SEARCH FOR SATELLITES AT CERES:UPPER LIMITS FROM DAWN'S FRAMING CAMERA

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Introduction

Hundreds of asteroids have small secondary satellites or are double, or even multiple body systems; yet Ceres doesn't and isn't. Dwarf planet Pluto has five satellites yet dwarf planet Ceres has none. Ground-based and space-based telescopic searches have yielded ever-decreasing limits on the size of any small secondary bodies gravitationally bound to Ceres (Bieryla et al. 2011, . The Dawn project's satellite working group conducted a satellite search during approach to Ceres searching close to the limb where previous searches could not. Images acquired for optical navigation and rotational characterization were also searched. More than 448 images were examined for evidence of moving objects gravitationally bound to Ceres during the dedicated satellite search at range of ~145,000 km from Ceres, and phase angle of 18°. No moving objects associated with Ceres were detected. The search extended down to Ceres' limb (previous searches went to 15,000 km above the limb) and extended the upper limit for the non-detection to 30 +/- 6 and 45 m +/-9 m radius for two effective exposure times (114s and 19s respectively). Previous upper limits to detection were in the 1-2 km range from Hubble Space Telescope observations (Byierla et al. 2011). The Dawn mission's search reduced the detection limit by two orders of magnitude. Why some asteroids have satellites and others don't is a matter for dynamical speculation.

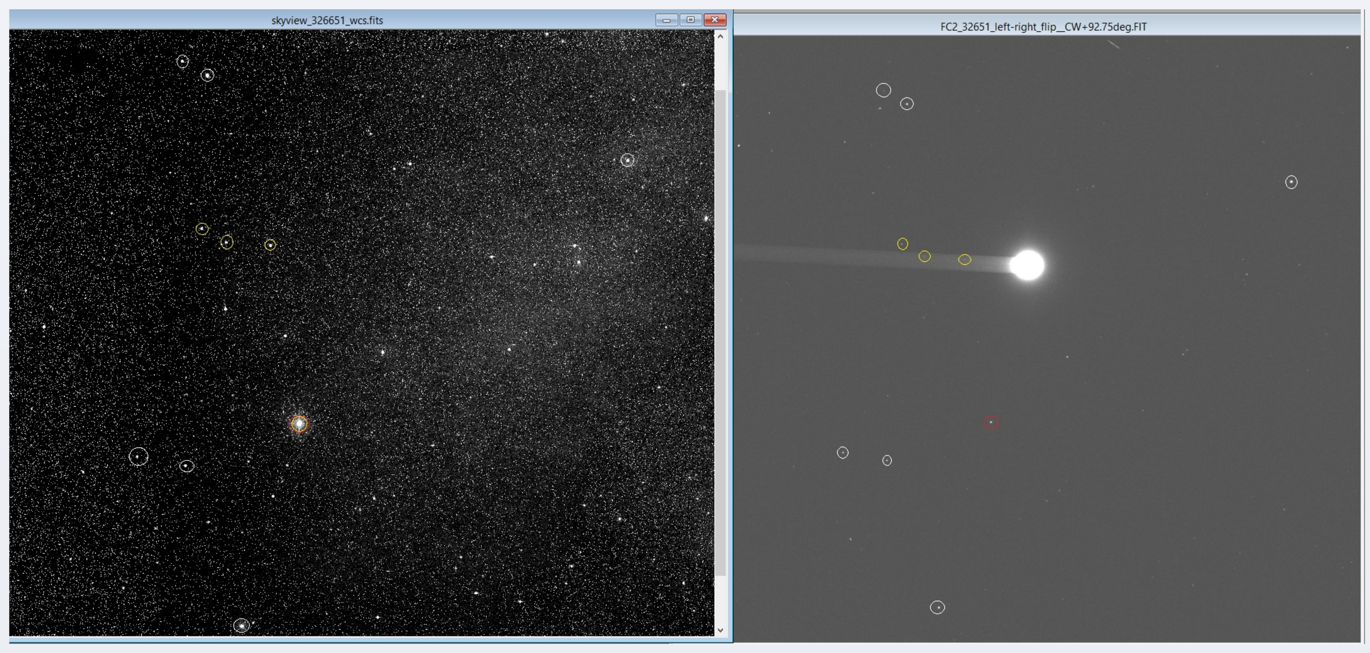

Fig. 1 Left: Photograph of 5° x 5 ° sky view at location of Ceres at the first Optical Navigation(OpNav) image, 32651. Stars seen with Dawn's framing camera are circled. Right: Framing Camera image 32651, showing Ceres (brightest object) and brightest of stars seen at left. The trail from Ceres is due to fast transfer into the CCD storage areas and is NOT a comet jet.

Observations

Our satellite search imaging strategy builds upon experience from Dawn mission's search for satellites at Vesta (McFadden et al. 2015) and the state of the spacecraft on approach to Ceres with only two of four reaction wheels operational (Rayman & Mase, 2014) . From Vesta, we realized that short exposures aligned and coadded provide more sensitive detection limits for moving objects. The driver for shorter exposures also coincided with the spacecraft's pointing limitations that were ~1pixel/s, on average. Because the width of spacecraft drift is different in each axis, the camera boresight traced out a broken path during a set of OpNav observations (Fig. 2). The optimuum exposure time for satellite search images was 2 seconds.

Fig. 2 Left Sum of 40 images of OpNav 1 showing spacecraft drift and short and long exposures. Right: Sum of long exposures only from OpNav 2.

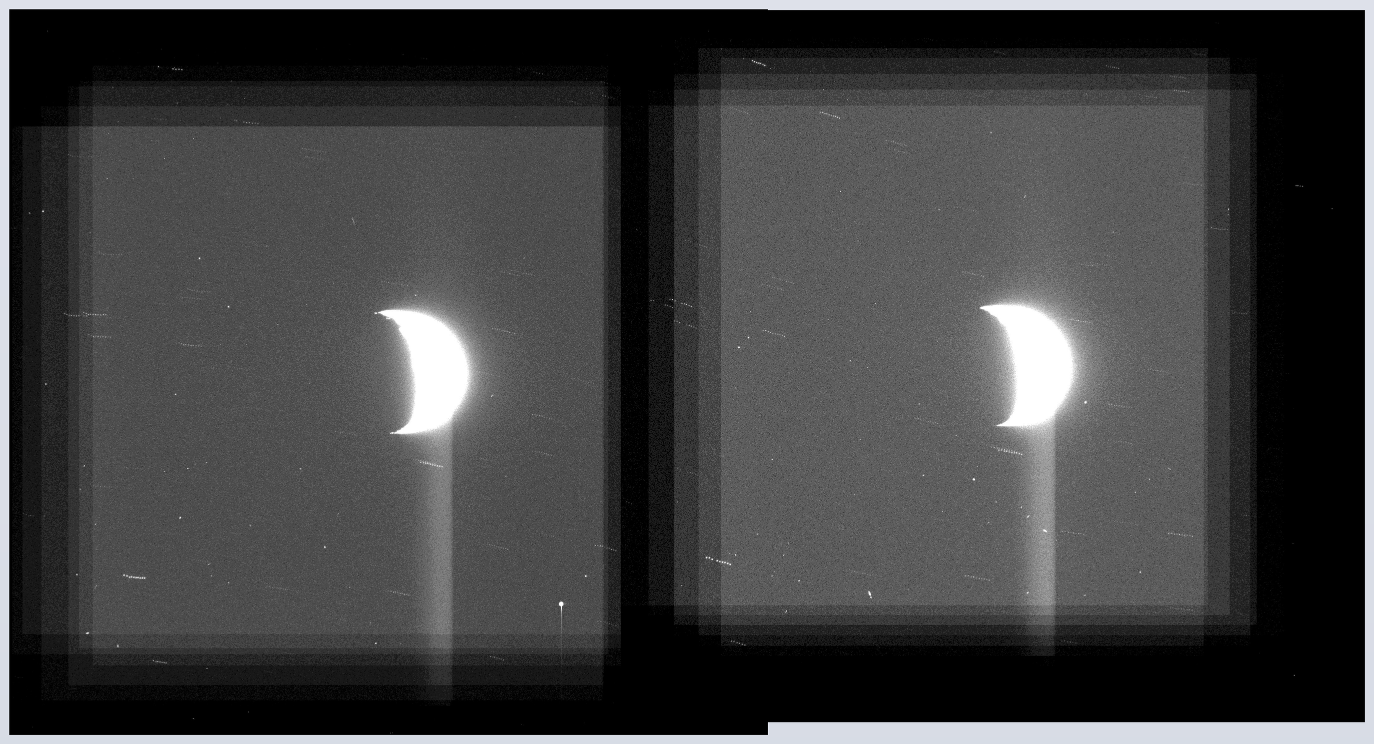

Fig.3 OpNav5, co-registered images on Ceres, co-added first 10 (left) and second 10 (right) of 20 OpNav images. Star in left image at lower right is Sirius (α Cma).

Satellite Search Methods

Start date	Feb 4, 2015 2015-035
Duration (1a/1b)	02:10:00/03:15:00
Range	149,000 &147,000 km
Phase	n/a
Latitude	-23 & -22 deg
Ceres size	n/a
FC2 Ceres images	0
FC2 star/satellite images	0 / 192 & 256
FC2 total images	448
FC2 exposures	2000 ms
FC2 compression	4:1
VIR cubes	0
VIR frames (IR+VIS)	n/a
VIR total frames	0
VIR repetition times	n/a
VIR compression	n/a

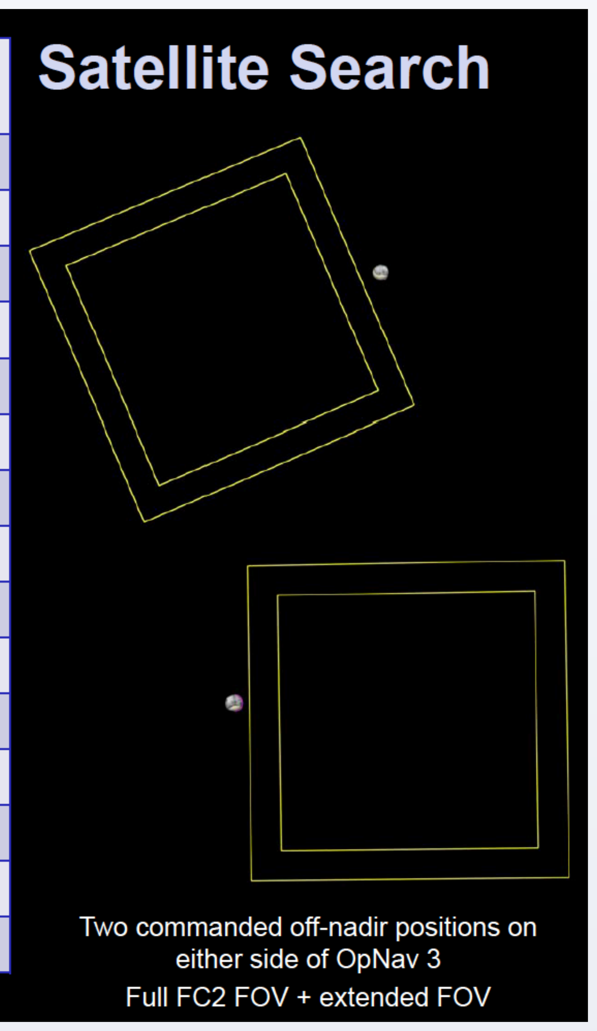

Fig. 4 Two dedicated satellite search segments were planned and executed following OpNav 3. Commanded pointing was offset from Ceres as shown, right.

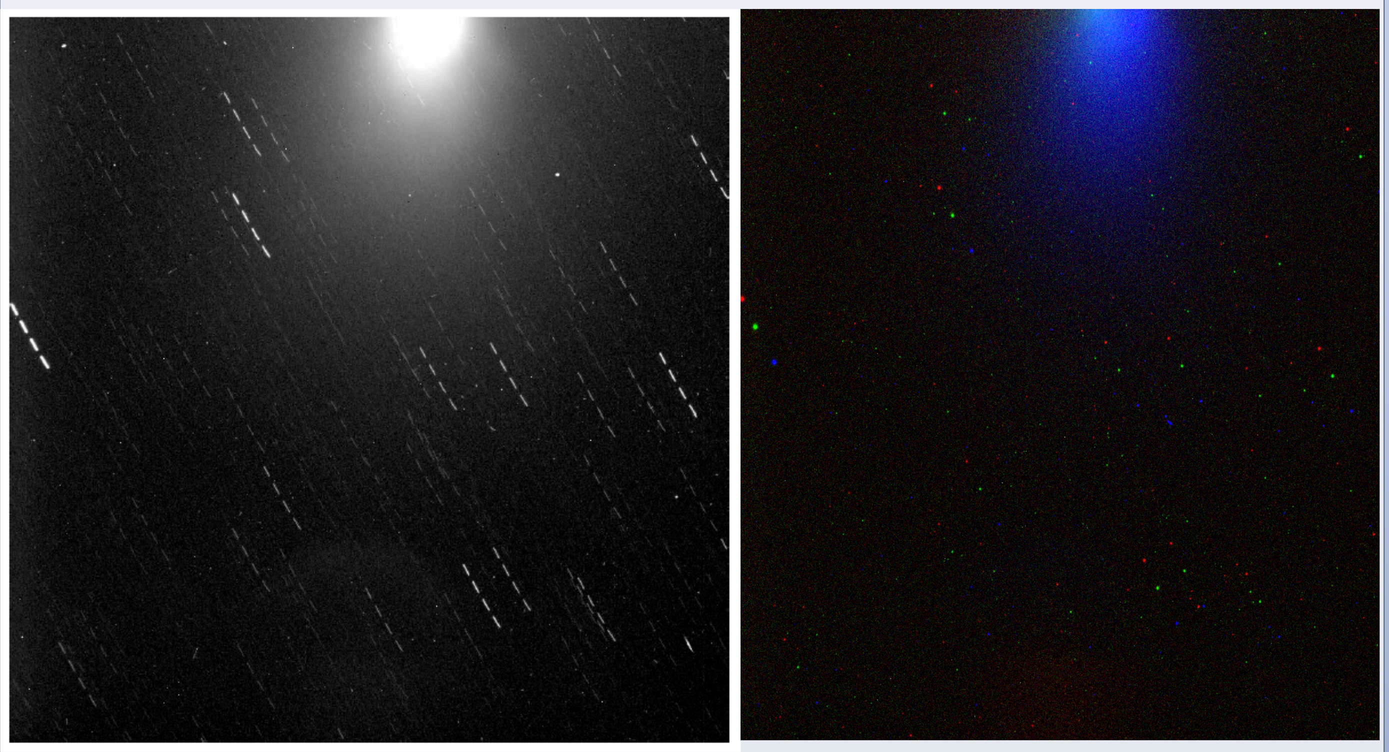

Fig. 5 a: Satellite search images, registered, stacked and displayed on a logarithmic brightness scale.
b:. . As a sanity check, the first (red), middle (green) and last (blue) images are combined and displayed verifying that images of astronomical objects, have all three, ordered colors in the trail.

Artifact Catalogue

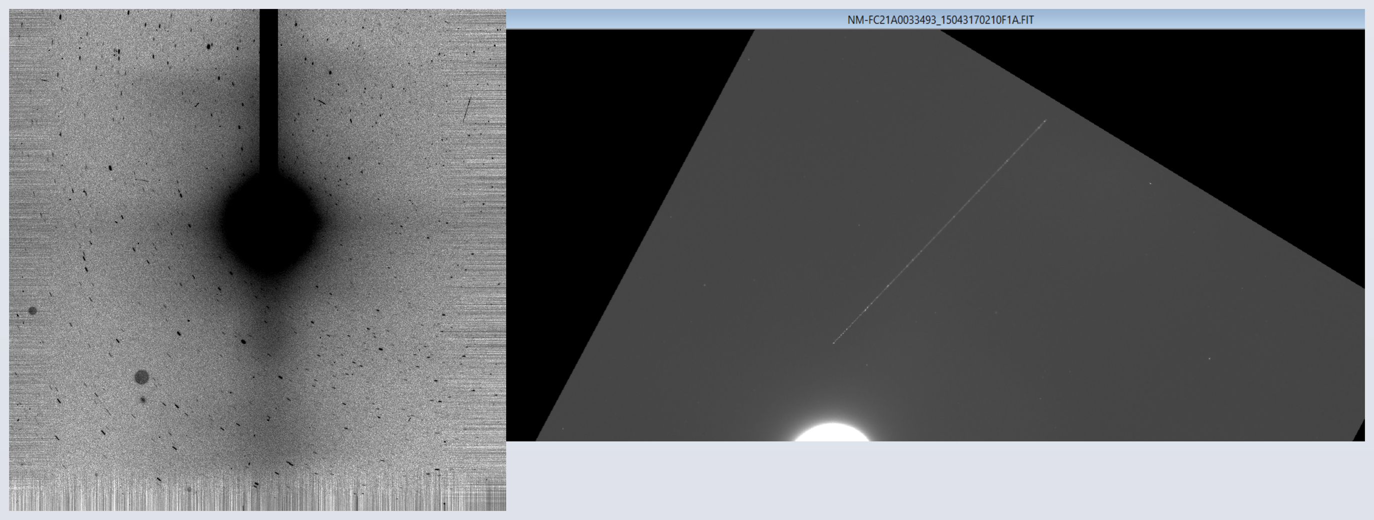

Fig. 6 left: blobs seen in OpNav 2. They are moving away from the spacecraft, are not associated with Ceres, And are believed to originate from the spacecraft. Right: cosmic ray at a glancing angle to the camera.

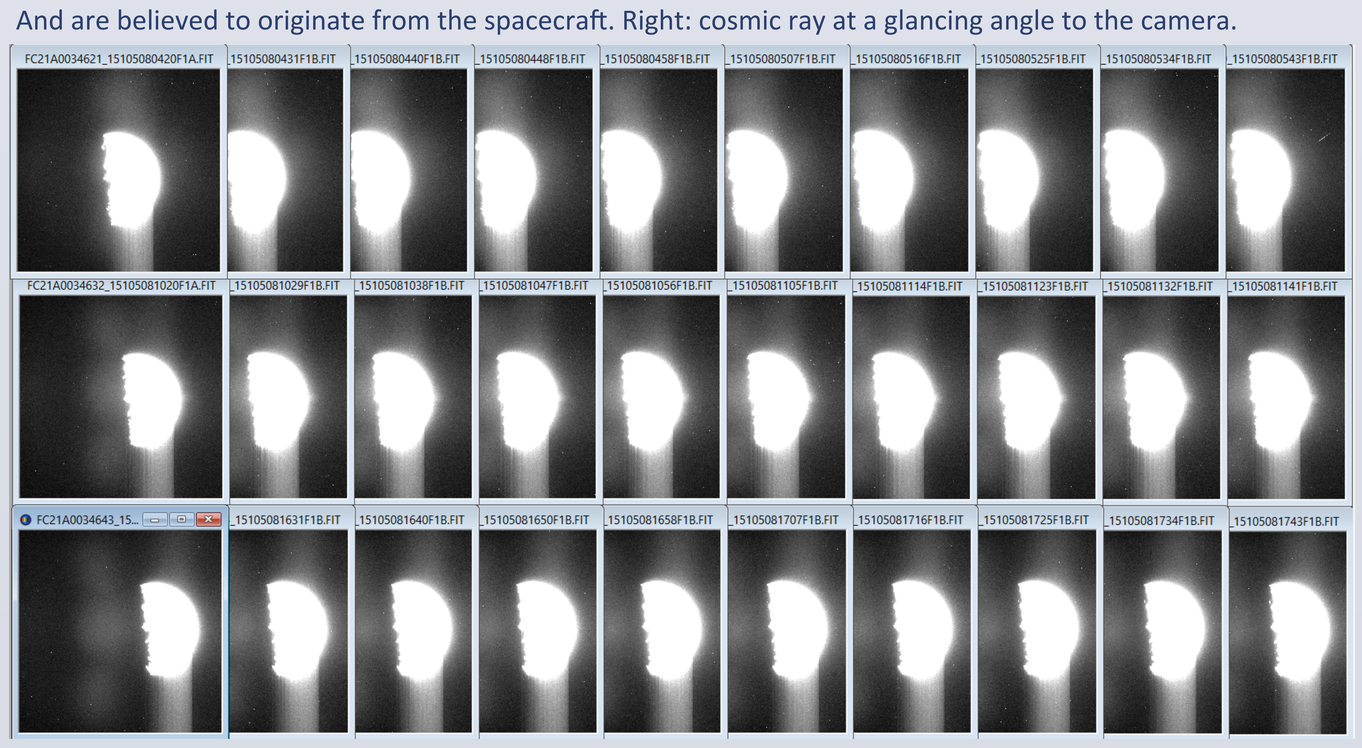

Fig. 7 A sequence of RC3 images with a hot pixel appearing near Ceres limb in the middle row.

Results and Upper Limits of Search

Nothing was found in motion under the gravitational influence of Ceres during any of the optical navigation sequences, the ride-along images, rotational characterization imaging, star tracker search, nor the dedicated satellite search sequences. These observations were carried out from January 13-April 29, 2015 when the spacecraft was 383,000 -14,000 km from Ceres. We were able to search down to Ceres' limb with the range of magnitude detection limits in Table 1.

Table 1: Observing circumstances for satellite search spacecraft activities and limiting size of any detectable object assuming Ceres albedo of 0.09 and phase function from Reddy et al. 2015.

UTC	Sequence	Range (km)	Phase	rh_SC (km)	ExpTime (s)	Mag	Mag (PhaseCorr)	Radius (m)	-
2015-01-13T20:20:50	OPNAV 1	383,111	26	423,264,313	1	10.5	9.2	188	
2015-01-25T22:21:22	OPNAV 2	238,100	23	424,697,185	1	10.5	9.3	112	
2015-02-04T07:46:06	OPNAV 3	146,722	18	425,776,594	2	10.5	9.5	64	
2015-02-04T05:01:06	MoonSearch1	147,707	19	425,763,617	2	11.7	10.7	38	
2015-02-04T11:03:06	MoonSearch2	145,548	18	425,792,084	2	11.7	10.7	37	
2015-02-25T19:07:36	OPNAV 4	40,450	96	428,141,982	2	12.8	9.2	20	
2015-03-02T00:32:56	OPNAV 5	49,417	123	428,591,048	2	12.8	7.6	51	
2015-04-10T08:06:46	OPNAV 6	33,734	131	432,360,785	2	12.8	6.9	48	
2015-04-15T08:11:03	OPNAV 7	22,827	90	432,792,575	2	12.8	9.5	10	
2015-04-25T07:10:01	RC3 HIGH_PHASE_SOUTH 1	13,974	111	433,680,279	5	10.5	6.2	29	
2015-04-25T07:10:01	RC3 HIGH_PHASE_SOUTH 1	13,974	154	433,680,279	5	10.5	1.3	274	
2015-04-29T06:20:01	RC3 HIGH_PHASE_NORTH 1	14,002	155	434,032,808	5	10.5	1.0	306	
2015-04-29T06:20:01	RC3 HIGH_PHASE_NORTH 1	14,002	95	434,032,808	5	10.5	7.0	20	

The upper limit of detectable radius of a satellite, had one been found, was between 20-360 m. This is 1 to 2 orders of magnitude smaller than determined from previous searches using Hubble Space Telescope (Bieryla et al. 2011, Demario et al (in prep). With decades of searching for satellites using multiple observational techniques and search strategies, from ground and spacecraft, the likelihood of finding satellites orbiting Ceres is small. There are no satellites of Ceres.

Discussion

Analysis of images acquired by the framing camera on the Dawn spacecraft have been searched for orbiting objects around both Vesta and Ceres. None larger than radius of 3-m (McFadden et al. 2015) and 20-m respectively (this work) have been found. A search for satellites around Pallas, the third largest asteroid was conducted using adaptive optics and nothing was found to an observational limit of 0.5 km (Vega & Marchi, 2015). Gaftonyuk & Gorkavyi (2012) look at the dependence of asteroids with satellites and the physical parameters of the primary's size and rotation rate, finding that the frequency of binary asteroids correlates with increasing rotation rate. The relationship between the existence of satellites or binaries and their mass is bifurcated. The physical conditions during asteroid formation do not support satellite formation around large asteroids.

Table 2- List of the 20 largest asteroids with presence of satellites (if any) noted.

Number	Name	Diameter (km)	Satellite name	Satellite name2
1	Ceres	946		
4	Vesta	525		
2	Pallas	512		
10	Hygiea	431		
704	Interamnia	326		
52	Europa	315		
511	Davida	289		
87	Silvia	286	Romulus	Remus
65	Cybele	273		
15	Eunomia	268		
3	Juno	258		
31	Euphrosyne	256		
624	Hektor	241		
88	Thisbe	232		
324	Bamberga	229		
45	Eugenia	214	Petit Prince (13km)	S2004(45) 1 (6km)
41	Daphne	189	S/2008(41) 1	
22	Kalliope	166	Linus (28 km)	
93	Minerva	141	Aegis (4km)	Gorgoneion(3km)
90	Antiope	87.8	S/2000(90) 1 (84km)	

None of the asteroids larger than 300 km diameter have satellites. These results change the question from why do large asteroids have no moons, to what is it about their formation conditions that prevent the largest asteroids from having satellites or anything gravitationally bound in the 10's m or larger size range?

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