On the Migration of the Galilean Satellites

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Summary

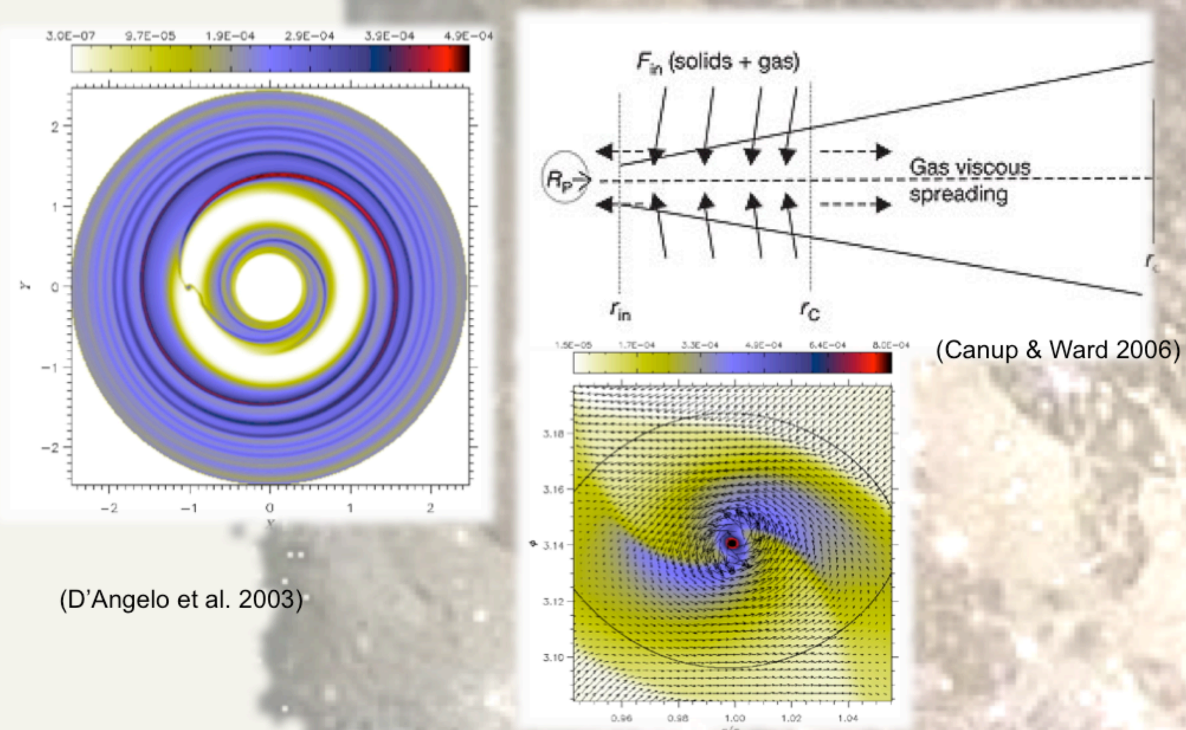
We have adopted the gas-starved subnebula model to study the migration of the Galilean satellites through their interaction with the circumjovian disk. An **improved gas-starved subnebula model** is constructed by enhancing the temperature profile treatment. By including **non-isothermal** effect in type I migration regime, **outward migration is possible** and there is a location where the disk torque is equal to zero. Using the improved gas-starved disk model, **multiple zero-torque positions** are produced. Satellite can converge to one of the zero-torque positions and moves towards Jupiter with the zero-torque positions. Including the effect of satellite growth slows down satellite migration. However, the Galilean satellites can **hardly be brought to their current locations without interactions between satellites**. Presence **of satellites of earlier generations** can slow down migration of the Galilean satellites.

1. Introduction

Regular satellites, including the Galilean satellites of Jupiter, are formed in **circumplanetary disks** composed of gas and dust. Satellites grow by accreting solid disk materials, and migrate due to their interaction with the disk. Both the accretion and migration of the satellites depend on disk properties. In this study, we focus on investigating the migration of the Galilean satellites in the circumjovian disk.

2. Gas-starved Subnebula Model

A gas-starved subnebula (Canup & Ward 2002, 2006; hereafter CW02) does not contain all the masses for forming the satellites at the start, and is supplied by a **slow inflow of gas and solid materials** from the solar nebula, in contrast to the minimum mass subnebula model, in which the disk initially contains all the materials required. Disk properties of a gas-starved disk are determined by the **disk viscosity parameter α**, **disk opacity K** and **material inflow timescale τ_G**.



(Canup & Ward 2006)

(D'Angelo et al. 2003)

By improving the temperature profile with a temperature-dependent opacity and the treatment of low optical depths, an

Improved Gas-starved Subnebula Model is constructed (Turner et al. 2013) , which introduces **non-smooth disk profiles**.

The circumjovian disk depletes as the inflow from the surrounding solar nebula decays. The **disk depletion timescale τ_{dep}** is determined by the **dissipation of the solar nebula**.

The Galilean satellites are the **last generation of satellites** formed in the circumjovian disk. The formation time of the satellites is regulated by the time needed for the inflow to deliver an amount of solid materials equal to the total satellite mass M_T to the disk, i.e. when the inflow timescale falls to

$$\tau_G = \tau_{dep}(M_J / M_T) / f$$

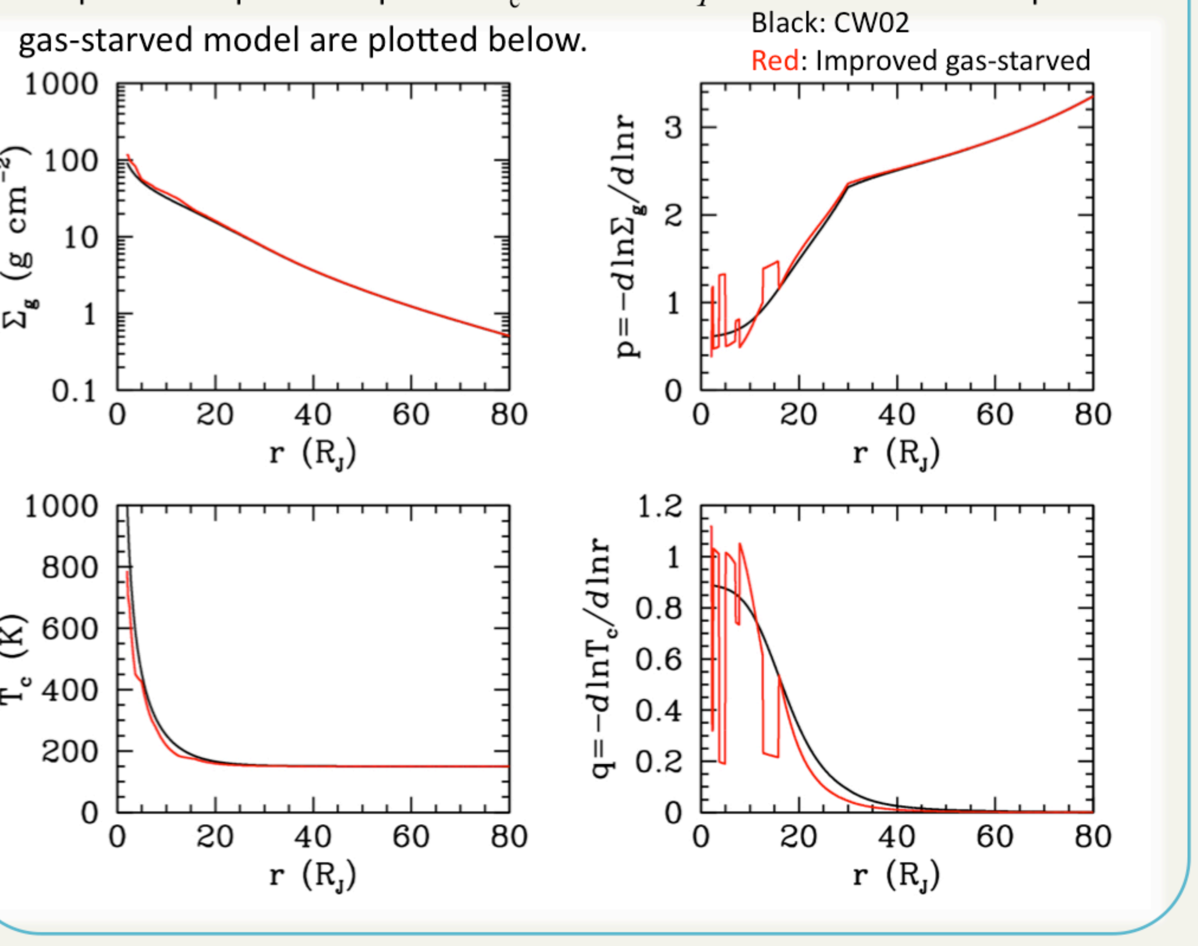
where f is the gas-to-solid ratio in the disk (Canup & Ward 2006).

In this work, we adopt a disk model appropriate for the last generation of satellites, with parameters of

- **Opacity K = 0.1 $cm^2 g^{-1}$** (CW02) or

  Opacity scaling factor f_{opac} = 0.1 (Improved gas-starved model)
- **Inflow timescale τ_G = 50 Myr**
- **Viscosity parameter $\alpha = 5\times10^{-3}$**

as the initial setting, and decay the inflow to the disk exponentially with **τ_{dep} = 1 Myr**. The surface density profile Σ_g and index p, and the midplane temperature profile T_c and index q in the CW02 and improved gas-starved model are plotted below.



3. Satellite Migration

The satellites interact with the circumjovian disk and migrate in the type I regime. In an **isothermal** disk, the magnitude of disk torque Γ on the satellite is controlled by **surface density index** p (= $-d\ln\Sigma_g/d\ln r$) only (Tanaka et al. 2002):

$$\Gamma / \Gamma_0 = -1.364 - 0.541p$$

where the normalised torque Γ_0 is a function of satellite-planet mass ratio M_s/M_J, satellite location a , surface density Σ_g, scale height H and Keplerian frequency Ω:

$$\Gamma_0 = \left(\frac{M_s}{M_J}\right)^2 \left(\frac{H}{a}\right)^{-2} \Sigma_g a^4 \Omega^2$$

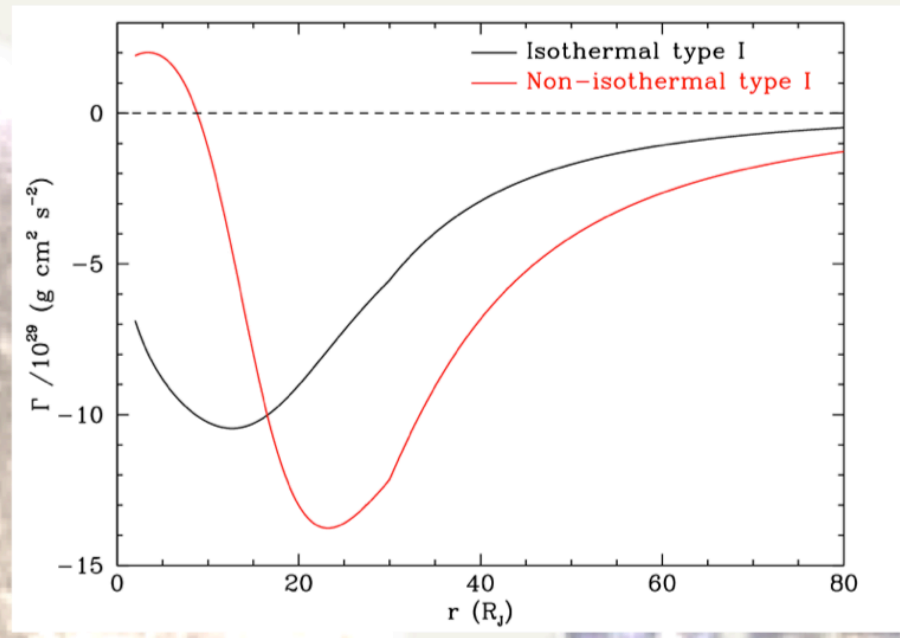
and the migration is **always inward**.

However, in a **non-isothermal** disk, with the effect of **unsaturated horseshoe drag**, the magnitude of disk torque is also determined by the **temperature profile index** q (= $-d\ln T_c/d\ln r$) (Paardekooper et al. 2010) :

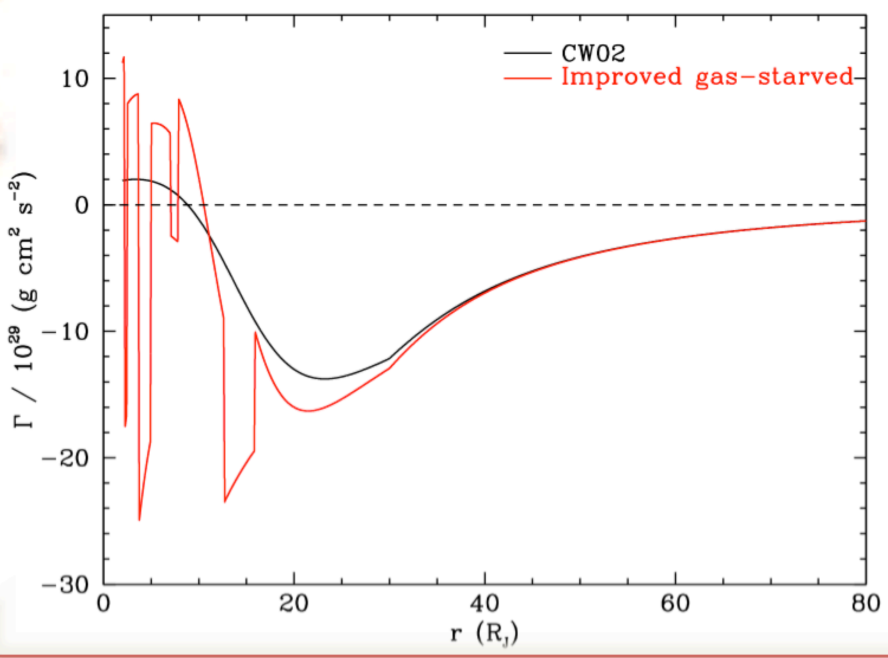
$$\Gamma / \Gamma_0 = -0.607 - 2.326p + 2.816q$$

and both inward and **outward migration** are possible.

The below plot demonstrates the differences between the two torques in a CW02 disk. Note that there is a location where the non-isothermal torque equals zero.



Non-smooth disk profiles in the improved gas-starved subnebula model produce multiple **zero-torque positions**. There are 4 stable zero-torque positions at which the satellite can be **trapped** in the improved disk model. The non-isothermal torques in the CW02 and improved gas-starved subnebula model are plotted below.



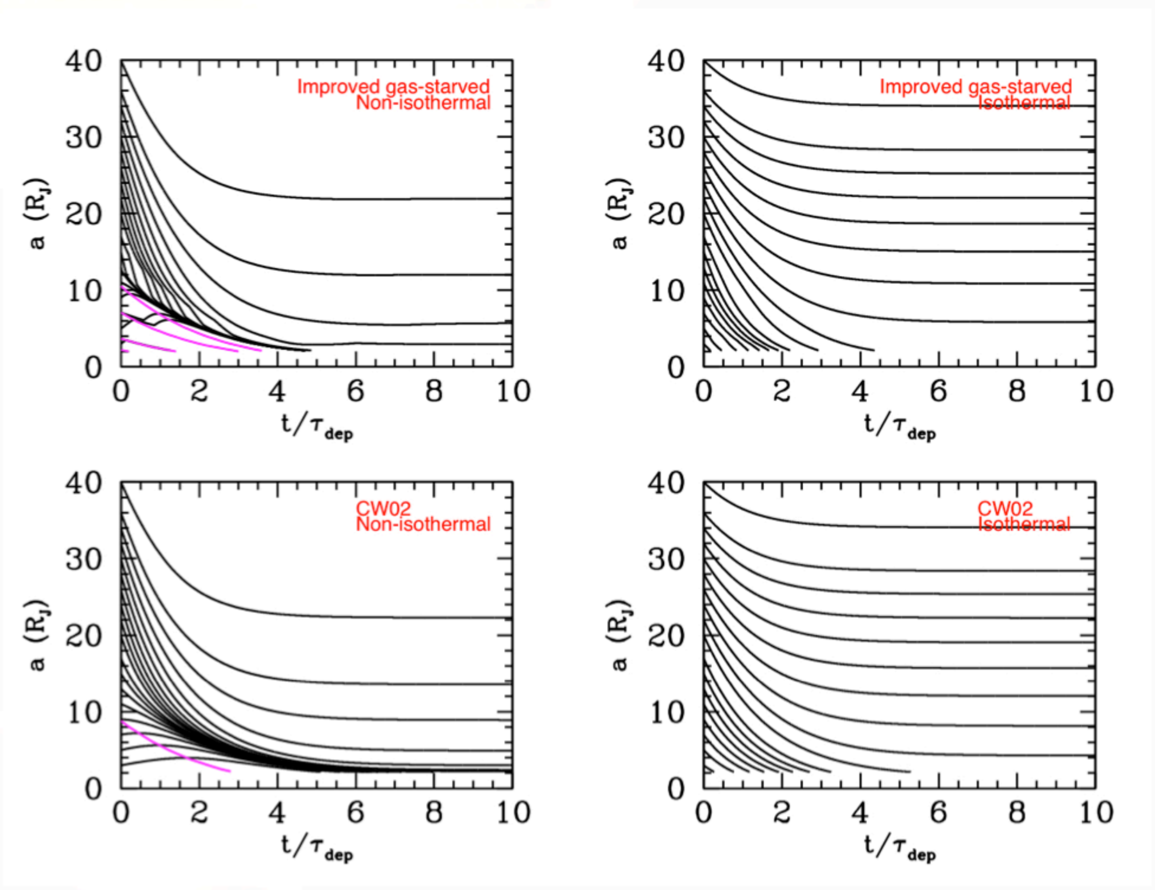
4. Migration of Satellites in the Disk

(a) Effects of Disk and Migration Models Adopted

Using the disk and migration models prescribed, the migration of a Europa-mass satellite is demonstrated in the below plots.

With consideration of the **non-isothermal** effect (left panels), **outward migration** is possible in the inner disk region in both disk models. Satellites at several initial locations eventually **converge to near one of these zero-torque positions** (plotted in magenta), and **move towards Jupiter with the zero-torque position**. The difference in the two disk models is more significant in the inner disk.

Considering the isothermal regime (right panels), the satellites always migrate inwards at all initial locations. The two model shows similar migration behaviour all over the disk.

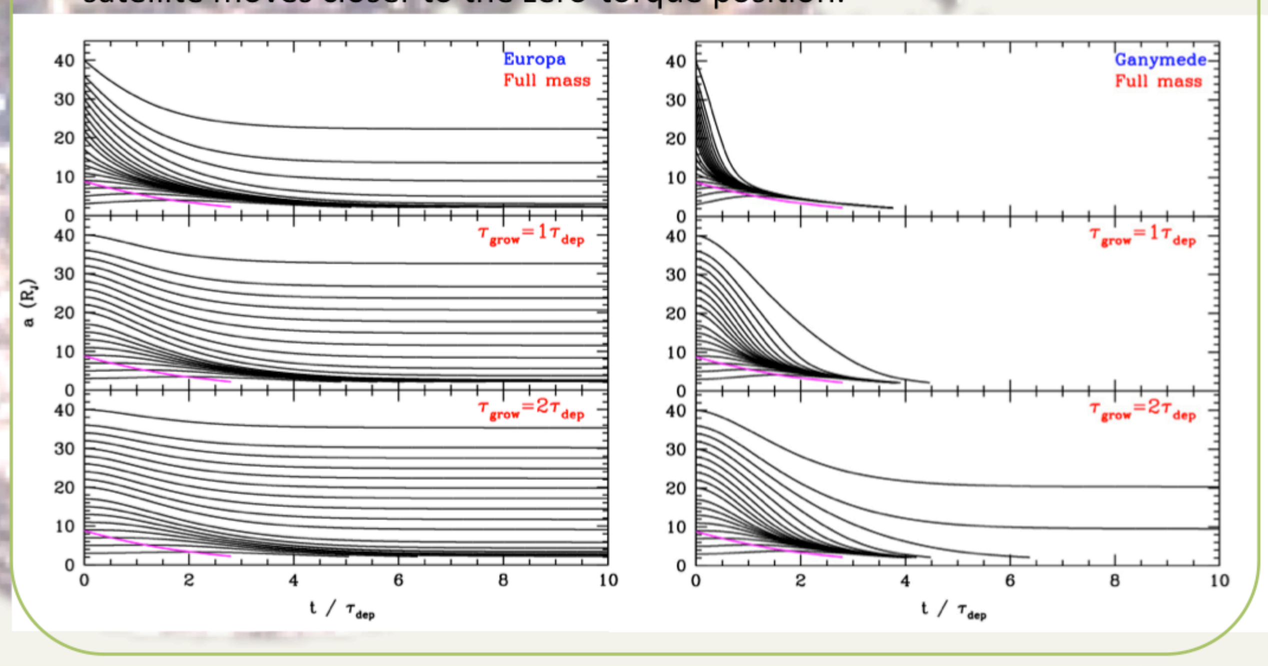


(b) Effects of Satellite Mass and Mass Growth

The migration of Europa-mass (left) and Ganymede-mass (right) satellites in different mass growth timescale is demonstrated in the below plots in the CW02 disk including the non-isothermal effect.

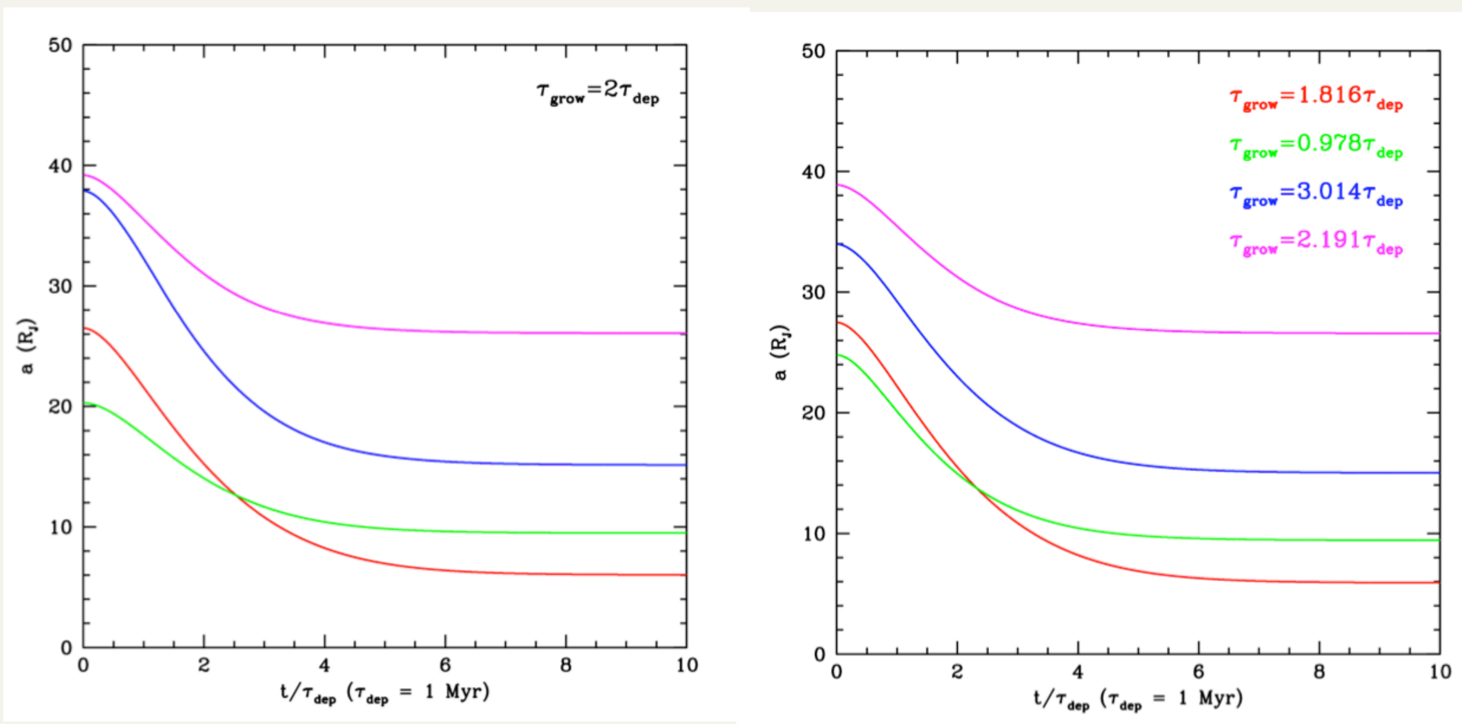
Including the effect of **satellite growth moderates** the migration of the satellites. Satellite migration with satellite mass growth timescale τ_{grow} equal to 1 τ_{dep} (middle panels) and 2 τ_{dep} (bottom panels) are plotted.

Satellites at several initial locations eventually converge to near one of these zero-torque positions (plotted in magenta), but **stay at a distance away**. That distance depends on **satellite mass**, where a more massive satellite moves closer to the zero-torque position.



5. Conditions for Current Configuration

(a) Initial Locations of the Galilean Satellites



We set the four Galilean satellites to migrate in the CW02 disk in the non-isothermal regime, and see where they should start in order to migrate to their current locations. We adopted two different growth models for the satellite:

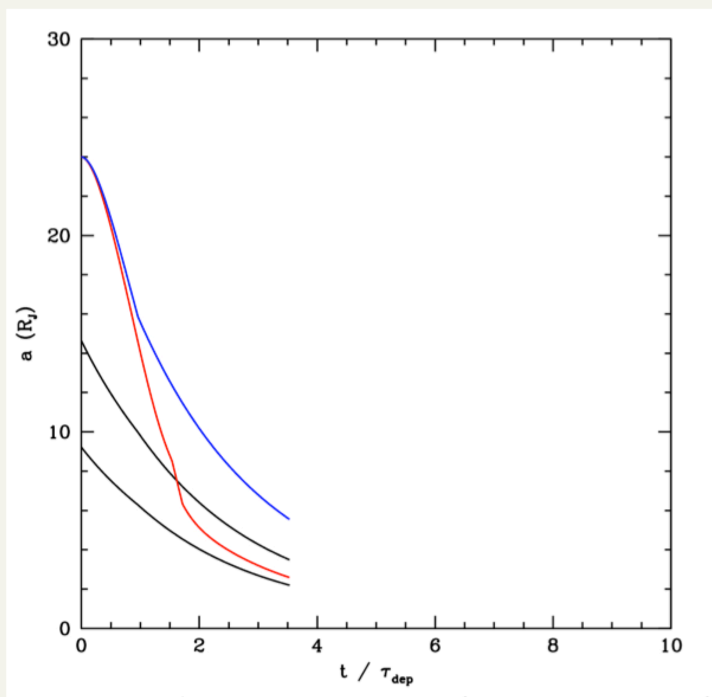
(1) all satellites growing in the same timescale of 2 τ_{dep} (left);

(2) their growth timescale τ_{grow} scaled by their current mass, so that the satellites grow at the same rate before gaining their full mass (right).

We found that **Europa has to be started in the interior of Io**, showing that **satellites cannot be brought to their current location without interaction between the satellites.**

(b) Effect of Satellites of Earlier Generations

Since the Galilean satellites are the last generation of satellites of Jupiter, there are **satellites of earlier generations** formed in the circumjovian disk in the gas-starved disk model. Some of these earlier-generation satellites may still be present in the disk during the early growth stage of the Galilean satellites, and are probably **trapped by one of the zero-torque positions** in the disk. This can cause the satellites to capture into **a chain of resonances**. This possibly **slows down** the migration of the Galilean satellites at the early stage. Eventually all the early-generation satellites converge into Jupiter with the zero-torque positions, leaving the Galilean satellites as the last-generation satellites of Jupiter.



Comparison between migration of Io in presence of satellites of earlier generation (plotted in blue) and without interactions with other satellites (plotted in red). In both cases Io is growing with growth timescale equal to 1 τ_{dep}. Io is slowed down by the inner two earlier-generation satellites (plotted in black).

(c) Other Possibilities?

To study the migratioin of the Galilean satellites in the circumjovian disk, one may also consider the following possible scenarios in satellite formation and migration:

- Saturation of the horseshoe drag (Paardekooper et al. 2011)
- Inner cavity of the circumjovian disk (Sasaki et al. 2010, Ogihara et al. 2012)
- Other satellite growth scenarios

e.g. Satellite growth starting at different time; Satellite growth with different timescales scaled with their forming locations