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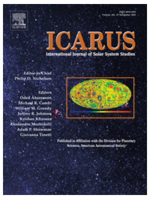

# Results of a hubble space telescope search for natural satellites of dwarf planet 1 ceres

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## ABSTRACT

In order to prepare for the arrival of the Dawn spacecraft at Ceres, a search for satellites was undertaken by the Hubble Space Telescope (HST) to enhance the mission science return and to ensure spacecraft safety. Previous satellite searches from ground-based telescopes have detected no satellites within Ceres' Hill sphere down to a size of 3 km (Gehrels et al. 1987) and early HST investigations searched to a limit of 1–2 km (Bieryla et al. 2011). The Wide Field Camera 3 (WFC3) on board the HST was used to image Ceres between 14 April–28 April 2014. These images cover approximately the inner third of Ceres' Hill sphere, where the Hill sphere is the region surrounding Ceres where stable satellite orbits are possible. We performed a deep search for possible companions orbiting Ceres. No natural companions were located down to a diameter of 48 m, over most of the Hill sphere to a distance of 205,000 km (434 Ceres radii) from the surface of Ceres. It was impossible to search all the way to the surface of Ceres because of scattered light, but at a distance of 2865 km (five Ceres radii), the search limit was determined to be 925 m.

## 1. Introduction

Ceres is the first object that was discovered in the asteroid belt between Mars and Jupiter. In many ways, it is a unique object, being the largest object, and the only one to assume a hydrostatic shape in the asteroid belt. It also possesses the spectral signature of phyllosilicates, organics, ammoniated species, and carbonates on its surface (Rivkin et al. 2002, Milliken et al. 2009, DeSanctis et al. 2015). In 2006, the IAU re-categorized Ceres to 'Dwarf Planet' alongside other objects such as Pluto and Eris. Dawn arrived at Ceres in March 2015. The first exploration of Ceres by the Dawn mission has provided opportunities to better understand Ceres' history, as well as the evolution of the early Solar System (Russell et al. 2007). With Dawn entering orbit with only two reaction wheels, serious constraints are placed on pointing, limiting the dedicated satellite search and the possibility of observations of such a satellite if one were detected (Polanskey et al. 2014). Thus, with the approach of Dawn imminent, we undertook a search for satellites of Ceres using the Hubble Space Telescope in April 2014.

Over 270 asteroids, even small ones, are known to have Moons or be binary (Johnston 2016). The first asteroid with a Moon was observed by the Galileo spacecraft in 1993 as it passed the 16 km S-class asteroid 243 Ida, revealing its small Moon Dactyl at a distance of 90 km (Chapman et al. 1995). There are 58 known satellites of near-Earth asteroids, 117 known around main belt asteroids, and at least 95 around minor planets elsewhere in the Solar System. Asteroid satellites can be formed by a number of processes, including impact ejection, impact disruption, and reaccretion (Weidenschilling 1980, Merline et al. 2002). Notably, the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect can cause elongated or odd-shaped asteroids that pass near the Sun to significantly increase in rotation speed (Lowry et al. 2007). As an asteroid releases heat as thermal energy, this process is also able to add angular momentum, causing an asteroid's rotation rate to change to a degree that fission may occur (Pravec et al. 2010). Ceres' spin rate, with a rotational period of nine hours, is too slow to fission material. However, with its large cross section, it has certainly experienced impact events that could liberate material to

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form Moons. Its hydrostatic shape with relatively subdued topography should allow for stable satellite orbits (Scheeres et al. 1996). However, the large asteroid 4 Vesta, which is about half the diameter of Ceres and is thought to have formed in a similar way, possesses no satellites down to a radius of 3–6 m (Memarsadeghi et al. 2012, McFadden et al. 2015). Either result would be of scientific value. Beyond the novelty of detecting a satellite, observations of a Moon could help constrain Ceres' history and composition. Differently from Vesta (Zappala et al. 1995), no meteorite has been identified as a spectral match for Ceres. This has been interpreted as one of many indications that Ceres is ice rich (Russell et al. 2007, Rivkin et al. 2014), thus discovery of a Moon could shed light on this hypothesis.

Satellite searches are common practice for small bodies, especially those with approaching spacecraft (e.g. Chapman et al. 2002). Weaver et al. (2006) and Showalter et al. (2011, 2012) discovered four additional satellites surrounding the Pluto-Charon system using the Hubble Space Telescope's cameras. In addition, McFadden et al. (2012) used similar Hubble imaging techniques to study the asteroid Vesta's neighborhood prior to Dawn's arrival. Their investigation concluded that no satellites existed that were larger than 22 +/- 2 m radius, a result which was confirmed and improved upon to 3–6 m when Dawn arrived at Vesta (Memarsadeghi et al. 2012, McFadden et al. 2015). Previously, Bieryla et al. (2011) searched for Moons around Ceres using the Hubble Space Telescope and found none down to a size limit of about 1 km. Ground-based observations of Ceres were also utilized to conduct a deep Moon search, returning no detections of satellites down to 2 km within Ceres' full Hill sphere (Bieryla et al. 2011).

## 2. Methods

### 2.1. Hubble Space Telescope Satellite Search

We used the Hubble Space Telescope's Ultraviolet and Visible Light Wide Field Camera 3 (UVIS WFC3), a third-generation HST instrument that provides the highest spatial resolution of any of its instruments at 0.04″/pixel. Unaffected by atmospheric variability that plagues ground-based telescopes, HST is ideal for the satellite search because of its extremely stable thermal environment, well-characterized detectors, and high sensitivity. We used an approach similar to satellite investigations that have been conducted for Vesta, Ceres, and Pallas using HST (McFadden et al. 2012, Bieryla et al. 2011, Schmidt et al. 2009). The goal of the study was to exceed the limits of previous satellite searches that were complete to object sizes of 1–2 km within the full Hill sphere. The 2006 HST study (Li et al. 2006) did not include many deep exposures required to detect satellites smaller than about 1 km since its focus was on Ceres itself, not potential satellites. The ground-based search was limited to observing far from Ceres due to atmospheric seeing limitations. Thus, we chose an approach that combined several techniques to draw out any possible satellites hidden by previous work.

We observed during four 96-min HST orbits between April 14 to 28, 2014 (HST program 13,503, PI Britney Schmidt). These observations occurred when Ceres was at 5° phase angle and reached an angular size of 0.82″. We obtained deep exposures with the WFC3 in the UVIS F350LP filter (long-pass, visible 300–800 nm). The observations were intentionally spaced at different intervals of 1 day, 5 days, and 8 days between orbits to minimize aliasing with any possible satellite orbital periods. We did not specify the orientation of the spacecraft, and so obtained a random distribution of the placement of the diffraction spikes to avoid obscuring satellites in a systematic way. The observations included short 0.5 s and 5 s exposures, reading out small subarrays to search near Ceres for close-in satellites missed by previous surveys (with less obscuration from saturation and scattered light). There were also mid- and long-exposures of 30, 120 and 180 s in duration where Ceres was intentionally overexposed to search the greater part of Ceres' Hill sphere (using full CCD readouts) for objects much smaller in size and/or further away from Ceres (which is significantly saturated in the long exposures). Details of the observations are shown in Table 1.

**Table 1**
Summary of exposures taken over the course of four HST orbits. All images were taken with the WFC3 camera in the F350LP filter.

| Hubble Space Telescope observations of Ceres | | |
|---|---|---|
| | Date and Time (UTC) | Exposure times |
| Orbit 1 | 14 April 2014, 16:04 – 16:39 | 120 s x 2, 30 s x 4, 5 s x 4, 0.5 s x 6 |
| Orbit 2 | 15 April 2014, 14:22 – 14:59 | 120 s x 2, 30 s x 4, 5 s x 4, 0.5 s x 6 |
| Orbit 3 | 20 April 2014, 12:18 – 12:52 | 180 s x 2, 30 s x 2, 5 s x 4, 0.5 s x 5 |
| Orbit 4 | 28 April 2014, 13:01 – 13:37 | 180 s x 2, 30 s x 2, 5 s x 4, 0.5 s x 5 |

### 2.2. Data processing and analysis

#### 2.2.1. Image products

Starting with calibrated WFC3 images retrieved from the Mikulski Archive for Space Telescopes (MAST), we further distortion-corrected, aligned, and combined the images to produce three different data products. Each image was 'drizzled', and then the images were aligned by placing the intersection of diffraction spikes, which corresponds with the center of Ceres, at the direct center of each image. Finally, the exposed portions of the images were rotated to place north up. The first product, a sum image, is simply a linear addition of multiple images, each with the same exposure time, taken during a single orbit. The second product, 'combine', is a clean image obtained by taking the median of each corresponding pixel in multiple images, and using that as the value to the corresponding pixel in the output image. In the case where there are only two such images per orbit, as is the case for the 120-s and 180-s exposures, this filter simply becomes a mean-filter, which acts to slightly suppress cosmic rays. For the third product, we applied unsharp-masking, a digital enhancement process in which a Gaussian convolution of the original was subtracted from the original image. We apply this to the clean, combined images in order to create an image product with a flatter dynamic range making it easier to identify faint candidate satellites. These processing methods are valuable for initial investigation because they remove a large number of obvious artifacts and stars while still allowing a thorough search. However, these methods can remove candidate objects from the data, so verification involves a careful inspection of these data products to rule out artifacts and identify candidate objects. We searched by comparing (blinking) the combined and single images to search for satellites using SAOImage DS9. In the final phase of the investigation, we added artificial Gaussian point-spread functions at different locations into the original data to simulate detectable satellites at a range of sizes. Based on whether or not these artificially added objects could be detected by the methods of the original search, a limitation on search magnitude could be set. In Fig. 1 we show an example HST search image, a 'sum' of two 180-s exposures, where Ceres is overexposed and placed in the center of the image. In Fig. 2 we show the same two 180-s exposures, as they appear when processed with 'combine' and 'unsharp', respectively.

#### 2.2.2. Search methodology

In order to compare the search results of the processed images with potential physical results, we investigated the expected motion of a true satellite between frames. The Hill sphere is a region