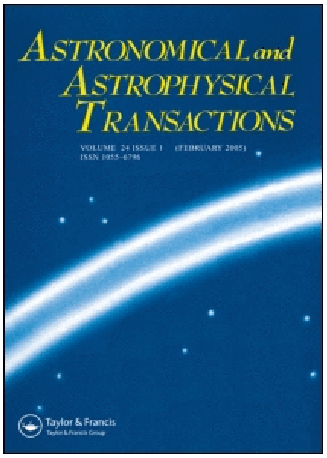

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SOME REAL PROBLEMS IN THE PHYSICS OF COMETS[1]

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The current state of problems in the physics of comets and astrophysics such as the problem of the anomalous distribution of emission of sodium-type metal atoms in the comae of comets, the problem of the origin of ions of refractory elements like Fe II in the comae of Halley 1986III-type comets, and the problem of X-ray activity of comets is considered. New possibilities for diagnostics of comets and interplanetary dust connected with spectral observations of comets with high spatial resolution and X-ray astronomy are indicated.

KEY WORDS Comets, metal atoms, metal ions, X-rays, spectral observations

1 INTRODUCTION

The anomalous distribution of radiation of sodium atoms in the head of the bright comet Mrkos, namely the intensity of the Na D-lines maximally displaced from the comet nucleus towards the Sun to the cometocentric distance $r_{\max}(\mathrm{Na}) \approx 2000$ km, was detected with the 200-inch Palomar telescope in August 1957. The origin of the phenomenon is a puzzle in the physics of comets (cf. Greenstein and Arpigny, 1962; Wurm, 1963; Dobrovolsky, 1966; Ibadov. 1983a, b; 1996c).

In situ measurements by the VEGA and GIOTTO spacecraft during their encounters with comet Halley in March 1986 near heliocentric distance $R = 1$ AU have led unexpectedly to the discovery of Fe II type ions (Balsiger *et al.*, 1986; Balsiger, 1990; Gringauz *et al.*, 1986; Gringauz and Verigin, 1990; Krankowsky *et al.*, 1986). Work on the problem of the origin of ions of refractory elements in cometary comae at large distances from the Sun is still in progress (Geiss *et al.*, 1986; Ip and Axford, 1986; Ibadov, 1992; 1996a, b).

The possibility of the generation of high-energy photons in comets and the detection of cometary X-rays has been considered during the last few decades (Ibadov,

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1980; 1983c; 1985; 1990; 1995). The discovery of X-ray emission from comets was made by ROSAT in March 1996 during observations of comet Hyakutake 1996 B2 and mechanisms for strong X-ray activity of comets should be found (Bingham *et al.*, 1996; Brandt *et al.*, 1996; Cravens, 1996; Dennerl *et al.*, 1996; 1997; Krasnopolsky, 1997: Lisse *et al.*, 1996a, b; Ip and Chow, 1997; Wickramasinghe and Hoyle, 1996).

In the present paper the current state of investigations of the problems mentioned above is presented and some prospects on observations of comets are indicated.

2 ANOMALOUS DISTRIBUTION OF EMISSION OF SODIUM-TYPE METAL ATOMS IN COMETARY HEADS

Present approaches to the interpretation of the anomalous distribution of sodium atom emission in the head of comet Mrkos 1957d/1957V may be divided into certain classes as follows. The optical approach accepts the optical thickness of the cometary coma in the sodium lines to be very large, $\tau_\lambda(\mathrm{Na}) \geq 1$, for a near-nuclear region, i.e. for cometocentric distances $r \leq 2000$ km (Greenstein and Arpigny, 1962). However, this assumption is made without a corresponding physical basis, namely without an analysis of the possibility of intense release of sodium atoms in the near-nuclear region.

The kinematical approach starts from the optically thin coma and attempts to explain the anomalous maximum of brightness as a classical Besset–Bredikhin envelope of the Na atoms which were ejected from the nucleus towards the Sun and then, under the action of light pressure, move in the opposite direction (Wurm, 1963). However, it is known (Dobrovolsky, 1966) that this explanation is contradictory to Mokhnach's law, since in this case the maximum of the brightness has to be near the nucleus at an arbitrary distribution of initial velocities of ejection.

The dust envelope approach proceeds from the viewpoint that sources of Na atoms are, together with the nucleus, also dust particles in the head of the comet (see also Delsemme, 1982; Donn and Rahe, 1982; Levin, 1964; Shul'man, 1972; Wyckoff, 1982). The anomaly in the distribution of the sodium intensity may then be explained if the presence of a non-moving dust envelope – a dusty halo – in the cometary atmosphere is supposed. However, both the absence of a wellexpressed correlation between the intensity of the Na spectrum and the continuous spectrum of the inner coma, and the observed gradual fall of the continuum intensity in the first 3000–8000 km from the nucleus towards the Sun, do not allow us to confirm this model with full confidence (Dobrovolsky, 1966).

The non-isothermal cometary dust approach is based on the effect of the depression of the cometary dust temperature in the inner comae of bright comets due to cooling of the dust by the dense cryogenic gas outflowing from the nucleus (Ibadov 1983a, b). Indeed, the rate of evaporation of dust particles of cometary atmospheres – potential sources of metal atoms in cometary comae – exponentially depends on their temperature, so that the spatial inhomogeneity of the dusty coma temperature, $T_d = T_d(r)$, may cause the corresponding inhomogeneous distribution of metal atom densities and its emission in the cometary heads.

At the same time the conglomerate model of cometary nuclei as a mixture of ices and solid particles, now generally accepted, allows highly intensive ejection of gases (H_2O, CO_2, etc.) from nuclei (see e.g. Boyarchuk *et al.*, 1986; Delsemme, 1982; Reinhard, 1986; Sagdeev *et al.*, 1986; Shulman, 1987: Whipple, 1989), especially at small heliocentric distances, $R \leq 1$ AU, where in the cometary spectra lines of metal atoms such as Na I are usually observed (see e.g. Levin, 1964; Oppenheimer, 1980).

Along with this, according to calculations (Bisikalo and Strelnitskij, 1985; Crovisier, 1984; Marcony and Mendis, 1983; Marov and Shematovich. 1987; Shimizu, 1976), the temperature of the cometary gas, $T_g(r)$, has a deep minimum ($T_{g\,\min} =$ 10–50 K at $r = 10^2$–10^3 km) because of the strong self-cooling of the gas due to its expansion and intense IR-radiation of cometary molecules. Within the whole inner coma ($r \leq 10^3$–10^4 km) $T_g(r)$ does not exceed the temperature of the sublimating surface of the nucleus which is itself always low: $T_n \leq 200$ K (Combes *et al.*, 1986; Lammerzahl *et al.*, 1987).

Analysis of the non-stationary equation for the temperature of cometary dust grains ejected from the nucleus into the coma shows that in the comae of bright comets there are two temperature zones: depression and vacuum zones. In the vacuum zone the temperature of dust particles is determined by the usual formula, $T_d = T_{vac} = T_0/R^{1/2}$, which is also used for solid particles in interplanetary space (cf. Dobrovolsky, 1966; Kristoferson and Fredga, 1976). In the depression zone located close to the nucleus the temperature of dust particles is determined mainly by the temperature of the cometary gas $T_g(r)$, i.e. T_d is lower than T_{vac}, (Ibadov, 1983a).

The extension of the temperature zones is determined from comparison of two characteristic distances: the length of dust temperature relaxation for cooling due to self-radiation, l_r, and the length of dust temperature relaxation for cooling by the cometary gas, l_g. From $l_g \leq l_r$ it follows that the criterion for the number density of the gas molecules providing the apparition of the depression zone is: $n_g \geq n_{cr} \approx 10^{13}/R^{3/2}$ cm^{-3} (Ibadov, 1983b).

The transition from the depression zone to the vacuum zone occurs at a cometocentric distance $r_{\max}$, where the temperature of the cometary dust becomes equal to the maximal temperature, corresponding to ther isothermal vacuum regime. Since the vapour pressure of the condensed substances depends on the temperature exponentially and the density of cometary dust varies as r^{-2}, the maximal density of metal atoms from cometary dust and correspondingly the maximal brightness of emission of metal atoms will be at cometocentric distance

$$r_{\max} = 2.5 \left(\frac{\alpha V_g Q_d R^{3/2}}{\varepsilon^{1/4} x^{3/4} \mu \mu_g k_s} \right)^{1/2}, \tag{1}$$

where α is the accomodation coefficient of the gas molecules (of H_2O type) on the surface of the dust grain, V_g is the local mean thermal velocity of molecules of the gas, Q_d is the observed dust production rate, ε and x are the integral heat radiation coefficient and the integral absorption coefficient of solar radiation respectively, $\mu \equiv Q_d/Q_g$, Q_g is the gas production rate of the nucleus, μ_g is the mean molecular weight, $k_s \equiv S_a/S_t$ is the anisotropy coefficient of matter ejection from the cometary nucleus, S_a is the area of the effectively emitting subsolar zone of the nucleus, and S_t is the total surface of the nucleus (Ibadov, 1996c).

For comet Mrkos 1957V during 17–19 August when $R = 0.559$–0.599 AU with Q_d ($R = 0.6$ AU) $= 10^9$ g/s (Liller, 1960), $\alpha = 1$, $V_g = 5 \times 10^4$ cm/s, $\varepsilon = x = 0.1$ (metallic particles), $\mu = 0.1$, $\mu_g = 20$, $k_s = 0.1$, according to (1) we get $r_{max} \approx 10^3$ km. This value is close to r_{max}(Na) from spectral observations (Greenstein and Arpigny, 1962). For comet Halley 1986III within the jets r_{max} ($R = 0.8$ AU) ≈ 70 km (Ibadov, 1992).

It follows from (1) that the total gas production rate of a comet, $Q_g = Q_d/\mu$, may be estimated if the value of the displacement of the emission maximum of sodium-type volatile metal atoms is determined from spectral observations.

3 ORIGIN OF REFRACTORY METAL IONS IN THE COMAE OF COMETS AT LARGE HELIOCENTRIC DISTANCES

The emissions of refractory metal atoms (Fe, Ni, Si, etc.) have usually been detected from sun-grazing comets at heliocentric distances $R \approx 0.01$ AU (see, e.g., Preston, 1967; Oppenheimer, 1980 and references therein). Meanwhile, *in situ* measurements carried out within the coma of comet Halley 1986III by the VEGA-2 and GIOTTO spacecraft at $R = 0.8$–0.9 AU led to the discovery of ions of Fe II type (Balsiger, 1990; Gringauz and Verigin, 1990).

At the same time calculations show that at the heliocentric distances under consideration ($R \geq 0.8$ AU) the sublimation of refractory dust particles of the cometary coma in the field of electromagnetic and corpuscular radiation of the Sun is negligibly small to account for the detected Fe II ions (Ip and Axford, 1986; Geiss *et al.*, 1986; Johnson, 1990; Ibadov, 1996a).

In the head of comet Halley the dust-to-gas production rate ratio is $\mu \equiv Q_d/Q_g \geq 0.1$ (Sagdeev *et al.*, 1986). The passage of such a dusty comet through the zodiacal dust cloud is accompanied mainly by explosion-type process, i.e. by the production of expanding plasma blobs from high-velocity collisions of cometary and zodiacal dust particles (Ibadov, 1987). The radial distribution of the number density of ions produced may by presented on the basis of the continuity equation as

$$n_\alpha(r, R) = \left(\frac{k_m A_\alpha \rho V}{m_\alpha V_\alpha}\right)\left(\frac{Q_d \sigma_{dd}}{4 m_d V_d k_s}\right)\frac{1}{r}. \qquad (2)$$

Here k_m is the coefficient for producing plasma blobs from cometary and interplanetary dust; A_α is the mean abundance of the type-α element in the colliding dust grains; $\rho \equiv \rho(R)$ is the spatial mass density of the zodiacal dust cloud; $V \equiv V(R)$ is the relative velocity of the colliding dust particles; m_α is the ion mass; V_α is the expansion velocity of the coma ion component; $\sigma_{dd} = 2\pi a^2$ is the effective cross-section for the collisions of cometary and zodiacal dust particles; m_d is the mean mass of the coma dust particles; and V_d is the mean velocity of their outflow from the nucleus.

It should be noted that the law of ion density distribution $n_\alpha \sim 1/r$ given by (2) coincides with the corresponding law established at $r \leq 10^4$ km by the *in situ* measurements of the GIOTTO mission (Balsiger *et al.*, 1986).

Taking the value of the number density of Fe II measured by the VEGA-2 spacecraft $n(\text{Fe II}, r = 2 \times 10^9 \text{ cm}, R = 0.8 \text{ AU}) = 1 \text{ Fe II/cm}^3$ (Gringauz *et al.*, 1987) and accepting $k_m = 2$, $A(\text{Fe}) = 0.2$, $V = 8 \times 10^6$ cm/s, $m_\alpha = 10^{-22}$ g, $V_\alpha = 7 \times 10^4$ cm/s, Q_d ($R = 0.8$ AU) $= 10^7$ g/s, $\sigma_{dd} = 6 \times 10^{-8}$ cm^2, $m_d = 10^{-12}$ g, $V_d = 5 \times 10^4$ cm/s, $k_s = 0.3$ (Sagdeev *et al.*, 1986; Keller *et al.*, 1986), according to (2) we find ρ ($R = 0.8$ AU) $= 5 \times 10^{-22}$ g/cm^3. This value corresponds to the mean mass density of the interplanetary dust (see, e.g., Grun *et al.*, 1985).

4 X-RAY ACTIVITY OF COMETS

The discovery of cometary X-ray emission was made by the orbiting X-ray observatory ROSAT on 27 March 1996 during observations of comet Hyakutake C/1996 B2 at geocentric distance of the comet 0.1 AU. The X-ray emitting region had a fairly symmetric shape along the Sun-comet axis with the brightness peaking at about 3×10^4 km sunward of the comet centre. The emission can be traced as far as 10^5 km on both sides along the radial direction and 1.5×10^5 km in the perpendicular direction. Assuming an average photon energy of 0.25 keV in the observed 0.09–2 keV range the total X-ray luminosity of the comet was estimated to be $L_x \approx 4 \times 10^{15}$ erg/s within an aperture of $r_c = 1.2 \times 10^5$ km (Lisse *et al.*, 1996a, b; Dennerl *et al.*, 1997).

A possible mechanism of X-ray emission from dusty comets is high-velocity collisions between cometary and zodiacal dust particles resulting in the generation of high-temperature plasma blobs, photons with the most probable energy $h\nu_m \approx 60/R$ eV, and X-ray luminosity

$$L_x = k_x(\pi r_x^2)\frac{\rho V^3}{2}\left(1 + \frac{2}{\pi}\frac{r_c}{r_x}\right) \approx \frac{L_{xo}}{R^5}. \tag{3}$$

Here k_x is the efficiency of conversion of kinetic energy of colliding dust grains into X-ray radiation, r_x is the effective radius of the collisionally thick dust coma which is equal to the expression in the second bracket in the right-hand side of Equation (2), L_{xo} is the value of L_x at $R = 1$ AU, L_x includes the X-ray emission from collisionally thick, $r \leq r_x$, and collisionally thin, $r_x \leq r \leq r_c$, zones of the coma. For comets like Halley 1986III using (2) and (3) we have $r_{xo} = r_x$ ($R = 1$ AU) ≈ 100 km and $L_{xo} = L_x$ ($R = 1$ AU) $\approx 10^{15}$ erg/s (Ibadov, 1990; 1995; 1996c).

In order to explain the strong X-ray luminosity observed by ROSAT a number of theoretical models have been proposed: small current sheets in the solar wind

(Brandt *et al.*, 1996); generation of keV electrons in the cometary coma via wave-particle interaction as the source mechanism of collisional excitation of the X-ray emission (Bingham *et al.*, 1996); charge transfer interaction between the highly charged solar wind heavy ions (C^{6+}, C^{5+}, O^{7+}, O^{6+}, etc.) and cometary molecules (Cravens, 1996); scattering of the solar X-ray radiation by very small dust particles of the cometary coma (Wickramasinghe and Hoyle, 1996); collisional self-generation of high-velocity dust particles of very small sizes (10–100 Å) in the cometary comas (Ip and Chow, 1997).

To identify the different mechanisms of X-ray generation in the cometary comae it is reasonable to get X-ray spectra of comets with high spatial and spectral resolution, the dependence of the spectra and X-ray luminosity of comets on heliocentric distance.

5 CONCLUSIONS

The distribution in the cometary comas of emissions of atoms of volatile metals, such as Na, may serve as indicators of physical conditions in the inner comae of comets, particularly in the gas–dust jets. The total gas production rate of comets may be determined from the displacement of the intensity maximum of sodium atom emission from the cometary nucleus towards the Sun, so that spectral observations of bright comets with high spatial resolution are reasonable.

Ions of refractory elements such as Fe II detected in the coma of comet Halley 1986III by the VEGA and GIOTTO missions have basically no cometary origin but may have an interplanetary origin and may serve as indicators of interplanetary dust clouds.

The problem of identification of different mechanisms of X-ray generation in comets is real. It is reasonable to get X-ray spectra of comets with high spatial resolution as well as the dependence of the X-ray spectra and luminosity of comets on heliocentric distance.

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