Spiral Bending Waves Launched at a Vertical Secular Resonance

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The excitation of spiral bending waves at a vertical secular resonance is described. These nodal bending waves are launched at sites where the secondary's nodal regression rate matches the disk's rate, and they propagate in both particle and gas disks. In planet–forming environments where the local disk mass is often in excess of the secondary's mass, it is the disk–gravity that determines the precession rates of the secondary as well as the disk material. If there is no gap in the disk, the resonance will lie quite close to the secondary's orbit a_s, and the bending waves will have a wavelength $\lambda \sim \sqrt{ha_s}$ where h is the disk scale height.

The excitation of nodal bending waves will damp out the secondary's inclination and ultimately shut off subsequent wave generation. An Earth–mass protoplanet embedded in a minimum–mass planetesimal disk will have its inclination damped out in less than ~ 400 orbits provided there is no gap in the disk and its Toomre stability parameter obeys $Q < 100$. The protoplanet's eccentricity is also damped at a comparable rate due to the excitation of spiral density waves at its apsidal secular resonance.

However disk stirring by the secondary or gap formation tends to weaken the wave interaction by slowing the secondary's nodal regression rate and pushing the resonance radially away. Consequently, a Jovian–mass protoplanet orbiting in a minimum–mass nebula gas disk will lose its inclination in ~ 600 orbits if it resides in a gap.

The consequences of these inclination and eccentricity–damping mechanisms for planet–formation will also be discussed.

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