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THE SOLAR WIND

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by

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SUMMARY

Parker's model of a spherically expanding corona, the "solar wind," is compared with D. E. Blackwell's observations of the 1954 minimum equatorial corona. A significant discrepancy is found between the predicted and the observed electron densities at distances from the sun greater than 20 solar radii. Blackwell's data are found to be consistent with a model in which the corona expands mostly within a disk less than 25 solar radii thick, lying within the sun's equatorial plane. The thickness of the disk as a function of distance from the sun is qualitatively explained in terms of magnetic pressure.

The solar wind is found to have a considerable effect on the lunar atmosphere. First, the calculated density of the lunar atmosphere is greatly reduced by collisions with protons in the solar wind. If the flux of particles in this wind has the conventional values ranging between 10^{10} to 10^{11} cm^{-2} sec^{-1}, the calculations yield a lunar pressure of 10^{-13} atmosphere of argon, in agreement with the value predicted by Elsmore and Whitfield on the basis of observations on the occultation of radio stars. Second, following a suggestion by Gold, it was found that the collisions of solar-wind protons with the lunar surface produce an atmosphere of cold neutral hydrogen with a density of $10^5/cm^3$ at the lunar surface. The density falls off at greater distances in accordance with the inverse-square law.

Estimates indicate that the interaction of solar particles with the neutral hydrogen will produce an extended lunar ionosphere with a density of the order of 400 protons/cm^3 in the vicinity of the moon.

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PROPERTIES OF THE SOLAR WIND DURING SUNSPOT MINIMUM

Recently Parker (Reference 1) suggested that the solar corona may be in a state of continual expansion, which he refers to as the "solar wind." The Parker model appears to effect a reasonable description of the corona's properties during sunspot maxima. In this section the applicability of the Parker model during a sunspot minimum is investigated. The electron density measurements obtained by Blackwell from the 1954 solar eclipse (Reference 2) and from airplane observations of the inner zodiacal light (Reference 3) are used.

Equations of Motion of the Corona

In the presence of a magnetic field $\underline{B}$ and a gravitational potential V the steady-state equations of motion of an ionized fluid with velocity $\underline{u}$, mass density ρ, and pressure P are:

$$\nabla \cdot \rho \underline{u} = 0 \tag{1}$$

expressing the conservation of mass, and

$$\rho \underline{u} \cdot \nabla \underline{u} = -\nabla P - \rho \nabla V + \frac{1}{4\pi} \nabla \times \underline{B} \times \underline{B} \tag{2}$$

expressing the conservation of momentum. There are also the equations of flux preservation

$$\nabla \times (\underline{u} \times \underline{B}) = 0 \tag{3}$$

and flux continuity

$$\nabla \cdot \underline{B} = 0 ,$$

and the equation of state

$$P = NkT , \tag{4}$$

in which T is the temperature and N is the particle density. The potential V is

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$$V = \frac{G\,M_\odot}{r}, \tag{5}$$

where G is the universal gravitational constant, $M_\odot$ is the sun's mass, and r is the radial distance to the sun.

The densities ρ and N can be related to the electron density n if it is supposed that the corona consists of one-fifth doubly ionized helium and four-fifths ionized hydrogen:

$$\begin{aligned} \rho &= \alpha M_H n \\ N &= 2\beta n\,, \end{aligned} \tag{6}$$

where M_H is the mass of a proton and α, β are the constants

$$\alpha = 1.286\,,$$

$$\beta = 0.929\,.$$

The Parker Corona Model

Parker solved a simplified form of the foregoing equations and derived the velocity distributions for a series of assumed temperatures. His calculations have been repeated, and the density distribution corresponding to the observed temperature has been derived. The temperature also has been calculated independently by fitting his results to the observed electron density near the sun's surface.

In the Parker model a spherical expansion is assumed at a constant temperature, and the magnetic field is neglected. With these assumptions, Equation 1 can be integrated immediately to give

$$n\,r^2 u = \text{constant}\,; \tag{7}$$

and Equation 2 becomes

$$\frac{\alpha M_H}{2}\, n\, \frac{\partial u^2}{\partial r} = -\,2\,k\,\beta T\,\frac{\partial n}{\partial r} - \frac{G M_\odot\, \alpha\, M_H\, n}{r^2}\,. \tag{8}$$

The abbreviations

$$\phi = \frac{\alpha}{\beta}\;\frac{M_H}{2}\;\frac{u^2}{kT}\,, \tag{9}$$

$$x = \frac{r}{r_0}\,,$$

$$n = n_0\,\nu\,,$$

where

$$r_0 = \text{the sun's radius},$$

$$n = n \quad \text{at} \quad r = r_0\,,$$

permit Equation 7 to be written as

$$x^2 \nu \sqrt{\varphi} = \sqrt{\varphi_0} \tag{10}$$

and with this, Equation 8 becomes

$$\frac{d\varphi}{dx} = \frac{\varphi}{x} \frac{4 - \frac{b}{x}}{\varphi - 1} . \tag{11}$$

A sketch of the φ - x plane is shown in Figure 1. It can be seen that there is a saddle point at $\varphi = 1$, $x = b/4$. Parker picks the solution that goes through the saddle point from low to high velocities. This is presumably the only stable solution. The other solutions require either too high velocities at $r = r_0$, or too high densities at $r = \infty$. This fixes the constant of integration, and from Equation 5,

$$\varphi - \ln \varphi = \frac{b}{x} - 3 + 4 \ln \frac{4x}{b} . \tag{12}$$

With Equation 10 this is sufficient to determine the velocity and density, once b is known.

When x is near unity, $\underline{u}$ is very small. It is then possible to determine b from the observed density curve by using the hydrostatic equation valid for zero velocity:

$$\nu = \exp\left[\frac{b}{2}\left(\frac{1}{x} - 1\right)\right] . \tag{13}$$

From Equation 13 and the values for ν given by the Jager (Reference 4) for $x < 3$, the value $b = 18.70$, which corresponds to a temperature of $T = 1.70 \times 10^6$ °K, is obtained.

Comparison of the Parker Model with Observation

The solid curve in Figure 2 shows the velocity calculated on the basis of the Parker model. It rises from 1.25 km/sec at the base of the corona to 560 km/sec at the orbit of the earth.

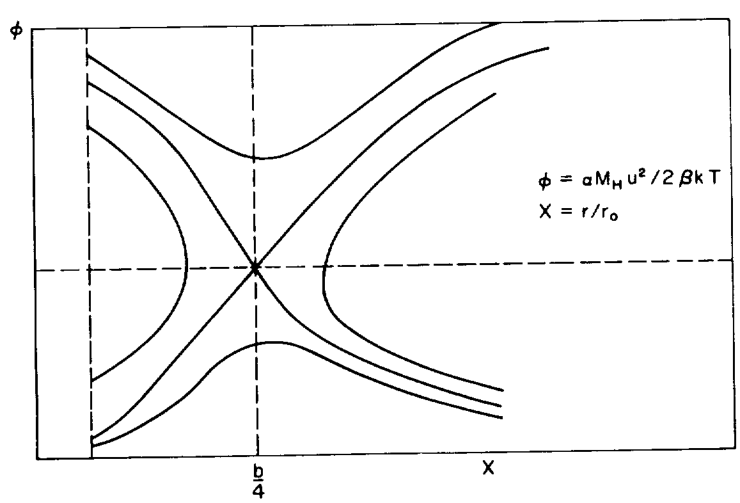

Figure 1 - The φ-x plane

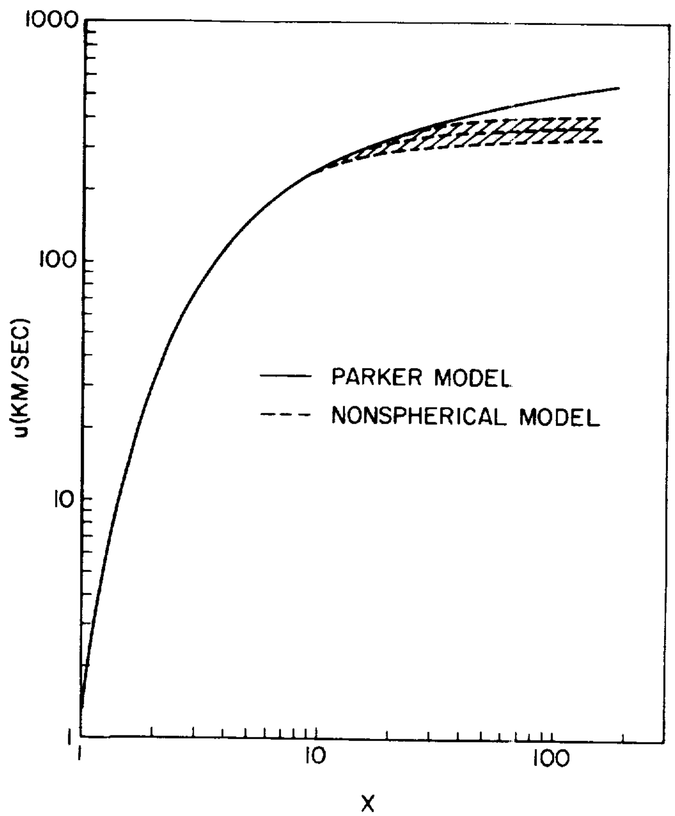

Figure 2 - The velocity distributions

The solid curve in Figure 3 shows the electron density variation predicted by the Parker model. The dashed curve shows the density variation as observed by Blackwell. The two dotted lines show the margins of error estimated by Blackwell as the result of experimental error and the uncertain polarization of the F corona.

At 150 solar radii the Parker model predicts one-thirtieth of the observed density.

Nonspherical Model

It is possible to reconcile Blackwell's results with the concept of an expanding corona if the hypothesis of a spherical expansion is dropped. From eclipse observations, it is well known that the minimum corona is greatly extended in the equatorial plane. It will therefore be assumed that most of the expanding gas moves nearly parallel to this plane, within a disk of thickness g (g is normalized so that $g(1) = 1$).

If u is interpreted as the mean radial velocity within this disk, then Equation 8 can still be used. The first integral of this equation is the Bernoulli relation

$$\frac{\alpha M_H}{2} u^2 - 2k\beta T \left(\frac{b}{2x} - \ln \nu\right) = \frac{\alpha M_H}{2} u_0^2 - k\beta T b \ . \tag{14}$$

Equation 7, however, must now be replaced by

$$x\, g(x)\, u\nu = u_0 \ . \tag{15}$$

The subscript "0" refers to conditions at the base of the corona.

These equations are sufficient to determine u and g as functions of x if Blackwell's values for ν are used and a value for u_0 is assumed. The choice of u_0 is based on the condition that the corona expands spherically near the sun. On this basis u_0 has the value given by the Parker model.

The velocity u is plotted as the dashed line in Figure 2. It is seen to be nearly constant at 380 km/sec near the earth's orbit. The thickness g is plotted as the solid line in Figure 4. The dotted lines in Figures 2 and 4 show the margins of error to be expected from the error in ν.

The thickness of the disk rises linearly to about $x = 10$, reaches a peak at $x = 25$, and falls slowly thereafter. If initially the disk is 1 solar radius in thickness, then near the earth it will have a width of 5 radii.

Magnetic Pressure

It is possible to obtain a qualitative explanation of the contraction of the disk in terms of magnetic pressure. Suppose that the magnetic field $\underline{B}$ within the disk is due to the blowing away of a dipole field. In order to obtain the order of magnitude of $\underline{B}$, assume that it is nearly parallel to $\underline{u}$. By writing

$$\underline{B} = K n \underline{u} \tag{16}$$

it is found that flux continuity requires that K be constant along a streamline. Thus, by using Equation 15, it is possible to write

$$B = \frac{B_0}{xg} . \tag{17}$$

Here B_0 is a function of the streamline and is determined by the original dipole field at the base of the corona. For instance, a field of 10^{-5} gauss at $x = 150$ would require a value of B_0 at the sun's equator of only 10^{-2} gauss.

These field strengths are sufficiently low to permit neglect of the gradient of the magnetic pressure $B^2/8\pi$ along the streamlines in comparison with the gradient of kinetic pressure. The inclusion of a magnetic field of this magnitude will not seriously affect the validity of the Bernoulli Equation (Equation 14). However, the magnetic field can produce a force transverse to the streamlines, which is assumed to be balanced by a small transverse pressure gradient; that is,

$$\nabla_{\perp} \frac{B^2}{8\pi} = - \nabla_{\perp} P . \tag{18}$$

If Equation 18 is integrated between the center c and the edge e of the disk, holding x fixed, then

$$\frac{1}{8\pi} \left(B_e^{\;2} - B_c^{\;2} \right) = P_c - P_e , \tag{19}$$

or

$$\frac{\Delta B^2}{8\pi} = \Delta P .$$

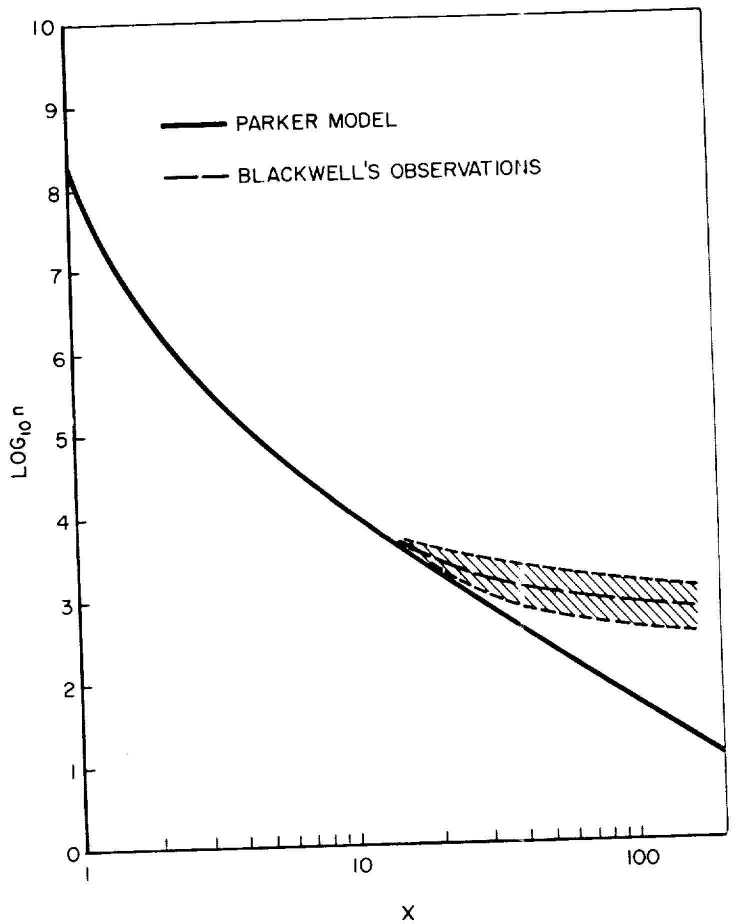

Figure 3 - The electron density distributions

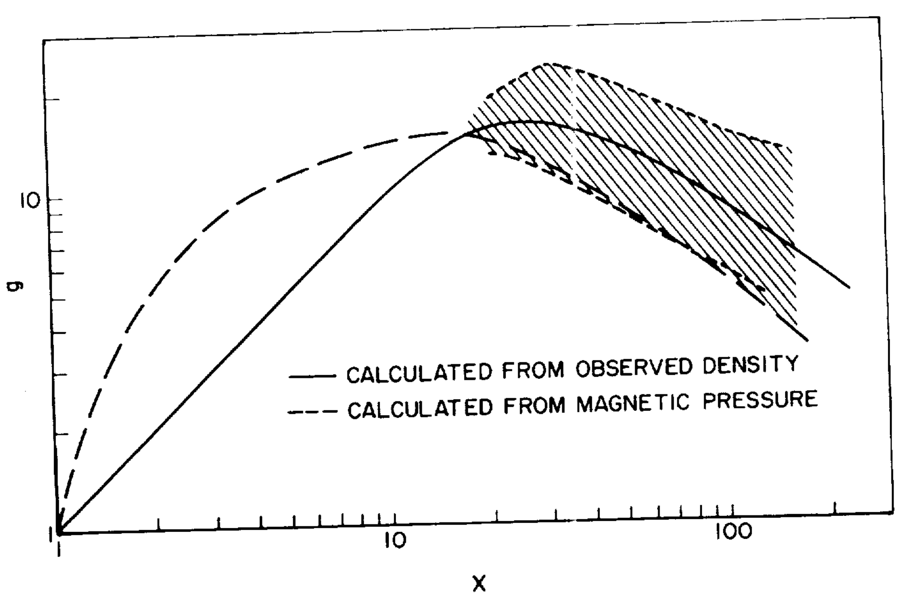

Figure 4 - The thickness of the coronal disk

From Equation 17,

$$\frac{\Delta B^2}{8\pi} = \frac{\Delta B_0^{\ 2}}{8\pi (xg)^2} \ . \tag{20}$$

It can also be assumed that

$$\frac{\Delta P}{P} \approx \frac{\Delta P_0}{P_0} \ . \tag{21}$$

Thus

$$\frac{\Delta B_0^{\ 2}}{8\pi (xg)^2} = \frac{\Delta P_0}{P_0} P = \Delta P_0 \nu \ , \tag{22}$$

$$\frac{\Delta B_0^{\ 2}}{8\pi} = \Delta P_0 \ , \qquad x = 1 \ ;$$

and ΔP_0 may be eliminated. Solving for g gives

$$g = \frac{1}{x\sqrt{\nu}} . \tag{23}$$

This curve is plotted as the dashed line in Figure 4; it has a peak at $x = 15$ in qualitative agreement with the curve of thickness calculated from the density distribution, but it is too high for $x < 10$.

Discussion

Nothing has been said thus far about the polar corona because of the lack of reliable density measurements at large polar distances from the sun. It is possible that the polar corona is in a state of spherical expansion; in that case its density at large distances will be considerably less than in the equatorial corona.

The sun's equator is known to be inclined at an angle of 7°15' to the plane of the ecliptic. During March and September, the earth will be at its maximum distance, 27 solar radii, South and North of the sun's equator. According to Figure 4 the earth during these months will be at least 12 solar radii outside of the direct equatorial flow, and in the presumably turbulent fringe region of the coronal disk. Therefore, geomagnetic disturbances may be expected to be especially prevalent during these seasons as has been, in fact, observed (Reference 5).

EFFECT OF THE SOLAR WIND ON THE LUNAR ATMOSPHERE

The composition and extent of the lunar atmosphere are determined by the competition between the processes of accumulation of gases from the surface and the escape from the atmosphere of those molecules with velocities sufficiently high to remove them from the gravitational attraction of the moon. Probable sources for the accumulation of surface gases are: the radioactive decay of potassium, producing argon; and residual volcanic activity, producing such gases as SO_2, CO_2, and H_2O. Estimates of the emission of these gases based on terrestrial data suggest a source of strength of 5×10^5 cm^{-2} sec^{-1} for argon, and 10^{10} cm^{-2} sec^{-1} for the volcanic gases (Reference 6). These estimates are, of course, highly questionable, and are used here for illustrative purposes.

The moon has one-eightieth of the mass and one-quarter of the radius of the earth. Its gravitational potential is therefore one-twentieth that at the surface of the earth. As a result of this low gravitational potential, gases escape much more rapidly from the lunar atmosphere than from the earth's atmosphere. The rate of escape also depends on the maximum temperature, which determines the number of atoms or molecules in the high-energy tail of the thermal distribution. Thermocouple measurements indicate a value of 370°K for this temperature (Reference 7).

If an isothermal atmosphere and a Maxwellian distribution of particle velocities with an infinite mean free path are assumed, a calculation based on the balance between these two processes leads to the following result for the equilibrium number density of atmospheric molecules at the lunar surface (Reference 8):

$$n_0 = J \sqrt{\frac{\pi m}{2kT}} \left(1 + \frac{mMG}{kTR}\right)^{-1} \exp \frac{mMG}{kTR} . \tag{24}$$

In Equation 24, J is the the number of molecules ejected from the lunar surface per square centimeter per second; T the lunar atmospheric temperature; m the mass of an atmospheric particle; M the mass of the moon; and R its radius.

When these values of J and T are used in Equation 24, it is found that for argon, $n_0 \approx 5 \times 10^{15}/cm^3$ or 10^{-4} atmosphere. A similar calculation for the volcanic gases leads to pressures greater than 1 atmosphere for SO_2 and CO_2, and to 4×10^{-8} atmosphere for H_2O. However, the latter values will be lowered substantially when allowance is made for the effects of photodissociation and chemical reactions with the crust, and for the fact that the age of the moon ($\approx 4.5 \times 10^9$ years) does not allow enough time for SO_2 and CO_2 to build up to equilibrium (Reference 6).

These estimates of the extent of the lunar atmosphere are seriously reduced by the effects of the solar wind. It appears, in fact, on the basis of conventional calculations of the probability of escape, that the solar wind will blow away all but a very small fraction of the lunar atmosphere.

Consider a solar wind consisting of protons with the conventional density of $10^3/cm^3$ and velocity of 10^8 cm/sec, or energy of 10 kev (Reference 9). In an elastic collision with an atom these protons will transfer an average of 1 kev of kinetic energy, which is sufficient for the escape of the atom. If it is assumed that every atom struck by a proton escapes, the rate of ejection of particles is readily calculated, and this gives for R_p the value of the rate of ejection of particles from the atmosphere (per cubic centimeter):

$$R_p = n_a n_p V_p \sigma_{el} . \tag{25}$$

2N

In Equation 25, n_p is the number density of protons, V_p is their velocity, and σ_{el} is the proton-particle elastic cross section. The equilibrium particle density at the lunar surface is estimated by equating the rate of ejection of particles from a vertical column 1 cm^2 in cross-sectional area, as calculated by Equation 25, to the rate of injection of particles J into the column at the surface. This gives

$$n_0 = \frac{J}{n_p V_p \sigma_{el} h} , \tag{26}$$

where h is the scale height of the isothermal atmosphere kTR^2/mMG. Taking σ_{el} to be 10^{-16} cm^2, it is found that $n_0 \approx 10^4/cm^3$ or 10^{-15} atmosphere for argon. For the volcanic gases, $n_0 \approx 10^8/cm^3$ or 10^{-11} atmosphere. This value represents an upper limit for these gases because photodissociation has been neglected.

When these values are compared with the results obtained earlier, it is seen that the solar wind reduced the density of the lunar atmosphere by a factor of 10^{11} for argon, 10^4 for H_2O, 10^{15} for CO_2, and 10^{22} for SO_2.

These results depend on the assumption that the moon's magnetic field is too feeble to shield the atmosphere effectively from the solar wind. If an upper limit of 100 gamma is assumed for the seleno-magnetic field (References 10 and 11), then the magnetic pressure of such a field of this intensity will indeed have no shielding effect.

The values quoted for argon and the volcanic gases lie to either side of an experimental estimate of 10^{-13} atmosphere, which has been derived from measurements of the lunar ionosphere by Elsmore and Whitfield (Reference 12).

THE MOON'S HYDROGEN ATMOSPHERE

Gold (Reference 13) suggested that the high-velocity protons from the solar wind will be absorbed by the lunar surface and subsequently emitted by the surface as a gas of neutral hydrogen at the temperature of the point of emission. Since the thermal velocity of the emitted gas is considerably smaller than the incident solar wind velocity, the density will be correspondingly greater, in accordance with the equation of continuity, and in fact great enough to produce a substantial lunar atmosphere of cool monatomic hydrogen.

The thermal velocity V_S of the gas escaping from the subsolar point is about 2.5×10^5 km/sec. This is slightly greater than the escape velocity $V_e = 2.4 \times 10^5$ km/sec. It follows that a large fraction of the atoms in this atmosphere will be in the process of escaping. A crude estimate of the density N_H may be obtained by considering the atmosphere to be in a state of radial flow outwards at the constant velocity V_S. The equation of continuity gives

$$N_H \sim \frac{1}{r^2} ,$$

and the constant of proportionality is obtained by requiring that the flux J of solar protons into the surface shall equal the outward flux of hydrogen atoms. Thus

$$N_H = \frac{J}{V_S}\left(\frac{R}{r}\right)^2$$

where R is the moon's radius. With $J = 10^{10}\ cm^{-2}\ sec^{-1}$, the quantity $N_H = 0.4 \times 10^5/cm^3$ is obtained at the moon's surface.

Summarized next is an attempt at a closer description of the hydrogen atmosphere taking into account the variation in the moon's surface temperature and the variation in the component of the solar proton flux normal to the moon's surface.

Denote by $d\sigma(P)$ an area element at the point P on the moon's surface. Each point receives particles from the incident solar stream at a rate $J_I(P)$, and from the rest of the moon's surface at a rate $J_A(P)$.

The particles absorbed from the solar stream are mostly protons. They will be emitted as neutral hydrogen atoms at a rate $R(P)$. A certain fraction $F_e(P)$ of the flux $R(P)$ consists of particles that escape to infinity; and the remainder consists of particles that return to the moon, where they are absorbed and subsequently re-emitted.

The fact that the thermal velocities involved are comparable with the escape velocity implies that the average path length between emission and absorption for the returning particles is a sizeable fraction of the moon's circumference. Thus, particles from a rather large area contribute to the rate $J_A(P)$. It therefore seems reasonable to assume that $J_A(P)$ is constant, $J_A(P) = J_A$.

If it also is assumed that the atmosphere is in a steady state, two equilibrium conditions must be satisfied by the various rates. First, to a good approximation each point must emit as many particles as it receives:

$$R(P) = J_A + J_I(P) . \tag{27}$$

Second, as many particles must enter the atmosphere as leave,

$$\int F_e(P)\ R(P)\ d\sigma(P) = \int J_I(P)\ d\sigma(P), \tag{28}$$

where the integrals are taken over the moon's surface.

Denote the angle between the point P and the subsolar point by θ. Then

$$\begin{aligned} J_I &= J \cos\theta \quad \text{for} \quad 0 < \theta < \frac{\pi}{2}, \\ J_I &= 0 \quad \text{for} \quad \theta > \frac{\pi}{2}. \end{aligned} \tag{29}$$

The quantities $R(P)$ and $F_e(P)$ can also be calculated if it is assumed that the emitted particles have a Boltzman distribution with density $N(P)$. Then

$$R(P) = \frac{2}{\sqrt{\pi}} N(P)\ V(P), \tag{30}$$

and

$$F_e(P) = \left\{1 + \left[\frac{V_e}{V(P)}\right]^2\right\} \exp - \left[\frac{V_e}{V(P)}\right]^2 , \tag{31}$$

where $V(P)$ is the local thermal velocity,

$$V(P) = \sqrt{\frac{2kT(P)}{M}} , \tag{32}$$

and V_e is the escape velocity,

$$V_e = \sqrt{2gR} . \tag{33}$$

If the surface temperature $T(P)$ is known, Equations 29 to 33 convert the equilibrium conditions (Equations 27 and 28) into two equations for the unknowns J_A and $N(P)$.

When the surface temperature determined by Pettit and Nicholson (Reference 14) is used, the curve shown in Figure 5 is obtained for

$$\frac{N \times 10^5}{J}$$

as a function of $\cos\theta$, where θ is the angle between P and the subsolar point S. For a solar wind flux $J = 10^{10}$ cm^{-2} sec^{-1}, there is obtained for the subsolar point

$$N_S = 0.39 \times 10^5/\text{cm}^3 ,$$

in good agreement with the more qualitative argument. On the dark side of the lunar surface, $N_D = 0.085 \times 10^5/\text{cm}^3$, with a ratio $N_S/N_D = 4$, is obtained, and also $J_A = 0.14\ J$.

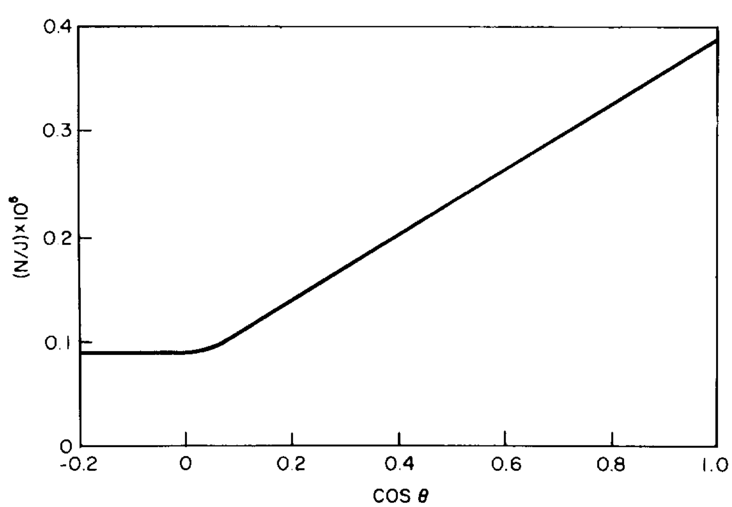

Figure 5 - The hydrogen density on the Lunar surface

THE LUNAR IONOSPHERE

In the lunar ionosphere the dominant ionization process is charge exchange between solar protons and hydrogen atoms. The cross section for this process is about $10^{-15}\,cm^2$ as compared with $10^{-18}\,cm^2$ for photoionization. In the following the ionization density due to charge exchange is computed upon the assumption that every ionized particle escapes from the moon's atmosphere. Although some newly ionized protons may be knocked into gravitationally bound orbits that do not intersect the lunar surface, it is not possible to estimate the density of such protons without a more detailed analysis of the velocity distribution in the hydrogen atmosphere. The ionization density computed from charge exchange is therefore to be regarded as a lower limit.

The effect on this atmosphere of charge exchange between the hydrogen atoms and the solar wind protons is now calculated as follows: The cross-section σ for this process, for protons of energies between 1 and 10 kev., is between 2×10^{-15} and $1 \times 10^{-15}\,cm^2$ (Reference 15). The number of slow protons produced per cubic centimeter per second is $N_H J \sigma$. Let N_p denote the density of the slow protons. If the moon's gravitational field and the energy transfer in the charge exchange are neglected, then it can be assumed that both the slow protons and hydrogen atoms are streaming radially outwards with constant velocity V.

The continuity equations for these two constituents of the atmosphere are:

$$\frac{1}{r^2}\frac{\partial}{\partial r}(N_H\, r^2\, V) = -N_H\, J\sigma ,$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}(N_p\, r^2\, V) = +N_H\, J\sigma .$$

It is found that

$$N_H = \frac{J}{V}\left(\frac{R}{r}\right)^2 \exp - \frac{J\sigma}{V}(r - R)$$

$$N_p = \frac{J}{V}\left(\frac{R}{r}\right)^2 \left\{1 - \exp - \frac{J\sigma}{V}(r - R)\right\}$$

Now

$$J = 10^{10}\ cm^{-2}\ sec^{-1}$$

$$V = 10^5\ cm/sec\ ;$$

thus,

$$\frac{J\sigma}{V} R \approx \frac{10^{10} \times 10^{-15}}{10^5} \times 1.7 \times 10^8$$

$$\approx 1.7 \times 10^{-2} ,$$

so that for $r < 100\ R$, it may be taken that

$$N_H = \frac{J}{V}\left(\frac{R}{r}\right)^2 ,$$

$$N_p = \left(\frac{J}{V}\right)^2 \sigma R\left[\frac{R}{r} - \left(\frac{R}{r}\right)^2\right].$$

The bracketed term possesses a maximum of 1/4 at $r = 2R$. With these values, then

$$N_H = 10^5\left(\frac{R}{r}\right)^2 ,$$

$$N_p = 1.7 \times 10^3\left[\frac{R}{r} - \left(\frac{R}{r}\right)^2\right]$$

At $r = 2R$, $N_p = 400/cm^3$ and at $r = 10R$, $N_p = 170/cm^3$ and should just begin to be detectable above the interplanetary density of $100/cm^3$. This is in agreement with the results reported by Krassovskii (Reference 11) for Lunik III, in which the interplanetary ion density was found to begin to increase above the ambient value at a distance of about $r = 10R$.

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