

Barium cloud experiments in the upper atmosphere

1 INTRODUCTION

Space techniques using sounding rockets, satellites and space probes made it possible to send instruments into space not only to measure the physical parameters of the surrounding atmosphere but also to carry out experiments in order to learn about matter and fields in space.

When injecting barium clouds into space, both measurement and experimentation occurs. The barium can be used to trace the movement of atmospheric plasma and thus to measure the electric fields. This is only valid if the artificial plasma cloud does not disturb the surrounding atmosphere too much. By injecting a stronger cloud, it is possible to study the active interaction with the surrounding magnetic field. In this way, one might study interesting general phenomena of a plasma. Experimentation occurs if the pressure of the artificial plasma is much stronger than the pressure of the magnetic field in space.

Experiments with artificial plasma clouds have provided new possibilities for studying the plasma under conditions that cannot be easily set up or may even be impossible to realise in a laboratory.

These experiments are comparable to methods of observing the velocity of a homogeneous fluid. A typical method involves spreading some coloured particles or metallic dust into the fluid. Normally, one uses only very small amounts in order not to disturb the behaviour of the fluid. More than 90 per cent of the cosmic objects are in a plasma state, but are also very dilute and therefore not visible except where concentrated in stars. The cosmic plasma consists mainly of

ionized hydrogen and helium molecules which have an extremely small cross section for light-scattering and so, like the even smaller electrons, do not scatter enough light to make their presence visible.

Therefore, it would be interesting to inject into a cosmic plasma a suitable material that has a cross section large enough for light-scattering to make the motion of cosmic plasma visible. For a plasma with very high electrical conductivity, this is of particular interest, since every motion perpendicular to the magnetic field lines of force can be described as the motion of the magnetic lines of force. H. Alfvén used the image of magnetic lines of force frozen in the plasma.

2 BIERMANN'S THEORY OF THE INTERACTION OF THE SOLAR WIND WITH THE IONIZED COMETARY TAILS

In 1950 Ludwig Biermann taught a course about comets at the Astronomical Observatory of the University of Göttingen. At that time, I was a PhD student attending these lectures. Biermann was puzzled about why tails with ionized molecules always pointed away from the Sun, while tails consisting of non-ionized molecules and dust were curved toward the Sun? The latter form could be explained by the solar light pressure and the motion of the comets around the Sun.

However, explanations of the light pressure as a force to blow away the ionized tails failed by orders of magnitude. Biermann developed the theory that the corpuscular radiation of the Sun was responsible for the high acceleration observed in the ionized tails. That the Sun sporadically emits a corpuscular radiation was known from the observed perturbation of

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the Earth's magnetic field. Not known at that time was that the Sun emits a corpuscular radiation continuously. This phenomenon was first detected by Russian spacecraft and by the US satellite Explorer X and explained theoretically by Eugene Parker (see Chapter 9).

Biermann published his theory of the interaction of solar corpuscular radiation with the ionized cometary tails in two papers (1951, 1952). In these, he demonstrated the close correlation of events in the tail of comet Whipple-Fedke with the registration of magnetic storms. In a later paper (dedicated to Heisenberg's 50th birthday) he showed that a similar correlation existed for the ionized tails of comet Halley in 1910.

3 PROPOSAL FOR AN ARTIFICIAL COMETARY TAIL

After the successful launches of the first artificial satellites and space probes in the late fifties, I discussed with Biermann at the beginning of 1960 whether German scientists should also get involved actively in space research by using sounding rockets, satellites or space probes and what role the Max Planck Institute for Physics and Astrophysics in Munich could play. In the astrophysical part of the Institute, only theoretical work was then being performed.

During this discussion, the idea of creating an artificial cometary tail in order to understand much better Biermann's theoretical concept of the interaction between the solar wind and the ionized cometary tail was launched.

Of course, using the same molecules observed in a natural cometary tail for such an artificial one would have been most attractive. But the calculation showed that several tons of carbon monoxide (CO) would be needed to create a visible artificial cometary tail (Biermann *et al.* 1961). Therefore other elements or molecules had to be found. In order to keep the cost down and the payload of the sounding rocket as light as possible, it was clear from the outset of the programme that the best energy source for ionizing and exciting the atoms in an artificial cloud was solar radiation. Furthermore, the cloud had to be observable from the surface of the Earth. These conditions led to a number of requirements for suitable elements or molecules: (1) The resonance lines of the ions had to be within the "optical window" of the Earth's atmosphere. (2) The time scales involved in exciting the expected lines of the ions, and photoionizing the neutral atoms had to be sufficiently short, (3) Since a chemical technique for the release was to be used, a low evaporation temperature was highly desirable.

The most promising elements to meet these requirements were some alkaline-earth metals, particularly barium, and probably some of the rare-earth elements, namely europium and ytterbium. We tried strontium and barium, and discovered that visible clouds could be created by using

barium. The required quantities were very low, of the order of some 10 to 100 grammes of Ba ions.

4 THE DEVELOPMENT OF BARIUM CLOUD EXPERIMENTS IN THE UPPER ATMOSPHERE

4.1 Development of the technique

In 1961 a small, newly formed group in Garching near Munich – the nucleus of the future MPI for Extraterrestrial Physics – began to develop the necessary technique for an artificial cloud experiment in the Earth's atmosphere with the help of sounding rockets. It was a very lucky coincidence that, during just this period, I met for the first time Jacques Blamont. This was at a meeting at the Royal Society where the first plan for the European Space Research Organisation (ESRO) was discussed. I mentioned to Blamont the idea of creating an artificial cometary tail. He had already used sounding rockets to release neutral sodium (Na) clouds in order to study the upper atmosphere, and invited me to fly a container of barium on one of these Centaure rockets.

Blamont (1983) wrote about the first experiments

The first operation started badly: Two barium burners (developed by the new group in Garching) were placed on Centaures launched in November 1962 from the French naval base at the Ile du Levant on the Riviera—both rockets failed (the first failures in the whole development history of the rocket...). Two other Centaures were used with complete success in Hammaguir in May 1963. Algeria had then become independent, and the Evian Agreement had authorised the use by the French Government for a further five years, until 1967, of the space complex built in Algeria by the army. The main part of the complex was in the town of Colomb-Béchar and the launch sites were located on a base built *ex nihilo* 130 km southwest of the town on a flat plateau covered with stones and sand. Our German friends had the responsibility for the burners, which were integrated into the nose cones in Hammaguir, and their photographic equipment was manned by a large team sited at the desert outpost, B-1 Nord', near Colomb-Béchar. I would like to recall the names of this enthusiastic group of fine young engineers, technicians and scientists with whom we spent many tense hours: Gerhard Haerendel, Herbert Bause, Hermann Föppl, Ludwig Heilmeyer, Hans Loidl, Friedhelm Melzner, Bernhard Myer and Hans Neuss. It was there (in the bar of the officers' cafeteria!) that I learnt from Prof. Reimar Lüst about the delicate technique of extracting oneself from a sinking submarine.

The results of the May 1963 ejection were decisive: we had to communicate to our German friends the results

given by our spectrographs: their spectacular clouds ... contained no barium atoms or barium ions ... but useless barium oxides and strong strontium lines (no strontium had been added to the mixture!!...). The principle of these ejections was changed and subsequent firings at the end of 1964 were a complete success. On 22 April 1966, a high-altitude ejection was performed using a Rubis rocket: the cloud which formed at an altitude of 2000 km was also observed from Germany. From then on the barium-cloud technique proved workable and since it has been used extensively in many scientific programmes.

To find an effective way to make barium evaporate, extensive laboratory experiments, as well as theoretical investigations, were carried out. The evaporation of Ba is achieved by a chemical reaction. We tried several different means with the most efficient one being a reaction between atomic Ba and copper oxide (CuO):



In this reaction part of the barium is burned and provides the heat necessary for the evaporation of the rest of the barium. An efficiency of about 10 to 20 per cent can finally be achieved: this means that from the volatile barium about 10 to 20 per cent Ba atoms could be observed. The Ba ions are generated by photoionization with a time scale of about 30 seconds. Most effective for this time scale is a metastable energy level of the atomic barium (Föppl *et al.* 1965, 1967).

4.2 The behavior of an artificial plasma cloud

The ionization can be observed not only spectroscopically but also directly with the unaided eye, because the barium cloud changes both colour and shape during the transition phase. The non-ionized cloud radiates in several green, yellow and red lines of the visible spectrum. After the initial, optically thick phase, the radiation in the green (spectrum) is the predominant colour in the neutral cloud. As the cloud becomes fainter because of photoionization, neutral strontium – always present as an impurity – remains. It ionizes much more slowly and radiates in the blue. The ionized barium atoms have spectral lines in the violet, blue and red regions of the spectrum, resulting in a purple colour. Hence the ionized cloud can be easily distinguished from the neutral one because the ionized cloud is purple and the non-ionized one is green and later blue.

A change of shape takes place as well: the neutral cloud is spherical and increases in diameter rather rapidly; the fast expansion is eventually slowed down by collisions of the barium atoms with other atoms and molecules in the Earth's atmosphere; thereafter the neutral cloud increases in size at a much slower rate by diffusion. Meanwhile, the ionized part of the barium cloud undergoes quite different

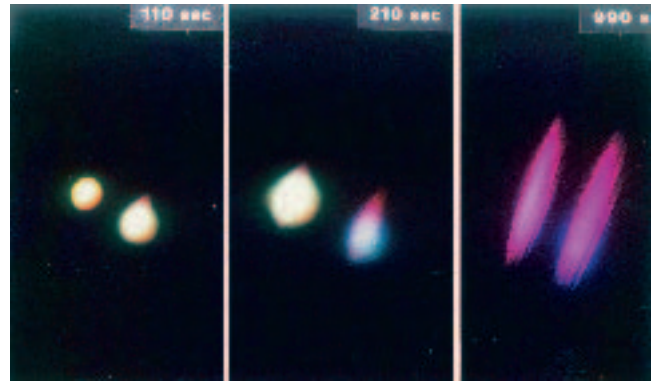


Figure 1 Two barium clouds at an altitude of 260 km. Photoionization by solar UV light is the cause of the changes in color and shape during the first two minutes. The barium clouds are shown at 110, 210 and 990 seconds after release. The neutral clouds are multicolored and spherical and initially show signs of high optical thickness. The ion clouds (purple) become elongated along the magnetic lines of force and show a field-aligned fine structure. (Source: Max-Planck-Institute of Extraterrestrial Physics.)

changes; the positively charged ions and the negatively charged electrons are trapped by the Earth's magnetic field, and they begin to spiral around the lines of magnetic force. For this reason the plasma cloud continues to grow only along the lines of force. The cloud thus becomes cigar-shaped and can be distinguished readily from the spherical non-ionized cloud (see Figure 1). Later, however, considerable distortion of this typical shape can be caused by an inhomogeneous electric field.

4.3 The different sounding-rocket launchings

During the period (from) 1961 to 1972, the Max Planck Institute for Extraterrestrial Physics participated in 66 sounding-rocket launchings with barium cloud experiments. We used French Centaure, Dragon and Rubis rockets; the English Skylark rocket; the Canadian Black Brant; and the US Javelin, Nike Tomahawk and Nike Apache rockets. Launchings took place as far afield as the Algerian Sahara, at Thumba (India), Sardinia (Italy), Kiruna (Sweden), Andoya (Norway), Fort Churchill (Canada) and Wallops Island (Virginia, USA).

Most of the clouds were released in the ionosphere at altitudes between 150 and 250 km. There were two principal reasons for choosing this range of altitude. The first was that these heights can be reached with small and relatively inexpensive rockets. Second, the motion of the plasma clouds yields information not only about the region of the ionosphere where the clouds are released but also, indirectly, about much higher regions in the magnetosphere.

The experiments were carried out during the twilight period in order to have conditions in which the clouds remained illuminated by the Sun, while the surface of the Earth was dark. The clouds were observed from two or more stations that had to be well separated so that the position of the cloud could be determined by triangulation. The stations were equipped with a variety of cameras, spectrographs and other instruments.

4.4 The drift of the plasma cloud

A magnetic field forces the ions and electrons in a helical path along the lines of magnetic force. It is possible for a particle to encounter two kinds of disturbing forces that will deflect it from this helical path. First, it can collide with another particle. However, in the Earth's atmosphere above 200 km, the frequency of such collisions is very low compared with the frequency of gyration. As a result, the predominant disturbing force is the electric field. In an electric field that is at right angles to the magnetic field, the charged particles of a plasma tend to drift in the direction perpendicular to both fields. An observer moving with the plasma drift velocity will see only the spiralling of the particles around the magnetic lines of force. In other words, in this moving frame of reference, the electric field no longer exists. As mentioned above, Alfvén describes such a case as one in which the lines of force are “frozen into the material”. His description is the same as saying that, during its motion, the plasma distributed along certain lines of force or within a flux-tube stays together, as far as motions at right angles to the magnetic field are concerned. Electric fields perpendicular to the magnetic fields and motions of magnetic field lines are consequently interchangeable notions in many situations.

The observed velocity of a plasma cloud can be expressed in terms of the strength of an electric field: a velocity of 100 m/s perpendicular to a magnetic field of 0.5 gauss (a typical strength for low altitudes) corresponds to an electric field strength of about 5 V/km.

Of course, some care is necessary in interpreting the motion of the plasma cloud in electric fields, since the wind of neutral atoms of the atmosphere might influence the motion of the cloud and, furthermore, the artificial plasma might disturb the surrounding medium by changing the electrical conductivity.

The first effect can be kept small by carrying out the measurements at altitudes where the collision frequency of the barium ions and the neutral particles is small compared with the gyration frequency of the barium ions around the lines of force. At altitudes above 180 to 200 km, this condition is fulfilled and the influence of the neutral wind can be neglected. The perturbation of the cloud in the surrounding medium can be kept small if only small amounts of barium are injected into the atmosphere. Fifteen grammes of barium ions are sufficient for a cloud to be observable for a

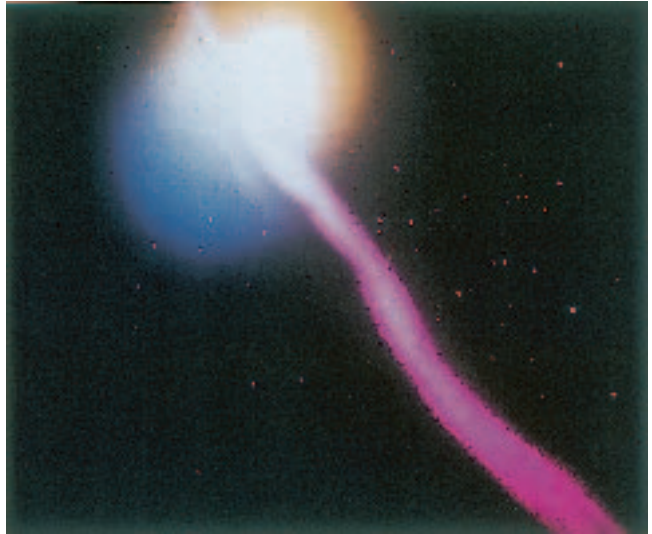


Figure 2 High and inhomogeneous electric fields lead to strong distortions of the ion cloud over hundreds of kilometers. (Source: Max-Planck-Institute of Extraterrestrial Physics.)

reasonable length of time without causing strong perturbations in the atmosphere (Figure 2).

5 MEASUREMENTS IN THE IONOSPHERE

In the following, the results of measurements in the different regions of the ionosphere are summarized (for more details see Haerendel *et al.* 1967, Föppl *et al.* 1968, Lüster 1969 and Haerendel 1987).

5.1 Low and mid-latitudes

To investigate the equatorial electrojet, barium clouds were released over Thumba (India) near the geomagnetic equator. The observed drift motions demonstrated an upward electric field of 1.8 to 5.4 V/km after sunset; the associated horizontal easterly field was weaker by a factor of about 3. These results on the horizontal fields are in agreement with measurements from radar echoes obtained from the incoherent backscatter facility in Jicamarca, although vertical fields could not be measured by this method.

While only a few experiments were done near the geomagnetic equator, quite a number of releases took place at mid-latitudes. In the sixties, all existing low-altitude data on electric fields in this regions were derived from barium cloud experiments.

In analyzing the experimental data one has to consider Ohm's law, which in the ionosphere has the following form:

$$\mathbf{j} = \vec{\sigma} \cdot \left(\mathbf{E} + \frac{1}{c} \mathbf{v}_n \times \mathbf{B} \right)$$



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