Extension of the Solar Corona into Interplanetary Space

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I shall first write down a number of observational facts, and then in another column compare them with the results of the theoretical program we have been carrying out at Chicago over the past few years. The purpose of this comparison will be to suggest experiments, some of which are already in progress, and which will perhaps resolve a few of the difficulties in our present knowledge of the dynamics of the interplanetary medium.

I shall start with the sun, since we believe, as Gold and others have pointed out, that it is the source of energy for all phenomena observed in the earth, in particular magnetic storms and auroras, and the source of energy for all the churning that apparently occurs in interplanetary space. Let me list a few basic facts about the sun that seem most pertinent to the problem.

On the one hand, there is the solar corona, whose density at a height of $3 \times 10^6$ km may be $3 \times 10^7$ atoms/cm$^3$. The corona is rather hot; active regions in the corona have temperatures, as determined by the Doppler widths of emission lines, of the order of 2 to 4 million degrees Kelvin. It is hardly necessary to point out that at these temperatures the gas will be completely ionized.

The temperature observations which I quote here are determined only near the sun where the solar corona is sufficiently dense that its emission is visible. Very roughly the temperatures have been determined out to 3 solar radii. Beyond that distance the temperature can only be inferred indirectly, and the degree of uncertainty becomes very great.

Somewhat farther out from the sun than the corona itself, in the region where comets are observed, at the distance of Mercury or farther, there is some additional information. Biermann has been investigating over some years now the dynamics of comet tails. In observations on the small knots in the tails of the comet he finds that they experience rather extreme outward accelerations from the sun, much too large to be explained by radiation pressure. Hence, he has inferred that there must be corpuscular streams blowing outward from the sun, which sweep the comet tails away and give the observed acceleration. These same corpuscular streams from the sun that are needed to account for the acceleration of comet tails seem also to be necessary and sufficient for producing the observed ionization and excitation of nitrogen and carbon monoxide in the tails.

In the sense of these indirect inferences Biermann observes gas moving outward from the sun. When the sun is not particularly active, he observes velocities of the order of 500 km/sec and densities of the order of 100 particles/cm$^3$ at the orbit of the earth. When the sun is more active, he observes an increase in the velocity of the streams to perhaps 1500 km/sec, and a density of perhaps $10^4$ particles/cm$^3$. This last estimate is very rough.

As has been pointed out in a previous paper, the gas is ionized and a good conductor of electricity, and therefore conveys with it whatever magnetic fields are present.

The Babcocks, looking at the Zeeman effect in certain photospheric lines, find that the sun has, at least toward the polar regions, a dipole-like field of about 1 gauss. They find that the equatorial magnetic field on the surface of the sun is also of the order of 1 gauss, but rather disordered. Let me note then that there is a field everywhere over the sun, and usually of about 1 gauss. Near the poles the field looks very much like a dipole. You are all familiar with the pictures of coronal tongues streaming outward from the polar regions, suggesting again that there is a field resembling that of a dipole.
near the poles and becoming radial at larger dis-
tances.

An interesting piece of data has been reported
recently by Hewish in observations on the scat-
tering of radio-frequency signals from the Crab
nebula. While the Crab is in transit past the
sun, Hewish can observe the scattering out to
about 20 solar radii, or a tenth of the distance
to the earth. As far out as he can observe, he
finds that the solar magnetic field is radial. In
other words, the radial coronal streamers ap-
parently extend out 20 or more solar radii.

Some further information that can be gained
about the magnetic field even farther from the
sun than 20 solar radii comes from observations
of cosmic rays. In particular, there is the well
known event of February 23, 1956, in which
the cosmic-ray intensity increased by a factor
of 200. The additional cosmic rays clearly came
from a flare on the sun. The implications in the
manner of arrival of the particles from the sun
are very interesting.

The cosmic-ray intensity rose sharply to its
peak value at the moment of arrival of the
flare particles, and then in a period of an hour
began a slow decay. After 20 to 40 hours, de-
pending on the latitude of observation, it had
dropped to normal.

The fact that the onset of these particles was
so extremely sharp indicates that they must
have come directly from the sun. No impeding
magnetic field existed to separate their transit
times. Therefore one infers that the radial field
observed by Hewish at 20 solar radii extended
in this case at least to the orbit of the earth.

Examination of the decay part of the cosmic
ray indicates that it did not drop off exponen-
tially, but like \( t^{-3/2} \). This power law is
a familiar one. Let us suppose that after the
flare the excess cosmic rays were somehow
trapped in the solar system, as must have hap-
pened, because they continued to arrive for
some 30 hours after the flare which produced
them had entirely disappeared. Then suppose
that the trapping mechanism disintegrates by
some process of diffusion. A simple solution is
obtained to the diffusion equation in which in-
tensity drops off as \( t^{-3/2} \) if the cosmic-ray par-
ticles are released in the center of a large three-
dimensional space filled with a medium that
impedes their flow.

Specifically, the cosmic rays were released at
the sun and came quickly to the earth. If out-
side the orbit of the earth there was a very
thick diffusing shell, the intensity at the earth
would drop off as \( t^{-4/3} \). But no shell is infinitely
thick, and when the particles finally reach the
outer surface of the shell it can be shown that
the solution to the diffusion equation turns
down into an exponential decrease. From the
point where the cosmic-ray intensity was ob-
served to turn down into a steeper decrease, it
may be determined that the shell extended out
to the orbit of Jupiter in the event of February
23, 1956. The inner surface of the shell was
placed at roughly the orbit of the earth or Mars.
The thickness of the shell was therefore 5 astro-
nomical units. If we assume a field strength of
10^{-4} gauss, and a scale of 10^{6} km for the disor-
organized regions in the field, we arrive at the
correct rate of diffusion.

This is the history of one of the great cosmic-
ray solar flares. As Gold mentioned, there are
other flares of more modest type. They do not
produce 10-bev particles, but rather a large
number of protons of 10 Mev. The particles
from these flares also come unimpeded from the
sun, again suggesting a radial magnetic field.
Again they seem to be stored for fairly long
periods of time, as though by an imperfect
barrier.

These are the observational facts that I con-
sider most relevant to the problem of the in-
terplanetary gas. Now let me present a brief
summary of theoretical results. I shall begin
with the solar corona, which is the prime mover
for the interplanetary medium.

It has been pointed out that the temperatures
in the solar corona are extremely high. When
we write down the barometric equations for the
corona, we find that the pressure does not van-
ish at infinity, suggesting that the solar corona
must expand continually into space. Therefore,
we add the term \( v \, dv/dr \) to obtain the hydro-
dynamic equation of motion for the corona. The
equation is nonlinear, but it may be solved on
the assumption of spherical symmetry in the
corona. It is not spherically symmetric; let me
make that clear. In fact, there are irregular re-
gions of activity in the corona, but the mathe-
matics cannot be carried through if these irreg-
ularities are included. I shall also assume that
the solar corona is isothermal radially.

On these assumptions, I have calculated the
velocity of the outward expansion of the solar corona, and the resulting gas density at the orbit of the earth. Results of the calculations shown in Figure 1 indicate that, if the solar corona has a temperature of $2.5 \times 10^6 \ °K$ to a distance of ten solar radii, then the velocity of the outward expansion will be slightly in excess of 500 km/sec and the density at the orbit of the earth will be a few hundred ions per cubic centimeter, as observed. This velocity agrees well with the outward expansion of the solar corona observed by Biermann. I suggest therefore that the corpuscular streams of Biermann are merely hydrodynamic expansion of the solar corona. In view of the simple hydrodynamic origin of the expansion, it seems appropriate to term the stream a solar wind.

Since the gas of the solar wind is ionized, it will carry with it the lines of force of the general solar magnetic field. Thus it would seem also to account for the radial fields inferred from the observed propagation of solar cosmic rays in interplanetary space, and inferred also from the radio observations of the Crab nebula carried out by Hewish.

The sun rotates, of course, so that the field is not entirely radial. Figure 2 sketches the degree of spiraling of the field for a solar wind with a velocity of 1000 km/sec.

The field at the orbit of the earth is very nearly radial. At the orbit of Jupiter, the opposite is true. The field is rather tightly spiraled. The field is unstable, because of the anisotropic expansion of the gas as it comes out from the sun. The collision rate is extremely low; hence if the gas expands in directions perpendicular to the radius, but not in the radial direction, its thermal motions become anisotropic and the gas itself becomes unstable. The field becomes disordered. Inserting reasonable parameter values, one finds as a rough result that the field should become disordered between the orbit of Venus and the orbit of Mars.

The field strength, extrapolated outward radially from the sun, and starting with 1 gauss at the sun, gives $2 \times 10^{-4}$ gauss at the orbit of earth. The characteristics of the instability being known, it may be predicted that the scale of the disordering should be $10^6$ km.

We then look back at our earlier inference on the size of the disordered regions in the field deduced from the cosmic-ray data, and we find that there is agreement between our earlier results and the present calculations on the solar
wind. Apparently we live inside the thick shell of a tenuous disordered field, extending from the orbit of the earth to the orbit of Jupiter. The fact that the disordered field is being convected outward by the solar wind, at 500 to 1500 km/sec, should have some effect on the cosmic-ray intensity. We believe that most of the cosmic rays come to us from interstellar space, and to get to the earth they must come through the disordered shell. Yet, if they are continually being swept outward by that shell, their intensity should be decreased inside the shell, that is, in the vicinity of the earth.

By assuming that the particles walk randomly through the disordered field, we obtain a diffusion equation that is easily solved. Figure 3 gives the results of the calculations for a solar wind of 1000 km/sec. The upper curve is the differential cosmic-ray spectrum at solar minimum, when the sun is relatively inactive, and we probably see a spectrum resembling that of the true galactic cosmic rays. The lower solid curve is the observed cosmic-ray spectrum during the years of peak solar activity. We see that the intensity, particularly at low energies, is very much depressed.

The vertical arrow indicates where the cosmic-ray intensity seems to cut off very sharply. The broken line represents the theoretical depression of the upper curve, the galactic cosmic-ray energy spectrum, by a 1000 km/sec solar wind in the disordered field beyond the orbit of the earth. It resembles the spectrum observed during times of solar activity. Hence this may be the origin of the 11-year cycle in the cosmic-ray intensity.

One may ask how these theoretical proposals can be tested. I think the most crucial piece of evidence will come not too long from now through observations that are being planned by Professor Rossi at MIT. Rossi proposes to measure directly the gas blowing outward from the sun, by a plasma probe to be flown in a vehicle included in the NASA program. The apparatus will determine the density and energy spectrum of both ions and electrons by a sophisticated form of ion trap. The observations will tell us in detail the solar wind velocity, density, temperature, and time variations. We should be able to proceed with a more elaborate theoretical model than the spherically symmetric one already treated.
A second important experiment is the accurate determination of the cosmic-ray variation. The cosmic rays vary with the 11-year-cycle. I have suggested very tentatively that this may be a heliocentric phenomenon, that is, that the variation probably occurs over the entire inner solar system. However, other events, such as the Forbush decrease, appear to be local phenomena. For example, the Forbush decrease shows geographical irregularities, and therefore at least a part of it must be geocentric. Webber, at Maryland University, who has been studying the observational data, suggests that the Forbush decrease may be a combination of heliocentric and geocentric effects. It would be very interesting to have detectors spaced near the earth and at various distances out from the earth to determine the precise separation of cosmic-ray variations into geocentric and heliocentric phenomena.

In the remainder of this paper I shall discuss the terrestrial effects of the solar wind.

I should like to note first that a solar wind blowing outward from the sun must exert a pressure against the geomagnetic field, inasmuch as the ionized gas of the solar wind is unable to penetrate the field.

Next, I should like to note the instability of the interface between the geomagnetic field and the solar wind. Suppose that the magnetic field is confined to the region below a certain plane, above which there is a beam of ions representing the solar wind. If the plane surface is then perturbed it can be shown that waves will appear in the surface and grow with time, displaying the analogue of the classical Helmholtz instability. A detailed investigation of the instability indicates that the waves in the surface of the geomagnetic field will have a velocity comparable to the solar wind velocity. The wavelength will be only slightly larger than the Larmor radius of the particles in the geomagnetic field, i.e., a few hundred kilometers.

If the outer surface of the geomagnetic field is unstable, it follows that the region of the interface will be disordered. One may then ask, to what extent will the gas from the solar wind disorder the field and push aside the lines of magnetic force, and how deeply will the solar wind insert tongues of gas between the lines of force of the geomagnetic field?

A rough estimate may be obtained by supposing that the tongue can probably penetrate to that depth in the geomagnetic field where geomagnetic pressure is equal to the wind pressure. With this assumption one finds that the normal solar wind, which has a velocity of 500 km/sec at a density of 100 particles/cm², can penetrate no deeper than to within 5 earth's radii from the center of the field. Outside 5 earth's radii the field must be strongly agitated. The enhanced solar wind of 1500 km/sec and 10⁹ particles/cm² can penetrate to within perhaps 2 earth's radii.

Now consider what might happen to an individual proton in the region of disordered fluence.

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**Fig. 4**—Comparison of the particle spectrum derived from the Fermi acceleration mechanism (calculated) with the observed primary auroral proton spectrum (observed). \( T_w \) is the kinetic energy of an ion moving with the velocity of the solar wind, in this case taken as 2000 km/sec.
tuations of the penetrating tongues. We expect that the Fermi mechanism will be operating. Since we cannot write down the field in detail, we cannot give a rigorous result for what will actually happen to the particle. But we can put a lower limit on the acceleration that will take place by representing the transition region between the geomagnetic field and the solar wind as a simple smooth shear in which ropes of magnetic flux are embedded. The calculated curve in Figure 4 shows the results of a calculation based on the above model. It is derived from a Fokker-Planck equation wherein the particles are random-walked out of the region while they are simultaneously undergoing Fermi acceleration. The curve in Figure 4 is based on a high solar wind velocity of 2000 km/sec.

The observed curve in Figure 4 represents the spectrum of primary auroral spectrum for protons as deduced by Chamberlain from observations of the aurora. The agreement between the two curves is reasonably good and suggests that the proposed mechanism may indeed be the origin of the auroral particles.

The Fermi mechanism does not appear to accelerate electrons by interesting amounts. But there is another mechanism, involving a plasma interaction, wherein the gas from the solar wind, mixing with the gas carried by the geomagnetic field, sets up strong velocity fluctuations in which the electrons receive about half of the ion energy. In this way the kinetic energy of the ions in the solar wind may be converted into the energy of individual electrons, suggesting as an order of magnitude the generation of 20-kv electrons in the interface between the solar wind and the geomagnetic field.

It is interesting to note that the energetic electrons and protons generated in the interface between the geomagnetic field and the solar wind will move freely along the geomagnetic field lines. Since the interface is located at 5 earth's radii, and the field lines passing through the equator at that distance intersect the surface of the earth at a latitude of 65°, we may expect that these particles produced by Fermi acceleration will be concentrated in a belt at 65°, which is in fact the center of the auroral zone.

There seems, then, to be a simple connection between the auroral latitudes and the depth to which the solar wind can penetrate in the geomagnetic field. The Fermi acceleration of particles occurring in the disordered interface between the magnetic field and the solar wind may account for the primary auroral properties, and plasma interactions may perhaps account for the electrons that participate in auroral activity.

It will be noticed that tongues of magnetic field from the sun have not been mentioned, although they play an important role in the consideration of Professor Gold. I believe that these tongues will not accomplish the objectives Gold has set out for them. He thinks oppositely. We will spare you the debate, because an experiment may be proposed to settle the issue. If we were to set up an observing station between the earth and the sun, at least as distant as the moon, we could detect the particles in transit from the sun to the earth, study the structure of the shock waves at the fronts of the expanding gas clouds, and perhaps measure magnetic field strengths.

But in particular, with regard to the question of the magnetic tongues, the particles should be detected at the outer station before they arrive at the earth, and, if the cloud is moving at 1000 km/sec and the station is at the orbit of the moon, they will be seen 4 minutes before they reach the earth. On the other hand, if, as I have suggested, there are no magnetic tongues, and particles simply come from the sun whenever they are on the right lines of force—remembering the solar field to be radial—then the delay time will not be 4 minutes, but rather a time appropriate to the actual velocities of the particles. For example, 10-Mev particles move at a speed of 50,000 km/sec and will traverse the moon-earth distance in 8 seconds.

A second experiment of value would be one concerned with the Forbush decrease. I have previously suggested that measurements of the cosmic-ray intensity at several distances from the earth would permit a separation of geocentric and heliocentric modulating factors. The value of these observations would be greatly enhanced if they could be supported with simultaneous magnetic field measurements at each space station, since most theories of the decrease agree in attributing them to magnetic fields, but the configuration and mode of opera-
tion of the fields are open questions. In general it is very important to support particle measurements with magnetic field observations.

**Discussion**

**Question:** One of the fascinating problems introduced by both of the previous speakers concerned the question of whether the motions of the solar wind or corpuscular radiation are indeed radial from the sun or whether they are spiraling in shape because of the rotation. Comets can give the answer to this question.

The second point is a suggestion in the placing of observing stations. There may be a use for the Lagrangian point in orbits between the earth and the sun, about 1.4 million miles from the earth.

**Question:** There is a second mechanism for feeding the Van Allen layer, which also depends on the solar wind. This is a simple scattering of the solar-wind protons in the outer atmosphere. When the scattering is through an angle of 10° or so, the particles are injected into trapped orbits with high efficiency.

Of course, the soft particles that have been detected in the outer layer are probably electrons. There may be 10-kv protons, however, because these could not be detected with the instrumentation flown thus far.

In the course of time a circulating belt of trapped 10-kv protons would accelerate the electrons in the outer atmosphere to comparable energies. We estimate the time required for such acceleration to be about 10 hours, which is reasonable.

So we believe that this very simple scattering mechanism, together with the hypothesis of the solar wind, can provide an adequate injection rate into the outer layer.

With respect to the inner layer, it is difficult to understand why, in times of unusual solar activity, the oncoming cloud does not perturb the earth's field sufficiently to feed soft particles directly into the inner layer. The population of the inner layer will then decay until replenished by another burst of solar activity without calling on the convection mechanism.

**Mr. Gold:** I do not understand why that would make a maximum. I could understand why the process would bring them down to the inner zone, but not why it would produce a separation between the zones.

I should like to ask Professor Parker what shape he does think would result in the magnetic field if a magnetized region, such as we know to be responsible for a solar outburst in the chromosphere—not in the corona—explodes, in addition to the configuration that he has been discussing in connection with the coronal outstream?

What will be the superposition of fields if we take a magnetic region in the close vicinity of the sun, in the chromosphere, where an outburst occurs such as we see, and material is flung out?

**Mr. Parker:** In the first place, the configuration will depend on the circumstances under which that explosion occurs. But to answer your question, let me construct what I think you have in mind. Consider the surface of the sun, and suppose that there is a field associated with a sunspot or some other active region, a fairly strong field, in excess of 1 gauss.

Suppose that underneath this there is an explosion which blows particles into space. I think this is what you have in mind. In that case, after the explosion, the lines of force will have just the configuration that you indicated in your drawings.

The question is now: will this configuration accomplish the objectives you proposed?

**Mr. Gold:** This will merely replace the other field that was previously there, will it not?

**Mr. Parker:** It will displace the radial field.