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REVISED ORBITS OF SATURN'S SMALL INNER SATELLITES

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ABSTRACT

We have updated the orbits of the small inner Saturnian satellites using additional *Cassini* imaging observations through 2007 March. Statistically significant changes from previously published values appear in the eccentricities and inclinations of Pan and Daphnis, but only small changes have been found in the estimated orbits of the other satellites. We have also improved our knowledge of the masses of Janus and Epimetheus as a result of their close encounter observed in early 2006.

Key words: planets and satellites: general – celestial mechanics

1. INTRODUCTION

Paper I (Spitale et al. 2006) reported on the determination of orbits of the small inner Saturnian satellites, Janus, Epimetheus, Atlas, Prometheus, Pandora, Pan, Methone, Pallene, Polydeuces, and Daphnis, using Earth-based and *Hubble Space Telescope* astrometry and *Voyager* and *Cassini* imaging observations; the *Cassini* data arc extended through 2005 November. Since that time *Cassini* has continued to collect observations. In this paper we report on the orbits as updated with observations through 2007 March.

2. ANALYSIS

Because of dynamical interactions between several of the small satellites and perturbations due to the major Saturnian satellites, we numerically integrate the equations of motion to model the satellite orbits except for those of Pan and Daphnis. We have found that the gravitational field of Saturn itself dominates the motion of Pan and Daphnis and that a simple precessing Keplerian ellipse is an adequate model for their orbits; the ellipse model is described in Paper I. Our numerical integrations account for the mutual interactions of Janus, Epimetheus, Atlas, Prometheus, and Pandora, the asphericity of Saturn's gravity field, and perturbations due to the major Saturnian satellites, the planets, and the Sun. We use the improved Saturnian system gravity field parameters (Jacobson et al. 2006), and we obtain the positions of the Sun and planets from JPL planetary ephemeris DE414 (Standish 2006) and the positions of the major satellites from recent ephemerides developed for *Cassini* operations. In the integrations Methone, Pallene, and Polydeuces are assumed to be massless; they are quite small and no reliable mass estimates are yet available for them.

We fit the orbits to the *Cassini* observations and to the same historic observations used previously (see Table 1 of Paper I). The number and time span of the *Cassini* observations for each satellite appear in Table 1 along with the root-mean square (rms) of the observation residuals. For all of the satellites the rms is less than the assumed data accuracy of 0.5 pixel; however, in all cases the rms is somewhat larger than that reported in Paper I. The increase is primarily due to the difficulty in determining the centers of the extended images of the satellites. The more recent observations have been made at closer ranges than the earlier ones; consequently, the extended images are larger and their centers are more uncertain.

Table 1
Summary of *Cassini* Observations

Body	Start date	End date	No. Observations	Sample (rms)	Line (rms)
Janus	2004 Feb. 06 03:12:06	2007 Mar. 16 12:19:25	1566	0.436	0.401
Epimetheus	2004 Feb. 06 03:12:06	2007 Mar. 16 12:33:53	1532	0.416	0.374
Atlas	2004 May 26 06:51:10	2007 Mar. 16 12:24:10	229	0.324	0.300
Prometheus	2004 Feb. 09 22:42:25	2007 Mar. 16 02:05:23	1077	0.368	0.339
Pandora	2004 Feb. 12 13:39:05	2007 Mar. 16 12:33:53	1222	0.360	0.395
Pan	2004 May 26 19:29:36	2007 Mar. 24 21:59:40	93	0.304	0.461
Methone	2004 May 12 01:12:34	2007 Mar. 16 15:24:10	136	0.236	0.276
Pallene	2004 Apr. 18 04:31:33	2007 Mar. 15 09:39:40	135	0.265	0.281
Polydeuces	2004 Apr. 02 05:42:33	2007 Mar. 14 22:59:25	157	0.287	0.273
Daphnis	2004 Oct. 24 11:38:27	2007 Mar. 24 21:59:40	52	0.679	0.941

Table 2 contains the revised elements and their errors for Pan and Daphnis. We find a statistically significant eccentricity and inclination for Daphnis and a reduction in Pan's estimated eccentricity of nearly three times its previous error and in its estimated inclination of about 1.5 times its previous error. The data arc extension for both satellites has also led to a reduction in their mean motion uncertainties. As in Paper I, rather than estimating a, $\dot{\varpi}$, or $\dot{\Omega}$, we computed them from secular perturbation theory; their errors derive from the uncertainties in the mean motions and in the second zonal harmonic of Saturn's gravity field.

The rms of the changes between our current numerically integrated orbits and those from Paper I over the time frame of the *Cassini* tour (2004 January–2009 January) appear in Table 3; the differences are expressed in terms of the radial (R), downtrack (T), and out-of-plane (N) directions. The largest changes are in the downtrack and are a consequence of improved determination of the various perturbations and resonances that affect the satellites' mean longitude (Paper I discusses the resonances). Note that there is very little change in the orbits of Pallene and Polydeuces as the ephemerides and GMs[4] of their respective dominant perturbers, Enceladus and Dione, are well known. The accuracies of the integrated orbits within the time frame of the *Cassini* tour may be found in Table 4; the errors have been reduced from those in Paper I. The largest error for all

[4] GM is the product of the Newtonian constant of gravitation G and the satellite's mass M

Table 2
Saturn Equatorial Planetocentric Elements

Element	Pan	Daphnis
Epoch (JD TDB)	2451545.0	2453491.91412
a (km)	133584.0(1)	136505.5(1)
e	0.0000144(54)	0.0000331(62)
ϖ (deg)	208(14)	83(12)
λ (deg)	146.592(4)	222.949(4)
i (deg)	0.0001(4)	0.0036(13)
Ω (deg)	282(101)	143(8)
$\dot{\lambda}$ (deg dey^{-1})	626.031735(2)	605.979162(5)
$\dot{\varpi}$ (deg dey^{-1})	3.20685(4)	2.96927(4)
$\dot{\Omega}$ (deg dey^{-1})	−3.19059(4)	−2.95486(4)

Notes. Longitudes are measured from the node of the Saturn equator on the ICRF equator. Element uncertainties are in parentheses.

Table 3
Satellite Orbit Changes—rms

Satellite	R (km)	T (km)	N (km)
Janus	6	23	2
Epimetheus	2	27	3
Atlas	1	60	1
Prometheus	1	13	1
Pandora	2	16	2
Methone	1	23	1
Pallene	1	9	1
Polydeuces	1	3	1

Table 4
Satellite Orbit 1σ uncertainties

Satellite	R (km)	T (km)	N (km)
Janus	5	20	5
Epimetheus	5	20	5
Atlas	5	40	5
Prometheus	5	20	5
Pandora	5	20	5
Methone	5	20	5
Pallene	5	10	5
Polydeuces	5	10	5

Table 5
Saturn Equatorial Planetocentric Elements Fit to Integration over the Time Span from 2003 January to 2005 January

Element	Janus	Epimetheus	Atlas	Prometheus	Pandora
Epoch (JD TDB)	2453005.5	2453005.5	2453005.5	2453005.5	2453005.5
a (km)	151460	151410	137670	139380	141710
e	0.0068	0.0098	0.0012	0.0022	0.0042
ϖ (deg)	288.1778	37.8567	332.2233	63.8218	50.6769
λ (deg)	171.4419	346.1286	130.0033	306.1166	253.2354
i (deg)	0.1640	0.3524	0.0031	0.0075	0.0507
Ω (deg)	46.9389	85.2616	9.3532	262.8166	327.2839
$\dot{\lambda}$ (deg dey^{-1})	518.238030	518.486468	598.312351	587.285237	572.788589
$\dot{\varpi}$ (deg dey^{-1})	2.0529	2.0553	2.8781	2.7577	2.5996
$\dot{\Omega}$ (deg dey^{-1})	−2.0449	−2.0473	−2.8682	−2.7449	−2.5879

Note. Longitudes are measured from the node of the Saturn equator on the ICRF equator.

satellites remains that in the downtrack direction, a consequence of the continuing difficulty of separating the mean motion from long-period mean longitude perturbations.

In Tables 5 and 6 we give descriptive mean elements for the numerically integrated orbits. These elements have been

Table 6
Planetocentric Elements Referred to the Local Laplace Plane Fit to Integration over the Time Span from 2000 January to 2010 January

Element	Methone	Pallene	Polydeuces
Epoch (JD TDB)	2453177.5	2453177.5	2453006.5
a (km)	194230	212280	377200
e	0.0000	0.0040	0.0192
ϖ (deg)	233.7336	78.3827	144.9124
λ (deg)	192.1600	125.4655	107.5819
i (deg)	0.0131	0.1813	0.1774
Ω (deg)	346.3250	7.4458	304.7164
$\dot{\lambda}$ (deg dey^{-1})	356.585232	312.027148	131.534744
$\dot{\varpi}$ (deg dey^{-1})	2.9251	0.6243	31.0812
$\dot{\Omega}$ (deg dey^{-1})	−0.8531	−0.6230	−30.1556
α[a] (deg)	40.5773	40.5770	40.5449
δ[a] (deg)	83.5375	83.5377	83.5384

Notes. Longitudes are measured from the node of the Laplace plane on the ICRF equator.
[a] α and δ are the ICRF right ascension and declination of the Laplace plane pole.

Table 7
Saturn Equatorial Planetocentric Elements Fit to Integration over the Time Span from 2006 July to 2008 July

Element	Janus	Epimetheus
Epoch (JD TDB)	245 3005.5	245 3005.5
a (km)	151 440	151 490
e	0.0068	0.0097
ϖ (deg)	287.6001	41.1061
λ (deg)	90.5925	278.1461
i (deg)	0.1639	0.3525
Ω (deg)	47.8714	82.5981
$\dot{\lambda}$ (deg dey^{-1})	518.345 648	518.0976 22
$\dot{\varpi}$ (deg dey^{-1})	2.0539	2.0517
$\dot{\Omega}$ (deg dey^{-1})	−2.0460	−2.0438

generated by fitting precessing ellipses to the integrations for the time frames indicated in the tables (the time frames are the same as those used for Paper I). The fits also included adjustments to the mean longitudes of Janus, Epimetheus, Atlas, Pandora, Methone, and Polydeuces to account for the dominant periodic perturbation (this is done to avoid aliasing long-period effects into the mean motions; in Paper I only the Polydeuces mean longitude was adjusted). The reference plane for the elements in Table 5 is the Saturn equator but the reference plane for those in Table 6 is the local Laplace plane of each satellite. The Laplace plane is the plane on which the orbit precesses almost uniformly; the orientation angles of the planes are provided in the table. In keeping with the relatively small changes from the orbits of Paper I, the changes in the mean elements are negligible except for those of Methone. The latter's semi-major axis is smaller as a direct consequence of correcting for the long-period longitude perturbation.

In early 2006 Janus and Epimetheus had a close approach and effectively swapped orbits; Table 7 provides mean elements for the swapped orbits. The semi-major axis of Janus has clearly been reduced and that of Epimetheus increased from the pre-2006 values in Table 5. The associated changes in the mean motions are also evident.

Revised GM values for Janus, Epimetheus, Atlas, Prometheus, and Pandora appear in Table 8 together with the

Table 8
GM Values ($km^3\ s^{-2}$)

Source	Janus	Epimetheus	Atlas	Prometheus	Pandora
Yoder, Synnott & Salo (1989)	135.5 ± 13.3	37.5 ± 3.7			
Rosen et al. (1991)	87^{+113}_{-20}	28^{+11}_{-7}		10 ± 5	9 ± 5
Nicholson et al. (1992)	132.1 ± 8.3	36.7 ± 2.0			
Jacobson (1996)	128.4 ± 6.0	35.7 ± 1.7			
Renner, Sicardy & French (2004)				$14.1^{+1.0}_{-2.5}$	$10.3^{+1.0}_{-1.9}$
Jacobson & French (2004)	126.9 ± 0.9	35.2 ± 0.3		12.0 ± 0.7	10.1 ± 0.5
Spitale et al. (2006)	126.58 ± 0.33	35.40 ± 0.09	0.44 ± 0.04	10.45 ± 0.13	9.05 ± 0.15
Current work	126.60 ± 0.08	35.13 ± 0.02	0.44 ± 0.03	10.64 ± 0.10	9.15 ± 0.13

previously determined values (note: the Janus GM in Paper I is erroneous). We have significantly reduced the uncertainties on the Janus and Epimetheus GMs as a consequence of their close approach.

3. CONCLUDING REMARKS

We have used *Cassini* imaging observations made subsequent to 2005 November to improve the orbits of Saturn's small satellites. We have found for the most part that differences from the orbits reported in Paper I are small. Consequently, we have increased confidence in our knowledge of the orbits and have reduced our estimates of their errors accordingly. As a direct result of fitting observations of Janus and Epimetheus through their close approach in 2006, we have also refined our estimate of their GMs. Additional *Cassini* observations are planned to the end of the prime mission in 2009 and on into the extended mission for several more years. Refinement of the orbits will continue as those data become available.

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