Hydrodynamic Simulations of Asymmetric Propeller Structures in the Saturnian Ring System

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Introduction

The non-Keplerian behavior of propeller structures in Saturn's outer A ring (Tiscareno et al., 2010; Seiler et al., 2017; Spahn et al., 2018) raises the question, how the propeller structure responds to the wandering of the central embedded moonlet. Here, we study numerically how the induced propeller structure is effected by a librational motion of the moonlet. It turns out, that this motion induces an asymmetry in the structural imprint of the propeller structure, where the asymmetry depends on the moonlet's libration amplitude and period. We make predictions for the resulting asymmetry for a moonlet with 400 m Hill radius. This allows to apply our findings to the giant propeller structures in the outer A ring – such as Blériot and Santos Dumont – which are of similar size. For Blériot, we find that, supposed the moonlet is librating with the largest observed period of 11.1 years and an azimuthal amplitude of about 1845 km (Seiler et al., 2017; Spahn et al., 2018), the asymmetry might be misinterpreted as noise. For Santos Dumont we expect that the asymmetry is observable in the images due to its larger radial amplitude.

Method

We use the isothermal hydrodynamic integration scheme by Seiß et al. (2017), which we modify by allowing the central moonlet to librate around its mean orbital position $\Omega = \sqrt{GM_p/r_0^3}$ within the simulation box. The azimuthal component y_m will be given by the Kepler shear, following from the proportionality of $dn/dt \propto da/dt$

$$x_m(t) = x_{m,0} \cos(\omega_{lib} t) \quad (1)$$

$$y_m(t) = -\frac{3}{2}\left(\frac{\Omega}{\omega_{lib}}\right) x_{m,0} \sin(\omega_{lib} t) \quad (2)$$

The radial amplitude $x_{m,0}$ and the libration period $T_{lib} = 2\pi/\omega_{lib}$ will be set initially.

We consider a moonlet size of $h = 400$ m in Hill radii, which is in the range of the expected size of Blériot(Hoffmann et al., 2016; Seiß et al., 2017). The other simulation parameters are chosen to fit the outer A ring conditions (Seiß et al., 2017).

The Asymmetric Density Profile

The moonlet libration breaks the point-symmetry of the induced propeller structure, where the perturbation by the moonlet's motion needs time to get transported to larger azimuthal distances. This results in a retardation.

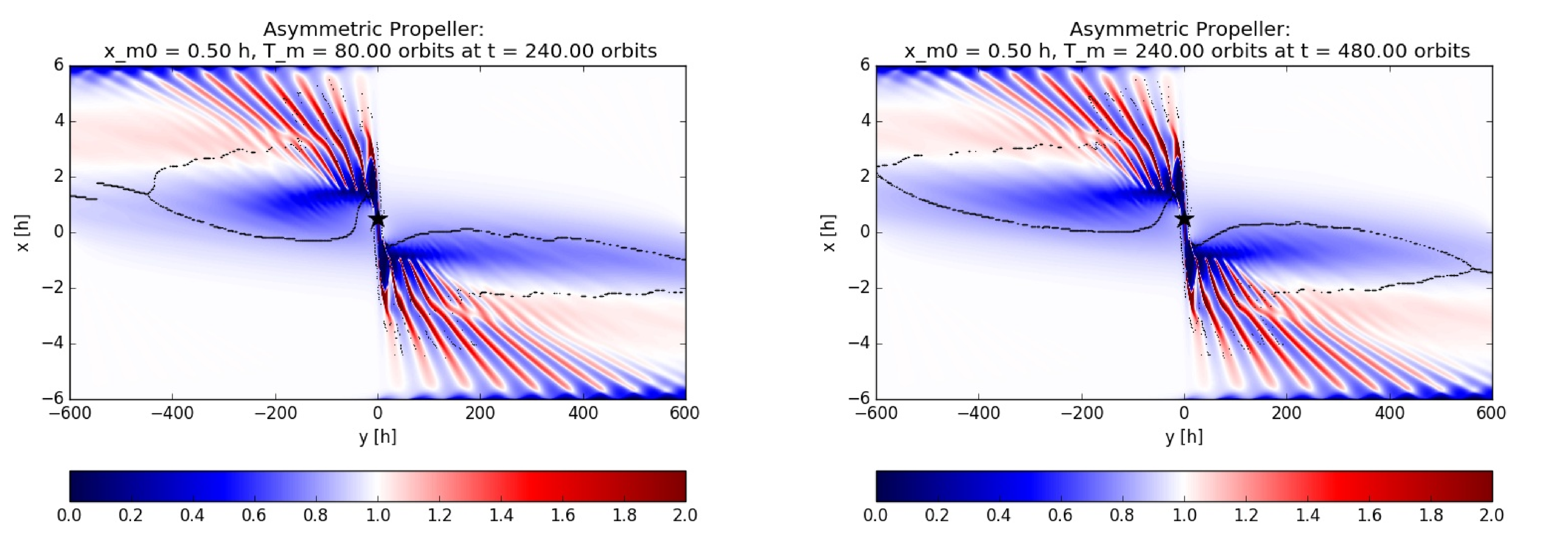

Figure 1: Simulation results for an embedded moonlet which librates with a radial amplitude of $x_{m,0} = 0.5$ h and a period of $T_m = T_{gap}$ (left) and $T_m = 3 \times T_{gap}$ (right). The moonlet is presented at the same libration phase. The colored area represents the density, where blue areas denote density depletion, while red color stands for density enhancement.

For our parameters the perturbation needs about 80 orbits to migrate through the gap structure, defining T_{gap} as a memory timescale in this way, which is a critical parameter for the observability of the asymmetry. As long as $T_{lib} \leq T_{gap}$, the retardation effect results in a strong asymmetry of the induced propeller structure, while for $T_{lib} > T_{gap}$ the the propeller structure looks less asymmetric.

The Asymmetric Gap Profiles

The moonlet libration changes the appearance of the propeller structure all the time according to the actual moonlet position resulting in changing gap properties (gap position, depth, width, length).

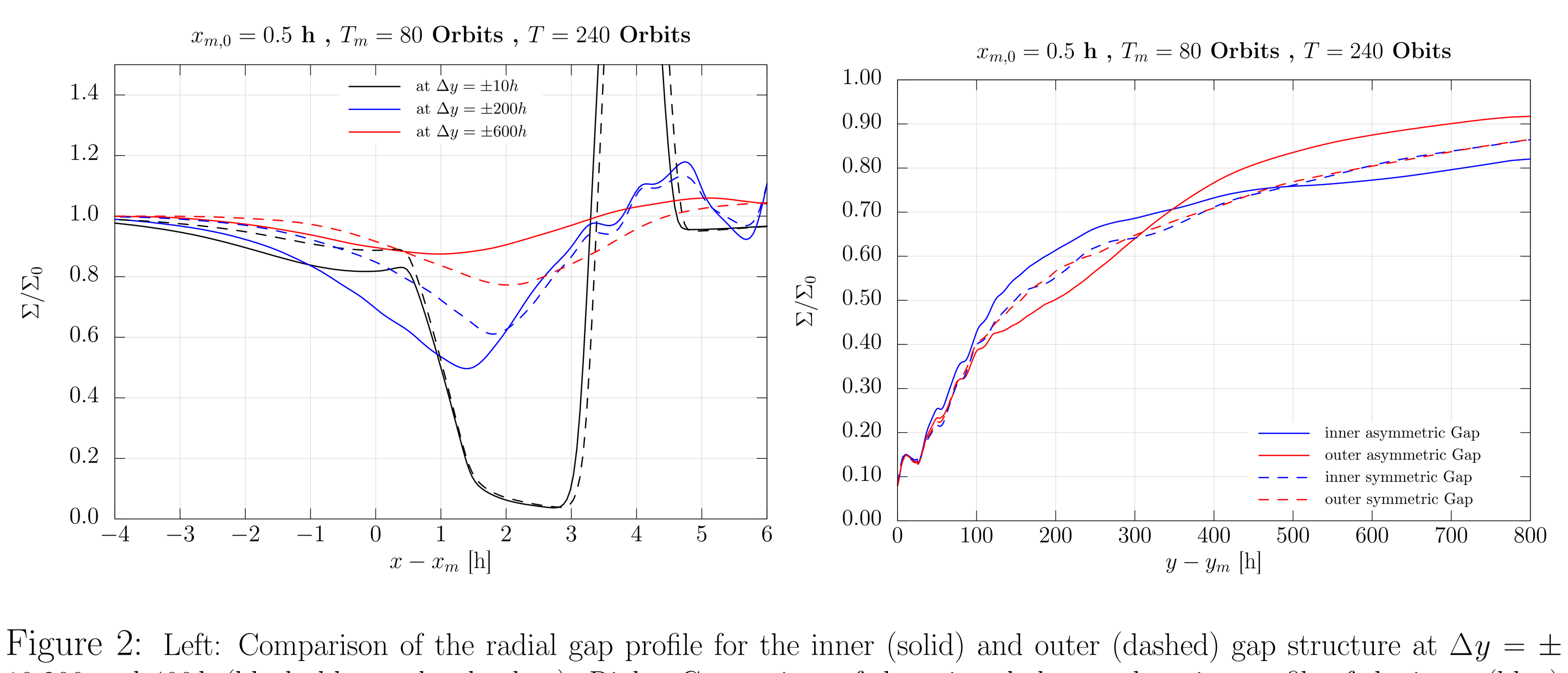

Figure 2: Left: Comparison of the radial gap profile for the inner (solid) and outer (dashed) gap structure at $\Delta y = \pm$ 10,200 and 400 h (black, blue and red colors). Right: Comparison of the azimuthal gap relaxation profile of the inner (blue) and outer (red) gap structure. The solid and dashed lines refer to the asymmetric and symmetric propeller.

The effect of the retardation can be seen in the gap profiles. In the close vicinity of the moonlet, the retardation is small and thus the gap structure follows the moonlet motion almost immediately, while for larger azimuths the retardation increases.

Asymmetry Observability: Timescales Matter

The asymmetry decreases for larger libration periods and for small radial amplitudes.

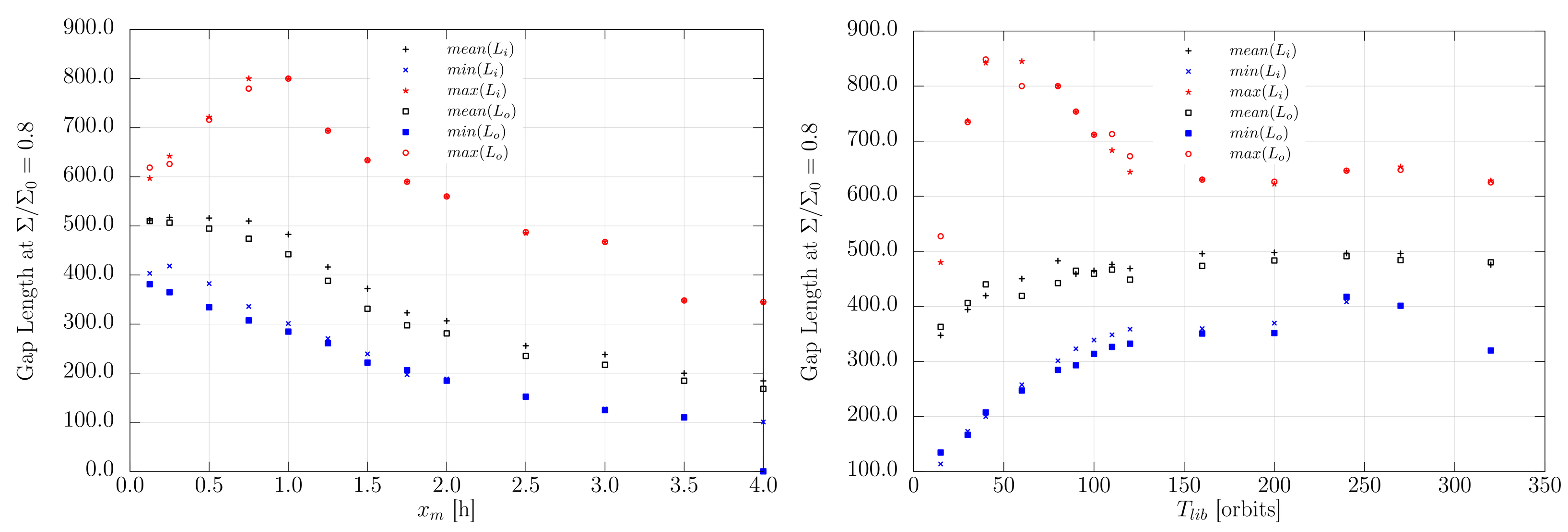

Figure 3: Left: Comparison of the maximum and minimum gap length for the inner and outer gap in dependence of the libration amplitude (left) and period (right). At $T_m = T_{gap}$ and $x_{m,0} = 1$ h an optimum for the asymmetry can be found.

The moonlet libration effects the gap lengths. Depending on the actual libration phase and the libration period, large length differences can be measured.

Main Results

1. The gap ends react to the changed propeller motion after a retardation time T_{gap}.
2. The retardation time takes the role of a gap memory timescale and can give information about changes of the moonlet motion.
3. The memory timescale T_{gap} is a critical parameter to distinguish a linear migration from a libration. For $T_{lib} \leq T_{gap}$ a harmonic motion can be identified in the azimuthal gap profiles, while for $T_{lib} > T_{gap}$ the harmonic motion would be indistinguishable from a linear migration.
4. The gap length changes with the moonlet size $h = a_0\sqrt[3]{M_m/3M_p}$ according to $h^3/\nu_0 \propto M_m/\nu_0 \propto L/\nu_0$ (Spahn and Sremčević, 2000), which effects T_{gap}. Thus, for smaller moonlet sizes, the gap length and T_{gap} decrease.
5. The asymmetry effects all properties of the gap profile (depth, width, position, length), where the azimuthal profile is the most favorable to study for processing ISS images.

Application to Giant A Ring Propellers

Blériot: From the first harmonic fit (Seiler et al., 2017) we expect the moonlet's azimuthal libration amplitude and period to be $y_{m,0} = 1845$ km and $T_m = 11.1$ years. This results in a radial amplitude of about $x_{m,0} = 0.177$ m ≈ 0.44 h, assuming $h = 450$ m (Hoffmann et al., 2016; Seiß et al., 2017; Spahn et al., 2018), respectively. The gap length of Blériot is about $L = 6500$ km and yields a gap time of $T_{gap} = 0.5$ years. Thus for Blériot $T_{lib} \gg T_{gap}$ needs to be considered. The asymmetry of Blériot's is rather small and its observability strongly depends on the actual libration phase of the moonlet.

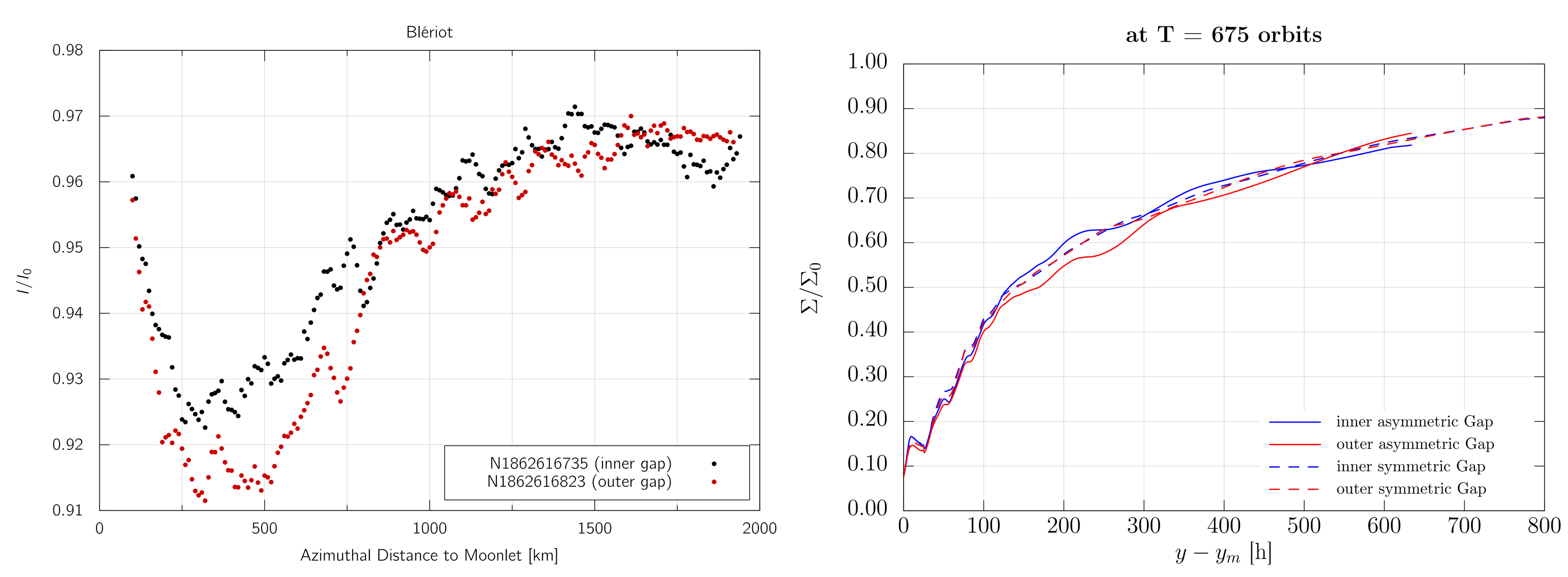

Figure 4: Comparison of the azimuthal gap profile for the inner and outer gap of Blériot(left, see also poster M10) and a corresponding simulation result with $T_m = 2 \times T_{gap}$ and $X_{m,0} = 0.5$ h (right).

Santos Dumont: Santos Dumont also shows an excess motion (Tiscareno, 2018, PSG). Although the moonlet ($h \approx 250$ m) is smaller than Blériot, its excess motion has an even larger amplitude $y_{m,0} = 3200$ km over a time span of $T_m = 10$ years, resulting in a radial amplitude of about $x_{m,0} = 250$ m, or $x_{m,0} = 1$ h, respectively. This, asymmetry should be large enough to be detectable.

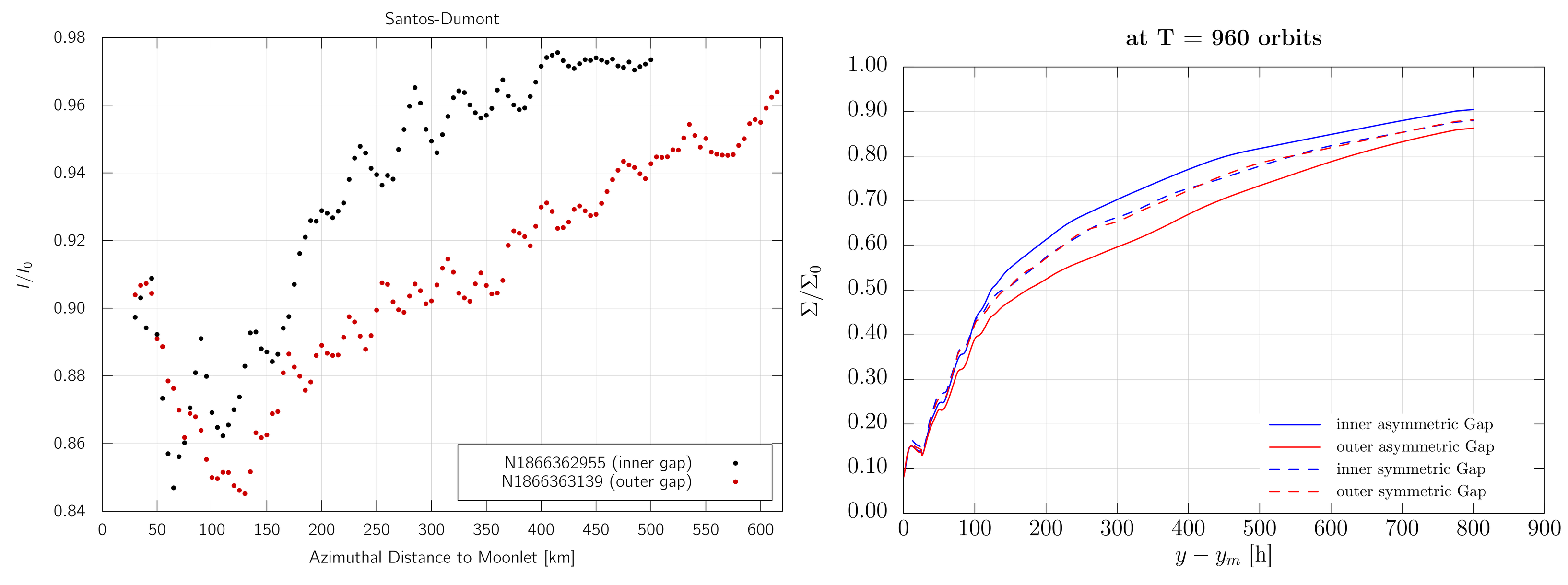

Figure 5: Comparison of the azimuthal gap profile for the inner and outer gap of Santos Dumont (left, see also poster M10) and a corresponding simulation result with $T_m = 2 \times T_{gap}$ and $x_{m,0} = 1$ h (right).

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