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The Estimation Of the Dust Content In the Atmosphere of Comet West 1975n

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Two components were distinguished in the spectra of comet West 1975n on the basis of multicolour photometry — the solar light scattered by cometary dust and the proper thermal emission of the dust. The temperature and mass of the dust in the cometary atmosphere are estimated depending on the position of the comet on its orbit, under the assumption of isothermal dust and spherical shape of dust particles. It is shown that more solid material is supplied to cometary coma from the nucleus in the period following the transit through the perihelion than in the identical heliocentric distances in the period preceeding the perihelion. The course of the time dependence of dust mass in coma suggests two phenomena: a) The surface layers of the solid cometary nucleus are mechanically destroyed by the absorbed heat so that b) larger dusty particles are ejected by nucleus after transition through perihelion and the possibility of their splitting is not excluded during their stay in the coma.

На основе многоцветной фотометрии кометы West 1975n отметились в ее спектре два компоненты — солнечный свет рассеяный кометарной пылью и термическое излучение пыли. Предпологая изотермическую кометарную пылевую оболочку и шарообразные пылевые частицы, оценяются температура и масса пыли в зависимости на положению кометы на орбиту. Показивается, что после прохождения кометы через перигелий кометарное ядро выбросивает в кому больше материала чем в одинаковых гелиоцентрических расстояниях до прохождения через перигелий. Ход зависимости массы пыли от времени является основой предложения двух еффектов: а) поверхностные слои кометарного ядра механически разрушены поглощенной теплотой вблизи перигелия, так что б) после прохождения через перигелий выбросиваются из ядра пылевые частицы большие чем раньше и не исключается их расщепление еще в течении их пребывания в коме.

Na základě vícebarevné fotometrie komety West 1975n byly v jejím spektru rozlišeny dvě složky — sluneční záření rozptýlené kometárním prachem a vlastní tepelná emise prachu. Za předpokladu, že kometární prachová obálka je izotermická a že prachové částice mají kulový tvar, byla odhadnuta teplota a hmotnost prachu v závislosti na poloze komety na dráze. Je ukázáno, že po průchodu komety perihelem je z jádra uvolňováno do komy více materiálu než ve stejných heliocentrických vzdálenostech před průchodem perihelem. Průběh závislosti hmotnosti prachu na čase nasvědčuje dvěma jevům: a) Povrchové vrstvy pevného kometárního jádra jsou mechanicky rozrušeny absorbovaným teplem při průchodu perihelem, takže b) po průchodu jsou z jádra uvolňovány větší částice než dříve a není vyloučeno jejich další štěpení ještě během jejich pobytu v komě.

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1. Introduction

At the present time the combined photometry and polarimetry of cometary comae in visual and infrared region represent the very appropriate possibility for the study of cometary dust. It is so because

i) relative size of coma is negligible with respect to the distances to observer (on the Earth) and to the Sun, so that the phase angle Sun-dust particle-observer is practically the same for all the particles in the coma; and because

ii) comae have approximately uniform distribution of all kinds of particles involved. (The solid grains beeing ejected from the physical nucleus of the comet are in very rapid motion with respect to the nucleus and their lifetime in coma is thus short.)

Except of the facts in the items above several other assumptions are generally accepted. The spherical shape of dust grains in coma approximates only roughly the real state, but its assumption is the unavoidable condition for the theoretical estimation of scattered light by the use of Mie's theory. If the distribution function of diameters of the optically active grains in coma can be represented by a simple monotonical and nearly flat function, the collective effect of all types of particles on scattering and absorption can be substituted by only one "mean effective" type. Sometimes the resonance effects arise in scattering patterns for certain values of wavelength and diameter of grains, but such a case is easily recognizable and can be omitted.

As generally stated, the dust material could consist both of silicate and graphite modes. For sake of comparison with cometary photometry the sample of some silicates and other materials was taken into account, namely obsidian, andesite, olivine, graphite and magnetite. The optical constants of these materials are given by Röser and Staude (1978).

This paper is aimed at the estimate of the dust amount in coma during the flight in the inner solar system. Photometrical data in the visual region of spectrum supply the information on the particles' sizes, if compared with the theoretical predictions assuming certain chemical composition. From the knowledge of particle diameters it may be easily deduced the amount of dust comparing the observed infrared fluxes from coma with the blackbody spectrum. As to make the results of Mie's theory comparable with the photometrical data, the logarithmic differences are inferred.

2. The Analysis of the Photometrical Data

The visual and infrated photometry was made by Ney et al. (1976) in the system UBVRI and other infrared bands up to 18 μm (Fig. 1). Since only the monochromatic fluxes $F_p(\lambda)$ are given in the units $Wm^{-2}\mu m^{-1}$, we introduce the logarithmic differences Δ instead of commonly used colour indices

$$\Delta = \log F_p(\lambda_1) - \log F_p(\lambda_2) \tag{1}$$

for $\lambda_1 > \lambda_2$. As the reference colours are taken the values of V, or the values R, H in case of absent V.

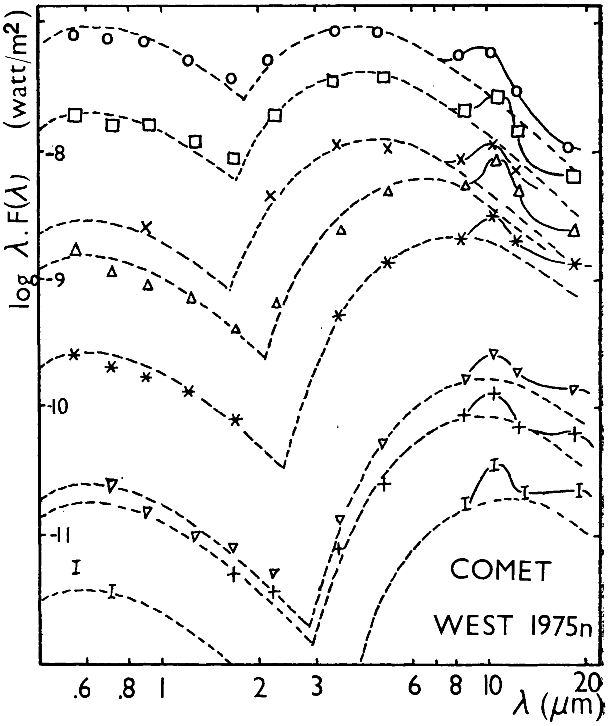

Fig. 1. The broadband photometry of Comet West 1975n by Ney (1976). The dashed line represents the blackbody spectra of the Sun and of the cometary dust.

○	February	25.8	(39°)
□	February	24.8	(51°)
×	February	22.8	(76°)
△	March	5.8	(80°)
*	March	10.8	(98°)
▽	March	21.8	(116°)
+	February	2.8	(150°)
I	April	5.6	(128°)

For the spherical particle of radius a and the refractive index m, Mie's theory calculates scattering functions $i_1(\vartheta)$, $i_2(\vartheta)$ depending on the phase angle ϑ ($180° - \vartheta$ is the angle Sun-particle-observer), and the efficiency factors Q_{ext}, Q_{scatt} and Q_{abs}. If the heliocentric distance of the comet is denoted by r and the corresponding geocentric distance by D, the flux that should be observed from one particle is given by

$$F = \frac{i_1(\vartheta) + i_2(\vartheta)}{2} \frac{C'}{4\pi D^2 k^2} F_{\odot}(r), \tag{2}$$

where F, i_1, i_2, $k = 2\pi/\lambda$ are wavelength dependent contrary to constant C'. $F_{\odot}(r)$

is the solar flux at distance r. The observed flux is proportional to flux F and then observed differences Δ_p are given by

$$\Delta_p = (\log i(\lambda_1)\,\lambda_1^2 - \log i(\lambda_2)\,\lambda_2^2) + (\log F_\odot(\lambda_1) - \log F_\odot(\lambda_2)), \tag{3}$$

where $i = i_1 + i_2$. The last equation can also be written in the simple form

$$\Delta_c = \Delta_p - \Delta_\odot , \tag{4}$$

where

$$\Delta_\odot = \log F_\odot(\lambda_1) - \log F_\odot(\lambda_2) \tag{4}$$

is the difference describing the solar spectrum only which may be taken from Allen (1978) – Fig. 2. The difference

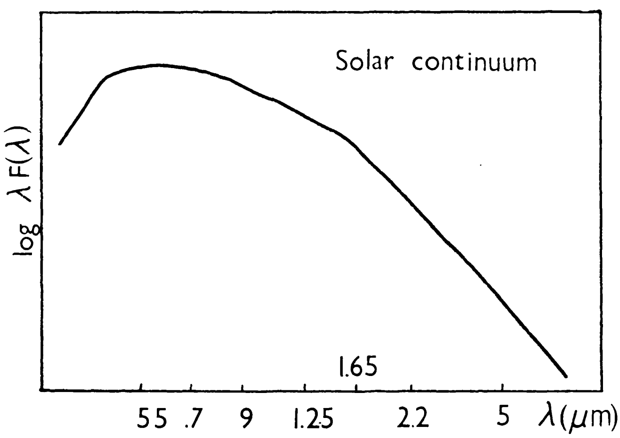

Fig. 2. The solar visual and infrared continuum in arbitrary units of $\lambda\ F(\lambda)$ by Allen (1978).

$$\Delta_c = \log i(\lambda_1)\,\lambda_1^2 - \log i(\lambda_2)\,\lambda_2^2 \tag{5}$$

characterizes the cometary dust and its value is both observable and theoretically calculable by help of Mie's theory. Sometimes it is useful to express the differences and fluxes in terms of product with the wavelength $\lambda\ F(\lambda)$. Then

$$\bar{\Delta}_p = \log \lambda_1\ F_p(\lambda_1) - \log \lambda_2\ F_p(\lambda_2) \tag{6}$$

$$\Delta_c = \bar{\Delta}_p - \Delta_\odot - (\log \lambda_1 - \log \lambda_2)\,. \tag{7}$$

As it can be easily seen from Fig. 1, the scattered solar light dominates the shortwavelength portion of the cometary spectrum till to bands H or K in dependence on the heliocentric distance. Thus, the comparable deviations from pure solar continuum characterizing the chemical composition of the dust may be drawn off only to limit band K. Numerical values of Δ_c taken by subtraction from Fig. 1 and Fig. 2 are given in Fig. 3.

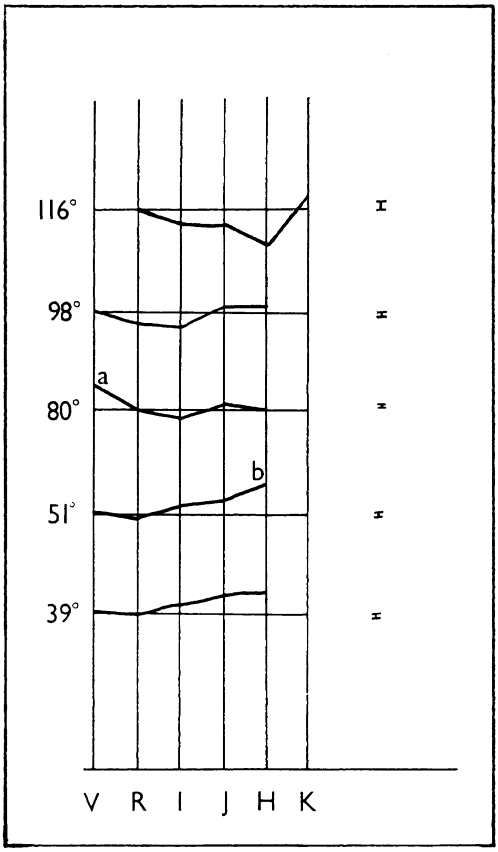

Fig. 3. The differences between the pure solar and cometary continuum. (*a* —probably overlapping by an emission molecular band; *b* — the influence of thermal radiation of the dust. I is the mean error bar.)

As it was mentioned above, the calculations of Mie's functions i_1, i_2 were performed for various silicate and other materials, whose refractive indices are listed in Tab. 1 in dependence on wavelength. The mean effective radius of model particles was varied from 0.25 μm to 7 μm. The values of phase angle ϑ at time of photometrical measurements follow from Fig. 4 and Fig. 5, where heliocentric/geocentric distances and phase angle of comet West are plotted vs. date. Summarizing the sample of parameters, for 5 kinds of material, 7 values of radius, 10 values of phase angles and 6 values of wavelength, the logarithmic differences were calculated which represents 2100 model calculations. The standard Mie's formulae were used according to Wickramasinghe (1974).

Table 1

Refractive indices of some materials

Band	λ(μm)	Obsidian*)	Andesite*)	Olivine**)	Magnetite**)	Graphite**)
		$\times 10^{-5} i$	$\times 10^{-5} i$	$\times 10^{-5} i$	$\times i$	$\times i$
V	.55	1.48— 23	1.47— 140	1.55— 4	2.5—0.6	2.15—1.3
R	.7	1.48— 30	1.47— 170	1.55— 5	2.4—0.45	2.2 —1.4
I	.9	1.48— 37	1.47— 210	1.50— 85	2.2—0.35	2.5 —1.65
J	1.25	1.47— 45	1.47— 280	1.50— 170	2.1—0.61	2.7 —2.0
H	1.65	1.46— 51	1.47— 330	1.50— 80	2.5—1.1	3.0 —2.2
K	2.2	1.45— 52	1.46— 390	1.50— 6	2.9—1.25	3.5 —2.9
L	3.5	1.42— 69	1.46— 580	1.50— 15	3.5—1.25	4.0 —3.6
M	5.0	1.35— 210	1.40— 860	1.45— 60	3.8—1.25	4.5 —4.2
	8.2	.68—42 000	.97— 16 000	1.20— 450	4.0—1.25	6.0 —3.5
	10	2.39—80 000	1.95—110 000			
	10.5	2.12—34 000	1.93— 86 000 2.16— 42 000	.11—150 000	4.0—1.35	6.5 —2.7
	13	1.61—24 000	1.67— 9 500	1.90— 50 000	4.0—1.6 4.5—3.0	7.0 —2.55
	19	1.23—42 000	1.78— 56 000	1.1 —250 000	5.0—1.7	7.7 —3.9

*) Pollack J. B., Toon O. B., Khare B. N., Icarus *19*, 372—389 (1973).
**) Röser S., Staude H. J., Astron. Astrophys. *67*, 381 (1978).

3. The Estimation of the Total Dust Mass in the Cometary Atmosphere

The result of comparison of the computed differences with the measured ones is given in Table 2. The materials used are the silicates with optical constants listed in Tab. 1. Assuming only one kind of dust chemical composition, the best accordance is reached for large andesite particles, having radii in limits approximately $1-3$ μm, but no other silicates can be strictly excluded. Most probable is the mixture of all silicates. On the other side, contrary to this reasonably good agreement no theoretical scattering curve of graphite and magnetite was similar to that observed in coma. Thus it can be concluded that in the cometary dust large silicate particles prevail. This result is generally in accordance with the presence of 10 μm and 20 μm silicate bands in the infrared spectra.

The silicate nature of dust in comet West was suggested by several authors also on the basis of polarimetric measurements (Narzihnaya, Shakhovskoy, Efimov (1977)). The negative polarization was found at phase angles near 180° (backscattering), whereas at small angles the polarization was positive. (The polarization is called positive/negative if the oscillation plane of electric vector of light is perpendicular/parallel to, with respect to the scattering plane given by the observer, the particle and the source of light.) Since the cometary dust is the main source for the zodiacal

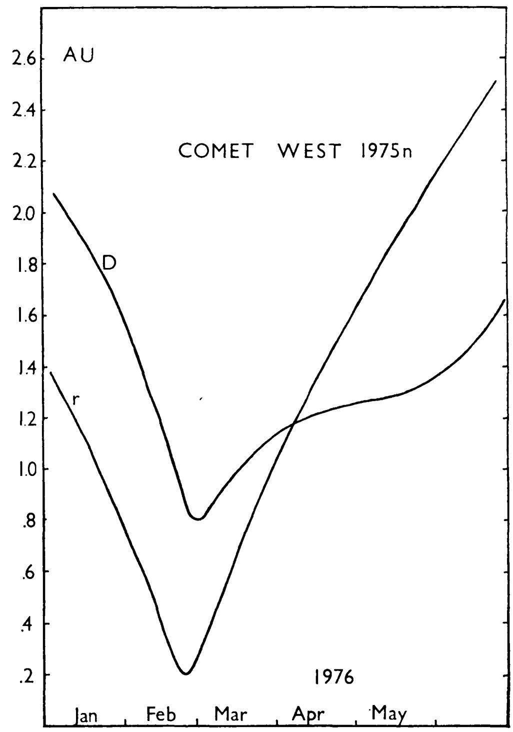

Fig. 4. The heliocentric (r) and geocentric (D) distances of Comet West 1975n, by IAU Circ. 2871 (1975).

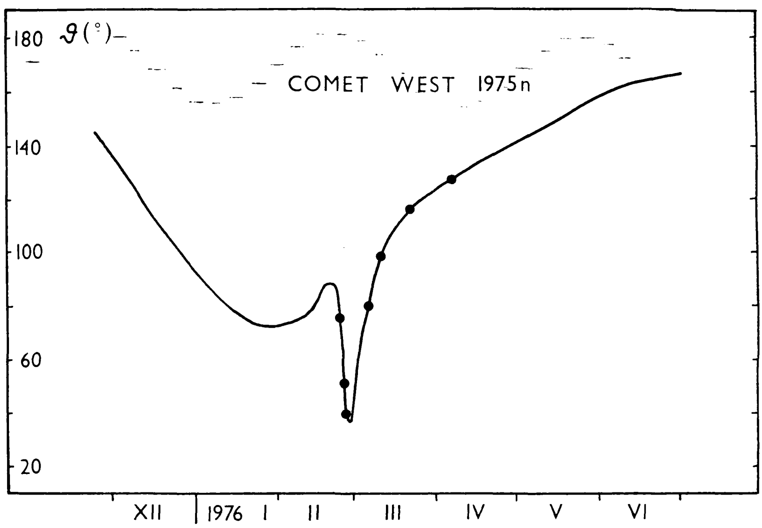

Fig. 5. The phase angle of Comet West 1975n. (● — the moments of photometrical measurements.)

Table 2.

Phase angle	39°			51°			80°			98°			116°		
Radius of grains	Material														
(μm)	Ob	An	Ol	Ob	An	Ol	Ob	An	Ol	Ob	An	Ol	Ob	An	Ol
0.25	—	—	—	—	—	—	—	—	—	—	—	—	0	1	0
0.5	—	—	—	0	0	1	1	0	2	1	2	1	1	2	1
0.75	0	0	—	0	0	0	1	2	1	3	3	2	2—3	3	1
1	—	—	1	0	1	0	1	1	2	1	1	2	1	0	2
1.5	2	3	0	—	1	2	0	2	0	0	1	0	2	1—2	2
2	—	—	1	1	1	3	2	3	1	—	3	0	1	0	2
2.5	2	1	2	1	0	1	2—3	3	1	0	1	1	2	2—3	2
3	1	0	0	1	0	1	1	0	1	0	2	—	1	0	3
4	1	0	3	2	1	1	2	2	—	3	3	2—3	2	0	1
5	1	1	—	—	—	0	1	1	—	2	1	1	1	1—2	1—2
6	—	1	0	—	—	0	0	0	—	—	0	2—3	0	1	1
7	—	—	—	—	—	—	0	0	—	0	0	—	0	1	2—3

Remarks:
0 no fit
1 theoretical and observed curves have the same trend of grows
2 both curves have identical interval of values and the same growing/decreasing tendency
3 excelent fit of the shapes of both curves
— no measurement was made
Materials: Ob = obsidian, An = andesite, Ol = olivine

light cloud, the switching positive-negative polarization measured by Frey et al. (1975) and others in zodical light confirms also the silicate composition of this dust.

Moreover, the negative polarization at high phase angles is possible only if the particles are large, because small particles (diameter < wavelength) scatter light according to the Rayleigh law and then the polarization should always be positive. The essential study of zodiacal light from this point of view by Röser and Staude (1978) shows that 80% particles in the zodiacal cloud have diameters of order $1-100\,\mu$m. Ney (1974) observed two comets – Kohoutek 1973f and Bradfield 1974b – and suggested the presence of two different dust materials in comae. The firts characterized by high albedo (probable dielectric silicates) is deposited in grains of radii less than 2 μm and the remaining material without any characteristic emission/absorption bands forms particles of radii greater than 20 μm.

The temperature T_g of dust grains is ballanced by the energy conservation law, which may be written for one particle as

$$\int_0^\infty \pi a^2 Q_{abs}(a, \lambda) \frac{L_\odot(\lambda)}{4\pi r^2} \, d\lambda = \int_0^\infty B(\lambda. T_g) \, Q_{abs}(a, \lambda) \, 4\pi a^2 \, d\lambda \qquad (8)$$

if the influence of collisions with interplanetary gas atoms and molecules is neglected. In the equation above $L_{\odot}(\lambda)$ is solar luminosity at wavelength λ, and $B(\lambda, T)$ is the Planck's function. By making simple rearrangements the equation takes the form

$$\frac{R_{\odot}^2}{4r^2} \int_0^{\infty} Q_{abs}(a, \lambda)\, B(\lambda, T_{\odot})\, \mathrm{d}\lambda = \int_0^{\infty} Q_{abs}(a, \lambda)\, B(\lambda, T_g)\, \mathrm{d}\lambda\,, \tag{9}$$

where $R_{\odot}$ is the radius of the Sun and $T_{\odot}$ is the effective solar temperature.

The monochromatic thermal luminosity of one dust grain is

$$4\pi a^2 Q_{abs}(a, \lambda)\, B(\lambda, T_g)\, \mathrm{d}\lambda \tag{10}$$

which implies the total thermal flux from all the particles in the coma (whose number is denoted by N)

$$F(\lambda) = \frac{a^2}{D^2} N Q_{abs}(a, \lambda)\, B(\lambda, T_g)\,. \tag{11}$$

If only the mean effective size of the grains is taken into account, the number N can be obtained from the measured flux $\lambda\, F_c(\lambda)$ as follows

$$\log N = \log(\lambda\, F_c(\lambda)) - \left(2 \log \frac{a}{D} + \log(\lambda B(\lambda, T_g)) + \log Q_{abs}(a, \lambda)\right), \tag{12}$$

where the first term on the right hand side is the value measured and the remaining is given theoretically.

The total mass of dust in coma is then

$$M = \tfrac{4}{3}\pi a^3 \bar{\varrho}\, .\, N \tag{13}$$

where $\bar{\varrho} \sim 2.5\ \mathrm{g\,.\,cm^{-3}}$ holds for most silicates. The temperature, number and total mass of dust grains in coma are given in Table 3. As the first approximation of temperature only the values of maximum thermal flux F_m and maximum B_m were taken, which must obey the same equation as flux and Planck's function at any other wavelength (Eq. 10). The radius of andesite particles in this table was assumed $a =$ $= 3\ \mu\mathrm{m}$.

The dependence of the total dust mass on time is plotted in Fig. 6. The curve has a striking character, because it is not symmetrical with respect to the heliocentric distance, since the thermal emission of the dusty coma is higher if the comet is receding from the Sun than if it approaches the Sun. The total mass of dust can be increased either if the number of grains in coma grows, or if the lumps of material released from the nucleus are larger. Since the mean size of particles have been derived from their scattering properties in the visual spectrum (independently of the thermal radiation and of the dust amount), both ways to enhance the total dust mass must be efficient in comet near perihelion.

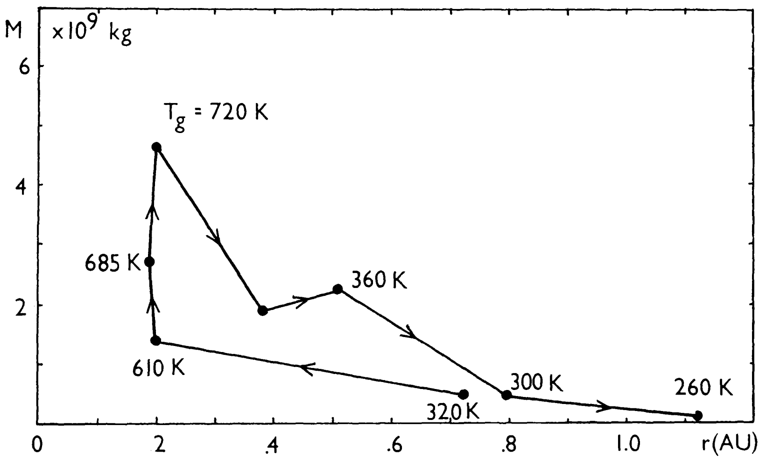

Fig. 6. The total dust amount in coma and the dust temperature T_g in dependence on heliocentric distance r.

4. Conclusion

Following the most accepted theory of cometary nuclei, the essential constituent of the surface material is the non homogeneous and "dirty" water ice containing other molecules and dust grains. This material is heated during the passage near the Sun and the surface layer evaporates releasing the solid grains frozen in it. (More exactly one can deal with the water ice sublimation rather than with the evaporation.) Since the area of the surface as well as the physical and chemical composition of the material does not change substantially during the perihelion passage, the rate of dust release should be nearly constant. This is correct especially when the surface temperature remains unchanged. However, this contrasts with the actual state of any comet at perihelion, as can be shown on Fig. 6 in case of comet West. Between Feb. 22.8 and Feb. 25.8 the heliocentric distance of comet West was ~ 0.2 AU (which ensured the constant solar flux absorbed by nucleus), but the amount of dust in coma rised three-times. Even if the lifetime of dust grains in coma (until they are expelled into the tail) is of the same order of some days, the enhanced dust production probably prevailed the effect of cumulation of the dust in coma. Thus the adequate mechanism of dust release must be searched.

Indeed, when one realises the mechanical and thermal properties of the nucleus resembling a huge snowball, the consequences of solar heat attack on it turn obvious. The surface layer suffer partially a mechanical damage and greater lumps of ice with

Table 3.

Comet West: Temperature and mass of dust and other characteristics of coma

Date (U.T.)	Feb. 2.8	Feb. 22.8	Feb. 24.8	Feb. 25.8	Mar. 5.8	Mar. 10.8	Mar. 21.6	Apr. 5.6
Phase angle ϑ	150°	76°	51°	39°	80°	98°	116°	128°
Geocentric distance D (AU)	1.52	0.92	0.85	0.82	0.84	0.91	1.05	1.16
Heliocentric distance r (AU)	0.72	0.20	0.19	0.20	0.38	0.51	0.80	1.14
λ_{max}(μm)	9.9	4.7	4.2	4.0	6.3	7.9	9.5	11.0
Temperature T_g(K)	290	610	685	720	455	360	300	260
$\lambda_m F_m(\lambda)$ ($\times 10^{-16}$)	82	12 000	42 000	98 000	6 300	2 200	170	21
$B_m(\lambda)$ ($\times 10^{-4}$)	28	1 100	1 900	2 500	260	80	32	16
Number of grains N ($\times 10^{20}$)	17	49	94	164	67	72	15	4
Total mass of dust M ($\times 10^6$ kg)	480	1 380	2 670	4 640	1 900	2 020	433	113

grains then peel from the surface than any before. Subsequently the lumps can be fragmented into smaller ones until the ice sublimates. By this way all types of frozen dust grains are supplied into coma.

However, Fig. 6 shows also a sudden increase of dust temperature in coma between the two dates mentioned above. This temperature rise from 610 K to 720 K implies that it can not be produced by the same type of grains, because the solar flux does not change at this period. Probably this phenomenon can be accounted for by a sudden increase of effective size of particles supplied by nucleus into coma. The detailed insight in Tab. 2 reveals the tendency of growing mean diameter of the particles with time. The larger the phase angle is, the better fit is found in all columns of Tab. 2. This is in agreement with results of Sekanina and Miller (1973), who have also found the relation between the change of particle size and temperature in the vicinity of perihelion for several other comets.

The question remains why large particles are not ejected into coma except in close solar neighbourhood. One attempt how to answer it relays on assuming the adhesive force of ice. The large grains can be released indeed by the evaporating ice, but the adhesive force does not permit them to leave the surface. Only if the surface layer is cracked and the ice lumps peel out, the large dust grains are borne out from the nucleus. Obviously when once the cracking of cometary material takes place, the following fragmentation or splitting of the lumps is very probable. The idea about the splitting of grains has been discussed in detail by Sekanina (1981).

It could be thus concluded that in "young" comets, i.e. those which have passed only few times through the solar neighbourhood, the mechanical resistance of the surface is less than in the periodic (and more evidently in the short periodic) comets, which have a consequence in the different mean size of particles in coma. The comet West is the proper example of such young comet, because the perihelion passage in 1976 was probably its first in the history.

A part of the present work was done by P. T. Duc (Vietnam Central Institute for Public Education in Hanoi) and it is completed in his PhD thesis.

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