Optical signatures of the beam-plasma interaction during the ECHO 7 sounding rocket experiment

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INTRODUCTION

Electron beams injected during the ECHO 7 sounding rocket experiment were used to investigate the large scale properties of the interaction of the beams with a neutral magnetized-plasma environment. This interaction, known as the beam-plasma interaction (BPI), can under certain conditions, modify or even destroy the adiabatic character of the initially injected beam. The characteristics of the BPI have been recently reviewed by Papadopoulos and Szuszczewicz (1988). Of fundamental importance is the determination of the conditions under which these collective beam-plasma effects would dominate especially in rocket experiments such as the ECHO series (Winckler, 1980) in which beams of electrons are also used to probe the distant magnetosphere. During the BPI, ambient electrons can be energized to suprathermal energies which can collisionally interact with the neutral atmosphere to produce luminosity. Measurement of this luminosity can then reveal information about characteristics of the electrons producing the light, and ultimately yield information about the BPI. This paper will show optical measurements of the luminosity made during the ECHO 7 experiment. The results presented will show images obtained by onboard low-light television camera, and photometric observations measuring the luminous manifestations of the BPI over an altitude range from 200 km to about 95 km.

EXPERIMENTAL CONFIGURATION

The ECHO 7 experiment was launched February 8, 1988 from Poker Flat Research Range. The scientific payload consisted of a 'MAIN' accelerator payload, and three free-flying subpayloads: Nose, Plasma Diagnostic Package (PDP) and Energetic Particle Package (EPP) carried aboard a Terrier Black-Brant IX sounding rocket. The rocket travelled on an eastward trajectory reaching an altitude of 291 km at apogee. The subpayloads were deployed from the MAIN while it was spinning at 0.6 rps. The NOSE was deployed at 4 m/s directly up the field, the PDP at 1.75 m/s towards magnetic south at an angle of 16 degrees to the field, and the EPP at 2 m/s at 25 degrees to the field in a westerly direction. Figure 1 is an illustration of the deployment geometry of the subpayloads with respect to the MAIN and injected beam. After subpayload deployment, the accelerator payload was completely despun and oriented north-south in a magnetic horizontal plane.

The MAIN payload contained a single diode electron gun, of a similar design as those used on previous ECHO missions (Winckler, 1982). The gun was capable of injecting electrons in two possible modes: a 'continuous' or swept energy mode (40 KeV to 8 KeV every 1 ms), and a 'discrete' or quasi-dc mode, injecting at 10 KeV (26 mA) or 36 KeV (180 mA). The continuous beam, injected at a pitch angle of 110 degrees, was used primarily for the conjugate echo portion of the experiment (Nemzek et al., 1989). The discrete beams, injected at pitch angles varying from 40 to 175 degrees, were used for the purpose of plasma heating, wave generation, and creating luminosity around the beam and MAIN payload. The gun was programmed to inject a sequence of pulses of 50, 100, and 150 ms, with similar duration off times, forming a pattern that repeated every 10 seconds. The gun was turned on at 180 seconds into the flight at an altitude of 250 km and operated until 499 seconds at an altitude of less than 90 km. Further details about the ECHO 7 mission can be found in Winckler et al., 1989.

OPTICAL INSTRUMENTATION

An Intensified Charge Injection Device (ICID) low-light-level television camera, manufactured by ITT, model 4562 was used to obtain images during the ECHO 7 flight. It was placed on the PDP and oriented along the spin axis back toward the MAIN (Figure 1) to view the light surrounding the MAIN and beam during gun operation. The camera operated in a standard video mode, capturing frames at 1/30 per second, which were telemetered in real-time to ground. A Fujinon F1.4, 25 mm lens was used, giving the camera a field of view of 15 x 20 degrees. The camera had a rated sensitivity of 10^{-6} footcandles, and was capable of discerning stars of magnitude 6.5.

In addition to the camera, a total of nine photometers were placed on the MAIN, PDP and EPP. Six photometers were filtered at 391.4 nm with a 10 nm bandpass, and two were filtered at 380.5 nm with a 5 nm bandpass, measuring the First Negative and Second Positive bands of molecular Nitrogen. One additional photometer measured white light (350 nm to 650 nm).

RESULTS

The photometers and television camera measured luminosity throughout the flight. At high altitudes, from 250 km on the upleg to about 215 km on the downleg, the large scale features of the beam were essentially invisible to the camera except during the injection of Attitude Control System (ACS) gas. Results reported in this paper are concerned with the variation of the large scale beam features during the downleg from 200 km to 95 km. The observations can be divided into three categories (A, B, C), depending on the altitude region and physical appearance of the beam. Region A extended from 200 km to 145 km, region B from 145 to 110 km, and region C from 110 to 95 km. A survey of these regions will follow.

During beam injection in region A, a column of luminosity surrounded the beam, and extended up and down the magnetic field line. A typical view of the beam injection is shown in Figure 2 at an altitude of 175 km for a 36 Kev injection at 110 degree pitch angle. The local time "23:24:12" or 443.85 flight seconds is shown at the bottom of the photograph. In the figure, the beam was propagating upwards along the field line, originating from the MAIN which is surrounded by the bright luminosity. The tail on the bright spot extending to the right-hand side of the photograph is an artifact of the camera due to the extreme brightness of this luminosity near the MAIN. The column of luminosity was initiated at gun turn-on and persisted the entire 100 ms beam injection. The intensity of the luminous column was uniform both up and down the field line and out to the full width of the 25 meter gyro-diameter. An analysis of the intensity of the light made during a number of similar injections as the rocket moved to lower altitudes is shown in Figure 3. The lower panel shows the relative intensity of the video output measured in portions of the beam column above and below the MAIN as indicated in the legend. The intensities of the luminosity measured in the different parts of the column have been determined by digital image processing techniques. In the upper panel, the neutral N_2 density is plotted versus altitude, and is seen to vary by five orders of magnitude between 200 km to 90 km. In region A, in which Figure 2 belongs, the luminosity in the portion of the beam column above the MAIN increased about a factor of two, while the altitude decreased from 190 to 150 km. The luminosity in the beam below the MAIN remained constant. The neutral density shown in the upper panel increased about a factor of 10 during this time. It is clear that the variation in the luminosity with altitude was not tied directly to the ambient neutral density, as would be the case if the luminosity were produced by collision of the primary beam with the neutrals.

During the transition from region A to B, a transient enhancement in portions of the beam column was observed. The region of unstable light production is denoted with an arrow as shown in Figure 3. This indicates that the luminosity in portions of the beam column appear to jump between two levels for successive images 1/30 s apart during the same 100 ms injection. The magnitude of the upper level saturated the video output, at a level greater than five times the normal intensity. Figures 4(a) and 4(b) show an example of this effect. Figure 4(a) shows a luminous column five seconds after the image shown in Figure 2, at an altitude of [illegible] km. The column in Figure 4 appears slightly rotated from that shown in Figure 2 due to the rotation of the camera on the PDP. The next image obtained 1/30 second later is shown in Figure 4(b). During this frame, a large enhanced region of luminosity developed in a portion of the beam column. The region extended about 300 meters up the field line from the MAIN. The part of the beam affected seems to be localized along the direction of the column in which the beam is propagating, and on the side of the beam column which is on the same field line as the MAIN. The intensity level in the enhanced region saturated the video output, as seen in Figure 3. A sharp demarcation between the normal diffuse column and the enhanced column is seen. Outside the enhanced region, the appearance of the column is the same as in the previous images. The enhancement at this time persisted only one TV frame (1/30 s). The light appears to be bi-modal, as if the production mechanism responsible for the light were being turned on and off in that portion of the beam column. The transient enhancements in the column are first seen at 443 s (175 km), and continue during the discrete injections until 458 s (150 km) as noted in Figure 3.

As the payload moved to lower altitudes, into region B, the enhancements change from transient (lasting 30 ms) to persistent, lasting throughout the gun pulse (100-150 ms). The appearance of the beam in region B is very similar to the transient enhancement shown in Figure 4(b). The only difference between the luminosity in region B, and that shown in Figure 4(b) is entirely due to increased duration and radial extent of the enhanced portion of the beam. The change in the duration and extent of the enhanced luminosity is first evident in the 36 KeV Out pulse at an altitude of about 145 km. The enhanced luminosity extends to the full width of the beam column, and is spread out along the field line engulfing the MAIN.

As the payload moved from region B to region C, the light level in the column decreased. Figure 5 shows a view at 98 km in which the larmor spiral of the beam is clearly visible. At this time, the beam was injected at 36 KeV with a pitch angle of about 130 degrees. The beam maintained its coherent spiral over a distance greater than 300 m. In addition to the 17 m wide larmor spiral there is a faint field aligned glow similar to that seen at higher altitudes.

Region C, extending from 110 to less than 90 km, is also the region where downward beams injected at higher altitudes deposit their energy creating artificial auroral streaks. However, the ground based television camera observations of these streaks from previous ECHO missions, (Hallinan et al., 1975), did not show any evidence of a larmor spiral structure. This may be due to the limited resolution of the camera. These streaks can be explained in terms of collisional processes in which luminosity is produced by primary and secondary electrons. The production mechanism of the helix also in region C is most likely tied directly to the interaction of the primary beam with the ambient neutrals.

The intensity of the luminosity produced at 98 km is comparable with that produced at higher altitudes (Region A) even though the neutral density has changed four to five orders of magnitude. It is clear that if the production mechanism of the light at 98 km is related directly to the primary flux of the beam, then it is doubtful the same mechanism could be responsible for the Region A light. The diffuseness and lack of larmor structure also points away from a luminosity production mechanism involving the direct excitation by collisions with primary beam with the neutrals. The luminosity is most likely produced by suprathermal electrons having been energized in a beam-plasma interaction.

A similar constant light intensity-altitude profile made during the Polar V experiment support the premise that the light around the payload at high altitudes is produced by suprathermal electrons energized in a BPI. (Grandal et al., 1980). Photometric measurements of luminosity made near the accelerator payload, observed a near constant light level from 215 km to 140 km. The intensity was inconsistent with luminosity produced either by primary or secondary electrons and were attributed to a flux of suprathermal electrons energized during a beam-plasma interaction.

Features of the beams in Figures 2, 4 (a,b) and 5 are similar to observations made during the Zarnitsa 2 experiment (Dokukin et al, 1981). Photographs taken by ground based cameras of the payload at an altitude of 150 km show a bright near-payload region extending 200 m to 300 m along the field line around the accelerator, and near rocket ray extending one to seven km below the rocket as the 7 keV beam was injected downward. The interaction region on Zarnitsa was attributed to the beam-plasma discharge (BPD) which was excited during beam injection.

The optical characteristics of the beam-plasma-discharge (BPD) as studied in the laboratory are very similar to the ECHO 7 results. The BPD is characterized by a dramatic increase in light at some critical threshold, determined by the beam parameters, neutral density and magnetic field strength (Hallinan et al., 1984). The enhanced luminosity displayed in Figure 4(b), and also in Region B, was most likely produced during a BPD. The critical threshold was attained as the neutral density increased during the downleg of the flight. The transition from region A to region B in the ECHO 7 observations occur in the neighborhood of 145 km, an altitude consistent with the Zarnitsa results, and also with theoretical predictions of BPD onset (Papadoupolos, 1982).

TRANSIENTS AND OSCILLATIONS

In Region A, from 190 km to 145 km, large periodic and random flucuations in the light were observed by photometers placed on the free-flyers. Figure 6 shows 1.4 s of data during which the beam injected in both continuous (CON) and discrete modes at pitch angles of 40 degrees (DOWN), 110 degrees (OUT) and 175 degrees (UP). During an UP injection at 448.2, a large oscillation was seen in the light near the MAIN by photometer PHP1 (See Figure 1 for photometer identification). In addition, PHP3 and PHP4 which intercepted the beam at about 650 m up the field line from the MAIN also recorded the fluctuations, which were found to be directly in phase with oscillations found near the MAIN. The variation in the luminosity during the oscillation event approaches 100 % of the total value, as if the light production mechanism were turning on and off. The frequency of the oscillation at this time was about 30 Hz. An analysis of several events during the downleg show that the frequency varied from 23 Hz to 42 Hz depending on the type of injection.

Large oscillations in the luminosity have been observed on previous ECHO flights. During the ECHO 4 experiment (Israelson and Winckler, 1979) a large 22 Hz oscillation in the light measured by photometers developed during the downleg of the flight. The ECHO 5 flight produced similar low frequency oscillations (Arnoldy et al., 1985). Laboratory measurements of the beam-plasma discharge also show numerous low frequency oscillations preceeding the onset of the BPD (Hallinan et al., 1984; Sivjee et al., 1989). The low frequency oscillations measured in flight preceeded the region B luminosity, and are most likely precusors to the BPD initiated in region B.

In addition to the low frequency oscillations, large transient flashes at gun turn on were observed during the downleg of the flight. Figure 6 shows a transient lasting 10-20 ms during the start of the OUT injections. The shape of the transients resemble one period of the oscillation events shown during the UP injection. The transient at 448.9 has a number of small oscillations following the main event which appear to be damped out. It is possible that the oscillation events were BPI unable to sustain themselves. Similar large scale transients were also observed by photometers onboard the accelerator payload during the ECHO 6 experiment (Franz et al., 1984). The transients reached as much as 10 times the steady state level, and involved the entire beam column, measured in a similar configuration as shown in Figure 1 (Franz and Winckler, 1989).

SUMMARY

This paper has shown some of the observations of the luminosity surrounding an electron beam-emitting rocket during the ECHO 7 experiment. It is clear that the observations of the luminosity cannot be explained by considering the light to originate from direct ionization of the neutral gas by the beam alone. The complex and non-linear behavior of the luminosity suggest that the beam interacted with the plasma (BPI) to produce a large population of suprathermal electrons which were responsible for the enhancment in the luminosity. In addition, the BPI transitioned into a BPD from about 145 km to about 115 to 120 km. The observations of the luminosity which are direct indications of these effects are:

1. A nearly constant intensity of luminosity produced in and around the beam which shows little variation with altitude.

2. The appearance of a bi-modal intensifications in the light, including both intensifications in small areas of the beam column, and large scale photometric transients, observed at gun turn-ons.

3. Large scale oscillations in the light of the beam column similar to those observed proceeding the onset of laboratory BPD.

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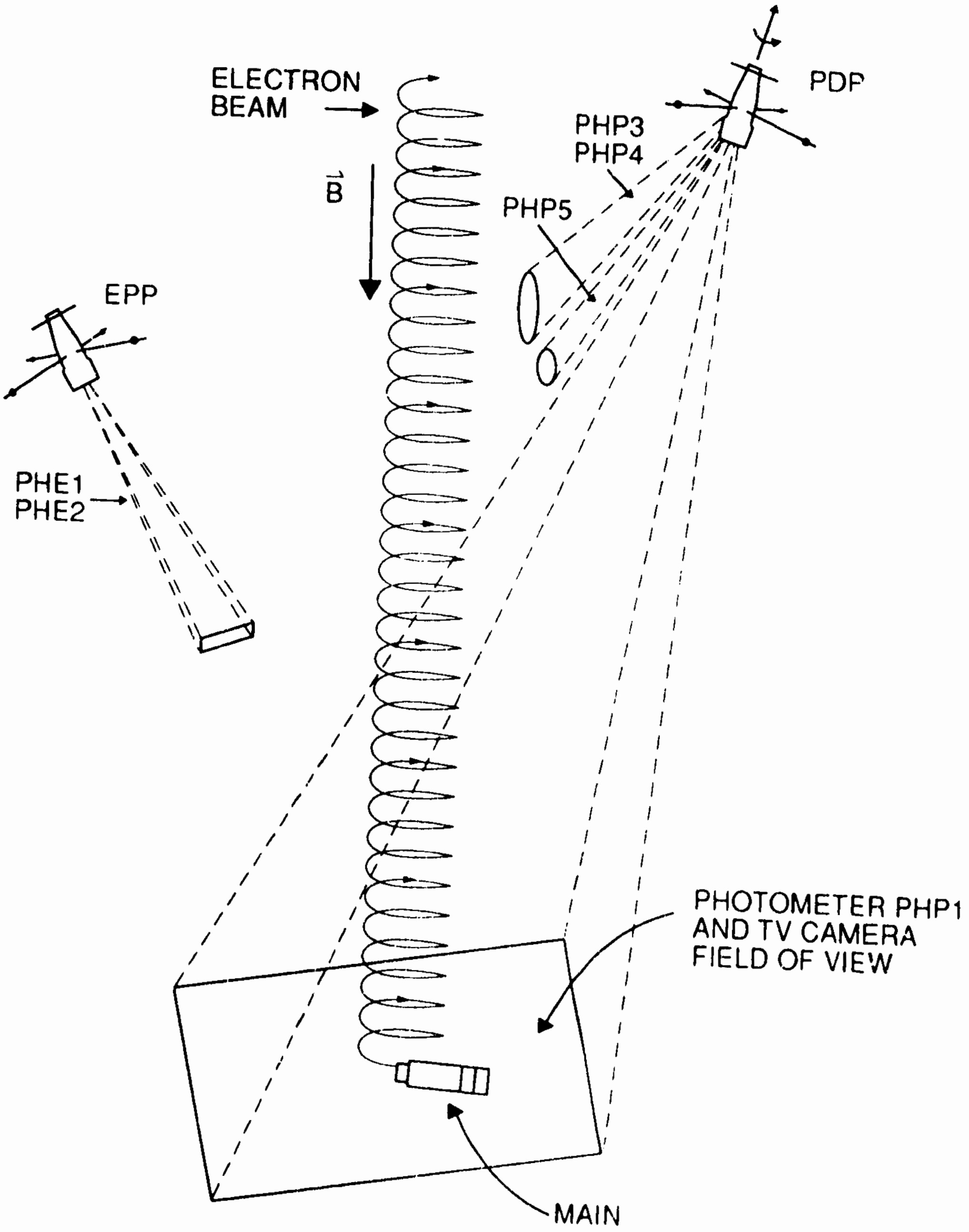

ELECTRON
BEAM
PDP
PHP3
PHP4
$\vec{B}$
PHP5
EPP
PHE1
PHE2
PHOTOMETER PHP1
AND TV CAMERA
FIELD OF VIEW
MAIN

FIGURE 1

FIGURE 2

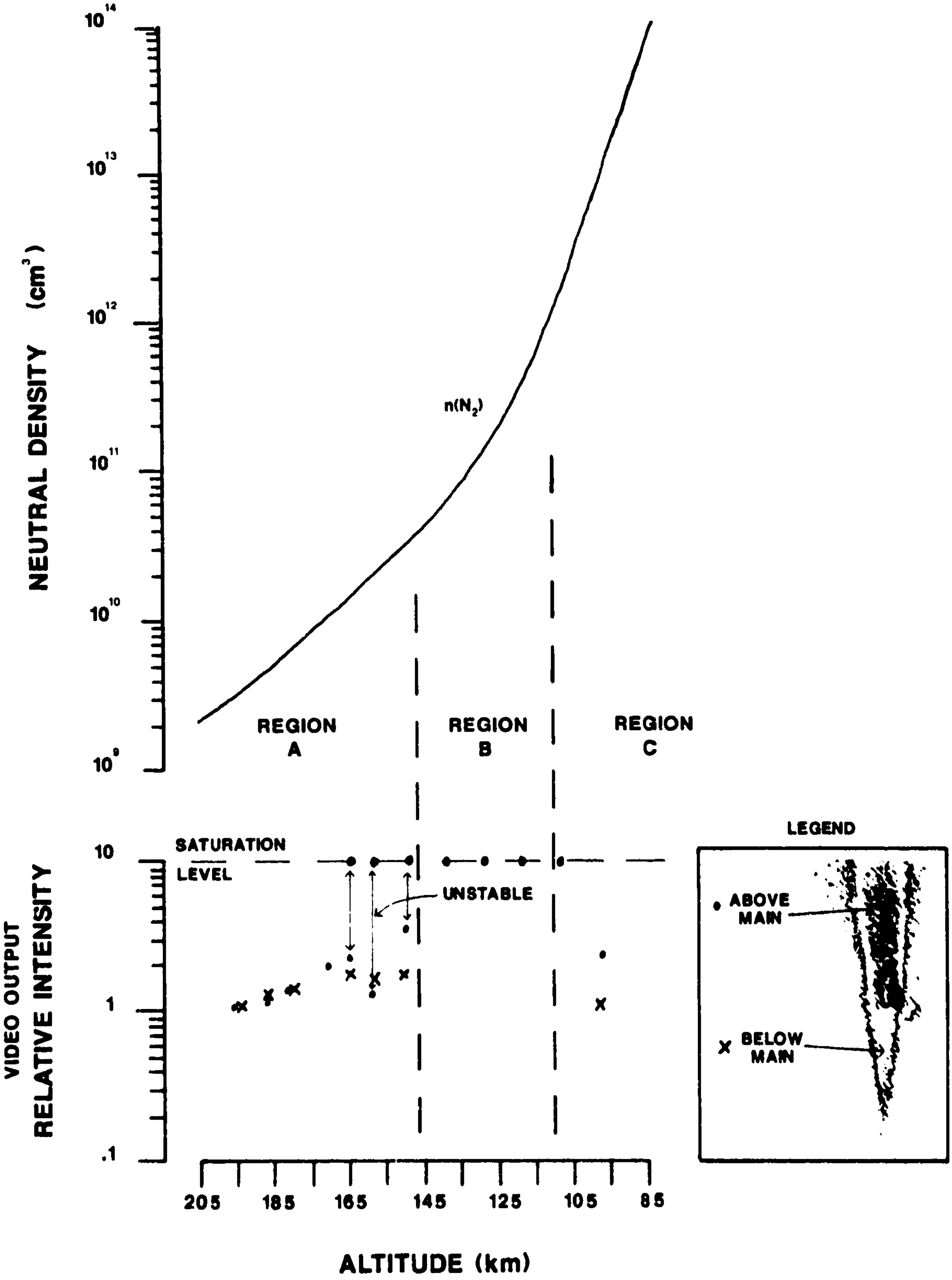
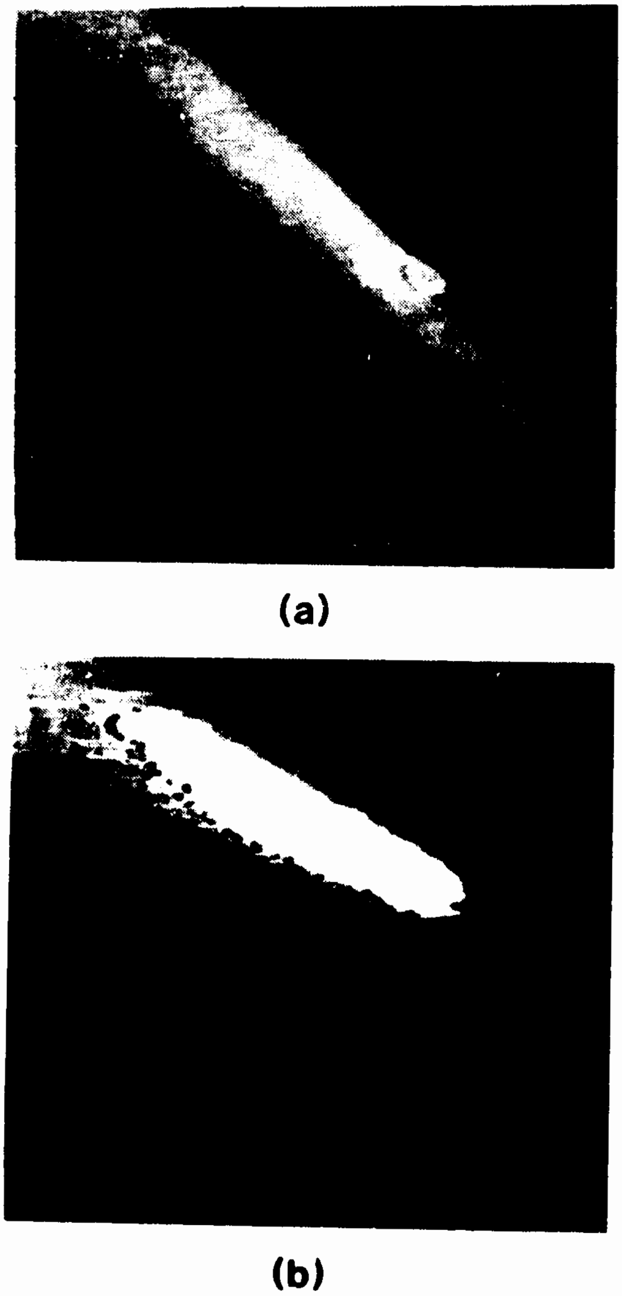

10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
NEUTRAL DENSITY (cm^{3})
$n(N_2)$
REGION A
REGION B
REGION C
SATURATION LEVEL
UNSTABLE
10
1
.1
VIDEO OUTPUT
RELATIVE INTENSITY
LEGEND
● ABOVE MAIN
X BELOW MAIN
205
185
165
145
125
105
85
ALTITUDE (km)

FIGURE 3



(a)

(b)

FIGURE 4

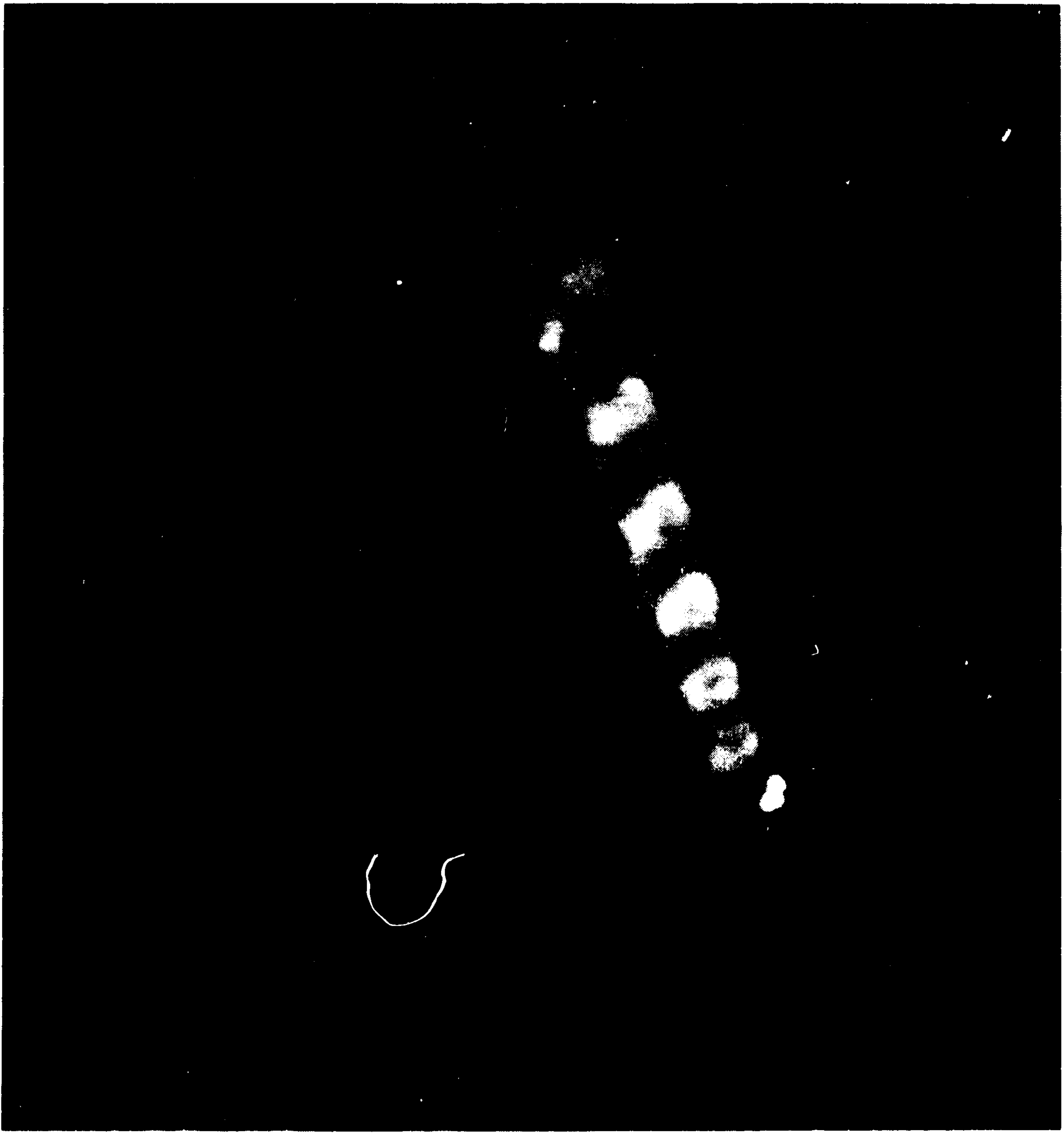


FIGURE 5

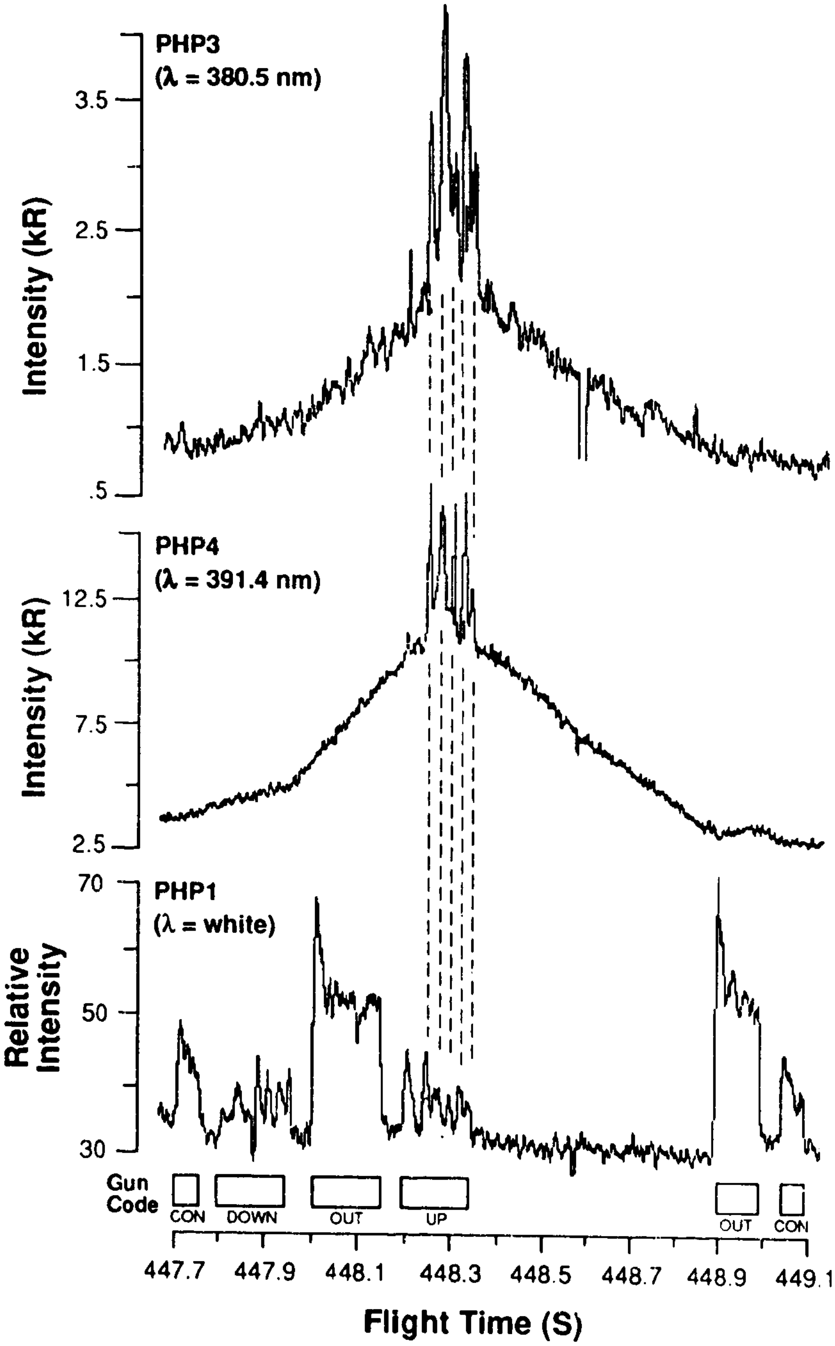

PHP3
(λ = 380.5 nm)
PHP4
(λ = 391.4 nm)
PHP1
(λ = white)
Intensity (kR)
Intensity (kR)
Relative Intensity
3.5
2.5
1.5
.5
12.5
7.5
2.5
70
50
30
Gun Code
CON
DOWN
OUT
UP
OUT
CON
447.7
447.9
448.1
448.3
448.5
448.7
448.9
449.1
Flight Time (S)

FIGURE 6