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Sedimentation of barium ions from the CRRES G-9 release

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Abstract. The CRRES G-9 barium release was designed for the investigation of the field line tracing between the release point at 17.4° N latitude and the area of ion cloud sedimentation at about -41° S latitude. Very recently published images of the ion cloud after the release showed the development of at least two weak filaments between the release point and the main ion cloud [*Zaitsev et al.,* 1996]. Observations made from an aircraft in the south Atlantic region verify that at least one of these filaments survived the transequatorial transit and was still separated from the main barium cloud during sedimentation.

Introduction

For many years chemical release experiments had been used to study the near-earth space environment by the creation of artificial plasma which can be used either as a tracer within or as a perturbation of the background plasma. The CRRES spacecraft [*Reasoner,* 1992; *Bernhardt,* 1992] was designed to perform release experiments in the ionosphere and magnetosphere for the study of the critical ionization velocity effect, stimulated particle precipitation, plasma instabilities, diamagnetic cavities, and field line tracing [see e.g. *Huba et al.,* 1992; *Wescott et al.,* 1994; *Delamere et al.,* 1996].

The G-9 barium release was designed to probe the transequatorial transit and sedimentation of barium ions by the injection of a certain amount of chemicals into a low L-value flux tube. The early development of the plasma cloud and the 'skidding', the **E** x **B** drift of the ion cloud due to the polarization within the cloud have been investigated [*Huba et al.,* 1992; *Delamere et al.,* 1996]. In a recently published paper *Zaitsev et al.* [1996] presented images of the very early temporal development of the G-9 barium cloud showing the skidding of the ion cloud and the development of two additional barium filaments between the release point and the field-aligned main ion jet. These images were taken from the research vessel "Professor Zubov" which was in a very favourable position during the G-9 release having the release close to magnetic zenith. Additional simulations of the initial evolution of the ion cloud taking into account an inhomogeneous ionization model and the background electric field verified the development of such filaments approximately 2 s after the release.

This paper presents optical data taken from an aircraft in the south Atlantic area showing that at least one of the filaments survived the transequatorial transit from the release point to the sedimentation area.

Experiment and data analysis

The CRRES satellite was launched on an Atlas Centaur rocket in July 1990 into a highly elliptical orbit inclined at 18° with a perigee near 400 km and an apogee near 33,000 km. 15 chemical release experiments were performed in different regions of the magnetosphere.

The G-9 release (Table 1) at an altitude of more than 400 km ensured gyration frequencies for the barium ions very much larger than the collision frequencies and therefore the ions could move unperturbed along the magnetic field lines. A B-707 aircraft of the Argentine Air Force cruising in the South Atlantic area at an altitude of 12,195 m (Fig. 1) observed the barium ion streak beginning 12 minutes after the release until about 1 hour, 10 minutes after release (Fig. 2). The aircraft carried an EBS-camera with an optics of 105 mm focal length and an interference filter at 455.4 nm wave length. The field of view was 15.4° x 11.5°. Integration times between 40 ms and 640 ms were used for the individual frames. The star background was used for exact position determination and geometric calibration. The cameras were calibrated with a standard light source of known spectral behaviour for the quantitative brightnesses and luminosity determination of the barium cloud.

Discussion

The spherical expansion of a cloud of N_o neutrals during a chemical release experiment can be described by a Gaussian distribution function

$$f(v) = \frac{N_o}{v_{th}\sqrt{\pi}} \exp\left[-\frac{(v-v_o)^2}{v_{th}^2}\right]. \quad (1)$$

Table 1. CRRES G-9 release experiment

Date	July 19, 1991
Time	08:37:07 UT
Latitude	17.418° N
Longitude	297.204° E
Altitude	441 km
Angle, **B**-**v**	98.2°
v of satellite	9.6 km/s
Gyrofrequency	3.5 Hz
Collision frequency	5.4×10^{-3} s^{-1}
Released Ba	10,405 g
Atoms at 40 % efficiency	1.8×10^{25}

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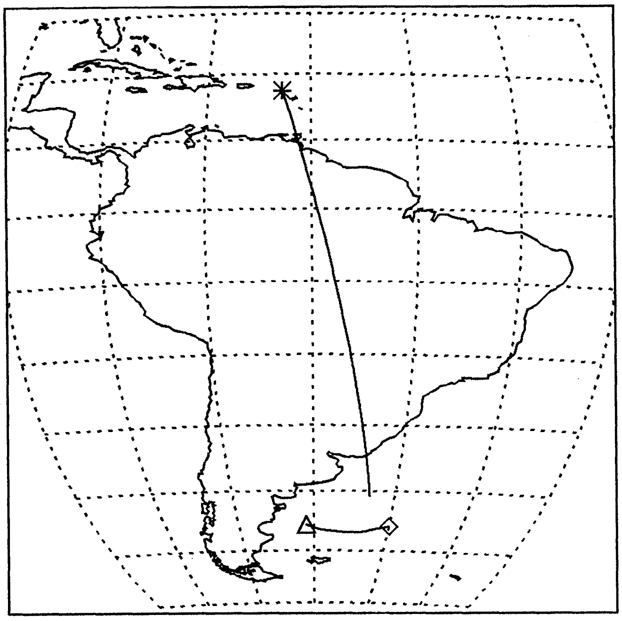

Figure 1. Map of south America with the G-9 release point (asterisk), the magnetic field line through the release point, and the position of the observation aircraft between the release time 08:37:07 UT (◇) and the end of observation at 10:00:00 UT (△).

The mean radial expansion velocity $v_o = 1.33$ km/s, and the ratio of the radial and the mean thermal velocity of the atoms $v_o/v_{th} = 4.5$ for the special mixture of boron-titanium thermite were determined in earlier experiments [*Wescott et al.,* 1994]. With a time constant of 28 s [*Hallinan,* 1988] the barium is ionized by the solar UV light and becomes coupled to the magnetic field.

During the collision free motion of ions along the magnetic field the total energy E (the sum of the kinetic and gravitational energies) and the magnetic moment μ

$$E = \frac{mv^2}{2} - \frac{GmM_\oplus}{R} \tag{2}$$

$$\mu = \frac{mv_\perp^2}{2B} = \frac{m\mathbf{v}^2 \sin^2\alpha}{2B} \tag{3}$$

are invariant. The symbols are the ion mass m, the mass of the earth $M_\oplus$, the distance to the earth center R, the total velocity **v**, and the perpendicular velocity $v_\perp$. In the earth's magnetic dipole field perpendicular and parallel momentum are transformed into each other according to increasing or decreasing magnetic field strength B. The ion motion is determined by the vector sum of the initial velocity of radial expansion within the neutral cloud and the satellite velocity. During the G-9 experiment the parallel velocity component of the cloud motion was 1.37 km/s. Due to these initial conditions 63 % of all ions can move into the southern hemisphere. All the other ions fall back into the ionosphere of the northern hemisphere, even if most of them have an initial velocity component into the southern direction, but the parallel kinetic energy is not high enough to climb to the highest point of the field line at about 2290 km above the geomagnetic equator.

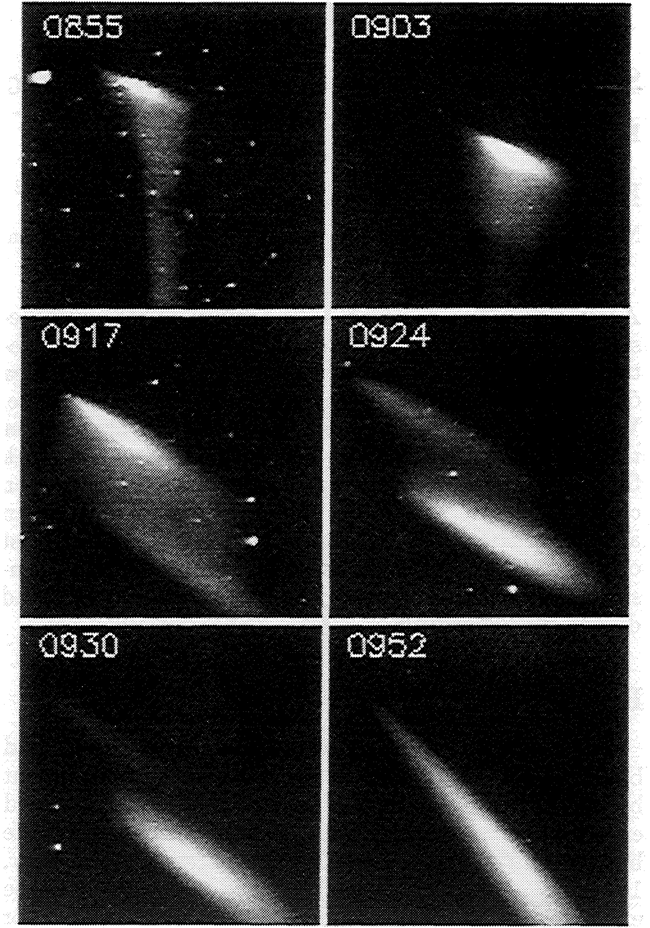

Figure 2. Images of the G-9 ion cloud observed from the aircraft. All images were contrast enhanced.

The increase of the maximum barium cloud brightness with time (Fig. 3) as well as the increase of the cloud luminosity (Fig. 4) are caused by the increasing number of ions arriving in the southern hemisphere due

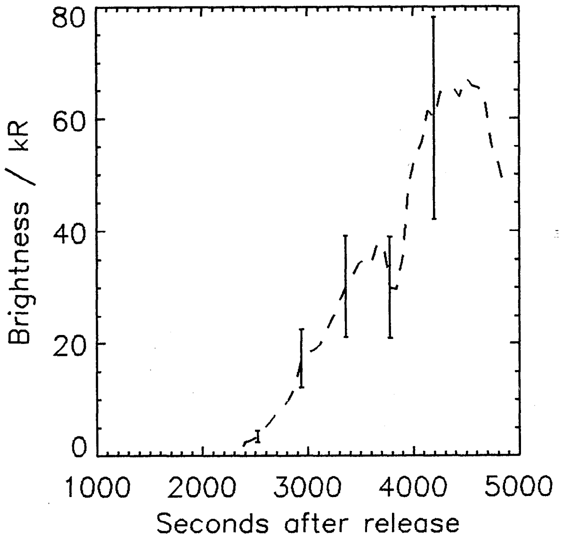

Figure 3. Maximum brightness of the G-9 barium cloud in the southern hemisphere determined from the aircraft observation.

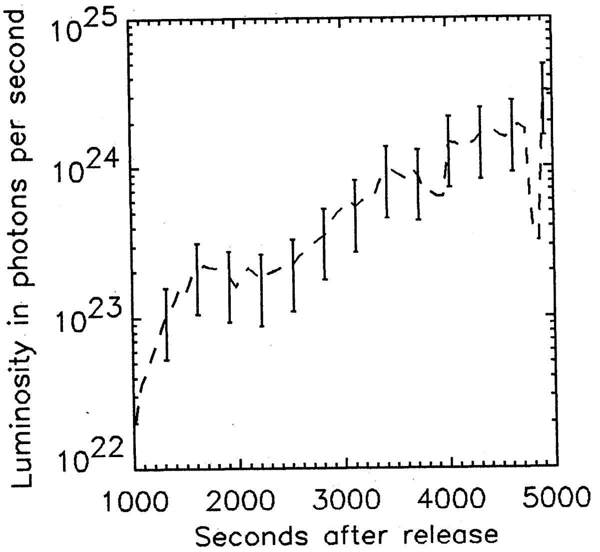

Figure 4. Luminosity of the G-9 barium cloud in the southern hemisphere determined from the aircraft observation. Due to a camera pan only a part of the complete cloud was within the field of view of the camera causing the low numbers around 4800 s after release.

to their different initial momenta. The apparent decrease of both curves at 3800 s after release is caused by an improper brightness conversion for a specific integration time, most probably due to an error during the calibration. 4500 s after release the sedimentating ion cloud became bigger than the field of view of the camera. Even though the cloud was observed until 6200 s after release no further total luminosities could be determined. The maximum reliable luminosity was measured 4900 s after release as 3.2 10^{24} photons per second. From an estimated yield of 1.8 10^{25} atoms (Table 1) with 63 % probability for them to travel as ions into the southern hemisphere and with an excitation rate of 0.34 s^{-1} [*Föppl et al.,* 1965] a luminosity of 3.8 10^{24} should be expected. Although this is 20 % larger than observed, the agreement is good because there was a small portion of the cloud outside the camera's field of view. In contrast to the much higher Doppler-increased excitation rates for ions moving with the satellite velocity [*Wescott et al.,* 1994] we had to use the excitation rate for ions at rest. The decreasing maximum brightness of the cloud after 4600 s is caused by the dilution of the cloud.

One special feature of the G-9 ion cloud after the transit of the ions into the southern hemisphere was a small streak west of the main ion cloud (Fig. 5). The greatest brightness of this streak could be observed 3950 s after release when 0.93 % of the total luminosity of the big main cloud could be determined in the filament. At that time the total luminosity was 9.5 10^{23} photons per second and therefore about 2.6 10^{22} barium ions were concentrated in the filament. However, it is not impossible that the number of ions in the filament further increased as did the main cloud, but the observation geometry from the flying aircraft changed in that way, that the filament could not be separated from the main cloud in later times.

Unfortunately the weak filament was only visible in the images of our high sensitive camera. Therefore, an exact triangulation of the filament position with data of other observers was impossible. But with the fit of magnetic field lines to the western edge of the barium clouds especially as long as there was a clear cloud of sedimentation and the part of the cloud along the tangent of the aircraft view, it was possible to calculated some quantities with small uncertainties.

The gyro-radius for Ba ions with the maximum perpendicular velocity within the release cloud was 500 m. Therefore, the minimum diameter of the filament must be in the order of 1 km. At 9:25 UT the distance between the aircraft and the filament was 736 km, which was determined with the best coincidence between a fitted field line and the western edge of the barium streak. Using the geometric calibration with the star background and this distance the diameter of the filament was determined with 2.0 km. However, the diameter in the southern hemisphere where the ions came to rest due to collisions with atmospheric neutrals needs not to correspond to the diameter of the filament estimated from the gyro-radius immediately after release.

The sedimentation of the barium ion cloud could not be analyzed until 2800 s after release because until then the altitude of the lower border of the cloud was determined by the altitude of the solar terminator. After that time the main cloud and the filament were sedimentating with velocities of 35 m/s and 23 m/s, respectively. These values are consistent with previously measured vertical velocities [*Rieger,* 1974] but are somewhat higher than the reported 10 m/s at 248 km. This is presumably due to the denser atmosphere and lower ion mobility at lower altitudes.

Conclusions

In the images taken shortly after release two filaments could be identified [*Zaitsev et al,* 1996]. In our images however, we could only doubtlessly identify one filament. Furthermore we can not without doubt determine, if the filament in our images corresponds to

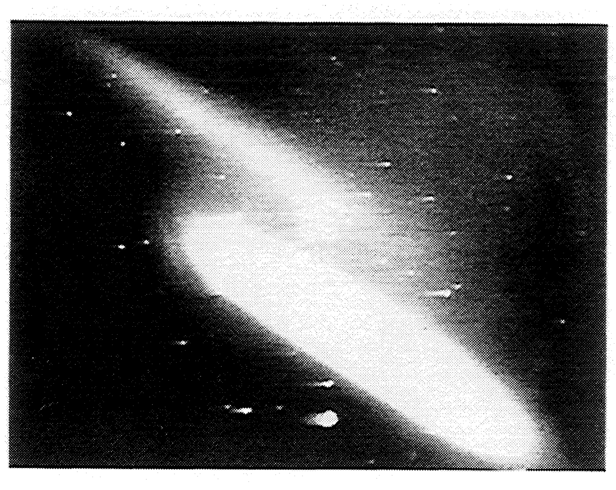

Figure 5. Image of the G-9 ion cloud observed from the aircraft at 09:25:20 UT. The image was extremely contrast enhanced in order to show the weak filament west (left) of the main cloud.

the 'first' or the 'second' filament in Zaitsev's images. There are two possible explanations. If we see the first filament, then the second filament can not be optically resolved from the main cloud. If we see the second filament, then the first filament has diluted below the sensitivity limit of our camera.

These filaments between the release point and the main ion cloud could not be identified in the images presented by *Delamere et al.* [1996] because these images were taken unfiltered in white light and overdriven by the bright release cloud. The striation discussed in [*Delamere et al.*, 1996] at the skidding distance of 17.5 km most probably coincides with the 'main jet' of *Zaitsev et al.* [1996] at 18 km distance from the release point. But further triangulation would be necessary to verify this identification. However, the striations are also not evident in the filtered images taken from Arecibo [*Huba et al.*, 1992], most probably because the brightness was below the sensitivity limit of the camera.

The simulations in [*Zaitsev et al.*, 1996] showed that the interaction of the heavy ion cloud with a background electric field of the order of 5 mV/m can reproduce the experimental findings of filament formation.

Artificially injected ion clouds in the ionosphere generally show a characteristic pattern of striations aligned with the magnetic field [see e.g. *Völk and Haerendel*, 1971]. Except for the small filament, no other filament could be observed in the sedimentating cloud. This fact, the transequatorial transit of the cloud, and the comparison with another release experiment will be the topic of a subsequent paper.

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