SOLAR PROTONS AS A MECHANISM OF SMOOTHING INTERPLANETARY FIELD LINES

by

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ABSTRACT

In this paper we investigate the possibility of having interplanetary field line smoothing caused by the pressure exerted by energetic protons accelerated and released during solar flares. For this purpose it has been derived a theoretical expression for the particle's pressure on the ambient magnetic field as a function of measurable parameters. In addition, a simplified model of the interplanetary magnetic field was developed in order to have analytic expressions for the magnetic pressure at any point in space. Finally the particle's pressure was computed as a function of heliocentric distances for two solar proton events of different strenght but otherwise similar. For the strongest case the interplanetary field pressure is greater than the particle's pressure inside 0.1 AU but it becames monotonically smaller beyond this point. For the other case the magnetic field pressure is much greater than the particle's pressure inside 1 AU. These calculations may explain why the strongest solar event produced the well known "energetic storm particle event" and not the other. It is concluded that, at least in certain solar flare events, energetic solar protons can smooth out inhomogeneities in the interplanetary magnetic field lines.

INTRODUCTION

In association with the arrival of solar-flare-induced shock waves at the Earth's orbit, an enhancement in the flux of the energetic solar protons is sometimes observed. These events are called Energetic Storm Particles (ESP) Events. Their main characteristics can be summarized as follows |1, 2, 3|. a) there exists a one-to-one correspondence with the ocurrence of Forbush decreases; b) there is a considerable enhancement in the >10 MeV proton intensity and, in some cases, it may contain relativistic electrons; c) the proton anisotropy is generally parallel to the actual direction of the interplanetary magnetic field; d) the energy spectrun is softer than the preceding flare effect.

Most recently, Medrano et al. |4| analyzing satellite data of more than two years, have concluded that the peak of the ESP events occur around 8 hours after the passage of the interplanetary shock waves. This is in remarkable agreement with the time elapsed between the arrival of the shock front and the driver gas ($\simeq$8 hrs), that can be inferred from Hirshberg et al. |5|.

Figure 1 shows three examples of low energy (0.7 - 7.6 MeV protons) ESP events as observed by the Explorer 34 cosmic ray experiment in August, September and November 1967 respectively (Palmeira, private communication). In all three diagrams the Y-axes display the counting rate corresponding to 0.7 MeV through 7.6 MeV protons. The time is displayed on the X-axis. The arrows indicate the occurrence of sudden commencements (SC), here taken as indicators of the interplanetary shock waves arrival |6|, and the presumed responsible flare (F). Notice, in all three diagrams, significant flux enhancements indicated by arrows (ESP peaks), several hours after the passage of the shock fronts. The average time separation between the SC's and ESP peaks, in Figure 1, was found to be of the order of 8 hrs |4|. Also, the particles were found to exhibit some anisotropy from directions presumably coincident with the interplanetary magnetic field lines.

Medrano et al. |7| proposed a model of solar cosmic ray propagation to explain the square wave-like proton flux enhancement observed by lunar experiments on August 5, 1972. This model postulates a field line smoothing on the magnetic field lines that exist in the discontinuity surface between the disturbed (otherwise ambient) solar wind and the piston-driven gas. We can consider two candidates for field line smoothing mechanisms. The first type could be due to the enhancement of MHD waves induced by the hot supersonic fresh plasma. This mechanism was investigates by Medrano and Kantor |8| and found to be possible in cases when both sides of the field lines are on the solar photosphere (this can happen when dipolar fields in the chromosphere are convected out by the highly conducting injected material). The second smoothing mechanism could be due directly to the pressure that the energetic particles exert on the magnetic field inhomogeneities. In this paper we investigate, with some quantitative calculations, the conditions under which we could have field line smoothing by means of this last mechanism.

PRESSURE OF THE PARTICLES ON THE MAGNETIC FIELD

The particle's pressure tensor in a stationary frame of reference is known to be

$$p_{ij} = \int m\, v_i\, v_j\, f(\underset{\sim}{r},\, \underset{\sim}{v},\, t)\, d^3v \tag{1}$$

where m = particle's mass, $\underset{\sim}{v}$ = velocity vector, $\underset{\sim}{r}$ = position vector, and $f(\underset{\sim}{r}, \underset{\sim}{v}, t)$ = particle's distribution function.

Notice, that p_{ij} is a symmetric tensor. It can be reduced to a diagonal form by using its principal directions ($\hat{\underset{\sim}{e}}_1$, $\hat{\underset{\sim}{e}}_2$, $\hat{\underset{\sim}{e}}_3$) in the velocity space; in other words $P_{ij} = P_i\delta_{ij}$ (no summation). Furthermore, if the $\hat{\underset{\sim}{e}}_3$ direction is coincident with the direction of the local magnetic field, then: $P_{11} = P_{22} = P_{\perp}$ and $P_{33} = P_{//}$. Where the perpendicular and parallel symbols refer to the direction of the magnetic field. Obviously the pressure exerted by the particles on the magnetic field is $P_{\perp}$.

$$P_{\perp} = \frac{1}{2} \int m\, v_{\perp}^2\, f(\underset{\sim}{r},\, \underset{\sim}{v},\, t)\, d^3v$$

This equation can be rewritten in terms of the particle's energy in the non-relativistic case:

$$P_{\perp} = \frac{1}{m} \left(\frac{2}{m}\right)^{1/2} \int E^{3/2} f(\underset{\sim}{r},\, \underset{\sim}{v},\, t)\, \sin^2\alpha\, dE\, d\Omega \tag{2}$$

where we took $v_\perp = v \sin\alpha$ (α=pitch angle) and expressed the integrand in terms of spherical coordinates.

According to |9|: $j(r, \Omega, E, t) = \frac{2E}{m^2} f(\underset{\sim}{r}, \underset{\sim}{v}, t)$

Furthermore, for the case of a constant source:

$$j(r, \Omega, E, t) = (\frac{R}{r})^2 \cdot j(R, \Omega, E, t)$$

where $j(R, \Omega, E, t)$ is a "known" differential flux at point R.

With all these substitutions, equation (2) becomes:

$$P_\perp(r, t) = 2\pi(\frac{m}{2})^{1/2} (\frac{R}{r})^2 \int E^{1/2} j(R, \alpha, E, t) \sin^3\alpha \, dE \, d\alpha \tag{3}$$

This is an approximate expression that can be used to evaluate the pressure of the energetic particles on the local magnetic field lines.

Assuming a cosine pitch angle distribution (which seems to be the case most of the time |10|) $j(R,\alpha , E, t) = j(R, E, t) \cos\alpha$, and a power low differential energy spectrum (reflecting the diffusive propagation of the particles) $j(R, E, t) \approx E^{-\gamma}$ where $\gamma > 0$, we can integrate equation (3):

$$P_\perp(r, t) = \pi(\frac{m}{2})^{1/2} \frac{j(R, E_1, t)}{1 - 2\gamma} \left[E_2^{3/2}\left(\frac{E_1}{E_2}\right)^\gamma - E_1^{3/2}\right]\left(\frac{R}{r}\right)^2 \tag{4}$$

E_1 and E_2 are two arbitrary limits in the energy spectrum.

For the case of Aug. 4, 1972 solar cosmic ray event (one of the strongest ever recorded |11|) we used $j(R, E_1, t)$ at $R = 1$ AU shown in Fig. 2 which after a least squares fit, gives $\gamma = 2.16$. For this case equation (4) is plotted in Fig. 3. This result will be used later to compare to the magnetic field strength.

INTERPLANETARY MAGNETIC FIELD

We first try to develope a model for the interplanetary magnetic field. The Faraday' low of induction when written in the frame of reference of the rotating Sun, yields:

$$\nabla \times \underset{\sim}{E} = 0$$

This result, combined with another of Maxwell's equation, considering a charge neutrality in space:

$$\nabla \cdot \underset{\sim}{E} = 0$$

indicates that near the photosphere the interplanetary electric field $\underset{\sim}{E}$ does not change the energy of particles and that $\underset{\sim}{E}$ is normal to the radial direction of the Sun. Therefore, in the reference frame of the Sun, charged particles do not "feel" an effective electric field.

Ohm's law gives

$$\underset{\sim}{j} = \sigma\underset{\sim}{E}' = \sigma(\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B})$$

For the case of a perfectly-conducting solar wind: $\underset{\sim}{E} = - \underset{\sim}{v} \times \underset{\sim}{B}$ However, in the reference frame of the rotating Sun, the charged particles <u>slide</u> along the field lines. This means

$$\underset{\sim}{v} \times \underset{\sim}{B} = 0 \qquad (5)$$

which tells us that, in fact the interplanetary electric field is zero everywhere in the reference frame of the Sun.

We shall work now with a third law of the Maxwell equations:

$$\nabla \cdot \underset{\sim}{B} = 0$$

This equation can be written in spherical coordinates considering only points on the eliptic plane ($\theta = \frac{\pi}{2}$) and also assuming that $\underset{\sim}{B}$ does not have a component normal to the eliptic.

$$\frac{1}{r^2}\frac{\partial(r^2 B_r)}{\partial r} + \frac{1}{r}\frac{\partial B_\phi}{\partial \phi} = 0 \qquad (6)$$

On the other hand, the θ component of equation (5) yields:

$$V_\phi B_r - v_r B_\phi = 0$$

The azimuthal component of the solar wind is given by:

$$v_\phi = |\underset{\sim}{\omega} - \underset{\sim}{\Omega}|r$$

where:

$\underset{\sim}{\omega}$ = angular velocity of the solar wind

$\underset{\sim}{\Omega}$ = angular velocity of the Sun

Hence:

$$B_\phi = \frac{|\underset{\sim}{\omega} - \underset{\sim}{\Omega}|r}{v_r} B_r$$

Equations (6) can be solved assuming azimuthal symmetry $(\frac{\partial B_\phi}{\partial \phi} = 0)$. The result is

$$B_r = \frac{R_0^2 B_0}{r^2} \tag{7}$$

On an inner boundary surface near the photosphere ($r = R_o$) the radial component B_r of the field becomes the total field $B_r = B_o$ such that $B_\phi = 0$, hence:

$$B_\phi = |\underset{\sim}{\omega} - \underset{\sim}{\Omega}| \frac{B_0}{v_r} \left(\frac{R_0}{r}\right)^2 \quad (r - R_0) \tag{8}$$

Equations (7) and (8) are identical to those obtained by Dessler |13| when $\underset{\sim}{\omega} = 0$ and $v_r = v$. These last conditions become nearly true for large values of r. In fact the angular velocity of the solar wind ω drops off very rapidly with distance as shown in figure 4 |14|.

For a quiet time magnetic field we took the Parker's solution |15| of the solar wind v_r for an isothermal corona, $T = 10^6\ {}^0K$, shown in figure 5.

We can calculate the magnetic pressure associated with each component B_r and B_ϕ. The result is shown in figure 6 where P_{Br} and $P_{B\phi}$, respectively, are the magnetic pressures mentioned above. They are shown normalized to the total pressure $P_B = \frac{B_0}{2\mu_0}$. This result is interesting because it confirms the spiral configuration of the interplanetary magnetic field, where the pressure associated with the radial component is larger than the azimuthal component of the field. The fact that both components are of the same strength near 1 AU is only a consequence of the conditions imposed upon equation (7) and (8).

Figure 7 shows the total magnetic pressure, as a function of distance (in astronomical units), computed using (7) and (8).

PARTICLE PRESSURE VERSUS MAGNETIC FIELD PRESSURE

We now compare the results obtained in the last two sections. In particular, we are interested in knowing whether the particle pressure prevails over the magnetic pressure, or viceversa, at different points in space. In other words, it is interest to know the relationship that exists between the particle pressure and field pressure as a function of heliocentric distance. We can make this comparison for the case of August 4, 1972 event for which we had computed the particle pressure shown in figure 3. Figure 8 displays the result of such comparison. Notice that near the Sun the magnetic pressure is stronger than the pressure on the field lines due to the energetic particles. However, at distances larger than 10^{-1} AU the particle pressure prevails upon the field. This means that more energy from the particles is available to distort the field configuration than there is available magnetic energy to react against the distortion. Hence, it is likely that a rearrangement of the field lines may have taken place, due to the action of the propagating energetic protons.

Likewise, figure 9 shows the result of the relationship between the proton and field pressures corresponding to a solar flare-related event of July 7, 1966 |16|. Although the differential energy spectra of both events corresponded to energetic protons released during the corresponding solar flares, only the event of August, 1972 produced a ESP event. Notice that the magnetic field pressure prevails inside, and well outside, the earth's orbit. In this case a modification of the configuration of the interplanetary field lines is unlikely to have taken place.

DISCUSSION AND SUMMARY

It has been demonstrated that certain proton events can modify the configuration of the ambient magnetic field lines. Since the particles are propagating following the gross structure of the interplanetary field, the rearrangement of these lines will follow the same direction. The net effect will be to smooth out the microstructure of the magnetic field. The question is what is the size of the inhomogeneities that can be smoothed by this process? In order to answer this question we consider two extreme cases. First, suppose that the gyroradius of the propagating particles is much greater than the scale length (any representative length) of the field inhomogeneities. In this case the particle will not "feel" anything and will keep propagating along the main component of the magnetic field. Next, suppose the gyroradius is much smaller than the scale length of the inhomogeneities. Here also the particles will propagate along the inhomogeneities except that the particles will behave like a moving fluid and hence "make feel" their pressure on the "container", modifying its shape in the same way that a garden hose reacts to the outgoing water. Therefore it seems reasonable to state that energetic protons from strong solar flare events can smooth out inhomogeneities of a size smaller than the gyroradii of the particles.

We can summarize our results as follows:

We have investigated the possibility of a field line smoothing mechanism via energetic particle propagation along magnetic field lines. For this purpose we have derived a theoretical expression for the particle pressure on the field lines and applied it to the well known August 4, 1972 solar proton event. We have also developed a simplified model for the interplanetary magnetic field in order to have a quantitative estimate of the magnetic field pressure at all points in the interplanetary space. Next, we have compared the particle and field pressures, having found that, at least for the strong event of August, 1972, the particle pressure was predominant over the field pressure starting at heliocentric distances of 10^{-1} AU and all the way out. The same computation has been performed for another solar flare-generated proton event (July 17, 1966), which did not have strong characteristics. We found in this case that the magnetic pressure prevailed inside (and far outside) 1 AU. The difference between both solar events is that the one of August 1972 produced a ESP event |7| while none was observable for the July 1966 case.

It is concluded, therefore, based only on pressure criteria, that certain solar flare-related proton events can produce smoothing or rearrangements in the ambient magnetic field lines.

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FIGURES CAPTIONS

Fig. 1 - Proton data for three different events. The arrows indicate the time of the shock wave arrival (SC) and the responsible flare(F). The ESP peak-arrows are the energetic storm particle events.

Fig. 2 - Proton spectrum measured on OV5-6 Satellite corresponding to one of the strongest solar cosmic ray events |12|.

Fig. 3 - Particle's pressure on the magnetic field lines as a function of the distance from the Sun for the August 4, 1972 event computed from equation (4).

Fig. 4 - Angular velocity of the solar wind as a function of radial distance from the Sun |14|.

Fig. 5 - Solar wind speed as a function of distance from the Sun. The distances are given in solar radii |15|.

Fig. 6 - Normalized magnetic pressures associated with the radial component B_r and azimuthal component B_ϕ of the interplanetary $\underset{\sim}{B}$ field. The heliocentric distance R is given in astronomical units (AU).

Fig. 7 - Total B-field pressure on the ecliptic plane as function of the heliocentric distance R in AU.

Fig. 8 - Comparison between the particle pressure P_{protons} for the August 4, 1973 event and the magnetic field pressure P_B at different points in the interplanetary space.

Fig. 9 - Same as figure 8 for the case of July 7, 1966 event. Both proton events originated during solar flares.

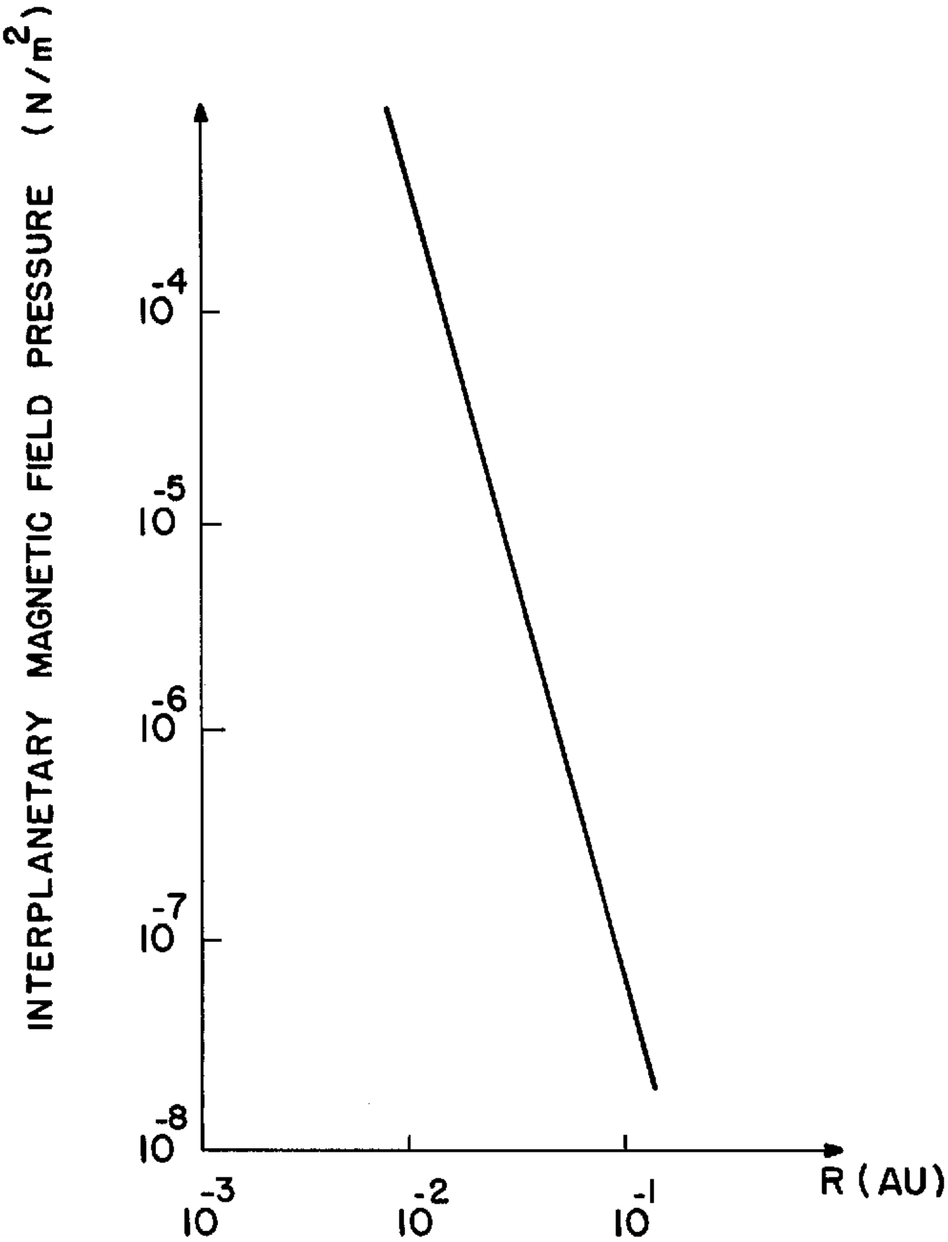

INTERPLANETARY MAGNETIC FIELD PRESSURE (N/m²)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻³
10⁻²
10⁻¹
R (AU)

Figure 7

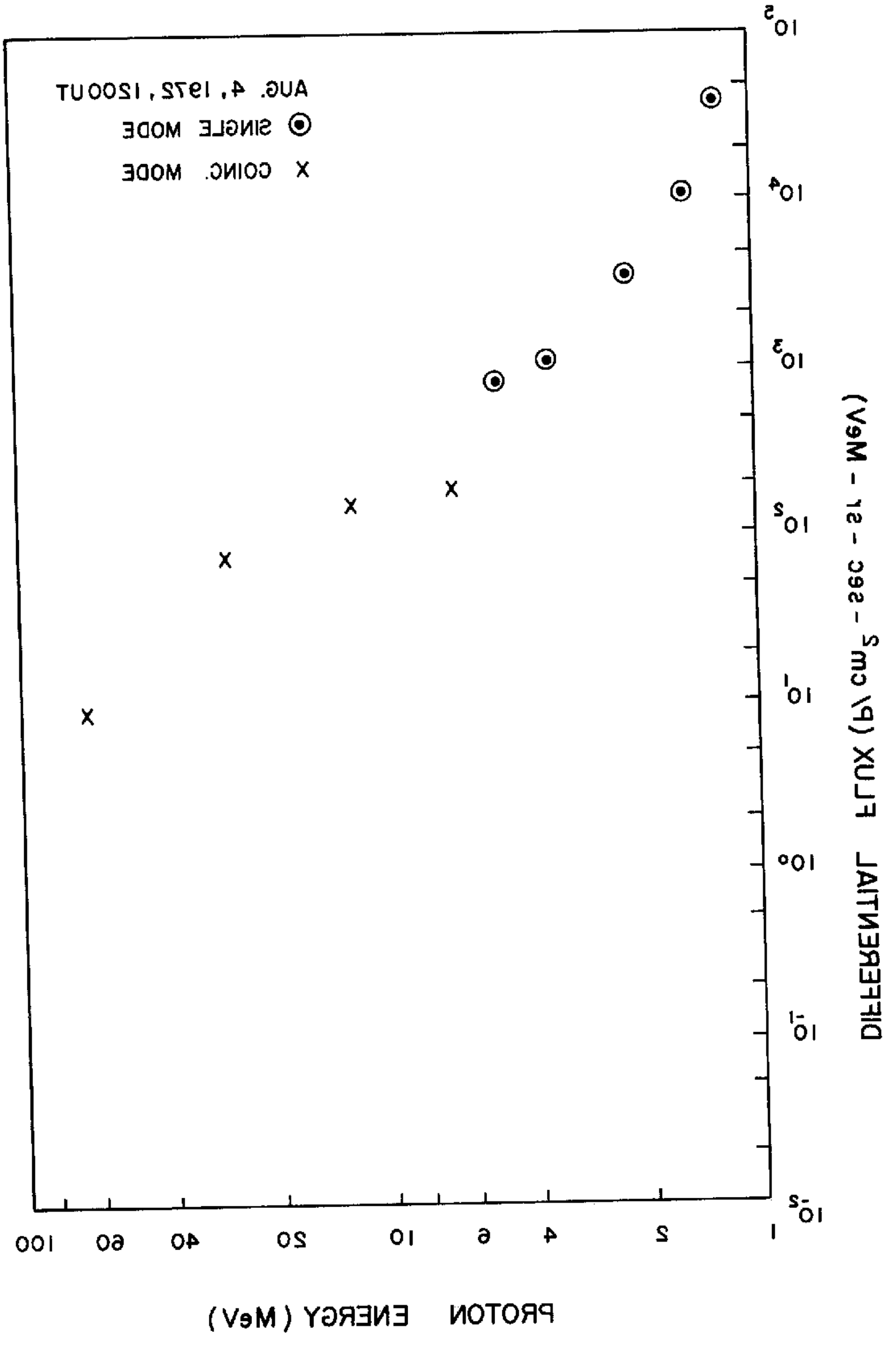

AUG. 4, 1972, 1200 UT
⊙ SINGLE MODE
X COINC. MODE
DIFFERENTIAL FLUX (P/cm^2 - sec - sr - MeV)
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
PROTON ENERGY (MeV)
1
2
4
6
10
20
40
60
100

Figure 2

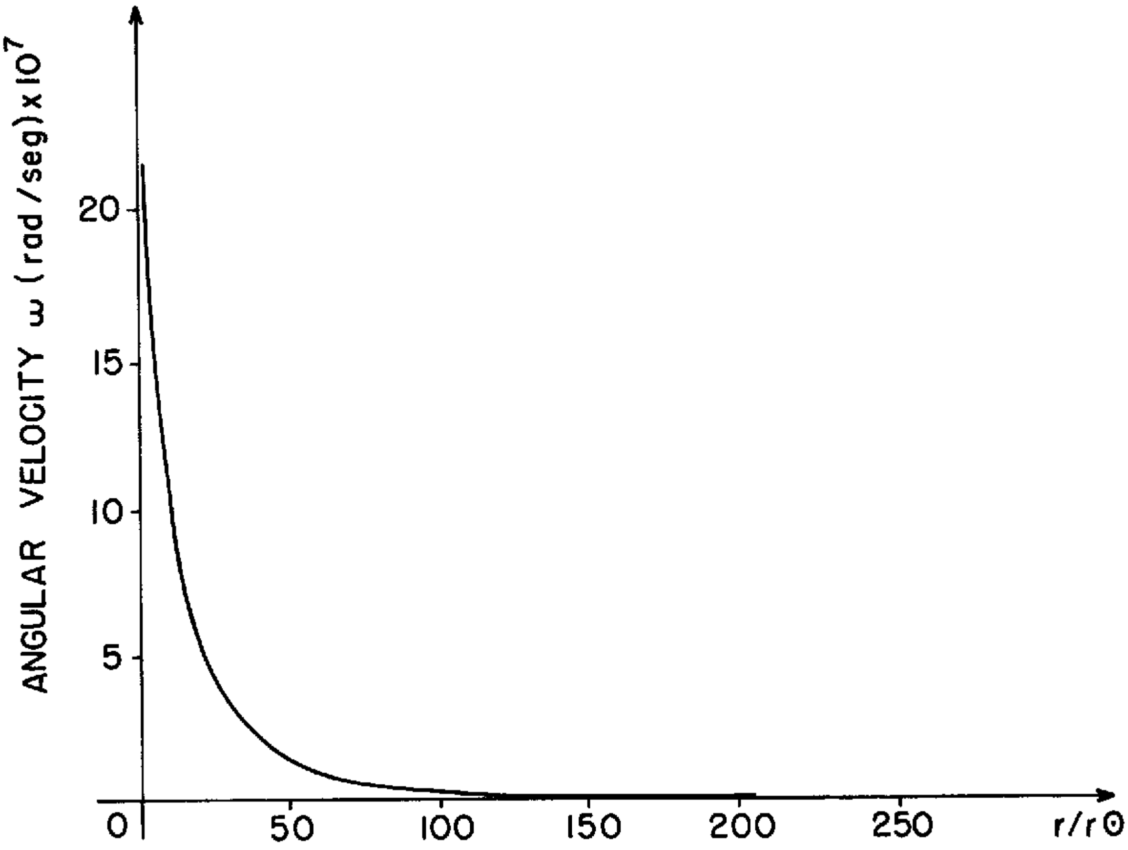

ANGULAR VELOCITY ω (rad/seg) x 10^7
20
15
10
5
0
50
100
150
200
250
r/r0

Figure 4

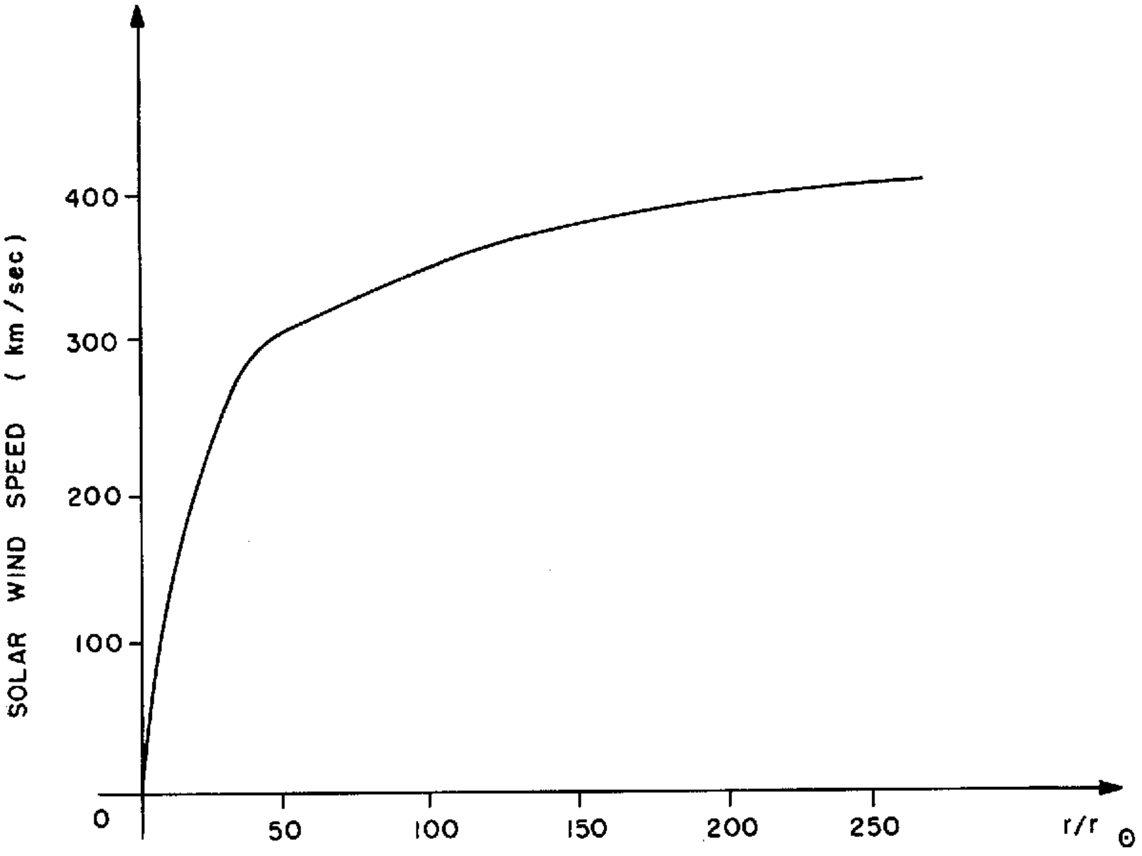


Figure 5

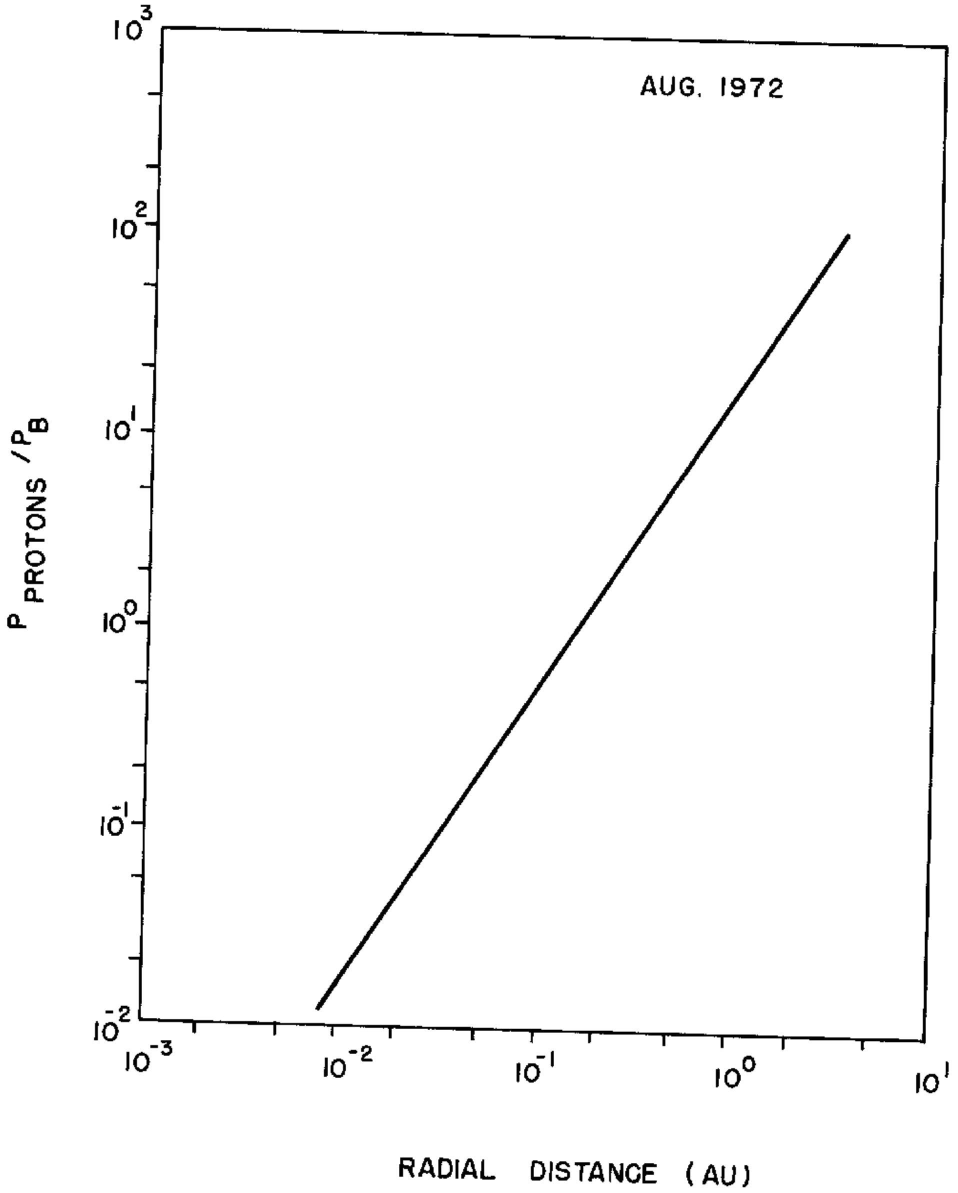

AUG. 1972
$P_{PROTONS} / P_B$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
RADIAL DISTANCE (AU)

Figure 8

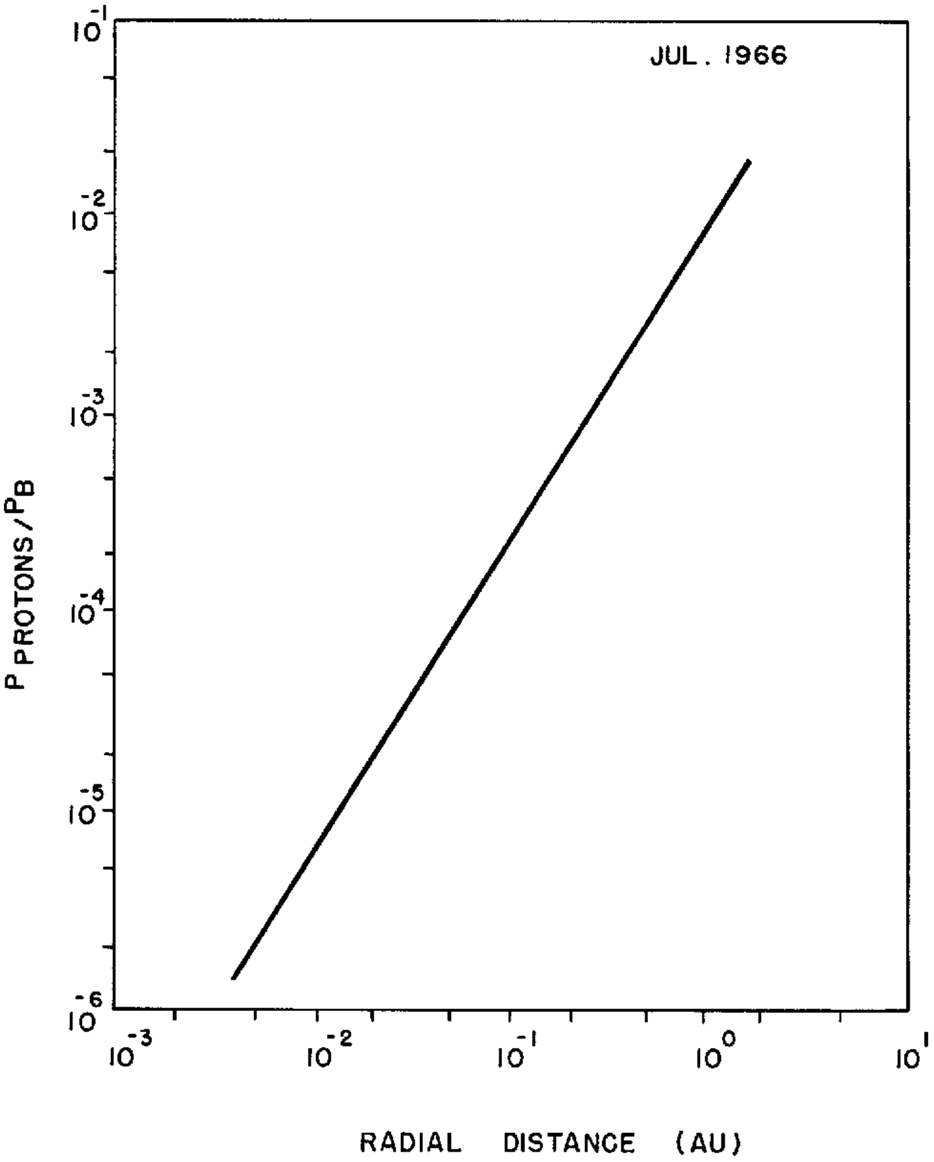
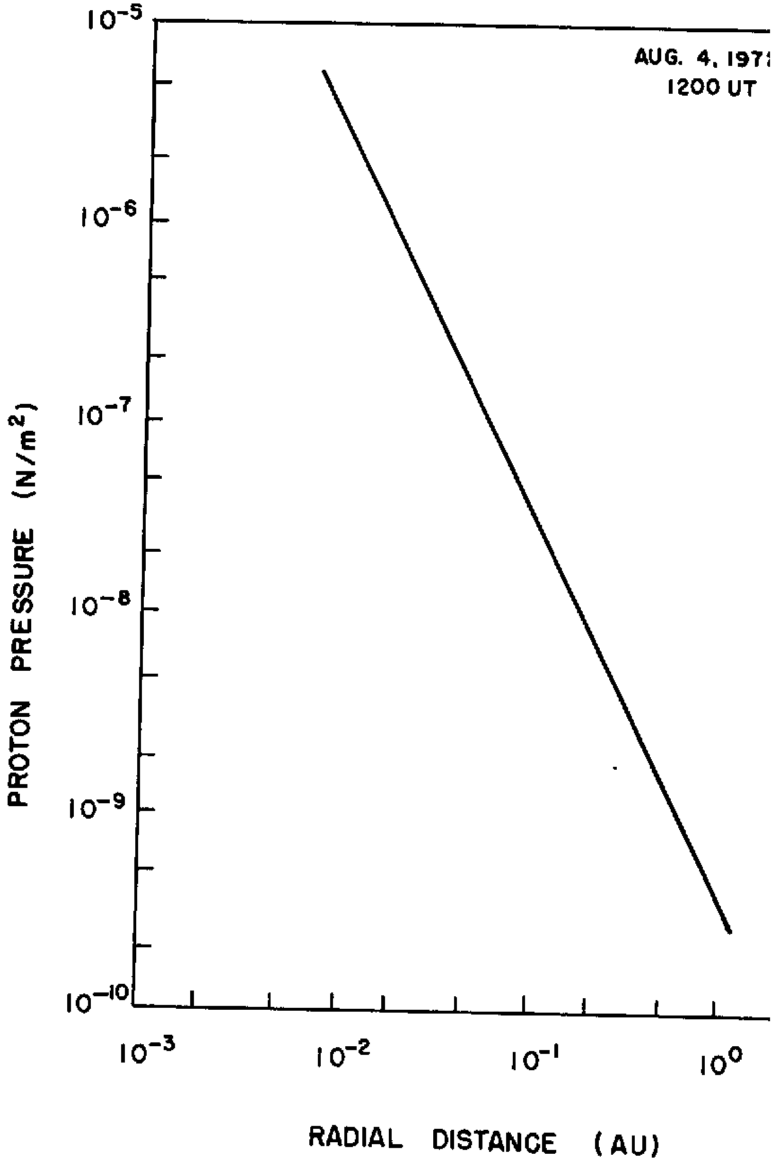
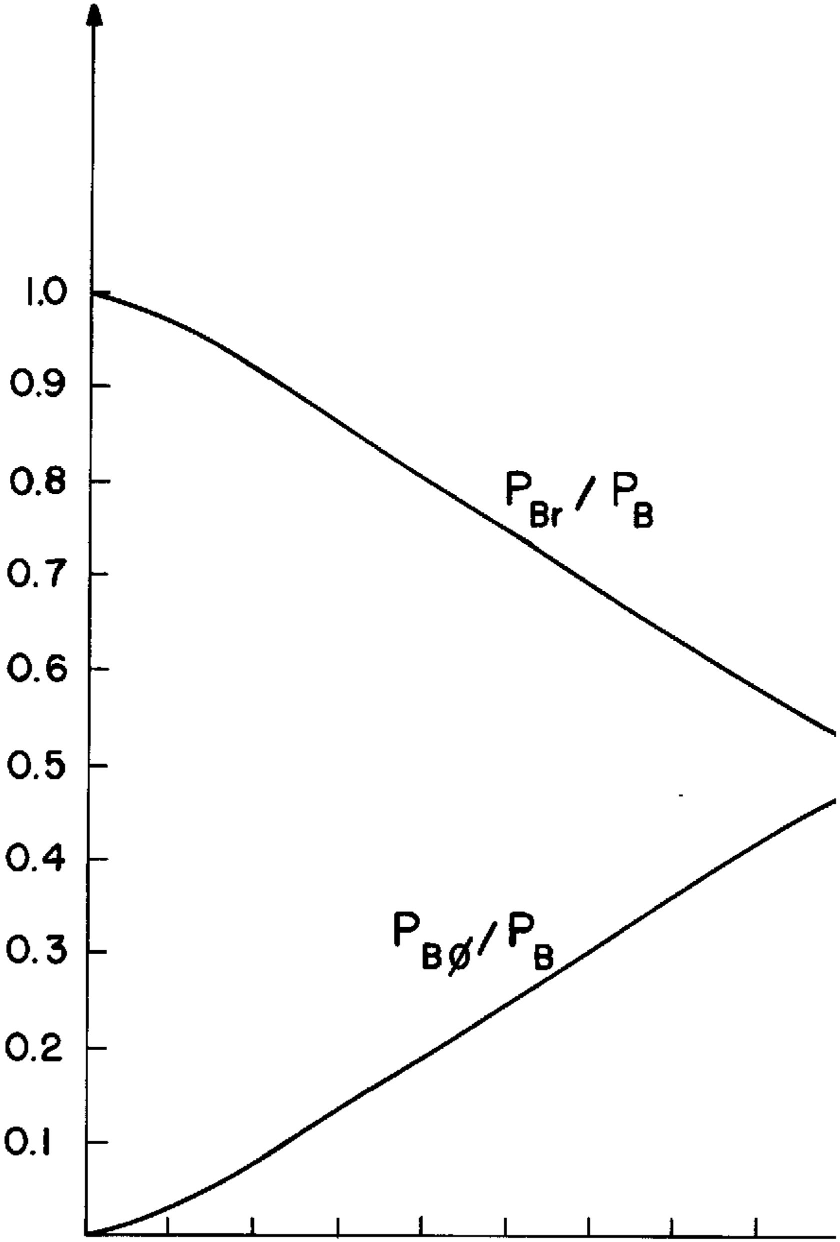

JUL. 1966
$P_{PROTONS}/P_B$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
RADIAL DISTANCE (AU)

Figure 9


AUG. 4, 197
1200 UT
PROTON PRESSURE (N/m^2)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-3}
10^{-2}
10^{-1}
10^{0}
RADIAL DISTANCE (AU)


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
P_{Br} / P_B
$P_{B\phi} / P_B$

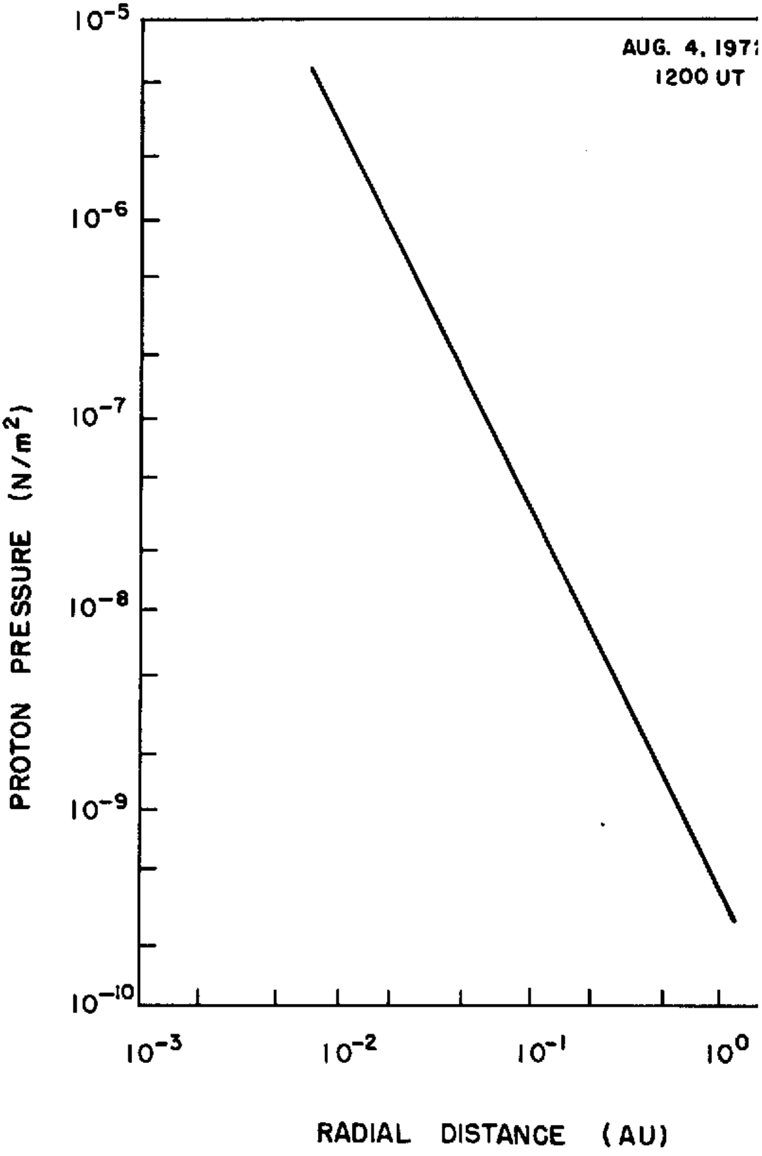

AUG. 4, 197
1200 UT
PROTON PRESSURE (N/m²)
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻³
10⁻²
10⁻¹
10⁰
RADIAL DISTANCE (AU)

Figure 3