ORBITAL DYNAMICS OF THE URANIAN SATELLITES BASED ON VOYAGER DATA

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The satellites of Uranus all have significant non-zero eccentricities and in the case of Miranda a significant inclination as well (Table 1). Squyres et al. (1985) studied the time scales and possible energy effects associated with the orbital evolution of these bodies, specifically the eccentricities. However, because of the uncertainty in the sizes and masses (data were based on estimates of Brown et al., 1982 and Brown and Cruikshank, 1983), there was a corresponding uncertainty in the results. The Voyager 2 encounter with Uranus in January 1986 provided more accurate estimates of the masses and sizes of the satellites (Smith et al., 1986). As a result, it seems useful to reexamine the orbital history and possible tidal heating by using the Voyager data. This is particularly relevant because Miranda, which had the largest pre-Voyager size uncertainty, is also the satellite which appears to have undergone the most extensive endogenic evolution.

Miranda and, to a certain extent, Ariel have undergone significant endogenic activity. Crater frequency data for Ariel (Plescia and Boyce, 1986a), in combination with the cratering time scale postulated by Smith et al. (1986), indicate that Ariel's surface is >3.5 Gy old and that no major resurfacing has occurred since. Miranda, on the other hand, has the least cratered surface of any satellite in the Uranian system (Plescia and Boyce, 1986b) and may have surfaces as young as several hundred million years old.

The relevant orbital dynamics equations (Peale, 1977; Peale et al., 1980) follow.

The change in orbital eccentricity (e) with time (t) is

$$de/dt = - (21\ k_2\ n\ M\ r^5\ e)/(2\ m\ a^5\ Q) \qquad (1)$$

where k_2 is the satellite potential Love number, n is the satellite mean motion, m and M are the masses of the satellite and Uranus, r is the satellite radius, a is the satellite semimajor axis and Q is the satellite dissipation function. The equation is an approximation because the term relating to the effect of dissipation within Uranus has not been included. Dissipation within Uranus is negligible and dissipation within the satellite is the dominant term.

The potential Love number (k_2) is

$$k_2 = (1.5)/[1 + (19\ u\ /\ 2\ p\ g\ r)] \qquad (2)$$

where u is the satellite rigidity, p is the satellite density, and g the surface gravity.

Finally, the homogeneous tidal heating rate (E) for a synchronously rotating body is approximated as

$$dE/dt = [(m^2\ n^5\ r)\ /\ (u\ Q)]\ [0.396\ e^2 + 0.0566\ o^2] \qquad (3)$$

where o is the spin obliquity: the angle between the spin vector and the orbit normal. If the satellite is in Cassini spin state 1 (o less than the orbital inclination), there is no obliquity-decay heating. If, however, this is not the case, the obliquity term can become important.

Assuming $u = 4 \times 10^{10}$ dyne cm^{-2}, a value typical for low-temperature ice, and $Q = 20$, the orbital eccentricity decay times and homogeneous tidal heating rates were calculated (Table 1). These results are similar to those of Squyres et al. (1985) and indicate that the calculated rates are relatively insensitive to the uncertainties in mass and density of the satellites. The calculations indicate that the present eccentricities of Miranda and Ariel should decay on time scales of 10^7 years, whereas those of Umbriel, Titania, and Oberon are stable for 10^8 to 10^9 years. The original eccentricity (e_o) is, however, unknown and could have been quite large.

To make the present orbital eccentricity of Ariel and Miranda long lived, such that a late-stage event to pump up the eccentricity is not neccessary, requires that either u or Q be increased. Neither parameter is well constrained because the interior thermal conditions and compositions of the satellites are uncertain. A Q of >100 would produce an eccentricity decay time of 10^8–10^9 years for Ariel and Miranda. Similarly, increasing u would also lengthen the decay time. Rigidities of 4×10^{11} dyne cm^{-2}, similar to rock rather than ice, would increase the decay time to 10^8–10^9 years.

When obliquity heating is not important, the tidal heating rates from eccentricity decay are about one to several orders of magnitude below that of the radioactive heating (Table 1). The low tidal heating and low radioactive heating of Ariel, Umbriel, Titania, and Oberon are consistent with their generally ancient age. Miranda, however, presents a significant problem because of the youthful appearance of its surface.

The inclusion of the obliquity term in equation (3) has important implications for Miranda. If Miranda occupies Cassini state 2 (o greater than the orbital inclination), then the obliquity term in equation (3) becomes important. Assuming that all of the satellites have obliquities equal to their inclinations, the tidal energy produced (*II*) was calculated (Table 1). For Ariel, Umbriel, Titania, and Oberon, the term remains unimportant because the obliquity is small. However, inclusion of the term for Miranda increases the heating rate by 3 orders of magnitude.

Alternatively, if there is no obliquity heating of Miranda, the eccentricity heating rate can only be raised to approximately that of radioactivity. Enchanced eccentricity heating will result, relative to the model in Table 1, by reducing either Q or u. For $Q = 1$ and $u = 4 \times 10^{10}$ dyne cm^{-2}, the heating rate is 3.03×10^{15} erg sec^{-1}, corresponding to a heat flow of 0.45 ergs cm^{-2} sec^{-1}. For $Q = 20$ and $u = 4 \times 10^9$ dyne cm^{-2}, the rate is 1.52×10^{15} erg sec^{-1}, corresponding to a heat flow of 0.20 erg cm^{-2} sec^{-1}.

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Table 1

		Miranda	**Ariel**	**Umbriel**	**Titania**	**Oberon**
Radius (km)		242±5	580±5	595±10	805±5	775±10
Density (gm cm^{-3})		1.26±0.39	1.65±0.3	1.44±0.28	1.59±0.09	1.50±0.10
Mass (gm)		7.48×10^{24}	1.35×10^{24}	1.27×10^{24}	3.47×10^{24}	2.92×10^{24}
Gravity (cm sec^{-2})		8.52	26.74	23.94	35.76	32.48
Semimajor axis (km)		129783	191239	265969	435844	582596
Eccentricity		0.0027	0.0034	0.0050	0.0022	0.0008
Inclination °		4.2	0.3	0.4	0.1	0.1
de/dt (Q=20) sec^{-1}		4.79×10^{7}	1.38×10^{7}	1.22×10^{8}	8.16×10^{8}	6.64×10^{9}
tidal heating erg sec^{-1} (Q=20)	*I*	1.52×10^{14}	1.02×10^{16}	1.70×10^{15}	8.18×10^{13}	8.37×10^{11}
	II	1.61×10^{17}	1.36×10^{16}	2.17×10^{15}	8.91×10^{13}	1.41×10^{12}
tidal energy heat flow erg cm^{-2} sec^{-1}	*I*	0.02	0.24	0.04	0.001	0.00001
	II	21.88	0.32	0.05	0.001	0.00002
radioactive heat flow erg cm^{-2} sec^{-1}		0.15	0.93	0.64	1.13	0.91

I does not include the obliquity term in equation (3)
II includes the obliquity term in equation (3).