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Abstract

A simple model of solar flare radiation event particle transport is developed to permit the calculation of fluxes and related quantities as a function of distance from the sun (R). This model assumes the particles spiral around the solar magnetic field lines with a constant pitch angle. The particle angular distributions and onset plus arrival times as functions of energy at 1 AU agree with observations if the pitch angle distribution peaks near 90°. As a consequence the time dependence factor is essentially proportional to R^{-1.7}, (R in AU), and the event flux is proportional to R⁻².

$$\left. \begin{matrix} \alpha \\ n \\ m \end{matrix} \right\} \text{approximately constants}$$

If the characteristics of the largest solar flare particle events are used to evaluate α , n , and m , the values obtained are approximately 0.022, 0.4, and 0.75, respectively. An attempt to incorporate the variations of these quantities due to radiation event size led to the relationships⁽³⁾

$$\begin{aligned} \alpha &= A^{-0.224} \\ m &= 16A^{-0.16} \end{aligned}$$

I. Introduction

Solar flare particle events constitute one of the important sources of natural nuclear radiation at 1 AU from the sun. Approximately 100 such events have been observed at the earth (see Table I),⁽¹⁾ ranging up to $\sim 10^{10}$ protons/cm²-event above 10 Mev. Various particle flux models have been developed describing the time and energy behavior observed at 1 AU. These models, coupled with prediction mechanisms (usually correlated to sunspot numbers) have been used to estimate the expected solar flare particle environment at 1 AU for future space missions. These techniques have also been used for missions to Mars (1.5 AU) and Venus (0.7 AU).

where all quantities are as previously defined. Incorporation of these relationships in Equation (1) yields formulae which account for the shorter rise and decay times and steeper energy spectra for the smaller events. However, the smaller event characteristics vary so much that generalizations are difficult and attempts to account for the size-dependent characteristics are generally more trouble than they are worth.

Based on Equation (1), the following relations have been derived:

$$\phi(>E_0) = \frac{A}{\alpha^2 E_0^m + 2n} \sim \frac{2100 A}{E_0^{1.55}} \frac{\text{particles}}{\text{cm}^2} \quad (2)$$

$$t_{\text{rise}} = \frac{1}{\alpha E_0^n} = \frac{45}{E_0^{0.4}} \text{ hr}$$

$$\tau_{\text{decay}} = \frac{2.15}{E_0^n} = \frac{100}{E_0^{0.4}} \text{ hr}$$

$$\hat{\phi}(>E_0) = \frac{A e^{-1}}{\alpha E_0^m + n} = \frac{17 A}{E_0^{1.15}} \frac{\text{particles}}{\text{cm}^2\text{-hr}} \quad (3)$$

$$\phi(E) = \frac{3200 A}{E^{2.55}} \text{ particles/cm}^2\text{-Mev} \quad (4)$$

$$\begin{aligned} \phi(E,t) &= A t e^{-0.022E^{0.4}t} \\ &\cdot (0.75 + 0.0088 t E^{0.4}) \frac{\text{particles}}{\text{cm}^2\text{-hr-Mev}} \end{aligned} \quad (5)$$

For missions which involve sending spacecraft far from 1 AU (e.g., the Mercury-Venus and the Outer Planet missions), the solar flare particle model developed from observations at 1 AU is not adequate. Specifically, the dependence of the solar flare particle event model on distance from the sun must be incorporated. This paper presents a simple model for incorporating this spatial dependence which agrees with the observations at 1 AU.

II. Model at 1 AU

The flux of solar flare particles observed at 1 AU is observed to rise quasi-linearly over a period of some hours to a peak value, then decay approximately exponentially over an appreciably longer period. The onset, rise, and characteristic decay times are functions of particle energy. A previously developed mathematical expression which has these characteristics is:⁽²⁾

$$\phi(>E_0, t) = \frac{A t e^{-\alpha E_0^n t}}{E_0^m} \frac{\text{particles}}{\text{cm}^2\text{-hr}} \quad (1)$$

where E_0 is the particle energy(Mev)
 t is the time from the arrival of the first particles (hrs)
 A is a normalization factor

These relationships have proven useful when applied to large solar flare radiation events at 1 AU. In particular, they have been applied to events for which the data was incomplete--some of the numbers in Table I were obtained this way.

These formulae have no dependence on the distance from the sun, and are therefore strictly

applicable to 1 AU only. In the following sections, modifications of these formulae to account for distance from the sun are discussed.

III. Particle Transport

In order to account for the dependence of the solar flare particle event model on distance from the sun, it is necessary to have a particle transport model. Since particle acceleration and particle transport are related during the acceleration portion of the particle event, it is desirable to go back to the solar flare itself.

A solar flare is an event observed to take place above the photosphere of the sun, generally lasting ≤ 20 minutes. The flare, which is most readily observed at the Lyman - α wavelength of ionized hydrogen ($\sim 1215 \text{ \AA}$) is believed to derive its energy from the collapse of the magnetic fields associated with sunspots. Various theories have been advanced to account for the acceleration of charged particles during or as a result of a solar flare. Among these theories are betatron acceleration and shock wave acceleration. In betatron acceleration, a charged particle orbiting above a collapsing sunspot gains energy as in a laboratory particle accelerator of the same name. In shock wave acceleration the absorption of the Lyman - α photons in the inner corona produces a supersonic blast wave which accelerates the charged particles. These proton acceleration mechanisms have been investigated by Gold,⁽⁴⁾ Wentzel,⁽⁵⁾ Parker,⁽⁶⁾ Weddell,⁽⁷⁾ and others. The evidence is not conclusive for any single mechanism, and both betatron and shock wave accelerations probably contribute.

Once the charged particles have been accelerated, their propagation away from the sun is controlled by the interplanetary magnetic fields. These interplanetary fields are complex, having time and spatial dependences which are not well known. However, by making some simplifying assumptions, it is possible to obtain a spatially dependent solar flare particle model.

If it is assumed that the quiet sun interplanetary magnetic field is essentially undisturbed during the propagation of the solar flare protons, it is possible to write:

$$B = \sqrt{\left(\frac{B_r}{R^2}\right)^2 + \left(\frac{B_\theta}{R}\right)^2}$$

$$Bq v_\perp = \frac{m v_\perp}{r}$$

$$J = m v_\perp r$$

$$v_\perp = v \sin \beta$$

$$v_\parallel = v \cos \beta$$

where

B is the solar magnetic field (webers/m²)

B_r is the radial component of B (webers/m²)
(see Figure 1)

B_θ is the aximuthal component of B (webers/m²)

R is the distance from the sun (AU)

q is the charge of the particles (coulombs)

v is the velocity of the charged particles (meters/sec)

v_⊥ is the perpendicular component of v (meters/sec)

v_∥ is the parallel component of v (meters/sec)

β is the pitch angle (angle v makes with the guiding center line of B). Since B_r ≈ B_θ ≈ 3.5 × 10⁻⁹ webers/m² (3.5 gammas) at 1 AU, B_θ is ≈ 5 gammas, and the gyroradius is 2.75 × 10⁷ √E meters, where E is in Mev. The gyroradius as a function of distance from the sun is approximately

$$r = 3.9 \times 10^7 R^2 \sqrt{\frac{E}{1 + R^2}} \text{ meters} \quad (6)$$

This function is plotted in Figure 2.

Assuming the particles spiral around the magnetic lines of force, it is expected that their gyroradius will increase as their distance from the sun increases. Based upon the above equations it is expected that their pitch angle β will decrease with distance from the sun, according to the well-known relationship.

$$\frac{J q}{2 m E} = \frac{\sin^2 \beta}{B} = \text{constant}$$

However, the pitch angle (β) cannot exceed 90°. If the charged particle has this limiting angle close to the sun, its pitch angle might be expected to become quite small by the time it reaches 1 AU. If a particle has a pitch angle of 90° starting at 10 solar radii, the calculated pitch angle will be ~ 3° by the time it reaches 1 AU (~ 215 solar radii) according to this model. Since solar flare event particles are observed at 1 AU to be essentially isotropic after the flux peak, this simplified model is clearly unrealistic.

It is possible to obtain reasonable agreement with observations at 1 AU by making the assumption that the pitch angle is independent of distance from the sun. This accounts for the fact that particles of a given energy with small pitch angles will arrive first (as is observed), and the resultant particle angular distributions spread as functions of time. To the extent that this model appears to agree with the observations at 1 AU, it may be useful for calculating the spatial dependence of solar flare particle radiation.

The transit time (t_{tr}) as a function of particle energy and pitch angle (both assumed to be constants of the motion) is

$$t_{tr} = \frac{s}{v_\parallel}$$

where s is the length of the line of magnetic flux which serves as the guiding center for the particle gyrorotation. This length(s) may be calculated from the relationship:

$$s = \int ds = \int \sqrt{(dr)^2 + (r d\theta)^2}$$

But since

$$\tan^{-1} \frac{r d\theta}{dr} = \tan^{-1} \frac{B_\theta}{B_r} = \tan^{-1} R$$

$$r d\theta = R dr$$

Therefore

$$s = \int_{r=0}^{r=R} dr \sqrt{1 + R^2}$$

$$= \frac{1}{2} \left[R \sqrt{1 + R^2} + \log (R + \sqrt{1 + R^2}) \right] \quad (7)$$

When the distance from the sun (R) is small the two terms are approximately equal in value, but as the distance from the sun increases, the first term predominates. This function is graphically displayed in Figure 3. A reasonable approximation is:

$$s \sim R \sqrt{1 + \frac{R^2}{4}} \quad (8)$$

If it is assumed that the pitch angle (β) of the particle is a constant of the motion, the transit time as a function of pitch angle and particle energy may be calculated. Based on Equation (7), the result is (for protons):

$$t_{tr} = 5.5 \times 10^3 \frac{\left[R \sqrt{1 + R^2} + \log (R + \sqrt{1 + R^2}) \right]}{\sqrt{E} \cos \beta} \text{ seconds} \quad (9)$$

where R is in AU and E is in Mev. With only a few percent error in the region of interest (0.1 - 10 AU) this may be approximated by

$$t_{tr} = 1.1 \times 10^4 \frac{R}{\sqrt{E} \cos \beta} \sqrt{1 + \frac{R^2}{4}} \text{ seconds} \quad (10)$$

Values of this function are listed in Tables II-IV, and are plotted in Figures (4) to (6). These figures show the expected dependence on proton energy (E), pitch angle (β), and distance from the sun (R). In principle, this expression may be solved to obtain any of the quantities as functions of the others. The quantity of major interest is the proton flux as a function of these parameters. This is determined by the initial proton distribution in β , assuming no protons are lost after being accelerated.

If no particles are lost after being accelerated, the total number per cm^2 per event is expected to be proportional to R^{-2} (R = distance from the sun in AU). Assuming an R^2 time-integrated spatial dependence effectively makes the solar flare particle event probability spatially independent. Any other assumption introduces the complication of a spatially dependent probability

function. Since the time-integrated particle flux for a mission is essentially the product of the flux per event and the probability of that event, little, if anything, is gained by considering a spatially dependent particle event probability.

If a significant fraction of solar flare particles is lost after being accelerated, the flux per event will exhibit an R^{-n} spatial dependence where $n > 2$ over the region where particle loss is important. The major probable loss mechanism is collision with objects in space (magnetospheres, planets, moons, etc.) Considering the relative emptiness of space this is not expected to be a major loss mechanism. Even the asteroid belt is only $\sim 10^{-6}$ opaque, which means that the solar flare particle traversing it will be small. (It may not be completely negligible, however, since the proton helical path length through the asteroid belts will be \sim two orders of magnitude larger than that of a solar photon). The probability of a solar flare particle encountering a planet, even assuming the particles are essentially confined to the ecliptic plane is $< 1\%$.

It is interesting to calculate the pitch angle which corresponds to the peak flux rate. At 1 AU the onset + rise time (time from the flare on the sun to the peak flux rate) is approximately:

$$t_{rise} \sim \frac{45}{E_0^{0.4}} \text{ hrs}$$

where E_0 is the proton energy in Mev. (This relationship was obtained by averaging the values observed for the largest radiation events--smaller events often have shorter onset + rise times). Since the proton transit time (given by Equation 9) is proportional to $E^{-0.5}$, there is apparently a constant delay time to be added. A little arithmetic shows that this delay time is $860/\cos \beta$ seconds. Thus:

$$t_{rise} = t_{tr} + \frac{860}{\cos \beta} \text{ seconds}$$

This accounts for the acceleration time during which the protons do not migrate away from the sun significantly as well as the time between the arrival of the first protons of a given energy and the peak flux of these protons. It will be noted that a fairly steep proton energy spectrum has been assumed (based on observations at 1 AU), since the onset + rise time for particles above energy E_0 is taken to be essentially that of particles of energy E_0 .

For 1, 10, and 100 Mev protons at 1 AU, the observed onset + rise times (t_{rise}) are $\sim 1.6 \times 10^5$ seconds, $\sim 6.5 \times 10^4$ seconds, and $\sim 2.6 \times 10^4$ seconds, respectively. The corresponding transit times are $\sim 1.5 \times 10^3$ seconds, $\sim 5.2 \times 10^4$ seconds, and $\sim 1.5 \times 10^4$ seconds. These are the transit times for protons with pitch angles of $\sim 86^\circ$. It will be noted that any change of pitch angle as the protons migrate away from the sun will decrease the transit time below that observed. Thus, unless there is some mechanism which acts to increase the

pitch angles of protons as they move away from the sun, the assumption of constant pitch angle appears to be superior to any obvious simple alternative. Also noteworthy, is that beyond 2 AU solar flares on the back side of the sun can be important sources of particles.

Another interesting conclusion, valid to the extent that the assumption of a constant pitch angle is valid is that the bulk of the protons have pitch angles close to 90° . Based upon Equation (2), only $\sim 26\%$ of the protons above a given energy have arrived at 1 AU by the time the peak flux rate of these protons has been reached. Thus, $\sim 74\%$ of the protons observed at 1 AU appear to have pitch angles between 86° and 90° . Assuming a random distribution of proton velocity directions prior to acceleration, a $\sin \beta$ pitch angle distribution would be expected from solid angle considerations. Apparently, the acceleration mechanism favors particles with pitch angles close to 90° . This seems to favor the betatron acceleration mechanism over the shock wave acceleration mechanism. However, since the constant pitch angle assumption is merely a simplified model, any conclusions based upon it must be considered uncertain.

The maximum pitch angle determines the limits of the particle angular distribution as a function of time and energy. The particle angular distribution within these time and energy dependent limits according to this model is determined by the initial particle pitch angle distribution. However, not enough angular distribution information is available to derive statistically meaningful pitch angle distributions as functions of time and energy. When such data becomes available, its incorporation into this model is straightforward.

IV. Spatially Dependent Model

It is now possible to use the transport model to calculate the parameters of the solar flare particle radiation as functions of distance from the sun. Since the pitch angle is assumed to remain constant, so does v_{\parallel} (the particle velocity parallel to the line of magnetic force which serves as the gyrorotation guiding center). The time for a particle to reach a given distance from the sun is simply proportional to the spiral path length (given by Equation 7). Thus, the time dependence of the solar flare particle flux is expected to be

$$t' \sim \frac{t}{f(R)} + t_0$$

where $f(R)$ is given by Equation (7) and t_0 is $\sim 1.2 \times 10^4$ sec. It is, therefore, possible to rewrite Equations (1) to (5) incorporating R (the distance from the sun, as a parameter). The results are: (8)

$$\phi(>E_0, t) = \frac{A (t-t_0) e^{-\alpha E_0^m f^{-1}(R) t}}{R^2 f^2(R) E_0^m} \quad (11)$$

$$\sim \frac{A (t-t_0) e^{-0.022E_0^{0.4} f^{-1}(R) t}}{R^2 f^2(R) E_0^{0.75}} \quad \frac{\text{particles}}{\text{cm}^2\text{-hr}}$$

$$\int \phi(>E_0) = \frac{A}{\alpha^2 R^2 E_0^m + 2n} \sim \frac{2100 A}{R^2 E^{1.55}} \frac{\text{particles}}{\text{cm}^2} \quad (12)$$

$$t_{\text{rise}} = \frac{1}{\alpha E_0^n f(R)} + t_0 \sim \frac{45}{E_0^{0.4} f(R)} \text{ hrs} \quad (13)$$

$$\tau_{\text{decay}} = \frac{2.15}{\alpha E_0^n f(R)} \sim \frac{100}{E_0^{0.4} f(R)} \text{ hrs} \quad (14)$$

$$\hat{\phi}(<E_0) = \frac{A e^{-1}}{\alpha f(R) E_0^m + n} \sim \frac{17 A}{f(R) E_0^{1.15}} \frac{\text{particles}}{\text{cm}^2\text{-hr}} \quad (15)$$

$$\phi(E) = \frac{3200 A}{R^2 E^{2.55}} \frac{\text{particles}}{\text{cm}^2\text{-Mev}} \quad (16)$$

$$\phi(E, t) = \frac{A t e^{-0.022E^{0.4} f^{-1}(R) t}}{R^2 E^{1.75}}$$

$$\left[0.75 + 0.0088 t f^{-1}(R) E^{0.4} \right] \frac{\text{particles}}{\text{cm}^2\text{-hr-Mev}} \quad (17)$$

where all symbols have been previously identified. As mentioned previously, $f(R)$ can be approximated by

$$f(R) \sim R \sqrt{1 + \frac{R^2}{4}}$$

For $R > 1$, this may be further approximated by $R^{1.7}$ with $\leq 15\%$ error at 1 AU and a smaller error for $1 < R < 5$.

The relative spatial dependences of the time-integrated particle flux rate ($\propto R^{-2} f^{-2}(R)$) are shown in Figure 7. These curves show that the relative solar flare particle environment becomes severe as the sun is approached. For the largest such particle event observed at 1 AU (11-12-60), the peak and time-integrated proton fluxes above 10 Mev at Mercury (~ 0.4 AU) would be $\sim 7.2 \times 10^5$ p/cm²-sec and $\sim 6.3 \times 10^{10}$ p/cm², respectively -- enough to affect sensitive spacecraft components. For this same event the corresponding numbers at Jupiter (~ 5.2 AU) would be 120 p/cm²-sec and 3.7×10^8 p/cm², which should cause no trouble.

It will be noted that particle loss and change of particle energy after acceleration have been neglected. If either of these changes takes place (and there is some evidence that they do), the solar flare particle environment as the sun is approached will be even more severe than here calculated. Conversely, at distances greater than 1 AU, the environment may very well be less severe than expected.

V. Conclusions

The solar flare particle event model developed to fit the observed data at 1 AU has been modified to account for the distance from the sun. This was accomplished by assuming each flare particle independently spirals around the solar magnetic field (carried frozen-in by the solar wind), while maintaining its pitch angle constant. Among the consequences of this transport model are:

- (a) The majority of the solar flare particles have pitch angles close to 90° . Calculated pitch angle particle distributions as a function of time agree fairly well with observations at 1 AU.
- (b) The solar flare particle flux rate is quite dependent on distance from the sun ($\sim R^{-3.7}$), while the time integrated particle flux obeys the expected inverse square distance relationship (R^{-2}).
- (c) The solar flare particle energy spectra are essentially independent of distance from the sun, since particle losses after acceleration are neglected. Some particle losses probably occur, leading to a softening of the energy spectra and larger flux spatial dependences than herein calculated.

This solar flare particle event model is directly applicable to missions which involve sending a spacecraft on missions in the ecliptic plane far from 1 AU from the sun. It is particularly applicable to missions to Mercury and to the outer planets. It is not intended to apply far from the ecliptic plane or past the heliosphere. Within these limits it provides an easy-to-use improvement over spatially independent models.

VI. Nomenclature

A	Normalization factor for solar flare particle event model
AU	Astronomical unit (1.5×10^8 km)
B	Solar magnetic field strength (webers/meter ²)
B_r	Radial component of solar magnetic field strength (webers/meter ²)
B_θ	Tangential component of solar magnetic field strength (webers/meter ²)
E	Particle energy (Mev)
E_0	Particle energy limit (Mev)
J	Angular momentum of particle gyrorotation around solar magnetic field line (kg-meter ² -sec ⁻¹)
m	Parameter in solar flare particle event model

n	Parameter in solar flare particle event model
q	Particle charge (coulomb)
R	Distance from sun (AU)
r	Radius of particle gyrorotation around solar magnetic field line (meters)
s	Length of solar magnetic field flux line (meters)
t	Time (hrs)
t_{rise}	Onset + rise time (time from flare on sun to particle flux maximum observed at R AU) (seconds)
t_r	Particle transit time from the sun (seconds)
v	Particle velocity (meters/sec)
$v_{ }$	Component of particle velocity parallel to solar magnetic field (meters/sec)
v_{\perp}	Component of particle velocity perpendicular to solar magnetic field (meters/sec)
α	Parameter in solar flare particle event model
β	Pitch angle of particle velocity with respect to solar magnetic field (degrees)
ϕ	Particle (proton) flux (particles/cm ² -hr-Mev)
$\int \phi$	Time-integrated particle flux (particles/cm ²)
$\hat{\phi}$	Peak particle flux rate (particles/cm ² -hr)
θ	Azimuthal angle (polar coordinate)

VII. References

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Table I. Annual Totals for Solar Flare Radiation Event Particle Fluxes at 1 AU

Year	Number of Events ($\int \phi > 10 \text{ Mev}$)					Annual Totals (particles/cm ²)		
	$>10^6$	$>10^7$	$>10^8$	$>10^9$	$>10^{10}$	$\int \phi > 10 \text{ Mev}$	$\int \phi > 30 \text{ Mev}$	$\int \phi > 100 \text{ Mev}$
1956		1	1	1		2.7×10^9	1.1×10^9	3.7×10^8
1957	1	4	6	3		1.0×10^{10}	8.5×10^8	5.9×10^7
1958	1	4	2	4		1.1×10^{10}	1.4×10^9	9.6×10^7
1959		1	1	5		2.2×10^{10}	4.3×10^9	4.2×10^8
1960	3	11	1	1	1	1.3×10^{10}	2.7×10^9	3.9×10^8
1961	1	5	3	1		2.1×10^9	4.2×10^8	4.9×10^7
1962						1.6×10^6	2×10^5	1.4×10^4
1963	1	1	1			5.6×10^8	6.5×10^7	6.4×10^6
1964		1	1			1.2×10^8	1.2×10^7	1.1×10^6
1965		2	1			2.2×10^8	2.2×10^7	2.0×10^6
1966		3	2			8.1×10^8	1.0×10^8	1.0×10^7
1967	3	4	1	1		2.2×10^9	2.7×10^8	2.8×10^7
1968	1	3	4	1		2.1×10^9	2.4×10^8	2.3×10^7

Table II. Transit Times (Seconds) for Protons as a Function of Pitch Angle at 1 AU

Proton Energy (Mev)	Pitch Angle						
	$\beta = 0^\circ$	$\beta = 15^\circ$	$\beta = 30^\circ$	$\beta = 45^\circ$	$\beta = 60^\circ$	$\beta = 75^\circ$	$\beta = 80^\circ$
1.0	1.23×10^4	1.27×10^4	1.42×10^4	1.74×10^4	2.46×10^4	4.75×10^4	7.08×10^4
3.0	7.1×10^3	7.32×10^3	8.2×10^3	1.0×10^4	1.42×10^4	2.74×10^4	4.07×10^4
10	3.9×10^3	4.04×10^3	4.51×10^3	5.52×10^3	7.82×10^3	1.51×10^4	2.25×10^4
30	2.24×10^3	2.3×10^3	2.58×10^3	3.16×10^3	4.47×10^3	8.62×10^3	1.28×10^4
100	1.23×10^3	1.27×10^3	1.42×10^3	1.74×10^3	2.46×10^3	4.75×10^3	7.08×10^3
300	8.18×10^2	8.47×10^2	9.45×10^2	1.16×10^3	1.64×10^3	3.16×10^3	4.71×10^3

Table III. Minimum Transit Times for Protons as a Function of Energy ($\beta = 0$)

Distance From Sun (AU)	Proton Energy (Mev)					
	1	3	10	30	100	300
0.1	1.07×10^3	6.2×10^2	3.4×10^2	1.95×10^2	1.07×10^2	7.1×10^1
0.4	4.3×10^3	2.48×10^3	1.36×10^3	7.8×10^2	4.28×10^3	2.84×10^2
0.7	8.0×10^3	4.63×10^3	2.55×10^3	1.46×10^3	8.0×10^3	5.33×10^2
1.0	1.23×10^4	7.1×10^3	3.9×10^3	2.24×10^3	1.23×10^3	8.18×10^2
1.5	2.09×10^4	1.21×10^4	6.6×10^3	3.8×10^3	2.09×10^3	1.39×10^3
2.0	3.16×10^4	1.82×10^4	1.0×10^4	5.74×10^3	3.16×10^3	2.1×10^3
3.0	6.05×10^4	3.48×10^4	1.92×10^4	1.1×10^4	6.05×10^3	4.0×10^3
4.0	9.95×10^4	5.75×10^4	3.16×10^4	1.81×10^4	9.9×10^3	6.6×10^3
5.0	1.5×10^5	8.65×10^4	4.75×10^4	2.73×10^4	1.5×10^4	9.95×10^3

Table IV. Transit Times (Seconds) for 1 Mev Proton as a Function of Pitch Angle

Distance From Sun (AU)	Pitch Angle						
	$\beta = 0^\circ$	$\beta = 15^\circ$	$\beta = 30^\circ$	$\beta = 45^\circ$	$\beta = 60^\circ$	$\beta = 75^\circ$	$\beta = 80^\circ$
0.1	1.07×10^3	1.11×10^3	1.24×10^3	1.52×10^3	2.14×10^3	4.13×10^3	6.15×10^3
0.4	4.3×10^3	4.45×10^3	4.97×10^3	6.1×10^3	8.6×10^3	1.66×10^4	2.48×10^4
0.7	8.0×10^3	8.27×10^3	9.25×10^3	1.13×10^4	1.6×10^4	3.09×10^4	4.6×10^4
1.0	1.23×10^4	1.27×10^4	1.42×10^4	1.74×10^4	2.46×10^4	4.75×10^4	7.08×10^4
1.5	2.09×10^4	2.16×10^4	2.42×10^4	2.96×10^4	4.18×10^4	8.07×10^4	1.2×10^5
2.0	3.16×10^4	3.27×10^4	3.66×10^4	4.47×10^4	6.32×10^4	1.22×10^5	1.82×10^5
3.0	6.05×10^4	6.26×10^4	7.00×10^4	8.57×10^4	1.21×10^5	2.34×10^5	3.48×10^5
4.0	9.95×10^4	1.03×10^5	1.15×10^5	1.41×10^5	1.99×10^5	3.85×10^5	5.75×10^5
5.0	1.5×10^5	1.55×10^5	1.73×10^5	2.13×10^5	3.0×10^5	5.8×10^5	8.62×10^5

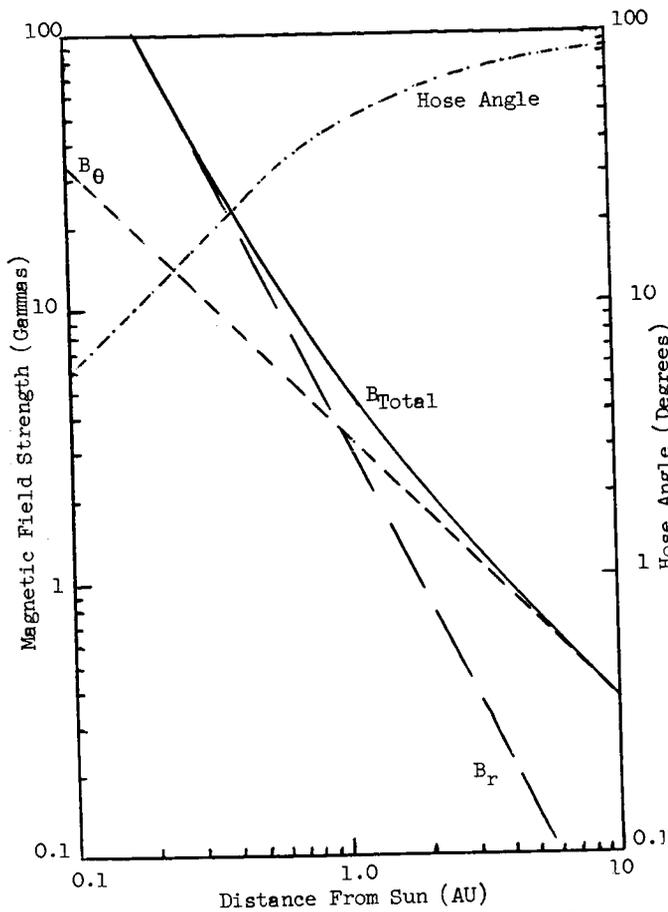


Figure 1. Characteristics of the Quiet-Sun Magnetic Field Carried Frozen in by the Solar Wind.

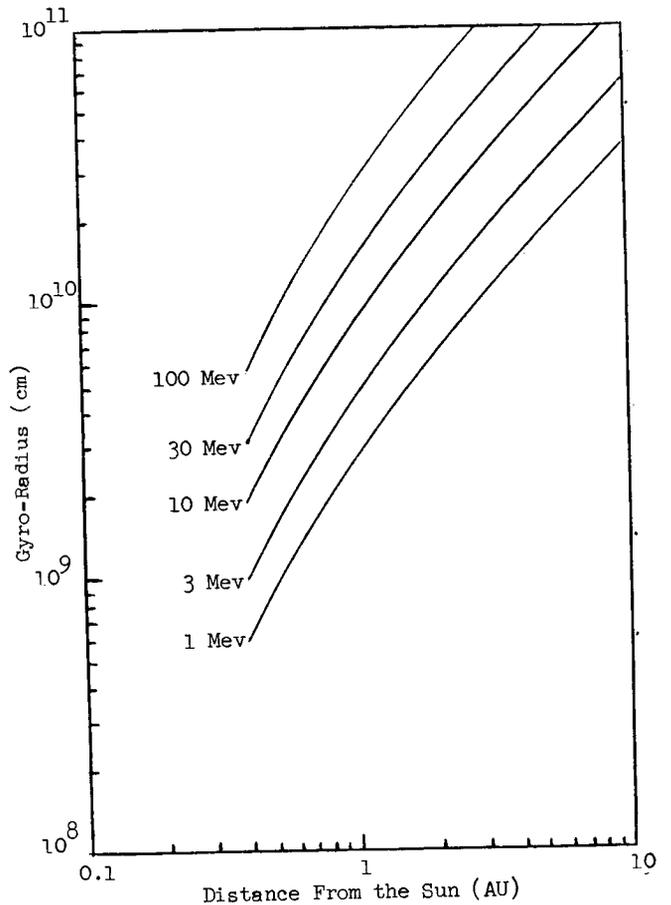


Figure 2. Proton Gyro-Radius as a Function of Distance From the Sun for Undisturbed Interplanetary Magnetic Field.

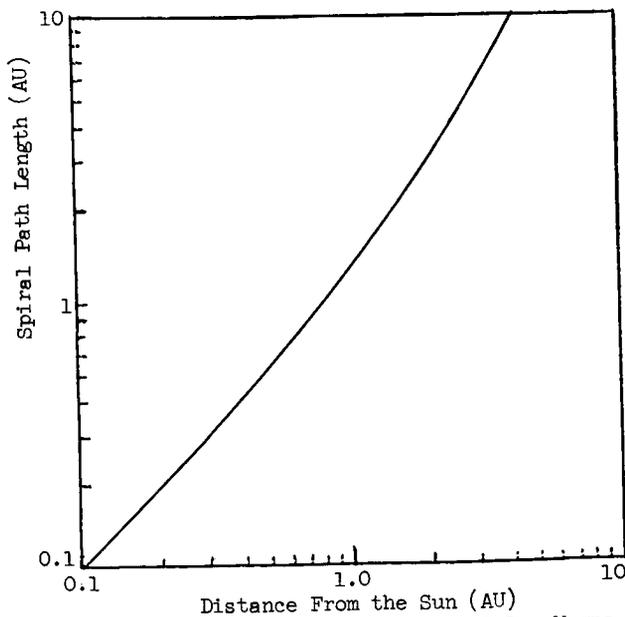


Figure 3. Spiral Path Length of Solar Magnetic Field as a Function of Distance From the Sun.

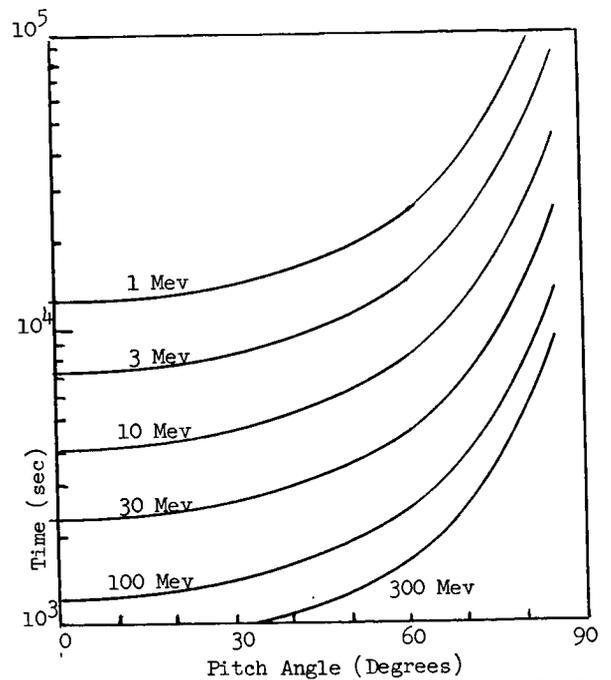


Figure 4. Transit Times for Protons at 1 AU as a Function of Pitch Angle (Assumed Constant) and Proton Energy

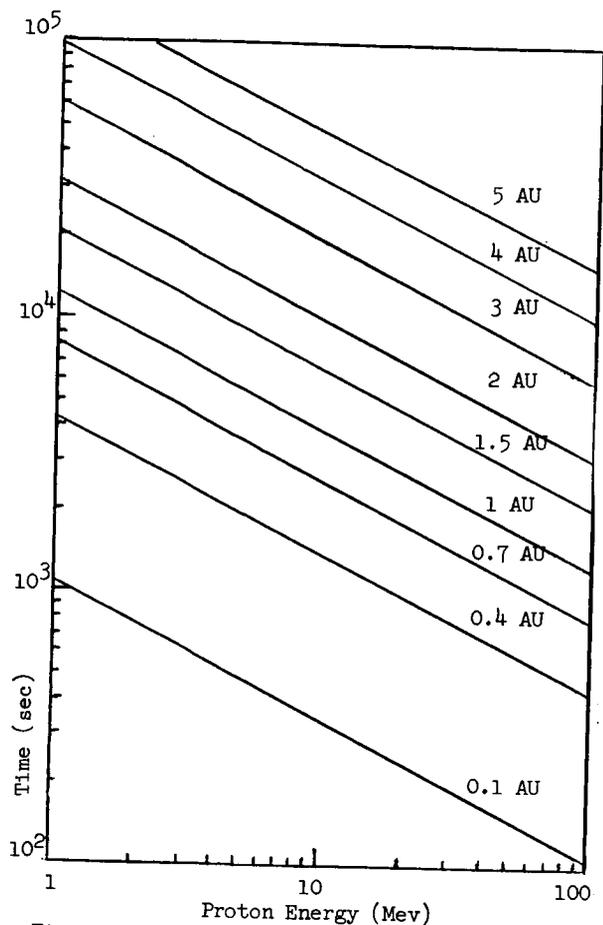


Figure 5. Minimum Proton Transit Time ($B = 0$) as a Function of Proton Energy and Distance From the Sun.

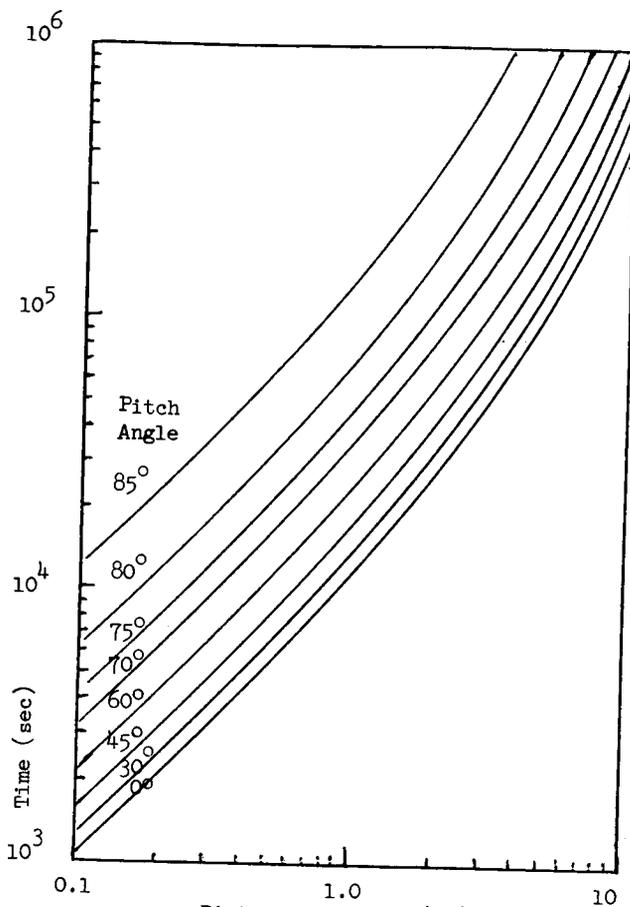
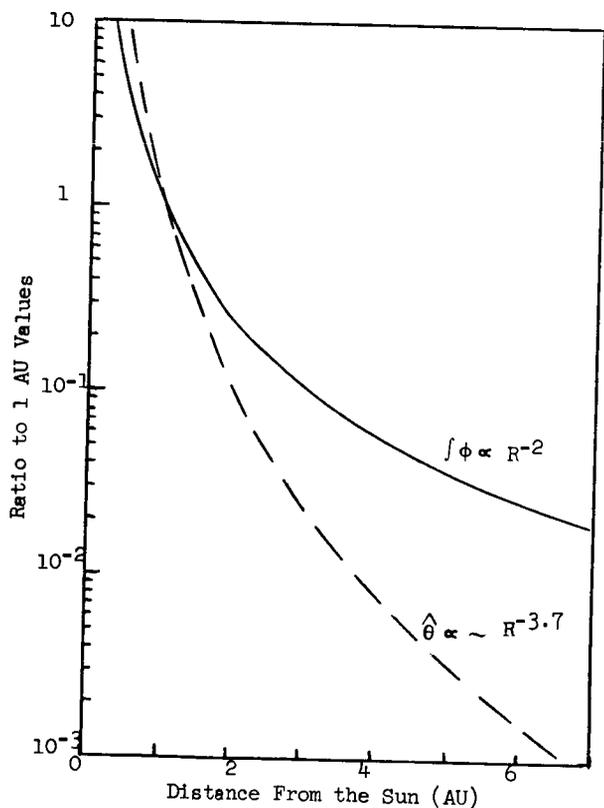


Figure 6. Proton Transit Time for 1 Mev Protons as a Function of Distance From the Sun and Pitch Angle.



← Figure 7. Ratio of Integral Particle Fluxes ($\int\phi$) and Peak Particle Flux Rate ($\hat{\theta}$) to the Corresponding Values at 1 AU