Dynamics of the CRRES barium releases in the magnetosphere

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Abstract. The Combined Release and Radiation Effects Satellite (CRRES) G-2, G-3, and G-4 ionized and neutral barium cloud positions are triangulated from ground-based optical data. From the time history of the ionized cloud motion perpendicular to the magnetic field, the late time coupling of the ionized cloud with the collisionless ambient plasma in the magnetosphere is investigated for each of the releases. The coupling of the ionized clouds with the ambient medium is qualitatively consistent with predictions from theory in that the coupling time increases with increasing distance from the Earth. Quantitative comparison with simple theory for the coupling time also yields reasonable agreement. Other effects not predicted by the theory are discussed in the context of the observations.

Introduction

Chemical releases in the ionosphere and magnetosphere are a type of active experiment that is designed to probe the ambient plasma and elucidate the interactions between newly created plasma and the ambient medium. In early January 1991 a series of barium releases by the Combined Release and Radiation Effects Satellite (CRRES) were performed at different altitudes. Each release in the series (identified as G-2, G-3, and G-4) contained identical amounts of barium (1.7 kg) and were done under similar quiet magnetospheric conditions (e.g., $Kp \sim 3$- for G-3). The objectives of the releases were to study diamagnetic cavity formation, unstable velocity distributions, and coupling of the ionized cloud to the ambient plasma. Table 1 shows the dates, times, geographic coordinates, and altitudes of the three releases.

Several ground stations participated in the release campaign. Stations in both North and South America tracked the barium clouds sometimes for periods of over an hour using image-intensified cameras. Individual ground stations were used in a preliminary study comparing the early time (<1-2 min) behavior of the barium clouds [Huba et al., 1992] and in a study concentrating on the early time behavior of the G-2 release closest to the Earth [Bernhardt et al., 1993].

The early time behavior of a release at the distances of the G-2, G-3, and G-4 releases is dominated by the formation and collapse of a diamagnetic cavity. This cavity forms because a current loop at the edge of the cloud created by the newly ionized barium ions and cold electrons on the surface of the cloud cancels the magnetic field inside the cloud. The maximum size of the cavity is attained when the kinetic energy of the release roughly equals the magnetic energy swept up by the expansion of the cloud [Huba et al., 1992]. Diamagnetic cavities were observed for all three releases in Table 1 [Singer et al., 1991; Bernhardt, 1992]. However, the cavity that is formed is unstable to several possible plasma instabilities and the cloud will structure and collapse on a timescale of seconds when it is still quite dense [Huba et al., 1992]. After this time the ambient magnetic field penetrates the cloud and the barium ions striate along this field.

Later time behavior of the ionized barium cloud depends on the size of the perturbation in the ambient medium. For large releases far from the Earth the cloud acts like a large inertial object. It striates along the magnetic field but continues to move in the direction of the spacecraft motion at the time of the release, dragging the imbedded ambient field with it [e.g., Mendes, 1973]. For smaller releases closer to the Earth the cloud represents a small perturbation in the ambient medium and is expected to rapidly couple to the ambient plasma motion. Theoretical study of this later time coupling of the cloud to the ambient medium suggests a relatively simple interpretation [e.g., Scholer, 1970]. The motional electric field of the cloud created by the differential motion between it and the ambient medium is transferred along the magnetic field as an Alfvén wave at the local Alfvén velocity. The cloud couples to the ambient plasma when this disturbance has swept up a volume of plasma along the flux tube that has a mass equal to the mass of the ionized cloud. After this time the cloud should have approximately the same velocity as the ambient plasma perpendicular to the ambient magnetic field but will continue to striate along the magnetic field.

The determination of the late time coupling for the CRRES releases requires combining ground station data using triangulation procedures to determine the cloud position in space as a function of time. In this paper, triangulation results from the three releases in Table 1 are presented. From these results the motions of the clouds are determined and compared to the simple theory of the later time coupling of the clouds to

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the ambient plasma outlined above. Section 2 of this paper contains a description and examples of the triangulation procedure. Section 3 contains a discussion of the verification of the triangulation results and the uncertainties in the procedure. Section 4 contains the determination of the cloud motion from the triangulated positions and a comparison of the three releases. Section 5 contains a discussion of the observational results and a comparison of these results with theory. Section 6 contains the conclusions.

Triangulation Data and Procedure

Although a large number of ground stations participated in the release campaign, ground station pairs that had large east-west baselines were better suited for the purposes of this paper (see below). An example of the G-2 release data from such a pair of stations is shown in Figure 1. This example will serve to illustrate the triangulation procedure used in this study. The procedure is semiautomated in that several computer programs do most of the computations but key decisions are left to the operator. It is similar to the procedure employed to triangulate one of the Active Magnetospheric Particle Tracer Explorers magnetospheric tail releases [Mende et al., 1989].

The top left-hand panel of Figure 1 shows data from Rosemary Hills, Florida (Latitude 29.4° N, Longitude 82.5° W) approximately 1 min after the G-2 release. These data were acquired from an image-intensified CCD camera with a field of view of 10° although the full field of view is not shown in Figure 1. Bright stars in the image are approximately 5th magnitude. The orientation of the magnetic field line, the location and direction of motion of the spacecraft at the time of the release as seen from the Rosemary Hills location are shown in the upper right-hand panel of Figure 1. The full field of view of the camera is shown by the box in that panel. The large, asymmetric, and bright circle in the upper left-hand panel of Figure 1 is the expanding neutral barium cloud. At the time of observation the CRRES spacecraft (solid square) was still located in the expanding cloud and both were moving ~6 km/s primarily in the direction of increasing elevation as shown in the upper right-hand panel. The thin line marked at one point by the cross is the ionized barium cloud striating along the ambient magnetic field near the release point. In subsequent images the neutral cloud expanded, continued to separate from the ionized cloud, became fainter, and was lost from view approximately 2 min after release. In contrast, the ionized cloud continued to striate along the field and was tracked for over 10 min after the release.

The bottom left-hand panel of Figure 1 shows data from Los Alamos (Breezy Point), New Mexico (Latitude 35.8° N, Longitude 106.2° W) at the same time as the Rosemary Hills image in the top panel. These data were also from an image-intensified CCD camera with a field of view of 4.5° although again, the full field of view is not shown. Stars in the image (for example near the line in the image) are 8th-9th magnitude. Similar to the image from Rosemary Hills, the Los Alamos image in the lower panel also shows the neutral cloud well separated from the ionized cloud that is striating along the magnetic field. Because of the aspect angle of the observations from Los Alamos (see the lower right-hand panel), the neutral cloud appears to be offset from the ionized cloud mainly in the azimuthal direction.

Image pairs from both ground stations were digitized from the original data for as many nearly simultaneous observations as possible after the initial release time. In the first part of the triangulation procedure the star fields in each image pair are identified using standard star charts. The right ascension and declination of the stars in the field of view are placed in a computer file and the pixel locations in the image are identified for two stars which act as reference stars. The star field is then plotted on the image to verify the location of other stars and the aspect ratio of the plotted star field is adjusted to fine tune the fit. The reference stars are then used to linearly interpolate pixel location on the image to right ascension and declination in the sky for the second part of the triangulation procedure.

To triangulate the ionized part of the cloud that is striating along the magnetic field, a point at the center of the striation on such as the one shown by the cross in the top left-hand image in Figure 1 is selected. Then, using an estimate for the distance of the ionized cloud from the Earth (based on the release distance), the computer draws a line segment 0.2 R_E long on the image acquired at the second site that corresponds to the line of sight in the direction of the point chosen on the first image. The center of the line segment is the estimated distance of the ionized cloud. Continuing with the example, this line is shown in the bottom left-hand panel of Figure 1. If the estimate of the distance from the Earth to the cloud is good, then the line should cross the striated cloud in the second image as illustrated in Figure 1. By selecting the position where the line crosses the center of the striation in the second image, the triangulated position for a point in the striated cloud is obtained. This procedure is repeated to determine other positions along the striated cloud. The entire procedure, including redefining the reference stars, is repeated for other image pairs from the releases. The end product of the triangulation procedure is a set of points (in geographic coordinates) along the center of the ionized cloud for each image pair. This set should be the locus of points along a magnetic field line in geographic coordinates. For the G-2 release, it was also possible to triangulate the neutral cloud position and size for approximately the first 2 min after the release (see Figure 1).

Since the cloud striates along the magnetic field which is approximately north-south, large east-west baselines are preferred for the triangulation. For these baselines the line of sight direction for the first image is nearly perpendicular to the ionized cloud in the second image as illustrated in Figure 1. For north-south baselines the line of sight direction would be nearly parallel to the cloud and the triangulation would be difficult [e.g., Mende et al., 1989].
Figure 1. Observations of the CRRES G-2 barium release (one minute after the release) from (top) Rosemary Hills, Florida and (bottom) Breezy point (Los Alamos), New Mexico. The large, asymmetric circle is the expanding barium neutral cloud while the thin line is the ionized cloud. The spacecraft position is shown by the large square. The cross in the upper panel and the 0.2 \( R_E \) line in the lower panel through the ionized cloud were used in the triangulation technique and are explained in the text.

Uncertainties in the triangulation procedure increase with increasing altitude of the release. Choosing station pairs with larger baselines partially compensates for this effect but the almost 3 \( R_E \) difference between the G-2 and G-4 release distances (see Table 1) is too big to be fully compensated by the available baselines. To illustrate this, Figure 2 shows an image pair from the G-4 release. The format is the same as in Figure 1, with the left hand panels showing the observations and the right hand panels showing the location of the magnetic field line and spacecraft as viewed from the observing site. The upper panel shows an image taken approximately 6.5 min after the release by an image-intensified CCD camera at Arecibo, Puerto Rico (Latitude 18.34° N, Longitude 66.75° W). The corresponding image from Los Alamos (Breezy Point) is shown in the lower panel. The same triangulation procedure discussed above was used on this image pair to produce the selected point shown by the cross in the upper panel and the corresponding 0.2 \( R_E \) line shown in the lower panel. Despite the larger baseline used in the G-4 triangulation it is clear from comparison of the line segments in the images in the lower panels of Figure 1 and 2 that the uncertainty in the triangulated cloud location for G-4 will be considerably larger than that for G-2.

Also, uncertainties in the triangulated points from a release will be largest in the radial direction from the Earth independent of the baseline used. This is because positions in the planes of the images (perpendicular to the radial direction) are much more accurately determined than positions...
Figure 2. Observations of the CRRES G-4 barium release (6.5 min after the release) from (top) Arecibo, Puerto Rico and (bottom) Los Alamos, New Mexico. The format is the same as in Figure 1. This release was much further from the Earth and, at this late time in the release, no neutral cloud is visible. The 0.2 RE line in the bottom panel is significantly shorter than in the same panel in Figure 1, indicative of the much further release distance for the G-4 release.

perpendicular to that plane. This will have additional effects on the results (discussed below).

Verification of the Triangulation Procedure

There are several ways to verify the accuracy of the triangulation results. In this section only two of these ways are considered. Further checks that concern the details of the interaction of the ambient plasma with the cloud will be discussed in the next section.

The first obvious verification of the triangulation results is to compare the triangulated position of the cloud at (or soon after) the release with the known location of the CRRES spacecraft. This single point comparison provides a measure of the absolute uncertainty (or offset) in the triangulated position of the cloud. For the G-2 release (closest to the Earth) the triangulated position of the cloud at the release time and the spacecraft position were indistinguishable, indicating an absolute error of less than 30 km (the limit of the resolution of the G-2 images). The differences in the triangulated and spacecraft positions for G-3 and G-4 were approximately 70 km. These larger absolute errors reflect the greater distance of the releases from the Earth when compared to that for the G-2 release.

The second verification is to use the well-known fact that the ionized cloud will striate along the magnetic field after the rapid collapse of the diamagnetic cavity [e.g., Mende, 1973]. Unlike releases in the magnetotail where the model magnetic field is somewhat uncertain and the release is used at least partially to identify the magnetic field [e.g., Mende et al., 1989], the G-2, G-3, and G-4 releases were sufficiently near the Earth and were done under sufficiently quiet conditions to have confidence in the model magnetic field. Therefore an additional test of the data that provides some information on the relative uncertainty in the measured points of the cloud is to compare the model magnetic field with a least squares fit through the triangulated points from an image pair. Table 2 shows the results of this comparison for all triangulated data in this study.
For each release in Table 2, the left-hand columns show the time in universal time (UT), and the right-hand column shows the angle between the model magnetic field (from the CRRES spacecraft ephemeris) and the least squares fit line through the triangulated points for that time. The angle can be relatively large (see, for example, the angle at 0625:57 UT for G-4) soon after the release because the line segment is short and the direction inferred from this segment has a large uncertainty. Angles for the last times listed (for example, 0227:03 UT for G-2) can be also relatively large because the ion cloud becomes faint and difficult to triangulate. However, for most times, Table 2 shows that the direction of the magnetic field inferred from the triangulation results agrees quite well with the model magnetic field direction. On average, the discrepancy is largest for the G-4 release. This is likely a combination of the decreasing accuracy of the model field and, more importantly, the greater distance for the G-4 release from the Earth, resulting in larger statistical errors in the triangulation. Even for this release, the average difference between the model field and the triangulated field is less than 10°. This provides confidence that the triangulation procedure is reasonably accurate.

Because of these observational problems, we deconvolve the motion along and perpendicular to the ambient magnetic field direction and concentrate only on the latter motion. In terms of the late time coupling of the cloud to the ambient plasma, the latter motion is more important since the barium ions are essentially free to move along the magnetic field.

The deconvolution is accomplished by rotating the coordinate system from the original geographic coordinates to a system where the magnetic field direction (defined by the least squares fit through the triangulated data) is along the z axis. An additional rotation is also made so that the y axis is oriented along the component of the spacecraft velocity (in the corotating frame) that is perpendicular to the local magnetic field vector at the time of the release. The x axis completes the right-handed coordinate system. Finally, this coordinate system is translated so that the origin is at the spacecraft location at the release time. It is important to note that this coordinate system is noninertial because the original geographic coordinate system is corotating with the Earth. Thus the coordinate rotation must be done for the triangulated data from each image pair separately.

For each image pair in a release the triangulated points along the magnetic field are projected into the x-y plane of this new coordinate system. Motion of the flux tube perpendicular to the magnetic field is then determined by the change in position of the clusters of points in the x-y plane as a function of time.

These projected points for the G-2, G-3, and G-4 releases are shown in Figures 3, 4, and 5, respectively. The component of the spacecraft velocity perpendicular to the magnetic field at the time of release (in units of 0.01 \( R_E \pm 1 \text{ km/s} \)) is shown in the figures by the arrow along the y axis. Short arrows in the figures show the radial direction to or from the Earth. The G-2 and G-3 releases occurred on the outbound part of the CRRES orbit so that the radial direction from the Earth and spacecraft velocity are in similar directions. The G-4 release occurred on the inbound part of the CRRES orbit so that the radial direction from the Earth and spacecraft velocity are in nearly opposite directions. The corotation direction is perpendicular to the radial direction. In the G-2 and G-4 releases the corotation direction was nearly in the x direction in Figures 3 and 5. However, for the G-3 release, the corotation direction has a substantial component in the y direction in Figure 4.

Cloud Motion

The later time barium cloud motion can be separated into striation along the ambient magnetic field and motion of the flux tube perpendicular to the ambient magnetic field direction. Determining the changes in the cloud size along the magnetic field has several observational problems. First, the cameras used to image the releases had relatively small fields of view. In the bottom left-hand panel of Figure 1 it is clear that the entire ionized cloud along the magnetic field is not within the field of view of the camera. This problem becomes particularly acute at later times when the cloud subtends an angle of many degrees in the sky. Ground observers were instructed to track one end of the cloud after the cloud moved out of the field of view. Triangulation of only the part of the cloud that was tracked produces an apparent motion along the field with time. A second problem with the observations is that the image intensity is not calibrated for the cameras used in this study. Therefore the apparent length of the cloud even at early times is a function of the (uncalibrated) images from different sites.
For the G-2 release it was possible to triangulate the center and outer radius of the neutral cloud for approximately the first 2 min. In the last image pair at 0219:03 the center of the neutral cloud was not in the field of view of the camera at one of the observing sites and had to be estimated from the curvature of the part of the outer radius of the neutral cloud in the field of view. The velocity of the neutral cloud is expected to be that of the spacecraft velocity at the release time. Figure 3 shows that the G-2 neutral cloud moved approximately in the +y direction in agreement with expectations. (The magnitude of the cloud velocity is discussed below.) The cloud also expanded with an expansion velocity of about 1.6 km/s. This velocity is somewhat higher but similar to previous estimates of the neutral cloud expansion [e.g., Bernhardt et al., 1993]. The ionized cloud motion is in stark contrast to this neutral cloud motion and expansion. The ionized cloud initially moved approximately in the direction of the spacecraft velocity vector for a distance of ~0.01 RE from the release point and then stopped for the rest of the approximately 11 min of observations. Evidence of the separation of the neutral cloud and the ionized cloud 1 min after the release can be seen in Figure 1. Because the coordinate system is corotating with the Earth, Figure 3 actually shows that after the first minute the ionized cloud acquired the corotational velocity of the ambient plasma but the neutral cloud moved with the spacecraft velocity and direction as if there were no corotational forces on it.

For the G-3 release only the ionized cloud could be tracked. Its motion perpendicular to the magnetic field in the corotating frame is shown in Figure 4. One of the obvious features of the "clusters" of triangulated points that are projected into the x-y plane in Figure 4 is that they line up along the radial direction from the Earth. If the statistical uncertainty in the triangulated position was the same in all directions, then the projected points would form a true cluster around the least squares position of the magnetic field in Figure 4. However, the uncertainty is not the same in all directions. As discussed above, the uncertainty in the radial direction is larger. Therefore the points that form short line segments for each time period show the uncertainty in the radial direction is of the order of 0.01 RE, but it is much smaller perpendicular to that direction. The G-3 ion cloud motion is significantly different from that for G-2. Because the motion is complicated, the dashed line connecting the
centers of each group of points shows the motion of the average position of the cloud with time. Considering the motion in the y direction first, Figure 4 shows that the G-3 cloud moved approximately along the spacecraft velocity vector for the first 1.5 min and then reversed its motion. It then moved in the -y direction for approximately another 2.5 min before stopping its y motion for the rest of the observing time.

The motion in the x direction for the G-3 release is unique to the three releases. The motion is nearly uniform after the first minute because the distance covered is approximately constant as is the time between observations (with the exception of a data gap between 0416 and 0419 UT). The velocity computed from the change in x position with time is approximately equal and opposite the corotation velocity of the plasma at the G-3 distance, indicating that the cloud was stationary with respect to the rotating Earth.

Like the G-3 release, only the ionized cloud could be tracked for G-4. However its motion was much less complicated when compared to that of the G-3 release. The G-4 motion perpendicular to the magnetic field is shown in Figure 5. The motion is relatively simple in that the cloud initially moved away from the release point along the spacecraft velocity vector direction (also the radial direction) for over 5 min after release and then slowed its y motion for the duration of the observation period. The offset of the motion in the x direction reflects the 0.01 RE offset in the triangulated and actual release positions. No motion in the x direction for the entire period indicates that the ionized cloud was corotating with the Earth throughout. Triangulation beyond 8 min after the release was not possible because the cloud became too faint at one of the observation sites to be reliably tracked.

Using consecutive triangulated y positions and the time between them, the y velocity of the cloud as a function of time for the three releases was computed. These velocity profiles are shown in Figure 6. The dashed line in each panel shows the component of the spacecraft velocity perpendicular to the magnetic field at the time of the release. Error bars on the velocity measurements of the ionized clouds are computed from the uncertainty in the triangulated y position and are based on the scatter of the points for an individual triangulated position in Figures 3, 4, and 5. These error bars are smaller than the symbol size for the G-2 release but increase significantly with increasing release distance from the Earth. Since the errors are computed using the statistical uncertainty in the location, if only one point is triangulated, (for
example, near the beginning of the release), then the uncertainties in Figure 6 do not fully represent the actual uncertainty in the measurements. This is apparently the problem with the initial measurements of the G-3 and G-4 releases, which indicate very low initial velocities.

For the G-2 release the neutral cloud center could be triangulated reasonably accurately except for the last point at 120 s after the release. For this point the uncertainty in the position may be larger than shown because the cloud was dissipating rapidly and the center had to be estimated from the curvature of the cloud in the field of view. Thus the apparent acceleration of the neutral cloud at 120 s is probably not real. In general, the neutral cloud moved away from the release point with the spacecraft velocity, in agreement with expectations. This provides additional confidence in the triangulation procedure. Also, for the G-2 release it is apparent that even with the first velocity measurement 1 min after the release, the ionized cloud had slowed considerably. The velocity rapidly decays to zero and remains close to that value for the duration of the observations.

The G-3 ionized cloud velocity profile is considerably different from that of the G-2 release. The first velocity point is somewhat below the spacecraft velocity; however, the basic trend is a positive velocity until 100 s after the release, then the velocity passes through zero and stays negative until 300 s after the release at which time the velocity returns to zero for the duration of the observations. The velocities for the last three points are somewhat suspect because the cloud was beginning to dissipate and move out of the field of view of the camera at one of the observing locations.

For the G-4 release the velocity appears to be higher than the spacecraft velocity at the release time. If this higher velocity were true, it would be an extraordinary finding for which we have no physical interpretation. However, the y velocity is almost entirely along the radial direction (Figure 5), where the uncertainties in the position are the largest. Also, this release was the furthest from the Earth of the three, and consequently the most difficult to triangulate. Since the error bars in Figure 6 are based only on the standard deviation of the y positions for adjacent times, they may not fully represent uncertainties in the positions in the G-4 event. This apparent higher velocity notwithstanding, the trend in the G-4 release is similar to the early time trends in the other releases. The release initially moves away with nearly constant velocity and then stops after approximately 300 s.

**Discussion**

The time required for a release to acquire the ambient plasma motion is proportional to the size of the perturbation on
Figure 6. The y velocities of the ionized clouds for G-2, G-3, and G-4. The G-2 neutral cloud moved with at least the spacecraft velocity for as long as it was reliably observed (the last point may be suspect). The ionized clouds all had the characteristic of moving at a velocity other than zero but eventually decaying to zero. Decay times for the three releases are shown by the vertical dashed lines.

Ambient medium. Since identical amounts of chemical were used in the G-2, G-3, and G-4 releases, the size of the perturbation depends only on the ambient plasma conditions, primarily the ambient density. Qualitatively, the density decreases with decreasing distance from the Earth so the time needed to acquire the ambient plasma motion (in these cases zero velocity in the y direction perpendicular to the magnetic field and perpendicular to the corotating direction) should increase for G-2 through G-4. The observations in Figure 6 are consistent with this expectation. The vertical dashed lines show where the ionized cloud velocity is 1/e of its initial velocity. These velocity decay times increase with increasing distance from the Earth. For the G-2 release the decay time was estimated by assuming that the velocity decreased linearly with time from the spacecraft velocity to the first observed velocity. For the G-3 and G-4 releases the initial velocity was assumed to be the spacecraft velocity and the average measured velocity, respectively.
Quantitative theory suggests that the decay time should be the time required for an Alfvén wave to propagate along the ambient field and sweep over a mass equal to the mass of the ionized cloud [Scholer, 1970]. Direct in situ observation of electric and magnetic fields during the CRRES G-9 barium release at 441 km altitude provide evidence for a standing Alfvén wave structure. This structure was capable of decelerating the ionized cloud on a timescale consistent with the braking time scale determined from the release images [Wygant et al., 1994].

Assuming that the Alfvén velocity does not change along the field line from the observation point to the ionosphere, then the mass of the cloud and the mass of plasma swept over by the Alfvén wave are related by

\[ \frac{M}{A} = 2\rho V_A \tau, \]  

(1)

where \( M \) is the mass of the cloud, \( A \) is the cross-sectional area of the cloud, \( \rho \) is the ambient mass density (here we assume protons only), \( V_A \) is the local Alfvén velocity, and \( \tau \) is the decay time or the time required for the cloud velocity to decrease to \( 1/e \) of its initial value. The factor of 2 comes from the fact that there are Alfvén waves launched in both directions along the magnetic field. A more accurate estimate of \( \tau \) would be obtained by modeling the change in the Alfvén velocity along the magnetic field. These and other assumptions are beyond the scope of this paper, and measurement uncertainties (see below) suggest that a higher level of sophistication may not be warranted.

Each release contained 1.7 kg of barium. Assuming that 40% of the released chemical ionized [Huba et al., 1992], the mass of the cloud was 700 g. Other quantities in (1) for the three releases are in Table 3.

The Alfvén velocity and the ambient density in Table 3 were determined from the in situ magnetic field and plasma wave data and are probably quite accurate when compared to other quantities in Table 3. We chose to estimate the cloud radius from the images. The estimates are about a factor of 20 times larger than a barium ion gyroradius at the release distances and are also larger by about a factor of 4 than the confinement radius [e.g., Huba et al., 1992]. Since the decay time is inversely proportional to the square of the cloud radius, using the gyroradius or the confinement radius in (1) would result in decay times of 400 and 20 times larger than those listed in Table 2, respectively. Table 3 shows that the estimated decay time is a factor of 2 larger than the observed decay time. However, the ratio of the estimated and observed decay times for the three releases are in reasonable agreement. Therefore we conclude that, although there is not detailed agreement between the observations and the predictions from (1), there is good enough quantitative agreement to conclude that the concept of the coupling of a release with the ambient medium suggested by Scholer [1970] is reasonable.

Also listed in Table 3 is the Alfvén transit time from the equator (at the distance of the release) to the ionosphere. This transit time was estimated from Mende et al. [1980, equation (3)], using a dipole magnetic field. It is clear from Table 3 that the time required for the release to couple to the ambient medium is considerably longer than an Alfvén transit time. In fact, the coupling would require of the order of 10 transit times or many reflections of the Alfvén wave disturbance off the ionosphere. Using the Alfvén transit time and the initial speed of the ionized cloud perpendicular to the magnetic field, the possibility that an Alfvén wave will return to the cloud before the cloud moves a substantial distance away can be estimated. By multiplying the Alfvén transit time by the spacecraft velocity perpendicular to the magnetic field (5.9, 2.88, and 2.1 km/s for the G-2, G-3, and G-4 releases, respectively) it is apparent that in all three cases, the Alfvén wave will return to the release point at about the same time that the release has moved approximately one ionized cloud radius away and the Alfvén wave has the possibility of reencountering the release in all three cases.

Reflection of the Alfvén wave off the ionosphere was considered in the original model of Scholer [1970]. In the reflection process, part of the wave energy is dissipated in the ionosphere. By applying (1) to the G-2, G-3, and G-4 release data we have assumed perfect reflection of the wave. Furthermore, we have assumed that the wave will return to the cloud to continue to interact with it for as many reflections (approximately 10) as required to stop the cloud. These assumptions, in addition to the assumption of a constant Alfvén velocity along the magnetic field are significant oversimplifications of the coupling process. Better modeling of the release may improve the overall agreement between observations and theory. However, the largest uncertainty in the observations is the cloud diameter. The diameter had to be estimated from the release images and, because the brightness of the cloud is a function of the exposure time, the sensitivity of the camera, and other factors, this estimate could be uncertain by as much as a factor of two. Since the cloud radius enters as the square in (1), the overall uncertainty may be quite large. This large uncertainty suggests that further refinement of the model may not be warranted.

A prediction from the wave reflection off the ionosphere was that the cloud could overbrake and acquire a velocity in the opposite direction of the original release velocity [Scholer et al., 1970]. The observations of negative velocities in Figure

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<td>Alfvén velocity km/s</td>
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6 for the G-3 release may be evidence for this overbraking. In addition, the G-3 release was the only release that had a substantial initial velocity in the corotation direction. Perhaps not by coincidence, the G-3 release was the only release that exhibited motion counter to the corotation direction. Following a procedure similar to that used by Wygant et al. [1994], we used the in situ measurement of the electric field inside and outside of the G-2, G-3, and G-4 releases to determine that in all three cases, the ambient plasma was corotating. Therefore the G-3 release was clearly not moving with the ambient plasma in the x direction in Figure 5. It is possible that the same over-braking observed in the y direction and predicted by Scholer [1970] is responsible for the x motion of this release. However, further work on the modeling of this and the other releases and the comparison of these models with the observations in this paper is needed to confirm this possibility.

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