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The magnitude and albedo of Mars

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Abstract

A comprehensive set of magnitudes obtained between 1954 and 2006 are analyzed. The martian brightness and its variations are characterized empirically at UBVRI wavelengths. Geometrical factors including phase angle, orbital longitude and rotation angle are distinguished from geophysical factors including dust storms and changing albedo features. The phase function indicates a brightness surge near opposition at all wavelengths except possibly in the U band. The color indices reveal increased reddening with phase angle. No significant brightness difference between morning and evening hemisphere observations is indicated with the possible exception of the I band. There is no conclusive evidence for inter-annual brightness variation during the years from 1991 to 2006 when abundant photometry is available. Major dust storms caused brightness excesses that were strongest in the R band at an average of ~0.15 mag more luminous than the empirical model for dust-free conditions. The storm of 2001 produced a rapid increase at the onset followed by a slower decline, while the 2003–2004 event show a more gradual increase. The return to normal brightness was linear in magnitude for both storms. Brightness excesses at longer wavelengths were about 0.20 to 0.25 mags at the peak of the 2001 storm. The observed geometric albedo of Mars is 0.059 ± 0.001 in U, 0.089 ± 0.001 in B, 0.170 ± 0.002 in V, 0.289 ± 0.003 in R, and 0.330 ± 0.003 in I. The corresponding albedo values for all five colors exceed those recorded in the literature, with larger percentage increases at shorter wavelengths.

Keywords: Mars; Mars, surface; Photometry

1. Introduction

Integrated magnitude is an important planetary parameter because it equates to albedo which, in turn, is a critical element of climate models. While there is an abundance of disk-resolved data from Mars-orbiting spacecraft its absolute calibration is somewhat uncertain and integration depends on the choice of scattering functions to account for the large range of viewing angles. At present there does not appear to be an accepted and published disk-integrated brightness for Mars based on disk-resolved images. Geissler (2005) and McEwen et al. (1994) have addressed some of the calibration and scattering issues. In any case, disk-integrated photometry remains a primary source of brightness data and will always be a good reference for comparison with disk-resolved data products.

The apparent magnitude of Mars is constantly changing due to geometrical and geophysical factors including dust that is redistributed on the surface by wind, the solar lighting angle and the phase seen by the observer, bright and dark albedo features rotating across the Earth-facing hemisphere, martian seasonal variations, and particulates suspended in the atmosphere during dust storms. The martian magnitude variations are more complex than those of Mercury (Mallama et al., 2002) which has no appreciable atmosphere and likewise with those of Venus (Mallama et al., 2006) which is shrouded entirely by clouds. The brightness variations of Mars are more like those of the Earth since both are significantly affected by their dynamic atmospheres and by albedo changes on regional scales (Wielicki et al., 2005).

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Table 1
Specifications of the UBVRI photometric system

Units are nm	U	B	V	R	I
Central wavelength	360	440	550	700	900
Full width at half maximum	70	100	90	220	240

2. Five-color photometry

2.1. Data from the literature

A set of band passes for ultraviolet (U), blue (B), and visual/green (V) photoelectric photometry was developed by H.L. Johnson in the 1950s. Red (R) and near-infrared (I) bands were added later to make the UBVRI standard which spanned the near-ultraviolet to near-infrared (Johnson et al., 1966). This system established the mags and color indices for celestial objects and was calibrated with a set of reference stars. Modern CCD photometers are also calibrated against the same standard stars and thus the UBVRI system remains the standard for wide-band astronomical photometry. The central wavelengths and band passes of the standard system are listed in Table 1.

Johnson and Gardiner (1955) obtained the first UBV photometry of Mars during the apparition of 1954. This limited observing program was followed by others of similar size in 1958 (de Vaucouleurs, 1959) and in 1960–1961 (Young, 1974). A more ambitious UBV campaign was carried out between 1963 and 1965 at Boyden Observatory in South Africa and LeHouga Observatory in France (Young and Irvine, 1967; Irvine et al., 1968a, 1968b). However, the most extensive magnitude series was acquired by Schmude (2006, 2004, and references therein; R. Schmude, private communications) in BVRI between 1991 and 2006. These observations constitute more than half of all the photometry in this paper.

Table 2 lists the quantity of data by filter for each source mentioned above and for two new sources that are described in the next two sub-sections. The biases are average residuals between individual data sources and the overall collection of data for each color. For example, the V data from LeHouga is 0.040 mag too faint relative to the model generated from all V data. These biases were computed in an intermediate step and then applied to the final empirical fits described in Section 3. The quality of those fits and of the photometry can be inferred from the RMS values, which were computed after correcting for biases. The internal RMS for a data source (e.g., Schmude's data) corresponds to the fit between that source of data and a model fit to that data alone (i.e., fit to Schmude's data alone). The internal RMS values run from a best of ±0.014 mag for the new ground based V filter data reported in Section 2.2 to a worst of ±0.054 for the U band data from Boyden. The external RMS for data, on the other hand, describes the fit between a single source of data and a model fit to the data of all sources combined. External RMS values range from a best of ±0.024, again for the new ground based V filter data reported in this paper, to a worst of ±0.090, for the B filter data of de Vaucouleurs. The overall RMS values for all data combined are on the order of 0.05 mag with the least being ±0.041 for V and the greatest being ±0.065 for B. Besides errors in the photometry and in the solutions, the RMS residuals include a contribution from martian brightness variations that are not modeled. Examples of omitted variations are clouds and other atmospheric phenomena, as well as surface changes.

2.2. New ground-based observations

Substantial new V band photometry of Mars was obtained during the apparition of 2005–2006 in order to supplement the data from the literature and to compare with the mags obtained concurrently by Schmude (private communication). The planet was very favorably placed for observation because of its high elevation during nighttime hours and because of the small angular distance to the standard star Hamal (α Aries). Hamal was an especially good reference because it is among the fundamental standard stars which define the UBVRI magnitude system. Additionally, its color closely matches that of Mars thus minimizing the uncertainty introduced by color transformation as discussed below. Hamal was used for reference on all 32 nights of observation, however, late on the final night the star ι Aurigae was used as the comparison in order to reduce the differential air mass with Mars. Johnson et al. (1966) also observed ι Aurigae and tied it into the UBVRI system as a secondary standard.

The telescope used for photometry is described by Mallama et al. (2002), but the CCD camera for recording the data reported here contains a Kodak KAF-0402ME chip in place of the smaller Texas Instruments element used previously. The larger chip permitted a 5 arc-min diameter circle to be used for planetary and stellar imaging, in addition to a surrounding annulus for sky brightness assessment. The large field of view is important because inadequate measurement size can produce anomalously faint differential mags for an extended planetary disk in aperture photometry. This bias is the result of scattering and diffraction which spills a higher proportion of the light from the disk outside of the measurement aperture as compared to that from a point-like star image. The large aperture, together with the high elevations of Mars and the comparison star during most of the observations, reduced this bias to an immeasurably small value. The remaining error sources, including random noise, correction for differential extinction and correction for color transformation, were addressed and minimized as follows.

Multiple CCD images of Mars and of the comparison star were averaged to reduce the random uncertainty for each magnitude reported in this paper. The 184 mags of Mars were derived from 2191 individual CCD images, for an average of 12 images of the planet per mag. The average of the standard errors of the mean, σ_M, for the 184 unprocessed measurements of Mars was 0.0023 mag. The same analysis of the averaged comparison star images indicates $\sigma_M = 0.0044$ of random uncertainty for the comparison mags. The better figure for Mars is due to a larger number of martian images and their greater signal-to-noise ratio.

Atmospheric extinction was measured nightly, and the differential air mass between Mars and the comparison star was kept as small as possible in order to minimize the error in this