DEVELOPMENT OF THE BARIUM SHAPED CHARGE TECHNIQUE IN JAPAN

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***Abstract*:** Generation of an artificial barium luminescent cloud is a useful technique to investigate configurations of magnetic field lines or electric fields in the upper atmosphere. To make such a plasma cloud of several thousands of kilometers long along a magnetic field line, it is necessary to initiate a well-collimated barium jet with an initial velocity of 8–12 km/s by using a shaped charge. This report explains a series of developments of the barium shaped charge techniques, such as molding of barium liners, prohibition of rust on the metallic barium, production of a plane detonation wave and a ground test of a barium ion jet.

1. Barium Shaped Charge Experiments

Barium ions are well suited for tracing out magnetic field lines, because they resonantly scatter the Ba II lines of sunlight and because ions are constrained to spiral about magnetic field lines while travelling freely parallel to the field.

By use of a high explosive shaped charge with a hollow conical liner of barium metal, detonated above 300 km altitude, a jet of barium plasma will be created with an initial velocity of about 8—12 km/s. Thus a significant amount of barium plasma can traverse several thousands kilometers along geomagnetic field line and can be traced by optical devices set up at several observing stations on the ground.

By determining the positions and time variations of this illuminated barium flux tube, configurations may be deduced of magnetic field lines in the unstable magnetospheric region or of electric field characteristics above the auroral zone (Wescott *et al.*, 1974, 1975, 1976; Rieger *et al.*, 1979).

2. Rocket Experiments on Board ♯K-9M-66

Figure 1 shows a schematic diagram of the barium vaporizer installed on the rocket. A jet of well-collimated high velocity plasma is produced by collapsing the wall of a hollow conical metallic barium liner with a high pressure detonation wave travelling parallel to the axis of liner. This plane detonation wave is generated by the shaped charge lens composed of composition *B* and baratol (Hunter *et al.*, 1969).

Above KSC (Kagoshima Space Center) the geomagnetic field makes an angle of about 30° with the launching vector whose direction is N145°E and elevation angle is 80°. The axis of the barium vaporizer was set at 30° to rocket axis. As ♯K-9M-66 has a spinning motion of 3 Hz and also a precession of about one several tenths of a Hz around the rocket axis, the axis of the barium vaporizer coincides with the magnetic

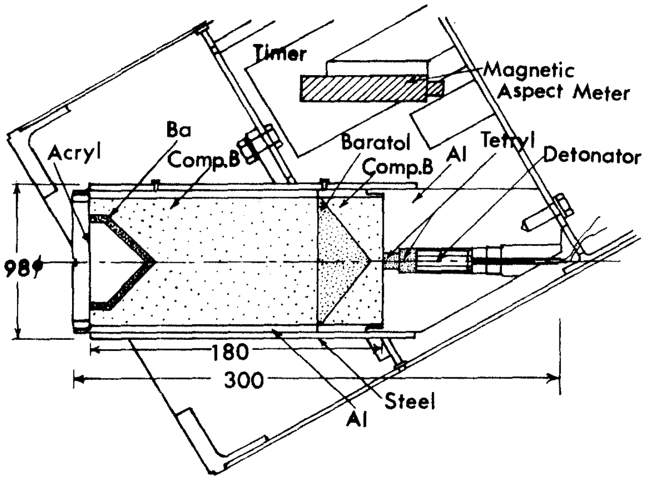


Fig. 1. Schematic diagram of the barium vaporizer and magnetic aspect meter unit in the ♯K-9M-66 rocket.

field every several scores of seconds during the rocket flight. A magnetic aspect meter is set parallel to the axis of the barium vaporizer as shown in Fig. 1 and when it indicates that the axis is less than 5° to the magnetic field, the detonator of the barium vaporizer is ignited by a relay action.

The ♯K-9M-66 rocket was launched at 18: 06 JST ($=X$) in the evening twilight on 21 January 1979, and at $X+5$ min 20 s the barium vaporizer was cut off from other payloads on the rocket, at an altitude of 350 km in the downleg of the rocket trajectory. Then the magnetic aspect meter operated from $X+5$ min 40 s to $X+6$ min 00 s. As the period of precession of ♯K-9M-66 was about 53 s, the direction of the aspect meter did not coincide with magnetic field line during the above 20 s and there followed the forced ignition of detonator by the action of the timer at $X+6$ min 00 s. Thus barium plasma was shot towards a direction of about 60° to magnetic field line.

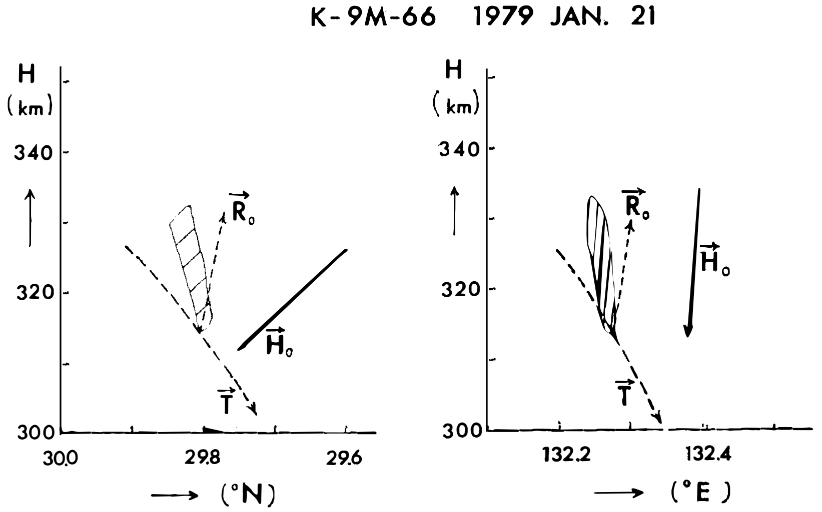


Fig. 2. Positions of the barium luminescent cloud made by ♯K-9M-66 rocket. H_0: direction of the earth's magnetic field. T: rocket trajectry. R_0: lauching vector of ♯K-9M-66 rocket. H: height. °N: the north latitude in degrees. °E: the east longitude in degrees.

At that time, height of the sun was $-9°$. It was evening on the ground and stars of fifth magnitude were well recognized, but in the upper atmosphere the barium jet was still illuminated by ultraviolet rays from the sun which ionized and resonantly radiated the Ba II λ 455.4 nm line strongly. Thus a barium artificial luminescent cloud was successfully photographed in the star background from the five observing stations of Uchinoura (KSC), Nango, Tanegashima Is., Yamagawa and Taniyama.

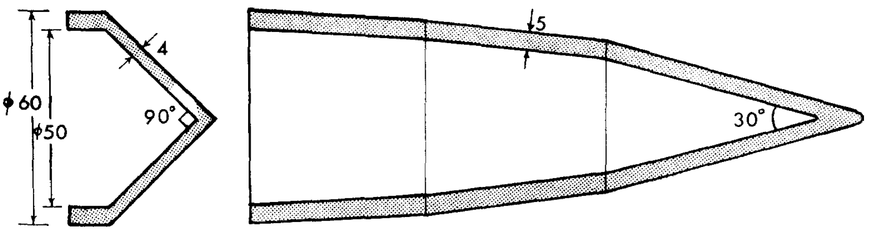
Figure 2 shows vertical projections of the barium cloud. Its shape is like a cylinder whose diameter is about 2 km and whose length is about 20 km at an altitude of 320 km. In this figure, it may be seen that the barium plasma cloud has been elongated away from the direction of geomagnetic field $\boldsymbol{H}_0$. As directions of $\boldsymbol{H}_0$ and barium jet did not coincide, the barium cloud continued to diffuse further away and at last it faded away in the sky.

3. Points of Improvement

It appears that barium shaped charge loaded on ♯K-9M-66 may be improved in the following ways:

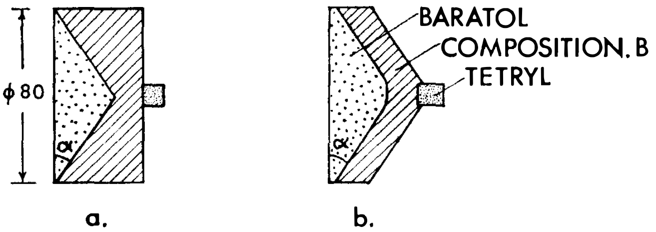
Firstly, the sensing time of the magnetic aspect meter must be longer than the period of precession of the rocket. It is planned that the sensing time of aspect meter be set for 90 s.

Secondly, the vertical angle of the conical barium liner should be decreased from 90° to 30° as shown in Figs. 3a and 3b. By this improvement, the barium liner will easily be vaporized both by the longer transit time of the detonation wave and the smaller thickness of the liner. Moreover the quantity of barium liner can be increased



a. 68g (0.5 mol) b. 340g (2.5 mol)

Fig. 3. Hollow cone of the barium liner.
a. Vertical angle of cone is 90°. b. Vertical angle of cone is 30°.



a. b.

Fig. 4. Configurations of the shaped charge.
a. Cylindrical type. b. Conical type.

from 0.5 mole to 2.5 mole.

Thirdly, the shape of shock wave lens will be improved. Figure 4a shows a cylindrical type shaped charge used in the ♯K-9M-66 experiment. In this case complex reflecting waves at bottom part of cylinder may disturb the main plane wave front. Figure 4b shows a conical type shaped charge to be used for future experiments. In this case the effect of reflecting waves will be surpressed and also the total weight of the shaped charge will be decreased. Further, the round shape of the top part of the baratol cone shown in Fig. 4b will make it easier to start the ignition than the sharp top cone shown in Fig. 4a.

4. Molding and Rust Proofing of the Barium Liner

An ingot of metallic barium has a cylindrical shape of 22 mm in diameter and 250 mm long. In order to mold this ingot to a hollow barium liner as shown in Fig. 3, at first it was molded into a disk of diameter 60 mm by a 10 t press as shown in Fig. 5a. Then using 7 types of shaped molds (from No. 1 to No. 7) it was wrung. In this case, however, the bottom center of liner was lacking because the process of mold work was concentrated to this part.

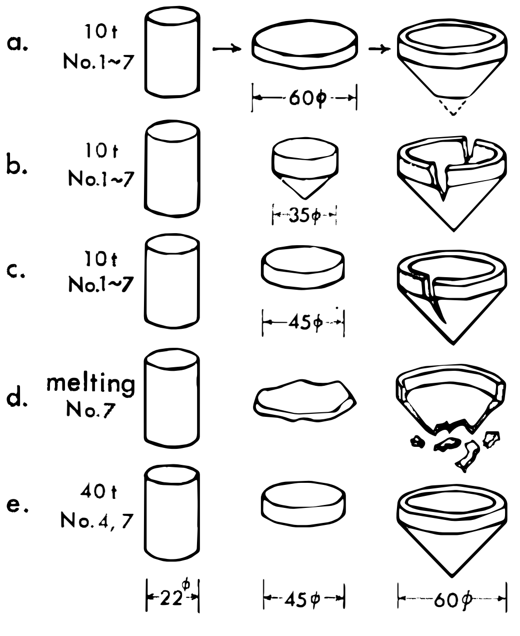


Fig. 5. Schematic diagram of the barium liner press processing.

To the next, at first it was molded to a hollow shape of diameter 35 mm and then wring pressed using in turn from No. 1 to No. 7 molds by a 10 t press. In this case, some cracks were seen at the rim as shown in Fig. 5b. Next we start with intermediate state of 5a and 5b, as shown in Fig. 5c, but still small cracks appeared. In the case of 5d, we melt metallic barium in the furnace filled with argon gas at a temperature of 750°C after which we poured them into No. 7 mold. In this case the liner became very brittle and broke into fragments.

In the case of Fig. 5e, only two molds, No. 4 and No. 7 were used, and the ingot was quickly pressed for several seconds by a 40 t press. By this process it was possible to get a barium liner of the desired shape.

In order to prohibit rusting of the barium liners, some kinds of coating substances such as kanepack, sealpeal, uletan etc. were tested. None of them, however, were sufficient to prohibit oxidation. Finally the following four layer method was found to be satisfactory for our purpose. At first the ingot is coated with barium oxide making a black film of BaC_4, and then it painted with paraffin wax, over which a sealpeal solution is poured and as the last step, again it is painted with paraffin wax.

5. Development of the Plane Detonation Wave Lens

In 1978, it was planned to develop a plane detonation wave lens in Japan. At that time, suggestions from Dr. R. A. JEFFRIES (Los Alamos Scientific Laboratory, University of California) were helpful to us and we decided upon baratol and composition *B* which correspond to a shaped charge of slow detonation velocity and of high detonation velocity, respectively.

Baratol, however, was difficult for plugging. Table 1 shows schematically how

Table 1. Plugging results of baratol having various mixing ratios.

Sample No.	TNT (%)	$Ba(NO_3)_2$ (%)	Granular distribution $Ba(NO_3)_2$ (%)				Plugging results
			20-48#	48-100#	100-150#	150-200#	
1	25	75	0	60	40	0	No fluidity
2	25	75	0	50	50	0	Impossible for plugging
3	25	75	11	41	24	24	Hard plugging
4	30	70	11	41	24	24	Separative tendency
5	28	72	11	41	24	24	Good

Table 2. Experimental results of detonation velocity.

Explosive	Density	Detonation velocity (m/s)	Mean detonation velocity (m/s)	Mixing ratio (%)
Composition *B*	1.64	7576 7692 7692 7652	7650	RDX: 60 TNT: 40 Wax: 2.8 (additional %)
Baratol	2.59	4760 4690 4734 4660	4700	TNT: 28 $Ba(NO_3)_2$: 72 (20-48# : 11 48-100#: 41 100-150#: 24 150-200#: 24)

the plugging process was improved. In sample No. 1, as the granular grades of $Ba(NO_3)_2$ were too large, they showed no fluidity.

In No. 2 also, they showed almost no fluidity. In No. 3, there was a little fluidity. In No. 4, the fluidity became large by increasing the mixing ratio of TNT, but at the same time the TNT and $Ba(NO_3)_2$ showed separative tendency. In sample No. 5, at last it was possible to plug the baratol into any mold, though baratol had still a coagulating tendency and its density showed some variation.

Table 2 shows measured results of detonation velocities of baratol and composition *B*, by the method of the double ion probe.

Figure 6 shows the testing apparatus for the shaped charge in which the L-part corresponds to the plane detonation wave lens. If V_B is the detonation velocity of baratol and V_C is that of composition *B*, the base angle of the cone α of baratol ought to satisfy the following relation:

$$\sin \alpha = \frac{V_B}{V_C} .$$

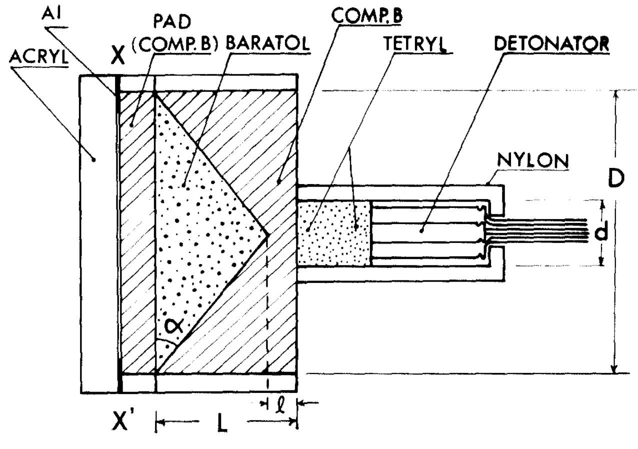


Fig. 6. Testing apparatus for the shaped charge lens to generate a plane detonation wave.

Thus the theoretical value of α is determined from Table 2 to be 36°. In the actual case, however, α will correlate with various factors such as the diameter of the shaped charge *D*, state of ignition at the top of baratol cone which will be influenced by the length l, and also the diameter of the tetryl d. Accordingly α should be determined from experiments. The composition *B* pad was inserted for smoothing out the plane wave.

When plane detonation wave front reaches the argon gas gap XX′ and strikes it, argon gas will then emit light strongly. The contour of the wave front may be recorded by a high speed streak camera of film speed 4000 m/s through a slit.

Figure 7 shows examples of these records. Figure 7a is the case of composition *B* only and the shape of the wave front is spherical. Figure 7b is the case $\alpha = 38°$ in which the shape of the wave front is concave. Figure 7c is the case $\alpha = 36°$ in which the shape of the wave front is still slightly concave.

It was deduced that the curvature of the wave front was determined mainly by the value of α and that there was almost no influence from d or l.

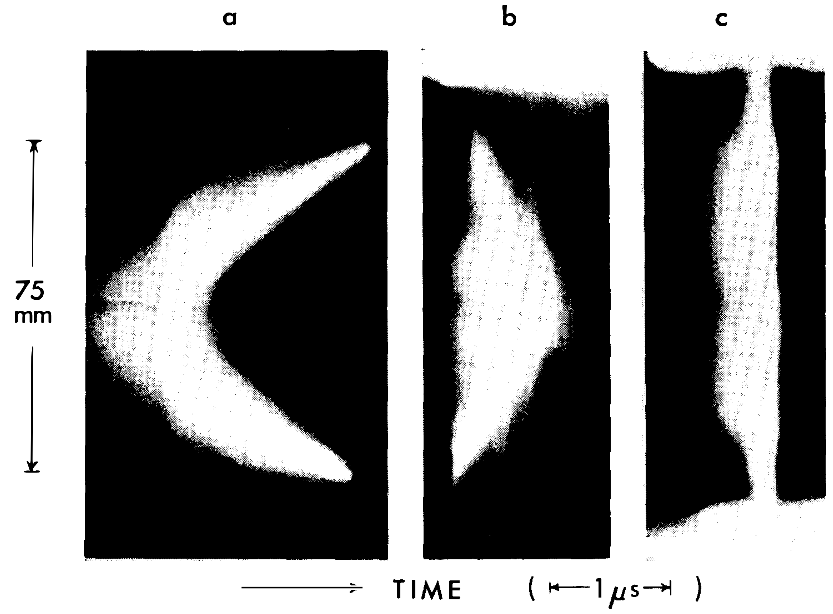


Fig. 7. *High speed streak photographs for determining the curvature of wave front.*
a. Case of composition B only: Wave front is convex.
b. Case of comp. B + baratol: Base angle of cone α = 38°. Wave front is concave.
c. Case of comp. B + baratol: Base angle of cone α = 36°. Wave front is slightly concave.

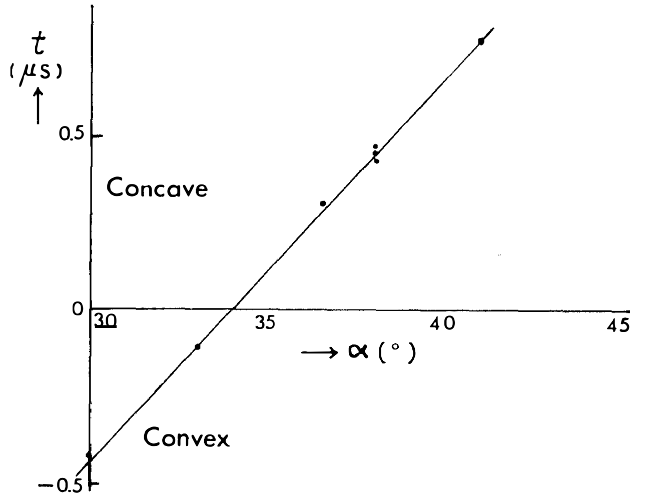


Fig. 8. *Relation between α and t. "t" corresponds to the time interval when the convex or concave wave front passes through the slit XX′ of 75 mm length.*

In Fig. 8 is shown the relation between α and the curvature of the detonation wave. From this graph it will be concluded that wave front becomes almost plane at $\alpha = 34°$.

The above plane wave experiments were performed at Hiratsuka Branch, Tokyo Industrial Laboratory in August and September 1978. In February 1981, other experiments of plane detonation waves using a new high resolution camera of Cordin 116 type were performed at the National Chemical Laboratory for Industry. Figure 9a is an example obtained by this camera using a cylindrical type shaped charge of $\alpha = 34°$. In Fig. 9a, are seen many fine structures in the wave front. Figure 9b is the

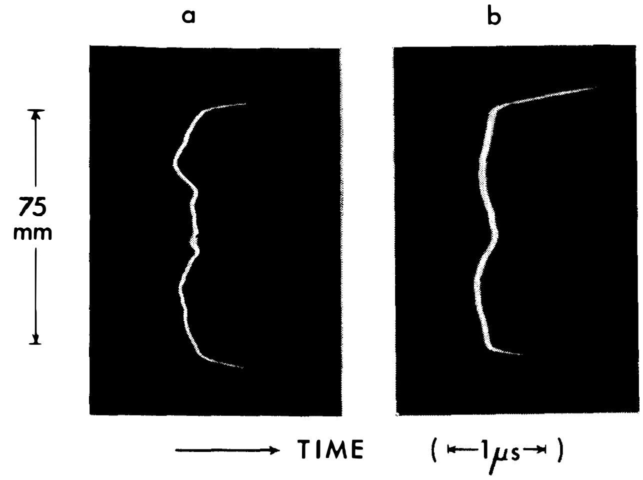


Fig. 9. New high speed streak photograph.
a. Case of comp. B + baratol: Base angle of cone $\alpha = 34°$. Cylindrical type shaped charge.
b. Case of comp. B + baratol: Base angle of cone $\alpha = 34°$. Conical type shaped charge.

one taken by using the conical type shaped charge $\alpha = 34°$ in which a few fine structures may still be seen.

These fine structures in the wave front may be due to the fluctuations of density of the baratol. We took an X-ray photograph of baratol, and it was found that some density fluctuations really do exist in baratol. It is planned now that at a time of the molding of the baratol, it has to be molded in a pressurized state and also a small amount at a time.

In Figs. 9a and 9b, also is seen the unnatural concave structure at the middle part of the wave front. This structure is perhaps due to the difficulty of ignition at the sharp top of the baratol cone. Hence in future it will be shaped with a curvature in this top part as shown in Fig. 4b (NAKAMURA, 1980).

The third set of experiments with above modifications will be performed in autumn of this year.

6. Ground Test of the Barium Jet

In October 1978, ground tests of the barium jet were carried out at Noshiro Rocket Testing Center, University of Tokyo, using apparatus as shown in Fig. 1. Two barium vaporizers were tested with weights of explosives shown in Table 3.

The barium vaporizers were set at an elevation angle of 45°, in a wooden box of 1 m × 1 m × 1 m surrounded by many sand bags. The barium jet was photographed by both a still camera and a 16 mm high speed movie camera with a Ba II λ 455.4 nm interference filter.

In the type A vaporizer, as the quantity of metallic barium was little, almost all the barium vapour was oxidized in the air and sufficient barium ions were not produced. On the other hand, in the type B vaporizer, sufficient ions were produced. The initial jet velocity was determined as 8.0–9.0 km/s from the movie film of 500 frames per second.

Table 3. Weights of explosives in the barium vaporizer.

Explosive	Density	Type A (g)	Type B (g)
Ba liner	3.5	65	85
Composition *B*	1.69	247	247
Baratol	2.62	132	130
Composition *B*	1.66	1067	1068
Tetryl	1.59	4.2	4.2
Total weight of explosives		1450.2	1449.2

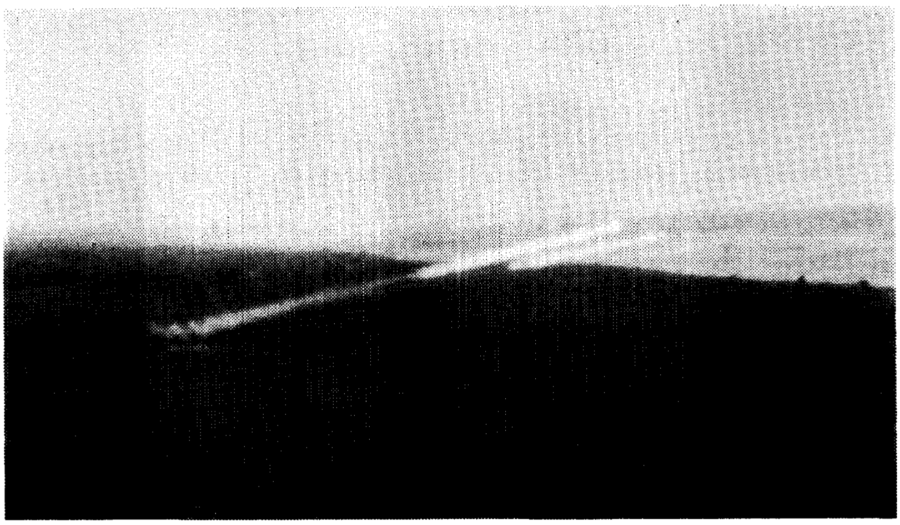


Fig. 10. Photograph of barium jet by the B type vaporizer with $\lambda=455.4$ nm interference filter.

In Fig. 10 is shown a barium jet which has some divergent structure and also is accompanied by several sub-jets.

In September 1981, another barium jet experiment will be performed at Noshiro Rocket Testing Center, using a 2000 frames per second movie. By this experiment, characteristics of the barium ion jet will be analyzed more minutely.

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