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DISCOVERY OF TWO ADDITIONAL JOVIAN IRREGULARS

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ABSTRACT

We report on the discovery of two previously undetected irregular satellites of Jupiter (S/2010 J 1 and S/2010 J 2) during recovery observations of other known satellites. S/2010 J 1 was discovered with the Palomar 200 inch Hale telescope on September 7 UT of 2011, while S/2010 J 2 was discovered on September 8 with the 3.5 m Canada–France–Hawaii Telescope. The satellites have *r*-band magnitudes of 23.2 ± 0.3 and 24.0 ± 0.3, for S/2010 J 1 and S/2010 J 2, respectively, indicating diameters of ∼2–3 km. Both S/2010 J 1 and S/2010 J 2 are on bound retrograde orbits. Time-averaged integrated orbits suggest the association to the Carme and Ananke groups, respectively. Given that the satellites were discovered within a small field during the routine observations of the previously known irregulars, their discovery agrees with predictions that other moons of similar sizes remain undetected in the Jovian Hill sphere.

Key words: planets and satellites: detection – planets and satellites: individual (S/2010 J 1, S/2010 J 2)

Online-only material: color figures

1. INTRODUCTION

The irregular satellites of the outer planets are interesting groups of objects that reside in distant, eccentric orbits with high inclinations. The irregular satellites are not believed to have formed in a circumplanetary nebula like the regular satellites, but rather to be captured planetesimals. Proposed capture mechanisms include collisions and three-body interactions (Nesvorný et al. 2004; Nicholson et al. 2008), perhaps during the giant-planet migration phase (Nesvorný et al. 2007). Other proposed capture mechanisms are discussed in Colombo & Franklin (1971), Pollack et al. (1979), Heppenheimer & Porco (1977), Agnor & Hamilton (2006), Astakhov et al. (2003), Vokrouhlický et al. (2008), and Philpott et al. (2010). During the past 20 years, there have been several surveys that searched for irregular satellites in the Hill spheres (the stable regions) surrounding the giant planets (Jewitt & Sheppard 2005; Gladman et al. 2001; Holman et al. 2004; Kavelaars et al. 2004, being the most recent large surveys of Jupiter, Saturn, Uranus, and Neptune, respectively). As a result, both Jupiter and Saturn have more than 30 known irregular satellites each (summary in Nicholson et al. 2008), and some trends in the physical properties of these populations are becoming apparent (Grav et al. 2003; Nicholson et al. 2008). For example, the irregular satellites seem to fall into groups (Kuiper 1956; Gladman et al. 2001; Carruba et al. 2002; Sheppard & Jewitt 2003; Nesvorný et al. 2003), similar to the ones seen in the asteroid belt. Within groups, members have similar orbital elements and comparable colors. For Jupiter, these groups are currently called the Himalia, Ananke, Pasiphaë, and Carme groups, all named after their largest member. It appears that the members of each group may have originated from a single parent body which has subsequently broken up (Kuiper 1956; Gladman et al. 2001; Carruba et al. 2002; Sheppard & Jewitt 2003; Nesvorný et al. 2003, 2004), as opposed to being captured directly from heliocentric orbits.

Many giant-planet irregulars still have uncertain orbits due to their long orbital periods and short data arcs. The on-sky uncertainty of an irregular satellite, as for any moving object, increases with time if left unobserved. If neglected for a sufficiently long time, the uncertainty grows so large that we effectively do not know where the satellite is and the object is declared "lost." Unfortunately, a number of Jovian and Saturnian irregulars have been sufficiently neglected since their discovery that they are now lost, and several more are currently on the verge of becoming lost (Jacobson et al. 2012). During the past two years, our group has run an observing campaign, primarily using the Palomar 200 inch Hale telescope, which has aimed at recovering satellites to prevent losing them. This has been a successful campaign, not only saving several satellites that would otherwise soon be lost, but also demonstrating that one can reliably estimate the on-sky uncertainty and thus show which satellites are in danger of becoming lost (Jacobson et al. 2012).

This manuscript describes the discovery of two Jovian irregulars (S/2010 J 1 and S/2010 J 2) during our recovery work, confirming that there remain moons with diameters greater than 2 km yet to be discovered, as predicted by Jewitt & Sheppard (2005).

2. DISCOVERY AND METHODS

On September 7 and 8 UT of 2010, our group used the Hale telescope with the Large Format Camera (24′ diameter mosaic field) for recovery of Jovian satellites at risk of becoming lost. The images were 180 s exposures in the Sloan *r* filter. The previously unknown moon S/2010 J 1 was first detected in the frames of this observing run (MPEC 2011-L06), while visually searching the frames for another object.

Another unknown moon, S/2010 J 2, was discovered using an automated pipeline in frames taken on September 8 of 2010 at the 3.5 m Canada–France–Hawaii Telescope (CFHT) with MegaCam (1 deg^2 mosaic field) while recovering other Jovians, with 140 s exposures in the *r* filter. S/2010 J 1 was also seen in the CFHT frames, giving a 31 hr arc with 115 astrometric points (MPEC 2011-L06). Upon closer inspection, S/2010 J 2

Table 1
Full Observing-run List

Date	Telescope	Observers	S/2010 J 1	S/2010 J 2
2010 Sep 7	Hale 200 inch	Jacobson, Brozović, Gladman, Alexandersen	y	y
2010 Sep 8	Hale 200 inch	Jacobson, Brozović, Gladman, Alexandersen	y	-
2010 Sep 8	CFHT	Veillet	y	y
2010 Oct 2	CFHT	Veillet	y	y
2010 Oct 9	CFHT	Veillet	-	y
2010 Oct 30	CFHT	Veillet	y	y
2010 Nov 1	CFHT	Veillet	y	y
2011 Jan 1 and 4	CFHT	Veillet	y	n
2011 Jul 6	NOT	Rousselot	n	-
2011 Jul 8	NOT	Rousselot	y	n
2011Aug 4 and 5	CFHT	Veillet	y	y
2011 Sep 3 and 4	CFHT	Veillet	-	y
2011 Oct 28	Hale 200 inch	Jacobson, Brozović, Nicholson, Alexandersen	y	y
2011 Oct 29	Hale 200 inch	Jacobson, Brozović, Nicholson, Alexandersen	n	y

Notes. Successful observations are denoted by "y," unsuccessful recoveries (due to weather) by "n," and "-" indicates when no attempt was made for that moon.

was then detected in some of the previous Hale observations, yielding a 30 hr arc with 74 astrometric points (MPEC 2011-L06). The *r*-band magnitudes on the two nights were on average 23.2 and 24.0 for S/2010 J 1 and S/2010 J 2, respectively, with about 0.3 mag variation due to photometric scatter and potentially rotational variation.

3. RECOVERY OBSERVATIONS

Designation of a planetary satellite, unlike asteroids and trans-Neptunian objects, requires not just observations on multiple nights, but also multiple dark runs, in order to prove that the object must be on a bound planetocentric orbit. This is a considerably more stringent requirement, necessitating considerable telescopic resources.

3.1. Targeted Recoveries

To confirm the nature of the candidate objects as Jovian satellites, our team performed extensive tracking observations during autumn 2010 and summer 2011. These tracking observations (MPEC 2011-R49; MPEC 2011-R50) were performed mostly from CFHT, with supporting observations from the Hale 200 inch Telescope and the Nordic Optical Telescope (NOT). A summary of all detections 2010–2011 are listed in Table 1.

Once several months of arc were obtained, the satellites were officially designated as satellite candidates by the International Astronomical Union, with the provisional names S/2010 J 1 and S/2010 J 2 (MPEC 2011-L06; Jacobson et al. 2011).

3.2. Archival Precoveries

With a one-year data arc, S/2010 J 1 and S/2010 J 2 could be determined with certainty to both be on bound, retrograde orbits around Jupiter. Their motion as seen from Earth, in jovicentric space, is plotted in Figure 1.

Once the preliminary orbits were accurate enough to predict on-sky positions several years away with only few arcseconds uncertainty, we embarked on a hunt for the newly discovered Jovian irregulars in the archival observations from 2003 surveys by Gladman et al. and Sheppard & Jewitt. These surveys independently used CFHT MegaCam to search the stable region of the Jovian Hill sphere for irregular satellites.

S/2010 J 1 and S/2010 J 2 could not be linked to any of the lost known satellites, but may still have been visible in the 2003 surveys. There are several reasons why these objects could be visible in the 2003 images, without having been declared as satellites at the time:

1. The 2003 searches were performed using automated pipelines, which have a slightly lower magnitude limit than a visual inspection for low signal-to-noise objects.
2. A non-insignificant fraction of the field of view is obscured by stars or occupied by chip gaps. The pipeline must be able to "see" the moving object on a triplet of images to declare a detection. So if the moon moves in front of a star or into a chip gap on one of the images, the pipeline will not detect it, whereas a visual inspection by a human might.
3. The projected area in 2003 closest to Jupiter could not be searched due to planetary scattered light. A few spikes of scattered light also obscure some more distant regions of the searched area, raising the background level of the images.
4. Even if found and measured, lacking multiple dark runs, the object would not have been declared a moon candidate.

Due to easy access (a local disk copy), we focused our archival search on the Gladman et al. archive. We first found astrometry of S/2010 J 1 from 2003 February 27 and 28 in a Gladman et al. archived astrometry file. These measurements had been produced by the automated search process that located all the objects that were moving near the Jovian rate and were thus considered to be candidate satellites. This apparition of S/2010 J 1 was located between the positions predicted (using the 2010 and 2011 data) by the Minor Planet Centre and the Jet Propulsion Laboratory's Horizons system, which were ∼4 arcmin apart. S/2010 J 1 was not located in any of the astrometry from 2003 March, April, or December, which explains why the satellite was never designated even though the two 2003 February nights were reported to the MPC.

We then proceeded to search all relevant archival images visually. The Canadian Astronomical Data Centre's Solar System

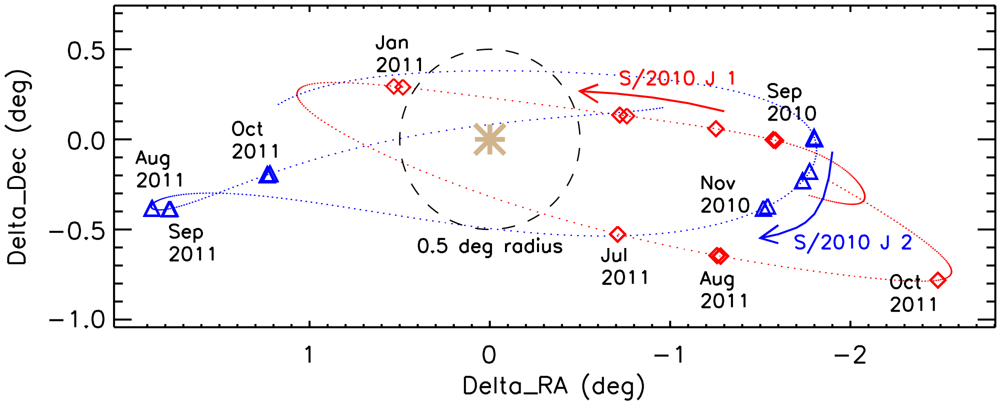

Figure 1. Offset plot showing the angular locations of S/2010 J 1 and S/2010 J 2 relative to Jupiter, as seen from Earth. Diamonds (red) show the locations of S/2010 J 1 in our 2010–2011 observations, while triangles (blue) show the locations of S/2010 J 2. The ephemerides for the best-fit orbits from JPL are plotted at 48 hr intervals, shown by the dark (red) and light (blue) dots for S/2010 J 1 and S/2010 J 2, respectively. The ephemerides are plotted for the two-year period 2010 March 1–2012 March 1, similar to the orbital period of the moons. The dashed circle of radius 0°.5 centered on Jupiter is for reference and to illustrate the area within which it is difficult to track satellites due to scattered light from Jupiter.

(A color version of this figure is available in the online journal.)

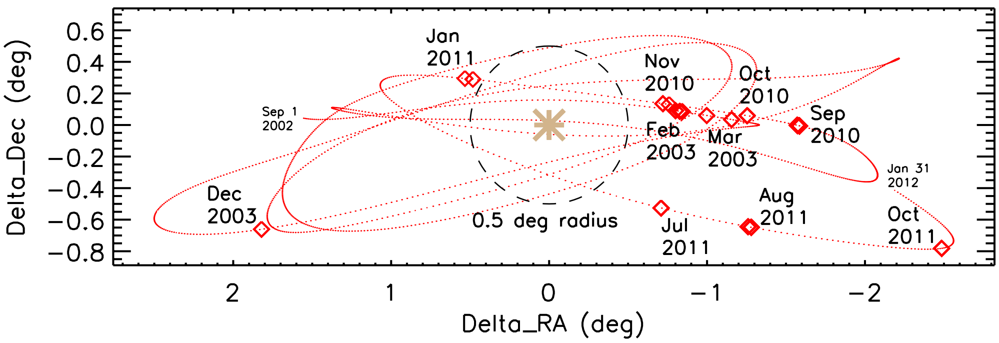

Figure 2. Offset plot similar to Figure 1, showing only S/2010 J 1 with all measurements in 2003, 2010, and 2011. The ephemeris has been extended, now running from 2002 September 1 to 2012 January 31 at 48 hr intervals.

(A color version of this figure is available in the online journal.)

Object Search (Gwyn et al. 2011) helped us identify which CFHT MegaCam fields were relevant for searching. S/2010 J 1 was visually identified at very low signal to noise in a triplet from 2003 March 27. Lastly, S/2010 J 1 was also detected on two images from 2003 December 24. In the third image, S/2010 J 1 was merged with a star and thus had not been picked up by the pipeline.

We again used the Solar System Object Search (Gwyn et al. 2011) to identify and download the relevant archival frames from the Sheppard & Jewitt survey. Upon visual inspection, these images yielded an additional three points on 2003 February 25 and two points on 2003 March 12, where the third image was of too poor quality for measurement. The remaining observations of both surveys had either poorer image quality, leaving S/2010 J 1 unmeasurable, or in three cases the ephemeris position of S/2010 J 1 was in a chip gap.

The resulting S/2010 J 1 astrometric points were included into the orbital fit one-by-one, as soon as they were found. Each new point led to the orbital improvements that allowed an easier recovery of the following point. The end result was an additional 16 astrometric points from 2003, which gave a combined 2003–2011 astrometry data set of 167 astrometric points and a data arc of 3168 days (MPEC 2011-S49). The motion of S/2010 J 1 as seen from Earth, in jovicentric space, can be seen in Figure 2.

S/2010 J 2 could not be seen in any of the 2003 imaging by Gladman et al. nor the Sheppard & Jewitt imaging, despite the on-sky uncertainties being only a few arcminutes. The images of 2003 February 27 and 28 had by far the best image quality, but despite an intense search, S/2010 J 2 was not seen on either night. S/2010 J 1 was close to the flux limit of the 2003 searches, so it is likely that S/2010 J 2 is beyond the limit of the archival exposures. With no 2003 astrometry, S/2010 J 2 has 116 astrometric points spanning a 418 day data arc from our 2010–2011 observations.

Table 2
J2000 Ecliptic Orbital Elements by JPL for Precessing Elliptical Orbits, Averaged over a 6000 Year Integration

	a ($\times 10^9$ m)	e	i (°)	P_λ (yr)	m_r
S/2010 J 1	23.45	0.25	165.	2.02	23.2
S/2010 J 2	21.01	0.23	149.	1.69	24.0

Notes. The nodal and pericenter precession periods are of order a century. Here a, e, i, P_λ, and m_r are the semimajor axis, eccentricity, inclination, orbital period, and r-band magnitude, respectively.

4. ORBITS AND SIZE

With >1 year data arcs, the jovicentric orbital elements of S/2010 J 1 and S/2010 J 2 are established to a few percent accuracy. The orbital elements, using all available data, can be seen in Table 2. Based on these elements, S/2010 J 1 is clearly a member of the Carme group, the most well-defined retrograde group (Sheppard & Jewitt 2003; Nesvorný et al.

2003). S/2010 J 2 is most likely part of the Ananke group. The Ananke group is more dispersed and overlaps somewhat with the equally dispersed Pasiphaë group (Sheppard & Jewitt 2003; Nesvorný et al. 2003). Photometric color information may help definitively determine which group S/2010 J 2 belongs to, as has been done for other moons (Grav et al. 2003).

The *r*-band magnitude of S/2010 J 1 and S/2010 J 2 are measured to be 23.2 ± 0.3 and 24.0 ± 0.3, respectively. These magnitudes suggest diameters of ∼3 km and ∼2 km respectively, using Equation (3) from Jewitt & Sheppard (2005), a correction of $m_r \approx m_R$+0.2, and assuming an albedo of ∼0.04. These sizes are of course uncertain, to within a factor of three, due to the unknown albedo of these objects. Jewitt & Sheppard (2005) state the completeness limit for Jovian satellites to be $m_R \approx 23.0$ (that is $m_r \approx 23.2$), but it is unclear if 50% or 100% completeness is meant. Sheppard & Jewitt (2003) predict ∼100 Jovian irregulars of $m_r < 24.2$. At time of writing, the Minor Planet Centre lists 59 known Jovian irregulars. Our observations covered 1 $\deg^2$, or just ∼4% of the projected area where stable orbits can exist around Jupiter. We discovered two previously unknown satellites, which is in reasonable agreement with the estimate that there remains ∼40 yet undiscovered satellites of $m_r < 24.2$.

5. CONCLUSION

Our observations discovered two previously unknown satellites in coverage of 4% of the stable region of Jupiter, confirming that at diameters ∼2–3 km ($m_r \sim 23.5$), the Jovian irregular population is numerous and incompletely known. These objects are close to the flux limit for 4 m telescopes and are as a result difficult to identify by automatic search algorithms. Even those moons that are found are easily lost again. These survey limitations are illustrated by our archival recovery of S/2010 J 1. A new search of the entire stable region would reveal many such satellites, but would be a considerable undertaking, requiring a large program with multi-night imaging in multiple dark runs followed by extensive recovery observations in following years to avoid losing the discovered moons.

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Facilities: Hale, CFHT (MegaCam), NOT

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