JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 91, NO. A7, PAGES 8051-8055, JULY 1, 1986

ORDERING OF MOMENTUM TRANSFER ALONG $\underline{V}\wedge\underline{B}$ IN THE AMPTE SOLAR WIND RELEASES

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Abstract. As part of the active phase of the AMPTE mission, clouds of neutral lithium and barium were released into the solar wind from the German Ion Release Module (IRM). In all cases the clouds ionize significantly in the first few seconds following the release, such that the solar wind flow is deflected. A magnetic cavity (field zero) is formed, but this is not associated with a total exclusion of solar wind protons. The close (~35 km for lithium, ~100-200 km for barium) proximity of another spacecraft, the United Kingdom Subsatellite (UKS), allowed good data coverage of the local environment. In the events the minimum Larmor radii of the solar wind protons is of the order of the size of the interaction region of the release; that of "picked up" release ions being one (lithium) or two (barium) orders of magnitude larger, which indicate the need for a hybrid description in which the release ions respond as particles to the magnetic field structures, supported by a charge-neutralizing electron fluid. We highlight important results from the data which, while invalidating a description using MHD theory, are consistent with an ordering of the momentum transfer approximately along the local $\underline{v}\wedge\underline{B}$ direction. We suggest that the existence of high proton flows in the interaction region requires a description which features at least two ion populations, and we show that this ordering may be predicted by treating the ions as a multi-fluid.

1. Introduction

On September 11 and 20, 1984, as part of the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission [Krimigis et al., 1982], two releases of ~3 x 10^{25} atoms of neutral lithium were made from the German Ion Release Module (IRM) spacecraft when it and the United Kingdom Subsatellite (UKS) were upstream of the earth's bow shock in the solar wind flow (in the ecliptic plane at ~19 R_E). For both releases the UKS and IRM (which carry a full complement of instruments) were known by radar ranging to be separated by about 35±5 km. It is also believed, at this time, that UKS lay upstream of the IRM. Although the absolute separation is known to ~10% these preliminary vector separation components could be in error by ~50% (G. Spalding, private communication, 1985). The releases were performed with the intention that the clouds would be produced in steady solar wind conditions. The lithium was then expected to photoionize, with a time constant (for the neutral density to fall by 1/e) of about 1 hour, the resulting plasma then interacting with the oncoming field and plasma. A later release of barium on December 27, 1984, was also made in the solar wind, on the dawn flank of the magnetosphere (almost in the ecliptic at r = 17 R_E, ϕ = -74^0, GSE polar coordinates). The separation of the UKS and IRM at this time was ~170 km with a similar uncertainty in orientation. The neutral barium cloud was expected to photoionize with a time constant of ~30 s. Ground- and aircraft-based observations were also made of the time-varying optical emission of the barium ions [e.g., Rees et al., 1986, Valenzuela et al., 1986].

The magnetic field signatures seen by both spacecraft for these releases have been reported by Luhr et al., [1986 (a), (b)]. In all cases the magnetic field measured shows clearly a region of zero field, which engulfs the IRM for ~10 s in the case of the lithium releases and for ~95 s for the barium release. This region of suppressed field is not seen to extend to the UKS position for any significant length of time, so that the scale size of the interaction region is known to be of the order of or less than the spacecraft separation. Estimates of this scale are generally smaller, for example, 60-70 km for barium [e.g., Luhr et al., 1986 (b)]. On the other hand, the Larmor radii of lithium and barium which have been accelerated as test ions in the ambient solar wind flow are ~$\frac{1}{2}$ R_E and ~10 R_E, respectively, shrinking by a factor of ~6-10 in the enhanced magnetic fields observed during these events. The corresponding gyroperiods in the ambient field are about 1 min for lithium and 20 min for barium. Even for solar wind protons these parameters are, at their smallest, of the order of the time and spatial scales of the events. This suggests that only the electrons, with gyroradii of a few hundred meters and gyroperiods of a few milliseconds, can be reasonably described as a single fluid in this interaction, the nature of the ion interaction being effectively limited by the spatial and temporal scales involved.

Lühr et al. [1986 (a), (b)] point out that the magnetic field signatures for the releases are consistent with the formation of a spatially coherent structure which moves away from the spacecraft rather than a purely temporal fluctuation of the field. The direction of the subsequent motion of this structure is not clear from the field data, however (but see Valenzuela et al. [1986] and Rees et al. [1986] for the case of Ba), and of course depends on the nature of the interaction of the cloud with the solar wind

Paper number 5A8111.
0148-0227/86/005A-8111$02.00

plasma flow. It is also apparent from the magnetic field data and the assumed orientation of UKS that the perturbed magnetic field tilts away from the ambient direction in a manner which seems consistent with field bending around and in front of the cavity. The existence of a magnetic cavity as a spatial structure indicates diamagnetic electron response, as has been predicted, for instance, by C. T. Dum, unpublished manusript, [1984], but then for low ambient flows.

Here, diamagnetic response assumes that the plasma environment of the cloud cannot necessarily initially respond to the existence of the solar wind plasma but can, on the time scale of the release event, respond to the ambient field via the release electrons. Of course, solar wind electron response in this hybrid sense also contributes to the observed field enhancement, which is larger than that expected from the diamagnetic effects due to the injected electrons alone. To what extent this diamagnetic response is modified to produce an asymmetrically draped field depends on what may be assumed about the coupling of the solar wind and release ions to the field. The consequence of a hybrid description, however, in which the electrons are treated as a single fluid and the ions as particles, is that a variety of mechanisms are available for the transfer of momentum from the oncoming solar wind to the release ions. Whereas some of these mechanisms have their counterparts in one fluid and MHD theory and ultimately act globally on the plasma via the net stress over the whole region, it is clear that others do not (instead achieving local stress balance). It is the latter that will be considered in the next section, given the symmetry of the interaction and the existence of high ambient flows, relevant to the solar wind releases. In section 3 we finally briefly review important features in the data which are consistent with this local momentum exchange.

2. General Features of the Interaction

A clear indication of the "particle-like" nature of the interaction is that, while clear deflections of the solar wind bulk flow are seen during both the lithium and the barium releases (~10% and ~80%, respectively) at IRM and UKS [Coates et al., 1986; Rodgers et al., 1986; Paschmann et al., 1986, W. Baumjohann, private communication, 1985], solar wind proton flow is still observed at the IRM when it is located within the diamagnetic cavity. This fact reflects the basic conflict between the frames of reference of the two ion species and is possible because the small-scale size allows the magnetic field to be decoupled from the ion motion. In order to see how momentum may be exchanged locally between the deflected protons and the release ions, we will, in this preliminary discussion, simply consider the fate of the ion populations which encounter the disturbed fields in the vicinity (but not within) the diamagnetic cavity (possible mechanisms for ion extraction from the field null region have been suggested by, for example, Haerendel et al. [1986]).

Since the Debye length is of the order of the electron gyroradii, we first assume that quasineutrality is maintained to a good approximation, so that the electrons behave as a single, massless, charge-neutralizing fluid. For the release ions, local solar wind flow will ultimately produce a local value of the electric field (given by the electron momentum equation with $m_e \to 0$). This is just the electric field in which the release ions (created almost at rest) are initially accelerated. For small perturbations to the flow (i.e., test ion behaviour), for example, the release ions are responding primarily to the existence of an ambient electric field given by $(-\underline{v}_{sw} \wedge \underline{B})$.

On the other hand, the comparatively large release ion density then implies that the magnetic field perturbation is essentially static in the frame of the ion cloud supported by the electrons, so that oncoming solar wind protons which move into this region of reduced flow will, in their rest frame, experience an electric field, associated with the magnetic field perturbation, which is in the opposite direction to that initially experienced by the release ions. In this way, the species are subject to accelerations in opposite directions so as to conserve momentum and which are ordered by the local value of the electric field in each ion rest frame. This process of momentum exchange must also imply some significant perturbation to the solar wind electrons which cannot be deduced without more rigorous analysis.

The relation of this local process to processes which might operate in a more global sense can be clearly seen by examining the moment equations for the ion distributions. C. T. Dum, unpublished manuscript, [1984] has similarly used these to compare the effects predicted by the kinetics of small-scale plasma clouds with the dynamics of MHD. As Dum points out, however, the presence of solar wind protons in the release ion cloud affects the assumption that the total ion current can be identified with the center of mass velocity. Here, since it is obvious that the bulk ion velocities of the species are not equal, it is clear that expressing the equations in terms of the center of mass velocity will obscure a complete description of the processes involved. Rather, a similar treatment to that of Leroy [1983] then for the case of a shock (i.e., planar geometry) is adopted, in which the ion moments are treated as separate fluids, i.e., a multifluid description. One can obtain, for each ion species α, using quasi-neutrality and treating the electrons as a single massless fluid,

$$m_\alpha n_\alpha \frac{D\underline{v}_\alpha}{Dt} = e n_\alpha \left(\underline{v}_\alpha - \frac{1}{n}\sum_{\alpha'} n_{\alpha'}\, \underline{v}_{\alpha'}\right) \wedge \underline{B} + \frac{n_\alpha}{n}\left(\underline{j} \wedge \underline{B} - \nabla\cdot\underline{\underline{P}}_e\right) - \nabla\cdot\underline{\underline{P}}_\alpha + S_\alpha \qquad (1)$$

where

$$n = n_e = \sum_\alpha n_\alpha$$

is the total ion density,

$$\underline{j} = e\left(\sum_\alpha n_\alpha \underline{v}_\alpha - n\underline{v}_e\right)$$

is the total current density,

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \underline{v}_\alpha\cdot\nabla$$

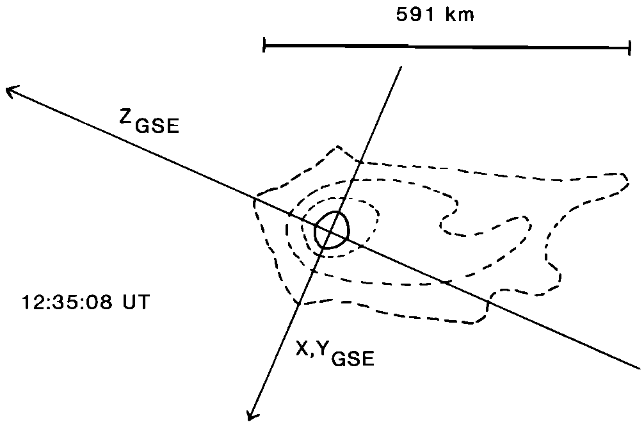

Fig. 1. Approximate sketch of the "cometary" image of the barium ion emission (at 4554 A^0) as photographed by Mendillo and Baumgardner (Mendillo et Al, 1985), ~3 minutes after the release. The -x and +z GSE axes have been projected into the plane of the paper (that is, the plane of the night sky), and at this time the z axis is oriented out of the plane by ~30^0. It is clear from the figure that the "comet" image is not aligned along the -x axis (the projected solar wind flow direction). The convection electric field direction is estimated to be predominantly in the +z direction.

is the convective derivative for "α", $\underline{\underline{P}}$ represents a pressure, S_α is a source term for production of release ions, and the subscript "e" refers to the electrons.

After Leroy a simple friction force has been assumed to represent the collisional term (higher particle correlations) exerted by the electrons.

The first term on the right-hand side of equation (1) corresponds to the local momentum transfer between species which has been described above and will become significant when there is a substantial difference in the velocities of each ion population, as is the case here. Within the simple two-ion species exchange described, the term predicts ordering of the momentum transfer along the local $\underline{v}\wedge\underline{B}$ direction (i.e., where $\underline{v} \simeq \underline{v}_{sw} >> \underline{v}_R$, $\underline{v}_R$ is the release ion bulk velocity). This term of course vanishes when we sum equation (1) over all species "α", since it just represents a momentum balance over the different ion species:

$$\sum_\alpha m_\alpha n_\alpha \frac{D\underline{v}_\alpha}{Dt} = \underline{j}\wedge\underline{B} - \nabla\cdot(\underline{\underline{P}}_e + \underline{\underline{P}}_i) + S_i \qquad (2)$$

where

$$\underline{\underline{P}}_i = \sum_\alpha \underline{\underline{P}}_\alpha \qquad S_i = \sum_\alpha S_\alpha$$

The remaining terms in equation (1) represent forces acting on all species (as is apparent from equation (2), and their net effect, which results from summing the forces over the interaction region, should be interpreted globally; i.e., in the case of $\underline{j}\wedge\underline{B}$ this depends on the type of current closure which exists. The detailed balance between species is now lost, however, from equation (2). Equation (2) becomes the single-ion fluid momentum equation when the ion populations are describable in terms of one species, since the first term in equation (1) then vanishes and equations (1) and (2) become the same. This occurs for the releases only when the solar wind ions are excluded from the cloud.

The breakdown of MHD is therefore seen to be fundamental to the symmetry of the interaction processes. It predicts total exclusion of the solar wind ions through the requirement that $\underline{B}$ is frozen into the ion flow [Krall and Trivelpiece, 1973], and this is consistent with the requirement that the scale size should be large compared to an ion gyroradius [Friedberg, 1982], since then the moments are self-averaging over the gyroscales and imply that the local momentum balance between species should be lost from equation (1). In this limit the ion velocity represents, to first order, a bulk ion pickup motion downstream at the local flow speed (and accelerated by $\underline{J}\wedge\underline{B}$), together with a cross-pickup current which supports an asymmetrical and draped field when the current closes via an Alfvenic wing or equivalent structure (see Southwood and Dunlop [1984] or, for example, Ip and Axford [1982] for the cometary and Venus interaction). The exact momentum balance is achieved globally via this structure.

3. Observations

Observations which are consistent with the local momentum ordering (discussed above) can be found, at least for lithium, in the ion data, where it can be shown for the release of September 20 [e.g., Coates et al., 1986] that at the UKS the lithium ion bulk velocity lies along the local convection electric field direction, i.e., along $\underline{E} = -\underline{v}\wedge\underline{B}$ (where $\underline{v}$ is the local measured bulk solar wind velocity) even during times when the solar wind is perturbed. This result is borne out by the interpretation of the IRM data by Paschmann et al. [1986]. In addition, the change in proton bulk velocity lies along and opposite to the lithium ion motion, as expected if local momentum transfer is the predominant effect. The ambient conditions for the other releases were much more disturbed and obscure similar results. Also, for barium, one might expect some substantial modification of simple momentum ordering by more complex dynamic effects in view of the larger perturbation to the flow. It is interesting, nevertheless, to compare the UKS magnetic field and ion flow profiles for the December 27 release (D. Rodgers, private communication, 1985). It is then found that there is a clear but crude similarity between the profile for $\underline{v}_x$ (GSE) and that for $\underline{B}_y$ and to a lesser extent between $\underline{v}_y$ and $-\underline{B}_x$. These deflections in $\underline{v}_x$ and $\underline{v}_y$ follow those in $\underline{B}_y$ and $-\underline{B}_x$ in a manner which is consistent (approximately) with the net deflection in the flow being in the direction of the local $\underline{v}\wedge\underline{B}$ direction. The gross deflections at both spacecraft are similar on this occasion. Both releases, therefore, indicate an asymmetric deflection of the flow with respect to the ambient flow direction, as implied by local momentum exchange.

The ground- and aircraft-based observations of the barium emissions at the time of the release show clearly an elongated structure which is greatly enhanced at one end. Close study of the images produced by M. Mendillo and J. Baumgardner (private communication, 1985) reveals that the structure is orientated within 20^0-30^0 to the z GSE direction, as shown schematically in Figure 1. The convection electric field, calculated by taking the ambient flow and the maximum field perturbation seen by either spacecraft, lies predominantly along the +z GSE axis, which also lies in the plane of observation (the plane perpendicular to the observer's line of sight). That the orientation of the image is more closely aligned to this electric field direction than to -x again suggests that hybrid effects dominate momentum transfer between solar wind and release ions. Of course, in view of the large local perturbation to the solar wind flow, the local convection electric field may deviate significantly from this +z direction, so that the structure would not be expected to lie close to the +z axis shown.

4. Conclusions

In this paper we have introduced an important implication of the scale sizes of the AMPTE releases, given the existence of high ambient flows, namely, that momentum transfer between the solar wind ions and the release ions can take place locally and hence is not necessarily flow aligned. This leads to the expectation of gross asymmetric motions of each of the two ion species with respect to the flow direction. We have indicated that treating the interaction in a particle-like way suggests that this momentum transfer can be expected, to some extent, to be ordered by the local convection electric field direction. This feature of the particle behavior is lost from any description which does not take into account the separate behavior of the species, only global terms which act on both species remaining in this case. Finally, we have indicated that an exchange of momentum between the solar wind ions and release ions that is not aligned with the solar wind flow direction is indeed seen in the data and, at least for the case of lithium, can be seen to be aligned along the local $\underline{v} \wedge \underline{B}$ direction.

It should be said, however, that our discussion is preliminary and should be viewed as explanatory rather than predictive. A more detailed summary of the data needs to be undertaken to clarify certain aspects of the model; in particular, it is not immediately clear precisely which role is played by the solar wind electron response to the modified field. We expect to clarify this and other details in a later paper. In particular, there is a need for further numerical simulations. In this respect, however, it should be noted that some previous one- and two-dimensional simulations have been performed [Lui et al., 1986; W. Sachs, private communication, 1985]. It seems clear that the restriction of both the magnetic field and the flow in the plane forces a quasi-MHD result in which the flow follows field pileup, the asymmetry of the motions out of the plane perpendicular to $\underline{B}$ being lost.

Finally, it is worth considering the possibility of instabilities associated with the free energy of the newly created barium ions streaming relative to the solar wind plasma, which would tend to disrupt the $\underline{v} \wedge \underline{B}$-ordered motion. Some studies in the low test ion density regime have already been done by Winske et al. [1985] and may be relevant to the fine structure observed in the images of the "tail".

Acknowledgments. We thank W. J. Hughes (for useful discussions relating to the cometary images) and M. Mendillo (for providing the images) who are both at Boston University.

The Editor thanks D. Winske and another referee for their assistance in evaluating this paper.

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(Received September 9, 1985; revised February 14, 1986; accepted February 20, 1986.)