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Techniques for the Measurements of the Line of Sight Velocity of High Altitude Barium Clouds

by S. B. Mende

Final Report

Doppler Velocity Observations of Plasma Clouds

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Abstract

It is demonstrated that for maximizing the scientific output of future ion cloud release experiments a new type of instrument is required which will measure the line of sight velocity of the ion cloud by the Doppler Technique.

A simple instrument was constructed using a 5 cm diameter solid Fabry-Perot etalon coupled to a low light level integrating television camera.It was demonstrated that the system has both the sensitivity and spectral resolution for the detection of ion clouds and the measurement of their line of sight Doppler velocity. The tests consisted of (1) a field experiment using a rocket barium cloud release to check the sensitivity, (2) laboratory experiments to show the spectral resolving capabilities of the system. The instrument was found to be operational if the source was brighter than about 1 kilorayleigh and it had a wavelength resolution much better than .2A which corresponds to about 12 km/sec or an acceleration potential of 100 volts.

The instrument is very rugged and therefore very simple to use in field experiments or on flight instruments. The sensitivity limit of the instrument can be increased by increasing the size of the etalon.

Introduction

The injection of visible artificial ion clouds provide a means of investigating the physics of space plasmas. This branch of physics includes a wide variety of phenomena from distant interaction between ionized comet tails and the interplanetary fields to the interaction of ionospheric ions with electric and magnetic fields, the atmosphere and the ionosphere. In a classical, ion cloud experiment, a rocket is launched which carries the chemical release cannister to the desired location. Barium vapor is ejected by a thermite reaction from the release cannister. When illuminated by sunlight the vaporized neutral barium ionizes with a time constant of 19 seconds and becomes an ion cloud. The solar ultra violet provides the energy for ionization. In sunlight a barium ion cloud glows, radiating at particular wavelengths through resonance scattering of the solar continuum. A barium cloud is a bright visible object for some minutes after release.

At low altitudes where the unionized atmosphere is still dominant, the motion of the ionized barium cloud is limited by collisions with the ambient atmosphere. Very soon after release the ion cloud comes to equilibrium with the ambient atmosphere and the observed velocities are representative of the atmospheric ion velocities. At higher altitudes the ion clouds are mainly controlled by the electric field which is perpendicular to the ambient magnetic fields. The velocity of the ion cloud is given by

$$V = \frac{E}{cB}$$

where E is the perpendicular electric field (e.s.u.), and B is the magnetic field (gauss). The purpose of numerous ionospheric Ba ion releases was the measurement of the ionospheric electric field perpendicular to the magnetic field and it used the technique of measuring the velocity of the barium cloud in the presence of the known magnetic field of the earth.[1] Since the direct measurement of electric fields in space plasmas is difficult by probe techniques, barium clouds were very useful in providing the first reliable data of ionospheric electric fields.[2]

More recently it has been shown that high altitude electric fields parallel to magnetic fields, play a significant role in the generation mechanism of the aurora. These parallel electric fields were found to occur at altitudes of 1 to 2 R_E (earth radii).[3] Although in principle these altitudes create no significant difficulty for triangulation of photographic records, in practice the situation is very difficult and parallel electric fields in the Ba clouds were detected only by inferring electric fields which account for the "anomalous" ion cloud behavior. Thus for the direct measurement of ion acceleration due to parallel electric fields in the auroral regions the Doppler, line of sight velocity measurement would be invaluable.

The plasma in the deep magnetosphere is very dynamic, being driven by electric fields and/or the configuration changes of the magnetic field. In situ barium releases in the magnetosphere would provide a very effective technique for the detection of the motions of the magnetospheric plasma. One of the most interesting regions of the magnetosphere is the magnetospheric tail where the dominant plasma motions are in a radial direction, i.e. towards or away from the earth. An observer located on the earth is restricted regarding the size of the triangulation baseline in measurement of the radial motions of the plasma clouds in the tail of the magnetosphere. Thus for the high altitude ion releases, the doppler velocity technique gives a unique observation method to obtain the plasma velocities in the geomagnetic tail.

Previous High Altitude Ba^+ Experiments

In the early experiments, high altitude rockets were used exclusively for carrying the thermite mixtures to the regions of interest. In 1969 a small barium cloud was released from a European satellite at about 16 R_E altitude. The scientific results from this release were somewhat limited because of the difficulties of observing a small cloud at such large distances. In 1971 a larger barium cloud was released from a scout rocket at 5 R_E.[4] In figure 1 we can see a high resolution picture of this cloud from a paper by Mende.[5] This picture was taken two minutes after release. At 5 R_E the cloud is freely expanding (there is no atmosphere at 5 R_E) against the magnetic field. The circular cloud is showing the neutral barium atoms which are expanding freely. The magnetic field aligned core is where the bulk of the ions are residing. A most interesting feature of almost all ion clouds are that they are very densely striated parallel to the magnetic field. These early striations are thought to be caused by instabilities in the interaction of the expanding plasma and the magnetic field.

Besides launching the thermite mixture directly into the high altitude regions of interest, other techniques were developed to carry the ionized barium aloft. High explosive shape charges can be used to generate high velocity jets of ions[6] which will travel along the magnetic field up to higher altitude. These can be therefore released by smaller, less expensive launch vehicles. There were several high altitude shaped charge experiments which found electric fields above 2,500 km in the auroral zone. Haerendel[7] found an example in which a barium cloud expansion velocity could only be made consistent with a field aligned electric field within the ion cloud. In another shape charge experiment, Wescott[8] find that after the cloud has elongated and traveled to very high altitudes, the cloud, 15 minutes after release, was found to brighten and break up to the 5,000 km altitude point into several features above the region. This observation can be made consistent with a shear in the perpendicular electric field. In a non-inductive situation (this is assumed to be such) a discontinuity in the perpendicular electric field is always equivalent to parallel electric field at the discontinuity. Thus this observation was also explained in terms of the existence of a layer of field aligned electric field. In another experiment,[9] the observed altitude of a shaped charge release experiment can be explained only if one assumes the existence of the electric field parallel to the magnetic field. This is because the altitude reached (50,000 km) could only be attained with the aid of an accelerating electric field. All of these above experiments were handicapped because no direct velocity measurements were made at that time. All velocity information was derived by triangulating photographic data obtained from several sites. Most of the photographic data was not on an absolute photometric scale. Since the cloud is relatively featureless in the dimension parallel to the magnetic field, it is very hard to ascertain that the two triangulating stations are observing the same feature of the cloud.

The auroral electric fields are known to be time variant. If an electric field were suddenly set up within a barium cloud then a corresponding change in the barium density distribution would result. This could be observed if absolute photometry were employed. In the past experiments however, conventional photographic techniques were used and unless the tip of the barium cloud traveled through a pre-existing electric field region, and thus gaining noticeable momentum, the electric field would be largely undetectable. A few years ago it was realized that ions released from an orbiting spacecraft at moderate altitude, say 1,000 km, would propagate to very high altitudes because of the "mirroring" forces. This provides another method of releasing ions at moderate altitude range and propelling them to higher altitudes to the interesting regions of space. In these experiments the released ions will have an initial velocity of approximately the same value as the vehicle (8 km/sec). The ions in the earth's field are executing gyro motion and they are analogous to elemental current loops. The ions are therefore magnetic and they experience an upward force anti-parallel and proportional to the gradient of the Earth's magnetic field. This is the so called "mirror" force. The magnitude of this depends on the magnetic moment of the ions i.e. their velocity perpendicular to the magnetic field.

In October 1978[10] barium was released at orbital velocity at 900 km altitude and was observed at 22,000 km, 20 minutes later. Once again an electric field had to be assumed to make the observations consistent with the very large vertical distances traveled by the ions.

There have been a number of reports of ions accelerating perpendicular to the magnetic field and at auroral latitudes. The line of site velocity measurement of barium ion clouds would provide another excellent measurement of the perpendicular acceleration mechanism. This acceleration results in ions of several kilovolts of energy and corresponding Doppler broadening. Once again the direct observation of line of sight velocities would confirm the satellite measurements by the optical technique. The release of visible ions in the magnetosphere and in the interplanetary medium is a very powerful tool in the investigation of the plasma physics of the regions. Past techniques used photographic triangulation to supply the data base for analysis. Virtually all of these experiments would have greatly benefitted from the simultaneous line of sight velocity measurement by doppler techniques. With the operational capability of the space shuttle, both the shaped charge and the orbital velocity release technique is expected to yield increasing opportunity for ion release experiments in the future. Thus the development of a line of sight doppler velocity measuring technique for ion releases is very desirable at this time.

Design Considerations

The velocity of ion clouds in the interplanetary field and magnetosphere are relatively high. These are plasmas which have been accelerated in the region of several electron volts to several thousand electron volts. In figure 2, we have illustrated the dependence of barium ion velocity on the accelerated energy and on the right hand scale we have illustrated the corresponding doppler shift of the 4936Å barium ion resonance line. From this graph it is evident that, for example, a shaped charge which is starting out with a 12 km per second energy due to its explosive release is equivalent already to 100 electron volt accelerating potential corresponding to doppler shift of approximately .2 angstrom. The electric fields, which are expected to be observed above the aurora, are of the order of several 100 eVs. The temperature of the drifting plasma in the geomagnetic tail is of the order of 1 keV. To detect the doppler shift of ion cloud with these kind of velocities require relatively modest resolution interferometry (.05 - .2 angstrom).

A much more stringent requirement comes from the fact that there is relatively little light available from the resonance scattered ion clouds. Even if the ion cloud brightness after release is relatively large, at later times the ion cloud disperses and produces very low brightness levels.

The Selection of the Spectrometer

The total light throughput of a spectrometer is given by the luminosity.[11,12,13] The luminosity L can be defined as

$$L = \varepsilon A \Omega \qquad (1)$$

where A = the area of the fully illuminated spectrometer, Ω = angular (solid angle) divengence of the light and ε is the transmission.

To evaluate competing systems, one may proceed by comparing those which have the required resolving capability, say .05 angstrom in wavelength. Circularly symmetric spectrometers such as the Fabry-Perot, Michelson interferometers, bi-refringent filters have well known throughput advantages at high resolution over grating spectrographs.[13] We have considered two spectrometers. One was the Lockheed tuneable bi-refringent filter[14] and a solid Fabry-Perot etalon.[15,16] The Lockheed bi-refringent filter has an entrance aperture of 3 cm and a total acceptance angle of 5 degrees. Thus the luminosity L = 225 cm^2

square degree times the transmission. This was measured and was found to be between 12-16% in the blue thus giving a total luminosity figure of 45 cm^2 square degree.

The properties of the solid Fabry Perot etalon are summarized in Table 1.

Table 1

Properties of solid Fabry-Perot etalon

Thickness: 1 mm (measured)

Refr. Index: 1.5224 (assumed)

FSR: 0.752 angstrom (measured at 4825 angstrom with laser)

FWHM: 0.050 angstrom (~2 mm area sampled)

$\delta\lambda$ (rms): 0.013 angstrom (@16 points, .3 inch apart)

Extinction: 133

Reflective finesse: 18

Measured finesse: 15

Inferred reflectivity: .83

Clear aperature: 5 cm (measured)

It is more difficult to calculate the total luminosity of the Fabry-Perot because one needs to define the acceptance angle.

In a high order classical Fabry-Perot spectrometer one can image the interferogram and use all the light in the fringes representing different orders. So although the acceptance angle for any particular fringe may be very small, by using a number of fringes one can multiply the total light throughput by the number of fringes. Alternately one can proceed as follows: The total field of view was $5^{o} \times 7^{o}$. Since the useful light within the selected waveband passes through only the area of the bright fringes one can only utilize a small fraction of the total light. The ratio of the area of dark to bright fringes in the Fabry-Perot is given by the finesse of the instrument. So the "useful" luminosity is given by the total luminosity (for $5^{o} \times 7^{o}$) divided by the finesse.

$$L_{FP} = \frac{.83 \times 5^{o} \times 7^{o} \times 5^{2} \ cm^{2}}{18} = 40 \text{ degree}^{2} \text{ cm}^{2}$$

Thus the two filters have comparable total luminosity throughput. However in the case of the Fabry Perot this light is concentrated in narrow rings which have a very high brightness per unit area and therefore easily detectable by low light level TV systems. In addition the "black" areas between the bright fringes represent useful wavelength information because this is the area where a bright fringe would represent the Doppler shifted plasma cloud. Thus a single picture taken by the Fabry-Perot provides both the wavelength and moderate spatial resolution. With the bi-refringent filter a sequence of images at different wavelength would be needed to recover the Doppler velocity profile. A television system can be regarded as a large detector array in which each pixel is functioning as a separate detector. In a conventional filtered imaging system the pixels are used to resolve spatial information in the image. In a conventional spectrometer the image is treated as a single spatially unresolved light source and the pixels are used to resolve wavelength. In both cases the large number of simultaneously operating pixels of the TV system greatly increase the detecting efficiency.

In the selection of the spectrometer type, we were also aware of the moderate spatial and wavelength resolving power requirement and opted for the scheme which provided simultaneous wavelength and spectral resolving capabilities in the same image thereby using the large array capabilities of the TV system to the fullest. As we have seen the two compared systems were basically identical in total light throughput. The bi-refringent tunable filter is a very powerful device of great flexibility but requires a complex computer control system and it was rejected in favor of a very much simpler solid Fabry-Perot etalon system.

Expected Measurable Cloud Brightness

The brightness of a distant Ba cloud such as the 5 Re Ba cloud is about 80 kilo Rayleigh (KR) at the time of release decaying to 1 or 2 KR in 10-15 minutes.[5] The number of detectable photoelectrons falling on a pixel per Rayleigh in an imaging detector is

$$N_p = \frac{10^6}{16}\frac{T\varepsilon D^2}{f^2}\frac{d^2}{} \qquad (ii)$$

where e = photo efficeincy (10%)

D = diameter of optics

d = linear size of pixel

f = focal length

T = transmission of optics

Note that

$$T \frac{D^2 d^2}{f^2} = L = \text{luminosity throughput } (\text{cm}^{-2} \times \text{rad}^{-2})$$

Hence: $$Np = \frac{10^6}{16} \; T \times L \qquad \text{(iii)}$$

$$= 6 \times 10^3 \times L$$

and for our instrument

$$= 73 \text{ per Rayleigh per sec}$$

The detection limit in a TV system however depends on the brightness or the rate of photoelectrons arriving on any one pixel. Applying formulae (ii) for a pixel of (.0195 degrees) or 0.045 mm x 0.045 mm and f = 135 mm

$$N_p = \frac{10^6 \times .81}{16} = 1.15 \times 10^{-7} = 5.8 \times 10.^{-3}$$

An image can be generated when 5-10 photons arrive on the target during the exposure. Thus a one second exposure should produce an image if the object is 860 Rayleigh or brightner.

Description of the System

The system is illustrated on Figure 3a. The light enters into the system from the night sky. Without the Fabry-Perot etalon an image of the cloud is generated as shown on Figure 3b. When the Fabry-Perot (1) which is mounted on a slider is pushed into the optical train the light goes through the Fabry-Perot and then the prefilter (2) and then the objective lens (3) which is an f/2 135mm focal length lens. The lens images the convolution of the Fabry-Perot interferogram and the barium cloud image on the photo cathode of the television tube (6). If the barium cloud image is stationary with respect to the observer, then the fringes will appear wherever the barium cloud is present in the field of view (Fig. 3d). By pushing in a slider with a screen (4) into the field of view and by illuminating it by the hollow cathode discharge barium reference lamp (5) one can obtain a reference interferogram (Fig. 3c) which is where the zero velocity fringes are located. If the barium cloud is stationary then the the two sets of fringes colocate. If the barium cloud is moving towards the observer than the cloud fringes are slightly blue shifted and appear to have a shorter radius i.e. the fringes would move in. The velocity can be measured by determining the offset in radius between the two fringe sets. Relating the wavelength shift $d\lambda$ to the velocity of the emitting source v gives

$$d\lambda = \lambda \frac{v}{c}$$

where c is the velocity of light.

The Fabry Perot formula for any bright fringe set is

$$2\mu t \cos\theta = n\lambda$$

where μ = refractive index

t = spacer thickness

θ = angle of ray divergence inside spacer

n = integer order of bright fringe

λ = wavelength

Differentiating with respect to angle as a function of change in wavelength, and replacing the angle inside spacer (θ) by angle outside in air (α)

$$\frac{2t}{\mu} \sin\alpha \, d\alpha = n d\lambda.$$

The change of fringe radius dr is related to the change in angle $d\alpha$

$$dr = f \sec^2\alpha \, d\alpha$$

where f is the focal length of objective.

Combining equations we express the velocity as a function of the offset in the radius

$$v = \frac{\cos^2\alpha \sin\alpha}{\mu^2 \left(1 - \frac{\sin^2\alpha}{\mu^2}\right)^{1/2}} \qquad \frac{c\,dr}{f}$$

where $\tan\alpha = \frac{r}{f}$.

Data Analysis

Another consideration involved during the development of the Fabry-Perot spectrometer was the manner in which the data could be analyzed. Clearly the idea is to compare images of the fringe pattern generated by the barium cloud to the reference fringe pattern of the barium discharge lamp. We can accomplish this using a video frame memory which stores a frame of video in digital form. The information content, both spatial as well as intensity, is then accessible with a minicomputer. This way the minicomputer can be used to perform this comparative analysis between the barium cloud and the reference fringe.

The comparison can proceed by first digitizing a reference frame and for each fringe order finding the mean radius and center of the circle it describes in the image plane. This can be done analytically using a least squares procedure to fit a large number points on the fringe to a general equation of a circle. Once the center is determined, a frame of video recorded of the barium cloud fringes can be digitized and a plot generated of the intensity of the fringes versus radius from the center of the image. This plot should show a broadening or shift of a fringe when compared to the reference fringe parameters. Hence the mean velocity of that part of the barium cloud can be calculated based upon the mean radius of that data fringe and the radius of the associated reference fringe.

System Tests

The system was assembled with a solid Fabry-Perot interferometer and the Westinghouse double intensified TV camera which was described by.$_{1}$[7] A special purpose long focal length optical system was used to couple the system in readiness for 6 earth radius barium cloud release. In another case this system was used with the direct 5 x 7 degree field of view mode as illustrated on figure 3. The system was fielded for use in shaped charge cloud release in Alaska in April 1981. In both of these experiments the launch vehicle failed and no high altitude high velocity barium releases were obtained. However, the system was tried on a low altitude atmospheric barium cloud release to show that the Fabry-Perot system is in fact capable of working at the luminosity level of barium clouds. In separate laboratory tests the entire system was verified to show that the interferometer is indeed capable of measuring the wavelength resolutions required from these experiments at the same low light levels.

In April 1981, the system was used to look at a barium release at 160 km altitude. At 160 km this experiment is still in the atmosphere and the velocities are low (less than 1 km per second). To maintain the large free spectral range for large Doppler Shifts we have chosen a low resolution, thin etalon. Because of this the cloud velocity is well below the design parameters of the instrument. Nevertheless, during this ion cloud release experiment, the instrument was operated and a large number of images were obtained. To show the type of images that we could get from this system we are showing Figure 4. In figure 4a the reference fringe pattern is shown as obtained by the television system using the reference fringe set produced by the hollow cathode discharge barium lamp. Figure 4b shows the fringe pattern generated by the barium cloud and figure c shows the barium cloud with the Fabry-Perot removed allowing all of the intensity to get through at all areas of the picture. From these tests it was demonstrated that the instrument has ample sensitivity in measuring barium ion clouds in the very narrow spectral band required for the detection of the line of sight velocities.

Since we were unable to observe a high altitude fast moving barium cloud it was desirabl to verify the wavelength resolving capabilities of the system in a separate laboratory test.

The spectrum of helium has suitably spaced line pairs to test the spectral resolving capabilities of the Fabry-Perot coupled television system. A He discharge lamp was set up followed by a monochromater to isolate the 4471 doublet of helium discharge flow. The two lines are at 4471.682 angstrom and 4471.479 angstrom with a difference of .203 angstrom. The light from the monochromator was incident on a ground glass screen. The TV system was used to look at the ground glass. The relatively low intensity of the resulting image required the taking 1 second duration exposures on the TV. The resultant image is shown on the Figure 5. The two components of the selected spectral feature had a large difference in intensity. The brighter feature overloads in the figure whereas the dimmer one is barely dicernable. However, Figure 5 clearly shows the spatial separation between the two.

Conclusions

It was demonstrated that for maximizing the scientific output of ion cloud release experiments a new type of instrument was required which will measure the line of sight velocity of the ion cloud by the Doppler technique. A solid Fabry-Perot etalon was selected because it provided a simple rigid instrument suitable for fielding on the ground or flying in space. The solid spaced Fabry-Perot in the high order classical configuration is capable of making moderately low spectral resolution images with a maximum of light throughput. Coupled to a low light level television system it can produce images of Ba clouds from which the line of sight velocity of the different parts of the ion cloud can be determined.

Since the construction of the instrument there has not been a suitable opportunity to observe a high altitude, high velocity ion cloud. There are a number of release experiments planned for the future, but for the purposes of this report we had to test the instrument capabilities in the lab or by looking at low velocity atmospheric release experiments. Using these tests we found that, as predicted, the instrument was sensitive enough to detect and measure the velocity of ion releases. Admittedly low altitude atmospheric releases (160 km altitude) will remain denser longer but during the initial phases the low altitude cloud provides an adequate simulation of the brightness of the high altitude cloud, because in the initial phases both clouds are optically thick and therefore produce closely the same brightnesses.

In a second and separate test in the laboratory we have subjected the instrument to a light source producing two closely spaced spectral lines with a spectral separation of .2 Angstroms. We demonstrated that the instrument clearly resolved the two features corresponding to a velocity separation of 12 km sec or 100 volt of accelerating potential. The instrument was capable of much higher limiting resolution.

The instrument was a prototype. It was used to demonstrate the technique. The etalon which was available for the demonstration had a clear aperture of 5 cm. Since the total light throughput of the system is proportional to the etalon aperture, a larger system would be highly desirable. Solid etalons have been made with clear apertures up to 10 cm. The resultant light gain would be of course four times the detection capability of the present system.

With the operational capability of the space shuttle we anticipate that ion release experiments will increase in frequency and the current development in improving the observational techniques is very timely.

The current instrument is basically very rugged because it uses a solid etalon as its spectral dispersive element. The etalon, unlike most conventional interferometers, is virtually immune to a vibration environment. It can be mounted in front of an already existing low light level TV system. This way a conventional TV system can be simply converted to a high efficiency interferometer for the measurement of the line of sight velocity. These properties of the system make it highly suitable for use on the space shuttle based low light level TV system of the Spacelab Atmospheric Emissions Photometric Imager.[18]

Figure Captions

1. Barium cloud at 5 Re in the magnetosphere.[5] The faint spherical cloud shows the expanding neutrals. Two main cigar shaped clouds contain the ions which are preferentially expanding along the magnetic field being restricted in the perpendicular direction. Magnetic field is in the direction from top left to bottom night. The vertical stripes are an artifact generated by the TV system.

2. Velocity of Ba ions as a function of accelerating potential (energy in eV-s). On the right hand scale the doppler shift is shown corresponding to the velocity, which is given in Angstrom assuming that the observed line is at 4939 angstrom.

3. The diagram of the Solid Fabry-Perot etalon TV System (A). (1) is the Fabry Perot etalon on a sliding mechanism. (2) is the fore filter, (3) is the lens. (4) is a small white screen also on a slider which can be pushed into the field to reflect the hollow-cathode discharge lamp, (5) for the generation of reference fringes. (6) is the schematic diagram of the doubly intensified SEC tube. Underneath we are illustrating the image of the cloud (B) with screen and Fabry Perot out of the way. (C) is the reference fringe set with both etalon and white screen in the way. (D) is the cloud as viewed through the Fabry Perot etalon.

4. a). Reference fringes during Ba ion cloud experiment, b.) fringes generated by Ba ion cloud, c.) ion cloud through fore filter only.

5. The helium lines at 4471.682 and at 4471.479. The separation of .2A would correspond to about 12 km/sec line of sight velocity or to a velocity change due to a 100 eV accelerating layer.

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ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

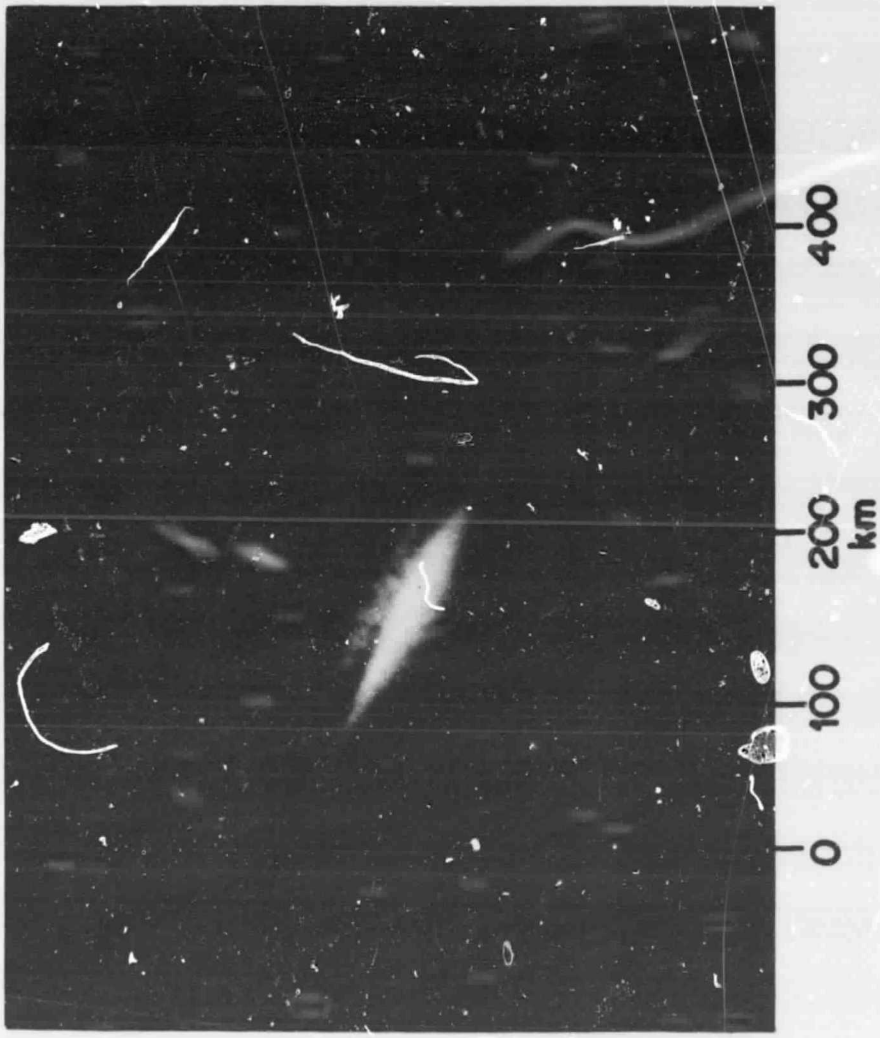

FIGURE 1.

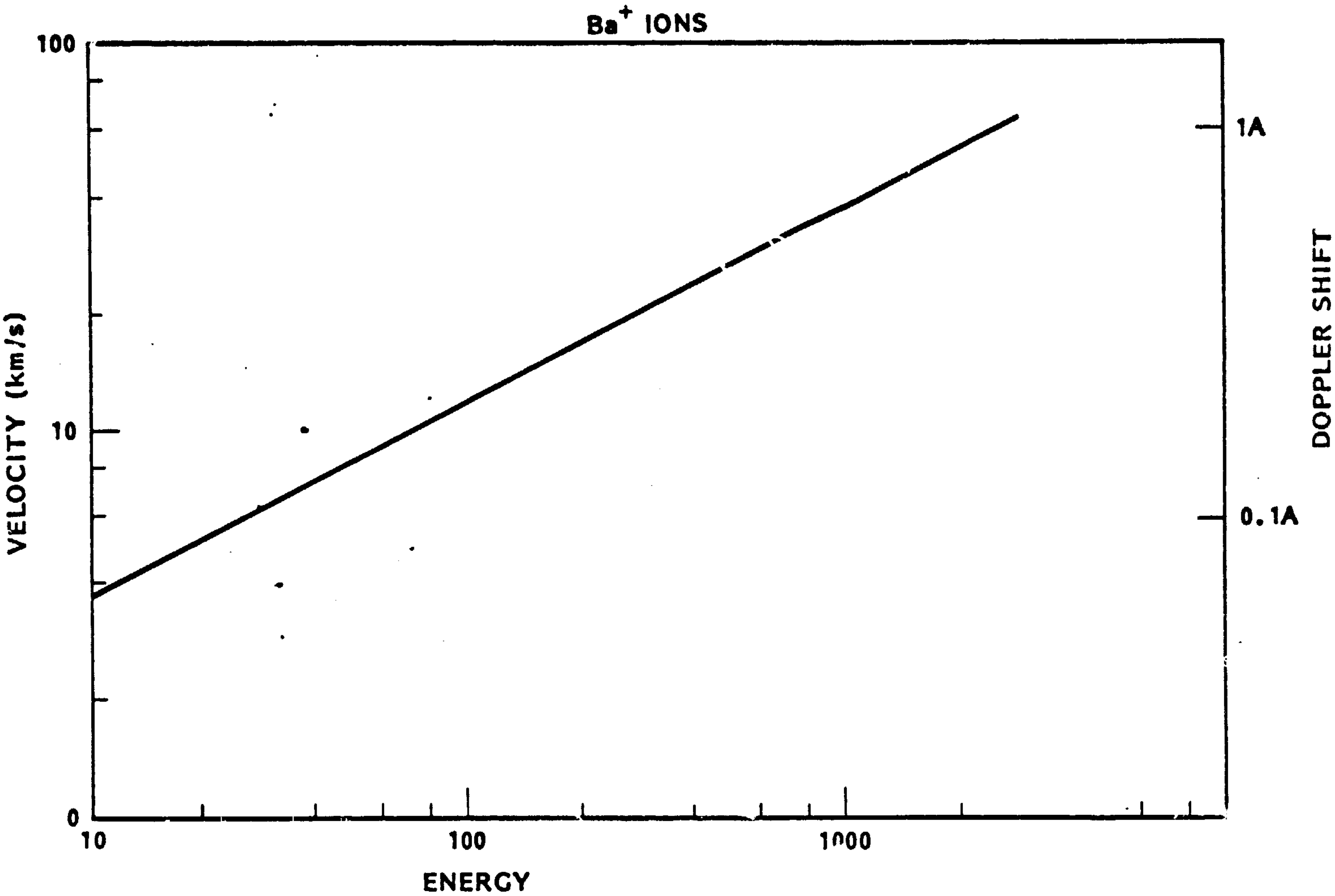
Ba+ IONS
100
10
0
VELOCITY (km/s)
1A
0.1A
DOPPLER SHIFT
10
100
1000
ENERGY

FIGURE 2.

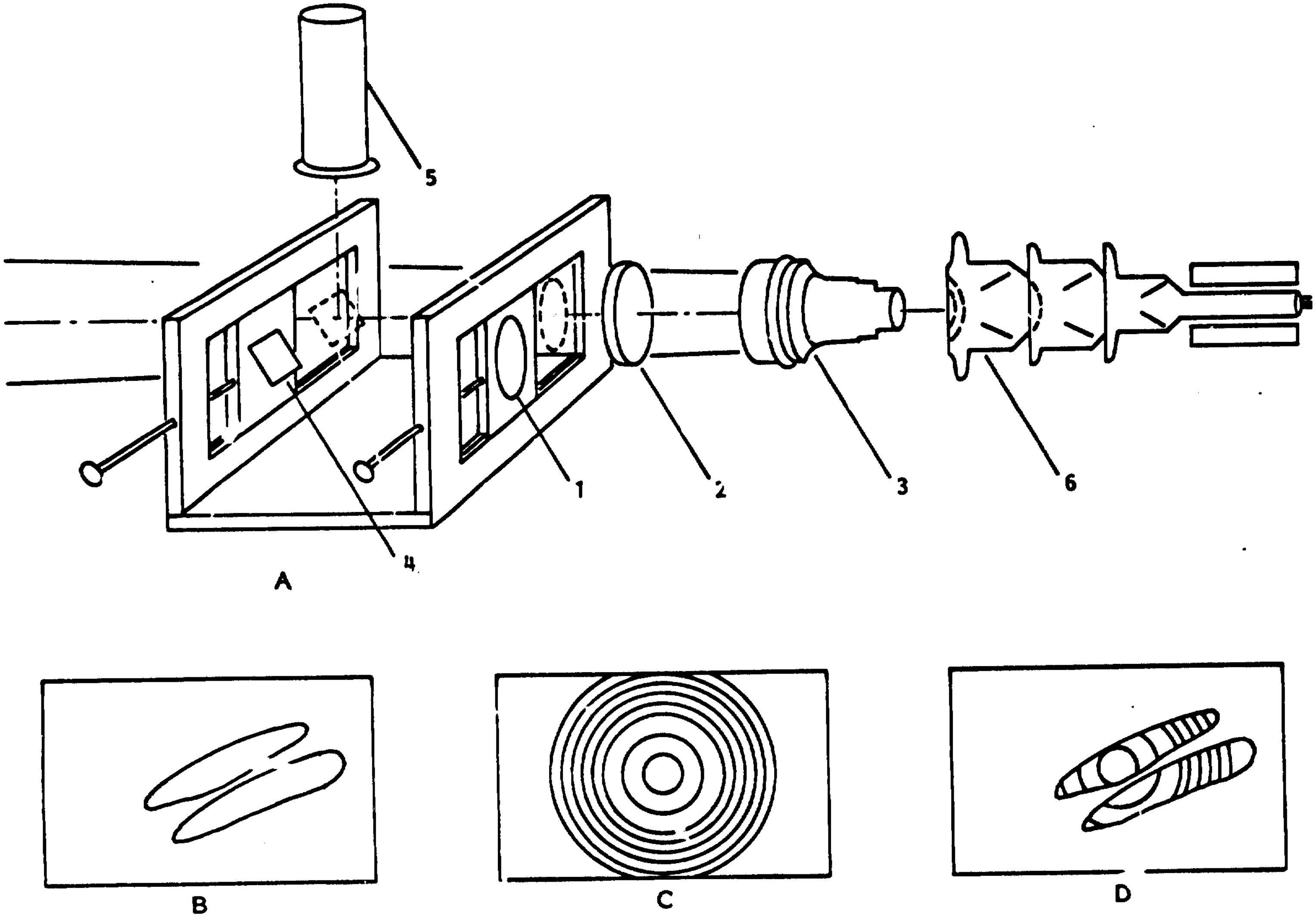

FIGURE 3.

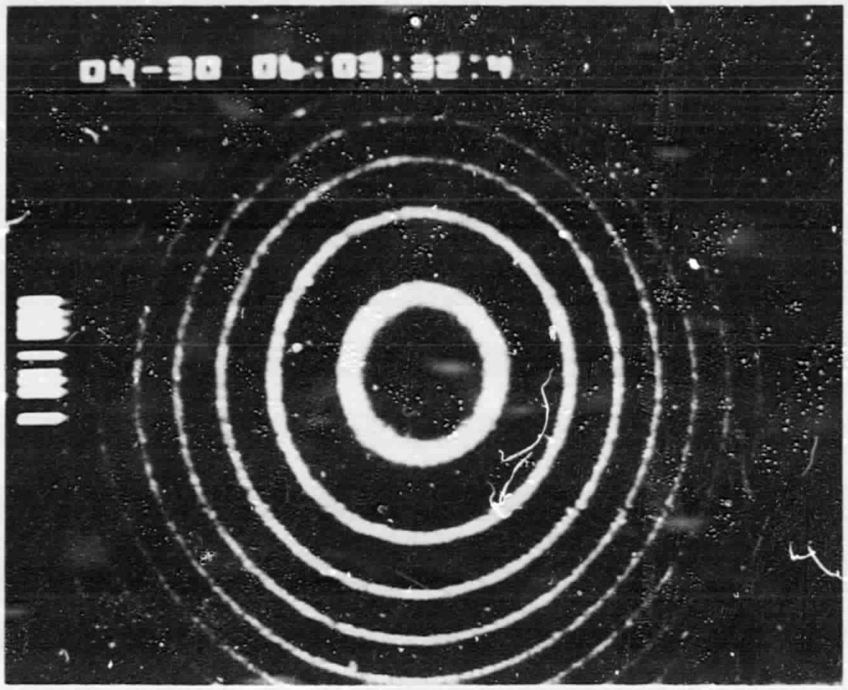

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Figure 4a.

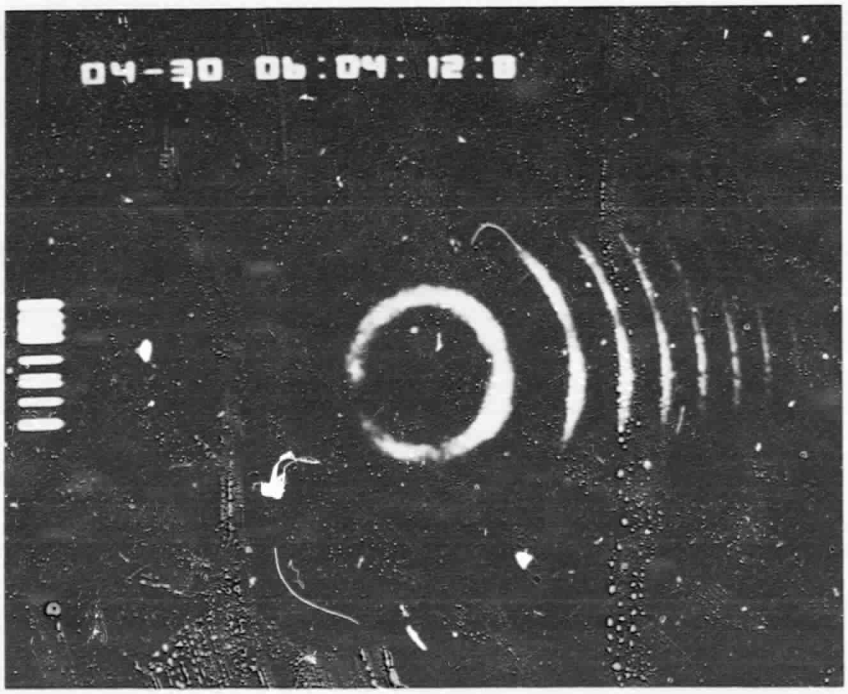

Figure 4b.

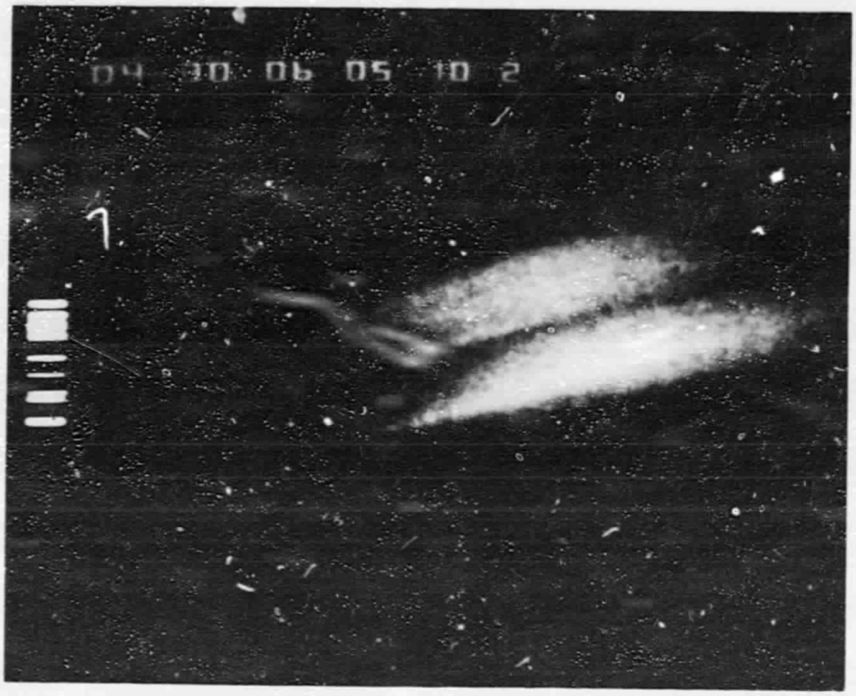

Figure 4c.