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Photometric properties of Ceres from telescopic observations using Dawn Framing Camera color filters

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ABSTRACT

The dwarf planet Ceres is likely differentiated similar to the terrestrial planets but with a water/ice dominated mantle and an aqueously altered crust. Detailed modeling of Ceres' phase function has never been performed to understand its surface properties. The Dawn spacecraft began orbital science operations at the dwarf planet in April 2015. We observed Ceres with flight spares of the seven Dawn Framing Camera color filters mounted on ground-based telescopes over the course of three years to model its phase function versus wavelength. Our analysis shows that the modeled geometric albedos derived from both the IAU *HG* model and the Hapke model are consistent with a flat and featureless spectrum of Ceres, although the values are ~10% higher than previous measurements. Our models also suggest a wavelength dependence of Ceres' phase function. The IAU *G*-parameter and the Hapke single-particle phase function parameter, *g*, are both consistent with decreasing (shallower) phase slope with increasing wavelength. Such a wavelength dependence of phase function is consistent with reddening of spectral slope with increasing phase angle, or phase-reddening. This phase reddening is consistent with previous spectra of Ceres obtained at various phase angles archived in the literature, and consistent with the fact that the modeled geometric albedo spectrum of Ceres is the bluest of all spectra because it represents the spectrum at 0° phase angle. Ground-based FC color filter lightcurve data are consistent with HST albedo maps confirming that Ceres' lightcurve is dominated by albedo and not shape. We detected a positive correlation between 1.1-μm absorption band depth and geometric albedo suggesting brighter areas on Ceres have absorption bands that are deeper. We did not see the "extreme" slope values measured by Perna et al. (Perna, D., et al. [2015]. Astron. Astrophys. 575 (L1-6)), which they have attributed to "resurfacing episodes" on Ceres.

1. Introduction

Ceres and Vesta, the targets of NASA's Dawn mission, represent two extreme evolutionary outcomes of the planetesimal population. Vesta, an igneous body with a differentiated crust, mantle and core, experienced significant heating similar to terrestrial planets including the Earth. Ceres, on the other hand, differentiated with a much different end result where water/ice is thought to dominate its mantle and an aqueously altered curst (e.g., McCord and Sotin, 2005; Rivkin et al. 2006). Ceres contains about 1/3 of the entire mass of the asteroid belt and is 3.5 times more massive the Vesta. With just 0.3 astronomical units (AU) separating the semi major axes of these two objects in the main belt, it remains unclear how these two objects could evolve to be so dramatically different in every aspect.

Ceres has been the focus of intense Earth-based (ground-based and Hubble Space Telescope) telescopic studies since its discovery in 1801 (e.g., Ahmad, 1954; Gehrels and Owings, 1962; Tedesco et al., 1983). However, several important physical properties (surface photometric properties) remain poorly constrained. Precise understanding of photometric behavior of a surface is vital for constraining its surface properties (e.g. composition, albedo, particle size, surface roughness, etc.). Observing geometry (phase angle) affects surface albedo and spectral band parameters (band depth

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and slope). Overlooking these effects leads to erroneous interpretation of surface composition, space weathering, and photometric properties (Reddy et al., 2012). Neither detailed modeling of Ceres' phase function, nor the study of its wavelength dependence, has been performed so far.

Phase angle is defined as the angle between the Sun and the observer as seen from the target object. Photometric phase functions of asteroids are derived by observing the change in brightness (typically in V magnitude) as a function of phase angle from ground-based observations and have been modeled using Hapke (1981, 1984, 1986) and Lumme and Bowell (1981) scattering theories. The phase function contains important information about the physical properties of the surface, such as single-scattering albedo, particle size, packing, large-scale roughness and transparency.

An important photometric effect is the steep increase in brightness for phase angles less than ~7° (the Opposition Effect) which has been explained as being a consequence of (1) disappearing shadows at extremely low phase angle (shadow-hiding opposition effect, or SHOE), and (2) constructive interference of coherent backscattered light (coherent backscattering opposition effect, or CBOE) (e.g., Shkuratov, 1988; Hapke, 1990; Rosenbush et al., 2006; Hapke et al., 2006; Muinonen et al., 2012). The amount of the opposition effect depends on the object's albedo; low and medium albedo objects (<25%) show less prominent opposition effect and high albedo objects (E-type asteroids and Vesta) show a more obvious and narrower opposition surge (Bowell et al., 1989).

Spectral phase effects are manifested primarily as "phase reddening" and band depth changes. Phase reddening is an effect where the spectral slope of the reflectance spectrum reddens with increasing phase angle. Band depth is also affected such that increasing phase angle causes deeper absorption bands (regardless of composition) (e.g., Reddy et al., 2012). Misinterpretation of surface composition (mineral abundance and space weathering effects) is possible if one does not correct for spectral phase effects (Reddy et al., 2012).

Dawn began its survey of Ceres in April 2015. The Framing Cameras (FC) on Dawn will map the surface in seven color filters (0.4–1.0 μm) and one clear filter with a best spatial resolution of ~35-m/pixel to understand its geology and cratering history (Sierks et al., 2012). Dawn is not expected to collect any data at phase angles <7°, and most data will be at phase angles between 20° and 80° due to trajectory and orbit constraints. Being in orbit around Ceres also means that the observing geometry will have correlations with sub-spacecraft latitude to some extent depending on the orbital altitude. These effects place limitations on the accuracy of photometric modeling (Li et al., 2013). Ground-based data were planned to overcome these interpretation limitations of Dawn data. Ground based photometric data taken through the FC filters can also be used to bridge Dawn FC data with previous ground-based studies by providing the same filter set as the former and similar spatial resolution to the latter. The usefulness of this study has been demonstrated in the similar work we performed for Vesta (Reddy et al., 2012). These ground-based observations and analysis have played an important role in the Vesta phase of the Dawn mission.

2. Observations and data reduction

2.1. Observations in 2011–13

Photometric observations of Ceres started in 2011 and were made with the seven Dawn FC filters (Table 1), a 0.30-m Schmidt–Cassegrain telescope (SCT) at Santana Observatory (SO) (Minor Planet Center/MPC Code 646), Rancho Cucamonga, California, and a 0.11-m refractor at Goat Mountain Astronomical Research Station (GMARS) (MPC Code G79), Landers, California. Subsequent observations in 2013 were obtained with the 0.35-m SCT at SO. All our photometric data were obtained using a SBIG ST-9e CCD camera. The choice of small telescope was dictated by the fact that Ceres was too bright (~8.0 V. Mag) for larger telescopes. A total of 17,789 photometric observations of Ceres were collected in seven Dawn FC filters during two oppositions with phase angle range of 0.82–21.4°. Observational circumstances for photometric data are shown in Table 2. In all our analyses data from both SO and GMARS is referred to as GMARS data.

Reduction and analysis of photometric data was done using Minor Planet Observer (MPO) Canopus software (Warner, 2006). MPO Canopus is a Windows-based integrated software package for astrometry and photometry. Canopus is capable of reducing photometric observations of asteroids, generating lightcurves, determining their rotation period, and constructing photometric phase curves. The MPOSC3 catalog that is native to Canopus software was used for photometric analysis. The MPOSC3 catalog includes a large subset of the Carlsberg Meridian Catalog and the Sloan Digital Sky Survey. A subset of the MPOSC3 catalog consisting of stars with about the same color as the Sun and having an accuracy of ~0.05 mag for V and 0.03 mag for R was used in the reduction. Using MPOSC3 photometric accuracy of 0.02 mag is typically achieved by averaging up to 5 comparison stars per field (Warner, 2006). Differential photometry was used with night-to-night calibration of the data (generally < ±0.05 mag) using field stars converted to approximate magnitudes based on Two Micron All-Sky Survey (2MASS) J-K colors. Since no star catalog values are available for the narrow band Dawn FC filters, the nearest broadband catalog value (BVRI) was used for the comparison stars in the field.

When the brightness of Ceres is compared with uncalibrated stars in a differential photometry manner it is not possible to calculate geometric albedo; instead, only relative albedo can be derived which can at least be used in constructing a reflectivity versus rotation variation for each FC band. Since Ceres has a rotation period (9.07 h) that is usually longer than a single night's observing session empirical adjustments were have to be made when comparing one night's light curve segment with another's in order to construct a complete phase-folded reflectivity variation.

2.2. Observations in 2014

Ceres was observed in 2014 in a way that was specifically designed for measuring albedo using the 7 Dawn FC filters. A 0.28-m and a 0.35-m Schmidt–Cassegrain telescope and SBIG ST-10XME CCD camera at the Hereford Arizona Observatory, HAO (MPC code G95) were used with the 7 FC filters to create a magnitude system for each of the filters by transferring Vega fluxes to Sun-like stars located near Ceres (Table 2). These secondary standard stars could then be observed in alternation with Ceres using standard all-sky observing techniques since both were at similar elevations (air mass values) throughout each observing session.

The advantage of this all-sky photometry calibration procedure over the use of background stars for differential photometry calibration is that systematic effects related to star color sensitivity are eliminated. Differential photometry requires the use of "CCD transformation equations" to remove differences in spectral response of a telescope system using a specific filter from the spectral response standard for that filter (e.g., V-band spectral response above the atmosphere). This problem is difficult enough when using a standard filter (e.g., V-band) for obtaining magnitudes associated with that filter because of response function differences produced by the CCD's quantum efficiency (QE), telescope optical