

**PHOTOMETRIC PROPERTIES OF CERES FROM TELESCOPIC OBSERVATIONS USING DAWN FRAMING CAMERA COLOR FILTERS.** V. Reddy<sup>1</sup>, J-Y. Li<sup>1</sup>, B. L. Gary<sup>2</sup>, R. Stephens<sup>3</sup>, R. Megna<sup>4</sup>, A. Nathues<sup>5</sup>, and L. Le Corre<sup>1</sup>, <sup>1</sup>Planetary Science Institute, Tucson, AZ 85719, [reddy@psi.edu](mailto:reddy@psi.edu); <sup>3</sup>Hereford Arizona Observatory, Hereford, AZ 85615; <sup>3</sup>Center for Solar System Studies, Rancho Cucamonga, CA 91730; <sup>4</sup>Riverside Astronomical Society, Riverside, CA. <sup>5</sup>Max-Planck Institute for Solar System Research, Goettingen, Germany.

**Introduction:** Ceres and Vesta, the targets of NASA's Dawn mission, represent two extreme evolutionary representatives of the planetesimal population. Ceres differentiated with a much different end result than Vesta where water/ice is thought to dominate its mantle (compared to olivine on Vesta) and an aqueously altered crust (e.g., [1] and [2]). Ceres also contains about 1/3 of the whole mass of the asteroid belt and is 3.5 times more massive than Vesta. Dawn is expected to start its observations of Ceres from orbit in April 2015. The Framing Cameras on Dawn will map the surface in seven color filters (0.4-1.0  $\mu\text{m}$ ) and one clear filter at  $\sim 35\text{-m/pixel}$  spatial resolution (only clear) to understand its geology and cratering history [3]. In addition, the visible and near infrared spectrometer (VIR), will obtain hyperspectral data (0.25-5.01  $\mu\text{m}$ ) of the entire surface at a resolution of  $\sim 100\text{-m/pixel}$  [4].

Ceres has been the focus of intense Earth-based (ground and HST) telescopic studies since its discovery in 1801. However, several important physical properties (e.g., composition & surface photometric properties) remain unconstrained or poorly constrained. Precise understanding of photometric behavior of a surface is vital for constraining its surface properties (composition, albedo, particle size, surface roughness, etc.). Observing geometry (phase angle) affects surface albedo, spectral band parameters (band depth and slope). If uncorrected, these effects lead to erroneous interpretation of surface composition, space weathering, and photometric properties [5]. Our goal is to constrain the photometric properties of Ceres since there has not yet been a detailed modeling of Ceres' phase function or a study of its wavelength dependence. With >660,000 asteroids discovered so far, and an ever-increasing cost of robotic exploration of small bodies, sending a spacecraft to many of these asteroids is inconceivable. Our study provides the opportunity to compare and validate existing ground-based tools and techniques for the characterization of small bodies.

**Dawn FC Filters:** The Dawn Framing Camera has seven color band filters and a broadband panchromatic (clear) filter. The seven color filters and one clear filter are named F1 through F8 in random order on the Dawn spacecraft. Filter F8 is the shortest wavelength filter at 438 nm and F5 is the longest filter at 965 nm (Table 1). The filters we used are flight spares that were mounted

in an standard 1.25" filter wheel for telescopic observations.

**Observations:** Photometric observations of Ceres were made with the Dawn FC filters using small telescopes in two phases. In the first phase, Stephens and Megna made observations in 2012-2013 with a 0.35-m SCT at Santana Observatory a 0.11-m refractor at Goat Mountain Astronomical Research Station. Nine nights were observed using the 0.11-m refractor at GMARS; all observations in 2013 were obtained with the 0.35-m SCT. The data were obtained using a SBIG ST-9e CCD camera in seven Dawn filters during two oppositions with phase angle range of  $0.82^\circ$ - $21.4^\circ$ .

A more robust data set involving the creation of a Dawn FC magnitude system was done by Gary in 2014 from Hereford Arizona Observatory using a 11-inch Celestron telescope and SBIG ST-10XME. Ceres was observed during the 3-month interval between March 16 to June 20 over a phase angle range of  $5.3^\circ$ - $20.8^\circ$ . Both data sets yielded lightcurves of Ceres in the seven Dawn filters.

**Data Reduction:** Data from 2012-2013 were reduced using MPO Canopus. The 2014 data was reduced using MaxIm DL and a spreadsheet that was designed for all-sky observations.

**Photometric Modeling:** We fitted the photometric data of Ceres through all FC filters with the IAU HG model [6]. Figure 1 shows the phase function through F2 (555 nm) as an example. The best-fit parameters at 555 nm are  $H=3.23\pm 0.02$  and  $G=0.07\pm 0.02$ . Compared to a previously reported model with  $H=3.38\pm 0.02$  and  $G=0.12\pm 0.02$ , based on ground-based observations in V-band [7], our best-fit model has an absolute magnitude that is  $\sim 0.15$  magnitude brighter, and with a steeper phase slope.

Assuming an equivalent radius of 470.7 km [8], we derived the geometric albedos for Ceres in the visible wavelengths region based on the best-fit H-parameters through all FC filters (Fig. 2). The geometric albedo of Ceres shows an overall flat and featureless spectral shape, consistent with previous observations. However, the geometric albedo spectrum we derived is slightly blue-sloped, and has higher values in 440 – 653 nm.

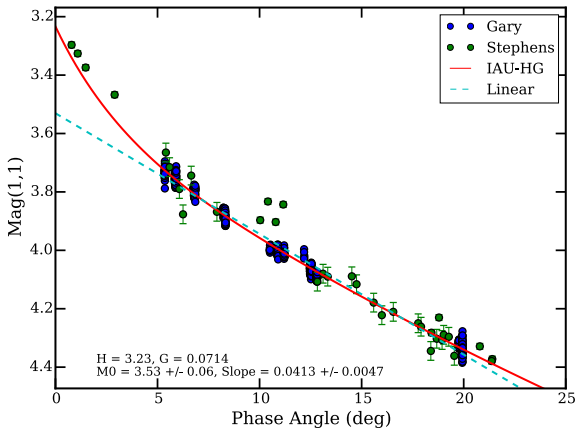
The wavelength dependence of the best-fit G-parameter (Fig. 3) suggests that the slope of the phase function of Ceres decreases with wavelength. Many factors affect the slope of a phase function, including

albedo (multiple scattering), the opaque internal scatterers in regolith particles, roughness, etc. Since the albedo of Ceres does not change substantially in the visible wavelength, the wavelength dependency of the slope of phase function cannot be attributed to varying multiple scattering with wavelength.

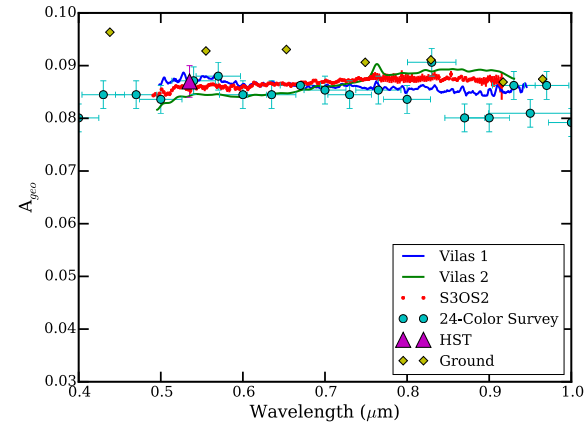
The lack of ground-based data at phase angles  $>25^\circ$  does not allow us to fully characterize the physical properties of regolith particles in terms of the internal structure based on forward scattering properties [9,10]. Dawn FC will collect photometric data at  $\sim 25^\circ$  to  $\sim 155^\circ$  phase angles [11], and should help determine the forward scattering properties of Ceres' regolith particles. For roughness, although it is a geometric property and should not depend on wavelength, shadows could be in principle washed out by multiple scattering, causing wavelength dependence for the modeled roughness. However, this effect has not been detected even for Vesta [12], whose albedo varies much more than that of Ceres in the visible wavelengths.

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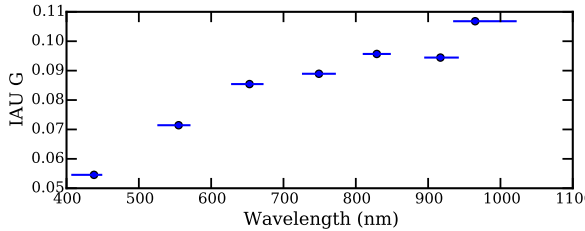
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**Fig. 1.** Phase function of Ceres through F2 (553 nm) filter.



**Fig. 2.** The spectrum of Ceres from various telescopic observations. The data points from previous HST observations (Li et al., 2006) and from this work are photometrically calibrated, while all other spectra (Vilas et al., 1998; Lazzaro et al., 2006; Chapman et al., 1993) are scaled to approximately match the geometric albedo at 553 nm from HST.



**Fig. 3.** The best-fit G-parameter for Ceres as a function of wavelength.

Dawn FC Designation	$\lambda_{\text{eff}}$ (nm)	FWHM ( $\mu\text{m}$ )
F8	$438^{+10/-30}$	40
F2	$555^{+15/-28}$	43
F7	$653^{+18/-24}$	42
F3	$749^{+22/-22}$	44
F6	$829^{+18/-18}$	36
F4	$917^{+24/-21}$	45
F5	$965^{+56/-29}$	86

**Table 1.** Dawn Framing Camera filter designations, band passes and FWHM used in our photometric study (Sierks et al., 2011)