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JACQUES BLAMONT*

Alkali metal cloud experiments in the upper atmosphere

Prior to the space age, scientists knew practically nothing about the neutral atmosphere above 30 km. The early sounding rockets greatly advanced our understanding of the physics of this region in a relatively short time. During the period 1954–1970, ejections of sodium atoms by rockets created clouds that remained observable for tens of minutes. Sodium atoms in the atmosphere above 90 km have a relatively long lifetime. They are visible at twilight from optical resonance induced by sunlight at D doublet wavelengths. The first sodium trail experiments gave entirely new insights into the physics, dynamics and structure of the neutral atmosphere from 90 to 400 km. The turbopause was discovered, winds were measured, and quantitative data on eddy diffusion and the first vertical structure of the neutral temperature were obtained.

THE SODIUM TWILIGHT AIRGLOW

Following a suggestion by Otto Struve (Elvey 1950), the word 'airglow' was adopted as a convenient designation for the radiation emitted by the Earth's upper atmosphere, other than that due to aurorae. If it is desired to specify the nocturnal emission alone, 'nightglow' is used. 'Dayglow' and 'twilightglow' are defined analogously.

As discovered independently by Currie and Edwards (1936), Chernaev and Vuks (1937) and Bernard (1938a), the intensity of the nightglow yellow emission line is greatly enhanced at twilight. Bernard (1938b) and, simultaneously, Cabannes *et al*. (1938) identified the emission as the sodium D doublet at $\lambda = 5890$ and 5896 Å. The explanation which immediately suggests itself is that there is resonance scattering of solar radiation by free sodium atoms:

$$\text{Na}\ (^2\text{S}) + h\nu\ (\lambda = 5890,\ 5896\ \text{Å}) \rightarrow \text{Na}\ (^2\text{P}) \qquad (1)$$

$$\text{Na}\ (^2\text{P}) \rightarrow \text{Na}\ (^2\text{S}) + h\nu\ (\lambda = 5890,\ 5896\ \text{Å}) \qquad (2)$$

An alternative explanation, advocated by Vegard (1947), was that the excited atoms are released in the photodissociation of some compound of the element.

Bricard and Kastler (1944) studied the absorption of the atmospheric D doublet by a sodium vapour cell kept at various temperatures, and from their results were able to show that the linewidth of the emission is of the order of 10^{-2} Å, which can be interpreted as indicating a temperature of the emitting atoms in the atmosphere of about 240 ± 50 K. This favours the resonance scattering theory, since in general the fragments of a molecule that has suffered photodissociation initially have considerable kinetic energy. Any doubt remaining was removed in 1949 when Bricard *et al*. (1949) proved that the $\lambda = 5893$ Å twilight emission is polarized. The extent of the polarization for an observing direction making a right angle with the direction of the Sun was found to be about 9%, as predicted, with resonance scattering assumed. Photodissociation would of course yield no polarization.

The variation is as would be expected. In the case of the morning twilight, for example, the intensity first increases as the Sun approaches the horizon, since the solar radiation can reach more sodium without attenuation in the lower atmosphere; it next reaches a plateau, and finally decreases again (Blamont 1956), this decrease being due to absorption of the solar radiation by sodium on the dayward side (Chamberlain

* Centre National d'Etudes Spatiales, Paris, France

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1956). The behaviour during evening twilight is similar but reversed in sequence.

Sanford (1950) was able to show that the total number of free sodium atoms present at night does not exceed 10^{10} in a column with a 1-cm^2 cross-section that extends from the ground to the top of the atmosphere. Hunten and Shepherd (1954) investigated the distribution. They found that the concentration of free sodium atoms is greatest at 85 ± 3 km, with a maximum around $10^3 cm^{-3}$, that below this level it falls off quite rapidly, and that above, up to at least 100 km and probably to 115 km, it falls off with a scale height of 7.5 ± 2 km. Hunten (1956) reported that the seasonal change in this altitude is not more than 1 or 2 km.

The presence of free atoms of sodium near the mesopause level can be explained (Chapman 1939, Bates 1947, Hunten 1954) by an equilibrium between creation processes by reduction of oxides:

$$NaO_2 + O\,(^3P) \rightarrow NaO + O_2 \tag{3}$$

$$NaO\,(X^2\Pi) + O\,(^3P) \rightarrow Na + O_2 \tag{4}$$

and destruction processes which are of two kinds, oxidation and ionization. Oxidation occurs through:

$$Na\,(^2S) + O_2\,(X^3\Sigma_g) + M \rightarrow NaO_2 + M \tag{5}$$

which Bawn and Evans (1937) have shown to be extremely rapid, and through

$$Na\,(^2S) + O_3 \rightarrow NaO + O_2 \tag{6}$$

Photoionization

$$Na\,(^2S) + h\nu \rightarrow Na^+\,(^1S) + e^- \tag{7}$$

tends to reduce the number of neutral atoms. It is opposed by several recombination processes, of which

$$Na^+\,(^1S) + O^-\,(^2P) \rightarrow Na + O \tag{8}$$

is thought to be the most effective in the upper part of the region where sodium can be detected. The rate coefficient for reaction (7) is about $1 \times 10^{-5} s^{-1}$ (Bates and Seaton 1950), and that for reaction (8) is probably of the order of $10^{-8} cm^3 s^{-1}$ (Bates and Boyd 1956). Hence, the daytime equilibrium value of the ratio of the concentration of sodium ions to the concentration of sodium atoms is given by

$$\frac{n(Na^+)}{n(Na)} = \frac{10^3}{n(O^-)} \tag{9}$$

and may thus exceed unity. The two processes concerned are very slow, however, and consequently equilibrium can scarcely be reached.

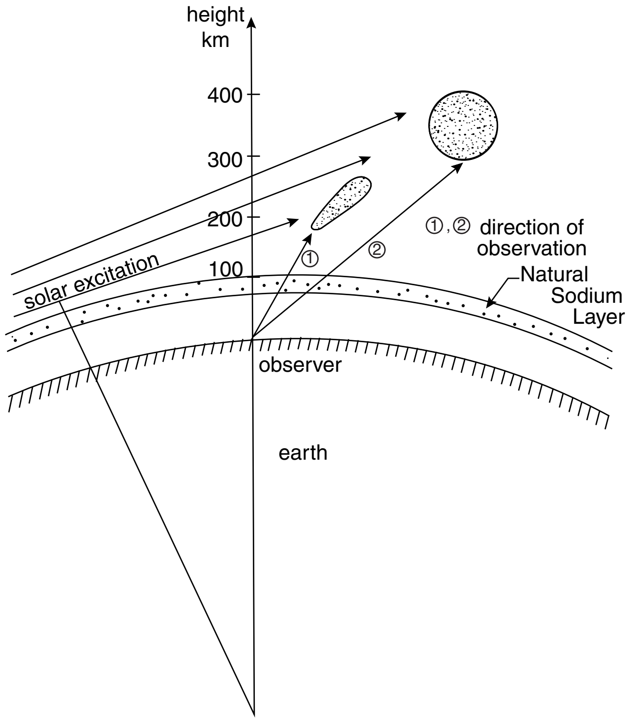

Figure 1 Geometry of a sodium cloud experiment; for example, at Wallops Island, on 13 September 1961, two clouds were formed one around 200 km, the other at 400 km. (From Blamont and Lory 1963b.)

The existence of free atoms of sodium at 85 km, and the proof by Bricard and Kastler that their emission is due to optical resonance excited by solar light, which renders them visible at twilight when the lower atmosphere is in shadow, led D.R. Bates in 1951 to suggest that the ejection of atomic sodium by a rocket in the high atmosphere could create a cloud visible at twilight (Figure 1). The experiment was performed successfully in 1954 by Edwards *et al.* (1956), and a number of Aerobee rockets were devoted to the creation of sodium clouds by the US Air Force Cambridge Research Center (Bedinger *et al.* 1957, 1958; Manring *et al.* 1959). The method was to ignite a mixture of $Al + Fe_2O_3$, called thermite, in which sodium pellets had been dispersed. The oxidation reaction of aluminium by iron oxide is extremely exothermic but stable; the mixture, placed in a container fixed in the rocket nose cone, melts, and sodium vapour is ejected in a steady stream. However, apart from the observation of strong wind shears which quickly deformed the clouds, no scientific results were obtained. The existence of intrinsic atmospheric turbulence was not recognized. Similar results were obtained by Groves (1960) with a Skylark rocket launched on 3 December 1958 at Woomera, Australia.

In 1957, France, having developed and built 15 Véronique rockets to be used for scientific purposes during the

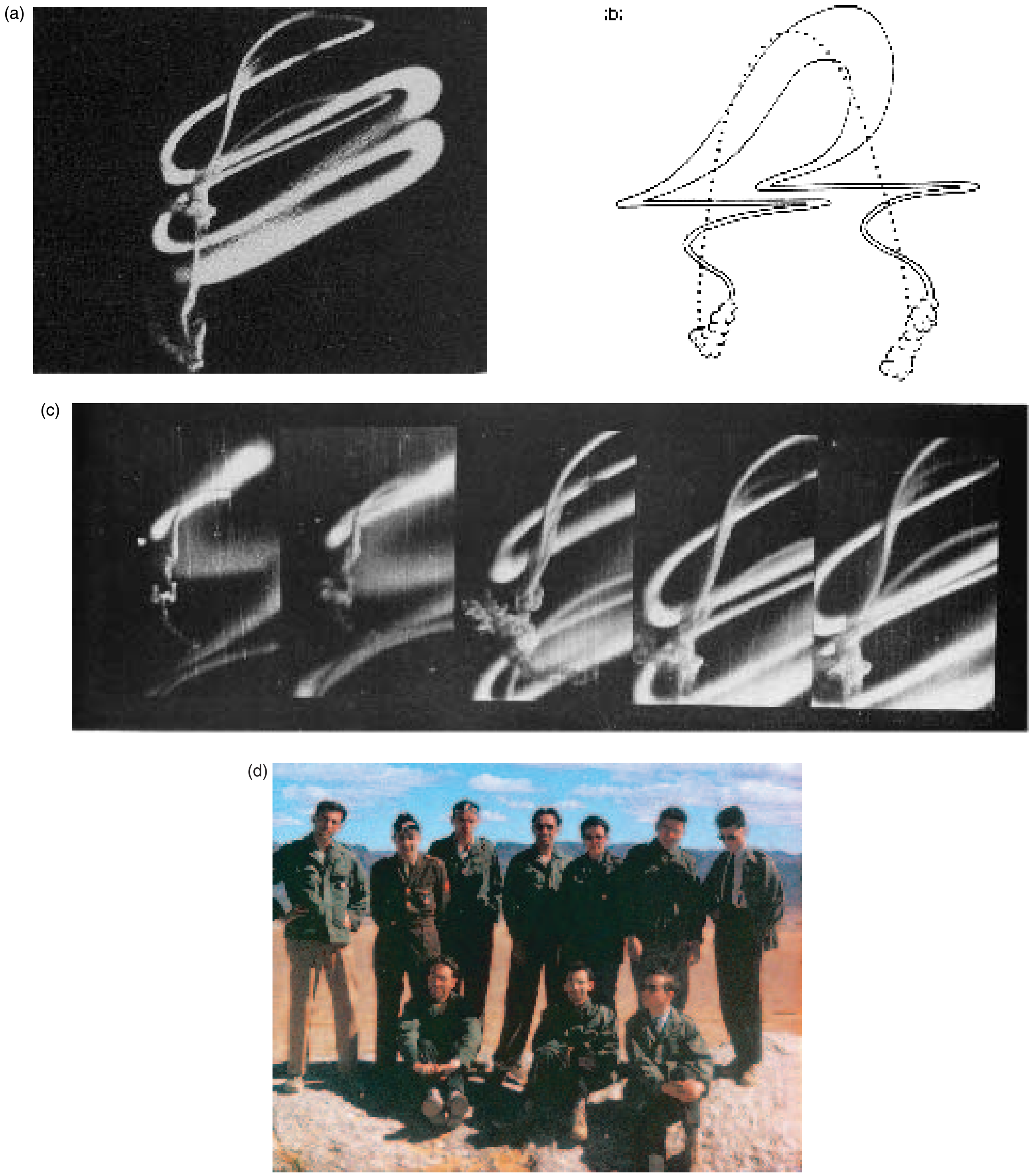

Figure 2 (a) The historic sodium cloud of 10 March 1959. From this picture, obtained at Colomb Bechar, Algeria, the existence of the turbopause was recognized for the first time. In order to understand this image, start at the widest part of the cloud (near the bottom of the picture), which corresponds to the maximum altitude reached by the rocket (130 km). From there, the trail divides into two identical, parallel smooth parts corresponding to the ascent and descent of the rocket. These parts are distorted by the wind. At the lowest altitude (102 km and below) there appears, both at ascent and descent, the sharp separation between the laminar atmosphere (smooth trail) and the turbulent atmosphere (globulous trail). (From Blamont (1966).) (b) Schematic drawing of sodium trail. The dotted line is the path of the rocket. (From Blamont and de Jager 1961.) (c) Evolution in time of the sodium trail obtained on 10 March 1959 at Hammaguir. From left to right: first picture is taken at L (time of launch) + 5 min; second at L + 8 min; third at L + 11 min; fourth at L + 12 min; fifth at L + 15 min. The turbopause already seen in the left-hand picture can be followed through the cloud's development. (From Blamont and Baguette 1961b.) (d) The March 1959 sodium cloud experiment team pictured at Colomb Béchar, Algeria. From left to right: (seated) M. Maguery, F. Roddier and J.Y. Gal; (standing) J. Blamont, C. Cohen-Tannoudji, J.P. Schneider, G. Courtès, M.L. Lory, P. Lena and P. Delache.

International Geophysical Year (IGY), had practically no budget for payloads, no science group, no experimented engineers and no equipment for telemetry, command or tracking. The author proposed to the French IGY Programme Office that a few of the available rockets should be devoted to sodium ejections. The on-board hardware would be extremely simple and cheap, and the rocket was ideally adapted to sodium ejections, since it was designed to carry a 100 kg payload to an altitude of 200 km. The launches would take place on the French Army proving ground of Hammaguir (31°N, 5°W), near Colomb Bechar (in what was then French Algeria) with the help of military resources and personnel.

The scientific objectives would be to study the atmospheric horizontal winds as a function of altitude, and to measure the temperature of the neutral atmosphere as a function of altitude. The observations, all performed on the ground, would be: for dynamical studies, triangulation of the cloud by cameras placed at four sites, each separated from 10 to about 100 km, forming roughly an equilateral triangle; and for temperature measurements, the absorption of the cloud's D line emission by three cells containing sodium vapour at different optical thicknesses.

The first launches took place on 10 and 12 March 1959 from Hammaguir, at dusk and dawn, respectively. On both occasions a sodium cloud was created above 85 km, the first one up to 130 km and the second up to 180 km. They remained visible for 20 minutes (Figure 2). Two major results were obtained from these flights (Blamont 1959, 1960):

1. A spectacular feature of the clouds was an abrupt change in their structure around 102 km: below this altitude, the clouds showed a small-scale motion field consisting of elements with an average diameter of about 0.5 km; above this altitude, the trails displayed a smooth character, not showing the slightest trace of small-scale motions. The region of transition was not thicker than 1 km. This was, as we will see, a major discovery.
2. The temperature of the sodium atoms in the clouds measured with the absorption sodium cell technique were found to be very high (3000 K). This was obviously spurious and due to the multiple scattering of the resonance line inside the cloud: for the first experiments, 10 kg of sodium had been included in the thermite container! It was therefore necessary to reduce greatly the amount of sodium ejected, and also to measure the optical thickness of the cloud in order to make certain that there would be regions in the cloud where the optical thickness would be small enough to allow linewidth measurements.

The potential for scientific purposes of sodium trails generated by rockets had therefore been demonstrated: studies of the dynamical structure of the atmosphere on the one hand, and measurements of the temperature of the neutral atmosphere on the other, could be undertaken. The decision was made by the French IGY Programme Office not only to devote eight Véronique rockets to the ejection of various chemicals, but also a number of the solid-fuel rockets under development, called Centaure (reaching 200 km) and subsequently Dragon (reaching 400 km). The programme was extended to sodium and potassium launches at various latitudes (central Sahara, Argentina, Canada, Sweden, USSR, India), to clouds created by explosives, which were found to exhibit the resonance fluorescence of the oxide AlO, and to barium clouds, in cooperation with R. Lüst's laboratory (Chapter 6). A Panel for Simultaneous Rocket Sounding Launches was created by COSPAR to support the effort. These experiments were carried out during the 1960s.

STUDY OF THE DYNAMICS OF THE ATMOSPHERE BETWEEN 90 AND 200 km

A sodium cloud created by the continuous ejection of vapour by a rocket as it ascends from 80 km to its maximum altitude (around 200 km) and descends is subject to three types of motions (Blamont 1959, Blamont and Barat 1967a):

1. Diffusion of sodium in the medium in a horizontal plane. The diffusion velocity varies inversely with the atmospheric density, and therefore increases with altitude.
2. Horizontal winds with a velocity up to $200\,\mathrm{m\,s^{-1}}$, a randomly distributed direction and horizontal scale above 100 km.
3. Turbulence in the lower part of the cloud (below 102–105 km), which gives it the appearance of a cumulus cloud, and stops abruptly above this altitude.

Diffusion of sodium

The sodium emitted at one point diffuses in two dimensions in a horizontal plane. A determination of the growth rate of the horizontal dimensions of the cloud (i.e. of the diffusion velocity of sodium in the medium) shows the following.

1. On the smooth part of the cloud, above 102 km, measurements show that the law of molecular diffusion is obeyed perfectly. The diffusion of sodium follows the atmospheric diffusion because the molecular (or atomic) masses are nearly identical. Therefore the distribution of sodium atoms at any given time as a function of the distance (r) to the centre of the cloud should be a Gaussian function $\exp(-r^2/L_0^2)$, where L_0 is given by:

$$L_0^2 = 4\,Dt \tag{10}$$

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