Asteroids, Comets, Meteors 1991, pp. 577-581
Lunar and Planetary Institute, Houston, 1992

S/35-89

140990

A CCD Search for Distant Satellites of Asteroids 3 Juno and 146 Lucina

p. 5

N93-19248

S. Alan Stern
Space Sciences Department
Southwest Research Institute
San Antonio, Texas

and

Edwin S. Barker
McDonald Observatory, University of Texas
Fort Davis, Texas

Abstract

We report the results of CCD searches for satellites of asteroids 146 Lucina and 3 Juno. Juno is one of the largest asteroids (D=244 km); no previous deep imaging search for satellites around it has been reported. A potential occultation detection of a small satellite orbiting 146 Lucina (D=137 km) km was reported by Arlot et al. (1985), but has not been confirmed. Using the 2.1m reflector at McDonald Observatory in 1990 and 1991 with a CCD camera equipped with a 2.7 arc-sec radius occulting disk, we were able to achieve limiting magnitudes of $m_R = 19.5$ and $m_R = 21.4$ around these two asteroids. This corresponds to objects of 1.6 km radius at Juno's albedo and distance, and 0.6 km radius at Lucina's albedo and distance. No satellite detections were made. Unless satellites were located behind our occultation mask, these two asteroids do not have satellites larger than the radii given above.

I. Introduction

The search for satellites of asteroids has been a topic of interest and discussion for some years. As described by Weidenshilling et al. (1989), evidence for asteroid satellites includes certain anomalously slow rotation rates, the shape of certain asteroid lightcurves, elongated asteroid images (e.g., 9 Metis) and the statistical frequency of doublet craters on the Earth and Moon (cf., the interesting recent work by Melosh and Stansberry 1991). Interest in binary asteroids has been further fueled by the discovery that Near-Earth Asteroid (NEA) 4769 Castalia (1989PB) is clearly bifurcated in radar images (Ostro et al. 1990).

In principle asteroid satellites could be created by several processes, including rotational fission, fragmentation followed by mutual capture, or as a result of ejecta from a low-speed collision. Theoretical results (Weidenshilling, et al. 1989; Chauvineau and Mignard 1990a,b) demonstrate that a range of long-term stable orbits exist, particularly for close binaries, even when solar and Jovian perturbations on the orbit are included.

The most immediate application of the discovery of an asteroid satellite would be the direct mass and density determination of the parent asteroid. Subsequent studies of the satellite's osculating elements would then permit information to be gleaned about the internal structure, tidal evolution, and lifetime of the parent-satellite system (particularly if the system has not reached tidal lock). The detection of asteroid satellites or orbiting debris would also (i) lead to new information on collision statistics in the parent-body orbit, and (ii) clearly be of interest to spacecraft mission designers. Yet another exciting opportunity would be the potential for observations of mutual occultation events between the asteroid and its satellite, which could reveal important details about the individual radii, shapes, and surface markings of the parent asteroid and the satellite.

The general absence of *large* satellites around the brightest asteroids (m_v <16.5) was noted almost 35 years ago (Kuiper et al. 1958) However, the presence of small satellites orbiting asteroids remains an open research topic. (e.g., van Flandern, Tedesco, and Binzel 1979; Weidenshilling, et al. 1989).

Two CCD imaging surveys for asteroid satellites have been reported in the past: Gehrels et al. (1987) and Gradie and Flynn (1988). Together these two groups searched the fields around 22 asteroids with detection limits of $m_v \sim 18 - 22$, which correspond to satellite diameters of a few km in most cases. No detections were made. Taken at face value, these searches indicate that less than $\sim 4\%$ of all asteroids have faint companions. In fact, owing to the concentration on relatively large asteroids and distant-satellite orbits, the actual satellite-occurrence statistics for the asteroid population as a whole could be quite different.

We report here the results of a project we undertook in preparation for a new satellite search around ~ 50 asteroids. In this pilot project, we made searches around two new objects: 3 Juno and 146 Lucina.

II. 3 Juno

The search for objects orbiting the S type 3 Juno was made on 7 May 1990 UT. Juno was near aphelion at a heliocentric distance of 3.34 AU, a geocentric distance of 2.36 AU, and less than 72 hours from opposition.

To conduct this search, we employed the 2.1m Struve reflector at McDonald Observatory, equipped with a focal reducing camera (FRC). The FRC employs a Tektronix 512x512 CCD with $15e^-$ readout noise. The FRC optical train was configured with an RG5 filter to reduce Rayleigh scattered moonlight, and a 5.4 arcsec diameter occulting disk to block the light of Juno itself. This configuration allowed us to search the entire region beyond ≈ 10 arcsec from Juno with the scattered light nearly-eliminated. In the region between 6 and 10 arcsec from Juno, which is outside the occulting mask but inside the region where diffraction, seeing, and finite pixel size effects contribute to scattered light, we found the scattered/diffracted light PSF to be angularly symmetric. This allowed us to search this region for discrete photometric peaks which might represent a close-in satellite. However, scattered/diffracted light statistics caused our detection limits in the 6-10 arcsec region to be $\approx$2 magnitudes less constraining than those beyond 10 arcsec. Calibration images of Juno itself were made in order to obtain a magnitude standard for this run.

The plate scale of the FRC was measured to be 1.01 arcsec/pixel. The clear field of the filter was 265 arcsec across. We estimate the size of Juno's sphere of influence, according to Szebehely's tidal stability criterion (Szebehely 1967), as:

$$R_{stab} = a_J(1 - e_J)\left(\frac{\mu}{81}\right)^{1/3} \tag{1}$$

where a_J is Juno's semi-major axis, e_J is Juno's orbital eccentricity, and μ is the ratio of Juno's mass to the solar mass. Taking Juno's radius to be 122 km (Tedesco et al. 1989) and adopting a density of 3 g cm^{-3}, we find $\mu = 1.14 \times 10^{-11}$ and$R_{stab} = 1.56 \times 10^4$ km. At the 2.36 AU geocentric distance on the night observed, this corresponds to a stability radius of 128 Juno radii or ≈9 arcsec on the sky. Given Juno's geocentric distance on the night observed, the 5.4" occulting disk prevented us from observing objects within ≈38 Juno radii of the asteroid, or 15% of the projected stability field. Assuming a bulk density of $\rho_{juno} = 3$ g cm^{-3}, a satellite orbiting synchronously with Juno would lie near $2.4R_{juno}$.

We guided the image on Juno while imaging the surrounding field in a series of deep CCD exposures. Over a period of an hour, we made eight CCD exposures of the field surrounding Juno. Juno's sky motion during our observations was 33 arcsec/hr. This rapid motion ensured that any suspect satellites could easily be seen to move with Juno against the fixed background star field. Assuming Juno's density is near 3 gm cm^{-3}, an object with a semi-major axis at the edge of the stablity region defined by Szebehely's criterion would have a period of 115 days. An object orbiting at the edge of our occulting disk would have a period of 18.6 days. Therefore, any satellite of Juno would be seen to move across the background star field very nearly in concert with, and in an essentially fixed relation to Juno.

The seeing in the Juno field images was typically 2-2.3 arcsec FWHM during our observations. This necessitated the use of a rather wide, 5.4" occulting disk. Eleven images of the field surrounding Juno were obtained, with exposure times ranging from 100 to 600 seconds. Seven of these images had 300 second exposure times.

The Juno field images were processed using IRAF and then looped on an image display device to search for co-moving companions. Different scaling and image processing methods (e.g., histogram equalization, smoothing, and removal of background stars) were used to assist in the satellite search. No co-moving object detections were made.

To determine the limiting magnitudes of the search, the DAOPHOT routine ADDSTAR (Stetson 1987) was used to create artificial stars on representative CCD images. A total of 1000 artificial stars were used to determine limiting magnitudes. These artificial stars were created spanning a range of magnitudes as low as 26, using an as-measured point-spread-function (PSF) of Juno; appropriate counting statistics were added to each artificial PSF. These artificial images were then examined visually in the same manner as the program images to find the number of stars detected as a function of magnitude. To convert instrumental magnitudes to observed magnitudes, the DAOPHOT routine PHOTOMETRY was used to measure the magnitudes of 3 Juno in our magnitude-reference frame. The differences between these instrumental magnitudes and their true observational magnitudes were used to scale the measurements of the artificial stars. Using these techniques we found the Juno images allowed us to detect co-moving objects as faint as $m_R = 19.5$ in the region beyond 10 arcsec from Juno and $m_R = 17.6$ in the region between 6 and 10 arcsec from Juno.

Juno's V magnitude on 7 May 1990 was 10.1. Based on the limiting R magnitude of 19.5 in our search, we conclude that no objects larger than $\approx 3.3\sqrt{\alpha}$ km were orbiting Juno beyond 37R$_{juno}$, at the time of our observations, where α is the albedo ratio of a prospective satellite to Juno.

III. 146 Lucina

On UT 5 and 6 May 1991 we observed the field around the C type 146 Lucina using the same instrument and observing protocols as the 3 Juno observations conducted in 1990. Taking Lucina's radius to be 68.5 km (Tedesco et al. 1989) and adopting a density of 3 g cm^{-3}, we find $\mu = 2.03 \times 10^{-12}$ and $R_{max} = 1.08 \times 10^4$ km. At the 1.73 AU geocentric distance observed, this corresponds to 100 Lucina radii or ≈86 arcsec on the sky.

On 5 May 1991 we obtained seven 600 second integrations on the field surrounding 146 Lucina using the same occulting disk as in the Juno work. On 6 May 1991 we obtained an additional 3 exposures of the surrounding field, two of which were 1800 sec in length; a third, 600 second exposure was also obtained. Given the 1.73 AU geocentric distance of Lucina on the two nights observed, the occulting disk prevented us from detecting any objects located within ≈3400km of the asteroid (50 Lucina radii; period=28 days); this distance corresponds to about 32% of size of the projected stability field (this constraint unfortunately does not includes the 1600 km projected distance at which Arlot et al. (1985) made the photoelectric detection of a putative satellite during a stellar occultation even; see below). Assuming a bulk density of $\rho_{lucina} = 3$ g cm^{-3} a satellite at the synchronous point would lie near $4.6R_{lucina}$.

Using the same analysis techniques as with Juno, a careful search of the images revealed no objects travelling with Lucina. In the 600 second CCD images we obtained a limiting magnitude of 21.4 for objects > 10 arcsec from Lucina, and 19.7 for objects 6-10 arcsec from Lucina. The 1800 sec exposures yielded a limiting magnitude of 22.6 for objects > 10 arcsec from Lucina, and 20.5 for objects 6-10 arcsec from Lucina. (The limiting magnitudes in this run were deeper relative to the 1990 Juno run than increased exposure time alone would imply; this is because, unlike the Juno run, moonlight was not a factor.

Lucina's V magnitude on 5 and 6 May 1991 was 12.3. Based on the limiting magnitude of our search, we conclude that no objects with albedo equal to Lucina's larger than ≈0.6 km were orbiting Lucina beyond 50 R_{lucina}. Because the satellite detection claimed by Arlot et al. (1985) occured at ≈23R_{lucina}, our results unfortunately cannot directly rule out (or confirm) theirs. We can, however, conclude that more distant satellites larger than our detection limit are unlikely (admitting the possibility of a satellite having been under the occulting disk). We further conclude that if the Arlot et al. "satellite" is real, it is likely in an orbit with $e < 0.5$ and $a < 5 \times 10^3$ km.

IV. Outlook

Our detection limits set new constraints on the probability of satellites around two asteroids not previously searched by imaging techniques. Unless by chance a satellite was hidden behind our occulting disk during our runs, neither 3 Juno nor 146 Lucina appear to have satellites >1.6 and > 0.6 km in radius orbiting them at > 40 and > 50 parent-asteroid radii, respectively.

We point out that groundbased coronographic searches for asteroid satellites in the main belt cannot escape the catch-22 imposed by seeing, which necessitates using an occulting disk larger than the apparent size of the synchronous orbit where tidal forces could be expected to bring debris after a collision. Therefore, although deep searches such as our can make progress in the more distant regions of asteroid stability fields, either Space Telescope or groundbased speckle techniques would be expected to yield the best results for searches in the prime, inner region near each parent asteroid. However, for NEAs, deep coronographic searches like ours (which probe to much fainter magnitudes than speckle techniques) *can* often probe inside the synchronous point, making such targets attractive future search candidates.

These findings constitute the first results of a planned McDonald CCD satellite-search campaign intended to triple the total number of asteroids surveyed for satellites by direct imaging techniques. We hope to survey several dozen asteroids (including many NEAs). Operating during dark time and with 1-1.5" seeing, we expect to routinely reach a limiting magnitude near $m_R = 23.5$ at 1-2 arcsec from our search targets.

Acknowledgments

Alan Harris and Tom Gehrels provided valuable critiques of this manuscript. This research was partially supported by a NASA operating grant to McDonald Observatory.

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