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INTERPLANETARY SPACE-A NEW LABORATORY FOR RAREFIED GAS DYNAMICS

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Abstract

Interplanetary space provides simultaneously the best vacuum available to man and, because of the solar wind, a tenuous and unsteady high-speed outflow of predominantly hydrogen gas from the Sun, a remarkable variety of rarefied gasdynamics phenomena to observe. This paper provides a review of these phenomena, and of the way in which the present level of understanding has been achieved.

Introduction

Rarefied gasdynamic phenomena observed in interplanetary space are not some insignificant stirrings of a few remaining particles in a near vacuum but a vital part of the transmission of effects of phenomena on the Sun to the Earth. It is not surprising that many aspects of interplanetary gasdynamics were totally unexpected before the satellite era. On the other hand, certain features had been anticipated in theorizing about the way in which observable solar and terrestrial phenomena might be related. From such studies in which observations were "explained" and "predictions" were made in terms of simple theories we are now well into a higher level of investigation in which observations are more comprehensive and accurate, and theories are more refined and quantitative. We intend here to provide an account of how this level has been attained, and

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some indications of the directions in which theory must be developed to keep pace with important observational developments.

The Pre-Satellite Era

For more than a century before the launching of the first spacecraft, it was known that a strong positive correlation exists between the sunspot number, auroral activity, and small transient changes in the geomagnetic field. From this, it was evident that the Earth's magnetic weather was influenced by changes on the Sun's surface in contrast to ordinary weather which is influenced by the changing geometrical relationships of the Earth and Sun.

In contrast to the slow and painstaking efforts required to establish statistical connections, the first indication of an explicit event on the Sun that might be connected with significant terrestrial consequences was sudden and unexpected. On September 1, 1859, the English solar astronomer, Carrington, saw an outburst of bright light within a large sunspot group; but within five minutes all trace of the event was gone, and the Sun appeared exactly as he had sketched it just before the event took place. At the same time, the Earth's magnetic field became abruptly disturbed. About 18 hours later, a great geomagnetic storm unprecedented in intensity and duration commenced abruptly. For several days, magnificent auroral displays were observed and telegraph communication was interrupted because of the current produced in the wires. In some cases this proved so powerful that the batteries were disconnected and the wires simply connected with the Earth. We would now regard the brief geomagnetic disturbance on September 1 as due to the fleeting enhancement of ionospheric currents by ultraviolet light and X-rays; and the great storm that commenced the next day as the effect of an interplanetary shock wave followed some hours later by solar matter ejected from the Sun by Carrington's flare.

While Carrington cautiously proposed a connection between the solar and terrestrial events, Kelvin and others dismissed the evidence as mere coincidence. Much later, Chapman and Bartels [1940] wrote in Geomagnetism (a 1050 page two volume work published just one year after Chapman and Cowling's Mathematical Theory of Nonuniform Gases, and lauded in reviews as the greatest on the Earth's magnetism since Gilbert's de Magnete published in 1600!) that Carrington's observation of a flare in white light remains unique, and that geophysicists would even then maintain a cautious attitude except for the clear relation found in 1935 and 1936 between solar eruptions and radio fade-outs which in turn tend to occur in coincidence with geomagnetic disturbances.

From this uncertain beginning, the Norwegians, Birkeland and Störmer began in 1896 a prodigious, experimental, theoretical, and observational effort to explain the aurora and related geomagnetic phenomena in terms of beams of electrons emitted from the Sun and guided into the polar regions by the geomagnetic field. (See Störmer [1955] for a summary.) In 1911, Schuster showed, however, that electrostatic repulsion would disperse the beam to far too low a density to account for the terrestrial phenomena. Nearly a decade later, Lindemann proposed that geomagnetic storms might be produced by electrically neutral streams of charged particles; i.e., a plasma. Chapman soon thereafter was at work developing consequences of this idea, first alone and then in collaboration with V. C. A. Ferraro.

By the beginning of the satellite era, there had emerged, (See Chapman [1963] for a résumé.) an incomplete, somewhat faulty, but still remarkably good, understanding of how ionized gas of solar origin might produce the observed geomagnetic variations and many associated effects. Interplanetary space was conceived to be primarily a vacuum invaded at times by clouds of plasma ejected by solar flares, and possibly continuously by longlived beams of plasma rotating with the Sun. The rotating beams were used to account for the 27-day recurrence pattern in geomagnetic and auroral activity by associating it with the rotation of the Sun. The plasma clouds were postulated to account for the flare-induced geomagnetic storms such as that associated with Carrington's observation.

Chapman and Ferraro also established that the geomagnetic field would shield the Earth from the solar plasma and that a thin current sheet at the boundary of the plasma would terminate the geomagnetic field. They discussed the nature of the interaction with the front of either a flare-induced plasma cloud or a rotating beam, developed a precise mathematical representation for both the steady and unsteady cases, and solved a number of problems to illustrate particular features of the interaction.

Near the Earth, the geomagnetic field is represented by a magnetic dipole at the center of the Earth having such a strength that $|B| = B_{eq} = 0.312$ gauss at the geomagnetic equator, and oriented so that the north geomagnetic pole is at 78.6° North latitude and 70.1° West longitude, near Thule, Greenland. Its properties are thus given by

$$B = -B_{eq} \; (a_e/r)^3 \; (\hat{\theta} \sin \theta + \hat{r} \; 2 \cos \theta) \qquad (1)$$

in which $a_e = 6.37 \times 10^8$ cm is the radius of the Earth, r is the geocentric distance, θ is the polar angle measured with respect to the north geomagnetic pole and $\hat{r}$ and $\hat{\theta}$ are unit victors in the r and θ directions.

No currents were presumed in the surrounding region, which is now called the magnetosphere; hence curl B as well as div B vanish there. The condition that the normal component B_n of the geomagnetic field must vanish at the boundary is supplemented by the relation $B^2/8\pi = p$ that equates the magnetic pressure at the boundary to the pressure p of the incident plasma. Although the details of the interaction are very different from those in ordinary rarefied gas flow incident on a solid obstacle, the net effect in a plasma having an ion number density n and mass m flowing with a free-stream velocity v_∞ is that $p = mnv^2 \cos^2\psi$ on an element of the boundary having its normal at an angle ψ to the free-stream direction.

Although the model had been established much earlier, it was not until well into the satellite era that even approximate solutions were obtained for the shape of the geomagnetic field boundary [Spreiter and Briggs, 1962 and Briggs and Spreiter, 1963]. Higher order solutions have been given most completely by Olsen [1969], but the results remain essentially the same as indicated by the earlier approximate solutions. In the idealized model of Chapman and Ferraro, the boundary is impermeable to the solar plasma, except possibly at a pair of neutral points at which the magnetic field vanishes and from which extend the only field lines that connect the boundary and the Earth. These points are of considerable current significance because they define weak spots in the boundary through which interplanetary plasma can enter the magnetosphere and precipitate into the upper atmosphere.

In the years immediately preceding the launching of the first satellite, analysis of the behavior of comet tails by Biermann [1951, 1957] and theoretical studies by Parker [1958] began to suggest the continuous rather than intermittent existence of a high-speed flow of solar plasma throughout interplanetary space. The idea of such a solar wind did not gain acceptance, immediately, however, since the comet analysis involved a number of uncertain assumptions, the theory was ambiguous, and no direct measurements could be made.

The nature of the ambiguity in the theory can be understood easily. The theory is just that of radially symmetric flow of a perfect gas in a centered inverse square gravitational field, under the assumption that the energy equation could be substituted for by assuming a simple polytropic law between the pressure and density. The governing equations have a family of solutions reminiscent of those for flow in a Laval nozzle. Parker chose the transonic solution that takes the flow from low subsonic speeds near the Sun to supersonic speeds beyond a few solar radii. Chamberlain [1961] however, argued that purely subsonic solutions were the appropriate ones. A few years earlier, moreover, Bondi [1951] had used the same basic model, but with the direction of flow reversed, to explain accretion of mass by a star, and possibility the high 2×10^6 °K temperature of the solar corona.

Results of Direct Measurement of the Solar Wind

It was Mariner 2 on its flight to Venus in the latter half of 1962 that resolved the controversies. The results [Neugebauer and Snyder, 1966, 1967] showed that the plasma flow was supersonic, always present, and that the mean values of the velocity, density, and temperature were approximately as indicated by the "first order" solar wind theories then available. With the existence of the solar wind established, there followed many refinements of the theory in which effects of heat conduction, viscosity, rotation, magnetic fields, and, most recently, fluctuations of the flow were included.

Later and more complete measurements with instruments that scanned in several directions have shown that the velocity distribution of the random motions of the particles is not isotropic and that the "temperature" is therefore different in various directions. By defining a quantity analogous to ordinary temperature in terms of the random motion of the particles in a given direction and by referring to it as the temperature in that direction, Hundhausen et al. [1967] have shown that the direction of the temperature anisotrophy is characteristically aligned with the interplanetary magnetic field, the maximum temperature is in the direction pointing away from the sun along the field lines, and the minimum temperature is in the direction transverse to the magnetic field. This indicates that heat is being conducted away from he sun along the magnetic lines of force. It is evident that such anisotropies have an important effect on the dynamics of the solar wind, but relatively little consideration has yet been given to them in refinements of the theory.

Another feature that needs additional consideration is the rotating sector structure discovered by Wilcox and Ness [1965] in the IMP 1 data. Although the sector is defined in terms of the predominant direction of the interplanetary field as away from or toward the sun, they showed that the velocity, density, magnetic field intensity, and geomagnetic activity index all display an organized reproducible variation within each sector. Wilcox [1968] and Schatten [1971] have examined the evolution of the sector structure throughout the years since its discovery. From data observed over less than whole 11-year solar cycle, and inferences from ground-based geomagnetic data, they conclude that the four sectors found in the IMP-1 data are representative of the solar minimum, whereas two sectors are more representative of the period near solar maximum.

In addition to the large-scale irregularities associated with the sector structure, the solar wind exhibits a wide variety of variations, both gradual and abrupt. Many are simply convected with the flow. Others propagate through the solar wind as shock waves. Most of these may be identified with large solar flares that occurred a few days previously. However, most solar flares do not produce shock waves at the orbit of Earth. Hundhausen [1972] used data from 19 shock waves, to seek the cause for such a selection. He concluded that the observed shock waves are produced by the relatively few flares that have a sufficiently high energy-mass ratio for escape against solar gravity.

Magnetohydrodynamic Representation of Solar-Wind Flow Fields

Most analyses of structures in the solar wind, and of the flow fields of the Earth, Moon, and planets, have been based on the continuum equations of gasdynamics or magnetohydrodynamics of a perfect dissipationless gas. That they can describe the behavior of a gas so rarefied as the solar wind is one of the surprises of space research, but their appropriateness has been confirmed in a wide variety of applications. To be precise, the equations are as follows

$$\partial\rho/\partial t + \nabla \cdot \rho \underset{\sim}{v} = 0 \qquad (2)$$

$$\rho D\underset{\sim}{v}/Dt = - \underset{\sim}{\nabla} p - \underset{\sim}{B} \times \underset{\sim\sim\sim\sim}{\text{curl}}\, \underset{\sim}{B}/4\pi + \rho \underset{\sim}{g} \qquad (3)$$

$$\partial\underset{\sim}{B}/\partial t = \underset{\sim\sim\sim\sim}{\text{curl}}\, (\underset{\sim}{v} \times \underset{\sim}{B}) \;,\; \text{div}\, \underset{\sim}{B} = 0 \qquad (4)$$

$$\frac{Ds}{Dt} = 0 \;,\; s - s_o = c_v \ln \frac{p/p_o}{(\rho/\rho_o)^\gamma} \qquad (5)$$

in which ρ, $\underset{\sim}{v}$, $\underset{\sim}{B}$, S, and $\underset{\sim}{g}$ represent the density, velocity, magnetic field, entropy, and gravitational acceleration. If effects of gravity are disregarded, solutions depend on two nondimensional ratios, Mach number $M = v/a$ and Alfvén Mach number $M_A = v/A$, where $a = (\gamma p/\rho)^{1/2}$ is the speed of sound and $A = (B^2/4\pi\rho)^{1/2}$ is the Alfvén speed. Both M and M_A are normally much greater than unity, values of about 10 being representative for the solar wind flow approaching the Earth's bow wave.

These equations must be supplemented by additional relations between conditions on opposite sides of possible discontinuities in the flow. At each element of such a surface, conservation of mass, momentum, energy, and magnetic field provide

$$[\rho \tilde{v}_n] = 0 \;,\; [\rho \tilde{v}_n v + (p + B^2/8\pi)\hat{n} - B_n \underset{\sim}{B}_t/4\pi] = 0 \qquad (6)$$

$$[\rho \tilde{v}_n (h + v^2/2) + \tilde{v}_n B^2/4\pi - (B_n \underset{\sim}{v} \cdot \underset{\sim}{B})/4\pi] = 0 \qquad (7)$$

$$[B_n \underset{\sim}{v}_t - \underset{\sim}{B}_t \tilde{v}_n] = 0 \;,\; [B_n] = 0 \qquad (8)$$

The square brackets indicate the difference between the enclosed quantities on the two sides of the discontinuity; $\tilde{v}_n = \underset{\sim}{v} \cdot \hat{n} - \lambda$ is the normal fluid velocity component relative to the normal velocity λ of the discontinuity surface; $\hat{n}$ and $\hat{t}$ are unit vectors normal and tangential to the discontinuity surface; and subscripts n and t indicate components of $\underset{\sim}{v}$ and $\underset{\sim}{B}$ in these directions. Five classes of magnetohydrodynamic discontinuities, tangential, contact, rotational, and fast and slow shock waves, are described by these equations. All except the contact discontinuity have been identified in the solar wind, and several are important in the flow field of the Earth and other major objects in the solar system [Hundhausen, 1970, and Spreiter and Alksne, 1970].

An important refinement of this theory is currently being developed to explain a number of features of the solar wind associated with the observed anisotropy of the temperature and pressure. In this approximation (see Burlaga [1971] for a review), the density ρ and velocity $\underset{\sim}{v}$ are defined by $\rho = \Sigma\, m_i n_i$ and $\underset{\sim}{v} = \frac{1}{\rho} \Sigma\, m_i n_i \underset{\sim}{u}_i$ in which m_i is the particle mass; and n_i, the number density of particles of species i, and $\underset{\sim}{u}_i$, the average speed of species i, are given in terms of the velocity distribution f in the usual way by $n(\underset{\sim}{r},t) = \int f(\underset{\sim}{r},\underset{\sim}{v},t)\, d\underset{\sim}{v}$, $\underset{\sim}{u}(\underset{\sim}{r},t) = \frac{1}{n} \int \underset{\sim}{v} f d\underset{\sim}{v}$. The governing differential equations remain as written in equations (2) through (5), except that the right-hand side of the latter is replaced by

$$\underset{\sim}{\nabla} \cdot [\hat{\mathbb{I}}(\sum_k p_{k_\perp} + B^2/8\pi) - \underset{\sim}{B}\,\underset{\sim}{B}\,\xi/4\pi] + \rho \underset{\sim}{g}$$

which reduces to

$$\underset{\sim}{\nabla} (\sum_k p_{k_\perp} + B^2/8\pi) - (\underset{\sim}{B} \cdot \underset{\sim}{\nabla})\, \underset{\sim}{B}\, \xi/4\pi + \rho \underset{\sim}{g}$$

when ξ, a measure of the anisotropy, is constant. The latter quantity is defined as $\xi = 1 - \frac{4\pi}{B^2} \sum_k (p_{k_{||}} - p_{k_\perp}$ in which $p_{k_{||}} = n_k m_k \int w_{k_{||}} w_{k_{||}}\, f\, d\underset{\sim}{v}$

and $p_{k_\perp} = n_k\, m_k \int w_{k_\perp}\, w_{k_\perp}\, f\, d\underset{\sim}{v}$

represent the pressure of the k^{th} species parallel and perpendicular to $\underset{\sim}{B}$, and $\underset{\sim}{w}_k = \underset{\sim}{v}_k - \underset{\sim}{u}_k$. These equations imply collective interaction of the particles. For motions normal to $\underset{\sim}{B}$, this is caused by the magnetic field; collisions are not necessary. For motions along B, details are not yet fully understood, but it is believed that such interactions are associated with fluctuations or wave-particle interactions. It is possible, moreover, that on some scales the interactions along the field lines are so weak that one should use a kinetic particle equation for motions along $\underset{\sim}{B}$.

Equations (2) through (4), or their anisotropic counterparts, must be supplemented to provide a closed set of equations. For the isotropic case, only one additional equation is needed, and it is frequently sufficient to use the adiabatic approximation indicated by equation (5). For the anisotropic case, there is one more dependent variable because of the two pressures $p_{\|}$ and $p_{\perp}$, and it is necessary to supply two additional relations.

One approximation that has sometimes been applied to the solar wind is that of Chew, et al. [1956] in which $D(p_{\perp}/\rho B)Dt = 0$ and $D(p_{\|}B^2/\rho^3)/Dt = 0$. The first is suggested by an adiabatic invariant of charged particle motion in a magnetic field; the second stems from the assumption of either no or constant heat flux along $\underset{\sim}{B}$. These equations were derived on the assumption that $\beta = nkT/(B^2/8\pi) << 1$, a condition that seldom applies in the solar wind.

For applications to the solar wind, Burlaga [1971] proposes that $p_{k_{\perp}} = A_{k_{\perp}} \rho^{\gamma_{\perp}}$ and $p_{k_{\|}} = A_{k_{\|}} \rho^{\gamma_{\|}}$ in which appropriate values for $\gamma_{\|}$ and $\gamma_{\perp}$ are still to be determined. For relatively small-scale features of the solar wind for which the magnetic field is reasonable orderly, he proposes that $\gamma_{\perp} = 2$ because there are 2 degrees of freedom normal to $\underset{\sim}{B}$ and $\gamma_{\|} = 3$ because there is only one degree of freedom along $\underset{\sim}{B}$. If, however, compressions along B are isothermal, since the conductivity along $\underset{\sim}{B}$ is high, he suggests that perhaps $\gamma_{\|}$ might be 1 rather than 3. It is quite possible, furthermore, that the appropriate value for γ depends on the scale of the phenomena being considered, since the magnetic field is probably more disordered when viewed on a large scale than on a small scale.

Just as for the isotropic fluid, additional equations must be supplied to relate conditions on opposite sides of discontinuity surfaces. We will not present further details, but refer the reader to Burlaga [1971]. There may be found, in addition, an account of the properties of both waves and discontinuity surfaces in the anisotropic collisionless medium described above, and a discussion of a variety of observations in space that give a sense of reality to the theory. Although the theory is clearly applicable to the solar wind, many consequences remain to be worked out. Nonlinear theories of waves, instabilities, and interaction of discontinuities and waves are needed, as are further developments of the effects of fluctuations, or possibly turbulence, in the flow. The effects of anisotropies on large-scale features of the solar wind, such as the sector structure, and on the flow about the Earth and other major objects in the Solar System are almost totally unknown at present, and demand investigation if one is to have a consistent theory of significant solar wind phenomena.

Solar Wind Flow Past the Earth - A Magnetic Planet

To calculate solar wind flow past the Earth, a knowledge of the density and velocity of the solar wind is needed. Even before this was acquired by Mariner 2 in 1962, early satellite data had confirmed the termination of the geomagnetic field at about the expected location. They also revealed an unanticipated transition region having fluctuating properties before steadier conditions typical of interplanetary space were reached. Various hypotheses were put forth at the time; but Axford [1962] and Kellogg [1962] correctly explained that the Earth's magnetosphere had a bow shock wave. Shortly thereafter, Spreiter and Jones [1963] used gasdynamic theory to calculate its location. They also noted that the fluctuating character of the post-shock gas is not unlike that calculated for collisionless shock waves by Auer et al. [1961, 1962].

The first Earth satellite to repeatedly carry plasma probes and magnetometers across the geomagnetic boundary and the bow wave was Explorer 18 or IMP-1 launched on November 27, 1963. As in the earlier measurements, the transition region is recognizable in the magnetometer records by the presence of fluctuations more substantial than in either the incident solar wind or the magnetosphere. The differences are even more obvious in the data from the plasma probes. Wolfe et al. [1966] showed there was a total absence of plasma flux when the spacecraft was within the magnetosphere and shielded from the flowing solar plasma. The presence of plasma flux in only a narrow range of energy levels satellite was beyond the bow wave indicates that the random thermal velocities of the particles in the incident solar wind are small compared with the directed bulk velocity of the flow. The broad energy spectrum observed in the intervening part of the orbit is indicative of the hot shocked plasma in the transition region.

Although the magnetopause and bow wave were not always distinctly revealed it was usually possible to distinguish the various regions. They were, moreover, close to the theoretical positions of the magnetopause and bow wave calculated by Spreiter and Briggs [1962] and Spreiter and Jones [1963]. Although the theoretical model was an inconsistant mixture of particle and fluid concepts, the results served to fix the ideas about the fluid-like nature of the flow field, and to encourage a re-examination of the entire problem from a consistant magnetohydrodynamic point of view.

The problem of solving the magnetohydrodynamic equations (2) through (8) for steady uniform flow at infinity past a magnetic dipole described by equation (1) remains intractable; but Spreiter et al. [1966] showed that approximate solutions of good accuracy can be attained upon introduction of several important simplifications beyond the obvious elimination of terms containing $\partial/\partial t$ or λ. Within the magnetosphere, $B^2/8\pi$ greatly exceeds p everywhere above a few hundred kilometers; and the dominant effect of the Earth is provided by the terms that remain when p and ρ are equated to zero, namely div $\mathbf{B} = 0$ and curl $\mathbf{B} = 0$. Near the Earth, $\mathbf{B}$ may be represented adequately by equation (1). The magnetopause must be represented by a tangential discontinuity, since that is the only solution of the conservation equations for which $v_n = B_n = 0$. Arbitrary differences in ρ, $\underset{\sim}{v}_t$, and $\underset{\sim}{B}_t$ are allowed across such a surface, but $p + B^2/8\pi$ must be the same on both sides. The bow wave can be represented only by a fast-shockwave solution of the conservation equations because the solar wind approaches the Earth with a mass flux $\rho_\infty v_\infty$ that greatly exceeds that which can pass through any of the other types of discontinuities. With the neglect of the small effects of terms containing $\underset{\sim}{B}$ and $\underset{\sim}{g}$ in equations (3), (6), and (7), the equations for the fluid motion reduce to those of gasdynamics; and the distortion of the interplanetary magnetic field can be determined in a subsequent step by solving the remaining equation with $\underset{\sim}{v}$ known from the gasdynamics results.

The free-boundary problem for the shape of the magnetopause can be made tractable by introducing the Newtonian approximation for the pressure on the magnetopause, i.e. by $p = K\rho_\infty v_\infty^2 \cos^2\psi = B^2/8\pi$ in which, K is a constant equal to 0.88 for high Mach number flow of a monatomic gas, although usually taken as unity in most applications of type described here. Since the resulting description coincides with that put forward more than 40 years ago by Chapman and Ferraro, it is paradoxical, but true, that the theory of the geomagnetic boundary shape is much older than the idea of the solar wind. It follows that the locations of the magnetopause and bow wave calculated previously remain appropriate, but the logical inconsistencies have been removed from the underlying theory.

The most detailed comparison of results calculated in this way and direct observations in space are those made by Spreiter and Alksne [1968] utilizing data from Pioneer 6 following launch on December 16, 1965, during a period of exceptionally low geomagnetic activity. The calculated and measured locations of the magnetopause and the bow wave were shown to be virtually coincident, and all the flow parameters to be in remarkable agreement with the theory. It is difficult to assess the implications of the remaining discrepancies, however, because of uncertainties and incompleteness of the data. The experimental values for p, for example, were judged by the experimenters [Wolfe and McKibbin, 1968] to contain a 50 percent uncertainly, and these given for the velocity are not actually for the bulk velocity, as considered in the theory, but for the speed of the ions that produce the greatest current per unit energy increment in the plasma probe. It is possible, moreover, that some of the observational variations not duplicated by the theory are the result of unkown changes in the interplanetary conditions that occurred when Pioneer 6 was behind the bow wave, and could be reproduced by the theory if the actual interplanetary conditions were better known.

At the present time, we may summarize the present state of the magnetohydrodynamic theory of the interaction of the solar wind and the Earth as being most thoroughly worked out for the more upstream portion of the flow field and for solar wind conditions that are steady and characterized by high (5 or greater) values for both M_{A_∞} to M_{A_∞}. In addition to the obvious need for solutions for the dynamical response of the flow to abrupt changes in conditions in the incident stream, since these often produce the most dramatic geophysical consequences, there are many ways in which the theory is notably incomplete. First of all, low values for M_{A_∞} , occasionally less than unity, are sometimes observed in the solar wind. There only now is beginning a discussion of such possible effects on the flow about the Earth and the attendant geophyical consequences [Formisano et al., 1971; Rizzi, 1971; and Fairfield,1971]. There is a great need for improved theoretical understandimg of the properties of the magnetic neutral sheet and the enveloping plasma sheet that extends downstream along approximately the centerplane of the magnetosphere tail. As noted above, the neutral points on the magnetosphere boundary have been long suspected from suggestions of Chapman and Ferraro to be of importance as exceptional regions through which charged particles from the solar wind could gain access to the inner magnetosphere. Spreiter and Summers [1967] have considered implications of the fluid theory for this region, concluded that a cusped shaped region of hot "stagnant" plasma extends toward the Earth from the vicinity of the theoretical neutral points of the idealized theory, and given expressions for the leakage rate of charged particles from the cusp based on Grad's [1963] analysis of the particle leakage from the ends of a mirror machine. At present time, there is a considerable effort in progress to measure particle fluxes from these regions, and to ascertain the resultant geomagnetic, auroral, and ionospheric effects. The stability of the magnetosphere boundary, and the bow wave, has been the subject of considerable speculation, but a comprehensive theory is lacking, as it also is for effects of fluctuations and anisotropies of the flow. Although much has been accomplished, the importance of acquiring a better understanding of the varied and subtle ways in which solar and terrestrial phenomena are related demands that more be done.

Solar Wind Flow Past Mars and Venus - Nonmagnetic Planets

If we now turn attention to Mars and Venus, we find that data acquired in recent years disclose a somewhat different type of interaction from that just described for the Earth. Neither of these planets has a significant magnetic field to withhold the solar wind, but they both have an upper ionosphere that is sufficiently conducting electrically to prevent the solar wind from flowing directly into the lower absorbing levels of the atmosphere. The solar wind is thus deflected around the ionosphere, and a bow wave is formed upstream of the planet, similar in many ways to that associated with the Earth. Aside from evident differences in the underlying physical processes at the ionopause, the surface that bounds the ionosphere and the solar wind, the principal difference between the flow fields around these planets and the Earth is the size of the cavity. Compared to the Earth, for which the nose of the magnetopause is at an altitude of about 60,000 km for representative solar wind conditions, the nose of the ionopause is at an altitude of about 500 km for Venus and only about 155 to 175 km for Mars.

It has been shown [Spreiter et al., 1970] that a theory for solar wind flow past Venus or Mars can be constructed analogous to that for Earth on the basis of the facts that the planetary magnetic field is weak or nonexistent, and that the ionospheric pressure p is sufficient to stop the solar wind. If effects of gas motions are neglected, conditions in the ionospheres of these planets may be idealized to the hydrostatic support relation $\underset{\sim}{\text{grad}}\, p = \rho \underset{\sim}{g}$, or $dp/dr = -\rho g$ that remains when $\underset{\sim}{v}$ and $\underset{\sim}{B}$ are zero in equation (3). If the scale height $H = kT/mg$ of the upper atmosphere is constant, the tangential discontinuity becomes $p = K\rho_\infty V^2_\infty \cos^2\psi = p_R \exp[-(r - r_R)/H]$ in which p_R is the pressure at a reference radius r_R.

Once the ordinary differential equation for the shape of the ionopause is solved, the properties of the surrounding flow may be calculated in the same way as for the Earth.

Spreiter and Rizzi [1972] have compared the locations of the ionopause and bow wave calculated in this way for conditions representative of Mars with the magnetic field measurements of Mariner 4 [Smith, 1969] as it flew by that planet. They showed that Mariner 4 crossed the theoretical location of the bow wave at two points, and that the magnetometer record displayed prominent discontinuities at virtually the precise times that the shock crossings were indicated. While there is always the possiblity that such sudden changes in the magnetic field may be the result of the passage of discontinuities in the solar wind, the coincidence with the theoretical results supports the proposition that these data do indeed provide the signature of a Martian bow wave. A half-hour gap in the data during the two hour Mariner 4 was behind the bow wave is indicative of the many difficulties of space research. During this interval, the spacecraft was directly in line behind the planet, as viewed from Earth, and no data could be received from it. Moreover Mariner 4 carried a plasma probe, but a malfunction prevented it from providing an independent indication of the shock crossings. Mariners 6 and 7 subsequently approached within 2000km of the Martian surface, but neither spacecraft carried a magnetometer, plasma probe, or energetic particle detectors. Had the geometry of the Mariner 4 encounter been slightly different, we might still have no direct observational knowledge of the nature of the Martian interaction with the solar wind and of the insignificance of its magnetic field in comparison with that of the Earth

Spreiter et al., [1970] have also made a similar comparison for Venus using the data from Mariner 5. [1967]. They showed that Mariner 5 crossed the bow wave at very nearly its calculated location but that there is no positive indication the spacecraft penetrated the ionopause to the extent indicated by the theory. Since the observations near the theoretical location of the ionopause indicate values for n/n_∞ and v/v_∞ that are about one-half the theoretical values for the flow exterior to the ionosphere, Spreiter et al., [1970] suggested that perhaps Mariner 5 entered a thick boundary layer separating the ionosphere and the flowing plasma, but not the ionosphere proper.

The Venus should have a thick boundary layer along the ionopause, whereas the Earth's magnetopause is astonishingly thin, is plausible in view of the fundamentally different nature of the two boundaries. The magnetopause is essentially a boundary between the flowing plasma and a relative vacuum, whereas the ionopause is a boundary between two bodies of plasma in relative motion. At the location of the ionopause indicated by the present dissipationless theory, the plasma velocity might be expected to be substantially less than indicated by the theory, as is indeed evident in the data of Mariner 5. A more detailed examination is clearly required before a definitive statement can be made, however.

We have subsequently carried out a more complete examination of one aspect of the interaction by developing an exact magnetohydrodynamic solution of the interaction under the assumption that the magnetic field is aligned with the flow direction in the incident solar wind, as it approximately was at the time of the Mariner 5 encounter with Venus [see Rizzi (1971) for a complete account]. In so doing, the ionopause was still represented by a tangential discontinuity, but the calculated values for $p + B^2/8\pi$ of the flow were used instead of the Newtonian approximation, and the flow field was computed using the equations of magnetodydrodynamics rather than gasdynamics.

These calculations were made possible by an extension to flows with rotation and embedded shock waves of a transformation scheme described for a succession of increasingly complex magnetodydrodynamic cases by Cowley [1960], Imai [1960], Iuriev [1960], Spreiter et al. [1970]. and Rizzi [1971]. According to this procedure, a general property of aligned flows that $\underset{\sim}{B} = \lambda(\psi)\rho\underset{\sim}{v}$, in which $\lambda(\psi)$ is a constant along each streamline, is supplemented by a set of transformed variables indicated by * and related to the original variables by $\underset{\sim}{v}^* = \underset{\sim}{v}(1 - \lambda^2\rho/4\pi)$, $\rho^* = \rho/(1-\lambda^2\rho/4\pi)$ $p^* = p + B^2/8\pi$, $h^* = h + (\lambda^2 \rho v^2/4\pi)(1 - \lambda^2 \rho/4\pi)$, and $s^* = s$ in which $\lambda^2 \rho/4\pi = 1/M_{A_\infty}^2 = \rho/\rho\, M_{A_\infty}^2$. Substitution of these relations into the equations for steady magnetohydrodynamic flow yields equations for the transformed variables that are identical to equations (2), (3), (5), (6), and (7) with $\partial/\partial t$, λ, and $\mathbf{B}$ equated to zero. They need to be supplemented by an "equation of state" relating ρ^*, p^*, and s^* to complete the system. Although the equation of state relating p, ρ, and s is the same as in ordinary gasdynamics for a perfect gas, the corresponding relation between p^*, ρ^*, and s^* is substantially different. It is that

$$p^*(\rho, s^*) = \left(1 - \frac{\gamma}{\gamma-1}\frac{\rho}{\rho_\infty M_{A_\infty}}\right) p_\infty \left(\frac{\rho}{\rho_\infty}\right)^\gamma \exp\left(\frac{s-s_\infty}{c_v}\right) + h_{st}\frac{\rho^2}{\rho_\infty M_{A_\infty}^2}$$

in which $\rho = \rho^*/(1+\lambda^2\rho^*/4\pi) = \rho^*/(1+\rho^*/\rho_\infty M_{A_\infty}^2)$ and $h_{st} = \frac{1}{2}v_\infty^2 + h_\infty = \frac{1}{2}v_\infty^{*2} + h_\infty^* = h_{st}^* = c_p T_\infty$

In this way, a correspondence is established between equations for magnetohydrodynamics for aligned flow and those of gasdynamics for a hypothetical gas obeying an unusual equation of state. The advantage is that existing methods for solving the gasdynamic equations can be applied with only minor modifications to obtain magnetohydrodynamic solutions.

Comparison of the results calculated in this way with the observations of Mariner 5 near Venus show that the shock location is predicted almost perfectly and that the penetration of the trajectory is not quite so deep into the inosphere. The conclusion is that a distinct improvement in the quality of the theoretical representation has resulted from an obvious, but complicated, improvement in the theory.

Solar Wind Flow Past the Moon

Solar wind flow past the Moon is notably different from that for either the Earth or the nonmagnetic planets, Mars and Venus. As with the other objects, it was only with the acquisition of data measured in situ that an end could be put to a period of speculation about the nature of the interaction. Although more recent measurements are revealing a rather rich substructure, plasma probe and magnetometer data from Explorer 35 placed into orbit about the Moon in July 1967, provided immediately the knowledge needed to specify appropriate boundary conditions to complete an idealized magnetohydrodynamic representation of the interaction. These conditions are that free-stream conditions exist directly up to the lunar surface, that the magnetic field is continuous from the solar wind into the Moon, that no significant electrical currents flow in the Moon in the steady state, and that there exists a void in the solar wind downstream from the Moon in which neither particles nor electrical currents are to be found. Two alternatives exist for describing conditions at the surface of this void, depending on whether or not an electric current sheet forms. If one does form, the boundary of the void must be represented by a tangential discontinuity. If no current sheet forms, the magnetic field in the Moon and the trailing void must join continuously with that in the surrounding flow. Both theory and data from Explorer 35 have been shown [Spreiter et al, 1970] to indicate that either possibility may occur, depending on the orientation of the interplanetary magnetic field.

Both a discrete particle representation [Whang, 1968a, b] and a continuum magnetohydrodynamic fluid [Spreiter et al, 1970] have been developed in detail to account for many aspects of the interaction. The latter reference, and also Ness [1970], provide an extensive discussion of the observations of Explorer 35, both alone and in conjunction with the data from Explorer 33 which was simultaneously monitoring the solar wind away from the influence of the Earth and Moon, and their relation to the theoretical predictions. Small perturbations of the interplanetary magnetic field intensity of the order of 20 to 30 percent are observed to be correlated with the location of the solar wind plasma umbra and penumbra. On some tranverses, characteristic alternations in sign (+ - + - +) of the magnetic perturbations are observed as the satellite traverses the lunar wake. On other traverses, no such alternations are evident, and only slight variations are apparent.

Some of the variations are understandable in terms of the direction of the interplanetary magnetic field and the orientation of the orbit with respect to the principal plane of symmetry defined by the incident solar wind velocity and magnetic field directions [Spreiter et al., 1970]. Others may be correlated with the diamagnetic properties of the solar wind, as measured by the ratio of the components of the plasma and magnetic pressures perpendicular to the magnetic field direction [Ness, 1970].

It is becoming evident from the data from the Apollo magnetometers on the surface of the Moon that the story is still far from complete, however. As reported by Driscoll [1972], the magnetic field at the lunar surface was measured to be 38 gammas at the Apollo 12 site, 43 and 103 gammas at two locations near the Apollo 14 site, only 6 gammas at the Apollo 15 site, and 120, 125, 180, 230, and 313 gammas at several locations near the Apollo 16 site. Since such intensities greatly exceed the critical value $B = (8\pi K\rho_\infty v_\infty^2)^{1/2}$ required to stop the solar wind at a stagnation point, it is apparent that modifications may have to be made to all the theories that assume that the solar wind flows without deviation into the lunar surface. Since even weaker magnetic fields would be sufficient to deflect the solar wind away from the flanks of the Moon, as seen from the Sun, it is quite possible that many of the small increases in magnetic field intensity seen just outside the lunar wake may be the result of localized outward deflections of the flow and their accompanying bow waves. It is apparent that future studies of the solar-wind lunar interaction will have to take these local magnetic irregularities into account.

While it is true that all of the perturbations of the solar wind resulting from interaction with the Moon are small, their implications go substantially beyond being just one more source of disturbance in an already fluctuating solar wind. From these studies can come many inferences about the lunar interior, a matter of interest both for its own sake and also for the perspective it offers on our knowledge of the Earth's interior. As summarized recently by Ness [1970], for example, it has been concluded from these data that neither the Gold-Tozer-Wilson mechanism of accretion of interplanetary field lines or the Sonett-Colburn-Hollweg mechanism of unipolar induction is of significance for the Moon. From the fact that there is little distortion in the transmission of microstructural discontinuities in the solar wind flow past the Moon, it has been concluded that the lunar interior must have a low electrical conductivity (less than 10^{-4} mho/m) and therefore a relatively cool interior of the order of $1000^{o}K$. Reconciliation of such conclusions with the presence of surface magnetic field intensities of the order measured by the Apollo magnetometers, and with the apparently universally high remnant magnetization of lunar rocks, is not easy; and in fact poses a major problem for anyone attempting to construct an acceptable model for the structure, composition, and evolution of the lunar interior. It is an intriguing thought for this Symposium that studies of rarefied gasdynamics might contribute to understanding the state of the lunar interior, not only at the present time but perhaps a few billion years ago.

Solar Wind Interaction with Other Major Objects in the Solar System

At the present time, direct measurements have been made of the interaction of the solar wind with the Earth, the Moon, Venus, and Mars in descending order of completeness. Although the surprises encountered with each of these objects should be sufficient to give pause to anyone about to speculate on the nature of the interaction with other major objects in the Solar System, the knowledge gained from their study gives a sense of perspective about the possibilities that did not exist as recently as only a decade ago. Briefly, the outlook appears as follows.

Mercury has no significant atmosphere, and its slow rotation rate of 59 days suggests that it may have no magnetic field. Its interaction with the solar wind is anticipated, therefore, to resemble that for the Moon. Jupiter emits radio signals that are interpreted as indicating that planet has an enormous magnetic field with a dipole moment that exceeds that of the Earth by a factor of about 3×10^{5}. It is anticipated, therefore, to have a magnetosphere like the Earth, but scaled up in size by a factor of approximately 50, considering both its magnetic field and the anticipated variation of the solar wind properties between the orbits of Earth and Jupiter. If, however, the solar wind should become subsonic inside the orbit of Jupiter, there would, of course, be no bow wave, and a new type of interaction would be anticipated. Virtually nothing can be said about the interaction of the solar wind with the remainder of the planets because of almost total lack of knowledge of properties of both the distant solar wind and the planetary magnetic fields and ionospheres. An additional possibility that might occur in the outer part of the Solar System, particularly if the solar wind should become subsonic, is that the flow may be deviated primarily by the gravitational field. In such a case, the object would act rather like a sink in the solar wind, drawing in the plasma as it approaches.

Noteworthy also is that five planetary satellites, including the four large Galillean moons, two of which are approximately the size of the Moon, are deeply embedded in the presumed magnetosphere of Jupiter, whether the solar wind is supersonic of subsonic. Similarly, our Moon spends about 7 days out of every 29.5-day synodic period in the region disturbed by the Earth. It is clear that conditions surrounding the Moon during these times differ greatly from those in the undisturbed solar-wind flow, but we are aware of no theoretical analysis of the details of the interaction.

Yet another class of interactions with the solar wind is that with comets having Type I, or ionized, tails. As noted at the beginning of this paper, it was, in fact the study of motions of such cometary tails that led to the first suggestion of the permanent existence of the solar wind by Biermann. While direct probing of a comet has not yet been attempted with a spacecraft, the great visibility of comets make them suitable objects for optical observation from the Earth. Although the analysis is still a rather preliminary stage of development, a magnetohydrodynamic model is beginning to emerge that is very similar to that described above for the Earth and neighboring planets, except that the cometary nucleus of 1 to 10 km radius is considered to be the source of a flow of neutral molecules as it comes into the warmer inner parts of the Solar System. These do not interact with the solar wind until they are ionized at some distance from the nucleus, primarily by photoionization and charge exchange, but probably by other mechanisms as well. The effect is similar in many respects to that of distributed mass injection into the flow surrounding the comet, and leads to an interaction region that is enormously larger than that which would be indicated by simple estimates based on solutions for flows without mass injection.

Concluding Remarks

In conclusion, perhaps the outstanding impression to be gained from this review is a realization of the tremendous gain in understanding of the properties of the solar wind and its interaction with objects in the Solar System that has been achieved in recent years through an intensive observational and theoretical program. The best progress has been made when at least a minimum of observational evidence is in hand to guide the theory along realistic paths, and when there is enough theory available to provide reasonably correct interpretations of data that are characteristically incomplete in coverage and often imprecise in detail. Much has been learned about how effects of events on the Sun are conveyed to Earth by the interplanetary medium; and much has been learned about the dynamical behavior of rarefied ionized gases. Study of the discrepancies between theory and observation is providing the inspiration to extend the theoretical analyses to include many features, such as those that involve effects of anisotropies, instabilities, waves, discontinuities, and other fluctuations possible in an ionized rarefied conducting medium, that are beyond the reach of the current theories based on magnetohydrodynamics or gas dynamics. Multicomponent collisionless plasma theory holds promise of providing understanding of many of these, but the required theory is much more complicated and far less developed for relevant flow configurations than the fluid theories reviewed here. Finally, perhaps the most intriguing fundamental question relates to the underlying reasons for the success of the continuum theories in dealing with the most rarefied gas presently accessible to direct measurements. Its proper resolution must be ranked among the more important goals to be achieved if the environment provided by interplanetary space is to fulfill its often expressed potential as a new laboratory for the study of rarefied plasmas. We thus conclude with the observation that the study of interplanetary dynamical processes provides both a new field of application for rarefied gasdynamics, and the opportunity to obtain deeper insight into the foundations of the subject itself.

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