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Photoevaporative Truncation of Circumplanetary Disks

T. R. Mitchell and G.R. Stewart
Laboratory for Atmospheric and Space Physics, Colorado, USA (tyler.r.mitchell@colorado.edu)

Abstract

We investigate the conditions under which the regular satellites of Jupiter and Saturn formed. The final stage of giant planet accretion is thought to occur slowly over a relatively long, 10 Myr, timescale. Gas accretion during this stage, through a completely or partially opened gap in the solar nebula, occurs slowly allowing for the condensation of ices, and incomplete differentiation, seen in the regular satellites of the giant planets. Furthermore, the dichotomy seen in the Jovian and Saturnian systems may be explained as this infall wanes or is completely shutoff as a result of gap opening or the global depletion of gas in the solar nebula. We present 1-D simulations of circumplanetary disks that couple the viscous transport of material with the loss of mass at the disk outer edge by far-ultraviolet photoevaporation (PE) as well as the infall of material from the solar nebula. We find that the circumplanetary disks of these protoplanets are truncated, as a result of PE, at a range of values with the mean corresponding to ≈ 0.16 Hill radii. These truncation radii are consistent with the current locations of the regular satellite systems of Jupiter and Saturn. We also find that PE can successfully act as a clearing mechanism for circumplanetary nebulae on the potentially short timescales, $10^2 - 10^4$ yr, over which mass accretion from the solar nebula wanes as a result of gap opening.

1. Introduction

Recently, Ward & Canup [4] have developed a comprehensive model that follows the formation and evolution of a giant planet, and subsequent circumplanetary nebula, from cloud collapse through the contraction phase. Despite the comprehensive nature of their model, they have yet to identify an appropriate mass loss mechanism and in their own words, "the outer edge of the disk, r_d, is not well defined other than it be much further out than the centrifugal radius". Given a moderate external FUV flux from either the central star or nearby high-mass stars, PE could provide a natural mechanism for both mass loss and truncation at the outer edge of circumplanetary disks.

Sasaki et al. [3] have recently published results from a suite of simulations in which the growth and dynamical evolution of proto-satellite embryos was modeled. They seek to explain why the Jovian regular satellite system consists of four nearly equal mass satellites whereas the Saturnian system contains one large satellite. They propose that the Jovian satellite system may have been "frozen" in place when Jupiter grew sufficiently large that a gap was opened in the solar nebula. In the Saturnian system, where only an incomplete gap may have formed, the slower shutoff timescale for material infalling from the solar nebula would have allowed its satellites to continue to dynamically evolve. Their models rely on a rapid dispersal mechanism for circumplanetary gas once the gap in the solar nebula has been opened. PE could provide just such a mechanism as well as help to determine a natural outer disk boundary. As with Ward & Canup [4], the models of Sasaki et al. [3] rely on an ad hoc outer disk boundary.

Recent simulations have investigated the tidal truncation of circumplanetary disks [2]. Tidal truncation simulations produce disks that are truncated at a radius corresponding to $\sim 0.4\, r_\mathrm{H}$, where r_H is the planet Hill radius. This outer disk radius is, however, too large to explain the compact configuration of the regular satellite systems of Jupiter and Saturn which extend to less than $0.06\, r_\mathrm{H}$.

2. Results

Phase change problems with moving boundaries, typically considered in problems of melting/freezing and heat ablation, have been studied for quite some time in the material sciences. We have adapted these methods to astrophysical disks in order to treat viscous spreading, mass infall onto the disk, and mass loss due to PE.

We have recently applied this model to protosatellite disks around the planets Jupiter and Saturn; with the addition of a parameterized mass infall from the solar nebula. With the addition of infall, the models are able to reach a steady state in which the infalling mass is balanced by the loss of mass onto the host planet and through the disk's edge due to PE.

One objective of this work is to show how a nominal FUV flux can photoevaporate the outer portions of circumplanetary disks and provide a natural truncation mechanism for the disk models of Ward & Canup and Sasaki et al. [4, 3]. We apply the Adams et al. [1] PE model to circumplanetary disks and find that the disks are truncated well inside the gravitational radius, $r_{\rm g}$. We ran a number of simulations with a variety of viscosities and envelope temperatures (FUV fluxes). Our fiducial models produce outer disk radii truncated at $0.057 r_{\rm H}$ and $0.17 r_{\rm H}$ corresponding to $123 R_{\rm J}$ and $63 R_{\rm S}$ respectively. These small outer disk radii may provide an obvious explanation for the locations of the regular satellites of Jupiter and Saturn.

Another objective of this work is the investigation of a rapid dispersal mechanism required by Sasaki et al. [3] to clear the circumplanetary nebulae of Jupiter and Saturn once accretion from the solar nebula has abated. Figure 1 shows the temporal evolution of Jupiter's circumplanetary disk as the infall is abated, assuming an exponential decay. The radial surface density is shown at 500yr increments, with the solid bold lines indicating $t = \tau_{\rm off}, 2\tau_{\rm off}$ and $3\tau_{\rm off}$, where $\tau_{\rm off}$ is the timescale over which the infall from the solar nebula ceases. A reasonable estimate for the infall decay timescale would be to assume a median value of $\tau_{\rm off} \approx 2.5 \times 10^3$ yr [3].

The total mass of the circumplanetary disk decreased nearly two orders of magnitude from over the course of this simulation. This simulation was done using a nominal FUV flux, which corresponds to an envelope temperature of 600K. Envelope temperatures can range from 100K to 3000K [1]. This shows that, even for a moderate FUV flux, PE is able to clear the Jovian subnebula on the very short timescale over which the infall wanes due to gap opening.

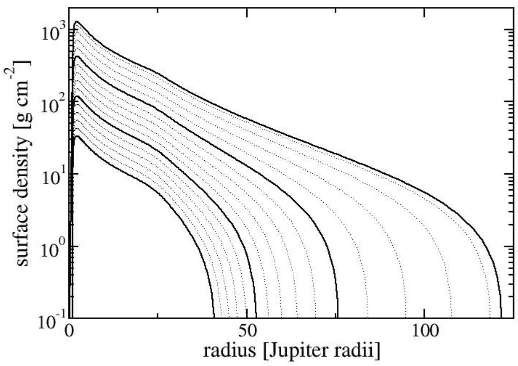

Figure 1: Temporal evolution of Jupiter's circumplanetary disk as the infall from the solar nebula exponentially decays. The radial mass surface density is shown at 500yr increments, with the solid bold lines indicating $t = \tau_{\rm off}, 2\tau_{\rm off}$ and $3\tau_{\rm off}$.

Acknowledgements

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