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Galactic Cosmic Ray Modulation in the Outer Solar System: Solar Wind Consequences

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Galactic Cosmic Ray Modulation in the Outer Solar System: Solar Wind Consequences

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GALACTIC COSMIC RAY MODULATION IN THE OUTER SOLAR SYSTEM: SOLAR WIND CONSEQUENCES

S. T. Suess, L. A. Fisk, and T. E. Holzer

It has recently been suggested that "quiet-time electron increases" may be indicative of a galactic cosmic ray modulation region in the outer solar system that is quite distinct from the modulation region in the inner solar system. We consider the effects of an outer modulation region on the solar wind expansion, finding that the effects are somewhat more important than those associated with only an inner modulation region, when the same constraints on galactic cosmic ray energy density are applied. We also find that the existence of an outer modulation region will not lead to a shock-free solar wind transition to subsonic flow (or even to a weakly shocked transition) in the absence of an interstellar neutral gas, and that the cosmic ray effects are less important than those of the neutral gas in the presence of an interstellar atomic hydrogen gas of density 0.1 cm^{-3}.

Key Words: Cosmic rays, heliosphere, solar wind

1. INTRODUCTION

Observations of increases in the intensity of 3 to 12 MeV interplanetary electrons by a factor of 3-5 have been reported on by McDonald et al. (1972) and labelled as "quiet time electron increases." A model for these increases is proposed by Fisk and Van Hollebeke (1972), predicting the existence of a modulating region for cosmic ray particles lying at about 30 AU and extending outward an undetermined distance from the sun. As usual, modulation here means a modification of the cosmic ray distribution function due to interactions between cosmic rays and irregularities in the magnetic field carried by the solar wind. This is in addition to the modulation in the inner (out to about 5 AU) solar system, and might be expected to produce a significant effect on the solar wind due to the momentum exchange between cosmic rays and solar wind via the magnetic field. As this effect has not been considered previously, we do so here.

The observations and arguments described by Fisk and Van Hollebeke are, briefly, as follows. A quiet time increase of 3 to 12 MeV interplanetary

electrons typically occurs approximately five solar rotations after an unusually large distortion of the interplanetary magnetic field lines appears at the earth. Evidence for this increased distortion, or "random walk," is an extended period when the amplitude of the cosmic ray diurnal anisotropy (measured by the Deep River neutron monitor) is relatively low. A delay of five solar rotations, assuming a constant solar wind speed of 400 km/sec and allowing for transit time of the electrons back to the earth, places the modulating region at about 30 AU. The increased random walk of the interplanetary field lines would, by inhibiting the instability discussed on page 2, cause a decrease in the normal level of modulation, resulting in a subsequent increase in the observed electrons at the earth.

The proposed mechanism to produce the modulation is a solar wind-cosmic ray streaming instability resulting from the high relative velocity of the cosmic rays, streaming in along spiral magnetic field lines, as compared to the radial outward solar wind velocity. This instability might be most likely to occur at 30 AU, as this is where the cosmic ray particle and solar wind energy densities may be comparable. However, it would be inhibited by an increased random walk of the field lines, since this would decrease the spiral angle and so decrease the relative velocity of the cosmic rays. The irregularities produced by the instability would be convected outward by the solar wind, producing cosmic ray modulation until they decayed. Since the magnetic field is irregular in space, there is a finite pressure exerted by cosmic rays on the solar wind (which in turn results in a distortion of the cosmic ray distribution function). The amplitude of the pressure, and pressure gradient, depends on the extent of the interaction region and on the percent of the cosmic ray energy available for modulation. Fisk and Van Hollebeke suggest that as much as 20% of the total cosmic ray energy density may be available to act on the solar wind, with the total cosmic ray energy density thought to be about 1 eV/cm^3. This value is derived by using the observed cosmic ray spectrum and modulation in the inner solar system to estimate the spectrum in the interstellar medium and then comparing this with theoretical arguments concerning the origin of cosmic rays and the consequent energy spectrum. Such a compari-

son allows 20% of the energy to be dissipated in the outer solar system to bring the two estimates into agreement.

Accepting this proposal, we have investigated the consequences of the pressure gradient on the solar wind expansion. We are particularly interested in whether the pressure gradient can significantly alter the location of the supersonic to subsonic transition (often thought of as the outer limit of the heliosphere) of the solar wind. Our conclusion is that, although the cosmic ray electrons may undergo significant modulation, as suggested by Fisk and Van Hollebeke, the location of the shock transition is not greatly altered. In addition, we also find that unless other processes exist (e.g., those described by Holzer, 1972), the transition cannot be of the shock free variety.

2. THEORY

To proceed with the analysis, we choose the simplest solar wind model consistent with the objective. Thus, we limit the study to the region of the solar equatorial plane (since the proximity of the modulating region, as the spiral angle of the interplanetary magnetic field, varies with latitude). We employ single fluid equations, neglect gravity and thermal conduction, and include the cosmic ray effect as a known additional pressure gradient in the momentum and energy equations. Hence, the momentum, continuity, and energy equations are, respectively,

$$\rho u \frac{du}{dr} = - \frac{dp}{dr} - q \tag{1}$$

$$\frac{d}{dr} (\rho u r^2) = 0 \tag{2}$$

$$\frac{1}{r^2} \frac{d}{dr} \left[\rho u r^2 \left(\tfrac{1}{2} u^2 + \frac{\gamma}{\gamma - 1} \frac{p}{\rho} \right) \right] = - qu \tag{3}$$

$$\gamma = 5/3$$

where ρ, u, and p are density, radial velocity, and pressure and where $q = d\pi/dr$, the cosmic ray pressure gradient. Making use of (2), we execute the derivative in (3), divide by u, subtract (1), and integrate once to obtain

$$p = p_o \, (\rho/\rho_o)^{\gamma}. \tag{4}$$

Hence, the pressure is still related to the density through the usual adiabatic equation.

Next, we reduce (1) - (3) to a single first order differential equation in M and r, where

$$M = u/c \tag{5}$$

$$c^2 = \gamma p/\rho. \tag{6}$$

Dividing (1) by ρ and making use of (4), (5), and (6), we obtain

$$(Mc) \frac{d(Mc)}{dr} = - \frac{c^2}{\rho} \frac{d\rho}{dr} - \frac{q}{\rho} \; ; \tag{7}$$

(2) and (6) are combined to yield

$$\frac{1}{\rho} \frac{d\rho}{dr} = - \left(\frac{1}{M} \frac{dM}{dr} + \frac{1}{c} \frac{dc}{dr} + \frac{2}{r} \right) \tag{8}$$

and substituting (8) into (7) gives

$$\frac{1}{M} \frac{dM}{dr} (M^2 - 1) + \frac{1}{c} \frac{dc}{dr} (M^2 - 1) = \frac{2}{r} - \frac{q}{\rho c^2} \, . \tag{9}$$

From (4), (6), and (8)

$$\frac{1}{c} \frac{dc}{dr} = - \frac{\gamma - 1}{\gamma + 1} \left(\frac{1}{M} \frac{dM}{dr} + \frac{2}{r} \right). \tag{10}$$

Substituting (10) into (9), we obtain the desired result.

$$\frac{1}{M} \frac{dM}{dr} (M^2 - 1) = \frac{\gamma + 1}{r} + \frac{\gamma - 1}{r} (M^2 - 1) - \frac{\gamma + 1}{2} \frac{q}{\rho c^2} \, . \tag{11}$$

Note that (11) agrees with equation (10) of Sousk and Lenchek (1969), if $q = \pi u/K$ (cf. equation (4) of Sousk and Lenchek) where K is the cosmic ray diffusion coefficient. We would like to express the last term in (11) as a function of M and r alone, regardless of the form of q. Using (4) and (2) gives

$$\rho = \rho_o \left(\frac{M_o r_o^2}{M r^2} \right)^{\frac{2}{\gamma+1}} , \tag{12}$$

$$u = u_o \left(\frac{M r^{1-\gamma}}{M_o r_o^{1-\gamma}} \right)^{\frac{2}{\gamma+1}} , \tag{13}$$

$$p = p_o \left(\frac{M_o r_o^2}{M r^2} \right)^{\frac{2\gamma}{\gamma+1}} , \tag{14}$$

$$c = c_o \left(\frac{M_o r_o^2}{M r^2} \right)^{\frac{\gamma-1}{\gamma+1}} , \tag{15}$$

where the zero subscript indicates evaluation at the inner edge of the modulation region. Evidently, if q is a function of r, ρ, u, and p only, then it is possible to write (11) as a function of M and r alone. Thus, the critical point of (11), which is defined as the point at which $(M^2 - 1)$ and the right side vanish simultaneously, is determined by

$$\frac{1}{r_c} - 1/2 \left(\frac{q}{\rho c^2} \right)_{\substack{r = r_c \\ M = 1}} = 0 \tag{16}$$

where $r = r_c$ is the radial distance to the critical point. In the special case where q is a constant, (4) and (14) can be combined to yield

$$r_c = r_o \left[\frac{2\gamma p_o}{q r_o} \; M_o^{\frac{2\gamma}{\gamma+1}} \right]^{\frac{\gamma+1}{5\gamma+1}} . \tag{17}$$

It is also possible to approximate (11) in the region of the critical point to find the slope at the critical point and the form of the characteristics in the vicinity of the critical point. This is done by expanding the variables around $M = 1$ and $r = r_c$ in Taylor series. Let

$$\mu = M - 1$$

and

$$\xi = \frac{r}{r_c} - 1 \ .$$

Using these, we obtain, to first order in μ and ξ,

$$\frac{d\mu}{d\xi} = a \frac{\xi}{\mu} + b \tag{18}$$

where

$$a = - \frac{\gamma+1}{2} - \frac{\gamma q r_c}{\rho_o c_o^2} \left(\frac{r_c^2}{M_o r_o^2} \right)^{\frac{2\gamma}{\gamma+1}} \tag{19}$$

$$b = \gamma - 1 - \frac{\gamma q r_c}{2\rho_o c_o^2} \left(\frac{r_c^2}{M_o r_o^2} \right)^{\frac{2\gamma}{\gamma+1}} \ . \tag{20}$$

A characteristic curve passing through the critical point has a slope at the critical point given by

$$S = \lim_{\substack{\text{line} \\ \xi \to o}} \frac{\mu}{\xi} \ .$$

From (18), this gives

$$S = - \tfrac{1}{2} \pm \tfrac{1}{2} \sqrt{- 1 - 10 \gamma} \ . \tag{21}$$

Since γ is larger than zero, the slope at r_c always has an imaginary component. This means that there is no continuous path through the critical point (for any set of solar wind parameters) from supersonic to subsonic flow. The only remaining possible type of transition is a shock.

The location of the shock is the radius at which (by using the Rankine-Hugoniot relations and considering the downstream flow) ρu^2 equals the total interstellar pressure (Axford, 1972), which is expected to be on the order of 10^{-12} dynes/cm^2 (Axford, 1972). ρu^2, the ram pressure, is calculated from the solutions to (11), which are found using a Runge-Kutta integration. To do this, an assumption must be made about the extent of the interaction region beyond 30 AU. For the first case, we take 50 AU as the distance beyond which the modulation is negligible, and take q as constant from 30 to 50 AU. 1/6 eV/cm^3 available from the cosmic rays for the pressure gradient. In addition

$$u_o = 400 \text{ km/sec}$$

$$\rho_o = 9.3 \times 10^{-27} \text{ gm/cm}^3$$

$$T_o = 2.0 \times 10^3 \ ^oK,$$

where ρ_o has been scaled as r^{-2} and T adiabatically from 1 AU. With these parameters, giving r_c = 43 AU, the Runge-Kutta integration of (11) gives the characteristic curves shown in figure 1. The curves are closed spirals, as was suggested by the slope at r_c having an imaginary component. In this figure, the solution corresponding to the above parameters is (approximately) the dashed segment near the top. Since the solar wind speed is highly supersonic at 30 AU, this characteristic curve segment is far from the critical point and is changed only slightly from the corresponding curve for no cosmic ray interaction. To the left, the solar wind would connect at the 30 AU vertical line with $M \propto r^{2/3}$. Beyond 50 AU, if there were no supersonic-subsonic transition, the solar wind would again continue with the same radial dependence of $r^{2/3}$. The increase of M(r) between 30 and 50 AU is less than $r^{2/3}$, so the cosmic ray pressure gradient does slow the flow.

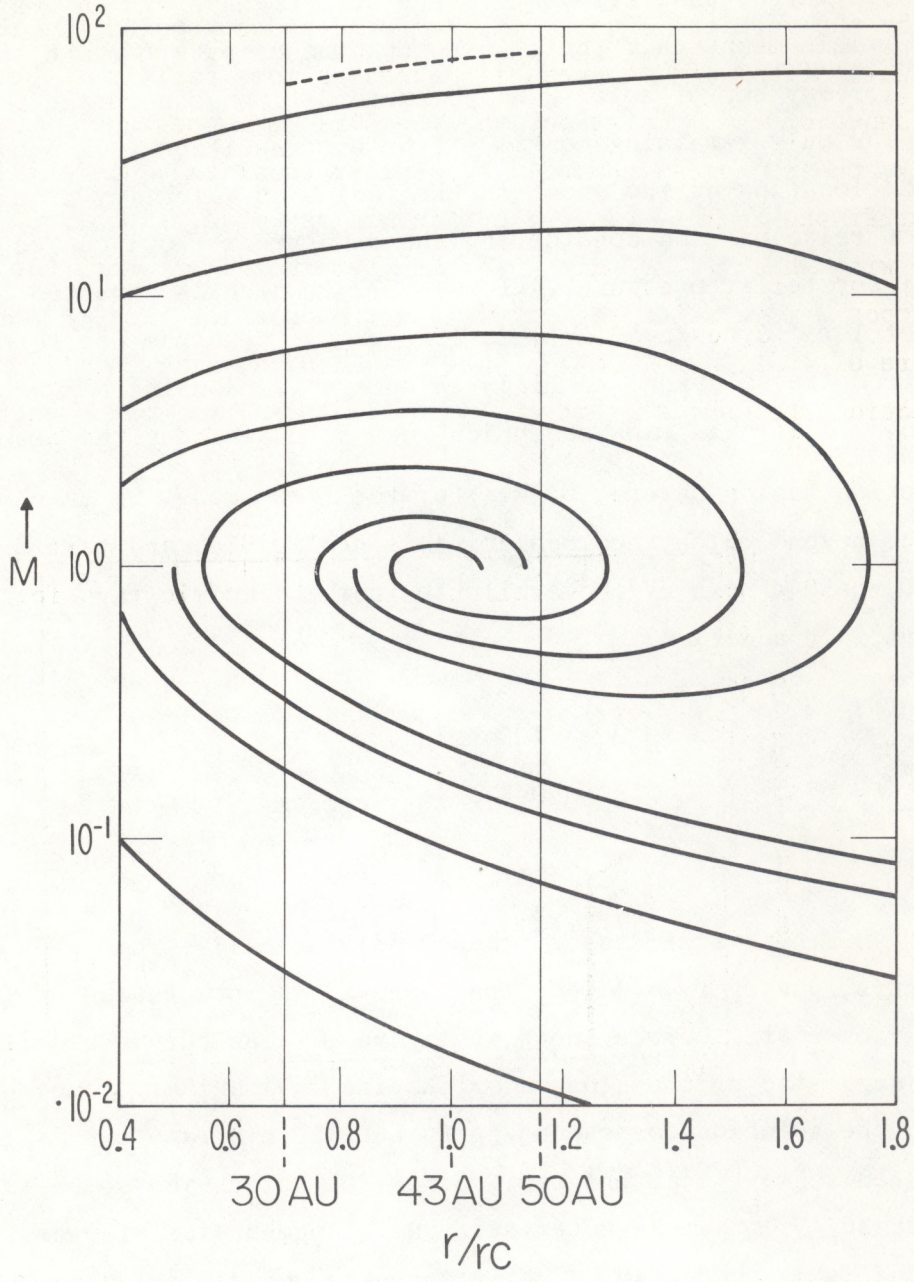

Figure 1. Mach number, M, versus r/r_c. r_c = 43.8 AU, u_o = 400 km/sec, T_o = 2000 ^oK, n_o = 5.56 x 10^{-3} cm^{-3}, r_o = 30 AU, q = 8.9 x 10^{-28} dynes/cm^3. The modulation region extends from 30 to 50 AU. The dashed line near the top illustrates where the solar wind then falls on this diagram, well away from the critical point.

Figure 2 shows the ram pressure where the interaction region is indicated by the vertical lines. Inside 30 AU and beyond 50 AU, this pressure would fall off as r^{-2}, whereas it decreases more rapidly in between. In the absence of any modulation, the pressure decreases as r^{-2} overall. Clearly, the ram pressure would eventually equal the interstellar pressure at some finite radius even without cosmic ray modulation, and it is this radius with which we compare with the corresponding radius the presence of the proposed modulation region. Without modulation, for an interstellar pressure of 10^{-12} dynes/cm^2, a shock would occur at about 115 AU. With the interaction, the shock is moved in to 113 AU. Thus, the change is small.

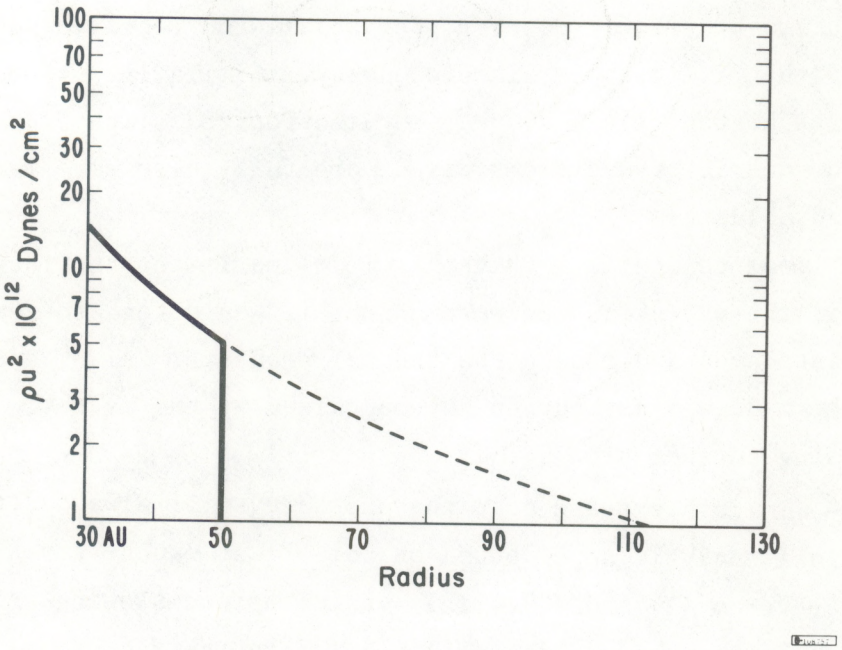

Figure 2. ρu^2, the ram pressure, versus radius for the same parameters used in figure 1. The dashed line illustrates the r^{-2} decay of the dynamic pressure beyond the modulation region.

Taking the interaction region to extend from 30 to 110 AU (but still with 20% of the total cosmic ray energy density available for q) roughly gives the maximum effect on the location of the shock, because the interaction region would not be expected to extend beyond the shock. In figure 3, we show the results for the ram pressure, in this case, where r_c = 68 AU. This does lower the ram pressure marginally more than the previous case, but only enough to bring the transition in to about 109 AU. To further understand the reasons for this result, it is useful to examine figure 4, which is a plot of the energetics within the interaction region. In this figure, the thermal and kinetic energy content minus these energy contents in the absence of any interaction are plotted as a function of radius. It is seen that the solar wind is heated and slowed with respect to the undisturbed flow. However, the solar wind receives much more thermal energy than it loses in kinetic energy. Similarly, the cosmic rays must also be heated (i.e., slowed, but isotropized slightly). The consequences for cosmic rays are discussed more fully elsewhere [see Suess, Fisk, Holzer, and Goldstein, 1974].

This tends to indicate that this model maximizes the interaction. That is, if thermal diffusion were added, it would tend to remove heat from the immediate area and reduce the thermal pressure. Also, a similar argument can be made against the energy contained by the magnetic field oscillations causing further slowing.

Since, in this extreme case the pressure still always decreases outward, a final analytic upper bound on the effect can be given by dropping the pressure from (1) and (3). This maximizes the slowing, since an outwardly decreasing pressure can only accelerate the flow.

The resulting equations are easily integrated identically to give

$$u = u_o - \frac{q(r^3 - r_o^3)}{3\rho_o u_o r_o^2} \tag{22}$$

$$\rho = \frac{\rho_o u_o r_o^2}{u r^2} . \tag{23}$$

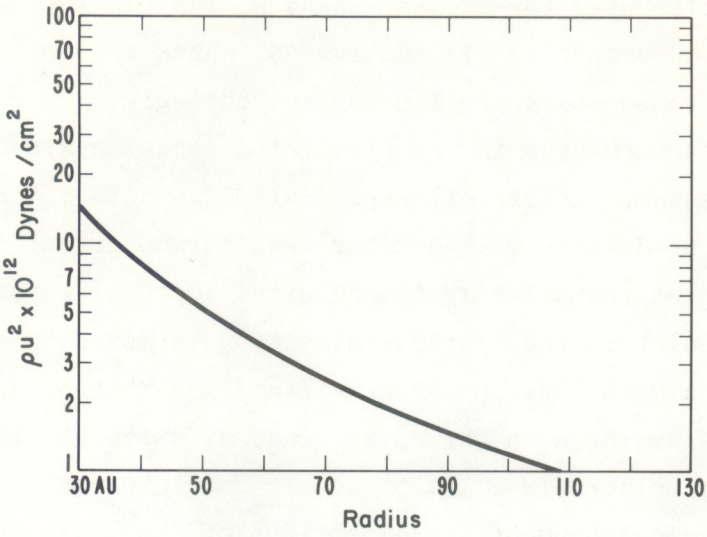

Figure 3. ρu^2, the ram pressure, versus radius for $q = 2.225 \times 10^{-28}$ dynes/cm^3, $r_c = 56.8$ AU. u_o, T_o, n_o, and r_o are the same as for figure 1. The modulation region now extends from 30 to 110 AU.

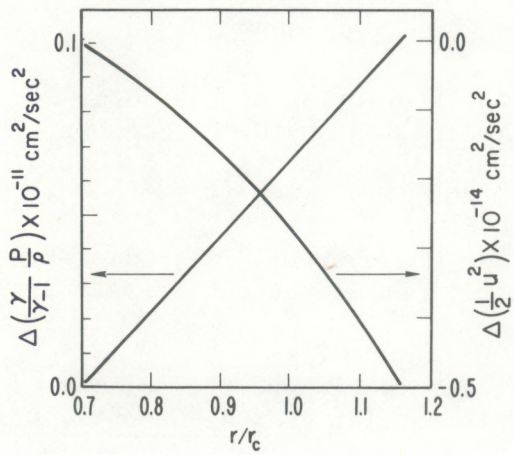

Figure 4. Shown is the increment of thermal energy density and the deficit of kinetic energy density above (or below) that for the flow when $q \equiv 0$, versus radius. The parameters are those of figure 1 with $r_c = 43.8$ AU.

Taking the examples used for figures 2 and 3, identical results are found. That is, the shock occurs as 113 and 109 AU, where the interaction region extends from 30 to 50 and 30 to 110 AU, respectively.

The percentage changes in the transition location are only weakly dependent on the assumed interstellar pressure, on whether q is a function of radius, and on the details of the solar wind parameters at 30 AU. Thus, even with motion of the solar system relative to the interstellar medium, the transition point in the upstream direction is moved by only about 6%. This is clearly a much less important effect than that of interstellar neutral (atomic) hydrogen on the solar wind, as discussed by Wallis (preprint, 1971) and Holzer (1972); although it should probably be considered in any similar calculation of the dimensions of the heliosphere for completeness while adding little to the complexity of the calculation. The effect does seem to be slightly more important in the solar wind expansion than the modulation in the inner solar system as examined by Sousk and Lenchek (1969).

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