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Global dust storms and highly polarizing clouds on Mars

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Abstract. The paper reviews our results about photometric ground-based observations of Mars during its great opposition of 1971 and near-perihelion oppositions of 1973 and 1975, as well as polarimetric observations of Mars with the Hubble Space Telescope (HST) at the time ofthe great opposition of 2003. The photometric observations cover long-term (1-3 months) disk-integrated and disk-resolved photometry of Mars during three global dust storms in 1971, 1973 and 1975, including the stages of development, maximum, and attenuation of the dust storms. Using data which showed anomalous changes of Martian brightness, the parameters of dust particles and dust storm as a whole were determined. These include the mean radius and single-scattering albedo of particles, the optical thickness of atmosphere in the maximum of a dust storm and the total mass of dust lifted up in atmosphere, and the temperature pulldown of Martian surface caused by dust storm. Polarimetric observations of Mars with HST revealed for the first time optically thin clouds made of highly polarizing scatterers in UV (330 nm). Analysis of HST data and their comparison with theoretical models allowed us to conclude that the Martian highly polarizing clouds can be formed in the very beginning of the nucleation of H2O ice crystals on submicron dust. Measurements of cloud dynamics has suggested the clouds to be located at 30-40 km above the Martian surface and migrate with velocity of 40-100 m/s.

Key words. : Mars, photometry, HST - polarimetry, dust storms, clouds

1. Introduction

Due to G. Schiaparelli's channels on Mars, the planet received great interest among the scientific community since the end of the 19th century. The famous Ukrainian planetologist N. P. Barabashov (1894-1971) observed Mars at our Observatory since 1912 and he carried out intensive observations of this planet for the great oppositions of 1924, 1939, and 1956. Before the next great opposition of 1971, the interest in Mars was still rather high due, to seasonal changes of an hypothesized Martian vegetation. At that time, one of the authors of the paper (D.F. Lupishko) was a post-graduate student of academician N.P. Barabashov and was preparing to observe Mars in 1971.

The principal task of the observations during the great opposition of 1971 was long-term photometric measurements by disk-integrated photoelectric and disk-resolved photographic methods. Thus, the results on Mars dust storms presented in this section were obtained about 35-40 years ago. Nevertheless, they may be interesting now for a wide scientific community,

Send offprint requests to: D. Lupishko as they were published in Russian journals that were not translated into English.

2. Photometric study of global dust storms on Mars

The observations were organized at the Gissar Observatory (Institute of Astrophysics of Tajik Republic, former USSR), located 15 km from Dushanbe-city, using a 70-cm reflector. The Kharkiv Observatory has the same telescope. However, Mars declination at the great opposition was negative and, therefore, the southernmost observatory in former USSR was chosen to observe Mars at 11 deg above the horizon as compared to the Kharkiv Observatory. For disk-integrated observations a photoelectric photometer working in the photon counting mode was used. These observations were performed with different narrow-band filters (see Table 1); photographic observations were carried out in Cassegrein focus (F=31 m) using four broad-band filters with $\lambda_{\max}$= 366, 429, 530, and 640 nm. All these observations were made from June to December 1971.

Fig. 1 shows obtained magnitude-phase dependences of Mars. The observations at phase angles $\alpha \geq 33$ deg correspond to the period of the global dust storm. One can see the anomalous changes of the disk-integrated brightness of Mars in that period: in the red part of the spectrum the brightness increased by 0.35 mag and in the UV part it decreased by 0.25 mag (see Table 1). Thus, at the dust storm maximum the color index (UV-Red) of Mars has increased by 0.60 mag, which is a very high value and can be easily detected.

In Fig. 2 comparison between our magnitude-phase curve and data from the "Mariner-9" mission (Thorpe 1973) is presented for the dust storm and clear Mars atmosphere; one can see good coincidence.

Near the opposition (10 August 1971), when the atmosphere of Mars was clear, the contrast of details on the disk returned to their usual values, while for the stage of dust storm the planet was visible as a homogeneous disk. In this case the distribution of brightness along the equator of intensity (the line on visible disk connecting the center of the disk and sub-solar point) is described well by the Lambert law (Fig. 3). It means that dusty atmosphere scatters sunlight like an orthotropic surface.

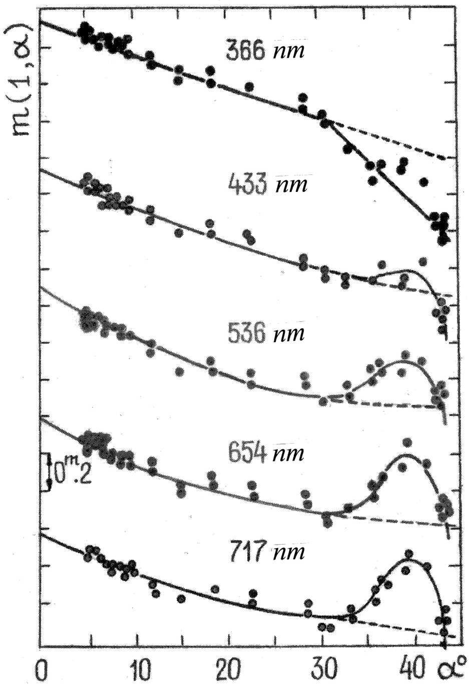

Fig. 1. Magnitude-phase dependences of Mars in the 1971 great opposition.

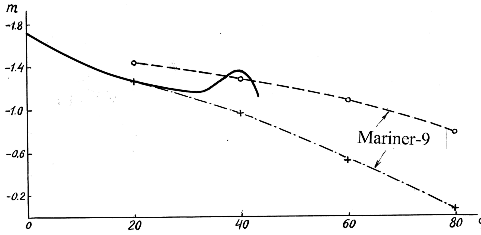

Fig. 2. Comparison of the obtained magnitude-phase curve for λ=585 nm (solid line) with the "Mariner-9" data: bottom and upper curves correspond to clear atmosphere of Mars and the global dust storm, respectively.

The disk-integrated photoelectric observations of Mars were continued in the near-perihelion oppositions of 1973 and 1975 at

Table 1. Relative changes of disk-integrated brightness of Mars at maximum stage of 1971 global dust storm

λ, nm	366	433	536	654	717
Δm, mag	+0.25	−0.07	−0.21	−0.34	−0.35

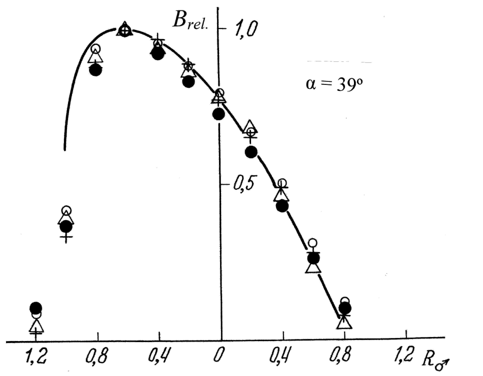

Fig. 3. Brightness distributions along the equator of intensity of the Martian disk during 1971 dust storm: • 366 nm, ∘ 435 nm, + 548 nm, Δ 625 nm.

the Observation Station of the Astronomical Observatory of Kharkiv University. The observations revealed two additional global dust storms (Alexandrov, Lupishko & Lupishko 1977): the observations in 1973 include the development of the global dust storm (1 Oct. to 25 Oct.), and the observations in 1975 include the attenuation of the global dust storm (16 Aug. to 10 Oct.). Magnitude-phase curves were obtained; the most impressive results of all these observations are shown in Fig. 4. These are time variations of color index (UV-Red), which are caused by the dust storm. The day and month of each observation is plotted on the abscissa.

As can be seen, in 1971, the global dust storm began on 18-20 Sept. and during a month it achieved the maximal intensity. Observations on 8-10 Dec. allow us to suppose that the dust storm continued up to Jan. 1972. But what anomalous changes of the color index took place in the 10 July - 10 Aug. period? Our observations before opposition (23 June - 10 Aug.) showed that Mars was systematically 0.1 - 0.2 mag. brighter than after opposition (10 Aug. - 18 Sept.) at the same phase angles (Alexandrov, Lupishko & Lupishko 1977). The contrasts of details on the Martian disk before the opposition were usually low or moderate, but not high, and in some regions of Mars local dust clouds were observed. The anomalous increase of the color index (UV-Red) of Mars up to 0.24 mag. since 10 July to 10 August clearly denotes (Fig. 4) that some regional dust storm was on Mars at that time, though it was not so intensive to develop into a global event and attenuated by 10 August.

In 1973 the global dust storm began approximately on 1 Oct., i.e. before the date of the opposition on 25 Oct., and obtained data showed a fairly speedy storm development. Probably it was even more intensive than that in 1971. Unfortunately, the observations were stopped on 25 Oct. 1973 just in opposition and, as it turned out later, near the maximum of the dust storm. However data obtained by other authors indicated that the dust storm continued about three months and only in January of 1974 detail contrasts on the disk returned to their usual values. In 1975 our observations included the dust storm in the phase of attenuation; the storm most likely was also global. One can see that this phase continued 2-3 time longer than the stage of dust storm development. Besides, some temporary increase of intensity can take place.

Thus, one can conclude that the data of Martian disk-integrated photometry with UV and red filters may clearly indicate the beginning and the end of dust storms as well as their development, attenuation, and intensity.

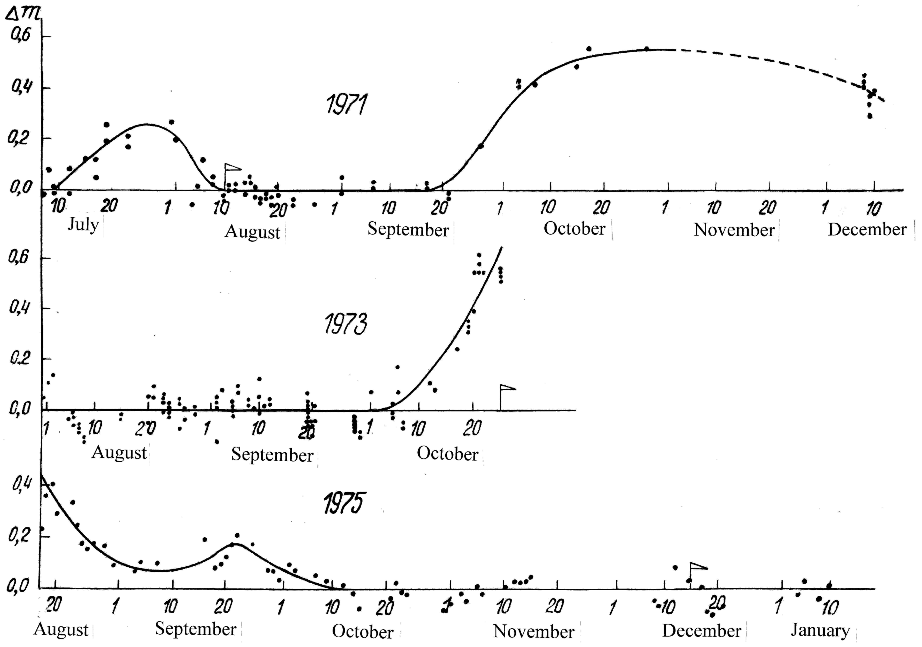

Fig. 4. Temporal variations of measured color index (UV-Red) of Mars caused by dust storms.

Therefore, such observations can be used as a simple and effective method of dust storm monitoring (Lupishko & Lupishko 1977).

What new quantitative information about physical parameters of the Martian dust storms did the observational data obtained give us? To answer the question we used: the measured absolute disk-integrated brightness of Mars in different spectral bands; the measured absolute brightness of the disk center and sub-Solar point in different spectral bands; an assumption about the optical constants $m = 1.5 - i(0.2 \div 0.3)10^{-3}$ corresponding to silicate and oxides (e.g., Liberman, Moroz & Khromov 1972); the simplest nonspherical scattering indicatrix of dust particles $X(\gamma)=1 + x_1 cos\gamma$.

With all these data and assumptions two possibilities were considered: the mean radius of dust particles is(a) r$\sim$ 1 μm and (b) r$\sim$ 10 μm. As a result, the following parameters of the global dust storm in 1971 were estimated (Alexandrov & Lupishko 1976):

- the single-scattering albedo of dust particles $\omega = 0.87 \div 0.99$ for the spectral interval $\triangle\lambda$ = 0.366 -0.625 μm;
- the mean radius of dust particles in the maximum of dust storm is r$\sim$10μm; according to "Mars-3" data (Moroz 1976), the mean size of dust particles was estimated to be equal to r$\sim$ 1 μm, however these measurements were realized in December of 1971, when the dust storm was greatly decayed. In reality there is some size distribution of dust particles and its submicron part can be essential. However, the large particles contributed to the optical properties of dust atmosphere much more, which makes the small particles photometrically imperceptible;
- the optical thickness ($\tau_0 \sim 40$) of the atmosphere in the dust storm maximum;
- the total mass of dust lifted up in the atmosphere, $\sim 10^{17}$ g at the particle density $\rho = 3g/cm^3$;
- temperature pulldown of the Martian surface

(60÷70 deg) caused by the dust storm due to “antigreenhouse effect” in the sub-Solar point, which is in good agreement with ground-based temperature measurements during that dust storm by (Liberman, Moroz & Khromov 1972). According to “Mariner-9” and “Mars-3” data (Golitsyn 1974) during the period of the 1971 storm attenuation the “antigreenhouse effect” was equal to $\triangle T \sim 25$ deg, which corresponds to $\tau_0 \sim 8$.

Based on these estimated parameters of dust particles and dust atmosphere as a whole, we can explain the anomalous brightness changes of Mars during the global dust storm in the following way:

1. Single-scattering albedo ω of dust particles is found to be essentially higher than that of the surface, which has to increase the Martian brightness especially in visual and red spectral ranges where ω tends to 1.
2. Surface particles suspended in the atmosphere do not produce the shadow-hiding effect; this also increases the planet’s brightness.
3. In red spectral range it is necessary to take into account an additional brightening of Mars due to invisibility of low-albedo mare regions during the dust storm. This factor may produce brightening up to 0.1 mag.
4. In the UV, on the one hand, the particle light absorption is more essential as compared with red wavelength and, on the other hand, scattering indicatrix of particles is more elongated because size parameter of particle $2\pi r/\lambda$ is about twice as large as that in the red part of the spectrum. Besides, there is no additional brightening due to masking mare regions. As a result, the brightness of dusty atmosphere turned out to be smaller than the brightness of the system “surface plus usual atmosphere”.

3. Imaging polarimetry of Mars with the Hubble Space Telescope in 2003

The degree of linear polarization of sunlight scattered by Martian atmosphere aerosols and surface soils bears information about particle sizes, compositions, shapes, and orientation. The degree and orientation of the polarization plane are functions of the phase angle Å and wavelength λ.

Polarimetric data collected during the 2003 great opposition. An international team of American and Ukrainian planetologists carried out joint observations with the Hubble Space Telescope (HST, NASA) (program HST-GO-9738 ”Spectroscopy and Polarimetry of Mars at Closest Approach”, see Shkuratov et al. 2005). These were the first polarimetric observations of Mars with HST and the first access of Ukrainian planetologists to HST. The observations in August and September 2003 took advantage of the closest Earth-Mars encounter as Mars passed within 0.372 AU of the Earth. The angular diameter of the apparent Martian disk was 25.1″.

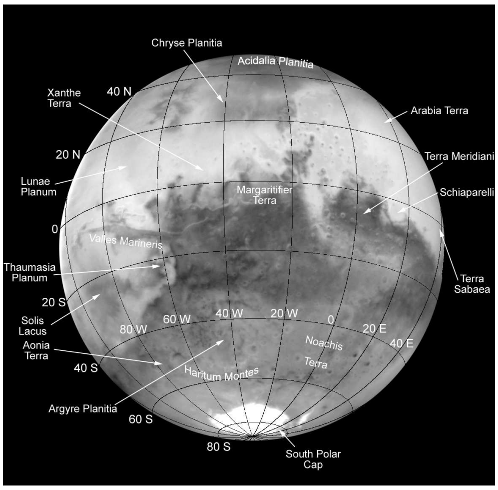

Fig. 5. A map of the Martian hemisphere centered at 19S, 34W presented by an image acquired in the red spectral band (658 nm).

Five series of images of Mars were taken on August 24, just before the closest approach, and on September 5, 7, 12, and 15. The phase angles at the observation moments were 6.4, 8.2, 9.7, 13.6, and 15.9 deg, respectively. The observations were timed to allow imaging the same hemisphere of Mars at all five phase angles (disk center at 19°S, 20°W - 35°W), including Valles Marineris, the contrasting albedo details of Terra Meridiani and its sur-

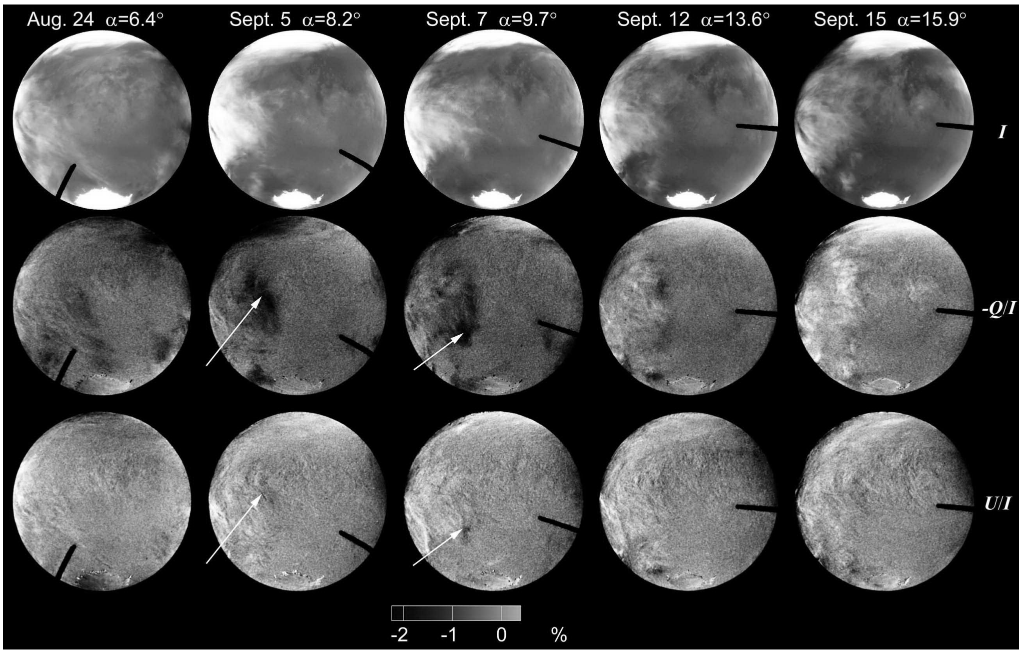

Fig. 6. Intensity I and normalized Stokes parameters -Q/I and U/I for Mars on the five observation dates for the filter 330 nm. The Stokes parameters are defined with respect to the photometric-equator-related reference frame. The black coronographic finger is shadowed area of the detector. The arrows show the polarimetric transient effect.

roundings (Fig. 5). This perihelion observation period corresponds to the Martian summer in the Southern hemisphere. The atmosphere was relatively free of both dust and water ice clouds. The images were taken with the High-Resolution Camera (HRC) of the Advanced Camera for Surveys (ACS, Pavlovsky et al. 2002). The diameter of Mars in the HRC field of view decreased from ~1010 to ~950 pixels from the first to the last observation series. The scale of the image was about 7 km/pixel in the center of the disk. Each observation series consisted of sets of images acquired with broadband spectral filters 250, 330, and 435 nm. The calibration of the observations had been performed using two standard stars with zero polarization and one standard star with high polarization.

Some results and their interpretation. The calibrated HST images of Mars were used to map the intensity I and Stokes parameter ratios -Q/I and U/I, where Q and U are the second and third Stokes parameters, respectively. The maps obtained in the spectral band 330 nm at all observation dates are depicted in Fig. 6. Note that these are the first near-UV polarization maps of Mars. Almost everywhere the ratio U/I is close to zero, and its spatial variations are noticeably weaker than those of the ratio -Q/I. The bright seasonal polar cap is clearly visible in the southern (bottom) portion of each image. The cap shrinks with time during the observation time span. We found that the contrast of all surface features outside the northern cloud belt is much lower in the UV range than in the visible part of the spectrum. This well-known effect is due to the fact that in the visible spectral range the surface scattering is the major contributor to the reflected light, whereas gas and aerosol scattering dominates in the UV range. Semitransparent cloud features are denser in the UV range, since scattering by fine aerosols is more effective at shorter wavelengths. Furthermore, the albedo contrast of mare and highland surface materials is much lower in the UV than in the visible range.

The most interesting phenomena revealed by these observations are transient high-polarization features. The maps in Fig. 6 show several such features with polarization degree exceeding 2% (here the negative sign of polarization denotes negative polarization branch of polarization-phase angle curve). The polarization contrast of these features is the highest in the UV filter 330 nm. They are especially prominent in the western (left) part of the disk and have different shapes and locations on September 5 and 7 (as indicated by the arrows in Fig. 6) before eventually fading away. These clouds are semitransparent so that surface albedo patterns and the Valles Marineris topography remain recognizable. The densest clouds are still seen in the blue filter 430 nm, though many clouds "disappear". It is interesting that in the same part of the Martian disk there are similar clouds that do not exhibit the strong polarization effect, apparently because they consist of different type of particles.

The high polarization of light scattered by these optically thin clouds indicates that they consisted of strongly polarizing particles. Analysis of obtained HST-data and comparison them with some theoretical data of light polarization by different atmospheric aerosols (Wolff & Clancy 2003; Zubko et al. 2006) let us to come to a conclusion that Martian highly polarizing clouds can be formed in the very beginning of the nucleation of H2O ice crystals on submicron dust. Measurements of synoptic cloud dynamics and comparisons of the derived values of the wind speed with climate models have suggested that the polarizing clouds are located at 30 - 40 km above the Martian surface and migrate with velocity of 40 -100 m/c (Kaydash et al. 2006).

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