Density waves excited by planets in an optically thin disk and gap formation

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We investigate gravitational interaction between a planet and an optically thin protoplanetary disk, taking account of radiative transfer.
A planet excites two density waves on both sides of the planet orbit due to Lindblad resonances.
The outer density wave exerts a negative torque on the planet while the inner density wave exerts a positive torque.
The sum of the two torque gives the net torque on the planet.
On the other hand, because of the disk-planet gravitational interaction,
a planet gives the disk angular momentum,
which make the disk a gap.
The gap avoids the rapid radial migration of the planet.
In most of the previous studies of density waves and gap formation, the isothermal equation of state has been assumed.
In this study, solving the energy equation in the linear calculation, we examine the effect of energy transfer on the wave excitation and damping.
At the stage of planet formation, the dust opacity is expected to be sufficiently low because of dust growth and planetesimal formation.
Thus we assume an optically thin gaseous disk.
We consider the amount of dust as a parameter and calculate the torque on a planet and gap formation.
Wave damping due to radiative transfer plays an essential role in the angular momentum transfer from the planet to the disk and in the gap formation.
The depth of the surface density gap increases with the strength of the wave damping.
When the disk viscosity and temperature is low,
the planet mass necessary for the gap formation can be the earth mass.