ELEMENTARY PROCESS AND METEOR TRAIN SPECTRA

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Interaction of the atmosphere and meteors is a unique phenomenon out of a great number of elementary processes taking place in gases. Ionisation, recombination, attachment, ion-exchange reaction, diffusion, and other processes connected with the ionized component manifest themselves as ionized meteor trails that can be observed by radars. Excited atoms and molecules of meteor and atmospheric origin, in their turn, determine meteor radiation and make them visible.

The theory of meteor radiation and ionization founded by ÖPIK E.J. (1933, 1955, 1958) and HERLOFSON N. (1948) has made considerable headway. It has been generally established that meteor radiation includes several characteristic parts: coma, wake and train (ASTAPOVICH, 1958; CEPLECHA, 1964, 1968, 1973; MILLMAN 1935, 1962, 1963, 1872; HALLIDAY, 1958, 1960, 1963). The Coma is a gaseous sheath encircling the meteor body and consisting of a mixture of air and vaporized meteor atoms and molecules. The lion's share of meteor radiation comes from the coma. The wake content is practically the same and stretches behind the meteor body for up to one kilometer. In some meteors, luminous trains are sometimes visible with the naked eye but they can always be easily detected by radar.

In the formation of the wake and train, meteor fragmentation plays a certain part along with elementary processes. The process of meteor fragmentation into large pieces can be observed both visually and optically (BRONSHTEN, 1981; ASTAPOVICH 1958; KRAMER and SHESTAKA, 1983). Upon separation from the parent body, fragments continue to evaporate becoming an additional source of the elementary processes causing meteor phenomena. Therefore, even though complicating somewhat the pattern of wake and train formation, fragmentation of itself cannot serve as the clue to the problem of meteor phenomena.

The meteor (coma) radiation spectrum contains mainly lines of atoms and ions of chemical elements of meteor origin (FeI, MgI, NaI, CaI, NiI, CaII, FeII, SiII, etc. -- about 20 all told) and depends largely on velocity, composition and structure of a meteor body. Ionic spectra are often observed in fast meteor radiation with the share of atmospheric bands and lines in it being very small (no more than several percent). The wake spectrum is characterized by a far lower excitation potential than the meteor itself. While a great volume of observational data concerning meteor spectra is constantly reviewed in the literature (BRONSHTEN, 1981; ASTAPOVICH, 1958; SMIRNOV, 1977; CEPLECHA, 1968; MILLMAN 1963; HALLIDAY 1960, 1963), the problem of meteor radiation still remains a most complicated and scantily explored one. The present paper deals with findings of research into the problem and tries to formulate the most pressing tasks for further investigation in this very important field of meteor physics.

Elementary and diffusion processes of meteor train decay have been studied chiefly using results of observations of radio-echo duration over a wide range (from fractions of a second to several minutes) and characteristic changes in distribution trends. According to this, the main part in the meteor train decay is played by ambipolar diffusion, dissociative recombination,

$$X_2^+ + e - X + X, \quad (1)$$

recombination with electron stabilization,

$$X^+ + e + e \rightarrow X + e, \quad (2)$$

electron attachment with neutral particles of atmosphere, and meteor

$$X + e \rightarrow X^- + h\nu \quad (3)$$

and atmospheric turbulent diffusion, (BRONSHTEN, 1981; KASHCHEEV et. al 1967; MANNING, 1958; FIALKO, 1961; BIBARSOV, 1979; TOKHTASJEV, 1976; POOLE and KAISER, 1967; NICHOLSON and POOLE, 1974; BAGGALEY and CUMMACK, 1974). The effectiveness of a particular process in the meteor decay is determined by its time-constant and probability as well as by the initial electron concentration in the trail. Specifically, the turbulent diffusion time constant is far greater than that of other processes, therefore it is typical only in long-lived meteor train decay. Ambipolar diffusion, on the contrary, plays the leading role at the beginning of a train. Various deionization processes accompanying meteor train decay cause intermediate breaks in the radio echo duration distribution.

Radar methods of observation, having a number of technical advantages, limit somehow the possibility of research into elementary processes of meteor wakes and trains for they are known to yield data bearing only on the electron component, usually giving no information about cross section and lengthwise distribution. The same can be said about ion and excited particle composition. Naturally, possessing so scanty experimental data, one cannot hope to definitely solve all the numerous problems of meteor physics.

The ion composition and role of various chemical reactions in the meteor trail decay was studied by BAGGALEY and CUMMACK (1974, 1976, 1979) using numerical simulation. Four kinds of metallic ions (Fe^+ 48.4%, Si^+ 33.9%, Mg^+ 10.4%, Na^+ 7,3%) were considered by them as initial data. Attachment and detachment, ion exchange reactions, radiation, dissociative recombination, and other processes were taken into account. Calculations were made for 70, 80, 90 and 100 km both for day and night. According to their results, the deionization process of meteor train decay is confined only to heights below 80 km. Along with metallic ions, their oxides and dioxides are present at all heights. The change in the ion composition from day to night is due largely to a diurnal change in O_2 atoms concentration. At 100 km, there was no significant difference between the day and night ion composition.

Radiation spectra contain plentiful information on elementary processes of meteor phenomena. For instance, CEPLECHA (1971) managed to detect a record number of nearly 1,000 spectral lines during a -12.5^m bolide flare.

Initial meteor train spectra were obtained in 1966 in Ashkhabad by NASYROV and NASYROVA (1966) using an optical system equipped with an octahedral prism. A meteor that produced this stable long-lived train belonged to the Leonid shower. But the system's insufficient linear dispersion made detection and identification of spectral lines difficult. Still, the analysis of radiation energy spectral distribution showed that meteor train luminescence was due mainly to the long-wave range of the spectrum (λ > 5000A). In addition, the train showed the signs of NaI (λ 5895A), MgI(λ 5182A) and OI (λ 5577A) lines.

Experimentally the task of registering meteor train spectra presents a rather complicated task needing a mobile optical system of great sensitivity and resolution and operating in the regime of very quick (fractions of a second) processes. It is only thanks to the progress of TV and electronic technology that this extremely difficult technical task has become a reality. First experiments using TV for meteor observations were held in Canada in the sixties (HEMINGWAY, et. al, 1971; MILLMAN et al, 1971; MILLMAN and CLIFTON, 1975; SPALDING et al, 1961), and in the seventies they were started in the Soviet Union in Ashkhabad.

The theoretical sensitivity of modern TV equipment reaches stars of 14^m. It goes without saying that due to a weakening of optical signals within the dispersing elements, the limit is considerably lower. Nevertheless, in contrast to photographic methods, TV and optical electronics enable the use of shorter exposures so that it is possible to obtain separate spectra of coma, wake and trains as well as to study the temporal dependence of certain spectral line intensities. By way of example, Fig. 1 shows a spectrogram of a meteor of about -1.5^m obtained in Ashkhabad using an optical electronic image-tube having an exposure of 1.0s. The first frame gives the initial meteor spectrum, the second shows a spectrum of the meteor train with the lines MgI (λ5183A), OI (λ5577A, NaI(λ5890A), Si II (λ6358A), OI (λ7772A), etc.

As was to be expected, the spectra of the wake and trains are much weaker than those of the coma and are characterized by lower excitation potentials.

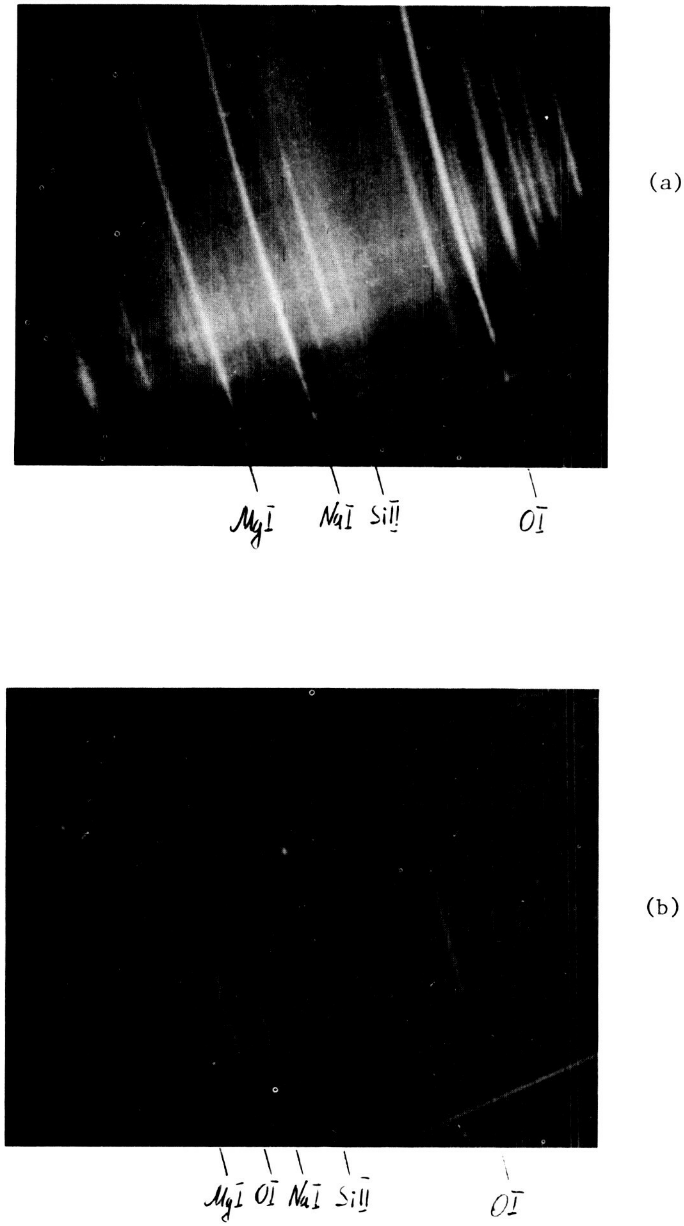

Fig. 1. Spectogram of a meteor of ~ -1.5 m obtained in Ashkhabad. (a) is the initial meteor spectrum, (b) a spectrum of the meteor train.

Table

Multiplets identified in the wake and train spectra.

	Numbers of Multiplets
OI	1, 4, 3 (forbidden line)
NaI	1
MgI	1, 2, 3, 9
SiI	3
CaI	1, 2, 3, 4, 18, 19, 21
FeI	1, 2, 3, 4, 5, 16, 20, 21, 23, 41, 42, 43, 268
FeII	27, 28, 37, 38, 42, 48, 49
CaII	1, 2
SIII	2, 4
N_2	1 positive lines system

The spectral composition of radiation consists mainly of multiplets of atoms and their ions. As to molecular lines, only the first positive system of N_2 has been positively identified as yet. An important peculiarity of meteor train radiation is the emission of the forbidden line OI (λ 5577A) which is usually very bright and is characterized by a relatively long duration. The rate of spectral lines extinction is different. Multiplets 1, 2, 3, 13. 14 of FeI and the MgI (5183A) lines last the longest.

Some elementary processes typical of meteor train radiation have been considered.

a. Sodium radiation. While spectra of the meteor coma and wake reveal eleven multiplets of Na radiation, meteor trains, as it was noted above, appear to possess only the doublet of λ5890A and λ5893A as yet. The yellow doublet is known to be the strongest of the sodium lines and is also observed in spectra of night emission and twilight luminescence of the upper atmosphere. Besides, intensive resonance scattering by sodium according to the scheme:

$$\text{Na}\ (^2S) + h\nu(\lambda\ 5893\text{Å}) \rightarrow \text{Na}(^2P),$$

$$Na\ (^2P) \dashrightarrow Na(^2S) + h\nu(\lambda\ 5893\mathring{A})$$

has been widely observed in recent years by lidar probes of the upper atmosphere (KHROSTIKOV, 1963; BAGGALEY and CUMMACK, 1979).

The mechanism of NaD doublet excitation was studied by S. CHAPMAN, (1955) W. BAGGALEY (1976) and others. The excited atoms of Na responsible for the yellow doublet radiation turned out to be a product of oxidation reactions, namely:

$$Na + O_3 \rightarrow NaO + O_2 \quad (4)$$

$$NaO + O \rightarrow Na(^2P) + O_2 \quad (5)$$

$$Na(^2P) \rightarrow Na(^2S) + h\nu\ \text{(doublet)} \quad (6)$$

An approximate numerical analysis of this catalytic cycle of Na considering diffusion is provided in BAGGELEY (1976) where it is shown that a meteor with brightness over -10^m can produce a luminescent trail of over one hour duration.

b. Meteor Atoms and Their Ionic Radiation. Elementary chemical reactions producing metallic atoms and ions have been the subject of intensive study during the last few years. Just as with Na, the chemistry of these particles to a great extent depends on oxidation reaction with O_3, i.e.,

$$M^+ + O_3 \rightarrow MO^+ + O_2 \quad (7)$$

At relatively low heights the process of oxidation may have the following stages:

$$M + X + Y \rightarrow MX^+ + Y \quad (8)$$

$$MX + O \rightarrow MO^+ + X \quad (9)$$

Here X, Y are atmospheric molecules of O_2, N_2, with excited metallic atoms M^* appearing as a product of the dissociative reaction:

$$MO^+ + e \rightarrow M^* + O \quad (10)$$

According to J. POOLE's estimates (1978, 1979b) radiation of certain multiplets of FeI, MgI, CaI in the meteor tail and trails can be explained by the chemical reactions (7-10).

The process of resonance charge-exchange of atom and molecular systems, that is

$$X^+ + M \rightarrow X + (M^+)^* \quad (11)$$

occupies an important place in the chemistry of meteor trails. X^+ ions of atmosphere molecules are a product of ionization, resulting from their collision:

$$X + Y \rightarrow X^+ + Y + e \tag{12}$$

J. POOLE (1979a) explains the appearance of the multiplet of H and K CaII lines, first positive line N_2 and separate multiplets of FeII by the processes (11, 12). The resonance H and K CaII lines are known among the brightest features of photographic meteor spectra. Most often these lines are observed in fast meteors. But when large meteor bodies enter the atmosphere with a flare, they show sharply increased lines of H and K CaII. J. RAJCHL (1972) when studying radiation of large meteor bodies came to the conclusion that, unlike the turbulent flow regime, flare-caused H and K CaII multiplets do not appear due to the resonant charge exchange, but as a result of radiative recombination of double-ionized CaIII. This process was subjected to a quantitative analysis by KRAMER and SHESTAKA (1983) of the H and K CaII lines in the wake of a bolide observed on August 13, 1974 by the instant exposure method.

c. <u>The Study of Atomic Oxygen Forbidden Green Line</u>. This line appears at rather high altitudes at the starting point of luminescence of meteor bodies having a great velocity. It reaches its maximum about 0.1 s into a meteoroid flight. These peculiarities of the 5577Å line radiation lead one to believe that excitation of OI responsible for this radiation is a result of ionization and recombination processes in the meteor wake and trains (BAGGALEY, 1976, 1977, 1978; OVEZGELDYEV et al., 1976; BAKHARAV, et al., 1970) according to which the excited O (^{1}S) atoms, causing the green line emission, result mainly from two-phase chemical reactions:

$$O^+ + O_2 \rightarrow O_2^+ + O\ (^3P) \tag{13}$$

$$O_2^+ + e \rightarrow O(^1S) + O(^1D) \tag{14}$$

Considering the possibility of $O(^1S)$ transformation from its ^1D condition into a ^3P condition and deactivation by collisions,

$$O(^1S) \rightarrow O(^1P) + h\nu(2972\text{Å}) \tag{15}$$

$$O(^1S) + M \rightarrow O(^1D,\ ^3P) + M^* \tag{16}$$

BAKHAREV et al (1970) derived an expression enabling them to determine the time dependence of the 5577A line relative intensity. That is,

$$\frac{I}{I_o} = 2\ \exp\ (-At) - \exp(-kt) \tag{17}$$

The coefficient A depends on altitude, while coefficient K depends both on altitude and meteor body parameters at the level of E-region where A of the green line is about 2.7 s^{-1}.

The formula (17) makes it possible to account for the basic morphological perculiarities of the green line in meteor train spectra. It is in keeping with this formula that the 5577A emission can be observed only at the start of meteor entry into the ionospheric E-region. The density at lower altitudes makes collision deactivation likely. If the coefficient A equals 2.7s^{-1} at 100 km, it is about 100 s^{-1} at 80 km. The same effect explains the fact that this line is usually observed only in trains of fast meteors, the latter being known to start luminescence at higher altitudes than slower ones.

Thus, in this short review its possible to see that considerable progress has been achieved in this area of meteor physics. The conventional observational approach to this study continues to make progress with hardware being extended and improved. In this context, special emphasis should be given to the TV and optical electronic methods from which unique data on faint meteors spectra and, what is more, spectra of their trains have been obtained.

Mechanisms of excitation of individual spectral line radiation have been studied experimentally and theoretically and it has been demonstrated that such processes as oxidation, resonant charge exchange, dissociative recombination and others play an important part in the chemistry of excited particles. The foundation has been laid toward simulating the elementary processes of meteor physics. Having a number of advantages and possibilities, this method is sure to find a wide use in the future. Speaking of future research, it must also be noted that the problem of further improving spectral observations and the methods of quantitative analysis is very important with a view to carrying out comprehensive radar, optical, optical electronics and TV measurements. Together these can help solve many problems facing meteor physics.

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