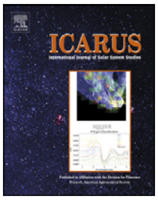
Icarus 202 (2009) 12–16

Contents lists available at ScienceDirect

Icarus

www.elsevier.com/locate/icarus



A survey for satellites of Venus

Scott S. Sheppard[a,*], Chadwick A. Trujillo[b]

[a] Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd. NW, Washington, DC 20015, United States
[b] Gemini Observatory, 670 North A'ohoku Place, Hilo, HI 96720, United States

ARTICLE INFO

Article history:
Received 19 November 2008
Revised 12 February 2009
Accepted 15 February 2009
Available online 23 February 2009

Keywords:
Venus
Satellites, general
Irregular satellites
Planetary formation

ABSTRACT

We present a systematic survey for satellites of Venus using the Baade–Magellan 6.5 m telescope and IMACS wide-field CCD imager at Las Campanas observatory in Chile. In the outer portions of the Hill sphere the search was sensitive to a limiting red magnitude of about 20.4, which corresponds to satellites with radii of a few hundred meters when assuming an albedo of 0.1. In the very inner portions of the Hill sphere scattered light from Venus limited the detection to satellites of about a kilometer or larger. Although several main belt asteroids were found, no satellites (moons) of Venus were detected.

1. Introduction

The Hill sphere radius, r_H, is the limiting radius for orbits of planetary satellites in the presence of the Sun's gravitational field and can be expressed as

$$r_H = a_p \left[\frac{m_p}{3M_\odot} \right]^{1/3}, \tag{1}$$

where a_p, m_p and $M_\odot$ are the semi-major axis, mass of the planet and mass of the Sun, respectively (Hill, 1884; Innanen, 1979; Murray and Dermott, 1999). Hamilton and Krivov (1997) showed analytically that the possible stability limit for satellites could be closer to around $0.7r_H$. To date no known permanent satellite of any planet has an orbit beyond $0.7r_H$ from its primary.

Venus and Mercury are the only planets in our Solar System without any known satellites. Recent surveys of the giant planets have shown they have extensive small outer satellite systems (Gladman et al., 2000, 2001, 1998; Sheppard and Jewitt, 2003; Sheppard et al., 2005, 2006; Holman et al., 2004; Kavelaars et al., 2004). These small outer irregular satellites of the giant planets were likely captured from heliocentric orbit near the end of the planet formation epoch (see Jewitt and Haghighipour, 2007; Nicholson et al., 2008 for recent reviews on irregular satellites). Recent surveys show that the terrestrial planets Mars and Mercury do not have any outer satellites like the giant planets (Sheppard et al., 2004; Nicholson and Gladman, 2006; Warell and Karlsson, 2007).

The last published survey for satellites of Venus was performed using photographic plates in 1956 (Kuiper, 1961). The 1956 satellite search reached a limiting magnitude no better than about 16th in the R-band for areas of the Hill sphere distant from the planet. Thus the survey could have detected objects larger than about 2.5 km in radius at large distances from Venus. Closer to the planet, the 1956 survey was only able to obtain a limiting magnitude of about 14th, corresponding to objects larger than about 6 km in radius.

The possible detection and discussion of a Venus satellite dates to at least 1645 when F. Fontana mentioned the observation of a possible Venus satellite. Possible satellites of Venus were reported several more times by many different and usually experienced observers (including G. Cassini) in the late 1600's and 1700's (Blacklock, 1868). So many detections of a possible Venus satellite were made that J. Lambert computed possible orbits and tables for the putative Venus satellite in the late 18th century (Blacklock, 1868; Anonymous, 1884). There has been no report of a Venus satellite since 1768 with many notable astronomers such as W. Herschel and E. Barnard attempting detection. Hobbyists today have looked at Venus many times over with telescopes that are more powerful than those from the 17th and 18th century with no satellites reported.

Satellites have been invoked to explain Venus' retrograde rotation as well as its impact crater record. A Venus satellite (either previously escaped or currently in-situ) could slow the rotation of Venus through planet-satellite tidal friction, similar to the Earth–Moon system (McCord, 1968; Singer, 1970; Kumar, 1977; Donnison, 1978; Malcuit and Winters, 1995). Bills (1992) notes that the pristine state of most of Venus' impact craters is consistent with recent tidal-induced decay of a swarm of small satellite frag-

---

[*] Corresponding author.
E-mail address: sheppard@dtm.ciw.edu (S.S. Sheppard).

0019-1035/$ – see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2009.02.008

ments, possibly from the destruction of a large parent satellite. Alemi and Stevenson (2006) suggest it is surprising that Venus has no satellites since its very likely that Venus suffered several large impacts in the very early Solar System. These impacts would have a good chance of creating a satellite, similar to how the Earth–Moon and Pluto–Charon systems may have formed (Canup and Asphaug, 2001; Canup, 2005; Stern et al., 2006).

Several authors have noted that Mercury and Venus may not have large natural satellites as a consequence of strong solar gravitational tides, which make large satellites unstable around the inner most terrestrial planets (Counselman, 1973; Ward and Reid, 1973; Burns, 1973; Yokoyama, 1999). If Venus' slow rotation is primordial, Rawal (1986) finds that Venus has trouble retaining all but the most distant and smallest primordial satellites. Satellites larger than a few km would slowly spiral into the planet within the age of the Solar System.

Venus does have a few known quasi-satellites such as 2002 VE_{68} (Mikkola et al., 2004). Quasi-satellites are objects that orbit the Sun in ellipses and have similar periods to the planet (Wiegert et al., 2005). In the planet's reference frame the object resembles a retrograde elongated orbit around the planet. These types of orbits are usually destabilized over long periods of time by gravitational interactions with neighboring planets (Mikkola et al., 2006). 2002 VE_{68} is only expected to be a Venus quasi-satellite for a few thousand years (Mikkola et al., 2004). Any primordial Venus Trojans are also unlikely to be stable for the age of the Solar System (Tabachnik and Evans, 2000; Brasser and Lehto, 2002; Scholl et al., 2005).

To date the Hill sphere of Venus has not been systematically surveyed for possible small satellites with modern sensitive wide-field CCDs. In order to constrain the presence of any small satellites of Venus a deep CCD survey of the space around Venus was performed that is several magnitudes more sensitive than any previously published surveys for satellites of Venus.

2. Observations

Observations were made at the beginning of the night on UT October 7, 2005 with the Baade–Magellan 6.5 m telescope at Las Campanas, Chile. Images were acquired in the R-band with the IMACS wide-field CCD imager. IMACS has eight 2048 × 4096 pixel CCDs with a pixel scale of 0.20 arcseconds per pixel. The eight CCDs are arranged in a box pattern with four above and four below and about 12 arcsecond gaps between chips. The field-of-view for IMACS is circular with a radius of about 13.7 arcminutes giving an area of about 0.17 square degrees. This setup means the sky is vignetted at the extreme corners of the outer CCDs and thus the corners are not used in the data analysis. Dithered twilight flat fields and biases were used to reduce each image. Landolt (1992) standards were used to calibrate the data photometrically. The night was clear and photometric during all the observations.

During the observations Venus was near its highest point in the Southern evening sky and thus between an airmass of 2.0 and 2.4. Delivered image quality was between 1.2 and 1.3 arcseconds Full Width at Half-Maximum (FWHM). The apparent magnitude of Venus was about -4.1 with a surface brightness of about 1.5 magnitudes per square arcsecond. Venus' angular diameter as seen on the sky was about 19 arcseconds with about 62% of Venus illuminated. Venus' geometric circumstances at the time of observations are shown in Table 1.

Table 1
Venus geometrical circumstances.

UT date	R (AU)	Δ (AU)	α (deg)
2005 October 7	0.7282	0.8782	76.3

Quantities are the heliocentric distance (R), geocentric distance (Δ) and phase angle (α).

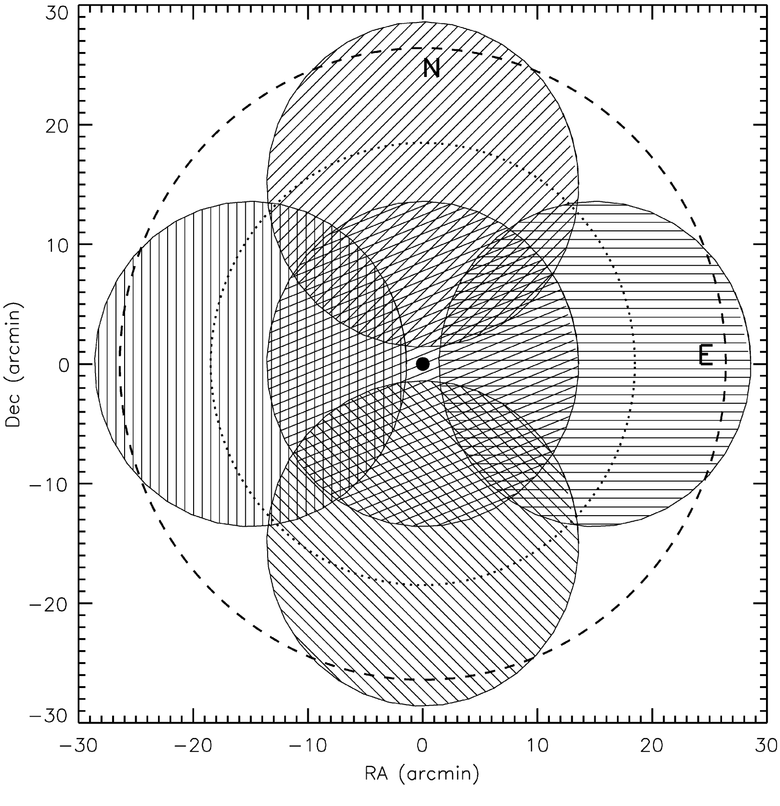


Fig. 1. The area surveyed (shaded regions) around Venus (black circle) for satellites using the Magellan–Baade 6.5 m telescope. Four fields (One North, South, East and West of Venus) were imaged three times each around the planet on UT 2005 October 7. An additional field was imaged three times with Venus placed in the center of the detector. The dashed circle shows Venus' Hill sphere and the dotted circle shows the theoretical outer limits for stable Venus satellites ($0.7r_H$).

Table 2
Venus satellite survey fields.

Field	RA (hh:mm:ss)	DEC (dd:mm:ss)	EXP[a] (s)	Airmass	Filter	UT[b] (hh:mm:ss)
Center	15:43:48	−22:13:10	2	2.0–2.1	R	23:47:31/23:49:27/23:51:18
West	15:42:47	−22:13:17	10	2.1–2.2	R	23:53:12/23:59:43/00:03:00
East	15:44:56	−22:13:15	10	2.1–2.2	R	23:55:37/23:57:43/00:01:43
South	15:43:53	−22:58:24	10	2.2–2.4	R	00:05:38/00:09:25/00:18:58
North	15:43:54	−21:28:25	10	2.2–2.4	R	00:07:31/00:11:15/00:15:23

[a] The exposure time of each image.

[b] The starting UT time of each image in the three image sequence. Images with starting times of 23 hours were taken at the end of UT October 6, 2005 while images with starting times of 00 hours were taken at the beginning of UT October 7, 2005.

Table 3
Asteroids in the Venus survey fields.

Object	Coordinates (J2000)			Offsets		Motion		
	RA (hh:mm:ss)	DEC (dd:mm:ss)	m_R (mag)	ΔRA (arcmin)	ΔDEC (arcmin)	dRA (″/hr)	dDEC (″/hr)	Detected (exp/act)
Venus	15:43:52	−22 : 13 : 30	−4.1	0.0	0.0	160	−45	Y/Y
44375	15:44:02	−22 : 09 : 03	20.6	2.2E	4.5N	46	−10	N/N
7408	15:43:10	−22 : 14 : 03	18.3	9.8W	0.5S	80	−17	Y/Y
76111	15:44:06	−22 : 03 : 46	20.2	3.3E	9.7N	52	−13	N/N
21748	15:43:55	−22 : 24 : 01	19.8	0.8E	10.5S	84	−17	N/N
141541	15:44:35	−22 : 22 : 14	20.5	10.0E	8.7S	82	−20	N/N
32536	15:44:07	−22 : 26 : 42	18.0	3.5E	13.2S	52	−7	Y/Y
2005 GS78	15:42:33	−22 : 07 : 20	20.5	18.2W	6.2N	54	−21	N/N
51666	15:43:00	−21 : 55 : 50	19.5	12.0W	17.7N	54	−17	Y/Y
174368	15:44:26	−21 : 53 : 28	20.5	7.9E	20.0N	36	−15	N/N
44717	15:42:21	−22 : 22 : 19	19.0	21.1W	8.8S	84	−19	Y/Y
169311	15:42:13	−22 : 16 : 21	20.5	22.9W	2.9S	59	−11	N/N
5710	15:42:16	−22 : 20 : 52	19.0	22.3W	7.4S	68	−14	Y/N
109417	15:43:54	−21 : 49 : 22	19.9	0.4E	24.1N	49	−4	Y/Y

Only asteroids in our survey fields and brighter than the maximum red magnitude survey limit, 20.8 magnitudes (see Fig. 2), on UT October 7, 2005 are presented. Because the survey's limiting magnitude becomes brighter closer to Venus the last column details if each object was expected (exp) to be detected and if it was actually (act) detected in our survey. The asteroid information was obtained through the Minor Planet Center's MPChecker program.

The most difficult aspect of a Venus satellite search is the large amount of scattered light from Venus. All images had a strong gradient in the background because of this scattered light. The light gradient was removed by using the FMEDIAN task in IRAF. The FMEDIAN task replaces each pixel value with the median of the pixel values around it. For the Venus images each pixel had a box of 15×15 pixels used for the median. The FMEDIAN image was then subtracted from the original image. Applying FMEDIAN to the images allows them to be easily visually searched for moving objects.

Substituting the mass of Venus, $m_p = 4.87 \times 10^{24}$ kg, and the mass of the Sun, $M_\odot = 1.99 \times 10^{30}$ kg, into Eq. (1) yields a Venus Hill sphere radius of $r_H = 1.0 \times 10^6$ km. Using data from Table 1, we compute that Venus' Hill radius on October 7, 2005 as seen from Earth was about 26.6 arcminutes (about 18.6 arcminutes for $0.7r_H$), very similar to the full diameter of the field-of-view of one IMACS image. In total the Hill sphere of Venus covered about 0.62 square degrees in area as seen from the Earth during the observations.

Fig. 1 illustrates the sky area surveyed around Venus. Data were collected at two epochs (Table 2). First, three 2 s exposures with Venus centered on the IMACS imager were obtained. These very short exposures prevented the CCDs from being completely saturated and allowed satellites close to Venus to be imaged. The second part of the survey had Venus just offset to the North, South, East and West of the IMACS field-of-view. Three 10 s images were obtained of Venus in each of the offset positions. On average there were about 4 min between exposures of Venus in the same orientation.

3. Analysis and results

The apparent Right Ascension (RA) and Declination (DEC) motion of Venus during the observations is shown in Table 3. Possible Venus satellites would be expected to have similar apparent motions as Venus (160″/hr in RA and −45″/hr in DEC). Trailing losses from the apparent motion of possible satellites was insignificant since the few tenths of arcsecond trailing that would occur in the 10 s images was much less than the 1.2 to 1.3 arcsecond image quality. All known main belt asteroids in the survey fields had apparent RA motion of less than 90″/hr in RA and less than −20″/hr in DEC (Table 3). No candidate satellites of Venus (RA motion >90″/hr) were found through visually blinking the survey fields. Five main belt asteroids were detected in the survey fields with apparent motions between about 50 and 80 arcseconds per hour in RA (see Table 3).

The apparent red limiting magnitude, m_R, of the survey was determined by placing artificially generated objects with motions similar to that of Venus into the survey images. The artificial objects had R-magnitudes ranging between 14 and 21 magnitudes and were matched to the point spread function of the images. The 50% differential detection efficiency was found to be 20.4 magnitudes for the artificial moving objects in the 10 s images most distant from Venus (Fig. 2). Scattered light was significant near Venus and the detection efficiency versus distance from Venus is shown in Fig. 3. The 10 s images became saturated around 3 arcminutes from Venus where the detection efficiency was around 18.6 magnitudes. For the 2 s images with Venus centered on the array, saturation occurred around 1.3 arcminutes from Venus with a detection efficiency at about 16.1 magnitudes (Fig. 3). About 90% of the Hill sphere around Venus was covered and about 99% of the Hill sphere within the theoretically stable area for satellites of $0.7r_H$. The percentage of the Venus Hill sphere covered per limiting red magnitude is shown in Fig. 4.

The corresponding radius limit, r, of an object to the apparent red magnitude, m_R, can be found through (Russell, 1916)

$$r = \left[\frac{2.25 \times 10^{16} R^2 \Delta^2}{p_R \phi(\alpha)}\right]^{1/2} 10^{0.2(m_\odot - m_R)} \tag{2}$$

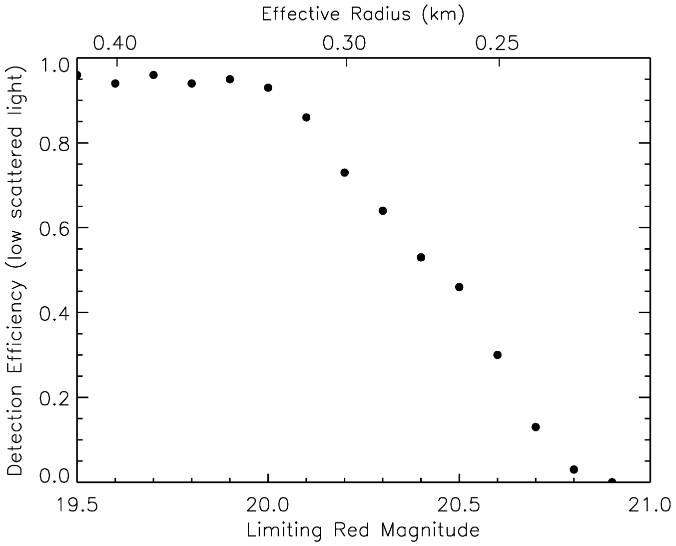


Fig. 2. Detection efficiency of the artificially placed objects during visual blinking of the fields. The 50% differential detection efficiency is at about 20.4 mag. This efficiency is valid for the periphery of the survey area, where scattered light is minimized. The calculation of the effective radius assumes an albedo of 0.1.

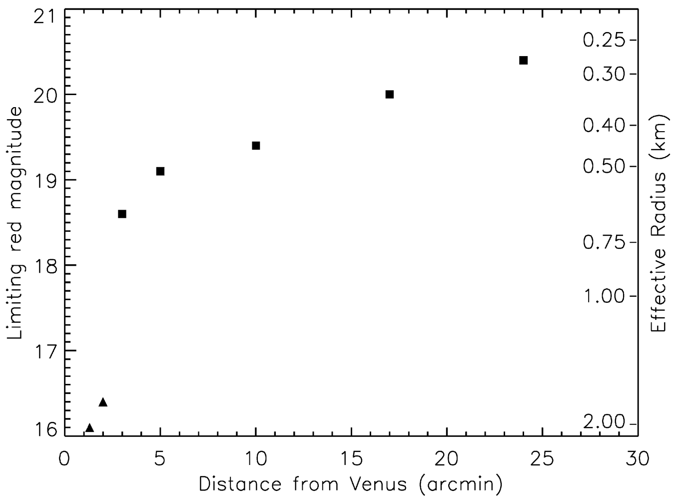


Fig. 3. The 50% detection efficiency of the survey versus distance from Venus. Squares represent the detection efficiency for the four 10 s fields with Venus offset from the center of the detector. Triangles show the detection efficiency for the 2 s field with Venus centered in the middle of the array. The calculation of the effective radius assumes an albedo of 0.1.

in which r is in km, R is the heliocentric distance in AU, Δ is the geocentric distance in AU, $m_\odot$ is the apparent red magnitude of the sun (−27.1; Livingston, 2000), p_R is the geometric red albedo, and $\phi(\alpha)$ is the phase function in which the phase angle $\alpha = 0$ deg at opposition. For an assumed linear phase function the notation $\phi(\alpha) = 10^{-0.4\beta\alpha}$, where β is the "linear" phase coefficient, is used. Using data from Table 1 along with an S-type asteroid albedo of 0.1 and a linear phase coefficient of $\beta = 0.03$ mags per degree, as found for Mercury and S-type asteroids (Veverka et al., 1988; Muinonen et al., 2002), shows that 20.4 magnitudes corresponds to satellites that are about 0.3 km (300 m) in radius at Venus' observing geometry. Figs. 2 and 3 show how the satellite radius corresponds to the survey's detection efficiency. This survey is a factor of about 50 deeper in flux than the most recently published survey for satellites of Venus (Kuiper, 1961).

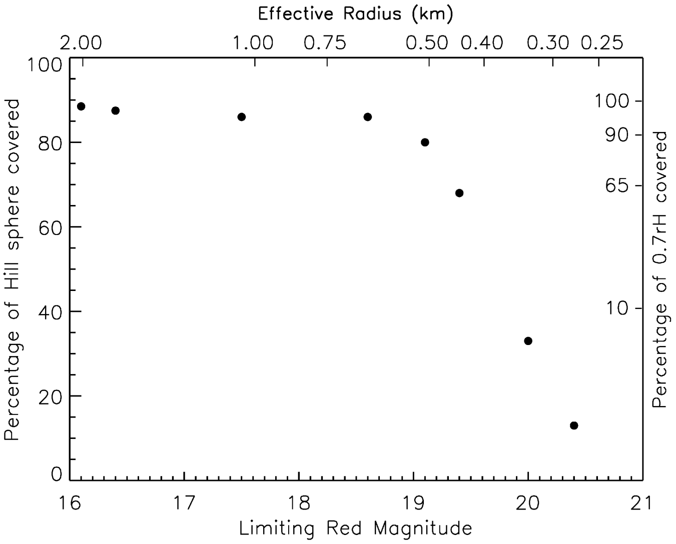


Fig. 4. The completeness of the survey coverage of the Venus Hill sphere versus the limiting red magnitude. Because of the strong scattered light near Venus a smaller percentage of the Hill sphere was covered at fainter magnitudes. The survey covered about 90% of the Venus Hill sphere and about 99% of the Venus Hill sphere within $0.7r_H$ or the theoretically stable region for satellites of Venus. The percentage of the Hill sphere covered takes into account the amount of area the survey covered at a particular limiting red magnitude and the efficiency of detection at that magnitude. The calculation of the effective radius assumes an albedo of 0.1.

4. Summary

No satellites of Venus down to about 0.3 km in radius were found in a survey that covered about 90% of the Hill sphere and 99% of the theoretically stable region for satellites of Venus. The survey improves the non-detection of satellites around Venus by about a factor of 50 over previously published work. This result shows that either Venus never acquired any satellites larger than about 1 km or confirms that natural satellites larger than about 1 km around Venus were unstable over the age of the Solar System.

Acknowledgments

This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile. C.T. was supported by the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., on behalf of the international Gemini partnership of Argentina, Australia, Brazil, Canada, Chile, the United Kingdom, and the United States of America.

References

Alemi, A., Stevenson, D., 2006. Why Venus has no moon. Bull. Am. Astron. Soc. 38, 491.

Anonymous, 1884. The problematical satellite of Venus. The Observatory 7, 222–226.

Bills, B., 1992. Venus: Satellite orbital decay, ephemeral ring formation, and subsequent crater production. Geophys. Res. Lett. 19, 1025–1028.

Blacklock, A., 1868. The satellite of Venus. Astron. Register 6, 196–197.

Brasser, R., Lehto, H., 2002. The role of secular resonances on Trojans of the terrestrial planets. Mon. Not. R. Astron. Soc. 334, 241–247.

Burns, J., 1973. Solar system—Why are there no satellites for the inner planets? Nat. Phys. Sci. 242, 23.

Canup, R., 2005. A giant impact origin of Pluto–Charon. Science 307, 546–550.

Canup, R., Asphaug, E., 2001. Origin of the Moon in a giant impact near the end of the Earth's formation. Nature 412, 708–712.

Counselman, C., 1973. Outcomes of tidal evolution. Astrophys. J. 180, 307–316.

Donnison, J., 1978. The escape of natural satellites from Mercury and Venus. Astrophys. Space Sci. 59, 499–501.

Gladman, B., Nicholson, P., Burns, J., Kavelaars, J., Marsden, B., Williams, G., Offutt, W., 1998. Discovery of two distant irregular moons of Uranus. Nature 392, 897–899.

Gladman, B., Kavelaars, J., Holman, M., Petit, J., Scholl, H., Nicholson, P., Burns, J., 2000. Note: The discovery of Uranus XIX, XX, and XXI. Icarus 147, 320–324.

Gladman, B., Kavelaars, J., Holman, M., Nicholson, P., Burns, J., Hergenrother, C., Petit, J., Marsden, B., Jacobson, R., Gray, W., Grav, T., 2001. Discovery of 12 satellites of Saturn exhibiting orbital clustering. Nature 412, 163–166.

Hamilton, D., Krivov, A., 1997. Dynamics of distant moons of asteroids. Icarus 128, 241–249.

Hill, G., 1884. Mr. G.W. Hill's paper on lunar theory. Mon. Not. R. Astron. Soc. 44, 194–196.

Holman, M., and 13 colleagues, 2004. Discovery of five irregular moons of Neptune. Nature 430, 865–867.

Innanen, K., 1979. The limiting radii of direct and retrograde satellite orbits, with applications to the Solar System and the stellar systems. Astrophys. J. 84, 960–963.

Jewitt, D., Haghighipour, N., 2007. Irregular satellites of the planets: Products of capture in the early Solar System. Annu. Rev. Astron. Astrophys. 45, 261–295.

Kavelaars, J., Holman, M., Grav, T., Milisavljevic, D., Fraser, W., Gladman, B., Petit, J., Rousselot, P., Mousis, O., Nicholson, P., 2004. The discovery of faint irregular satellites of Uranus. Icarus 169, 474–481.

Kuiper, G., 1961. Limits of completeness. In: Kuiper, G., Middlehurst, B. (Eds.), Planets and Satellites. Univ. of Chicago Press, Chicago, pp. 575–591.

Kumar, S., 1977. The escape of natural satellites from Mercury and Venus. Astrophys. Space Sci. 51, 235–238.

Landolt, A., 1992. UBVRI photometric standard stars in the magnitude range 11.5–16.0 around the celestial equator. Astrophys. J. 104, 340–371.

Livingston, W., 2000. Sun. In: Cox, A. (Ed.), Allen's Astrophysical Quantities. AIP Press, New York, pp. 339–380.

Malcuit, R., Winters, R., 1995. Numerical simulation of retrograde gravitational capture of a satellite by Venus: Implications for the thermal history of the planet. Lunar Planet. Sci. 26, 885–886.

McCord, T., 1968. The loss of retrograde satellites in the Solar System. J. Geophys. Res. 73, 1497–1500.

Mikkola, S., Brasser, R., Wiegert, P., Innanen, K., 2004. Asteroid 2002 VE_{68}, a quasi-satellite of Venus. Mon. Not. R. Astron. Soc. 351, L63–L65.

Mikkola, S., Innanen, K., Wiegert, P., Connors, M., Brasser, R., 2006. Stability limits for the quasi-satellite orbit. Mon. Not. R. Astron. Soc. 369, 15–24.

Muinonen, K., Piironen, J., Shkuratov, Y., Ovcharenko, A., Clark, B., 2002. Asteroid photometric and polarimetric phase effects. In: Bottke Jr., W., Cellino, A., Paolicchi, P., Binzel, R. (Eds.), Asteroids III. The Univ. of Arizona Press, Tucson, pp. 123–138.

Murray, C., Dermott, S., 1999. Solar System Dynamics. Cambridge Univ. Press, Cambridge.

Nicholson, P., Gladman, B., 2006. Satellite searches at Pluto and Mars. Icarus 181, 218–222.

Nicholson, P., Cuk, M., Sheppard, S., Nesvorny, D., Johnson, T., 2008. Irregular satellites of the giant planets. In: Barucci, M., Boehnhardt, H., Cruikshank, D., Morbidelli, A. (Eds.), The Solar System Beyond Neptune. The Univ. of Arizona Press, Tucson, pp. 411–424.

Rawal, J., 1986. Possible satellites of Mercury and Venus. Earth Moon Planets 36, 135–138.

Russell, H., 1916. On the albedo of the planets and their satellites. Astrophys. J. 43, 173–195.

Scholl, H., Marzari, F., Tricarico, P., 2005. The instability of Venus Trojans. Astron. J. 130, 2912–2915.

Sheppard, S., Jewitt, D., 2003. An abundant population of small irregular satellites around Jupiter. Nature 423, 261–263.

Sheppard, S., Jewitt, D., Kleyna, J., 2004. A survey for outer satellites of Mars: Limits to completeness. Astron. J. 128, 2542–2546.

Sheppard, S., Jewitt, D., Kleyna, J., 2005. An ultradeep survey for irregular satellites of Uranus: Limits to completeness. Astron. J. 129, 518–525.

Sheppard, S., Jewitt, D., Kleyna, J., 2006. A survey for "normal" irregular satellites around Neptune: Limits to completeness. Aston. J. 132, 171–176.

Singer, S., 1970. How did Venus lose its angular momentum? Science 170, 1196–1198.

Stern, S.A., Weaver, H., Steffl, A., Mutchler, M., Merline, W., Buie, M., Young, E., Young, L., Spencer, J., 2006. A giant impact origin for Pluto's small moons and satellite multiplicity in the Kuiper belt. Nature 439, 946–948.

Tabachnik, S., Evans, N., 2000. Asteroids in the inner Solar System. I. Existence. Mon. Not. R. Astron. Soc. 319, 63–79.

Veverka, J., Helfenstein, P., Hapke, B., Goguen, J., 1988. Photometry and polarimetry of Mercury. In: Vilas, F., Chapman, C., Matthews, M. (Eds.), Mercury. The Univ. of Arizona Press, Tucson, pp. 37–58.

Ward, W., Reid, M., 1973. Solar tidal friction and satellite loss. Mon. Not. R. Astron. Soc. 164, 21–32.

Warell, J., Karlsson, O., 2007. A search for natural satellites of Mercury. Planet. Space Sci. 55, 2037–2041.

Wiegert, P., Connors, M., Brasser, R., Mikkola, S., Stacy, G., Innanen, K., 2005. Sleeping with an elephant: Asteroids that share a planet's orbit. J. R. Astron. Soc. Can. 99, 145.

Yokoyama, T., 1999. Dynamics of some fictitious satellites of Venus and Mars. Planet. Space Sci. 47, 619–627.