

EFFECTS OF INTERSTELLAR PARTICLES UPON THE INTERPLANETARY MAGNETIC FIELD

Paul J. Coleman, Jr., and Edwin M. Winter

ABSTRACT The flow of interstellar neutral particles into the interplanetary medium and their subsequent ionization in the presence of the electromagnetic field of the solar wind can cause a loss of field angular momentum by the solar wind. One effect of this loss of field angular momentum is a significant unwinding of the spiral field. This effect is evaluated using simple models for neutral density and ion production. For a free-stream interstellar medium with a neutral hydrogen density of 1 cm^{-3} and a velocity relative to the sun of 10 to 20 km-sec^{-1} , the spiral angle at the orbit of Jupiter will be less than its nominal value of 45° at the orbit of the earth.

INTRODUCTION

Recent Lyman α measurements with instruments on board Vela 4 [Chambers *et al.*, 1970] and OGO 5 [Thomas and Krassa, 1970] satellites indicate that neutral interstellar matter penetrates interplanetary space to within a few AU of the sun. Each of these instruments detected a definite maximum in the scattered Lyman α intensity. In each case the minimum was 180° from the maximum. The OGO 5 investigation reported a parallax effect over a 6-month period of observations of the position of these features. This was interpreted by Thomas and Krassa as showing that the distance of the interstellar hydrogen is comparable to the diameter of the earth orbit.

The Vela 4 and OGO 5 results place the maximum at different positions. The former show the maximum in the direction of the solar apex motion, which is approximately 50° from the ecliptic. The latter show this enhancement to be at the same galactic longitude but near the ecliptic in the direction of Scorpio-Sagittarius.

Blum and Fahr [1969; 1970a,b] considered the behavior of a neutral interstellar medium moving relative to the solar system. As a result of this relative motion (~ 10 - 20 km/sec), some neutral hydrogen moves into

interplanetary space. The lifetime of these neutrals, which are exposed to solar energetic ultraviolet radiation, is determined by the appropriate ionization time. The neutral penetration distance is then determined by the relative velocity. If the interstellar medium is at rest in the galactic frame, it will be seen to approach the solar system from the direction of solar apex motion. Motion of the interstellar gas relative to the galactic frame can alter the speed and direction of approach of the neutrals. For velocities comparable to the solar apex velocity, the theory of Blum and Fahr predicts penetration to within several AU of the earth's orbit.

Apparently, then, the region of solar wind flow several AU outside the orbit of the earth consists of flowing solar wind plasma moving relative to the neutral interstellar medium. This neutral hydrogen is continuously exposed to ionizing radiation and, when ionized, is accelerated by the solar wind electromagnetic field. The effect of this volume mass source on the mechanical variables of the solar wind flow was considered for a gas dynamic case by Semar [1970], although details such as the mechanism for accelerating the particles were not discussed.

In this note we show that one important effect of these ionized interstellar particles is to unwind the spiral of the interplanetary magnetic field. Thus, at any point, the deviation of the mean spiral angle from its predicted value may be a sensitive indicator of the density of these particles.

The authors are at the Department of Planetary and Space Science and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California.

ANGULAR MOMENTUM

A neutral atom, when ionized in an electric and magnetic field, will be accelerated in the $\mathbf{E} \times \mathbf{B}$ direction. If \mathbf{E} is produced by a plasma moving with velocity V_p so that $\mathbf{E} = -(1/c)(\mathbf{V}_p \times \mathbf{B})$. The force on a charged particle moving with an arbitrary velocity \mathbf{V} in a plasma moving at velocity V_p is given by $\mathbf{F} = e(\mathbf{E} + \mathbf{V} \times \mathbf{B})/c$. Using the above electric field, this becomes [cf. *Winge and Coleman, 1968*].

$$\mathbf{F} = e(\mathbf{V} - \mathbf{V}_p) \times \frac{\mathbf{B}}{c} \quad (1)$$

Thus, for the case where $\mathbf{V} \times \mathbf{B} = \mathbf{V}_p \times \mathbf{B}$, the particle will experience no force.

Particles ionized in the moving plasma will experience no force after the acceleration to the $\mathbf{E} \times \mathbf{B}$ velocity. Unless the magnetic field is perpendicular to \mathbf{V}_p , this acceleration will have a component transverse to \mathbf{V}_p .

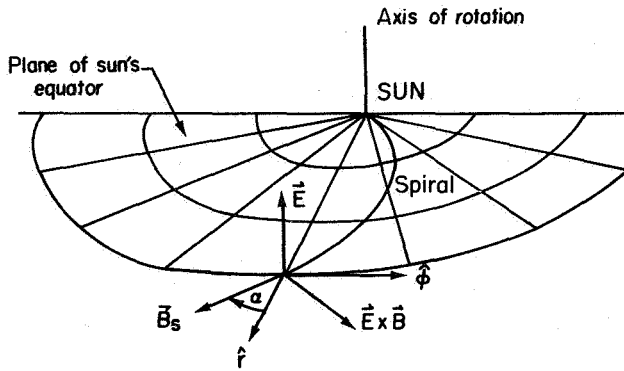


Figure 1 EXB drift direction in the solar wind.

In the solar wind the situation is as shown in figure 1. Thus, the solar wind electromagnetic field will lose angular momentum to interstellar particles that are moving directly toward the sun at the time they are ionized. This loss of angular momentum to these particles is then

$$\frac{dL_m}{dt} = -A_p V_D \times \mathbf{r} \quad (2)$$

where A_p = rate of mass addition per unit volume, $\mathbf{V}_D = (1/B^2)\mathbf{E} \times \mathbf{B}$ is the drift velocity so that $V_{D\phi}$ is the ϕ component of the drift velocity, that is,

$$V_{D\phi} = \frac{c(\mathbf{E} \times \mathbf{B})_\phi}{B^2} = \frac{[-(\mathbf{V} \times \mathbf{B}) \times \mathbf{B}]_\phi}{B^2}$$

$$= \frac{V_\phi - V_r B_\phi^2}{B^2} - \frac{V_r B_r B_\phi}{B^2} \quad (3)$$

and V is the solar wind velocity. We have neglected the time required to accelerate the newly ionized particles to the drift velocity.

The solar wind electromagnetic angular momentum flow is given by equation (4)

$$\frac{dL_m}{dt} = -\mathbf{r} \times (\mathbf{J} \times \mathbf{B}) = -\frac{\mathbf{r} \times [(\nabla \times \mathbf{B}) \times \mathbf{B}]}{4\pi} \quad (4)$$

which can be expressed for a spherically symmetric solar wind as

$$\frac{dL_m}{dt} = -\frac{B_r(d/dr)rB_\phi}{4\pi} \quad (5)$$

the torque associated with magnetic stress per unit volume [cf. *Weber and Davis, 1967*]. Equating (5) and (2):

$$B_r \frac{d}{dr} (rB_\phi) = 4\pi A_p r V_\phi \left[\frac{1 - B_\phi^2}{B^2} - \frac{4\pi A_p r V_r B_r B_\phi}{B^2} \right] \quad (6)$$

In the case where

$$V_r \gg \frac{V_\phi(B_r^2 + B_\phi^2)}{B_\phi B_r}$$

or

$$V_r \gg \frac{V_\phi B_r}{B_\phi}$$

the first term on the right side of equation (6) can be neglected. Typical values at 1 AU are

$$|B_r| \approx |B_\phi| = 3.0 \gamma$$

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

$$V_\phi = 5 \text{ km/sec}$$

Models of the solar wind flow in the outer solar system [*Weber and Davis, 1967; Weber and Davis, 1970*] do not show any increase in V_ϕ . Furthermore, B_r/B_ϕ decreases as $1/r$. Equation (6) can therefore be written as

$$\frac{d}{dr} (B_\phi r) = \frac{4\pi(B_\phi r)A_p V_r}{B_\phi^2 + B_r^2} \quad (7)$$

or on integration

$$B_{\phi r} = B_{\phi 0} r_0 \exp \left(- \int_{r_0}^r \frac{4\pi A_p V_r dr}{B_{\phi}^2 + B_r^2} \right) \quad (8)$$

Even in the case of mechanical interactions, the solar wind velocity V_r remains essentially constant to a distance at which mass loading affects the momentum in the radial direction. *Semar* [1970] determined this distance to be considerably beyond 5 AU. The quantity A_p in equation (8) is the rate of plasma mass addition per unit volume, and it may be approximated by

$$A_p = \frac{q_p \rho_n r_0^2}{r^2} + \frac{q_c \rho_n r_0^2}{r^2}$$

where q_p is the photoionization rate, q_c is the charge exchange rate, and ρ_n is the neutral density. The rate of charge exchange reactions in the solar wind is the subject of some debate. Various proposed rates and cross sections are given in table 1. The rate of photoionization, however, is more accurately known [*Hinteregger*, 1960;

Table 1. Comparison of published charge exchange rates.

Charge-exchange cross section in solar wind	Charge-exchange ionization rate
$3 \times 10^{-16} \text{ cm}^2$	$7.5 \times 10^{-8} \text{ sec}^{-1}$ [Walker <i>et al.</i> , 1970]
$3 \times 10^{-15} \text{ cm}^2$	$6 \times 10^{-7} \text{ sec}^{-1}$ [Semar, 1970]
10^{-15} cm^2	$1.5 \times 10^{-7} \text{ sec}^{-1}$ [Blum and Fahr, 1970a]

Walker et al., 1970; *Semar*, 1970]. In this paper, we assume $q_p = 4.5 \times 10^{-7} \text{ sec}^{-1}$ in agreement with the above authors. This is the value for photoionization of atomic hydrogen at 1 AU for a fairly active sun. This value will also serve as the total ionization rate, keeping in mind a possible error of a factor of 2 due to the additional contribution of charge exchange. For the neutral density in interplanetary space ρ_n , we will use the densities introduced by *Blum and Fahr* [1969, 1970a,b]. If the gravitational effects of the sun are neglected, the density of neutrals at a distance r measured from the sun in the direction of the incoming interstellar particles is given by

$$\rho_n = \rho_{n0} e^{-(qr_0^2/V_H r^2)}$$

where

- ρ_{n0} the interstellar density external to the solar system
- q photoionization rate at 1 AU
- r distance from the sun
- V_H velocity of the interstellar medium relative to the sun
- r_0 radius of the earth's orbit

A net effect of gravity over light pressure (as was assumed in *Blum and Fahr* [1970a]) will result in greater densities in the inner solar system. For a relative interstellar velocity of 20 km/sec, the neutral density will be $1/e$ times its density outside the solar system at approximately 3.5 AU.

Equation (8) can be integrated numerically by iterative methods and behavior of B_{ϕ} compared with that predicted by the spiral angle model. However, it is immediately apparent that for the limiting case in which there is no relative motion between the interstellar medium and the solar wind, the usual spiral field, with B_{ϕ} varying inversely with r , results.

RESULTS AND DISCUSSION

The results of this integration for rB_{ϕ} are plotted in figures 2 and 3. We assumed that, at $r = 0.1$ AU,

$$B_{\phi 1} = 30 \gamma \quad B_{r1} = 300 \gamma \quad V_r = 400 \text{ km/sec}$$

The values of the magnetic field vector components were chosen to yield $B_{\phi} = B_r = 3\gamma$ at 1 AU for the spiral model in which there is no interaction of the solar wind with interstellar matter.

The radial magnetic field is also plotted. For all positions where $B_{\phi r}$ is greater than B_r , the spiral angle will

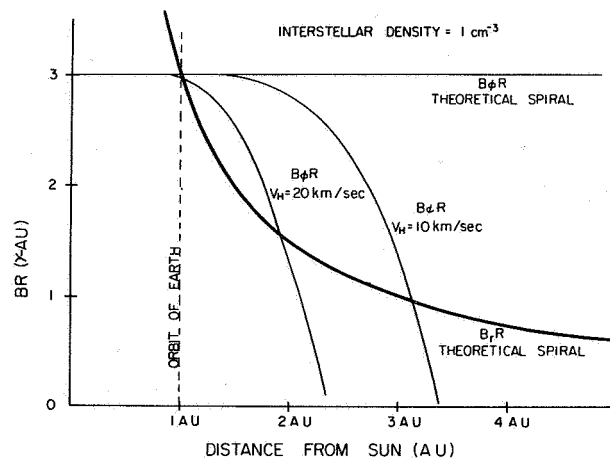


Figure 2 Magnetic field strength for interstellar density $\rho_0 = 1 \text{ cm}^{-3}$.

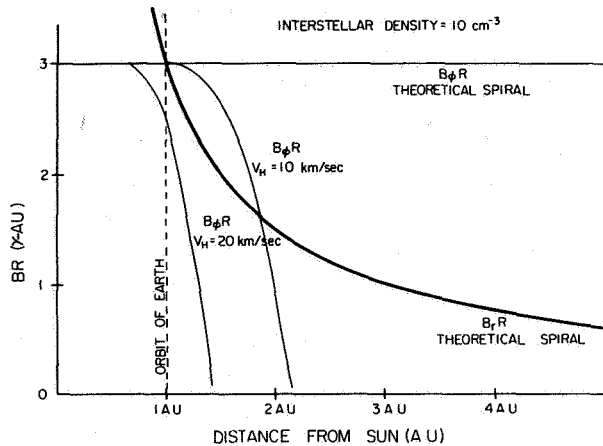


Figure 3 Magnetic field strength for interstellar density $\rho_0 = 10 \text{ cm}^{-3}$.

be greater than 45° . Thus, for the case in figure 2 with V_H , the free-stream velocity of the interstellar neutrals relative to the sun equal to 10 km/sec and radially inward in the solar equatorial plane, the spiral angle will increase through 45° at the orbit of the earth increasing with distance from the sun. Because of loss of angular momentum to the interstellar hydrogen, the spiral angle will again decrease to 45° near 3 AU. The unwinding of the spiralled interplanetary field in the direction of interstellar inflow can be seen from the following argument considering currents.

One can describe the effect on B_ϕ in another way. A current density $\mathbf{J} = J_\theta \hat{\theta}$ is associated with the acceleration of the interstellar particles in the direction of $\mathbf{E} \times \mathbf{B}$. For B_r outward from the sun, J_θ is northward. Since $\nabla \times \mathbf{B} = 4\pi \mathbf{J}/c$

$$\frac{d|rB_\phi|}{dr} = -\frac{4\pi J_\theta r}{c}$$

Thus, there is a negative gradient of $|rB_\phi|$ with r , the distance from the sun.

CONCLUSION

The effect of ionization of interstellar particles on the electromagnetic angular momentum of the solar wind has been examined. For models that predict penetration of significant densities into the solar system, a significant departure from spiral angle (unwinding) is indicated. The

effect will be a maximum in the direction of the approach of interstellar gas.

ACKNOWLEDGMENTS

We wish to thank C. R. Winge, Jr., for helpful discussions. The computer calculations were funded by the Regents of the University of California. One of us (EMW) was supported by a traineeship from the National Science Foundation. The work was also supported in part by the National Aeronautics and Space Administration under research grant NGL 05-007-004.

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DISCUSSION

J. C. Brandt What would be the effect, if the density at infinity were in fact one-tenth, which seems more probable at the present time.

P. J. Coleman It's directly proportional to the momentum. If the velocity were 20 km/sec, it would be slightly less than I showed for the curve of 1 and 5 km/sec. I think one can look at this as the interaction of an electromagnetic wave with these newly ionized particles, the absorption of the wave by the freshly charged particles. The momentum components that are of interest here are the radial and azimuthal ones, at least insofar as this unwinding of the spiral is concerned.

T. G. Cowling Would it be correct to say that, in effect, we have a reduced conductivity so that the freezing-in condition is being violated?

P. J. Coleman I prefer to look at it as the results of polarizing the particles as they become ionized. I think the net effect is the same, that is, there is a current flow and the spiral field straightens out. The results may be the same either way except perhaps that this process may not involve any dissipation that changes the temperatures of the freshly ionized interstellar particles. Instead all the energy may go into directed flow.

T. G. Cowling Yes, but you are in fact dissipating energy. You have energy continually transmitted between the neutrals and the charged particles because they are trying to move with different velocities, one frozen-in and the other not.

P. J. Coleman It is true that they have different velocities, but we have neglected particle-particle interactions altogether. So in this simple model the transformation of electromagnetic energy into mechanical energy is such that all of the former goes into directed flow energy rather than thermal energy.

L. Davis, Jr. There are many alternative ways of looking at this, all of which, if done carefully, lead to the same result. The way that seems convenient to me is to regard the incoming neutrals as flowing through the other medium. When they first become ionized they still have the same velocity, with components parallel and perpendicular to the magnetic field. The parallel component merely continues as a guiding center drift until some instability or irregularity causes the particles to be swept up by the wind. The perpendicular component becomes thermalized and the particles immediately become hot. They will be very hot because they get a thermal velocity roughly corresponding to the solar wind speed. The average velocity normal to the field in this thermal motion will be zero. In other words, to give them this average velocity requires a transfer of momentum to them which will come out of the momentum for the whole ensemble of gas and magnetic field and will lead to the change of the spiral angle, as Paul described.

P. J. Coleman I would just like to add one thing. Your mention of instabilities to me implies a process that is effectively dissipative and I don't think dissipation is required. This is the simplest case in which the particles are cold and they get ionized in the presence of the solar wind electromagnetic field.

W. I. Axford I don't understand this result at all! The essential effect is that you are adding new particles to the solar wind and that these are given a component of velocity in the sense of corotation with the sun and also the radially outward component. The momentum change appears to me to be such that the spiral must become tighter rather than open up.

P. J. Coleman What you're talking about is the situation in which the mechanical component of the momentum is conserved. But in the model I have described, we consider the solar wind momentum in two parts, electromagnetic and mechanical, and simply treat the transformation of the electromagnetic part into mechanical momentum in the newly ionized particles. You could almost consider that the motion of the solar wind particles is unaffected by this loss of the electromagnetic component of the momentum.

W. I. Axford You must conserve total momentum and satisfy the equations of motion. I don't think you split the momentum up as easily as that.

P. J. Coleman I'm conserving total momentum. Perhaps you could look at it this way. If we neglect the solar wind flow, which we can't do, and let these newly ionized particles interact with a pure electromagnetic wave, the wave would give them a kick such as this.

T. E. Holzer The thing that seems peculiar to me is that you are imparting momentum to the particles in the direction in which you must impart momentum to the field in order to unspiral the field and you are claiming that the field becomes unspiraled, or unwound. It seems to me that instead of subtracting two momenta and coming out with zero net change you are adding the two. Do you see what I mean?

P. J. Coleman No. The solar wind has electromagnetic momentum in the positive ϕ direction.

T. E. Holzer And you want to reduce that.

P. J. Coleman Yes. Suppose we think about the interstellar matter coming in along the direction of relative motion. Then it has no angular momentum relative to the sun to start with and if we look right along that line those particles will be kicked so that they have positive azimuthal or ϕ momentum. I say that this momentum is just the part that was originally electromagnetic.

T. E. Holzer What if you had a circular field? How much angular momentum would the field be able to impart to the particles?

P. J. Coleman A circular magnetic field?

T. E. Holzer Yes.

P. J. Coleman If there is no electrical field around, none.

T. E. Holzer Isn't that the condition toward which you are going if you reduce the angular momentum? You reduce the capability of the field to give angular momentum to the particles. If you straighten the field out you're going to be exerting more angular momentum than ever. Are you not?

P. J. Coleman It's true that I would be if I were transferring mechanical momentum from one species to another. Perhaps we should talk about this in private.

L. Davis, Jr. I have a lot of sympathy for everyone involved in this discussion. I have some advantage over many of you because I heard this from Paul a couple of days ago. My first reaction was that if you transfer momentum in the plus ϕ direction to the gas as it is ionized, it obviously flattens the spiral out rather than steepens it. After thinking about it overnight I'm about 95 percent convinced that Paul is right and I have the usual 5 percent residual doubt. Until I have really seen all the mathematics I won't fully understand it, but I think the argument goes like this. Imagine you've made a solution for this whole angular momentum problem, the kind that Weber did, but now you put in this transfer of angular momentum to the infalling material. So you've got your integral for the constant total angular momentum of the electromagnetic field plus particles. This solution, of course, has the characteristic that at least some of the constants are determined by the requirement that the solution pass through the critical point. The solution on both sides of the critical point is partly determined by this requirement; it isn't completely determined by local effects. Next, consider what you see as you go out from a region into which no infalling neutral gas penetrates to one in which neutrals are being ionized and added to the solar wind. In the latter region you see the infalling material being added to the angular momentum budget. Thus, just as Paul says, to keep the total angular momentum constant, the field has to carry less angular momentum here than it did in the inner region and it is more nearly radial where infalling gas is being ionized than it is farther in.