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TITLE

CREATING UNSTABLE VELOCITY-SPACE DISTRIBUTIONS WITH BARIUM INJECTIONS

AUTHOR(S) Morris B. Pongratz

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CREATING UNSTABLE VELOCITY-SPACE DISTRIBUTIONS WITH BARIUM INJECTIONS

Morris B. Pongratz

Space Plasma Physics
Group ESS-8 MS D438
Los Alamos National Laboratory
Los Alamos, New Mexico, USA 87545

ABSTRACT

Large Debye lengths relative to detector dimensions and the absence of confining walls makes space an attractive laboratory for studying fundamental theories of plasma instabilities. However, natural space plasmas are rarely found displaced from equilibrium enough to permit isolation and diagnosis of the controlling parameters and driving conditions. Furthermore, any plasma or field response to the departure from equilibrium can be masked by noise in the natural system. Active experiments provide a technique for addressing the "chicken or egg" dilemma. Early thermite barium releases were generally conducted at low altitudes from sounding rockets to trace electric fields passively or to study configuration-space instabilities. One can also study velocity-space instabilities with barium releases. Neutral barium vapor releases wherein a typical speed greatly exceeds the thermal speed can be used to produce barium ion velocity-space distributions that should be subject to a number of microinstabilities. We examine the ion velocity-space distributions resulting from barium injections from orbiting spacecraft and shaped-charges.

Keywords: Active Experiments, Barium injections, Plasma Instabilities, Velocity-Space Instabilities

1. INTRODUCTION

Active experiments in space plasmas can be used to study the space plasma environment *per se* or to exploit the space plasma as a laboratory to examine fundamental questions of plasma physics. The space plasma environment can be studied using passive techniques such as small barium tracer releases (Ref. 1) or by using perturbing techniques such as water releases to deplete the thermal plasma. In this paper we examine active experiments as a means of studying fundamental plasma instability theories.

Barium releases have been used to study configuration-space instabilities such as the Gradient Drift or ExB instability (Refs. 2,3). In these experiments the integrated properties of the velocity distribution functions are significant, e.g., the gradients in the plasma density. Also the perturbations to the ambient electric and magnetic fields (waves) have time scales slower than the ion gyrofrequency and spatial scales much longer than ion gyroradii.

Plasma microinstabilities deriving free energy from unstable velocity-space distributions may also be studied using barium releases, especially when the barium is released in a direction perpendicular to the geomagnetic field, B. Because of the comparability of Debye lengths and the characteristic lengths of particle detectors, particle velocity distribution functions can be measured more easily in space plasmas than in laboratory plasmas. However, in practice this capability is difficult to exploit for plasma microinstability studies because the natural space plasma remains near an equilibrium configuration. In the natural space environment there is also the difficulty in determining whether the waves produced the particle distribution function or the particle distribution function caused the waves, for example, the "chicken or egg" question of ion conics and ion cyclotron waves. We will show that by using barium release techniques unstable velocity-space distribution functions can be artificially created in space plasmas allowing an investigation of the instability theories via the classical scientific method of hypothesis testing.

Unstable velocity-space distributions generally have some non-Maxwellian or non-isotropic features such as interpenetrating cold beams or different temperatures parallel and perpendicular to B. Free-energy sources may also act together. Simons, et al. (Ref. 4) examined the case where a combination of a configuration-space source (a density gradient) and a velocity-space source (a ring-like $V_\perp$ distribution) resulted in a lowered threshold for instability turn-on.

In creating artificial velocity-space distributions one must be concerned that they are practical, in that they simulate distributions likely to be found in space or the laboratory. We will demonstrate that barium injections can produce velocity-space distributions similar to those measured near the earth's bow shock. These distributions are also similar to those of the Io torus ions and those produced in CTR neutral beam heating experiments. One must also be concerned about the degree to which the simulation plasma is homogeneous in the sense that the microinstability theory requires. We will show that barium releases can frequently meet homogeneity conditions whereas "gun-type" injections can rarely meet them. Another important plasma parameter that can be varied in a controlled manner is the plasma beta, the ratio of particle kinetic energy density to the magnetic field energy density. Near the release and at early times the plasmas can have beta > 1, while at late times and large distances the beta is small and electromagnetic effects should play no significant role. Releases at large altitudes may be able to generate conditions where the released ions have characteristic speeds that are super-Alfvenic in the surrounding plasma, but a discussion of such a release is beyond the scope of this paper.

2. DESCRIPTION OF EXPERIMENTS

We have examined the barium ion configuration- and velocity-space distributions produced by two barium injections. In both experiments the barium is injected with near 90° pitch angles and photoionization with a 20 second time constant is assumed to be the sole ionization mechanism.

2.1 Satellite-borne Barium Release

We first consider a thermite barium release from a satellite similar to the CAMEO releases (Ref.5). NASA's Chemical Release Module (CRM) is designed to release two 5 kg or 20 kg thermite barium cannisters. We consider an experiment wherein two 20 kg cannisters are released over the ionospheric observatory at Arecibo, Puerto Rico. We have assumed that about 10% of the barium would be vaporized in the release. Therefore, the two cannisters would release a total of about 30 moles of barium neutral atoms. We have assumed that the CRM would be moving at about 7.5 km/s in a 23° inclination orbit at 450 km altitude. Total particle kinetic energy for this experiment would be over 100 Megajoules.

2.2 Rocket-borne High Explosive Shaped-Charge Injection

The second example models the Los Alamos-sponsored Buaro shaped-charge injection conducted in 1976, 450 km above the Hawaiian Islands (Refs. 6-8). In this experiment high explosive shaped-charges compress conical barium liners vaporising about 10% of the barium metal and producing a metal vapor jet with a cone-shaped velocity distribution. The liners each contain 1430 grams of barium metal. Several of these high explosive, conical liner assemblies were simultaneously detonated producing about 7 moles of fast barium metal vapor. The total particle kinetic energy was about 50 Megajoules.

3. THE SOURCE MODEL

We have developed a Monte-Carlo computer model of the phenomenology of a barium vapor release in the earth's ionosphere. Our model is designed to model the velocity distribution of the neutral barium atoms as they leave the thermite cannister or the shaped-charge. The atomic barium velocity distribution is modeled very simply. A conical velocity distribution is assumed with a half-angle, θ. Within the conical shape all velocities between a minimum velocity, V_{min}, and a maximum velocity, V_{max}, are equally likely, i.e., a flat distribution. Thermite releases from sounding rockets are modeled with a large half-angle, say 179° and a minimum speed of zero and a maximum speed of the thermal speed, say 1 km/s. Shaped charge injections are modeled with a half-angle of 15° and a minimum speed of 5 km/s and a maximum speed of 15 km/s. A thermite release at orbital velocity can be modeled by a half-angle of about 7.6° and a minimum speed of the orbital velocity minus the barium thermal speed, e.g., 6.5 km/s, and a maximum speed of the orbital velocity plus the barium thermal speed, e.g., 8.5 km/s.

The barium atoms are assumed to follow ballistic trajectories until they are either photoionized or undergo a collision (see below). The only force in the ballistic trajectory is gravity. The atoms are followed until they are thermalized via collisions or to a prespecified time. If the atoms are moving above the solar terminator they are subject to photoionization. When the random numbers indicate photoionization the particle is converted to an ion moving (initially) with the same velocity vector as the atom. Photoionization is the only ionization mechanism assumed to be operating. We assume that the barium atoms do not shield each other from the photoionizing solar radiation. Once ionized the barium must follow the more complicated trajectory of an ion in a magnetic field. This trajectory is gyromotion plus guiding center motion. Forces are due to gravity and an inhomogeneous magnetic field ("mirror force"). Barium ions with perpendicular speeds in excess of about 6 km/s will rise in altitude because the mirror force exceeds gravity.

While the particles are following either the neutral or ion trajectories they may suffer elastic, hard sphere collisions with neutral air atoms or molecules (represented by a mean mass of 28 amu) that can give them randomly assigned, new velocity vectors. Inelastic collisions are not included in the computer code. Charge-exchange collisions are included. No collective effects are calculated for the assembly of particles.

The computer code can produce configuration- and velocity-space presentations of the particle positions. The configuration-space presentations are the integrated, or column, density as observed from a particular observation station. The velocity-space presentation is calculated by examining the velocity vectors of each particle in a box located some distance, D, in front of the release. The box has sides of dimension, S. Care must be exercised to insure that the box is smaller than the beam size.

The velocity vectors are sorted into components parallel and perpendicular to B. The perpendicular components are further sorted into components in the magnetic East direction, V_{px}, and a component perpendicular to that, V_{py}. Point plots are then constructed showing the density of particles in velocity-space in these coordinate systems.

For the cases studied for this paper the parallel component of the barium velocity is generally very small so the density in (V_{px}, V_{py})-space contains the more important information. Typical distributions are either beam-shaped, cresent-shaped or ring-shaped. Note that the barium ions tend to be about ten times faster than the thermal speeds of the ambient O^+ ions. Therefore, as they are created, the barium ions may be subject to fast-growing ($\gamma \sim \omega_{LH}$) two-stream instabilities that could thermalize the beams. On the other hand instabilities feeding free energy to cyclotron mode waves probably do not grow fast enough to disrupt the initial formation of ring-shaped distributions.

4. CALCULATED INITIAL CONDITIONS

4.1 Satellite-borne Barium Release

We have calculated the barium neutral and ion densities as a function of the downrange distance from the release, D, and time after the release. The size of the box, S, was varied keeping the S/D ratio constant. We also have plots showing the velocity-space density. The velocity-space plots tend to exhibit beam-, cresent- or ring-shaped distributions depending upon the ratio of the barium ion cyclotron period, τ_Q, to the arrival time difference, t_A, given by

$$t_A = D/(V_{max} - V_{min})$$

When $t_A < \tau_Q$, the distribution is beam-shaped. When $t_A > \tau_Q$, the distribution is ring-shaped. When $t_A \sim \tau_Q$, a cresent-shaped distribution is predicted.

Table 1 shows the temporal evolution of a one mole barium ion plasma at a downrange distance of 5 km.

TABLE 1

Time [s]	Ion Density [cm^{-3}-$mole^{-1}$]	Distribution Shape
0.65	$5.3x10^5$	Cresent
0.75	$1.0x10^6$	Cresent
0.85	$1.5x10^6$	Ring
0.95	$1.9x10^6$	Ring
1.00	$1.3x10^6$	Ring
1.25	$8.3x10^5$	Ring

Note that the density decreases after reaching a maximum because the mirror force moves the barium upwards out of the box.

Table 2 shows the peak barium ion densities per mole of released vapor and the time the peak density occurs for a release over Arecibo.

TABLE 2

D [km]	t_{peak} [s]	Peak n_i [cm^{-3}-$mole^{-1}$]	Distribution Shape
1	0.15	$1.5x10^7$	Beam
3	0.65	$2.4x10^6$	Cresent
5	0.95	$1.9x10^6$	Ring
10	1.50	$4.9x10^5$	Ring
20	3.25	$1.1x10^5$	Ring

The peak density as a function of D can be fit by

$$n_i = 1.65x10^7\ D^{-1.59}.$$

For a 0.3 Gauss magnetic field, the magnetic energy density is approximately $3.5x10^{-3}$ ergs/cm^3. For this release scenario the kinetic energy per barium ion relative to the magnetic field is about $6.4x10^{-11}$ ergs/ion (40 eV/ion). Therefore, the barium ion plasma beta, the ratio of kinetic energy density to magnetic field energy density, is about unity when the ion density is $\sim 5.6x10^7$ cm^{-3}. For a 30 mole release this condition should hold for $D < \sim 3.9$ km. The barium ion plasma beta would be greater than 0.1 for $D < 15$ km. Note that our single particle computer code predictions do not consider high beta effects.

To what extent is the barium ion plasma homogeneous in the direction parallel to the magnetic field? Must a theoretical description of the potential instabilities consider boundary effects or finite k_z effects? The barium plasma has an advantage over "gun-type" injections in that some barium atoms expand parallel to B prior to photoionization. Assuming that a cloud extent of at least ten gyroradii parallel to B serves as a condition of homogeneity, we can find the time it takes for a barium cloud to expand enough to satisfy this condition. The thermite barium expands about 1 km/s in each direction along B. The barium ion gyroradius is about 0.36 km. Therefore, in 1.8 s the cloud has expanded to about ten ion gyroradii in length parallel to B.

Figures 1-4 show the barium ion velocity-space distribution that would be measured by a detector onboard the satellite. Note that the instrument would get a snapshot of the distribution at a given stage in its evolution. Figure 5, reproduced with permission from Paschmann et al. (Ref. 9), shows the evolution from a beam to a cresent to a ring of ion velocity distributions in the $V_\perp$ plane measured by the ISEE 1 satellite as it penetrates the earth's bow shock. Note that although the origins of the velocity distributions are different in the two cases, the subsequent evolution due to microinstabilities may be similar. Diagnosis should be simpler in the active experiment because the environment should be more noise-free and temporal and spatial effects are better measured .

4.2 Shaped-Charge Injection

We have also calculated the velocity-space distributions to expect for a shaped-charge injection as a function of D and time. The results, per mole of vaporized barium, are shown in Table 3.

TABLE 3

D [km]	t_{peak} [s]	Peak n_i [cm^{-3}-$mole^{-1}$]	Distribution Shape
5	1.00	$2.5x10^5$	Lumpy Ring
10	2.00	$7.2x10^4$	Ring
15	3.00	$3.1x10^4$	Ring

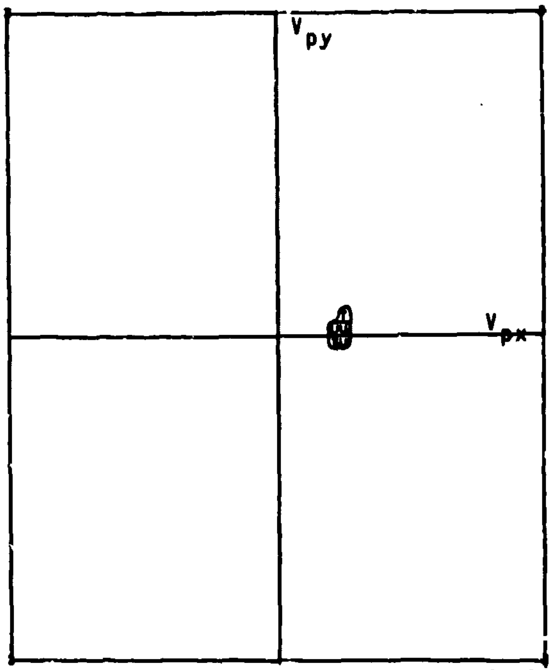

Figure 1. Calculated barium ion velocity distribution in the (V_{px}, V_{py})-plane at D = 1 km and 0.13 s after the release. For a 30 mole release the calculated barium ion density is 3.0×10^{8} cm^{-3} and the beta is 5.3. The cross-hairs mark the (0, 0) values for V_{px} and V_{py}. The barium ions have a beam-shape moving through any thermal ions at about 7.5 km/s.

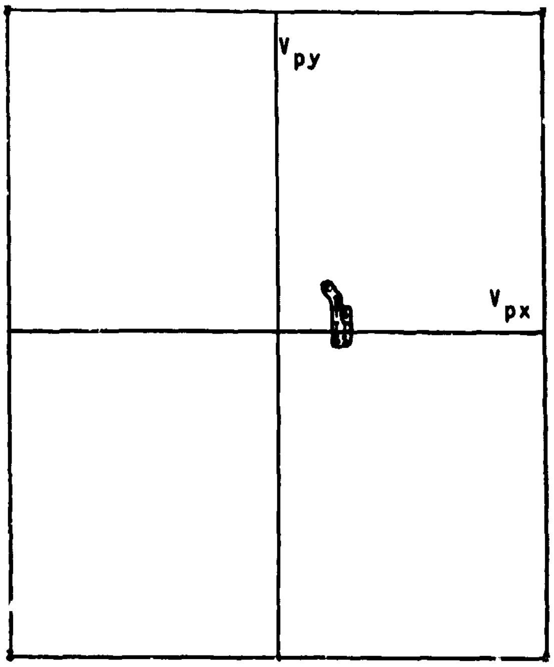

Figure 2. Calculated barium ion velocity distribution in the (V_{px}, V_{py})-plane at D = 3 km and 0.40 s after the release. For a 30 mole release the calculated barium ion density is 5.1×10^{7} cm^{-3} and the beta is 0.91. The cross-hairs mark the (0, 0) values for V_{px} and V_{py}. The barium ions have begun to evolve from a beam-shape to a cresent-shape. Typical ion speeds are about 7.5 km/s.

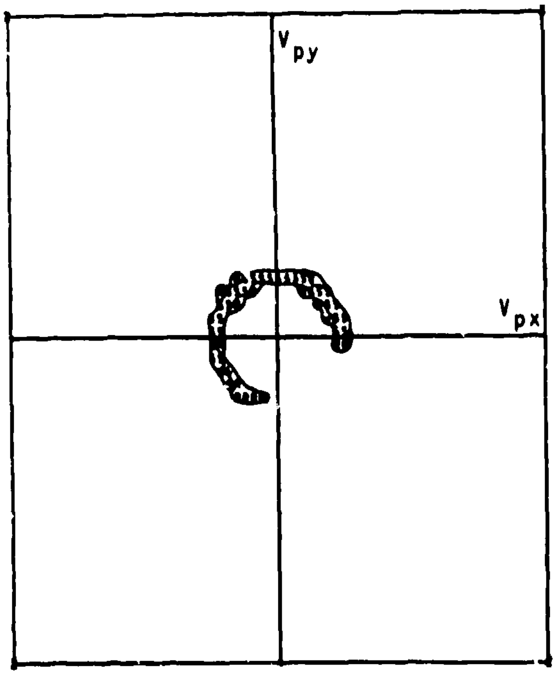

Figure 3. Calculated barium ion velocity distribution in the (V_{px}, V_{py})-plane at D = 6 km and 0.80 s after the release. For a 30 mole release the calculated barium ion density is 3.9×10^{7} cm^{-3} and the beta is 0.69. The cross-hairs mark the (0, 0) values for V_{px} and V_{py}. The barium ions have a cresent-shape in (V_{px}, V_{py})-space. Typical ion speeds are about 7.5 km/s.

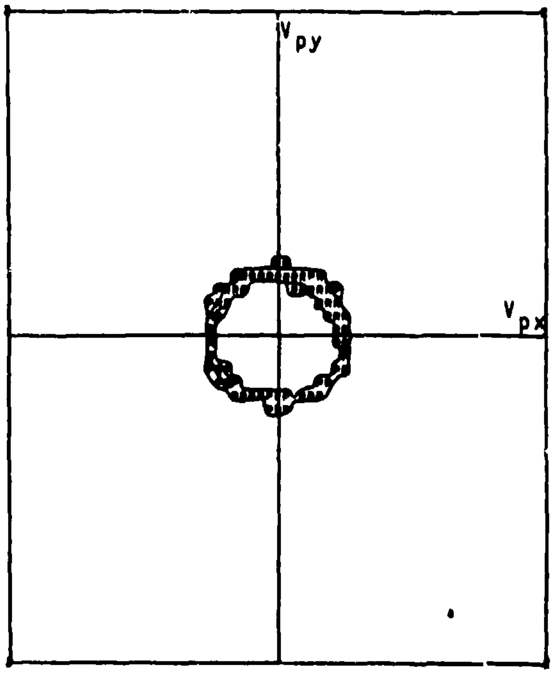

Figure 4. Calculated barium ion velocity distribution in the (V_{px}, V_{py})-plane at D = 9 km and 1.20 s after the release. For a 30 mole release the calculated barium ion density is 7.8×10^{6} cm^{-3} and the beta is 0.14. The cross-hairs mark the (0, 0) values for V_{px} and V_{py}. The barium ions have a ring-shape in (V_{px}, V_{py})-space. Typical ion speeds are about 7.5 km/s.

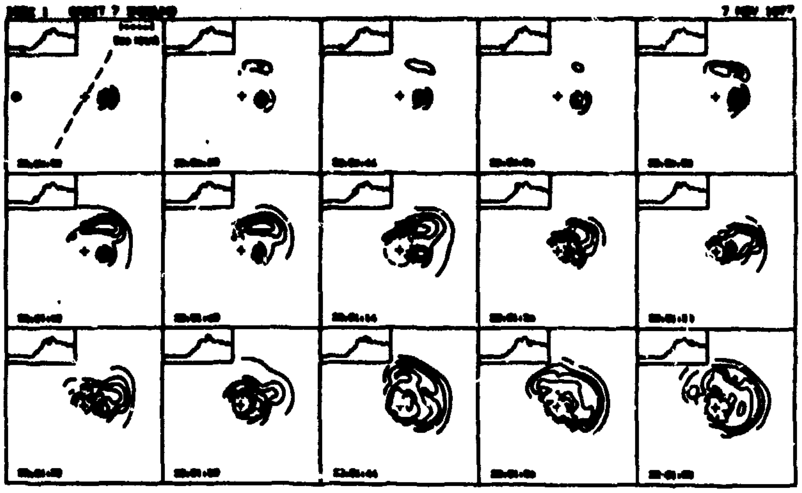

Figure 5. Ion velocity distributions, spanning the range from the pure solar wind to well downstream of the shock ramp, as measured on 7 November 1977. The relative positions of the measurements are indicated by the solid dots on the plasma density profiles shown as inserts. To emphasize the evolution of the distributions only every other one is shown, as indicated by the progression of universal time. The distributions are shown as contours of equal phase space density in two-dimensional velocity space. Adjacent contours represent a jump of one decade in phase space density. The (v_x, v_y)-plane is parallel to the ecliptic, with v_x pointing towards the sun. The + symbol represents the origin of the coordinate system, fixed with respect to the satellite, and also approximately with respect to the shock. The velocity scale is indicated in the upper right-hand corner of the first frame. The first frame also shows the orientation of the shock front (dashed line). The asterisk in the second frame indicates the predicted velocity of the gyrating ions at their turning point. A circle of constant speed is marked in frame number 8.

The peak densities as a function of D can be expressed as

$$n_i = 3.3\times10^6 D^{-1.89}$$

The shaped-charge ions average about 1.1×10^{-10} ergs/ion (70 eV/ion). The density needed for beta to exceed unity is about 3.2×10^7 cm^{-3}. For the Buaro shaped-charge injection (7 moles), beta exceeded unity for D < 1 km and beta exceeded 0.1 for D < 3.7 km.

For a shaped-charge injection the neutral barium expands parallel to B with a typical speeds of about 10 km/s times the tangent of 15°, the half-angle. Again using a length of 10 gyroradii parallel to B as a condition of homogeneity we find that for the shaped-charge gyroradius of 0.48 km the plasma meets this condition in about 1.8 s.

We have also calculated the barium plasma density gradient (in the direction parallel to the injection) as a function of time at a distance, D, of 10 km. Table 4 shows the results.

TABLE 4

Time [s]	Gradient Length [km]	Gradient Length [gyroradii]
1	2.3	4.8
2	5.6	11.7
3	8.5	17.8

Note that as time increases, the continuing photoionization of barium atoms acts to smooth the rather steep gradient. Simons, et al. (Ref. 3) calculated that the presence of a gradient would act to lower the threshold for an instability driven primarily by the free energy in a ring-shaped velocity distribution. The instability has been postulated to explain the prompt onset of field-aligned striations in the Buaro plasma.

For both the satellite and shaped-charge injections the barium ion velocity-space distributions exhibit large ratios of the perpendicular temperature to the parallel temperature, $T_\perp \sim 20\, T_\parallel$.

5. DISCUSSION

Results of the Buaro and CAMEO experiments confirm several assumptions of our model. First, anomalous ionization processes may operate, but photoionization accounts for the production of the bulk of the barium ions. Second, some pitch-angle diffusion and/or velocity-space diffusion may occur, but the observations of the barium ions moving upwards against gravity suggests that the ions retain a significant enough fraction of their initial perpendicular velocity to provide a mirror force.

6. SUMMARY

We have demonstrated that barium injections should produce ion velocity-space distributions with free energy in a variety of forms. The barium ion plasmas should have a range of plasma betas. Because the initial conditions can be predicted these active experiments should permit testing plasma instability hypotheses.

7. ACKNOWLEDGMENTS

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