REVISED ORBITS OF SATURN'S SMALL INNER SATELLITES

R. A. Jacobson¹, J. Spitale², C. C. Porco², K. Beurle³, N. J. Cooper³, M. W. Evans³ and C. D. Murray³

¹ Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, USA; robert.jacobson@jpl.nasa.gov
² Cassini Imaging Central Laboratory for Operations, Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, CO 80301, USA
³ Astronomy Unit, School of Mathematical Sciences, Queen Mary, University of London, Mile End Road, London, E1 4NS, UK

Received 2007 September 20; accepted 2007 October 20; published 2007 December 7

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 are 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

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 $a$, $\omega$, or $\Omega$, 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.

**Table 2**

Saturn Equatorial Planetocentric Elements

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

**Table 3**

Satellite Orbit Changes—rms

<table>
<thead>
<tr>
<th>Satellite</th>
<th>$R$ (km)</th>
<th>$T$ (km)</th>
<th>$N$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Janus</td>
<td>6</td>
<td>23</td>
<td>2</td>
</tr>
<tr>
<td>Epimetheus</td>
<td>2</td>
<td>27</td>
<td>3</td>
</tr>
<tr>
<td>Atlas</td>
<td>1</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>Prometheus</td>
<td>1</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>Pandora</td>
<td>2</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>Methone</td>
<td>1</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>Pallene</td>
<td>1</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Polydeuces</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
In Tables 5 and 6 we give descriptive mean elements for the numerically integrated orbits. These elements have been 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.

Table 5

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

Table 6

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

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.

Table 7

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

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

Table 8
$GM$ is the product of the Newtonian constant of gravitation $G$ and the satellite's mass $M$

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 $GM$s. 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.

We would like to thank the Cassini Navigation Team for their support in finding serendipitous observations among the optical navigation images. The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

Jacobson, R. A. 1996, BAAS, 28, 1185 First citation in article | NASA ADS | Order from Infotrieve