Planetary migration is one of the most serious problems to systematically understand the observations of exoplanets. We clarify that the theoretically predicted type II migration (like type I migration) is too fast, by developing detailed analytical arguments in which the timescale of type II migration is compared with the disk lifetime. In the disk-dominated regime, the type II migration timescale is characterized by a local viscous diffusion timescale, while the disk lifetime is characterized by a global diffusion timescale that is much longer than the local one. Even in the planet-dominated regime where the inertia of the planet mass reduces the migration speed, the timescale is still shorter than the disk lifetime except in the final disk evolution stage where the total disk mass decays below the planet mass. This suggests that most giant planets plunge into the central stars within the disk lifetime, and it contradicts the exoplanet observations that gas giants are piled up at $r \gtrsim 1$ AU. We examine additional processes that may arise in protoplanetary disks: dead zones, photoevaporation of gas, and gas flow across a gap formed by a type II migrator. Although they make the type II migration timescale closer to the disk lifetime, we show that none of them can act as an effective barrier for rapid type II migration with the current knowledge of these processes. We point out that gas flow across a gap and the fraction of the flow accreted onto the planets are uncertain and they may have the potential to solve the problem. Much more detailed investigation for each process may be needed to explain the observed distribution of gas giants in extrasolar planetary systems.

Key words: accretion, accretion disks – methods: analytical – planet–disk interactions – planets and satellites: formation – protoplanetary disks – turbulence

1. INTRODUCTION

The accumulation of observed exoplanets around solar-type stars has revealed a number of interesting features of the exoplanets (e.g., Udry & Santos 2007). For instance, radial velocity observations suggest that gas giants tend to orbit around their host stars more frequently at $r \gtrsim 1$ AU (e.g., Mayor et al. 2011). As another example, both radial and Kepler transit observations infer that low-mass planets, also known as superEarths, are more common than massive planets (e.g., Howard et al. 2010; Borucki et al. 2011). These features are prominent in the mass–period diagram and are utilized for examining the current theories of planet formation (Ida & Lin 2004; Mordasini et al. 2009a).

Planetary migration is one of the most important processes for interpreting the observations, and hence for understanding planet formation in protoplanetary disks (see Kley & Nelson 2012 for a most recent review). It arises from tidal interactions between protoplanets and the surrounding gaseous disks (Goldreich & Tremaine 1980; Ward 1986; Tanaka et al. 2002). There are two modes in migration that are distinguished by planetary mass: type I and type II migrations. In principle, type I migration is effective for low-mass planets such as terrestrial planets or cores of gas giants and is well known as one of the most serious problems in theories of planet formation. The most advanced studies show that the timescale of type I migration is very rapid ($\sim 10^3$ yr for an earth-mass planet at $\sim 1$ AU) and its direction is highly sensitive to the properties of disks such as the surface density, temperature, viscosity, and opacity of the disk (e.g., Paardekooper et al. 2010). Such kinds of complexity in type I migration prevent us from systematically understanding how planets form in protoplanetary disks under the action of type I migration. Currently, a number of mechanisms have been proposed for resolving the problem of type I migration. For example, Hasegawa & Pudritz (2011) have recently focused on some kinds of inhomogeneities that are considered to be present in protoplanetary disk and investigated how the disk inhomogeneities give rise to trapping sites in disks at which the net torque becomes zero and type I migration is halted (also see Matsumura et al. 2007; Ida & Lin 2008; Lyra et al. 2010; Hasegawa & Pudritz 2010; Kretke & Lin 2012). The sites are often referred to as planet traps (Masset et al. 2006). It is important that planet traps are very useful for systematically examining the formation of planetary system architectures (Hasegawa & Pudritz 2011).

Type I migration becomes faster as planetary mass increases. However, when a planet becomes massive enough to open up a gap in the disk, the planet starts migrating with disk gas accretion, which is called “type II migration” (e.g., Lin & Papaloizou 1986a, 1986b; Nelson et al. 2000). Since the problem of type I migration has attracted a huge amount of attention and the transition to type II generally makes the migration slower (Ward 1997), the problems of type II migration may have been overlooked. As shown below, however, type II migration is not as slow as anticipated so far. This is because the migration timescale is determined by a local viscous diffusion timescale $\tau_{\text{vis}}(r)$, which is generally much shorter than the disk lifetime $\tau_{\text{disk}}$ as shown in Section 2. Since the disk lifetime represents a timescale of when gas disks dissipate globally, $\tau_{\text{disk}}$ can be referred to as a global viscous diffusion timescale. Indeed, the

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4 Since massive bodies that undergo type I migration accumulate around planet traps, the formation of planetary cores is considered to be significantly enhanced there (e.g., Sándor et al. 2011). This invokes another terminology—planet traps are referred to as “convergence zones” in the context of planetary growth (Mordasini et al. 2011; Cossou et al. 2013). It is emphasized that these two are essentially identical to each other.
population synthesis calculations show that most formed gas giants migrate to the proximity of the host star (e.g., Ida & Lin 2008). This is inconsistent with the radial velocity observations which show that most observed gas giants are piled up at \( \gtrsim 1 \) AU with few hot Jupiters (Mayor et al. 2011).

In this paper, we clarify the problem of too-fast type II migration through analytical arguments. One may wonder whether the problem of type II migration would be solved when a number of additional physical processes are considered, such as dead zones, photoevaporation, and gas flow across a gap formed by a type II migrator. We will, however, show below that dead zones and photoevaporation are not crucial for solving the problem of type II migration. While gas flow across a gap formed by a massive planet may have the potential to solve the problem, the details of this process have not yet been clarified.

The plan of this paper is as follows. In Section 2, we define two important timescales that are determined for disks regulated by viscous diffusion: \( \tau_{\text{vis}} \) and \( \tau_{\text{disk}} \), and then we demonstrate how fast type II migration is by focusing on a timescale argument. In Section 3, we examine three additional physical processes that are often considered in more detailed calculations: dead zones, photoevaporation, and gas flow across a gap formed by a planet, and discuss how ineffective they are for resolving the problem of type II migration. We summarize our discussion in Section 4.

2. PROBLEM OF TYPE II MIGRATION

2.1. Steady Accretion Disk

The radial velocity \( (v_r) \) and disk mass accretion rate \( (\dot{M}_{\text{vis}}) \) due to viscous diffusion are given by (see Frank et al. 1992, for a review)

\[
v_r = \frac{3v}{2r} \left( 1 + \frac{2r}{\Sigma v} \frac{\partial (\Sigma v)}{\partial r} \right),
\]

\[
\dot{M}_{\text{vis}} = 2\pi r \Sigma v_r = 3\pi \Sigma v \left( 1 + \frac{2r}{\Sigma v} \frac{\partial (\Sigma v)}{\partial r} \right),
\]

where \( r \) is the disk radius, \( \Sigma \) is the disk surface density, \( v = c_s H \) is the kinematic viscosity, \( c_s \) is the sound speed, and \( H \) is the disk scale height at \( r \). We adopt the \( \alpha \)-prescription for quantifying \( v \) (Shakura & Sunyaev 1973). We take a positive sign for the inward motion when defining \( v_r \). We first assume a standard self-similar solution for viscous diffusion with \( v \propto r \) (Lynden-Bell & Pringle 1974). At \( r \ll r_d \), where \( r_d \) is a characteristic disk size beyond which \( \Sigma \) exponentially decays (see Figure 1), the second terms of Equations (1) and (2) are neglected compared with the first terms because \( \partial (\Sigma v)/\partial r \propto \Sigma v/r_d \):

\[
v_r \simeq \frac{3v}{2r},
\]

\[
\dot{M}_{\text{vis}} \simeq 3\pi \Sigma v = 3\pi \alpha c_s H \Sigma.
\]

Hereafter we assume these relations.

5 In the population synthesis calculations by Mordasini et al. (2009a, 2009b), such a problem was not recognized. This is because of their prescriptions for gas accretion onto planets. Adopting the prescriptions, the effect of planetary inertia is so enhanced and it halts the migration. For details, see the discussion in Section 3.3.

2.2. Local and Global Viscous Timescales

We define a local viscous diffusion timescale as \( \tau_{\text{vis}} = r/v_r \), using the above model. From Equation (3), this timescale reads:

\[
\tau_{\text{vis}} \simeq \frac{2r^2}{3v}.
\]

Since it is assumed that \( v \propto r \), corresponding to disks with constant \( \alpha \) and with the disk temperature being proportional to \( r^{-1/2} \), where \( \alpha \) is the parameter of the \( \alpha \)-prescription for viscosity (Shakura & Sunyaev 1973), we obtain \( \tau_{\text{vis}} \propto r \) (for \( r \ll r_d \)). Equation (5) can also be expressed in terms of \( M_{\text{vis}} \) and \( M_d(r) \), where \( M_d(r) \) is the total disk mass within \( r \). This becomes possible by the fact that \( \Sigma v \) is constant. As a result, the surface density becomes \( \Sigma \propto 1/r \), and \( M_d(r) \) is given as

\[
M_d(r) = \int_r^\infty 2\pi r \Sigma v dr = 2\pi \Sigma (r)r^2.
\]

Then, Equation (5) is written as (see Equations (4) and (6))

\[
\tau_{\text{vis}} \simeq \frac{M_d(r)}{M_{\text{vis}}}. \tag{7}
\]

We can also apply Equation (7) for characterizing a global viscous diffusion timescale that is calculated as

\[
\tau_{\text{disk}} \simeq \frac{M_d(r_d)}{M_{\text{vis}}}, \tag{8}
\]

where \( M_d \) is obtained at \( r \ll r_d \) (but not at \( r = r_d \)). Since \( r_d \) is the initial disk size or the disk radius in which most disk masses are contained (see Figure 1), we can call \( \tau_{\text{disk}} \) the disk lifetime.

The observations of protoplanetary disks in (sub)millimeter wavelengths infer that the median value of \( M_d(r_d) \) is \( \sim 10^{-2} M_\odot \) for classical T Tauri stars (CTTSs; e.g., Andrews & Williams 2005; Andrews & Williams 2007; also see Williams & Cieza 2011 for a most recent review). In addition, the observations of the disk accretion rate show that \( M_{\text{vis}} \sim 10^{-8} M_\odot \) yr\(^{-1}\) for CTTSs (e.g., Hartmann et al. 1998; Calvet et al. 2004). These observations are consistent with the near-IR observations which show that \( \tau_{\text{disk}} \) is a few million years (e.g., Hartigan et al. 1995; Haisch et al. 2001). Combining such observations with the relation \( \tau_{\text{vis}} \propto r \), the local viscous timescale can be written as (see Equations (7) and (8))

\[
\tau_{\text{vis}} = 2r_{d} \tau_{\text{disk}} \sim \frac{r}{r_d} \times (10^6–10^7) \text{ yr}. \tag{9}
\]

Thus, the viscous diffusion timescale (either local or global) can be determined by the characteristic disk radius or by the total disk mass that is contained in the characteristic disk radius.

2.3. Too-fast Type II Migration

We show that a timescale of type II migration is expected to be too short to retain gas giants at large \( r \). There are two regimes in type II migration: disk-dominated and planet-dominated migrations. These regimes are distinguished by the ratio of planetary mass (\( M_p \)) to the total disk mass within an orbital radius (\( r_p \)) of a gas giant. When

\[
M_p < M_d(r_p) = 2\pi \Sigma (r_p)r_p^2, \tag{10}
\]

the gas giant migrates with (unimpeded) disk accretion, which we refer to as “disk-dominated” type II migration. In this case,
the migration timescale is the same as the local viscous diffusion timescale:

$$\tau_{\text{mig, } d} = \frac{M_d(r_p)}{M_{\text{vis}}}, \tag{11}$$

where $M_d(r_p)$ is the total disk mass within $r_p$. Obviously,

$$\tau_{\text{mig, } p} \simeq \frac{r_p}{r_d} \tau_{\text{disk}} \ll \tau_{\text{disk}}, \tag{12}$$

because generally $r_p \ll r_d$. When planetary mass is larger than $M_d(r_p)$, disk accretion from outer regions must push the planet rather than the inner disk. Then, the migration speed is decreased by the inertia of the planet. This regime is referred to as the “planet-dominated” regime. In this regime, the type II migration timescale is given as (e.g., Syer & Clarke 1995; Ivanov et al. 1999; Ida & Lin 2004)

$$\tau_{\text{mig, } p} \simeq \frac{M_p}{M_{\text{vis}}}. \tag{13}$$

When the planet-dominated type II migration is compared with the disk-dominated one,

$$\tau_{\text{mig, } p} \simeq \frac{M_p}{M_d(r_p)} \frac{M_d(r_p)}{M_{\text{vis}}} = \frac{M_p}{M_d(r_d)} \tau_{\text{mig, } d}. \tag{14}$$

Thus, the type II migration slows down when type II migrators are in the planet-dominated regime ($M_p > M_d(r_p)$). However, since

$$\tau_{\text{mig, } p} \simeq \frac{M_p}{M_d(r_d)} \frac{M_d(r_d)}{M_{\text{vis}}} = \frac{M_p}{M_d(r_d)} \tau_{\text{disk}}, \tag{15}$$

$\tau_{\text{mig, } p}$ is still shorter than $\tau_{\text{disk}}$, except for the final stage of disk evolution, which may eventually be able to achieve the condition that $M_p \gtrsim M_d(r_d)$ due to the subsequent disk dispersal and/or the growth of planets.

In summary, the timescale of type II migration is generally shorter than the disk lifetime and this suggests that most formed gas giants plunge into the central stars within the disk lifetime; the only exception is gas giants forming in the end phase of disk evolution. If most of disk gas in the end phase is accreted by a giant, the condition $M_p \gtrsim M_d(r_d)$ can be satisfied for the residual disk gas. However, a very fine tuning is needed in this case for the planet to survive type II migration.\(^6\)

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\(^6\) Also see the discussion on planetary inertia in Section 3.3.

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3. ADDITIONAL PHYSICAL PROCESSES

As discussed above, the typical timescale of type II migration (either disk dominated or planet dominated) is much shorter than the disk lifetime, as long as an ordinary viscous disk with constant $\alpha$ is considered. To save a gas giant against type II migration, additional processes that may occur in protoplanetary disks must be considered. We discuss three possibilities here: dead zones, photoevaporation, and gas flow across a gap formed by a gas giant. We will, however, show that none of them plays a crucial role for the survival of the gas giant.

3.1. Dead Zones

Dead zones are considered to be present in the inner region of protoplanetary disks (e.g., Gammie 1996). In such a region, the high column density prevents gas from being ionized by X-rays from the central stars and cosmic rays. The suppression of ionization there leads to a poor coupling with magnetic fields threading disks. As a result, magnetorotational instabilities (MRIs) become inactive and the region is considered as an “MRI-dead” zone. With the $\alpha$-prescription, the strength of turbulence in the dead zone is about $\alpha_{\text{DZ}} \simeq 10^{-3}$–$10^{-6}$ (e.g., Inutsuka & Sano 2005), whereas $\alpha_{\text{DZ}} \simeq 10^{-1}$–$10^{-3}$ for the MRI-active region in disks (e.g., Papaloizou & Nelson 2003).

When dead zones are incorporated in disk models, one might consider that the problem of rapid type II migration could be resolved because the speed of type II migration ($v \sim 3v/2\pi$) will slow down in the dead zones via reduction of $\alpha$ (recall that $v \propto \alpha$). As discussed below, however, the presence of dead zones essentially leads to the same conclusion as above—only planets formed in the end stage of disk evolution may be able to survive.

We first discuss how the disk structure is affected by dead zones and then examine how the disk timescale is modified by them. Figure 1 schematically shows that the surface density of a disk jumps inside a dead zone. This occurs because $M_{\text{vis}} \propto \alpha \Sigma$ (see Equation (4)) and the value of $\alpha$ is much lower in the dead zone. In other words, the disk mass is piled up in the dead zone because the disk mass that flows from the outer active regions cannot be efficiently transferred there.

We can then define two kinds of lifetimes for disks with dead zones: the lifetimes for the “dead” inner disk ($0 < r < r_{\text{DZ}}$) and the “active” outer disk ($r_{\text{DZ}} < r < r_d$) (see Figure 1). The
former is regulated by the disk mass within the dead zone, so that the lifetime of the dead zone is given as

\[ \tau_{\text{disk}}^{DZ} = \frac{M_{\text{d}}^{DZ}}{M_{\text{vis}}} , \quad (16) \]

where \( M_{\text{d}}^{DZ} \) is the disk mass within the dead zone and is written by \( M_{\text{d}}^{DZ} = M_{\text{d}}(r_{\text{DZ}}) \). The lifetime for the active outer disk is determined by

\[ \tau_{\text{disk}}^{AZ} = \frac{M_{\text{d}}^{AZ}}{M_{\text{vis}}} , \quad (17) \]

where \( M_{\text{d}}^{AZ} = M_{\text{d}}(r_{D}) - M_{\text{d}}(r_{\text{DZ}}) \). As shown in Figure 1, the increment in \( \Sigma \) in dead zones can lead to \( M_{\text{d}}^{DZ} \) that is larger than \( M_{\text{d}}^{AZ} \). Equivalently, \( \tau_{\text{disk}}^{DZ} \) can become longer than \( \tau_{\text{disk}}^{AZ} \). As an example, we consider a disk that has \( r_{D} = 100 \) AU. Assuming that \( r_{\text{DZ}} = 10 \) AU, \( \alpha_{\text{DZ}} = 10^{-4} \), and \( \alpha_{\text{AZ}} = 10^{-2} \), we find that \( M_{\text{d}}^{AZ} = \int_{r_{\text{D}}}^{r_{D}} 2\pi r \Sigma dr = ((r_{D} - r_{\text{DZ}})/r_{D}) \alpha_{\text{DZ}}/\alpha_{\text{AZ}} M_{\text{d}}^{DZ} = 0.09 M_{\text{d}}^{DZ} \), where the relation \( M_{\text{d}} \propto \Sigma r \propto r/\alpha \) has been used. Thus, it is normally expected that \( \tau_{\text{disk}}^{DZ} > \tau_{\text{disk}}^{AZ} \).

We are now in a position to compare the type II migration timescale with the lifetime of disks with dead zones. Based on the discussion given in the above section, the comparison is essentially identical to estimating the mass difference between \( M_{\text{d}}^{DZ} \) and either the disk mass within \( r_{p} \) or planetary mass, depending on the regime of type II migration.

When planets are in the disk-dominated regime \( (M_{\text{p}} < M_{\text{d}}(r_{p})) \), the planets survive only at \( r_{p} \gtrsim r_{\text{DZ}} \). This is equivalently \( M_{\text{d}}(r_{p}) \gtrsim M_{\text{d}}^{DZ} \). It has been suggested that an outer boundary of the dead zone could be a planet trap for rapid type I migration (Matsumura et al. 2009; Hasegawa & Pudritz 2010, 2011). Recently, two-dimensional (2D) hydrodynamical simulations have confirmed the robustness of the trap (Regaly et al. 2013). As a result, gas giants can survive against type II migration if they form beyond \( r_{\text{DZ}} \). It is, however, more likely that giant planet formation takes place efficiently in dead zones, since most disk masses are distributed there. Then, planets formed at \( r_{p} < r_{\text{DZ}} \) will become hot Jupiters due to type II migration.

For the planet-dominated regime, planets are prevented from falling onto the host stars only when \( M_{\text{p}} > M_{\text{d}}^{DZ} \). This can be achieved only for planets that are formed at the end stage of disk evolution with the condition that \( M_{\text{p}} \sim M_{\text{d}}^{DZ} \) is satisfied.

In summary, while the problem of type II migration becomes less severe with the presence of dead zones, it does not essentially save gas giants from significant migration unless planets are formed beyond dead zones. More specifically, we obtain the survival condition that \( r_{p} \sim r_{\text{DZ}} \) for disks in which most disk masses are distributed within \( r = r_{\text{DZ}} \). For this case, the ratio \( \tau_{\text{mig}}/\tau_{\text{disk}} \) becomes closer to unity by a factor of \( M_{\text{d}}(r_{p})/M_{\text{d}}(r_{\text{DZ}}) \sim r_{p}/r_{\text{DZ}} \) than that in the case without a dead zone. However, the ratio does not exceed unity for most gas giants that form in the dead zone with high surface density.

### 3.2. Photoevaporation

Photoevaporation of gas disks may be another process for potentially saving gas giants from plunging into central stars. However, the current understanding of photoevaporation shows that photoevaporation would not be a key agent in the problem of type II migration, although more detailed observations and simulations in extreme-UV (EUV) flux from central stars are required.

#### 3.2.1. Basic Picture

Photoevaporation arises from heating gas in protoplanetary disks due to high-energy photons emitted from central and external stars (see Armitage 2011 for a most recent review). It is currently considered as one of the most promising processes for dissipating gas disks at the end stage of disk evolution and for determining disk lifetime. In principle, the high-energy photons ionize atoms and dissociate molecules in disks and result in their evaporation from disk surfaces. It has been recently shown that disk winds could also play a similar role (Suzuki et al. 2010; Bai & Stone 2013).

There is a critical disk radius beyond which the photoevaporation of gas plays a dominant role in disk evolution. The radius is referred to as the gravitational radius and is defined by

\[ r_{g} = \frac{G M_{\ast}}{c_{s}^2} \sim 10 \text{ AU} \left( \frac{M_{\ast}}{M_{\odot}} \right) \left( \frac{T}{10^{4} \text{ K}} \right)^{-1} . \quad (18) \]

This is derived from comparing the gravitational energy of gas with its thermal energy. It is noted that a more rigorous derivation predicts that the gravitational radius is likely to be smaller than that estimated from Equation (18) by a factor of a few.

Historically, Equation (18) was derived for photoevaporation induced by EUV photons that can ionize hydrogen atoms (Shu et al. 1993; Hollenbach et al. 1994). It is important that the value of \( r_{g} \) highly depends on the gas temperature that is heated by high-energy photons. For instance, EUV heating results in a gas temperature of \( 10^{4} \) K, whereas far-UV (FUV) and X-ray heating attains \( 10^{2} – 10^{3} \) K (e.g., Gorti & Hollenbach 2009). The low temperature in FUV and X-rays increases \( r_{g} \) by about a factor of 10 from that for EUV. Thus, only EUV heating can evaporate the inner region of disks.

Recent detailed studies have shown that the effects of photoevaporation on disk evolution are different for different sources (the central stars versus the external ones). When photoevaporation by the central star is considered, it can lead to the formation of a gap/inner hole in the gas disks (Clarke et al. 2001; Matsuymama et al. 2003a; Gorti et al. 2009; Owen et al. 2010). This arises from the combination of photoevaporation with viscous diffusion and can be understood as what follows. In the case of heating by the central star, photoevaporation is most efficient around \( r_{g} \) because the flux is proportional to square of the distance from the central star (e.g., Matsuymama et al. 2003a; Ruden 2004). Viscous diffusion is fast in inner regions, and when photoevaporation is considered, gas is not supplied anymore from outer regions. As a result, gap formation proceeds, followed by rapid viscous dissipation of the inner disk. For the case of heating by external stars, disks are evaporated in an outside–in manner down to \( r_{g} \) (Johnstone et al. 1998; Matsuymama et al. 2003a). This occurs because the outer disks have a larger cross section for photoevaporative photons.

#### 3.2.2. Slow-down Conditions

We now discuss disk evolution affected by photoevaporation and its effect on type II migration. Here we summarize

\[ v'(1/2 + w - G M_{\ast}/r_{g}) = (1/(\gamma - 1) + 1)(P/\rho) - G M_{\ast}/2r_{g} = c_{s}^2/(\gamma - 1) - G M_{\ast}/2r_{g} \]

where \( w = u + P/\rho \) is the specific enthalpy, \( u \) is the specific internal energy, and \( \gamma \) is 5/3 and 7/5 for monoatomic and diatomic molecules, respectively. Then the gas pressure in the flow plays a counteractive role against the gravitational energy and results in the reduction of \( r_{g} \). (Shu et al. 1993; Matsuymama et al. 2003b; Liffman 2003). The shrinking of \( r_{g} \) is confirmed by more detailed simulations (e.g., Font et al. 2004; Owen et al. 2010).
slowing-down conditions that can be achieved by photoevaporation (see Table 1). We mainly consider photoevaporation from the central star. We define $M_{\text{pe}}$ by the total photoevaporation rate integrated over the disk. For simplicity, we approximate $M_{\text{pe}}$ is contributed only from the region at $r \sim r_p$. We also define $M_{\text{vis}}$ by the disk mass accretion rate due to viscous diffusion at $r_p < r < r_g$, which is not affected by photoevaporation. We first focus on the case that no gap in a gas disk is formed by photoevaporation.

When planet formation proceeds beyond the gravitational radius ($r_p \gg r_g$), the migration rate is the same as that in the case without the effect of photoevaporation, so that we can apply the same argument as in Section 2.3. For the case that $r_p < r_g$, on the other hand, the disk accretion that exerts torque on the planet and contributes to type II migration is decreased from $M_{\text{vis}}$, while global disk depletion still occurs with $M_{\text{vis}}$. It is therefore expected that the chance of survival of giant planets can increase according to photoevaporation. We thus examine the case that $r_p < r_g$ in detail. In this case, the net disk accretion rate $M_{\text{acc}}$ is given as (e.g., Ruden 2004)

$$M_{\text{acc}} = M_{\text{vis}} - M_{\text{pe}}. \quad (19)$$

Since it is currently considered that no gap formation proceeds, $M_{\text{vis}} > M_{\text{pe}}$. Then type II migration timescales, Equations (11) and (13), are written as

$$\tau_{\text{mig},d} = \frac{M_d(r_p)}{f_{\text{pe}} M_{\text{acc}}} \quad \text{(for the disk-dominated regime)}, \quad (20)$$

$$\tau_{\text{mig},p} = \frac{M_p}{M_{\text{acc}}} \quad \text{(for the planet-dominated regime)}. \quad (21)$$

Substituting $M_{\text{acc}} = f_{\text{pe}} M_{\text{vis}}$ with $f_{\text{pe}} = 1 - M_{\text{pe}}/M_{\text{vis}}$ ($0 \leq f_{\text{pe}} < 1$), the above two equations become

$$\tau_{\text{mig},d} = \frac{M_d(r_p)}{f_{\text{pe}} M_d(r_d) M_{\text{vis}}} = \frac{M_d(r_p)}{f_{\text{pe}} M_d(r_d) \tau_{\text{disk}}} \quad (22)$$

and

$$\tau_{\text{mig},p} = \frac{M_p}{f_{\text{pe}} M_d(r_d) M_{\text{vis}}} = \frac{M_p}{f_{\text{pe}} M_d(r_d) \tau_{\text{disk}}}, \quad (23)$$

where we have used $\tau_{\text{disk}} = M_d(r_d)/\dot{M}_{\text{vis}}$ because the global disk depletion timescale is not affected by photoevaporation (Ruden 2004). Thus, when photoevaporation is incorporated in disk models, type II migration slows down by a factor of $1/f_{\text{pe}}$ (since $f_{\text{pe}} < 1$), even if gap formation does not proceed.

We now discuss more crucial slowing-down conditions that are needed for saving gas giants from rapid type II migration. Based on Equations (22) and (23), the condition is $f_{\text{pe}} < \max[M_d(r_p), M_p] / M_d(r_d)$. More specifically, the survival condition, $\tau_{\text{mig},d} > 1$, is satisfied either if $f_{\text{pe}} \ll 1$ or if $M_d(r_p) \lesssim M_p$. The former case is equivalent to $M_{\text{vis}} \gg M_{\text{pe}}$, which implies the formation of a gap by photoevaporation. We therefore neglect the case here (see the discussion below). For the latter case, a modest value of $f_{\text{pe}}$ ($M_{\text{vis}} > M_{\text{pe}}$) is allowed. Thus, the more crucial slowing-down condition for the case of no gap formation is $M_{\text{pe}} \lesssim M_p$.

We consider the case that photoevaporation induces the formation of a gap in the gas disk. Although the self-similar solution cannot be applied to the gap formation case, the arguments developed in the above sections may be able to be applied to this case as well except for detailed numerical factors. It is noted, however, that we need to consider the lifetime of the inner disk separately from the lifetime of the outer disk that would be similar to the global disk lifetime ($\tau_{\text{disk}} = M_d(r_d)/\dot{M}_{\text{vis}}$). This is because the gap formed at $r = r_g$ divides the disk into the outer and inner ones.

For planets formed in the inner disk ($r_p < r_g$), the same arguments as planets in the dead zone are applied by replacing $r_{\text{DZ}}$ and $M_d^{\text{DZ}}$ with $r_g$ and $M_d(r_g)$ (see Section 3.1): planets can undergo slowed-down type II migration only at $r_p < r_g$ or when $M_d(r_g) \lesssim M_p$. Since planet formation is currently considered to take place in the inner disks, the most likely condition for slowing down type II migration is $M_d(r_g) \lesssim M_p$. We note that this argument can be applied only if gas giants are formed just after a gap is opened by photoevaporation. If the formation of planets takes place well after the gap formation and the gap is maintained for the remaining disk lifetime, then such planets cannot grow to gas giants. This is because the disk lifetime of the inner disk is much shorter than $\tau_{\text{disk}}$ ($r_g \ll r_g$), so that gas in the inner disk is rapidly accreted onto the central star.

When a planet is formed in the outer disk ($r_p > r_g$), a gap formed at $r_g$ can act as a barrier for subsequent type II migration if the gap is opened before it passes $r_g$. For this case, the slowing-down condition is essentially identical to the gap opening condition that is given as $M_{\text{vis}} \lesssim M_{\text{pe}}$ ($f_{\text{pe}} \ll 1$), or $M_d(r_g) \lesssim M_{\text{pe}} \tau_{\text{disk}}$.

We have so far discussed photoevaporation from high-energy photons from the central star. If we consider external stars, the disk is removed only in the outer parts (e.g., Johnstone et al. 1998; Matsuyama et al. 2003a). It decreases $\tau_{\text{disk}}$ due to the reduction in $r_g$ (see Equation (8)). Nonetheless, type II migration significantly slows down only if the disk gas at $r \sim r_p$ is quickly removed after the formation of a planet and before it migrates.

| Source Stars | Gap Formation | Positions of Planet Formation | Slowing-down Conditions | Survival Conditions |
|--------------|---------------|-------------------------------|-------------------------|---------------------|
| Central      | No            | $r_p \gg r_g$                 | $M_{\text{vis}} \gtrsim M_d(r_d)$ | Fine tuning          |
| Central      | No            | $r_p < r_g$                   | $M_{\text{vis}} \lesssim M_d(r_d)$ | Fine tuning          |
| Central      | Yes           | $r_p < r_g$                   | $M_{\text{vis}} \gtrsim M_d(r_d)$ | Fine tuning          |
| Central      | Yes           | $r_p > r_g$                   | $M_{\text{vis}} \lesssim M_d(r_d)$ | Gap formation is maintained when planets pass at $r = r_g$ |
| External     | No            | $r_p < r_g$                   | Gas disposal quickly proceeds at $r = r_p$ before planets migrate toward the central stars |

Notes. * This is applicable only if planet formation completes just after a gap is formed. If planet formation proceeds well after the gap formation and gaps are maintained for the rest of the disk lifetime, formed planets cannot grow to gas giants.
to the proximity of the central star. It requires fine tuning so that most of planets are not saved.

### 3.2.3. Survival Conditions

We now discuss how the slowing-down conditions derived in the above section can be feasible in protoplanetary disks, in the case of internal photoevaporation. Table 1 summarizes such survival conditions. For the case that the slowing-down condition is \( \dot{M}_p \gtrsim \dot{M}_{p,\text{base}} \), fine tuning is needed for saving gas giants from type II migration, regardless of whether or not gap formation proceeds due to photoevaporation. This was already discussed in Sections 3.2 and 3.1. Armitage et al. (2002) also derived the same conclusion.

The most promising situation may be that the slowing-down condition is \( \dot{M}_p \gtrsim \dot{M}_{p,\text{base}} \) (see Table 1). This is because type II migrants can be halted at \( r = r_g \) due to the formation of a gap by photoevaporation (if the gap is kept open when planets pass it. In fact, this scenario was already suggested by Matsuyama et al. (2003b). Nonetheless, this case may not be favored in protoplanetary disks. First, the above slowing-down condition becomes \( \dot{M}_{\text{pe}} \gtrsim 10^{-8} \, \dot{M}_\odot \, \text{yr}^{-1} \), when \( \dot{M}_{p}(r_g) \sim \text{a few} \times 10^{-2} \, \dot{M}_\odot \) and \( \tau_{\text{disk}} \sim \text{a few} \times 10^6 \, \text{yr} \), both of which are typical values for disks around CTTSs (Williams & Cieza 2011), are adopted. Although the recent models show that the photoevaporation rates in X-ray or EUV can afford such a high rate (Table 2), the rate may cause another problem: when FUV- and X-ray-induced photoevaporation is considered, \( r_g \) expands to \( \sim 100 \, \text{AU} \). The significant reduction in the surface density inside \( \sim 100 \, \text{AU} \), corresponding to \( \dot{M}_{\text{pe}} \gtrsim 10^{-8} \, \dot{M}_\odot \, \text{yr}^{-1} \), may inhibit the formation of gas giants that is most efficient around 1–10 \( \text{AU} \) (e.g., Ida & Lin 2004). Second, when EUV opens up a gap at a few \( \text{AU} \), gap formation will occur at \( \dot{M}_{\text{pe}} \gtrsim 10^{-10} \, \dot{M}_\odot \, \text{yr}^{-1} \) for EUV (Table 2; also see discussion in Section 3.2.4). This implies that the gap may not open until the final disk evolution stage of \( \dot{M}_{p}(r_g) < \text{a few} \times 10^{-4} \, \dot{M}_\odot \), which may be too late to save gas giants efficiently.

In summary, it is unlikely that photoevaporation can easily save gas giants against type II migration.

#### 3.2.4. Photoevaporation by EUV

As discussed above, EUV heating may play the most crucial role in gap formation in the inner region of disks, and hence in saving gas giants against type II migration. Based on the above estimate, this becomes possible if \( \dot{M}_{\text{pe}} \gtrsim 10^{-8} \, \dot{M}_\odot \, \text{yr}^{-1} \). Although Font et al. (2004) suggested a much smaller value \( (\dot{M}_{\text{pe}} \sim 10^{-10} \, \dot{M}_\odot \, \text{yr}^{-1}) \), \( \dot{M}_{\text{pe}} \) due to EUV heating is still unclear because the EUV emission is readily absorbed by interstellar matter (ISM) and it is very difficult to determine EUV flux straightforwardly (Gorti et al. 2009 and references therein).

Another issue to be considered is the dependence of EUV flux on mass accretion rates onto the central star (\( \dot{M}_{\text{acc}} \)). This is because the dependence is directly related to whether or not a gap is created. FUV flux is considered to be produced by the accretion shock of disk gas onto the central star, so that a positive correlation between FUV flux and \( \dot{M}_{\text{acc}} \) is expected. Actually, a recent observation (Ingleby et al. 2011) suggests that FUV flux is proportional to accretion luminosity \( (\propto \dot{M}_{\text{acc}}) \). With such a correlation, it is difficult for FUV heating to cause a gap in the disk. If photoevaporation due to FUV heating is causing a gap, \( \dot{M}_{\text{acc}} \) decreases. Accordingly, FUV flux decreases as well, which prevents the gap from opening. If EUV flux also has a correlation with \( \dot{M}_{\text{acc}} \), a gap would not be opened by this self-regulation process.\(^8\)

The ultimate energy source for high-energy photons from the central star is disk gas accretion. Nonetheless, it is not necessary to assume that all photons should follow the same dependence on \( \dot{M}_{\text{acc}} \). This is because emission mechanisms can be different for photons with different wavelengths. For example, X-rays can be considered to have a weak dependence on \( \dot{M}_{\text{acc}} \) (Drake et al. 2009). Currently, the emission mechanism and the \( \dot{M}_{\text{acc}} \) dependence have not been clear for EUV. They should be clarified as well as the EUV flux amplitude in order to clarify the importance of the effect of photoevaporation on type II migration.

### 3.3. Gas Flow across a Gap Formed by Giant Planets

We have so far discussed physical processes that can affect the disk structure globally. In this section, we focus on a process that takes place locally in disks. More specifically, we examine the flow of gas around a gap formed by a massive planet.\(^9\)

It is well established that type II migration divides disks into the inner and outer ones by forming a gap due to the tidal torque between massive planets and the surrounding gaseous disks (e.g., Lin & Papaloizou 1986a, 1986b; Nelson et al. 2000). In the above sections, we have adopted the innate disk accretion rate (\( \dot{M}_{\text{vis}} \) or \( \dot{M}_{\text{acc}} \))estimating the timescales of type II migration (see Equations (11) and (13)). This is essentially identical to assuming that disk accretion from the outer disk fully contributes to pushing giant planets inward. This assumption led to the conclusion that type II migration is too fast for gas giants to survive for long orbital periods.

We here discuss the possibility that only a fraction of disk accretion from the outer disk can involve moving massive planets. This can be achieved if gas in the outer disk flows into the inner disk across a gap and the gas is subsequently accreted onto the central star. If this is the case, the timescale of type II migration is expected to become longer than the previous estimate. This occurs because the effective disk accretion rate that regulates the migration timescale is reduced (see Equations (11) and (13)). More physically, the effective mass of the outer disk that essentially pushes a planet inward becomes smaller due to the gas flow from the outer to the inner disk across a gap.

We estimate how type II migration slows down by the gas flow. This can be done by decomposing the innate disk accretion rate (\( \dot{M}_{\text{vis}} \)), which originates from the outer disk and involves pushing a gas giant inward, into the following components:

\[
\dot{M}_{\text{vis}} = \dot{M}_{\text{cross}} + \dot{M}_p + \dot{M}_{\text{mig}},
\]

where \( \dot{M}_{\text{cross}} \) is the component of gas that flows into the inner disk across a gap without pushing or being accreted by the planet, \( \dot{M}_p \) is the gas that flows into the gap and is

---

\(^8\) Matsuyama et al. (2003a) numerically show that a gap is formed even if EUV heating is directly related to the disk accretion. It is not clear why they found a gap.

\(^9\) Note that in Section 3.2 we focused on a gap formed by photoevaporation, whereas here we discuss a gap formed by gravitational perturbations from a planet.
or eventually accreted by the planet, and $\dot{M}_{\text{mig}}$ is the gas that cannot flow into the gap and indeed pushes the planet inward. Then, Equations (11) and (13) can be rewritten as

$$\tau_{\text{mig},d} = \frac{M_d(r_p)}{\dot{M}_{\text{mig}}} = \frac{M_d(r_p)}{f_{\text{flow}} M_{\text{vis}}},$$

(25)

and

$$\tau_{\text{mig},p} = \frac{M_p}{\dot{M}_{\text{mig}}} = \frac{M_p}{f_{\text{flow}} M_{\text{vis}}},$$

(26)

where

$$f_{\text{flow}} = 1 - \frac{M_{\text{cross}} + M_p}{M_{\text{vis}}}.$$  

(27)

Thus, the timescale of type II migration becomes longer if gas flow across a gap ($M_{\text{cross}} \neq 0$) is taken into account (since $f_{\text{flow}} < 1$).

We now discuss the survival condition in detail. In the limit of $M_p = 0$, gas giants are saved from plunging into central stars due to rapid type II migration if either $M_{\text{cross}} \approx M_{\text{vis}}$ or $M_p(r_p) \lesssim M_p$ is satisfied. As discussed above, the latter condition requires fine tuning, so that the former one has a better chance. Consequently, when gas flow across a gap becomes comparable to the inner disk accretion rate, this process can act as an effective barrier for type II migration.

Although recent numerical studies show that a considerable amount ($M_{\text{cross}} \sim 10\%$–$25\%$ of $M_{\text{vis}}$) of gas flows into the inner disk across a gap (e.g., Lubow et al. 1999; D’Angelo et al. 2002; Lubow & D’Angelo 2006), the required amount of gas flow may be too high to be achieved. One may thus tend to conclude that gas flow across a gap formed by gas giants also cannot be a solution to the problem of rapid type II migration. Nonetheless, we suggest that the gas flow may still have more potential to save gas giants due to the following associated processes.

First, when gas in the outer disk passes through a gap, the gas follows a horseshoe orbit around the planet. It is thus anticipated that the flow results in the enhancement of coronation torque. Since the inward gas flow dictates that the coronation torque transfers angular momentum from the gas to the planet (e.g., Ward 1991; Masset 2001, 2002), the gas flow gives rise to an additional slowing down in type II migration. This kind of the angular momentum transfer is very efficient and is considered to be the origin of type III migration (Masset & Papaloizou 2003). It is proposed that type III migration is very fast and effective for planets with intermediate masses such as Saturn. Although detailed 2D hydrodynamical simulations are needed for quantitatively estimating how much amount of gas flow is demanded for type II migration to be halted, gas flow that amounts to a fraction of $M_{\text{vis}}$ may be large enough.

Second, if a planet accretes gas that flows into a gap, the gas accretion can provide additional slowing down of the planet. As shown in Equation (27), $f_{\text{flow}}$ becomes small if $M_p > 0$, which slows down type II migration further. Note that numerical simulations show that gas flow across a gap generally accompanies gas accretion onto a planet (e.g., Lubow et al. 1999; D’Angelo et al. 2002; Lubow & D’Angelo 2006), so that the survival condition derived above ($M_{\text{cross}} \approx M_{\text{vis}}$) is likely to be overestimated. In addition, gas accreted onto a planet mainly originates from the outer disk rather than the inner one. This indicates that, as the planet accretes gas, the specific angular momentum of the planet increases. The increment eventually leads to outward migration. Moreover, gas accretion increases the effects of planetary inertia that also acts as a brake on type II migration.

Thus, gas flow across a gap formed by a massive planet invokes the relevant processes that can serve as additional mechanisms for slowing down type II migration, and hence may have some potential to resolve the problem of too-rapid type II migration.

As discussed above, the effects of planetary inertia are likely to be tightly coupled with gas flow around a planet and planetary growth. We here examine how different is the fate of gas giants by adopting different treatments.

Mordasini et al. (2009a, 2009b) and Rice et al. (2013) assumed that type II migration starts after a growing planet satisfies the thermal condition for gap opening, which is given as $r_H > H$, where $r_H$ is the Hill radius of the planet. They nevertheless assumed that the planet keeps accreting gas of $M_{\text{vis}}$, following D’Angelo et al. (2003) and Lubow & D’Angelo (2006) which showed that significant fraction of $M_{\text{vis}}$ crosses the gap. This is essentially identical to assuming that

$$M_p = \dot{M}_{\text{mig}} = M_{\text{vis}}(\text{with } M_{\text{cross}} = 0)$$

(28)

in our formalism. Note that, with their prescription, $d\log M_p/d\log r_p = (1/M_p)(dM_p/dr_p)(dr_p/dt) \sim -d(M_{\text{vis}}/M_p)/(M_{\text{vis}}/M_p) \sim -\pi$ (also see Equation (13)). Then, as a giant planet migrates, $M_p$ rapidly increases while $M_d(r_d)$ is decreased by the planetary growth. As a result, the planet migration is halted well before the planet migrates to the proximity of the central star, except for the cases in very massive disks. It is obvious, however, that this assumption cannot satisfy Equation (24).

In addition, even in the simulations of D’Angelo et al. (2003) and Lubow & D’Angelo (2006), gas flow across a gap is significantly reduced after planets have grown to $\sim 10 M_J$, where $M_J$ is the mass of Jupiter. This trend is also supported by Dobbs-Dixon et al. (2007). Thus, it is very unlikely that planetary growth proceeds consecutively with $M_p = M_{\text{vis}}$. Moreover, such continuous gas accretion would result in the formation of gas giants that are too massive, which is inconsistent with observations. In fact, Mordasini et al. (2009a, 2009b) considered relatively strong external photoevaporation (see Section 3.2) to suppress the formation of too-massive planets. This provides another interesting suggestion that if this is the case, the final stage of planetary growth that can be regulated by gas flow across a gap should be intimately linked to disk disposal mechanisms.

On the other hand, Ida & Lin (2004, 2008) adopted a prescription that gas accretion onto planets is truncated after the thermal condition for gap opening is satisfied, according to the results of Bryden et al. (1999) and Dobbs-Dixon et al. (2007). In addition, they assume that type II migration starts when the viscous condition for gap opening is satisfied, which is usually applicable for much smaller planetary masses than those for the thermal condition. Adopting our formalism, their prescription is translated as

$$M_p = M_{\text{cross}}(\text{with } 0 < M_{\text{cross}})$$

(29)

and

$$M_{\text{mig}} = M_{\text{vis}}.$$  

(30)

This also cannot satisfy Equation (24). Nonetheless, the treatment of the latter may be more conservative than that of the former, since planetary growth is not so enhanced. As a result, type II migration is much more effective in the latter’s results...
than in the former’s. More detailed hydrodynamical simulations are needed to study the gas accretion rate onto planets after gap opening and the condition for the start of type II migration.

We have so far focused on type II migration of single planets. What happens for the planetary migration of a pair of massive planets? Masset & Snellgrove (2001) investigated the consequence of planetary migration for a system of massive planets like Jupiter and Saturn. They showed that the outer light planet, which is initially located far away from the inner massive planet, catches up to the inner one and is trapped in mean-motion resonances. Also, they demonstrated that the system migrates outward together after the trapping and sharing of gaps formed by both planets. This outward migration arises mainly from an increased mass flow through the overlapping gap from the outer to the inner disk (also see Morbidelli & Crüa 2007).

Thus, the gas flow around a gap formed by planets needs to be investigated in detail to understand type II migration more accurately.

4. SUMMARY AND DISCUSSION

We have analytically investigated the timescale of type II migration in gas disks that is regulated by viscous diffusion. We point out that theoretically predicted type II migration is so fast that gas giants migrate to the proximity of the central stars except for a very narrow window of timing between the formation of gas giant planets and disk gas depletion. Such efficient migration is inconsistent with the semimajor axis distribution of extrasolar gas giants obtained by radial velocity surveys. The inertia of a planet, the presence of an MRI dead zone, and internal/external photoevaporation make type II migration less efficient. However, none of them saves gas giants from significant migration with the current knowledge of each process, if gas flow across a gap from the outer disk to the inner disk or that accreted by a planet is negligible.

We formulate type II migration and disk lifetimes based on disk accretion rates that push planets inward and remove the disk. With this formulation, we can consistently discuss the comparison between the migration and disk depletion timescales, and the effects of the planetary inertia, dead zones, photoevaporation, and gas flow across a gap formed by a massive planet.

The “planet-dominated” regime where the inertia of a planet decelerates the migration is distinguished from the “disk-dominated” regime by the condition that planetary mass, $M_p$, is larger than the disk mass within the planetary orbit, $M_d(r_p)$, where $r_p$ is the planet’s orbital radius (see Equation (10)). We have adopted a standard self-similar solution for quantifying both the local and global timescales of the disks. In this solution, the disk accretion rate $M_\text{vis}$ is constant in the regions well inside the disk size, $r_d$. The local viscous timescale is given by $M_d(r_p)/M_\text{vis}$, and it can be used as the timescale of disk-dominated type II migration, whereas the disk lifetime is given by $M_d(r_d)/M_\text{vis}$. The timescale of planet-dominated type II migration is given by $M_p/M_\text{vis}$ (see Equation (14)).

Since most disk masses are distributed in the outer disk and it is usually expected that $r_p \ll r_d$, then $M_d(r_p) \ll M_\text{vis}$. Thus, we have shown that gas giants can survive against type II migration only if they are formed in the final stage of disk evolution in which $M_p > M_d(r_d)$—fine tuning is needed to prevent the loss of gas giant planets into host stars. This kind of problem in type II migration has been overlooked in the literature because the problem of type I migration is very serious.

We have examined additional physical processes that can be present in more detailed disk models: dead zones, photoevaporation of gas, and gas flow across a gap formed by a type II migrator. They may be considered to be potential agents for slowing down type II migration. When disks have dead zones, most disk masses are contained in a dead zone. As a result, the radius of an outer boundary of the dead zone must be effectively regarded as $r_p$, which makes $M_d(r_d)$ closer to $M_d(r_p)$. However, $M_d(r_d)$ does not become smaller than $M_d(r_p)$. Consequently, the migration timescale cannot be longer than the disk lifetime (except in the final disk evolution stage with $M_p > M_\text{vis}$).

Internal photoevaporation is effective in a narrow region near a gravitational radius $r_g$. If $r_g > r_p$, it decreases the disk accretion rate, and hence planets undergo type II migration less efficiently. This may result, however, in gas surface density that becomes too low to produce gas giants. If photoevaporation is effective at $r_g < r_p$, the removal of disk gas inside $r_g$ works as a barrier to migration. Only EUV photoevaporation makes $r_g$ as small as the radius of gas giant formation site ($r = 1–10$ AU) (note that FUV and X-ray photoevaporation is effective in more distant regions). It is nonetheless currently inferred that EUV flux is too weak to open up a gap in a disk except for the final disk evolution stage. Thus, although the problem indeed becomes less severe, dead zones and the photoevaporation of gas cannot be crucial, as individual processes, for resolving the problem of too-rapid type II migration.

We note that EUV heating is the most uncertain because EUV is readily absorbed by the ISM. Thus, studying EUV flux and its photoevaporation both observationally and theoretically in more detail is required to discuss the effects of photoevaporation on type II migration more accurately.

If a significant fraction of disk accretion crosses a gap around the planetary orbit, the disk accretion rate to push the planet is decreased. We have suggested that associated physical processes such as coronation torque and gas accretion onto a planet can act as additional brakes for rapid type II migration. Thus, the flow of gas around a gap may be potentially important for solving the problem of type II migration. Nonetheless, it is obvious that more detailed studies are needed to examine its effect on type II migration more seriously.

It is interesting that Hasegawa & Pudritz (2012) have recently shown that the observed mass–period relation can be reproduced well if multiple planet traps are incorporated in disks for trapping rapid type I migration. They considered both dead zones and photoevaporation in single disks. Also, they focused on planet formation beyond dead zones. As discussed above, these all act to slow down type II migration. That is why their results do not suffer from the problem of type II migration significantly. Obviously, it is important to investigate the problem of type II migration in detail and examine the individual and combined effects of dead zones, photoevaporation of gas, and gas flow across a gap formed by massive planets.

In a subsequent paper, we will undertake the tasks of performing numerical simulations of viscously evolving disks and investigating the problem of type II migration.

10 Recently Hasegawa & Pudritz (2013) have improved their model and investigated the statistical properties of planets formed at multiple planet traps. They have found that, even if planet traps are incorporated, somewhat slowed-down type II migration is likely to be preferred for quantitatively reproducing the observations of exoplanets. This is because the “initial” distribution of planets that is generated by planet traps and can reproduce the observations tends to be washed out by type II migration.
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REFERENCES

Andrews, S. M., & Williams, J. P. 2005, ApJ, 631, 1134
Andrews, S. M., & Williams, J. P. 2007, ApJ, 671, 1800
Armitage, P. J. 2011,ARA&A, 49, 195
Armitage, P. J., Livio, M., Lubow, S. H., & Pringle, J. E. 2002, MNRAS, 334, 248
Bai, X.-N., & Stone, J. M. 2013, ApJ, 769, 76
Borucki, W. J., Koch, D. G., Basri, G., et al. 2011, ApJ, 728, 117
Bryden, G., Chen, X., Lin, D. N. C., Nelson, R. P., & Papaloizou, J. C. B. 1999, ApJ, 514, 344
Calvet, N., Muzerolle, J., sar Briceño, C., et al. 2004, AJ, 128, 1294
Clarke, C. J., Gendrin, A., & Sotomayor, M. 2001, MNRAS, 328, 485
Cossou, C., Raymond, S. N., Pierens, A. 2013, A&A, 553, L2
D’Angelo, G., Henning, T., & Kley, W. 2002, A&A, 385, 647
D’Angelo, G., Kley, W., & Henning, T. 2003, ApJ, 586, 540
Dobbs-Dixon, I., Li, S. L., & Lin, D. N. C. 2007, ApJ, 660, 791
Drake, J. J., Ercolano, B., Flaccomio, E., & Micela, G. 2009, ApJ, 699, L35
Font, A. S., McCarthy, I. G., Johnstone, D., & Ballantyne, D. R. 2004, ApJ, 607, 890
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Gammie, C. F. 1996, ApJ, 457, 355
Goldreich, P., & Tremaine, S. 1980, ApJ, 241, 425
Görti, U., Dullemond, C. P., & Hollenbach, D. 2009, ApJ, 705, 1237
Görti, U., & Hollenbach, D. 2009, ApJ, 690, 1539
Haisch, K. E., Jr., Lada, E. A., & Lada, C. J. 2001, ApJ, 553, L153
Hartigan, P., Edwards, S., & Ghandour, L. 1995, ApJ, 452, 736
Hartmann, L., Calvet, N., Gullbring, E., & D’Alessio, P. 1998, ApJ, 495, 385
Hasegawa, Y., & Padritz, R. E. 2010, ApJ, 710, L167
Hasegawa, Y., & Padritz, R. E. 2011, MNRAS, 417, 1236
Hasegawa, Y., & Padritz, R. E. 2012, ApJ, 760, 117
Hasegawa, Y., & Padritz, R. E. 2013, ApJ submitted
Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, ApJ, 428, 654
Howard, A. W., Marcy, G. W., Johnson, J., et al. 2010, ScL, 330, 653
Ida, S., & Lin, D. N. C. 2004, ApJ, 604, 388
Ida, S., & Lin, D. N. C. 2008, ApJ, 685, 584
Ingleby, L., Calvet, N., Hernández, J., et al. 2011, AJ, 141, 127
Inutsuka, S., & Sano, T. 2005, ApJ, 628, L155
Ivanov, P. B., Papaloizou, J. C. B., & Polnarev, A. G. 1999, MNRAS, 307, 79
Johnstone, D., Hollenbach, D., & Bally, J. 1998, ApJ, 499, 758
Kley, W., & Nelson, R. P. 2012, ARA&A, 50, 211
Kretke, K. A., & Lin, D. N. C. 2012, ApJ, 755, 74
Liffman, K. 2003, PASA, 20, 337
Lin, D. N. C., & Papaloizou, J. 1986a, ApJ, 307, 395
Lin, D. N. C., & Papaloizou, J. 1986b, ApJ, 309, 846
Lubow, S. H., & D’Angelo, G. 2006, ApJ, 641, 526
Lubow, S. H., Seibert, M., & Artymowicz, P. 1999, ApJ, 526, 1001
Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603
Lyra, W., Paardekooper, S.-J., & Mac Low, M.-M. 2010, ApJ, 715, L68
Masset, F., & Snellgrove, M. 2001, MNRAS, 320, L55
Masset, F. S. 2001, ApJ, 5558, 453
Masset, F. S. 2002, A&A, 387, 605
Masset, F. S., Morbidelli, A., Crida, A., & Ferreira, J. 2006, ApJ, 642, 478
Masset, F. S., & Papaloizou, J. C. B. 2003, ApJ, 588, 494
Matsumura, S., Pudritz, R. E., & Thommes, E. W. 2007, ApJ, 660, 1609
Matsumura, S., Pudritz, R. E., & Thommes, E. W. 2009, ApJ, 691, 1764
Matsuyama, I., Johnstone, D., & Hartmann, L. 2003a, ApJ, 582, 893
Matsuyama, I., Johnstone, D., & Murray, N. 2003b, ApJ, 585, L143
Mayor, M., Marmier, M., Lovis, C., et al. 2011, arXiv:1109.2497v1
Morbidelli, A., & Crida, A. 2007, Icar, 191, 158
Morbidini, C., Alibert, Y., & Benz, W. 2009a, A&A, 501, 1139
Morbidini, C., Alibert, Y., Benz, W., & Naef, D. 2009b, A&A, 501, 1169
Morbidini, C., Dittkrist, K.-M., Alibert, Y., et al. 2011, in IAU Symp. 276, The Astrophysics of Planetary Systems: Formation, Structure, and Dynamical Evolution, ed. A. Sozzetti, M. G. Lattanzi, & A. P. Boss (Cambridge: Cambridge Univ. Press), 72
Nelson, R. P., Papaloizou, J. C. B., Masset, F., & Kley, W. 2000, MNRAS, 318, 18
Owen, J. E., Ercolano, B., & Clarke, C. J. 2011, MNRAS, 412, 13
Owen, J. E., Ercolano, B., Clarke, C. J., & Alexander, R. D. 2010, MNRAS, 401, 1415
Paardekooper, S.-J., Baruteau, C., Crida, A., & Kley, W. 2010, MNRAS, 401, 1950
Papaloizou, J. C. B., & Nelson, R. P. 2003, MNRAS, 339, 983
Regály, Z., Sándor, Z., Csomós, P., & Ataiee, S. 2013, MNRAS, 433, 2626
Rice, K., Penny, M. T., & Horne, K. 2013, MNRAS, 428, 756
Ruden, S. P. 2004, ApJ, 605, 880
Sándor, Z., Lyra, W., & Dullemond, C. P. 2011, ApJ, 728, L9
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shu, F. H., Johnstone, D., & Hollenbach, D. 1993, Icar, 106, 92
Suzuki, T. K., Muto, T., & Inutsuka, S. -i. 2010, ApJ, 718, 1289
Syer, D., & Clarke, C. J. 1995, MNRAS, 277, 758
Tanaka, H., Takeuchi, T., & Ward, W. R. 2002, ApJ, 565, 1257
Udry, S., & Santos, N. C. 2007, ARA&A, 45, 397
Williams, J. P., & Cieza, L. A. 2011, ARA&A, 49, 67