GEOPHYSICAL RESEARCH LETTERS, VOL. 13, NO. 9, PAGES 925-927, SEPTEMBER 1986

ON THE INITIAL MOTION OF ARTIFICIAL COMETS IN THE AMPTE RELEASES

K. Papadopoulos[1] and A. T. Y. Lui[2]

[1]University of Maryland, College Park, Maryland 20742

[2]The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland 20707

Abstract. The early time ($t < 300$ s) interaction of the Ba^+ cloud with the solar wind during the AMPTE comet release is examined, with an emphasis on the issue of the Ba^+ ion magnetization. It is shown that the observed magnetic field profile is consistent with the Ba^+ ions being magnetized, in the sense that the cloud radius $L > R_{Ba^+}$, where R_{Ba^+} is the Ba^+ gyroradius. As a consequence, any momentum coupling force $\boldsymbol{F}$ between the Ba^+ cloud and the solar wind in their relative streaming direction will produce an $\boldsymbol{F} \times \boldsymbol{B}$ acceleration drift in a direction consistent with the observations. The drift will cease when the cloud expands to the extent that the magnetic field inside the cloud is reduced to satisfy $L < R_{Ba^+}$. The implications of the model to observables of the interaction are discussed.

Introduction

On two separate occasions, barium clouds were released in the solar wind just outside the earth's magnetosphere by the AMPTE (Active Magnetospheric Particle Tracer Explorer) mission to create an artificial comet. Detailed descriptions of the first release on December 27, 1984 were documented in a series of articles in Nature (Vol. 320, April 24 issue). The most surprising feature of the AMPTE artificial comet observations has been that the momentum coupling between the solar wind and the released cloud during the first 4.6 min occurred at right angles to the flow of solar wind. Only at late times, when the cloud's brightness decayed substantially, was the cloud accelerated in the solar wind direction [Valenzuela et al. 1986; Rees et al., 1986]. The observed trajectory was consistent with a nearly constant acceleration of 20 m s^{-2} and resulted in a displacement that exceeded 1000 km after 5 min. Haerendel et al. [1986] assumed that the Ba ions were unmagnetized in the region where the magnetic field penetrated the Ba^+ cloud and was compressed [Luhr et al., 1986]. Haerendel et al. attributed the transverse displacement of the cloud to the recoil of head and tail caused by the extraction of Ba^+ ions by the interplanetary electric field.

The purpose of this paper is to examine more closely whether Ba^+ ions in the cloud are magnetized. Here, we consider a Ba^+ ion magnetized if it executes a large fraction of its gyration during its transit time through the compressed magnetic field region shown in Figure 1. If, on the other hand, the trajectory is a slightly deflected straight line, the Ba^+ ion is considered unmagnetized. It is argued here that for the observed magnetic field profile, the Ba^+ ions are magnetized within a time scale shorter than 1 min. As a consequence, any momentum coupling force $\boldsymbol{F}$ between the solar wind and the Ba^+ cloud, laminar or turbulent [Papadopoulos et al. 1986], will produce a lateral $\boldsymbol{F} \times \boldsymbol{B}$ displacement in the direction that is the same as the observed lateral motion of the cloud. The observed acceleration force is then used to compute the magnitude of the coupling force $\boldsymbol{F}$ and to compare it with available models.

Paper number 6L6253D.
0094-8276/86/006L-6253$03.00

Ba^+ Ion Magnetization and Forces

In the reference frame of the Ba cloud, which we take initially to be similar to the Ion Release Module (IRM) spacecraft reference frame, the magnetic field will penetrate with the fluid velocity $U_f(t)$ which can be computed by standard models [Clark et al. 1973]. Referring to Figure 1, which shows in situ plasma parameters including the magnetic field measured at IRM, we can estimate that the distance L between the points A and B is given by $L \approx \bar{U}_f(t)\,\Delta\tau$, where $\bar{U}_f(t)$ is the average velocity of the field penetration during the time t_0 to $t_0 + \Delta\tau$. The gyroradius of the Ba^+ ion during that time will be given by $\bar{R}_{Ba} \approx \bar{U}_f(t)/(e\bar{B}(t)/M)$ where $\bar{B}(t)$ is the average value of the magnetic field. The magnetization condition then becomes $\bar{R}_{Ba}/L \ll 1$. Since $\bar{R}_{Ba} < \bar{U}_f(t)/(eB_{min}(t)/M)$ where B_{min} is the minimum value of the magnetic field during this time scale, we conclude that the Ba^+ ions will be magnetized in the region corresponding to the distance L if

$$B_{min}(\mathrm{nT}) \geq 24/\Delta\tau(\mathrm{min}) \qquad (1)$$

Notice that the condition given by (1) is independent of the field penetration speed since the same speed $\bar{U}_f(t)$ enters the transformation of time into length and the value of the ion gyroradius. From Figure 1 it is clear that (1), which is an overrestrictive condition, is easily satisfied within the range A to B. The magnetization time scale is of the order of a few gyrotimes, or $\approx$80–90 s for an average value of $\bar{B}(t) \approx$ 80–90 nT. This is shorter than the drift time associated with the cloud observations of Figure 2 [Valenzuela et al. 1986]. The motion of the Ba^+ cloud is given by

$$\frac{d\boldsymbol{u}}{dt} = \frac{1}{M}\left(\boldsymbol{F} + e\boldsymbol{u} \times \boldsymbol{B}\right) \qquad (2)$$

where $\boldsymbol{F}$ is the force, laminar or turbulent, between the solar wind and the Ba^+ cloud. Since $\boldsymbol{F} = -\hat{e}_x F_x$ and $\boldsymbol{B} = \hat{e}_y B_y$ (adopting the solar ecliptic coordinate system), for time scales longer than 70–80 s, equation (2) will produce a drift in the $-\hat{e}_z$ direction consistent with the direction of the observed lateral motion of the cloud. The value of drift velocity will be given by

$$\boldsymbol{U}_D = -\hat{e}_z U_D = -\hat{e}_z \frac{F_x}{eB_y} \qquad (3)$$

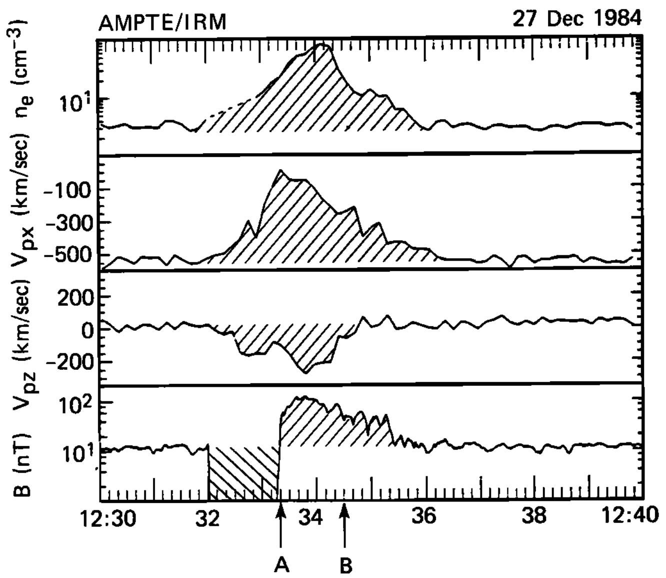

Figure 1. The time profiles of electron density (n_e), solar wind flow (V_{px}, V_{pz}) and magnetic field (B) recorded by the IRM for the December 27, 1984 artificial comet release. The region marked between A and B denotes the field compression region in which the barium ions are magnetized (from Haerendel et al., 1986).

Notice that if the coupling force F_x drops slower than the value of B_y as a function of time, the Ba$^+$ cloud will be accelerated at a rate

$$\dot{U}_D \sim \frac{d}{dt}\,\frac{F_x(t)}{B_y(t)} \tag{4}$$

By comparing equations (3) and (4) with the observed displacement, we can deduce the coupling force F implied by our hypothesis of magnetized Ba$^+$. This will be done in the next section.

Implications of the Model to the Coupling Force

We demonstrated above that the Ba$^+$ is magnetized inside the region marked between A and B. This is consistent with the analysis given in Papadopoulos et al. [1986] that demonstrated that the momentum coupling between the solar wind and the Ba$^+$ cloud arose from the cross field ion-ion instability at distances upstream of point B, while Larmor coupling prevailed downstream of point B.

We examine next the implications of the model to the understanding of the coupling forces by using the observations implied by Figure 2 [Valenzuela et al. 1980].

(i) Since the drift is attributed to magnetization of the cloud, the termination of the drift corresponds to the time that the Ba$^+$ gyroradius becomes larger than the cloud size. This occurs after approximately 256 s (i.e., position 4 of Figure 2).

(ii) Following 256 s, the cloud acceleration in the x direction can be estimated by comparing positions 4 and 5 as

$$\frac{\Delta U_x}{\tau_i} \approx \frac{6}{24}\ \text{km s}^{-2} = 0.25\ \text{km s}^{-2} \tag{5a}$$

Therefore an estimate of the force F_x is

$$F_x = M\,\frac{\Delta U_x}{\tau_i} \tag{5b}$$

From Equations (3) and (5b) we find

$$U_D = \frac{\Delta U_x}{\Omega_{i0}\tau_i}\cdot\frac{B_0}{B_y(t)} \tag{6}$$

where $\Omega_{i0} = 7 \times 10^{-3}\ \text{s}^{-1}$ is the Ba$^+$ gyrofrequency in the ambient field $B_0 \approx 10$ nT. This will give a drift velocity of 2.7 km s^{-1} during the initial time (after the magnetization time scale), i.e. when $B_y \approx 130$ nT, if we assume that the force F_x computed from (5a) is not a strong function of time.

(iii) From Equation (6), we find that a constant acceleration following the initial magnetization can be acquired if the magnetic field inside the cloud decreases linearly with time with a time constant τ_B.

Writing $B_y(t) = B_{y0}\,\tau_B/t$, we obtain

$$\dot{U}_D = \frac{\Delta U_x}{\Omega_{i0}\tau_i}\,\frac{B_0}{B_{y0}\tau_B} \tag{7}$$

For $\dot{U}_D \approx 20\ \text{m s}^{-2}$ and $B_{y0} \approx 130$ nT, we find $\tau_B \approx 137$ s. It also implies that the cloud stops being magnetized when the magnetic field has been reduced to about 70 nT. The

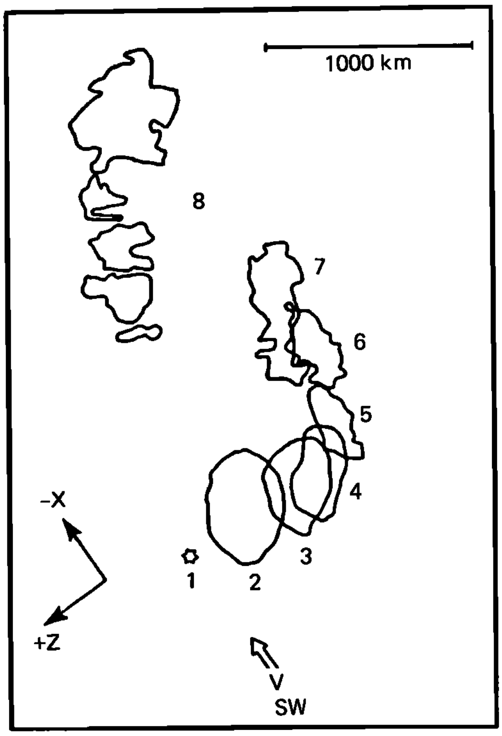

Figure 2. A schematic diagram to show the barium cloud trajectory and outline for the December 27, 1984 artificial comet release. Barium was injected at 12:32:01 UT on that day. The times corresponding from 1 to 8 are 4 s, 181 s, 242 s, 256 s, 280 s, 288 s, 294 s, and 306 s, respectively, after the release. The initial lateral motion of the cloud is suggested here to be an $F \times B$ drift motion for the magnetized barium cloud (from Valenzuela et al., 1986).

dependence of magnetic field inside the cloud on $1/t$ is indicative of a one- rather than two-dimensional cloud expansion across the magnetic field.

Summary and Conclusions

We presented above a model describing the initial Ba^+ cloud observed in the AMPTE program. The model stresses the diamagnetic aspects of the interaction (i.e., $\nabla \times \boldsymbol{B} \neq 0$), and is based on the fact that over relatively short times the Ba^+ gyroradius becomes shorter than the cloud radius. This is shown here to be a direct implication of the observed magnetic field profile. The physics of the magnetic field penetration and compression in the cloud is not elaborated here since the subject has been discussed elsewhere [Lui et al., 1986]. The observed sideways displacement of the cloud is then a natural consequence of the coupling force F_x between the solar wind and the Ba^+, and is independent of its precise nature. The acceleration values predicted by the model are consistent with the observations based on the value of F_x implied by cloud trajectory shown in Figure 2. The termination of the transverse cloud displacement after 280 s is interpreted as caused by the loss of magnetization of the Ba^+ cloud, in the sense of $L < R_{Ba^+}$, arising from the reduction of the magnetic field value inside the cloud.

It is beyond the purpose of this letter to present a critique of an alternative model discussed by Haerendel et al. [1986] and Cheng [1986], based on a rocket effect resulting from ion extraction by the inductive solar wind electric field at the northern edge of the cloud. We simply state here some obvious difficulties associated with the model.

(i) While Ba^+ ion extraction definitely occurs and is clearly seen in computer simulations of the process [Goodrich et al., 1986], the recoil can be balanced easily by the solar wind diversion and does not have to be transmitted by some unknown internal forces to the southern part of the cloud.

(ii) Our arguments show that the bulk of the Ba^+ cloud is magnetized. Any recoil or polarization electric field built on the cloud edges will produce a motion along the solar wind direction.

(iii) Arguments based on the build-up of electrostatic polarization across the cloud are based on the high "dielectric constant" equations first presented by Schmidt [1960]. As shown in the above reference, they are valid only if $\nabla \times \boldsymbol{B} \approx 0$, i.e. the induced currents do not affect the magnetic field, a situation clearly violated during the early times of the interaction.

If we take the size of the cloud at the termination of the lateral drift at 280 s after release as 400 km, the condition of loss of magnetization at a field value of 70 nT implies that the Ba^+ speed U_{rel} in the reference frame of the magnetic pulse is larger than 20 km s^{-1} ($U_{rel} > 20$ km s^{-1}), which is not an unreasonable situation.

In concluding, we should mention that the interaction process is rather complex and phenomena associated with $\boldsymbol{F} \times \boldsymbol{B}$ drifts as well as recoil processes are probably occurring and affecting different classes of Ba^+ ions. On the basis of our admittedly simplified model, we believe that $\boldsymbol{F} \times \boldsymbol{B}$ effects are dominant at early times. We are in the process of conducting extensive computer simulations of the interactions in order to elucidate the relative strength of the various interactions and the validity of the approximations used in our as well as other models.

Acknowledgment. This work was performed at The Johns Hopkins University Applied Physics Laboratory (JHU/APL) during the sabbatical year of K. Papadopoulos. It was supported in part by NASA under Task I of Contract N00024-85-C-5301 to JHU/APL and in part by NSF Grant INT 83-04379 to the University of Maryland.

References

Cheng, A. F., Transverse deflection and dissipation of small plasma beams and clouds in magnetized media, *J. Geophys. Res.*, (in press) 1986.

Clark, R. W., J. Denavit, K. Papadopoulos, Laminar interactions in high Mach number plasma flows, *Phys. Fluids, 16*, 1097, 1973.

Goodrich, C. C., A. Mankofsky, A. T. Y. Lui, K. Papadopoulos, Hybrid simulations of the AMPTE lithium and barium releases in the solar wind, *EOS Trans. AGU, 67*, 334, 1986.

Haerendel, G., G. Paschmann, W. Baumjohann, C. Carlson, Dynamics of the AMPTE artificial comet, *Nature, 320*, 720, 1986.

Luhr, H., D. J. Southwood, N. Klocker, M. W. Dunlop, W. A. C. Mier-Jedrzejowicz, R. P. Rijbeek, M. Six, B. Hausler, and M. Acuna, In situ magnetic field observations of the AMPTE artificial comet, *Nature, 320*, 708, 1986.

Lui, A. T. Y., C. C. Goodrich, A. Mankofsky, K. Papadopoulos, Early time interaction of lithium ions with the solar wind in the AMPTE mission, *J. Geophys. Res., 91*, 1333, 1986.

Papadopoulos, K., J. D. Huba, and A. T. Y. Lui, Collisionless coupling in the AMPTE artificial comet, *J. Geophys. Res.*, (in press) 1986.

Rees, D. J., T. J. Hallinan, H. Stenback-Nielsen, M. Mendillo and J. Baumgardner, Optical observations of the AMPTE artificial comet from the Northern Hemisphere. *Nature, 320*, 704, 1986.

Schmidt, G., Plasma motion across magnetic fields, *Phys. Fluids, 3*, 961, 1960.

Valenzuela, A., G. Haerendel, H. Foppl, F. Melzner, H. Neuss, E. Rieger, J. Stocker, O. Bauer, H. Hofner, and J. Loidl, The AMPTE artificial comet experiments, *Nature, 320*, 700, 1986.

A. T. Y. Lui, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20707-6090.

K. Papadopoulos, University of Maryland, College Park, MD 20742.

(Received June 25, 1986;
Accepted July 23, 1986.)