IMAGING POLARIMETRY OF MARS WITH HUBBLE SPACE TELESCOPE IN 2003 OPPOSITION.

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Introduction: The polarization state of solar light scattered by atmospheric aerosols may provide information about particle size, shape and orientation; polarization of light scattered by surfaces bears information about small-scale structure. During Mars close approach to the Earth in 2003 an extensive series of observations was carried out by the Hubble Space Telescope (HST) [1]. This series included (for the first time) high resolution polarimetric observations. We present results of the initial processing of these observations.

Observations: Five series of images of Mars at phase angles about 6, 8, 10, 13 and 16° were taken with polarization filters in Aug. - Sept. 2003. The moments for observations were chosen so that Mars was turned to the observer by the same side (disk center at 19°S 20-35°E) containing Valles Marineris and contrasting albedo details of Terra Meridiani and surroundings. Images were taken with the High-Resolution Channel (HRC) of the Advanced Camera for Surveys (ACS) [2]. Mars diameter in the HRC field of view (FOV) decreased from ~1010 to ~950 pixels from the first to the last series. Coronographic spots in the HRC FOV have obscured a small portion of the disk. Each series consisting of 4 sets of images taken with different wide-band spectral filters (F250W, F330W, F435W, and F814W). Each set contained 3 images taken with 3 polarization filters (POL0UV, POL60UV, and POL120UV). Unfortunately, images in the infrared F814W filter are overexposed, and bright areas of the planet are saturated and contain no information. Darker regions are suitable for further analysis. In other filters the exposure was perfect.

Data processing: The standard pipeline calibration including corrections for dark current, flat field, and geometric distortion has been routinely applied to each image by the HST data retrieval facility. We identified and removed the cosmic-ray tracks with an original heuristic algorithm based on the fact that the tracks are sharper than any image details. Then we coregistered 3 polarimetric components (images) within each set. This procedure was not trivial, because rotation of Mars between the consecutive exposures was not negligible. After geometric correction for Mars rotation, the residual coregistration errors were still too high for further processing (up to 1.5 pixels). These errors were caused by inaccuracy (at 10^{-3} level) of scale knowledge and FOV distortion correction. We removed the residual coregistration errors with an original heuristic algorithm based on maximization of local covariation of images. Final coregistration accuracy was at ~0.3 pixels level. Then we applied polarimetric calibration for each set of 3 polarimetric images, as described below.

Calibration: Linear polarization of scattered light can be described by a set of two parameters, for example, the degree of linear polarization P and polarization plane position angle ϕ, or normalized Stokes parameters $Q/I = P \cos2\phi$ and $U/I = P \sin2\phi$. Circular polarization cannot be derived from observations with polarization filters. Moreover, if the light has a circularly polarized component, its linearly polarized component cannot be derived unambiguously, because the optical scheme of ACS includes the metallic inclined mirror that works as a phase retarder [3]. The described observations are free of this problem, because at small phase angles the Martian surface and aerosols do not have noticeable circular polarization.

The instrumental polarization of ACS HRC is fairly high (~ 9%), and the use of pre-flight data on HRC optical elements will not give reliable calibration. In-flight calibration has not been accomplished yet, however, some calibrating observations have been made. In particular, there are observations of two standard non-polarized stars and one standard polarized star for all filter combinations used for Mars imaging. For filters F250W and F435W, the polarized star was measured twice at different position angles. We used these measurements to derive a calibration procedure useful for processing the observations of Mars.

When $P \ll 1$, the relationship between the pair Q/I and U/I and the pair of ratios of intensities in the 3 polarization filters is linear; hence, it is described by 6 parameters (the most general linear relationship between two pairs of quantities). The measurements of a not polarized star and a polarized star at two position angles provide a minimal set of observations to derive a meaningful calibration. Such a calibration is not perfect, because (1) some inaccuracy can arise from spectral differences of Mars and of the stars (the filter spectral bands are wide, and spectral dependence of instrumental polarization and retardance is strong); and

(2) there are indications of variations of the instrumental polarization over the FOV. For filters F220W and F814W the calibration observations are not enough to derive the calibrating coefficients (there are 4 equations for 6 unknowns). Observations of Mars themselves can be used for calibration purposes: the symmetry demands that at small phase angles the polarization plane at the center of the disk is parallel to the incidence plane (photometric equator). Since the orientation of the photometric equator of Mars within the FOV is approximately the same in all 5 series of observations, this symmetry consideration actually adds one additional constraint, yet another is required. We applied a heuristic regularization procedure that implicitly involves the pre-flight estimates of polarization efficiency of the filters [3]. This gave us calibration for all 4 filters. Comparison of the results obtained with our heuristic procedure and the "exact" calibration with the standard star for F435W filter shows good agreement. The results of the heuristic calibration cannot be considered as quantitatively accurate, but they allow mapping of polarization degree, its phase dependence, and reliable recognition of polarization variations.

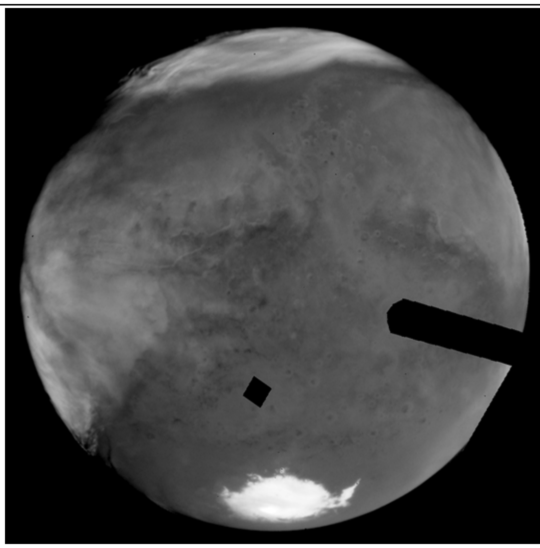

Figure 1. An initial image of Mars (filter F435W) acquired at a phase angle near 10°.

Preliminary results: Figure 1 shows an initial image of Mars acquired in the blue spectral band at a phase angle near 10°. Figure 2 presents a corresponding distribution of polarization degree *P*. Typical values of *P* are ~1%. Minimal values of *P* are observed for the south pole cap and some clouds (< 0.1%). The surface at the Martian disk center shows $P \approx 1.5\%$. There are portions of clouds with *P* as high as 2.5%. The polarization degree is high at the Martian limb, as expected. In the northern cloud belt the systematic change of the polarization plane occurs from the western to eastern limb. Such a pattern indicates that the clouds are made of oriented particles larger than a certain size (because smaller particles are always oriented chaotically due to the Brownian motion). The dust storm displays polarization almost indistinguishable from the bright surface, which is natural, because the dust storm is optically thick, and the bright areas of the surface presumably are composed of the same particles. Thus high signal-to-noise ratio of the source images as well as the calibration procedure allow reliable identification of polarization variations.

For the UV filters, the scattered light mostly comes from aerosols. Haze in areas free of clouds and dense dust display strong variations of polarization degree in the UV. This indicates spatial inhomogeneity of the suspended fine aerosols and processes responsible for their properties.

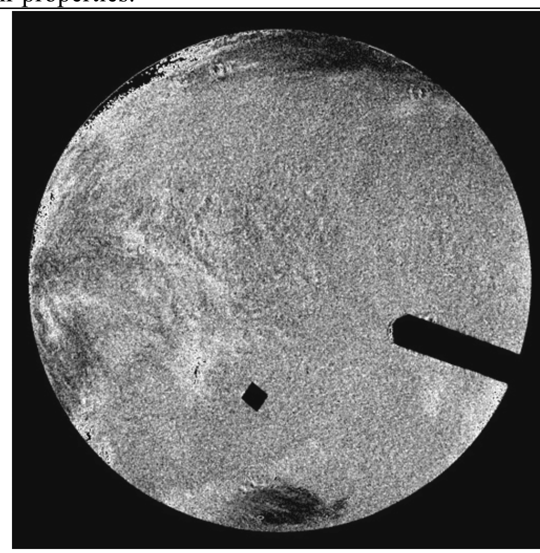

Fig. 2. Polarization degree distribution (filter F435W) at a phase angle near 10°.

Conclusions and future work. The HST observations allowed us to obtain reliable and informative maps of polarization across Mars. This proves that despite strong instrumental polarization, phase retardance and problems with calibration, the ACS camera is an excellent tool for polarimetric studies of the planets. Analyses of obtained polarimetric images promises new constraints on size, shape and orientation of particles constituting Martian aerosols. Further analyses of these results, especially together with simultaneous MGS TES observations promises new insight into microphysics of aerosols with possible wider implications in global climate models.

References. [1] Bell J. F. et al. (2003) AGU Fall Meeting, P12C-01. [2] ACS instrument handbook, STScI, 2003, http://www.stsci.edu/hst/acs/documents/ [3] ACS ISR 01-01 http://www.stsci.edu/hst/acs/documents/isrs/isr0101.pdf