EPSC Abstracts
Vol. 6, EPSC-DPS2011-185, 2011
EPSC-DPS Joint Meeting 2011

Gap opening beyond dead zones by photoevaporative winds: Implications for transition disks and planetary migration

R. Morishima (1,2)
(1) University of California, Los Angels, California, USA, (2) Jet Propulsion Laboratory, Pasadena, California, USA
(ryuji.morishima@jpl.nasa.gov)

Abstract

In the present study, we infer connections between properties of protoplanetary disks in the process of their dispersal, so-called transition disks, and orbital configurations of exoplanetary systems. Our gas disk model takes into account dead zones and photoevaporative winds induced by X rays from the central stars. We find that a gap opens at a radius outside the dead zone, even when a large mass accretion onto the central star remains. This may explain large gap sizes and high mass accretion rates seen in transition disks. The timescale since a gap opens until gas accretion onto the central star stops increases with mass loss rate of photoevaporative winds unless it is too large. Using this disk model, we also investigate planetary migration. For Type I migration of rocky planets, we adopt the rates from recent theories which indicate that outward migration can occur in optically thick disks. For Type II migration, we simply assume that giant planets migrate together with gas, if the disk mass is larger than the planet mass. Our model shows that rocky planets migrate toward equilibrium radii with zero torque; the inner radius is the snow line and the outer radius locates slightly inside the outer edge of a dead zone. If giant planets form at the latter radius, they tend to migrate outward for a case with strong photoevaporative winds, whereas giant planets hardly stay at large radii with weak photoevaporation winds. Rocky planets can migrate close to their host stars only if optically thin disks can survive for a long time after dead zones disappear. Such a situation is realized with weak photoevaporative winds, but this may be not very common. This may explain why the number of Earth to Neptune size hot planets found by the Kepler mission, after corrections of observation biases, increases with size, as the planet migration rate increases with mass.

1. Introduction

Recent observations revealed disks in the process of dispersal, so-called transition disks [1]. They have optically thick outer disks whereas inner disks with sizes up to 70 AU are optically thin. A puzzling thing is that a large fraction of transition disks exhibit gas accretion onto their central stars and their accretion rates are close to T Tauri disk accretion rates, $\sim 10^{-8}$ $M_\odot$/yr [1]. Photoevaporation models with standard α-viscosity disks are not able to reproduce large sizes of inner holes and high mass accretion rates [2]. In this study, we will show that a disk model which takes into low viscosity regions called dead zones [3] and photoevaporative winds well reproduces both large gap sizes and mass accretion rates observed in transition disks.

We also investigate migration of both rocky and giant planets using our disk model and adopting the latest migration theories. Recent Type I migration theories indicate that in optically thick gas disks the planetary migration rate is largely reduced or even outward migration occurs if the disk entropy gradient is negative [4]. Even after disks become optically thin, Type I migration may be slowed down if the surface density increases with radius. Such a condition may be realized at the inner edge of a dead zone [5].

2. Model

The one dimensional equation for viscous evolution of the surface density is solved numerically including a mass loss term of photoevaporative winds. Dead zones are modeled after [6]. The mass loss flux due to photoevaporative winds given in [3] is used. For disk temperatures, we consider contributions from viscous heating, irradiation from the central star, and the back ground temperature.

For the type I migration of rocky planets, we adopt the prescription of [7]. For Type II migration, we simply assume that giant planets migrate together with gas if the disk is more massive than the planet. When the planet is more massive than the disk, the Type II migration rate is reduced by a factor of the planet-to-disk mass ratio [8].

3. Results

Figure 1 shows an example of time evolution of a disk with a dead zone. The inward mass accretion rate remains nearly constant as long as the dead zone exists. The zero radial velocity points locates at the outer edge of the dead zone and migrates inward with time. Outside the dead zone region, the radial velocity of gas is outward. This outward flux is caused by strong photoevaporative winds. Eventually a gap opens outside of the dead zone, even when the accretion rate onto the central star remains high.

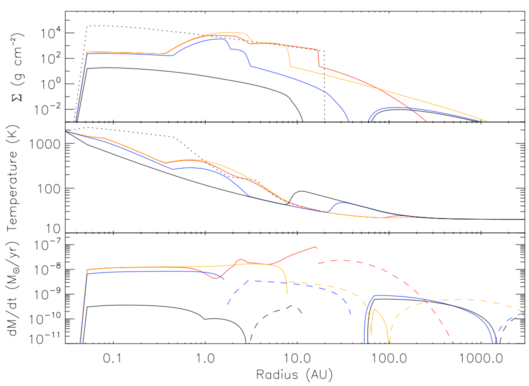

Figure 1: Evolution of surface density, temperature, and mass accretion rate. Black dotted lines are initial conditions. Red, orange, blue, and black solid lines are values at 0.1, 2.0, 5.0, and 5.35 Myr from the beginning, respectively. Mass accretion onto the central star stops at 5.37 Myr. In the panel of the mass accretion rate, solid lines represent inward accretion whereas dashed lines represent outward motion of gas.

Figure 2 shows time evolution of semimajor axes of rocky planets and giant planets, which are assumed to continuously form at radii of rocky planets, in a disk shown in Fig. 1. There are two equilibrium radii for rocky planets: the inner one is the snow line, and the outer one locates slightly inside the outer edge of the dead zone. Giant planets which form at the snow line migrate inward. Giant planets which form at the outer radius also migrate inward first, but eventually they start to migrate outward. This is because the outer edge of the dead zone also migrates inward and its rate exceeds the radial inward velocity of gas.

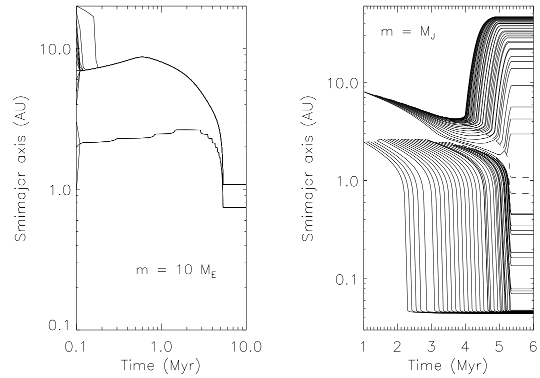

Figure 2: Orbital evolution planets in a disk shown in Fig. 1. Left: Orbital evolution of rocky planets due to Type I migration. Right: Orbital evolution of giant planets due to Type II migration. The dashed lines are semimajor axes of rocky planets.

4. Summary and Conclusions

We find that observed properties of transition disks are well reproduced if the mass loss rate of photoevaporative winds is strong and the surface density of ionized active layers is not large. In such a situation, both rocky and giant planets can stay at large radii. If photoevaporative winds are weak, planets inevitably migrate toward close to their host stars.

References

[1] Merín, B., and 20 coauthors, 2010. Astrophys. J. 718, 1200–1223.

[2] Owen, J. E., Ercolano, B., Clarke, C.J., 2011. Mon. Not. R. Astron. Soc. 412, 13–25.

[3] Gammie, C.F., 1996. Astron. and Astrophys. 457, 355–362.

[4] Paardekooper, S.-J., Baruteau, C., Crida, A., Kley, W., 2010. Mon. Not. R. Astron. Soc. 401, 1950–1964.

[5] Paardekooper, S.-J., Papaloizou, J.C.B., 2009. Mon. Not. R. Astron. Soc. 394, 2283–2296.

[6] Suzuki, T.K., Muto, T., Inutsuka, S., 2010. Astrophys. J., 718, 1289-1304.

[7] Lyra, W., Paardekooper, S.-J., Mac Low, M.-M., 2010. Astrophys. J. 715, L68–L73.

[8] Alexander, R.D., Armitage, P.J., 2009. Astrophys. J. 704, 989–1001.