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The dynamical environment of Dawn at Vesta

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ABSTRACT

Dawn is the first NASA mission to operate in the vicinity of the two most massive asteroids in the main belt, Ceres and Vesta. This double-rendezvous mission is enabled by the use of low-thrust solar electric propulsion. Dawn will arrive at Vesta in 2011 and will operate in its vicinity for approximately one year. Vesta's mass and non-spherical shape, coupled with its rotational period, presents very interesting challenges to a spacecraft that depends principally upon low-thrust propulsion for trajectory-changing maneuvers. The details of Vesta's high-order gravitational terms will not be determined until after Dawn's arrival at Vesta, but it is clear that their effect on Dawn operations creates the most complex operational environment for a NASA mission to date. Gravitational perturbations give rise to oscillations in Dawn's orbital radius, and it is found that trapping of the spacecraft is possible near the `1:1` resonance between Dawn's orbital period and Vesta's rotational period, located approximately between 520 and 580 km orbital radius. This resonant trapping can be escaped by thrusting at the appropriate orbital phase. Having passed through the `1:1` resonance, gravitational perturbations ultimately limit the minimum radius for low-altitude operations to about 400 km, in order to safely prevent surface impact. The lowest practical orbit is desirable in order to maximize signal-to-noise and spatial resolution of the Gamma-Ray and Neutron Detector and to provide the highest spatial resolution observations by Dawn's Framing Camera and Visible InfraRed mapping spectrometer. Dawn dynamical behavior is modeled in the context of a wide range of Vesta gravity models. Many of these models are distinguishable during Dawn's High Altitude Mapping Orbit and the remainder are resolved during Dawn's Low Altitude Mapping Orbit, providing insight into Vesta's interior structure. Ultimately, the dynamics of Dawn at Vesta identifies issues to be explored in the planning of future EP missions operating in close proximity to larger asteroids.

1. Introduction

The Dawn Discovery mission was successfully launched on September 27, 2007, and is the first NASA science mission making use of solar electric propulsion (EP), enabled by the earlier Deep Space 1 technology demonstration mission (Lehman, 1999). As a consequence of the efficiency of this low-thrust, low-acceleration system, Dawn is able to rendezvous with the two most massive objects in the asteroid belt, Vesta then Ceres. These targets were selected in order to study the earliest stages of planetary evolution for an object that formed dry (Vesta) and another that formed with substantial amounts of water (Ceres) (Russell et al., 2004).

Dawn's first target, Vesta, has a semi-major axis of 2.36 AU and is located in the inner main asteroid belt. It is unique in having a basaltic crust that has survived over the age of the solar system, providing important constraints on models of the collisional evolution of the asteroid belt (e.g., Davis et al., 1985). It has been spectroscopically linked to HED meteorites on the Earth (McCord et al., 1970), which represent approximately 6% of all meteorite falls today (McSween, 1999). It has been inferred from those meteorites that Vesta is a differentiated object with an iron-rich core (Newsom, 1984; Ghosh and McSween, 1996; Righter and Drake, 1996). Hubble observations of Vesta revealed an object with an equatorial radius around 289 km and polar radius of 229 km, but with a substantial impact crater covering much of its southern hemisphere and distorting its shape (Zellner et al., 1997; Thomas et al., 1997a, b). This giant impact likely gave rise to the Vesta collisional family, which spans the inner main belt from the ν_6 secular resonance with Saturn on its inner edge to the `3:1` mean motion resonance with Jupiter, separating it from the outer main belt. Some Vesta material entering these resonances would have their orbits pumped into Mars- and eventually Earth-crossing orbits, resulting in the HED meteorites recovered on the Earth (e.g., Migliorini et al., 1997). Dawn may provide connections between specific areas of Vesta's surface and HED (and possibly other) meteorites.

Dawn executed a Mars gravity assist on February 17, 2009, to align its orbital inclination with that of Vesta. Dawn arrives at Vesta in July 2011 when it will enter an initial orbit having a

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radius of 2700 km (Survey orbit), from which it will obtain a preliminary shape model using the Framing Camera (FC) and spectrally map the entire illuminated surface using the Visible InfraRed mapping spectrometer (VIR) (Russell et al., 2006, 2007b). Assuming the rotational pole of Thomas et al. (1997a), Vesta's obliquity is 27.2°. Dawn arrives at Vesta at the time of maximum illumination of the southern hemisphere and its large crater. After completing the Survey orbit phase, Dawn uses its EP thrusters to descend to a High Altitude Mapping Orbit (HAMO) at approximately 950 km radius from which it will use the FC to map Vesta's surface and determine its global shape and local topography using stereophotoclinometric techniques (e.g., Gaskell et al., 2008). Dawn will then descend to its Low Altitude Mapping Orbit (LAMO) of around 460 km radius from which it will map Vesta's elemental composition using the Gamma-Ray Neutron Detector (GRaND). The Survey, HAMO, and LAMO phases are nominally 7, 27, and 90 days in duration (Russell et al., 2007a), but this is subject to further planning for the 8 month stay at Vesta, which may be extended to a year. Because Dawn uses its EP thrusters for orbit transfers, transitions between these different phases are expected to take around a month (Russell et al., 2007b).

To maximize the science return from the mission, we are interested in determining the lowest orbital radius from which Dawn can safely execute LAMO. The closer to the surface we can make observations, the better the spatial resolution of FC and VIR observations. However, a lower LAMO most benefits observations by GRaND. The spatial resolution of the GRaND instrument is approximately 1.5 times the altitude (Prettyman et al., 2003). At nominal 460 km orbital radius for LAMO, this altitude will vary between 175 km near the equator and 231 km near the south pole. By decreasing LAMO to 400 km, the number of GRaND resolved elements on Vesta increases by more than 50%, improving our ability to identify geochemical units and relate them to HED meteorites (Prettyman et al., 2010). Going lower also improves GRaND signal-to-noise and may enable an accurate determination of Mg and Si, which are important discriminators among the various rock types expected on Vesta (Prettyman, priv. comm., and Prettyman et al., 2010). However, lower orbits and corresponding decreased orbital periods increases the need for desaturation of the spacecraft angular momentum, increasing the operational burden, which is not explored here.

A Vesta gravity model is also greatly improved with reduced altitude, allowing for better detection of mascons and determination of Vesta's higher order gravitational terms. At HAMO, the gravity field is determined to at least degree 4 and at LAMO this is expected to improve to at least degree 10 (Russell et al., 2007b). Depending on the accuracy of Doppler and Doppler-rate data, simulations later in this manuscript show that these numbers can be significantly improved, reaching degree 10 at HAMO and degree 20 at LAMO.

While there are science benefits from a minimum radius LAMO, Vesta's large mass and deviation from sphericity raises the question of how its gravity field will constrain the lowest orbital radius at which Dawn can safely operate. In addition, the long transfer times between Survey, HAMO and LAMO mean that Dawn will be slowly transiting commensurabilities between its orbital period and Vesta's rotational period, where perturbations on Dawn's orbit may be significant.

With this work we explore the dynamics of the Dawn spacecraft in a polar orbit within 1000 km from Vesta. The gravitational potential of Vesta is determined assuming diverse and extreme scenarios for its interior structure, to ensure the dynamical environment is sufficiently explored and that the results are representative of what the mission is likely to experience once there. The orbital maneuver from HAMO to LAMO using EP to slowly spiral in is also simulated, to assess the effect of mean motion resonances.

2. Modeling the gravitational field of Vesta

In general, the gravitational potential of a body with arbitrary shape and mass distribution can be described using the spherical harmonics series (Kaula, 1966)

$$U(r,\theta,\phi)=\frac{GM}{r}\left[1+\sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\frac{r_0}{r}\right)^{l}P_{lm}(\cos\theta)(C_{lm}\cos m\phi+S_{lm}\sin m\phi)\right] \tag{1}$$

where G is the universal gravitational constant, M is the total mass of the body, $\{r,\theta,\phi\}$ are the body-fixed barycentric spherical coordinates of the point where the potential U is computed, r_0 is an arbitrary reference radius usually corresponding to the radius of the Brillouin sphere, the smallest sphere enclosing the body, $P_{lm}(\cos\theta)$ is the associate Legendre function. Using this series, the Stokes coefficients $\{C_{lm},S_{lm}\}$ uniquely characterize the potential of the body. In cases where the mass density distribution $\varrho(r,\theta,\phi)$ of a body is known, then the coefficients $\{C_{lm},S_{lm}\}$ of the series in Eq. (1) can be determined by integrating over the volume V of the body (Kaula, 1966)

$$C_{lm}=\frac{1}{M}\int_V\varrho(r,\theta,\phi)\left(\frac{r}{r_0}\right)^{l}P_{lm}(\cos\theta)\cos m\phi\,dV \tag{2}$$

$$S_{lm}=\frac{1}{M}\int_V\varrho(r,\theta,\phi)\left(\frac{r}{r_0}\right)^{l}P_{lm}(\cos\theta)\sin m\phi\,dV \tag{3}$$

The integration over the volume of the body is typically performed numerically, i.e. using Monte Carlo integration techniques (i.e., Press et al., 1992). In the Monte Carlo integration, each integral $I=\int_V f\,dV$ is approximated by $I\simeq V\langle f\rangle$, where $\langle f\rangle$ is the mean value of the integrand inside the volume. Both V and $\langle f\rangle$ are computed by randomly sampling points inside the body's volume. The nominal error on the result of a Monte Carlo integration is $\sigma_I=V\sigma_f/\sqrt{N}$, where σ_f is the variance of the integrand, and N is the number of sample points used.

The Stokes coefficients can be more readily compared and used in numerical work when their magnitude is normalized (i.e., Kaula, 1966), and in this manuscript we use the following normalization rule:

$$\{\overline{C}_{lm},\overline{S}_{lm}\}=\sqrt{\frac{(l-m)!}{(l+m)!}\frac{(2-\delta_{0m})}{(2l+1)}}\{C_{lm},S_{lm}\} \tag{4}$$

This normalization produced results in agreement the Stokes coefficients of the asteroid 433 Eros produced by the NEAR mission, see Section 3.

In order to use this formalism to model Vesta's gravitational potential, and thus the dynamics of a spacecraft in its proximity, we need a model for its shape and a model for its mass density distribution.

Analysis of Hubble Space Telescope (HST) observations of Vesta have yielded accurate determination of its size, shape and rotational state (Thomas et al., 1997a). The overall shape of Vesta can be fit by a triaxial ellipsoid of radii 289, 280, 229, ±5 km (Thomas et al., 1997a). The shape is not perfectly ellipsoidal, with departures of 15–20 km from the smooth ellipse, and a large indentation with depth of 20–30 km and diameter of about 200 km in the southern hemisphere (Thomas et al., 1997a). The rotation period used for Vesta is of 5.3421288 h (Thomas et al., 1997a), and for the purpose of this work, we assumed Vesta to be a primary axis rotator. The 3D shape model obtained by Thomas