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SR90, STRONTIUM SHAPED-CHARGE CRITICAL IONIZATION VELOCITY EXPERIMENT

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Short title: Strontium Critical Velocity Experiment

Abstract. In May 1986 we carried out an experiment to test Alfvén's critical ionization velocity (CIV) effect in free space, using the first high explosive shaped charge with a conical liner of strontium metal. The release, made at 540 km altitude at dawn twilight, was aimed at 48° to **B**. The background electron density was 1.5×10^4 cm^{-3}. A faint field-aligned Sr^+ ion streak with tip velocity of 2.6 km s^{-1} was observed from two optical sites. Using two calibration methods, we calculate that between 4.5×10^{20} and 2×10^{21} ions were visible. We have calculated an ionization time constant of 1920 s for Sr from the solar UV spectrum and ionization cross section which combined with a computer simulation of the injection predicts 1.7×10^{21} solar UV ions in the low-velocity part of the ion streak. Thus all the observed ions are from solar UV ionization of the slow (less than critical) velocity portion of the neutral jet. The observed neutral Sr velocity distribution and computer simulations indicate that 2×10^{21} solar UV ions would have been created from the fast (greater than critical) part of the jet. They would have been more diffuse, and were not observed. Using this fact we estimate that any CIV ions created were less than 10^{21}. We conclude that future Sr CIV free space experiments should be conducted below the UV shadow height and in much larger background plasma density.

Introduction

Alfvén (1954) and later Alfvén and Arrhenius (1975) proposed a theory of the formation of the solar system which provided a means of separating the elements depending upon their ionization potential. As a part of that theory it was proposed that if a neutral gas streaming through a plasma across a magnetic field exceeds a critical velocity: $V_c = (2W_i/M_a)^{\frac{1}{2}}$, (where W_i and M_a are the ionization potential and atomic mass of the neutral gas), then the neutral gas would rapidly ionize. For a central attracting mass, Alfvén showed that the critical velocity relationship led to a critical accretion radius for each of four groups of the most abundant elements with apparently good agreement with the mean distance of several groups of satellites such as the terrestrial and the giant planets, or the Galilean moons in the Jovian System (Mobius et. al., 1979).

Laboratory experiments documenting the critical velocity effect have been carried out for years and were reviewed by Danielsson (1973). Mobius et al., (1979), pointed out that:

> "All the laboratory experiments besides scaling in dimensions are different from Alfvén's cosmogonic scenario in two basic features:
>
> - The magnetized plasma is moving with respect to the neutral gas, caused by the external discharge voltage,
> - Walls are present, making up the discharge chamber."

Several free space experiments have been made to test the critical ionization velocity effect with more appropriate scaling factors and without walls. For a review of theory, laboratory and free space experiments see Newell (1985). The experiments have used barium and strontium vapor with critical velocities of 2.7 km s^{-1} and 3.5 km s^{-1}, respectively. Haerendel [1982, 1988] observed 16-18% ionization of those neutrals that exceeded the critical velocity from a conical barium shaped charge detonated 30° to **B** well below the solar UV horizon in project Porcupine. Deehr et al. [1982] detected strontium ions in the sunlit detonation of a radial barium shaped charge. The strontium was present as a 1% impurity in the barium, and the analysis shows that about 50% of the strontium ionized – at a time when less than 1% ionization would be produced by solar UV. In 1983 two experiments were carried out from rockets at the magnetic equator in Peru. Star of Lima [Wescott et al., 1986a; Torbert and Newell, 1986] was a barium conical shaped charge fired perpendicular to B in partial solar UV illumination. Optical observations indicate that 2.5 to 5×10^{20} Ba ions were produced, which could have been due to the solar UV ionization. Star of Condor [Wescott et al., 1986b] was a radial shaped charge lined with strontium metal and detonated such that Sr vapor was produced at all pitch angles to **B**. The detonation produced 43% of the neutral gas with velocity component perpendicular to **B** greater than the 3.5 km/s critical velocity. Ten minutes after detonation, a field-aligned ion streak was observed; it was estimated to contain 2.4×10^{19} ions, which is 0.004% ionization of the Sr vapor. This amount can be explained by solar UV and initial Maxwellian temperature tail ionization.

In order to understand the apparent failure of the Alfvén mechanism to produce a cascade of ionization in the 1983 Peru experiments, we carried out three additional CIV experiments from rockets at Wallops Island in May 1986. CRIT I, used two barium conical shaped charges detonated below the solar UV cutoff altitude at 45° to B at different distances from a well-instrumented mother payload (Stenbaek-Nielsen, et al. 1990; Brenning et al. 1990). There was also a daughter payload several kilometers up the magnetic field line.

The third experiment, called SR90, consisted of a high-explosive conical shaped charge with a strontium metal liner on a Taurus-Nike-Tomahawk fired 9 minutes after the launch of the barium experiment rocket. The Sr release was in full solar UV radiation. Föppl et al. [1965] estimated the solar UV ionization time constant for Sr atoms to be 4545 seconds. Based upon this very long ionization time constant, it was assumed that the solar UV contribution to the ionization processes would be negligible compared with the Alfvén mechanism; however, we have found this to be an unwarranted assumption. This paper addresses the optical observations, computer simulations, and analysis of the SR90 experiment. There were no in situ diagnostics other than background electron densities from the Millstone Hill radar.

The SR90 Experiment

The Taurus-Nike-Tomahawk, 38.008 UE, was launched from Wallops Island May 13, 1986, at 0756:00 UT. The payload consisted of an attitude control system, timers and power supplies to detonate a single high-explosive conical shaped charge aimed forward and coaxial with the rocket. The shaped charge consisted of 7.4 kg of 75/25 OCTOL high explosive, with a tapered 30-degree conical liner of Sr metal weighing 0.57 kg. The 2-axis attitude control system was set to nominally align the shaped charge at 45° to B, but the azimuth was undetermined; detonation could occur anywhere on a 45° cone about B.

The detonation occurred at 0801:29 UT, at 539.6 km altitude, 37.72°N lat and -74.72°E long. By triangulation, the axis of the neutral strontium jet was upwards at a geodetic elevation angle of 26° and azimuth of 212°, giving an actual angle of 48.2° with respect to B. The experiment was observed from three primary optical sites using low light level imagers: Wallops V25, 37.861°N, -75.457°E, about 2 km from the launcher; Duck, NC, 36.182°N, -75.751°E; and at Cape May, NJ, 38.945°N, -74.883°E. NASA film cameras were also operated at Wallops Island near the control center.

At Duck, NC, observations were made using an intensified film camera and an intensified silicon intensified target (ISIT) TV system. Figure 1 shows a picture of the neutral jet taken in white light from the ISIT TV 11.5 seconds after detonation.

The detonation azimuth and elevation were very fortunate for analysis of the neutral velocity distribution, as the viewing angle between Duck and the jet was close to 90°, allowing the best neutral velocity distribution from a shaped charge that we have ever obtained. The ISIT image, Figure 1, was digitized and each pixel value was printed out. The corresponding distances along various angles away from the detonation point were calculated and plotted on the pixel diagram. We were able to fit Gaussian curves across the jet at various distances, and to integrate the total intensity of all neutral Sr gas in velocity intervals $\Delta \upsilon$ of 0.875 km s^{-1}. The Gaussian function for axis intensity, or density dependence, for the fast portion of the jet ($\upsilon>8$ km s^{-1}) has a half amplitude angle of 6.6° and is given by:

$$I = I_0 e^{-\frac{\theta^2 \ln 2}{(6.6°)^2}}$$

where θ is the angle from the central axis in degrees, and I_0 is the intensity (or neutral density) at the center. For velocities between 3.5 and 8 km/sec the half amplitude angle is near 10°, and for the very low velocity material ($\upsilon<3.5$ km s^{-1}) the half angle is close to 22°.

Figure 2 shows the differential velocity function derived from integrating the total pixel counts per 0.875 km s^{-1} increments. The apparent tip velocity was slightly over 13 km/sec. The differential velocity distribution was normalized by assuming that 15% of the 0.556 kg Sr liner was vaporized, based on vacuum chamber experiments with small Ba and Sr shaped charges (Michel, 1969, 1974).

Föppl et al. [1965] estimated the ionization time constant for strontium at about 4545 sec and noted "...which is of course highly uncertain." We used this value in planning the experiment, but after the experiment we were able to calculate a better number. Using the newer experimental ionization cross section between 1700-2400Å of Lütjens [1973] which he estimates is good to 30%, convolved with the solar UV spectrum of Banks and Kockarts [1973] we find an ionization time constant of 1920 s ($\pm$ 30%). With 5.7×10^{23} Sr atoms available for ionization and a time constant of 1920 sec, in 0.1 s there should be 3×10^{19} ions, in 1 sec, 3×10^{20} ions, and in 10 s, 3×10^{21} ions produced.

Analysis of the Sr metal chips left over from machining the cone indicates that there were 2.13% Ba atoms by weight impurity, or 0.012 kg of Ba in the cone. Assuming 15% vaporization of the Ba, and a solar UV ionization time constant of 28 sec [Hallinan, 1988], the number of Ba ions would equal the number of Sr ions, but they would not be visible through the Sr ion filters.

Optical Observations

At Duck NC, the Sr injection was also observed with an intensified film camera with a narrow band 4078Å interference filter on the principal SrII line. A faint field-aligned streak of Sr^+ ions was observed. Figure 3a-f shows a sequence of portions of six intensified camera frames which were digitized electronically. The bright oval-shaped feature at, Fig. 3a, is the explosive debris cloud with broad band emissions coming through the 4078Å filter. The field-aligned streak can be seen coming upward from slightly left of center of the debris cloud at 6.6 s and progressing up the field line in successive 2-s intervals. The last frame Fig. 3f, at 63 s shows the streak visible about 85 km along the field line (distances in 20km ticks shown along the field line).

The early time apparent velocity of the tip of the field-aligned Sr^+ jet is about 2.6 km s^{-1}. With an injection of pitch angle 48.2° to **B**, the corresponding neutral Sr velocity would be 3.9 km s^{-1}. This agrees well with the low-velocity peak in the differential velocity distribution, Figure 2. The low-velocity peak is estimated to contain 2.3×10^{23} atoms of Sr.

The ISIT camera at Duck in white light is less sensitive than the intensified film camera and the bright neutral Sr cloud partially obscured the direction up the magnetic field line. No ion streak is evident, even with post facto 3-second integration, but this is consistent with the observed brightness and the sensitivity of the camera.

A pair of imaging photon detectors (IPD) observing in the ion and neutral emission lines, respectively, were operated at the Wallops V25 site in the launch complex. The neutral cloud was very bright, and about 15 seconds after release it became necessary to stop down the lens aperture to prevent damage to the detector. Unfortunately, the neutral and the ion detector were both stopped down. As a result the later ion images are very noisy and are not of as good quality as the images from Duck. No prompt ions could be identified but a faint trail of Sr ions was detected along B above the release over a period of 2-3 minutes following the release. No Sr ions were seen on images at Cape May due to the geometry of the release, the brightness of the neutrals and the sensitivity of the camera in white light.

Brightness of the Ion Streak and Ion Production Estimate

An estimate of the brightness of the field aligned streak shown in Figure 3f at 63 s after release can be made using several methods. The most direct is using the IPD data, but because the lens was stopped down, the signal to noise is low resulting in a large uncertainty on the result. The streak is not discernible in individual IPD images, but can be brought out by summing several images. The IPD employs photon counting technique and thus is absolutely calibrated. The brightness of the ion cloud near 63 s, as observed in the IPD images, is 100-200 R.

The second method combines the intensified camera data from Duck and the Wallops Island IPD data. Both data sets are observations filtered on the 4078Å SrII line. The intensified film camera is not absolutely calibrated, but an estimate of the ion cloud brightness can be made using images from the IPD (prior to that instrument being stopped down) for calibration of corresponding images from the intensified camera. Assuming the high explosive debris cloud to be broad-band emissions, the IPD images indicate its brightness at 6.6 s after release to be 40 R/Å. The intensified camera was equipped with a filter of 44Å FWHM and 40% peak transmission.

From densitometry of the original Duck intensifier film frame and the film development characteristics, we measured the ratio of ion line streak brightness to center of explosive debris (broad band emissions) brightness at 6.6 seconds after detonation to be 0.66. Using the IPD based brightness of 40 R/Å for the debris cloud, the ion cloud would have a brightness of 1200 R at 6.6 s. The brightness of the ion cloud decreases as 1/time because of velocity dispersion. Thus at 63 s the brightness would be 125 R which is within the brightness range established based on the IPD data.

Number of ions in cloud:

To obtain the number of ions in the cloud the emission rate is required. For strontium in full sunlight, Föppl et. al. (1967) report an emission rate at 4078Å of 0.087 photons/ions, assuming all ions to be in the ground state. This rate was calculated assuming the depth of the solar Fraunhofer absorption line to be 2%. Newer solar spectral data (Beckers et al., 1975) of the solar flux at the top of the atmosphere indicate a brighter solar continuum than that used by Föppl et. al., and the depth of the absorption line to be closer to 4%. This alone would raise the emission rate by more than a factor of 2. We have not been able to perform a detailed calculation of the strontium emission rate as for example has been done for barium by Stenbaek-Nielsen (1989), but using the newer solar data by Beckers et. al. (1975) we calculate an emission rate of 0.2 photons/ion -s.

Because of the deep Fraunhofer absorption line in the solar spectrum, a Doppler shift of the resonance line can change the emission rate drastically. However, the ions present in the ion cloud discernible at 63 s would all have low velocities, ($v<2.6$ km/sec) and the change in the resonance relative to the solar spectrum due to a velocity component in the direction of the Sun (Doppler effect) is very small and can be ignored. Therefore, for the estimate of the number of ions in the image, no Doppler connection is required to the emission rate of 0.2 photons/ion.

We converted the film frame at 63 seconds to a digitized image, subtracted the background and printed out all the pixel values. The intensity calibration of the image derived above defines the brightness in all pixels of the cloud. The triangulated distance from the station to the cloud was 600 km and the field of view of the image was 4.9×5.9 degrees. The total number of ions in the cloud observed in the image is, by integration over all pixels in the image, found to be 4.5×10^{20} ions. This value corresponds to 0.17% of the total amount of strontium at velocities less than 3.5 km/sec.

Model to Calculate Synthetic Images

The number of ions observed can be compared with the number of ions expected from photoionization. In order to estimate how the neutral Sr jet and field-aligned Sr ion streak would appear to optical imagers at the various sites used in the experiment, we made computer simulations of the solar ionization produced effects using a time constant of 1920 s. The synthetic images were constructed by calculating brightness at individual points across a 6°×3.6° image plane. We assumed the neutral and ion jets to be optically thin, so that the brightness is simply the integration of radiation over all particles along the line of sight. For the ion-emission rate we used 0.2 photons/ion -s.

The model calculations assumed that the neutral particles followed straight-line trajectories, traveling radially outward from the site of the shaped-charge explosion. The neutral density was calculated from the differential velocity distribution function

$$\eta = \frac{d^2F}{dvd\theta} \qquad (1)$$

which is the number of particles with speeds between v and $v + dv$ and with polar angles θ and $\theta + d\theta$, where θ is the angle between the burst direction and the radial vector. Rotational symmetry about the burst direction was assumed. Specifically, we assumed

$$\eta = \mu \, N \, F(v) \exp\left(\frac{-\theta^2 \ln 2}{(\Delta\theta)^\circ} \right) \qquad (2)$$

where N is the total number of strontium neutrals in the beam, μ is a normalizing constant and the angular width of the beam, $\Delta\theta$, was taken to be a function of the velocity. The velocity distribution, $F(v)$, and angular half width were inferred from TV observations from Duck as shown in Figure 2. The neutral density is given by

$$n_n = \frac{\eta(v,\theta)}{r^2 t} e^{-t/\tau} \bigg|_{v=r/t} \qquad (3)$$

where r is the distance from the burst point, and τ is the photoionization lifetime of a Sr neutral, which we have calculated to be 1920 s.

The calculation of the ion density is based on the assumption that the ion, upon creation, moves parallel to the magnetic field at a velocity equal to the projection of the velocity of the parent neutral upon the magnetic field direction. The ions may be described in terms of the distribution function $f = f(\mathbf{x}, v_s, t)$, where v_s is the velocity parallel to the magnetic field. The distribution function satisfies the equation

$$\frac{\partial f}{\partial t} + v_s \mathbf{1}_b \cdot \frac{\partial f}{\partial \mathbf{x}} = \frac{1}{\tau_0} n_n(\mathbf{x},t)\, \delta\left(v_s - \frac{\mathbf{x} \cdot \mathbf{1}_b}{t}\right) \qquad (4)$$

where $\mathbf{1}_b$ is the unit vector in the direction of the magnetic field. This states that the total time derivative for ions with velocity v_s is given by the rate of decay of the neutrals present in a given volume element.

The solution to (4) may be evaluated by integrating the right-hand side along the ion trajectories:

$$f = \frac{1}{\tau_0} \int_0^t dt'\, n_n(\mathbf{x}',t')\, \delta\left(v_s - \frac{\mathbf{x} \cdot \mathbf{1}_b}{t'}\right) \qquad (5)$$

where

$$\mathbf{x}'(t') = \mathbf{x} - \mathbf{1}_b v_s (t - t') \qquad (6)$$

The ion number density is obtained by integration of f over the velocity v_s, which is easily done because of the δ-function in the integral. The result is

$$n_i = \frac{1}{\tau t}\int_0^t dt'\, t' n_n[x - (1_b \cdot x)1_b(1 - t'/t), t'] \qquad (7)$$

Upon substituting expression (3) for the neutral density

$$n_i = \frac{1}{\tau t}\int_0^t dt' \frac{\eta(r', \theta', t')}{r'^2} e^{-t'/\tau} \qquad (8)$$

where

$$r'^2 = \left(x - \sigma_x s\right)^2 + \left(y - \sigma_y s\right)^2 + \left(z - \sigma_z s\right)^2 = x'^2 + y'^2 + z'^2$$

and

$$\theta' = \tan^{-1}\left[\frac{\left(x'^2 + y'^2\right)^{\frac{1}{2}}}{z'}\right]$$

and $s = (1 - t/t')r \cos\Omega$, where Ω is the angle between the direction of **x** and the magnetic field. The σs are the direction cosines of the unit vector 1_b.

The calculation of the image intensities from the volume densities is then a matter of integrating the volume densities n_n and n_i along a line of sight. The line-of-sight direction is specified in terms of view angles, α and β, from the observation point. The picture coordinates are αcosβ and αsinβ, where α is the angle between the view direction and the line-of-sight to the burst, and β is an azimuthal angle about the line-of-sight to the burst measured from the projection of the burst direction on the plane normal to the line-of-sight to the burst. The details of converting the coordinates in which the density is computed to geocentric coordinates (in which the observer's position, burst location and magnetic field direction are computed) to the picture coordinates are tedious, and will not be repeated here. The results of the calculations are synthetic images projected on the image plane as viewed from the observation point.

Figure 4 shows a contour plot of the brightness of the Sr ions at 4078Å as viewed from Duck at $t + 65.2$ seconds. We used the emission rate of 0.2 photons/ion s. The initiation point is at the lower left corner. The upper right end of the streak would correspond to 2.6 km s^{-1} in the neutral velocity distribution, Figure 2. Thus the streak shown is from neutrals within the low velocity peak, all with velocities less than the critical velocity.

This simulated view can be compared with the observed streak a 63 s shown in Figure 3f. The simulation of the ion streak, Figure 4, does not correspond exactly with the observed streak Figure 3f because the actual ions are affected by gravity and $E \times B$ drift. By 63 seconds ions with initial velocities less than 1.5 km/sec will have reached their maximum altitude and begin to fall back down along B.

The maximum brightness in the simulated image, figure 4, is 175R, which agrees well with the observed brightness of the streak (100-200R based on the IPD images from Wallops, and 125R based on the intensified camera images from Duck). Also, the appearance of the streak in the simulation is very much as that observed in the Duck image (fig 3f). This is a rather important point. The presence of a field-aligned streak along the release field line could be taken as evidence of a CIV process present only in the vicinity of the release, but the simulation clearly shows that the streak also can be produced by a uniform ionization rate. Thus we must conclude that the observed ions can all be accounted for by solar UV ionization.

Conclusions

We have carried out a free space CIV experiment using the first shaped charge with a conical strontium metal liner, but no CIV ions were detected. The use of a conical liner was an improvement over the "Star of Condor" Peru experiment, which used a radial shaped charge, in that a higher peak velocity and a much more dense jet were produced. The ambient plasma background density in both experiments was similar: 2×10^4 cm^{-3}. In the Peru experiment we only detected a Sr ion streak 10 minutes after the injection and estimated that we could see 2.4×10^{19} ions, or 0.004% of the vaporized Sr. As the Star of Condor ion streak was first noticed 10 minutes after the injection, it is likely that many of the ions initially formed by solar UV were no longer dense enough to be detected, and the ion inventory was low.

In the SR90 experiment we detected a faint SrII field-aligned streak (about 150R) in 4078Å light from the Duck and Wallops V25 optical sites. The tip of the streak had a velocity of 2.6 km s^{-1}, which corresponds to 3.9 km s^{-1} in the initial 48° to B neutral jet. From several calibrations of the brightness of the ion streak we estimate that the detectable portion contained about 10^{21} ions to an uncertainty of a factor of 2. A computer simulation using a new computation of the solar UV ionization time constant (1920 s) shows 1.7×10^{21} ions in the slow portion of the ion streak. We note that the SR90 ion streak detected is from the portion of the neutral jet with velocity perpendicular to B which is below the Alfvén critical velocity of 3.5 km s^{-1}.

Although no high velocity ($\upsilon>2.6$ km/s) ion jet was observed, the IPD ion images available combined with model calculations allow an estimate to be made of the maximum number of CIV ions that could have been present. The release was observed from Wallops V25 near the edge of the IPD field of view where the ion filter unfortunately rapidly cuts off. Solar UV and CIV ions in a fast ($v \approx$ 9Km/s) field aligned ion jet would have been clear of the bright explosive debris area about 5 seconds after release and out of the field of view about 9 seconds after release. We have an IPD image covering the time interval 4 to 10 seconds after release. There is a slight increase in the counts in the general area where the jet should be just at the edge of the pass band of the filter. A computer simulation at 10 seconds indicates that the solar UV produced ions should have a brightness of 30R, which our calibration indicates is just below the limit of detectability where the fast ion streak should be. We therefore conclude that if there were CIV ions present in numbers comparable to the solar UV produced ions we should have seen them. This sets the maximum number of CIV ions which could have been produced in the fast jet, but not detected, at less than 2×10^{21} to within a factor of two, or less than 0.18% yield of the vaporized Sr.

Since this maximum possible CIV yield is a factor of 100 less than the Porcupine experiment in which the ambient plasma density was 6×10^{5} cm^{-3}, or 30 times greater, we conjectured that future CIV experiments should have high ambient background plasma density. This was proven to be true in the CRIT II experiment carried out on May 4, 1989 from Wallops Island. In this experiment the ambient background density was 6X10^{5} cm^{-3}, and preliminary analysis indicates about 4% CIV ionization (Torbert, 1989; Stenbaek-Nielsen et al. 1989).

On the positive side we were able to obtain the best alkali metal shaped charge neutral velocity distribution as a function of radial angle from the detonation point and as a differential number of neutrals per unit velocity. We also calculated a solar UV ionization time constant for Sr of 1920 s (to 30%) which agrees with the observed ion inventory. If the Sr experiment had been carried out in high ambient electron density and produced 4% CIV ionization, the solar component would be negligible, but it is clear that future Sr CIV experiments should be carried out below the solar UV height. Such an experiment is planned for August, 1990 from the CRRES satellite. On the other hand, Sr vapor releases in the distant magnetosphere or in the solar wind might have advantages over faster ionizing Ba or Eu to produce larger volumes of ions.

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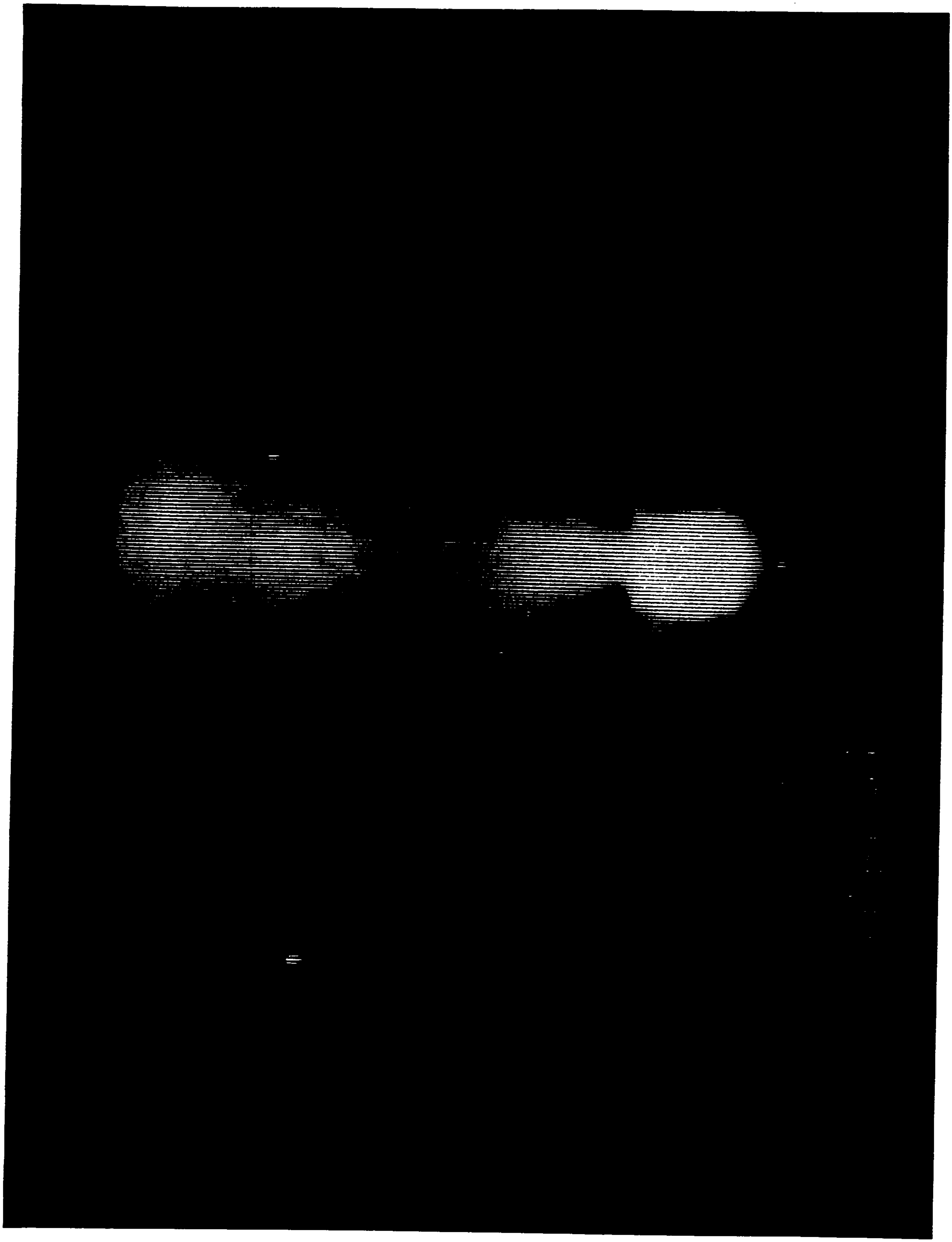
Figure Captions

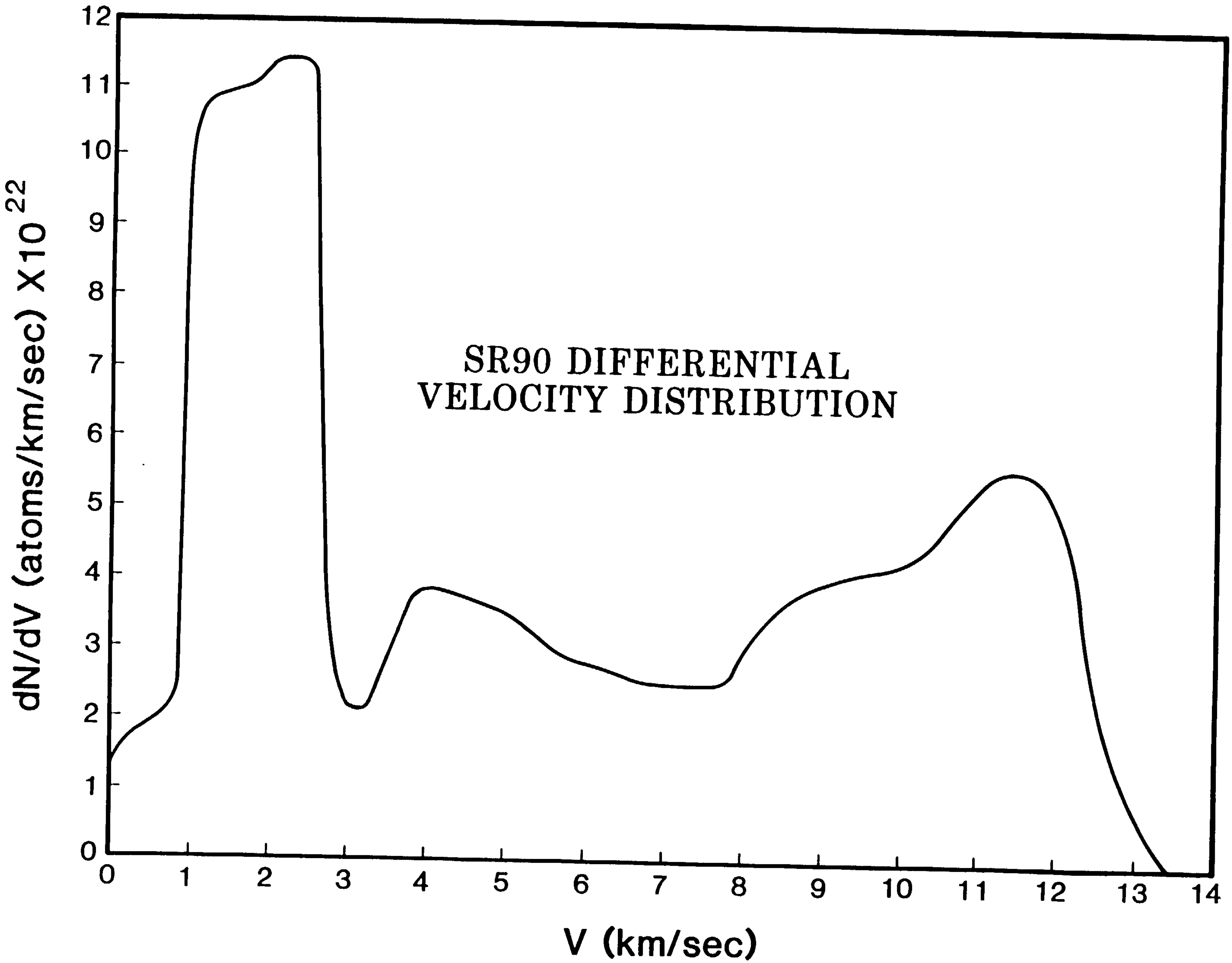
Fig. 1. TV picture of SR90 neutral jet in white light at 11.5 seconds from Duck, NC.

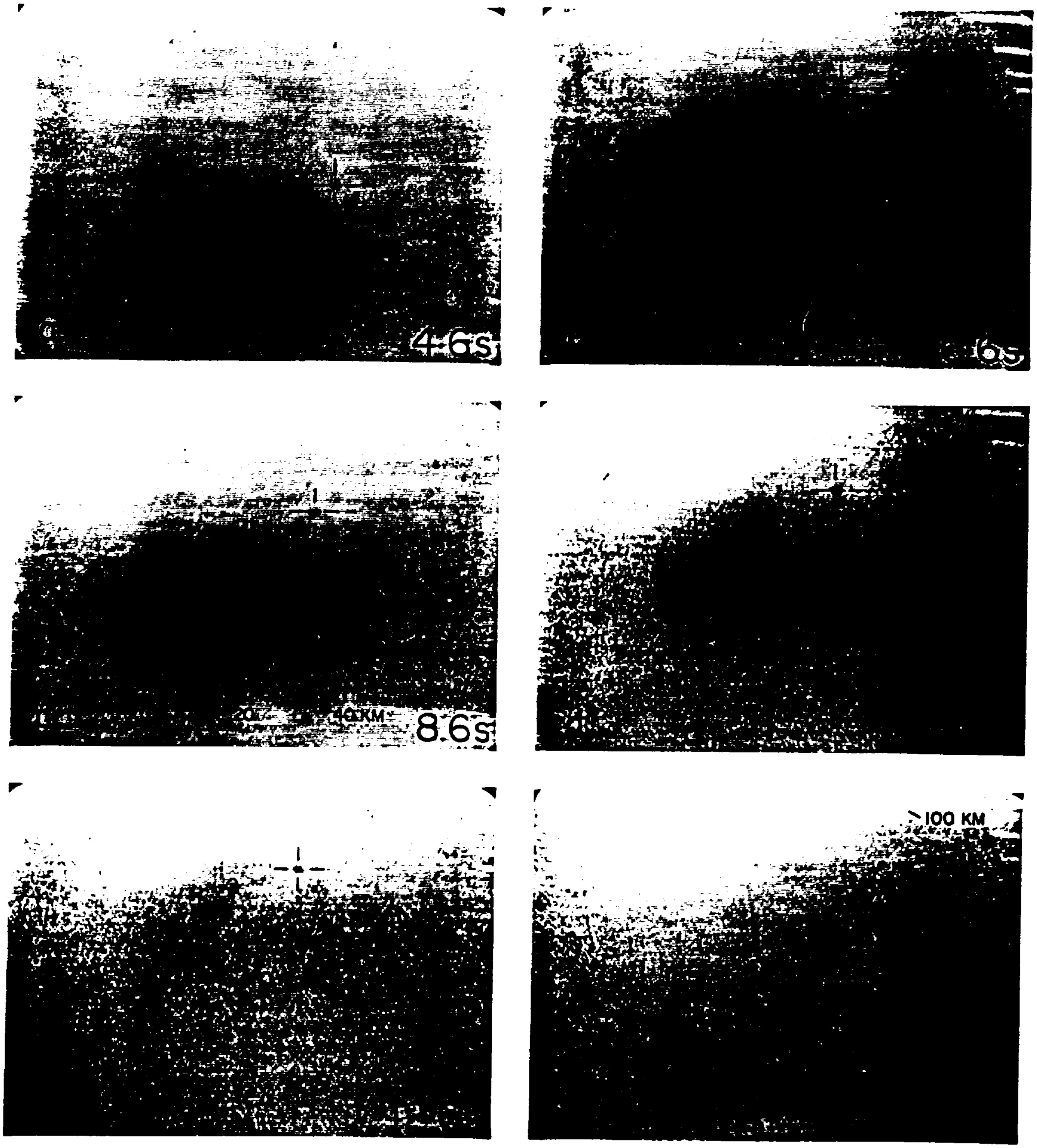
Fig. 2. Differential strontium neutral velocity function. The scale is derived from the assumption that 15% of the liner is vaporized.

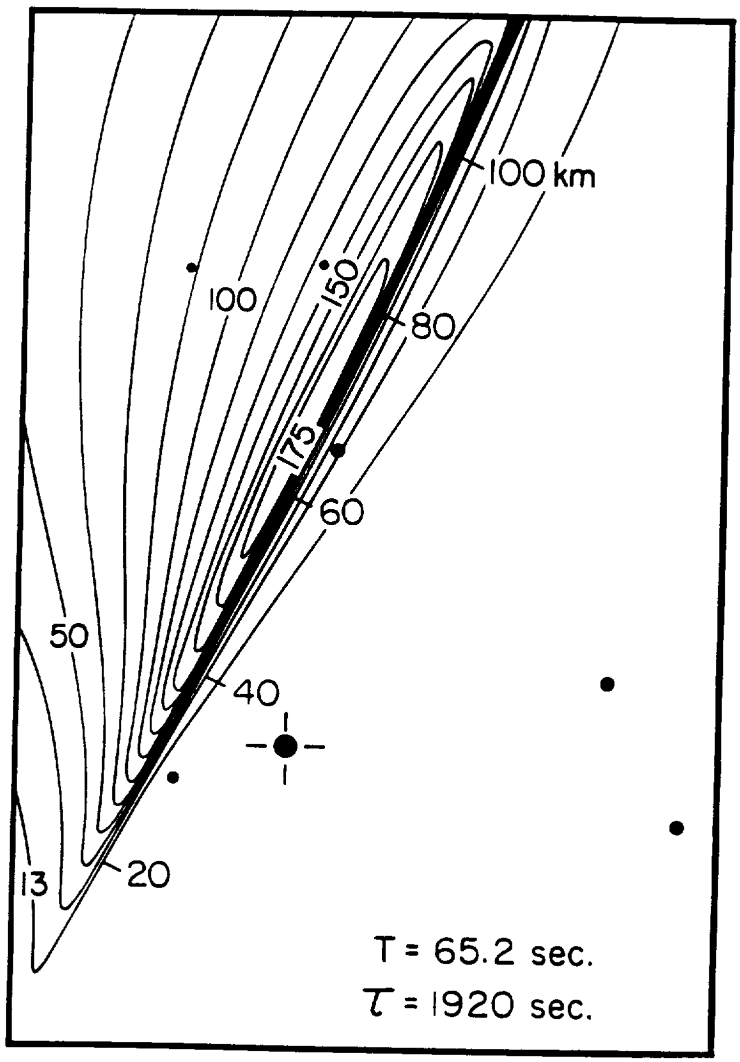
Fig. 3a-f. TV frames from portions of digitized intensified film camera at Duck, NC, showing the development of a slow ($v < 2.6$ km/s) Sr ion streak. The brightest star shown with a cross is Cygnus i. The next brightest star is Cygnus θ. The distance along the magnetic field line from the burst point is shown in 3f.

Fig. 4. Contour plot of computer simulation of Sr ions brightness in 4078Å at 65.2 s after detonation as viewed from Duck, NC. The burst point is at lower left hand corner, and 120 km of field-aligned streak are shown. Tick marks show distance in km along B. The total ion count in the $6° \times 3.6°$ field of view is 1.71×10^{21} ions. Only the brightest portion of the streak would be visible on the Duck intensified camera frame (Figure 3f).




SR90 DIFFERENTIAL
VELOCITY DISTRIBUTION
dN/dV (atoms/km/sec) X10^22
V (km/sec)
0 1 2 3 4 5 6 7 8 9 10 11 12
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14


4.6s
8.6s
40 KM
>100 KM



BRIGHTNESS 4078 Å (R)