JOURNAL OF RESEARCH of the National Bureau of Standards—D. Radio Propagation
Vol. 65D, No. 6, November–December 1961

The Solar Wind [1]

E. N. Parker

Contribution from Enrico Fermi Institute for Nuclear Studies and Department of Physics, University of Chicago, Chicago 37, Ill.

(Received June 19, 1961)

Hydrodynamic expansion of the solar corona is the basis for "solar corpuscular radiation." The quiet day coronal temperatures of 1 to 2×10^6 °K yield a solar wind of several hundred km/sec and a density of 5 to 50 particles/cm^3 at the orbit of Earth. The solar wind draws out into space the lines of force of the general one-gauss solar field, to give an interplanetary field that is basically spiral in character with a density of the order of a few times 10^{-5} gauss at the orbit of Earth. The enhanced corona may sometimes have temperatures of 4×10^6 °K or more immediately following a large flare. Such explosive heating leads to a 1 to 2×10^3 km/sec blast wave into planetary space. The blast wave sweeps up the quiet-day solar wind ahead and kinks the quiet-day field, raising the density of the field to several times 10^{-4} gauss on some occasions. The galactic cosmic ray particles are swept back by the kink, producing a Forbush-type intensity decrease. Altogether, the blast wave and its magnetic field constitute the "enhanced solar corpuscular radiation."

It is shown that the alternative magnetic tongue model of Gold and others [1960] is untenable because the "tongue" would not reach the earth until many hours after the arrival of the blast wave.

1. Introduction

It was pointed out several years ago [Parker, 1958a] that the solar corona is too hot to be confined by the solar gravitational field. In place of the older view of the corona as an extended, but static, atmosphere it was shown that the corona must expand continually into space. A study of the hydrodynamic equations showed that the solar corona is steadly expanding with a velocity that is only a few kilometers per second in the lower corona but which becomes supersonic at large distances from the sun. The result is a continuing outward flow of coronal gas through interplanetary space, which we have called the *solar wind* to emphasize its hydrodynamic nature. The observed quiet-day coronal temperatures of 2×10^6 °K indicate that the quiet-day solar wind velocity is of the order of 150 to 500 km/sec. The density of the solar wind at the orbit of Earth is determined by the existing temperature observations to lie in the range 5 to 200 atoms/cm^3. Thus the quiet-day solar wind represents a proton flux in the range 10^8 to 10^{10}/cm^2 sec at the orbit of Earth.

Some time before these calculations were made it had been pointed out by Biermann [1951, 1952, 1957] that the observed outward acceleration and the observed ionization and excitation of type I comet tails can be explained only as the result of continuing quiet-day solar corpuscular radiation. He originally estimated that the corpuscular flux was of the order of 10^{10} protons/cm^2 sec at the orbit of Earth, recently [Biermann, 1960] revising the estimate downward to 10^9 protons/cm^2 sec on the basis of laboratory measurements of the appropriate charge exchange cross sections.

Upon completion of the solar wind calculations it was at once obvious that Biermann's solar corpuscular radiation was in fact the hydrodynamic solar wind from the steadily expanding corona.

There are many other phenomena, such as the aurora, geomagnetic activity, etc., which are conventionally ascribed to solar corpuscular radiation. They too are the consequence of the solar wind. On an interplanetary scale the solar wind is hydrodynamic, but on a planetary scale its low density renders it corpuscular in many respects.

Since this first identification of solar corpuscular radiation with the expanding corona, we have explored a number of consequences of the solar wind [Parker, 1958 b, c; 1960, 1961 a, b]. It now appears that the solar wind is the dominant interplanetary dynamical force and is responsible for the interplanetary magnetic field configuration, the observed modulation of the galactic and solar cosmic ray intensity, the quiet day and the enhanced geomagnetic activity, etc.

Recent direct observation of the solar wind near Earth [Bridge, 1961] has determined its quiet-day velocity to lie in the range 250 to 400 km/sec, with a density of 10 to 20 protons/cm^3. The total flux is of the order of 0.5×10^9 protons/cm^2 sec. An observation of the quiet-day solar wind in January and September of 1959 had been reported earlier by Shklovskii et al. [1960] to suggest a flux of 0.2×10^9 protons/cm^2 sec, but the rather large corrections that had to be applied to the data make it uncertain as to how meaningful the flux estimate really was.

[1] Paper presented at 1961 Spring meeting of the URSI, Washington, D.C.

2. The Expanding Corona

2.1. Quiet Sun

The simplest model of the quiet corona is one which assumes spherical symmetry about the center of the sun. Then if r is the radial expansion velocity as a function of distance from the center of the sun, the hydrodynamic equation for stationary expansion is

$$v\frac{dv}{dr}+\frac{1}{NM}\frac{dp}{dr}+\frac{GM_\odot}{r^2}=0, \qquad (1)$$

where N is the number of atoms per unit volume, G is the gravitational constant, and p is the hydrostatic pressure. Since the coronal gases are fully ionized and largely hydrogen, M is the mass of the hydrogen atom and the hydrostatic pressure is $p\simeq 2NkT$. Conservation of mass requires that

$$Nvr^2=N_0v_0a^2 \qquad (2)$$

where the subscript zero denotes the value at the reference level $r=a$. Choosing $a=10^6$ km, N_0 is of the order of $10^7/\mathrm{cm}^3$. It will be sufficient for our purposes here to discuss the simple case of an isothermal corona. The more general case has been considered elsewhere [Parker, 1960].

For an isothermal corona, $T=T_0\simeq 2\times 10^6$ °K, and (1) can be integrated to give

$$\frac{1}{2}(v^2-v_0^2)-\frac{2kT}{M}\ln\frac{v}{v_0}-\frac{4kT}{M}\ln\frac{r}{a}+\frac{GM_\odot}{a}\left(1-\frac{a}{r}\right)=0 \qquad (3)$$

upon using (2) to eliminate N. The result is a one parameter family of curves $v(r)$ for any given value of T_0, with v_0 as the parameter. The general form of the family is sketched in figure 1. The solution of physical interest is the solution starting from the origin and passing up through the critical point to supersonic velocity at infinity. The coordinates of the critical point are (v_c, r_c) where

$$\frac{1}{2}Mv_c^2=kT,\quad GM_\odot M/r_c=4kT. \qquad (4)$$

The value of v_0 for this solution is the lower positive root of

$$\frac{Mv_0^2}{2kT}-\ln\frac{Mv_0^2}{2kT}=-3+\frac{GM_\odot M}{akT}-4\ln\frac{GM_\odot M}{4akT} \qquad (5)$$

The coronal expansion will automatically drift into this solution whatever its initial expansion rate. The solutions with smaller v_0 go to $r=\infty$ on the lower branch of $v(r)$, which can be maintained only by a large inward pressure from $v=\infty$. In the absence of such an inward pressure the expansion will accelerate to the solut on through the critical point. There are no solutions above the solution through the critical point which start at the origin. Thus, the only available solution for expansion in the absence of an inward pressure at $r=\infty$ is the solution through the critical point, which starts with the velocity v_0 given by (5). It has been pointed out by Clauser [1960] that this expansion of the corona is analogous to the expansion of a gas through a Laval nozzle, with the gravitational field playing the role of the throat.

The expansion velocity as a function of radial distance is shown in figure 2 for a number of coronal temperatures. The observed coronal temperatures are of the order of 2×10^6 °K [Billings, 1959], but even low temperatures like 1×10^6 °K give solar wind velocities of the order of several hundred kilometers per second.

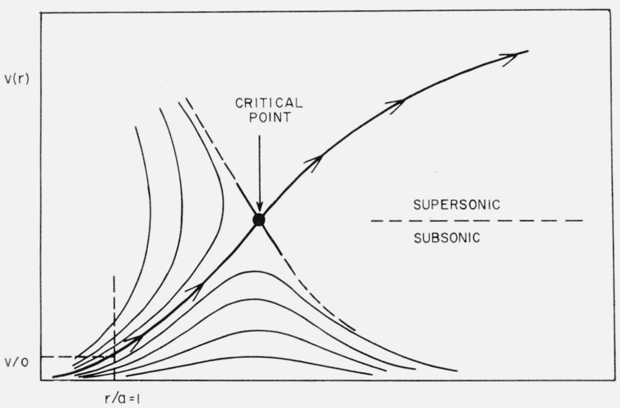

Figure 1. *The family of solutions of equation (3) for a given coronal temperature T_0.*

The solution of physical interest is the one passing through the critical point, given by eq (4). The critical point is analogous to the point of sonic transition in a Laval nozzle.

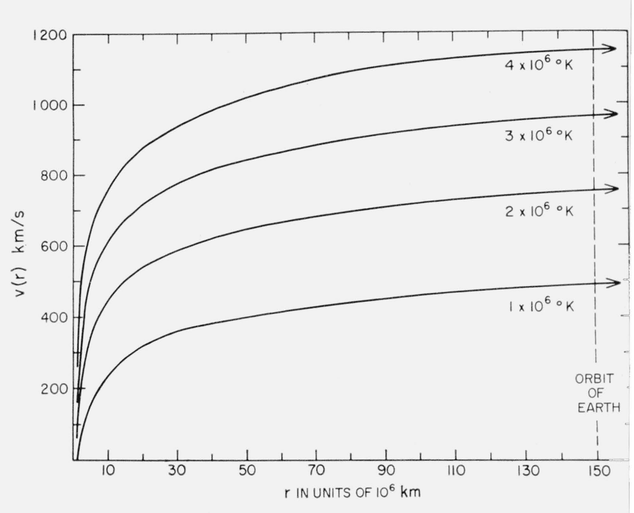

Figure 2. *The steady expansion velocity as a function of radial distance for a model isothermal corona.*

The two lower curves, for 1 and 2×10^6 °K, are applicable to the quiet corona. The upper curve, for 4×10^6 °K, gives an indication of the rate of expansion of the enhanced corona.

2.2. Active Sun

It is observed that following a large solar flare the coronal temperature over the general region of the flare may increase to 4×10^6 °K or more [Christiansen, Yabsley, and Mills, 1949; Christiansen and Warburton, 1953]. The result is a hydrodynamic explosion of the corona outward into space. The expansion velocity may be in excess of 1000 km/sec, as is evidence from figure 2. The asymptotic form of the resulting blast wave from the sun may be treated using the similarity transformations of the progressive wave [Courant and Friedrichs, 1949]. The idealization is made that the corona has spherical symmetry; i.e., the entire corona is heated to 4×10^6 °K, rather than the portion over the active region in which the flare occurred. The 300 km/sec velocity of the quiet day solar wind ahead of the blast wave is neglected, and the temperature of the quiet day wind is assumed to be so small that the 10^3 km/sec velocity of the blast wave represents a very high Mach number. The resulting blast wave profiles are shown in figure 3. The shock transition at the front is of the collisionless type and involves a density increase by a factor of four above the quiet-day value. The shape of the blast wave behind the shock transition depends upon how hard the enhanced corona pushes from behind. In the event that the corona should push so hard that the energy of the blast wave increases linearly with time after leaving the sun, then the relatively thin, high-density profile identified by $\lambda=1$ in figure 3 is the result. If the corona should not push at all once the blast wave is on its way, then a linear decrease of density behind the front is the result, identified by the sawtooth profile for $\lambda=3/2$ in figure 3. In either case an enhanced coronal temperature of 4×10^6 °K near the sun yields a blast wave with a velocity of $1\text{–}2\times10^3$ km/sec, and a density of the order of 10^2 cm^3 at the orbit of Earth [Parker, 1961, a and b]. Thus the blast wave represents the "enhanced solar corpuscular radiation" responsible for the geomagnetic storm, the Forbush decrease, etc.

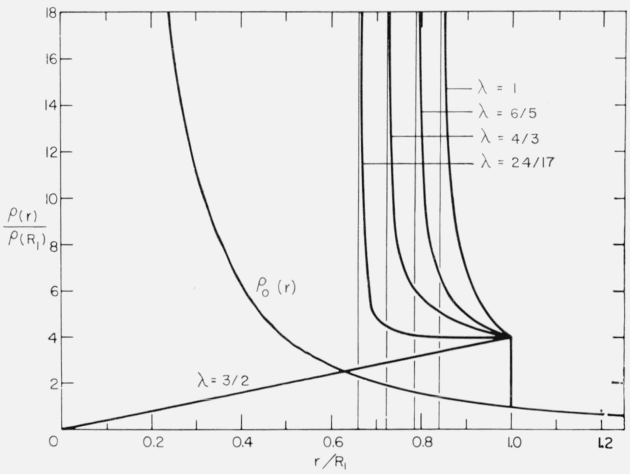

FIGURE 3. *Blast wave profiles from the active corona.*

The quiet day solar wind density is given by $\rho_0(r)$, and is essentially proportional to $1/r^2$. The shock transition at the head of the blast wave is at $r=R_1$, where the density jumps by a factor of four from the quiet day value. The parameter λ is an inverse measure of how strongly the enhanced corona is driving the blast wave from the rear: If the corona does not push at all on the blast wave, then $\lambda=3/2$ and the sawtooth profile is the result; if the corona pushes so hard that the energy of the blast wave increases linearly with time, then $\lambda=1$ and the blast wave lies between $r/R_1=0.84$ and $r/R_1=1.0$.

An important point to be noted is that the blast wave consists of gas which had already left the sun before the occurrence of the flare. It is material which has been swept up as the wave advances outward into space. The material in the corona at the time of the flare is behind the rear of the blast wave profile. This must be borne in mind in the next section when we discuss the interplanetary magnetic field configuration.

3. Interplanetary Magnetic Fields

3.1. Quiet Sun

The magnetic fields in interplanetary space are composed of the magnetic lines of force of the general solar field [Babcock and Babcock, 1955; Babcock, 1959] which are pulled outward from the sun by the expanding corona. The magnetic fields associated with active regions on the sun are usually considerably in excess of 1 gauss, so that they can to a large degree withstand the expansion of the local corona, remaining fixed over the active regions. The hydrostatic pressure in the solar corona is of such an order, 10^{-2} dynes/cm^2, as to suggest that only fields of the order of one gauss can be extended by the solar wind. The simplest model, then, is one in which a corona with spherical symmetry expands outward, carrying with it the dipole-like fields of the polar regions of the sun. Such an idealized picture ignores the many complications of the disordered one gauss fields which are undoubtedly carried outward from the equatorial regions. The idealization also ignores the many interesting complications that result from the fact that the actual corona expands more rapidly and densely in some directions than in others. However, the idealization of a radial solar wind with spherical symmetry in a dipole field serves to illustrate the general principles and to give a rough idea of the overall interplanetary magnetic configuration to be expected. When more comprehensive observations allow greater detail to be filled into the present simple theoretical models, the many irregularities and swirls which undoubtedly exist in the interplanetary field may be taken into account. Ignoring the irregularities now will give a conservative estimate of the cosmic ray effects to be discussed in the next chapter.

The lines of force of a general solar dipole field represent the two parameter family of curves

$$r-a\simeq\frac{\gamma}{\Omega}(\phi-\phi_0),\ \theta=\theta_0$$

upon extension into space by the quiet day solar wind of velocity γ. The solar angular velocity Ω is

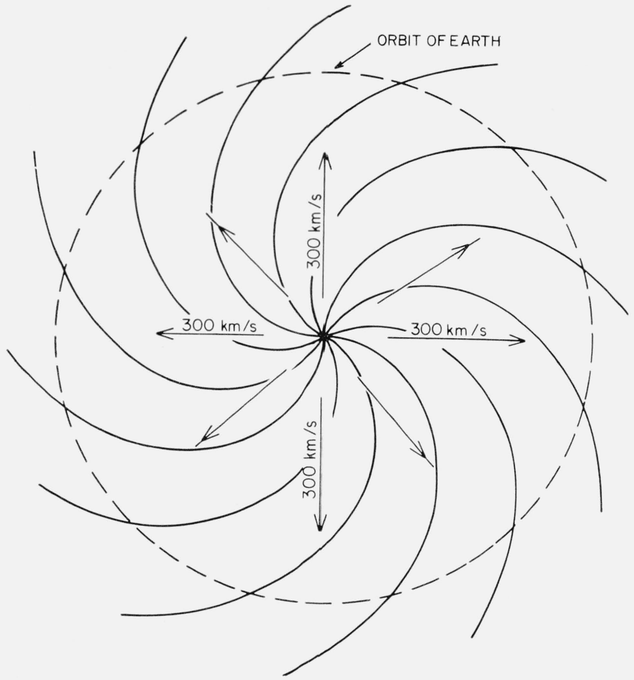

FIGURE 4. *Projection onto the equatorial plane of the lines of force of the solar fields extended by a quiet-day radial solar wind of 300 km/sec.*

approximately 2.6×10^{-6} radians/sec, and (θ_0, ϕ_0) is the position, in spherical polar coordinates, of the intersection of the line of force with the reference level $r-a$ in the lower corona. The radial component of the field is

$$B_r(r, \theta)=B_r(a, \theta)\left(\frac{a}{r}\right)^2,$$

the meridional component is zero, and the azimuthal component is

$$B_\phi(r, \theta)=B_r(a, \theta)r\Omega/v.$$

Projection of each line of force onto the solar equatorial plane is an Archimedes spiral, shown in figure 4 for $\gamma=300$ km/sec. It is readily seen that the field is principally radial inside the orbit of Earth and principally azimuthal beyond. One gauss at the solar photosphere yields about 2×10^{-5} gauss in the radial direction at a distance of one astronomical unit.

3.2. Active Sun

The quiet-day interplanetary field shown in figure 4 is deformed by the blast wave from the corona over a flare as shown in figure 5. Again the case $\lambda=1$ represents the situation when the enhanced corona is pushing hard on the rear of the blast wave, and $\lambda=3/2$ when the blast wave is coasting. In either case the field may reach 10×10^{-5} gauss at the front of the wave. When the corona is pushing hard on the rear of the blast wave the field toward the rear may easily be 40×10^{-5} gauss or more.

It has been suggested that the "enhanced solar corpuscular radiation," which we suggest is a hydrodynamic blast wave from the corona, sometimes draws out a loop of field from the active region, giving a magnetic tongue which is responsible for many of the effects associated with the enhanced corpuscular radiation (see discussion and references in Gold, 1960). Presumably the expanding interior of the magnetic tongue is partially shielded by the fields of the tongue from the galactic cosmic ray intensity, giving the Forbush-type cosmic ray decrease in coincidence with the geomagnetic storm resulting from the impact of the gas in the tongue against the geomagnetic field; once the tongue has engulfed Earth, it affords free access of solar protons from the sun to Earth; the tongue stores the solar protons following the emission from the sun, etc. In this way it has been argued that the tongue explains most of the observed cosmic ray phenomena associated with "enhanced solar corpuscular radiation."

We object to the tongue model of the interplanetary field on a number of points. First of all, the magnetic configuration of the blast wave fields shown in figure 5 possess the same properties as the tongue so far as modulating and channeling galactic cosmic rays and solar protons. Thus the tongue is not unique and seems an unnecessary complication. Second, and more serious, is the objection that the tongue cannot possibly arrive at Earth with the "enhanced solar corpuscular radiation." Whatever the nature of the outburst on the sun which leads to the enhanced radiation, the result is a blast wave which scoops up the interplanetary gas ahead to form a wave as shown in figure 3. The active coronal material is behind the blast wave, and hence so is the magnetic tongue which the coronal material is supposed to carry. Even in the extreme case that the enhanced corona is pushing so hard on the rear of the blast wave that $\lambda=1$ (which requires that the 10^6 °K coronal temperatures extend all the way to the rear of the wave) the tongue is 0.16 a.u. behind the front of the blast wave, which means a delay of the order of 6 hr in the arrival of the tongue. Yet it is clear in many cases that the cosmic ray modulation etc., begins with the first onset of geomagnetic activity. The tongue configuration is shown in figure 6 for the special case that $\lambda=3/2$. The tongue extends barely beyond the orbit of Mercury when the blast wave reaches the orbit of Earth.

4. Cosmic Ray Modulation

4.1. Quiet Sun

The general outward flow of nonradial magnetic fields from the sun tends to push back the galactic cosmic ray particles and thereby decrease the cosmic ray intensity in interplanetary space below the interstellar level. This reduction follows the general solar cycle and is usually referred to as the 11-year variation. There are many individual effects which probably contribute to the total reduction: the ideal-

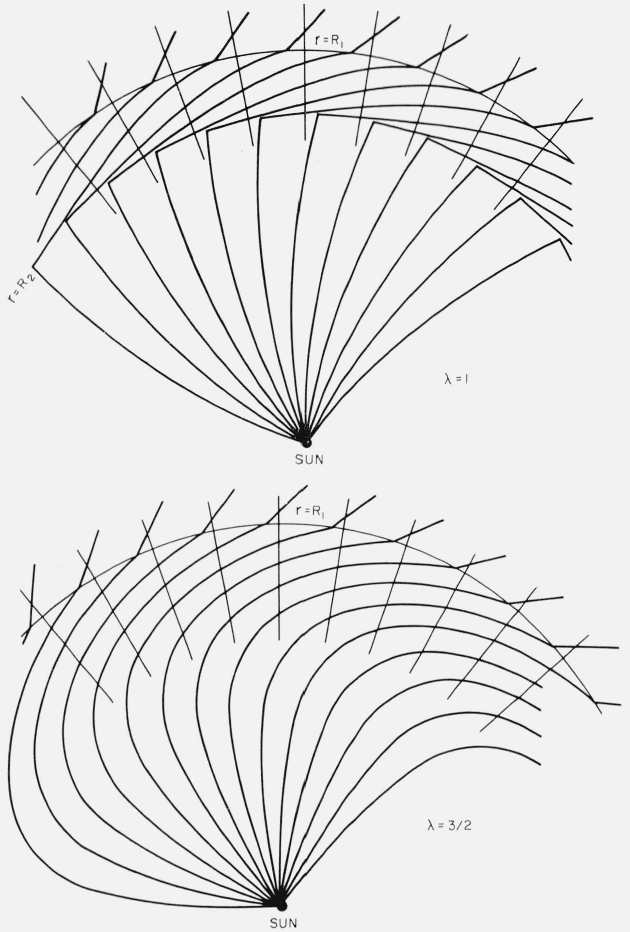

FIGURE 5. *Deformation of the quiet-day field shown in figure 4 by the freely coasting blast wave, $\lambda=3/2$, and by the driven blast wave $\lambda=1$.*

The shock transition is at $r=R_1$. The rear of the blast wave is at $v=R_2$.

ized quiet-day interplanetary field shown in figure 4 is, in effect, a giant corkscrew conveyor which revolves once every 27 days with the sun and tends to push outward the galactic particles sliding inward along the lines of force. There is reason to expect disordering in the interplanetary field, some examples of which have been cited elsewhere [Meyer, Parker, and Simpson, 1956; Parker, 1958c]; the disordering contributes to the trapping of solar particles and to the impediment of galactic cosmic ray particles diffusing inward from interstellar space.

These effects are large and contribute significantly to depression of the cosmic ray intensity. The depression is of the order of a factor of three at 1 Bev (see for instance Simpson, 1960) and probably more at lower energies. We may hope that one day interplanetary observation may decide what effects predominate.

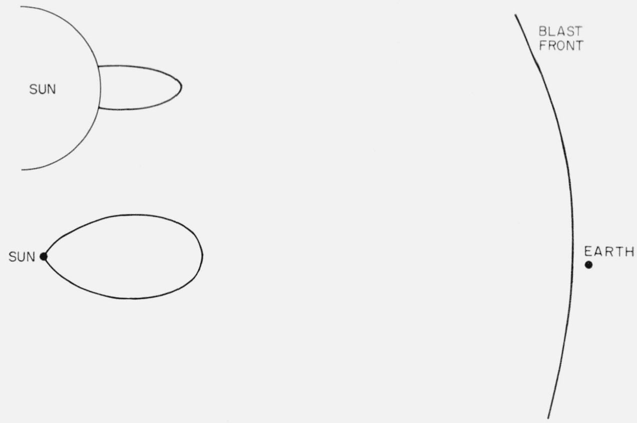

FIGURE 6. *A re-entrant loop of magnetic field in the solar corona before an outburst is shown, followed by its extension into space by the blast wave $\lambda=3/2$.*

The loop remains in association with the coronal gas with which it moves following the outburst. The blast wave ahead of the loop consists of interplanetary gas (the quiet-day solar wind) swept up to form the blast wave.

4.2. Active Sun

The magnetic configuration carried by the blast waves from the active corona, and shown in figure 5 for an idealized case, have the basic characteristic of a strong magnetic field (probably $10–50\times10^{-5}$ gauss) in the wave, with an essentially radial field connecting into the sun from behind. The strong fields result from the twisting and pinching together of the quiet-day lines of force. The resulting constriction in the lines of force represents a serious impediment to the passage of cosmic ray particles. Thus the blast waves will have a tendency to store energetic protons of solar origin behind them, and to push back galactic cosmic ray particles ahead of them, as required by observation (see for instance, Steljes et al., 1961). The Forbush decrease for the idealized model shown in figure 5 may be as large as 40 percent, and more if any complications are permitted in the idealized field configuration. The energy dependence of the cosmic ray decrease can be estimated if it is remembered that the blast waves are in fact not spherical but occupy a solid angle of the order of one steradian. The diffusion of cosmic rays from the sides of the region swept out by the blast waves gives an energy dependence to the fractional decrease of the cosmic ray intensity as shown in figure 7. The parameter ν in the figure is a measure of the angular width of the blast wave. The computed energy dependence is found to be not unlike the observed energy dependence of the Forbush decrease (see for instance MacDonald and Webber, 1960) viz, proportional to reciprocal rigidity, or flatter.

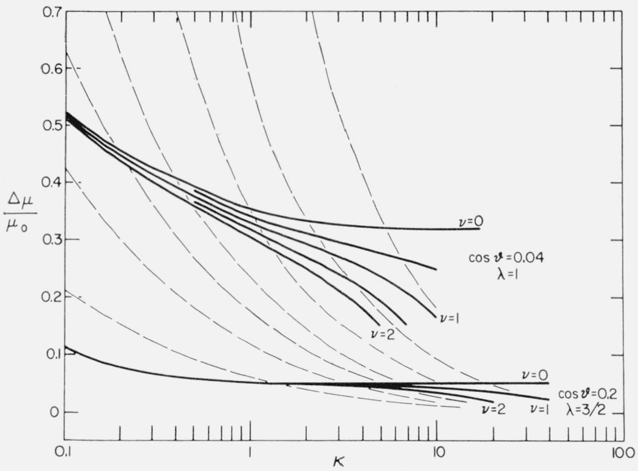

FIGURE 7. *The fractional depression $\Delta\mu/\mu$ of the cosmic ray intensity as a function of proton energy κ (in units of 931 Mev) for a freely coasting shock, $\lambda=3/2$, and for the hard driven shock, $\lambda=1$.*

The parameter ν is an inverse measure of the angular width of the blast wave as seen from the sun. The broken lines represent reciprocal rigidity, for purpose of comparison.

5. Summary

The purpose of the paper has been to describe in a semiquantitative way the solar wind model of interplanetary dynamical processes. The model affords a deductive approach to the problem of interplanetary plasmas, fields, and cosmic ray variations, starting with the hydrodynamic theory of the expanding solar corona. The observed coronal temperatures and their variations lead through such idealized models as we have discussed to the kind of "corpuscular" and cosmic ray effects that are known from observation. As direct observation of interplanetary conditions become more comprehensive with the progress of space experimentation, we look forward to filling in the many details which are missing from the present simple model.

6. References

Babcock, H. D., The sun's polar magnetic field, Astrophys. J. **130,** 364–365 (1959).

Babcock, H. W., and H. D. Babcock, The sun's magnetic field, 1952–1954, Astrophys, J. **121,** 349–366 (1955).

Biermann, L., Kometenschweife und solare Korpuskularstrahlung, Zeit. f. Astrophys. **29,** 274–286 (1951).

Biermann, L., Uber den Schweif des Kometen Halley im Jahre 1910, Zeit. f. Naturforsch. **7a,** 127–136 (1952).

Biermann, L., Solar corpuscular radiation and the interplanetary gas, Observatory **77,** 109–110 (1957).

Biermann, L., Paper presented at 4th Symposium on Cosmical Gas Dynamics, Varenna, Italy (August 1960).

Billings, D. E., Distribution of matter with temperature in the emission corona, Astrophys. J. **130,** 961–971 (1959).

Bridge, L., Paper presented at Spring Meeting of AGU, Washington, D.C. (April 1961).

Christiansen, W. N., and J. A. Warburton, The distribution of radio brightness over the solar disk at a wavelength of 21 centimetres, Australian J. Phys. **6,** 190–202 (1953).

Christiansen, W. N., D. E. Yabsley, and B. Y. Mills, Measurements of solar radiation at a wavelength of 50 centimetres during the eclipse of November 1, 1948, Australian J. Sci. Research **A2,** 506–523 (1949).

Clauser, F. H., Paper presented at 4th Symposium on Cosmical Gas Dynamics, Varenna, Italy (August 1960).

Courant, R., and K. O. Friedrichs, Supersonic flow and shock waves, pp. 419–421 (Interscience Publishers, New York, N.Y., 1948).

Gold, T. H., Energetic particle fluxes in the solar system and near the earth, Suppl. Astrophys. J. **4,** 406–416 (1960).

MacDonald, F. B., and W. R. Webber, Changes in the low-rigidity primary cosmic radiation during the large Forbush decrease of May 12, 1959, J. Geophys. Research **65,** 767–770 (1960).

Meyer, P., E. N. Parker, and J. A. Simpson, Solar cosmic rays of February 1956 and their propagation through interplanetary space, Phys. Rev. **104,** 768–783 (1956).

Parker, E. N., Dynamics of the interplanetary gas and magnetic fields, Astrophys. J. **128,** 664–676 (1958a).

Parker, E. N., Interaction of the solar wind with the geomagnetic field, Physics of Fluids **1,** 171–187 (1958b).

Parker, E. N., Cosmic-ray modulation by solar wind, Phys. Rev. **110,** 1445–1449 (1958c).

Parker, E. N., The hydrodynamic theory of solar corpuscular radiation and stellar winds, Astrophys. J. **132,** 821–866 (1960).

Parker, E. N., Sudden expansion of the corona following a large solar flare and the attendant magnetic field and cosmic-ray effects, Astrophys. J. **133,** 1014–1033 (1961a).

Parker, E. N., Sudden expansion of the corona following a large solar flare and the attendant magnetic field and cosmic-ray effects, Astrophys. J. **133,** 1014–1033 (1961b).

Shklovskii, I. S., V. I. Moroz, and V. G. Kurt, The nature of the earth's third radiation belt (in Russian), Astron. Zh. **37,** 931–934 (1960). For English translation see Soviet Astronomy **4,** No. 5, 871–873 (March–April 1961).

Simpson, J. A., Variations of solar origin in the primary cosmic radiation, Suppl. Astrophys. J. **4,** 378–405 (1960).

Steljes, J. F., H. Carmichael, and K. G. McCracken, Characteristics and fine structure of the large cosmic-ray fluctuations in November 1960, J. Geophys. Research **66,** 1363–1377 (1961).

(Paper 65D6–157)