Estimation and Modeling of Enceladus Plume Density Using Attitude Control Data Collected By the Cassini Spacecraft during Low-altitude Enceladus Flybys

Eric K. Wang and Allan Y. Lee

Mail Stop 230-104
Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, CA 91109-8099
California Institute of Technology
Eric.K.Wang@jpl.nasa.gov
(818) 393-1132

The Cassini spacecraft was launched on 15 October 1997. After an interplanetary cruise of almost seven years, it arrived at Saturn on June 30, 2004. Major science objectives of the Cassini mission include investigations of the configuration and dynamics of Saturn's magnetosphere, the structure and composition of the rings, the characterization of several of Saturn's icy satellites, and Titan's atmosphere constituent abundance.

The attitude of the Cassini spacecraft could be controlled using either a set of eight thrusters or a set of three reaction wheels. Thrusters are used to control the spacecraft attitude during low-altitude Titan and Enceladus flybys. During these flybys, Cassini will experience significant atmospheric or plume torque, and only thrusters have the control authority to guarantee spacecraft safety. The Reaction Wheel Assemblies (RWAs) are used primarily for attitude control when precise and stable pointing of a science instrument is required. During a low-altitude flyby of Enceladus, with the spacecraft controlled either by RWA or thruster, the magnitudes of plume torque imparted on the spacecraft can be estimated.[1,2]

Enceladus is a small icy satellite of Saturn with a mean radius of 247 km. In 2005, Cassini made several flybys of Enceladus (cf. Table 1). Observations made during those flybys confirmed the existence of a water vapor plume in the south polar region of Enceladus. Additional Cassini science measurements revealed four prominent linear fractures, each separated by about 30 km and spanning 130 km in length straddling the South Polar Region. These fractures, informally termed "Tiger stripes," show dark flanks in the near-IR and are anomalously warm. The Tiger stripes are a likely source of tectonic activities and plume generation. From these Tiger stripes, materials are vented from the interior of the moon to hundreds of kilometers above the moon's surface. Cassini science instruments also revealed the presence of molecular nitrogen, carbon dioxide, methane, propane, and several other species in these watery geysers. The discovery of watery geysers from Enceladus is an important and unexpected discovery made by Cassini. Hence, Enceladus watery plume has become one of the key science investigations of the

Cassini Equinox mission (an extension of the Cassini Prime mission, from July 2008 to September 2010). It will continue to be one of the key science objectives for the Cassini Solstice mission (a second mission extension, from October 2010 to May 2017).

Table 1. Targeted Enceladus Flybys In 2005–2010

Flyby	ECA* Date	ECA Altitude (km)	ECA Location	Velocity (km/s)
E1	03/09/2005	501	-	6.6
E2	07/14/2005	170	-	8.2
E3†	03/23/2008	50	20° S, 135° W	14.4
E4	08/11/2008	50	28° S, 98° W	17.7
E5	10/09/2008	25	28° S, 97° W	17.7
E6	10/31/2008	196.9	-	17.7
E7	11/02/2009	99	89° S, 159° W	7.7
E8	11/21/2009	1602.9	-	7.8
E9	04/28/2010	99	89° S, 147° W	6.5
E10	05/18/2010	434.6	-	6.5
E11	08/13/2010	2550.4	-	6.8
E12	11/30/2010	47.9	61° N, 53° W	6.3
E13	12/21/2010	47.8	61° N, 233° W	6.2

*ECA = Enceladus Closest Approach
†*Highlighted flybys have ECA altitudes that are lower than 100 km.*

During an Enceladus flyby, the watery plume will impart torque on the Cassini spacecraft. As such, thrusters must be fired to maintain the commanded spacecraft flyby attitude. Thrusters' on-time telemetry collected could be used to estimate the magnitude of the imparted torque, and indirectly the density of the Enceladus plume. Similarly, if the spacecraft is controlled by reaction wheels during the flyby, reaction wheel-related telemetry could be used to estimate the plume density. In fact, since the Cassini reaction wheel control system is designed for precision attitude control and produces high-resolution telemetry data, they could also be used to provide good estimates of low plume density for all low-altitude flybys of Enceladus.

Attitude control telemetry data collected from several past low-altitude Enceladus flybys revealed the presence of attitude control error transients when the spacecraft was near the Enceladus Closest Approach (ECA) of these flybys. These high-resolution attitude control errors were collected at a high telemetry frequency of 2 Hz. They could be used to estimate the time histories of the total disturbance torque imparted on Cassini.

The time rates of change of the per-axis accumulated angular momenta could be used to reconstruct the magnitudes of the per-axis disturbance torque imparted on the spacecraft.[1,2] In order to maintain the quiescent inertial attitude of the spacecraft, the three RWAs must "absorb" the angular momenta imparted on Cassini due to the (time-varying) plume-induced torque. As a result, the RWA spin rates changed as the spacecraft passed through the plume cloud. The total angular momentum of the spacecraft could be computed using knowledge of the RWAs' inertia properties, the S/C inertia properties, and the telemetry data of the S/C's rates and RWA spin rates. The total angular momentum vector of the spacecraft could then be fitted with a, for example, 5th order polynomial of time. An example based on telemetry data collected from the Enceladus-3 flyby is depicted in Fig. 1. The time rates of change of these per-axis angular momenta are the per-axis torque imparted on the spacecraft.

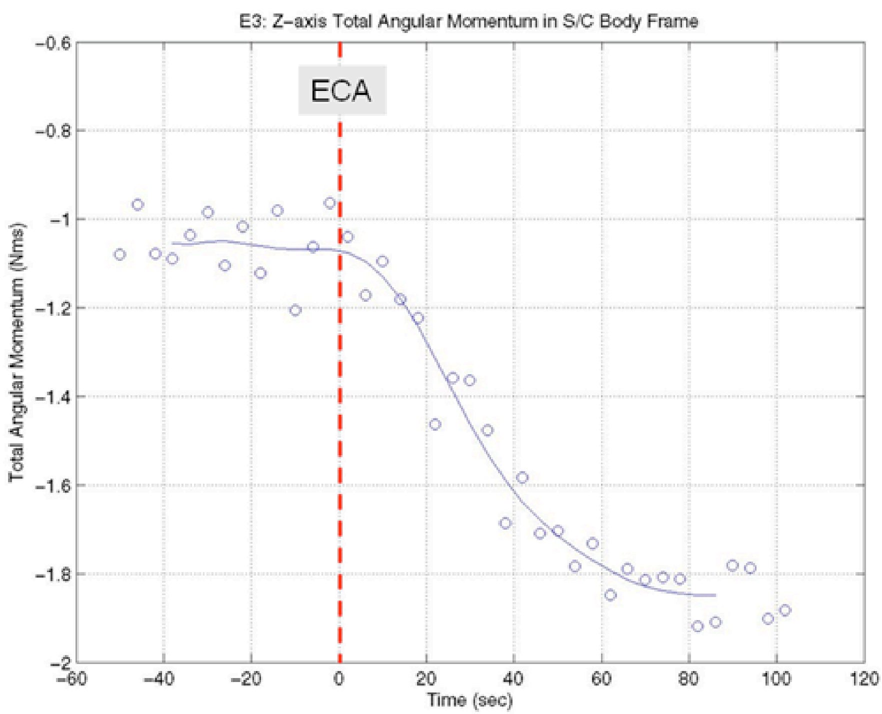

Fig. 1 Computed Z-axis Angular Momentum During Enceladus-3 Flyby

The Enceladus density is related to the torque imparted on the spacecraft by the following approximate equation:[1,2]

$$\vec{T}_{Plume}(t) \approx \frac{1}{2} C_D \rho_{Plume}(t) V(t)^2 A_{Projected}(t) \quad \vec{u}_V(t) \times [\vec{r}_{CP}(t) - \vec{r}_{CM}] \tag{1}$$

In this equation, $T_{Plume}(t)$ is the torque imparted on the spacecraft that was estimated using the approach described above. $\rho_{Plume}(t)$ is the time history of the Enceladus plume density, in kg/m^3, and is the "unknown" quantity. The spacecraft velocity relative to Enceladus is denoted by $V(t)$ (in m/s), and is estimated by the Cassini Navigation team for each Enceladus flybys. The orientation of the velocity vector as expressed in the S/C's coordinate frame is denoted by the unit vector u_V. The area of the spacecraft projected onto a surface that is perpendicular to the vector u_V is denoted by $A_{Projected}$ (in m^2). The displacement vectors, from the origin of the spacecraft coordinate frame to the spacecraft's center of mass and center of pressure (in meters) are denoted by r_{CM} and r_{CP}, respectively. Both vectors as well as the projected area are estimated by ground software. Finally, the dimensionless quantity C_D is the drag coefficient associated with the free molecular flow of Enceladus' plume constituents past the body of the Cassini spacecraft. It is known from past research ($C_D \approx 2.1 \pm 0.1$).

The time histories of the three per-axis Enceladus plume torque estimated using the methodology described above could be used to reconstruct the Enceladus plume density, as a function of time. Using the known flyby trajectory design, we can also compute the time histories of the spacecraft Enceladus-relative altitude. Accordingly, the variation of Enceladus' plume density as a function of flyby altitude could be modeled for each one of these Enceladus flybys.

Enceladus plume density modeling is being studied widely. Their results were reported in the literature.[3] In the literature, the structure of the Enceladus plume density is commonly modeled using the following relation:

$$\rho(R,\Theta) = \rho_0 [\frac{R_E}{R}]^2 \exp[-(\frac{\Theta}{H_\Theta})^2] \exp[-\frac{R - R_E}{H_d}] \tag{2}$$

In this expression, R is the radial distance of the S/C from Enceladus' center of mass (cf. Fig. 2), Θ is the angular distance of the S/C from the plume axis (centered at the c.m. of Enceladus), and R_E is the radius of Enceladus. Additionally, ρ_0, H_Θ, and H_d are model parameters.

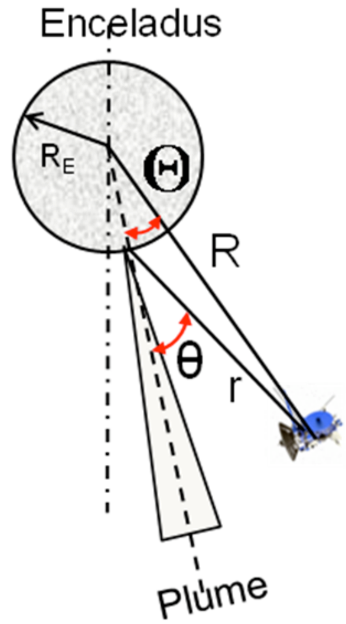

Figure 2. Enceladus Plume Model

In our study, a similar but simplified model will be used:[2]

$$\rho(\mathrm{r},\theta) = \mathrm{K}_{\rho}[\frac{\mathrm{R}_{\mathrm{E}}}{\mathrm{r}}]^{\frac{3}{2}} \exp[-\frac{\theta}{\mathrm{K}_{\theta}}] \tag{3}$$

In equation (3), r is the radial distance of the S/C from plume source, and θ is the angular distance of the S/C from the plume axis (centered at the surface of Enceladus). In this model, only two free model parameters (K_ρ and K_θ) will be needed. The magnitudes of these model parameters could be determined by comparing the time histories of the density predicted by the model (cf. equation (3)) and that estimated via flight data. One way to do that is to use the "simplex" method described in Ref. 4.[2] Values of model parameters that minimize the difference between the model and flight data could be determined for each and all Enceladus flybys. Based on these individual plume density models, an overall Enceladus plume density model could be synthesized.

References

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