnetic" or "Alfven" speed, which happens to be (*14*) only about one-sixth of the speed of the solar wind as it passes the earth.

In these circumstances the solar plasma is expected to behave much as the wind in a wind tunnel behaves when it flows at supersonic speeds past an obstacle. A shock wave (of a new, "noncollisional" type) is expected to be established on the sunward side of the magnetopause (*24–26*). The solar wind is expected to lose much of its forward momentum as it passes through this shock wave, and to be deflected into an irregular, turbulent, "subsonic" flow that passes round the cavity region. If the analogy with wind-tunnel experiments is complete, much of the forward momentum should be regained in the course of the passage, and the solar wind should flow away from the vicinity of the earth at "supersonic" speeds once again (see Fig. 1).

This modification in our picture has a profound implication concerning geomagnetic and auroral storms, but for the moment we need only note that it will undoubtedly modify the anticipated shape of the magnetopause (*25, 26*). Calculations based on the specular reflection of noninteracting particles can scarcely provide the details we will want in the future, even when they take into account isotropic pressure fields of an assigned nature, however much they may serve as a guide at present.

The second modification concerns a possible linkage of the field lines of the interplanetary magnetic field to those of the geomagnetic field. Special attention has been focused by Dungey (*27*) on the case of an interplanetary field that is directed more or less southward in the vicinity of the earth, and for this case he infers a topology of field lines which is given in one meridional section by Fig. 2. With such a topology, he infers a splitting and confluence of the path followed by the solar plasma at a singular ("neutral") point near the midnight meridian, a return flow through the region of closed geomagnetic field lines closer to the earth, and a further splitting and confluence at a second singular point near the noon meridian, as illustrated.

Some of the geophysical consequences of such a model are presented later in this article. For immediate purposes it should be noted that the magnetopause loses all of its earlier attributes and indeed its identity as well: the solar and terrestrial plasmas are no longer separated by a uniquely defined interface but, instead, are free to merge in a broad transitional region. We may if we like identify a pseudomagnetopause, defined by the field lines that emerge from the singular points, but its role is to mark a reversal in the flow pattern of the plasma, and it acts not as a frontier but more as a gateway.

The weight of direct evidence does not support Dungey's model, in that the interplanetary field appears to lie nearly in the plane of the ecliptic (*22, 23*). But this evidence is severely limited in scope, it exhibits fluctuations, and it is mainly concerned with conditions that obtain in the absence of, or in advance of, an enhanced burst of solar plasma. Further discussion here is based on the supposition that a true magnetopause exists—that Fig. 1 applies—during normal conditions and often in the presence of enhanced plasma flow, but nevertheless it is recognized that the magnetopause may vanish—that Fig. 2 may become relevant—under the influence, on occasion, of a southward-directed magnetic field carried by an ejected tongue of solar plasma.

Direct Detection of the Magnetopause

Among the least ambiguous measurements of the magnetopause to date are those conducted on the satellite Explorer 12, as reported by Cahill and Amazeen (*28*). In a sucession of outbound and inbound trajectories not far from the sun-earth line, the satellite passed through a sharp transitional region in which the magnetic field underwent major alteration. On the inner side it was somewhat stronger than a direct extrapolation upward from the earth's surface would have implied, and this finding is in agreement with the expectations of the magnetopause theory. On the outer side the field was often much weaker and invariably exhibited major fluctuations (see Fig. 3). Even when the strength of the field was maintained across the interface, the orientation changed drastically. (Insofar as the external field exhibited a preferred direction, that direction was roughly southward. This result lends mild support to Dungey's model, but the field as measured is undoubtedly distorted from its natural form by the flow round the magnetopause, so the significance of the result with respect to Dungey's model is highly debatable.) The outer region is now usually identified with the domain of the turbulent flow that follows the shock front of Fig. 1, and this interpretation is borne out by associated plasma measurements (*28*).

As observed by Explorer 12, the magnetopause has an apparent thickness of 100 kilometers or so, and this may increase on occasion to as much as 1000 kilometers. Its location varies, presumably in response to changes in solar-wind pressure; it has been found at

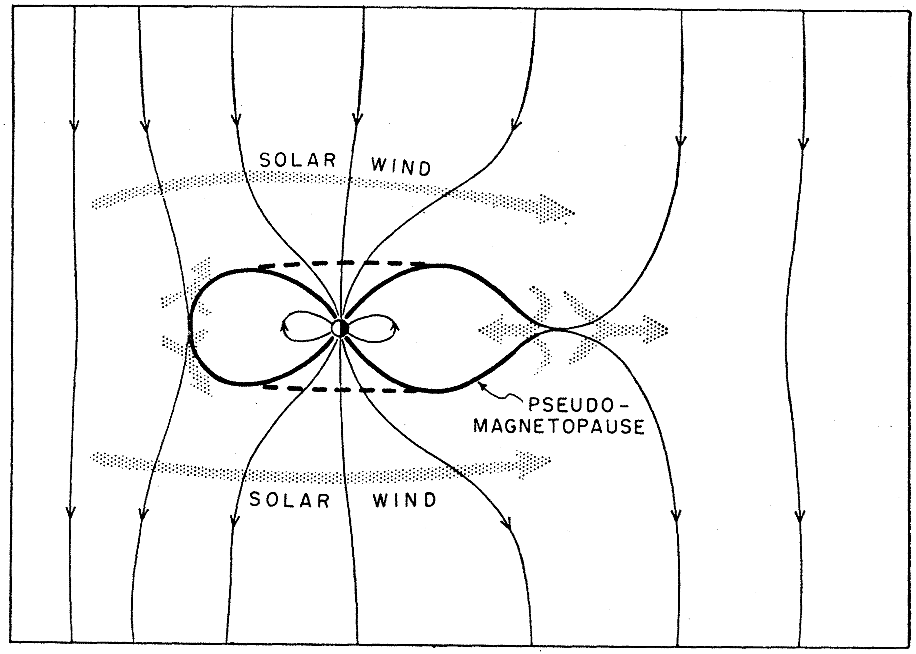

Fig. 2. The topology of magnetic field lines (thin lines) as given by Dungey (*27*); a southward-directed interplanetary field and a flow of solar plasma (broad shaded arrows) are assumed. The pseudomagnetopause is shown in section, by heavy lines; it is doughnut-shaped, and the broken line represents the projection of its profile onto the sun-earth meridional plane. A shock front is to be anticipated, as in Fig. 1, but its probable form is not so clear, and it is not shown here.

geocentric distances throughout the range 8 to 12 R_E in the measurements published to date, and at times it has apparently moved past the satellite as the latter flew smoothly in its orbit. The extent to which these movements may influence the apparent thickness is as yet uncertain.

Although the observations of Cahill and Amazeen refer to conditions near the sun-earth line, they may be complemented by data from other satellites and space probes in different orbits (*13, 30, 31*). An extreme case is provided by the satellite Explorer 10, which measured magnetic field and plasma

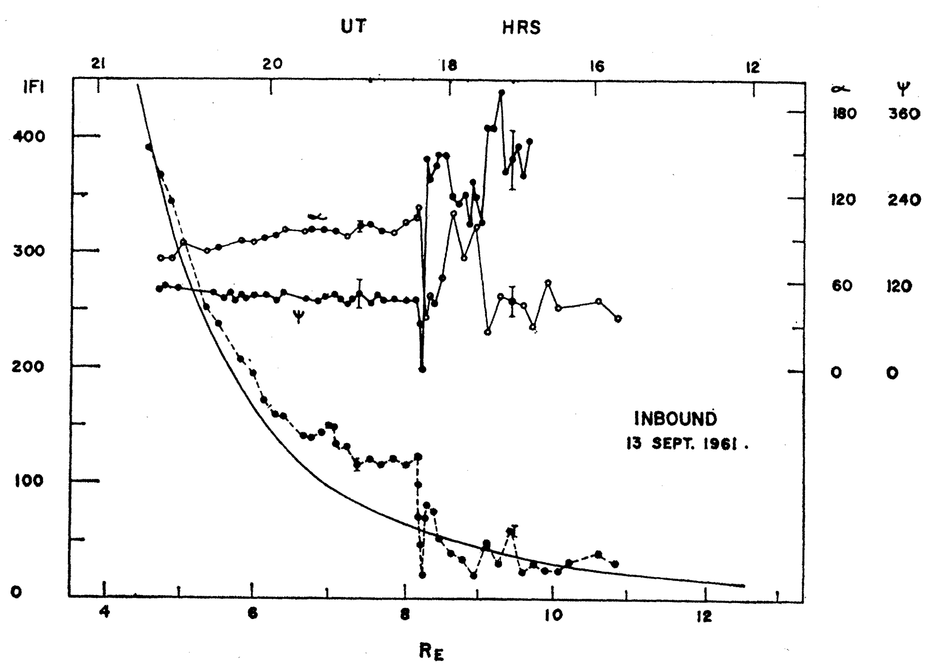

Fig. 3. The magnetic-field strength ($|F|$, measured in units of 10^{-5} gauss) and field orientation (given by angles α and ψ) as functions of geocentric distance in units of earth radii (R_E); the magnetopause transition near 8 R_E is clear. [From Cahill and Amazeen (*28*)]

flux up to heights exceeding 40 R_E on the night side of the earth (largely between the 9 and 10 P.M. meridians), and at an angle (at the greater heights) of 35 to 40 degrees below the plane of the ecliptic. The magnetic measurements (*31*) are interpreted as revealing a relatively stable geomagnetic field out to a distance of 22 R_E, although the strength and orientation of that field were grossly distorted from their theoretically extrapolated values at heights above 10 or 12 R_E. A sudden transition into a realm of irregular fluctuation occurred just beyond 22 R_E, but a stable field of the earlier form reappeared on occasion at greater distances. The initial transition is presumed to have marked the magnetopause as it existed at the time, and associated plasma measurements (*13*) support this view. The subsequent transitions similarly mark the magnetopause, although they have not been fully interpreted; the satellite could have been moving nearly parallel to a spatially undulating interface, or the interface could have been moving backward and forward in response to changing solar winds. The latter interpretation seems by far the more probable and is consistent with our knowledge of movements for the subsolar region.

To date, none of the satellite measurements has indicated the existence of the anticipated shock wave. This may be attributed to the fact that no suitable vehicle has yet probed the region of its presumed location, at distances ranging upward from some 15 R_E or so at the subsolar position, but this observational gap should soon be closed.

Associated Geophysical Phenomena

Although it lies at a great distance from the earth, the magnetopause is thought to play a considerable part in a number of phenomena observed at ground level.

Dungey, who was among the first to appreciate the significant changes of a decade ago, very quickly came to the conclusion that the interface region may be unstable along its flanks, just as a flag in the wind is unstable (*17*), and this conclusion has received substantial theoretical support from the more detailed analyses of subsequent authors (*10, 32*). Dungey inferred that the disturbances thus created would propagate toward the earth's surface along geomagnetic field lines, both as hydromagnetic waves and as acoustic waves. Although the evidence adduced in support of the proposed propagation as acoustic waves is not now considered relevant, there is good reason to suppose that the hydromagnetic waves are indeed observed and are responsible, for example, for strong ground-level magnetic fluctuations, micropulsations, and diffuse radio-detected aurora that occur persistently at high latitudes near the noon meridian, even in the absence of magnetic storms (*33*). Some indication of the instability itself might be inferred from the data of Explorer 10, in that the magnetopause appears to cross back and forth over the satellite a few times in the course of a single transit (*31*), although this same effect could be produced by large changes in an inherently stable boundary.

A different type of instability has been thought by some to occur on the sunward face of the magnetopause—an instability whereby the interface could be penetrated by small blobs of solar plasma—and the resultant capture of energetic particles within the geomagnetic domain has been suggested as a stage in the development of magnetic storms (*34*). The detailed nature of this instability has been a matter of much debate, all of it based on models that did not yet contain a shock front, and the very existence of the instability has been called into question (*35*) on empirical grounds that are themselves of questionable validity (*36*). The relevant satellite data do not exhibit any gross instability on the sunward face (*28*), but small-scale instabilities may nevertheless be present.

Geomagnetic storms are widely believed to begin with the impact of an enhanced flow of solar plasma on the magnetopause (*15*), the transition being marked on some occasions by an incident shock front and on others simply by a gradual change. In either event, the altered conditions would be transmitted toward the earth by hydromagnetic propagation, and would there account for the observed "initial phase," with or without a "sudden commencement."

Instability of the flag-flapping type, mentioned earlier, is expected to transmit momentum from the solar wind outside the magnetopause to the terrestrial plasma within it, thereby driving this terrestrial plasma toward the night side of the magnetosphere. A return flow may then be inferred, along a less-exposed path well within the cavity. Such a circulation must be accompanied by corresponding motions throughout the ionized region of the terrestrial atmosphere, in conformity with the frozen-field theorem. The whole process can be shown to account for certain aspects of the upper atmosphere at high latitudes even on magnetically quiet days and, when enhanced under a strengthened solar wind, for many of the phenomena that come into play during the "main phase" of a magnetic storm (*37*).

Although the circulation must be a feature of such storms and its attendant processes may indeed have the importance just implied, its origins may well lie eslewhere than in the instability mechanism. Virtually all the proposed alternatives depend, however, on interactions of one type or another at the magnetopause. They include, for example, an assumed penetration by the solar wind on the flanks (*38*) or on the sunward face (*39*), and processes that follow upon the simple deformation of the geomagnetic field lines that accompanies compression of the interface (*40*). The last of these proposed alternatives is particularly attractive.

Consequences that are the same in many respects as those of the foregoing mechanisms follow application of the Dungey model pictured in Fig. 2, although the detailed argument runs along slightly different lines. There are further advantages implicit in Dungey's discussion; according to his model, the solar wind makes direct contact with the terrestrial plasma and so can transfer energy and particles more efficiently, and the night-time neutral point is capable of engendering instabilities in the flow pattern near the midnight meridian, which is the place where irregular "sub-storms" appear to be born in the course of major storms.

Still further possibilities are open to us if we adopt the more flexible position previously suggested—namely, that Fig. 1 applies during normal conditions and often in the presence of an enhanced plasma flow but that Fig. 2 may become relevant on certain occasions. Those occasions, we will now assume, arise at times of major magnetic storms. We lose nothing, and gain much, with such an assumption.

We may still account for the persistent phenomena of midday at high latitudes, mentioned earlier, and for the occurrence of an "initial phase" behavior when the solar flow strengthens.

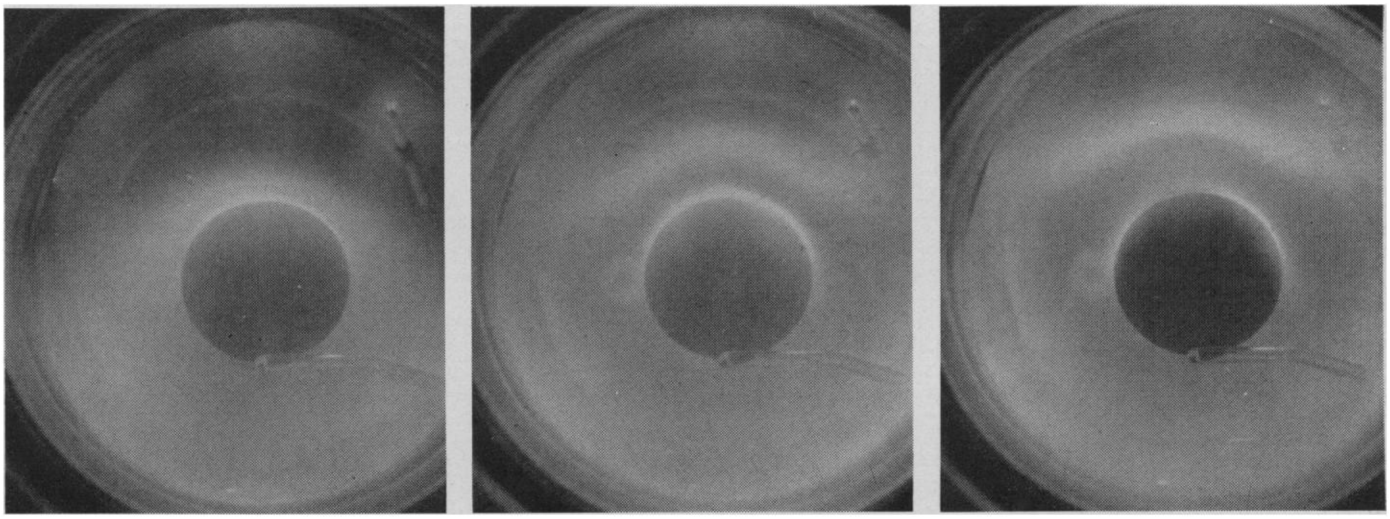

Fig. 4. Representative laboratory examination of a scaled magnetopause. (Left) no magnetic field; (middle) intermediate magnetic field; (right) strong magnetic field. The central circle contains a magnetic dipole source (not visible) with axis horizontal, and plasma is incident from above at high speed. The illuminated region results from a heating of the plasma when it is stopped, and its displacement upward in the frames at middle and right results from the influence of the magnetic field. [Courtesy RCA Victor Company, Montreal]

We may similarly account for a minor convection even on quiet days (and its effects are indeed observed on such days) with some degree of enhancement when the solar wind is strong. This enhancement may be minor so long as a true magnetopause persists, and may then intensify greatly if and when the southward field required for Fig. 2 becomes available. We may, on this basis, account for either the presence or the absence of strong "main phase" characteristics following a strong "initial phase" behavior, and some such account is required by the observations (*41*).

The requirement for a southward-directed interplanetary field runs counter to observational evidence, as I have already mentioned, and to certain theoretical considerations as well. But in both cases the objections apply primarily to quiet conditions; it may be that the field is directed southward only at times of disturbance. Moreover, there is reason to believe that at times of disturbance the enhanced flow of solar gas is contained in a "tongue" and carries field lines which are linked to the sun at both ends (*42*); the field lines may assume a north-south orientation as they double back toward the sun. Whether the field itself were then directed toward the north or toward the south would probably depend on the direction of more intense fields near the sun, and the sense might well tend to be opposite for disturbances originating in the northern and the southern solar hemispheres. This would provide a possible explanation for one very remarkable fact (*43*): that solar flares in the Northern Hemisphere have been far more effective in producing great magnetic storms on earth than those in the Southern Hemisphere have been, except for one class of flare that is associated with magnetically abnormal "unipolar" sunspots.

These speculations cannot be pursued in detail here, but they illustrate the fascinating realm to which studies of the magnetopause can lead. We may return to reality with a consideration of a process that is very probably influenced by the interface region and that has a major commercial consequence.

The greater part of the world's long-distance communications are carried by radio transmissions, and the quality of these transmissions depends on the characteristics of the ionized regions at heights of 60 to 300 kilometers. Solar emissions can disrupt much of the radio traffic in various ways: briefly, in sunlit regions, by direct illumination of the lower levels of ionization; more extensively, but in sporadic fashion, at higher latitudes where auroral processes (associated with geomagnetic storms) come into play; and most extensively, indeed over the whole of the "polar cap" regions, under the indirect influence of energetic protons incident from the sun.

These protons are ejected from a certain type of solar flare. They are often associated with enhanced plasma flow, but they travel at much higher speeds than the plasma and can cause a "blackout" of radio links well in advance of the related magnetic storm. The blackout often persists for days on end and can therefore be of major concern. Trans-Atlantic communications are particularly susceptible to serious disruption by this means, for many of the radio paths skirt the zone in which the blackout normally occurs (*44*). The precise location of the edge of that zone is, then, a matter of interest, and here the magnetopause seems to play its part.

The solar protons are deflected on entering the geomagnetic field, and it is because of this that they are confined to high latitudes. But if the protons should still be incident when the storm-producing plasma arrives from the sun, the confinement is reduced and the penetration extends to lower latitudes. This alteration has been attributed to the contraction of the magnetopause under the influence of the solar wind (*45*). Alternatively, it might now be attributed to the onset of Dungey's topology, and so to the disappearance of the normal magnetopause. Thus, tenuous though it may be, the interface can play a part in our everyday lives.

Laboratory Studies

It is apparent from the foregoing discussion that much of the study of the magnetopause is theoretical and extremely speculative, and that much of the remainder involves exceedingly costly experiments conducted at great distances above the earth. It is of interest, then, to note one facet of the study which can be undertaken at moderate expense in more conventional surroundings.

Plasma technology has advanced rapidly in recent years, to the point where some aspects of the natural phenomena may be modeled on a laboratory scale. The scaling of the processes from hundreds of kilometers in nature to a fraction of a meter in the laboratory is not without its difficulties, and indeed it cannot be carried out for all the relevant parameters simultaneously. Nevertheless, it is possible to separate some phenomena from others, and to scale them individually (see Fig. 4). Even this process is not without its dangers, and results obtained from it can never be considered definitive. But as a complementary program, designed to limit theoretical speculation and influence its course, or designed to suggest modifications in space probes and thereby increase their efficiency, this type of attack has a valuable part to play (*46*).

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46. Preparation of the manuscript was supported in part by the National Science Foundation, under research grant GP-797.

News and Comment

Education Aid: University Survey Finds That Despite Difficulties, U.S. Programs "Highly Beneficial"

One of the myths surrounding federal support for university research and education is that government money is trouble in disguise.

Magnified bits of evidence, and an occasionally egregious case, exist to support this myth; and now and then a university administrator will drop out of the grants derby to issue an alarm on the perils of federal aid, thereby breaking into the popular prints and confirming the preconceptions of those who oppose a larger federal role in university finances. Nevertheless, when the pains of federal aid are compared with its benefits, it appears that the unhappy side effects have often been overemphasized while the extremely useful achievements have come to be taken as a matter of course. Such a comparison is contained in a study issued this week by the American Council on Education; hopefully, it will serve to increase the amount of realistic thinking that goes into discussions of what role the federal government is, and should be, playing in the support of the nation's universities.

The study, "Twenty-six Campuses and the Federal Government," was conducted by the Carnegie Foundation for the Advancement of Teaching. It is contained in a special issue of *The Educational Record*, available for $1.50 from the Publications Division, American Council on Education, 1785 Massachusetts Ave., NW, Washington 36, D.C.

Prepared by an advisory committee chaired by Nathan M. Pusey, president of Harvard University, the report is a compilation of "self-studies" by 26 fairly representative institutions on their involvement with the federal government. Although it is somewhat dated, covering the years 1959–60, it is prob-