1. INTRODUCTION

The Kepler Mission, launched in 2009 March, photometrically monitors a large patch of sky with sufficient precision to detect terrestrial-sized planets in potentially habitable orbits. The Kepler Mission has released their initial 16 month data of 2321 transiting planet candidates (Batalha et al. 2012; Fabrycky et al. 2012). The mission is sensitive to a larger range of semimajor axes than ground-based transit surveys (Borucki et al. 2011). More than a dozen multiple transiting planet systems have been revealed (Steffen et al. 2010). Therefore, we assume the semimajor axis of Planet 01 is not well determined, the estimated value indicates that they are very close to the central star. The orbital period ratio of each pair is \( P_{02}/P_{03} \approx 2.033 \) and \( P_{01}/P_{02} \geq 1.896 \). The eccentricities are estimated to be zero and no evidence for large eccentricities has been revealed (Steffen et al. 2010). Therefore, we assume the eccentricities to be zero in this work. Based on the possibility of observing such a three-planet system, the planets likely occupy nearly coplanar orbits with a small deviation of inclination from the fundamental framework (Steffen et al. 2010).

It is well known that the planetary configurations involved in 4:2:1 MMR also occur in both our solar system and exoplanetary systems. For instance, the Galilean moons of Jupiter had been revealed in a three-body Laplace resonance over several hundred years. In addition, another example is that three super-Earths constitute the HD 40307 system, where three planets are near 4:2:1 MMRs (Papaloizou & Terquem 2010), similar to KOI-152. For HD 40307, three protoplanets formed in the protoplanetary disk with a configuration near MMRs, which strongly constrains the planetary formation and orbital migration theories. In this sense, the formation scenario of such a near Laplacian configuration is of great interest to researchers, and such investigations may test some planetary formation theory.

According to the core-accretion model, a planet with semimajor axis \( a \) can grow up with the material surrounding it to mass \( M_{\text{iso}} \) (Ida & Lin 2004)

\[
M_{\text{iso}} \approx 0.16 \frac{3}{4} \gamma_{\text{esc}} \left( \frac{\Delta E_2}{10 R_h} \right)^{3/2} \left( \frac{a}{\text{AU}} \right)^{3/4} \left( \frac{M_\ast}{M_\odot} \right)^{-1/2} \frac{M_\odot}{M_\ast},
\]

(1)

where \( R_h = (m/3M_\odot)^{1/3}a \) is the Hill radius of a planet with a mass \( m \), and \( \Delta E_2 \approx 7-10 \) \( R_h \) is the so-called feeding zone of the planet, \( M_\ast \) is the mass of central star, \( f_2 \) is the enhancement factor to the minimum mass solar nebula, \( \gamma_{\text{esc}} \) is the volatile mass.
enhancement for exterior or interior to the snow line \(a_{\text{ice}}\) with a value of 4.2 or 1, respectively. For KOI-152, we adopt \(a_{\text{ice}} = 5.29\) AU (Ida & Lin 2004). If three planets formed in the region as shown in Table 1 with their estimated minimum masses, \(f_D\) should be at least 0.37. Hence, we may conclude that it is impossible that all planets formed in situ.

Now, it is widely believed that there are mainly two formation mechanisms to produce short-period planets, e.g., planet–planet scattering and planetary migration (Rasio & Ford 1996). The planet–planet scattering scenario always requires a massive planet to stir up the eccentricities of other bodies and trigger the scattering process. After this process has finished some planets may obtain high eccentricity (Rasio & Ford 1996), away from their initial locations. However, the planets of KOI-152 are near 4:2:1 MMR with nearly circular orbits, and in this sense it seems impossible for the tune scattering scenario to yield such a precise configuration.

Another mechanism is that orbital migration occurs in the gaseous disk (Goldreich & Tremaine 1980; Lin et al. 1996). Multiple planets are likely to be captured into MMRs given an appropriate migration speed (Masset & Snellgrove 2001). As MMR commonly emerges in planetary systems, orbital migration is now considered to be one of the plausible mechanisms to form such systems. Take the GI 876 system as an example: consisting of four planets, GI 876 b and GI 876 c are locked into 2:1 MMR, which can be explained by the migration scenario (Lee & Peale 2002; Ji et al. 2002, 2003; Zhou et al. 2005; Zhang et al. 2010).

Recently, an alternative scenario of a collision–merger has been proposed to account for the formation of short-period planets (Ji et al. 2011). In this mechanism, several embryos can be excited by giant planets after the gas of the disk depletes and then merge into a larger body moving on a close-in orbit. Nevertheless, in these scenarios, planets are not easy to form in MMRs.

Considering the aforementioned factors, we propose a scenario to produce a configuration of KOI-152. First, three planets are assumed to have formed in the region away from the star with their nominal masses. Then, the planets may undergo type I or II migration due to interaction with the gaseous disk until they halt at the inner region of the disk. In this phase, three planets are trapped into MMRs during the migration. Finally, tidal effects, arising from the central star, circularize their orbits.

Such a scenario has been supposed by Terquem & Papaloizou (2007). They calculated a series of runs that are composed of 10–25 planets or planetary cores in a disk with masses ranging from 0.1 to 1 \(M_\oplus\), which undergo type I migration. They showed that hot super-Earths or Neptunes do not become isolated during their inward migration, and the companions on near-commensurate orbits always survive. Nevertheless, in their work, the authors did not consider the effect of different speed of type I migration, which can occur. In a more recent work, Papaloizou & Terquem (2010) investigated the formation of the HD 40307 system, bearing a resemblance to KOI-152. They adopted a similar formation scenario and found that in the end of the simulations, the planets are driven out of Laplace resonances due to tidal effects with the central star, and they finally reach a planetary configuration very close to HD 40307. Furthermore, Wang & Zhou (2011) accounted for the contribution of type I migration and mainly focused on the speed of migration under the perturbation of gas giants in the outer region in M dwarf system. They further point out that pairs of planets favor forming not only near the 2:1 MMR but other first-order resonances.

One of the important factors that influence final configurations is holes in the gas disk. In general, holes can appear at two positions. One is the boundary of the dead zone and the active zone in the midplane of the disk responding to the magnetorotational instability (MRI). For a protostellar gas disk in ad hoc \(\alpha\)-prescription (Shakura & Sunyaev 1973), the mass accretion rate, \(\dot{M}_g = 3\pi\alpha c_s h \Sigma_g\), is constant across the whole disk, where \(h = c_s/\Omega_k\) is the disk scale height, \(c_s\), \(\Omega_k\), and \(\Sigma_g\) are the sound speed of the midplane, the Kepler angular velocity, and the gas density, respectively. As the value of \(\alpha\) decreases from the active zone (∼0.018; Sano et al. 2000) to the dead zone (∼0.006), in the midplane the value of the gas density in the dead zone (outer) is three times that in the active zone (inner). Then a maximum density location occurs. Another is the inner hole of the disk caused by the coupling of the star’s magnetic field with the gas. Gas falls onto the surface of the central star under the effect of the torque induced by the stellar magnetic field, a truncation happens at the inner region, and an inner hole appears. A maximum density of the gas disk appears at the boundary of the inner hole. Due to the variation of density, the speed of type I migration may be changed. The two mentioned regions play a significant role in forming the final planetary configuration, especially for low-mass planetary systems.

In this work, we focus on exploring the configuration formation of KOI-152, mainly on the following aspects: (1) the speed of type I migration of planets, (2) the density profile of the gas disk, (3) the possible range of masses of three planets, and (4) the nature of the star in the system. This paper is organized as follows: in Section 2, we introduce the adopted disk model, orbital migration, and eccentricity damping models in the investigation. In Section 3, we present the simulation method and outcomes. Finally, we conclude and summarize the results in Section 4.

### 2. MODELS

#### 2.1. Disk Model

In order to explore the configuration formation, we consider a system consisting of a central star and three planets, which formed far away from the star. We assume that three planets are initially embedded in a gaseous disk. The surface density is given as (Pringle 1981)

\[
\Sigma_g = \frac{\dot{M}}{3\pi \nu(a)},
\]

where \(\dot{M}\) is the accretion rate of the star and \(\nu(a)\) is the effective viscosity at the orbit of a semimajor axis \(a\). According to the observation of young cluster \(\rho\)-Oph, the accretion rate of the star can be written as (Natta et al. 2006; Vorobyov & Basu 2009)

\[
\dot{M} \simeq 2.5 \times 10^{-8} \left(\frac{M_\ast}{M_\odot}\right)^{1.3 \pm 0.3} M_\odot \text{ yr}^{-1}.
\]

According to Equation (3), the accretion rate of star is \(\sim 3.87 \times 10^{-8} M_\odot \text{ yr}^{-1}\) for this system. Nevertheless, the value

### Table 1

| ID  | Semimajor Axis (AU) | Period (days) | Eccentricity | Mass (\(M_\oplus\)) |
|-----|---------------------|---------------|--------------|---------------------|
| 152.03 | 0.124  | 13.48       | 0.00         | 15             |
| 152.02 | 0.199  | 27.40       | 0.00         | 15             |
| 152.01 | 0.305  | \(\geq 51.94\) | 0.00         | 60             |
will decrease, on average, with the evolution of the T Tauri star and its disk. Hence, herein we consider the star accretion rate in the range of $[1 \times 10^{-9}, 5 \times 10^{-8}]$ $M_\odot$ yr$^{-1}$. The effective viscosity of the disk is $\nu(a) = \alpha_c h$, where $\alpha$ and $c_s$ represent the efficiency factor of angular momentum transport and sound speed at the midplane, respectively; $h = c_s/\Omega$ means the isothermal density scale height; and $\Omega$ refers to the Kepler angular velocity (Shakura & Sunyaev 1973). Because of the effect of MRI, the values of $\alpha$ in the active zone and the dead zone are quite different. The effective value of $\alpha$ is as expressed as (Kretke & Lin 2007; Kretke et al. 2009)

$$a_{\text{eff}}(a) = \frac{a_{\text{dead}} - a_{\text{mri}}}{2} \left[ \text{erf} \left( \frac{a - a_{\text{crit}}}{0.1 a_{\text{crit}}} \right) + 1 \right] + a_{\text{mri}},$$

(4)

where $a_{\text{mri}}$ and $a_{\text{dead}}$ denote the value of $\alpha$ in the active zone and the dead zone, respectively. Herein, we choose $a_{\text{dead}} = 0.001$ and $a_{\text{mri}} = 0.01$ (Sano et al. 2000). The parameter $a_{\text{crit}}$ in the error function erf is the location of the boundary of MRI and $0.1 a_{\text{crit}}$ represents the width of the transition zone. $a_{\text{crit}}$ is modeled as (Kretke et al. 2009)

$$a_{\text{crit}} = 0.16 \text{AU} \left( \frac{M_*}{10^{-8} M_\odot \text{yr}^{-1}} \right)^{4/9} \left( \frac{M_*}{M_\odot} \right)^{1/3}$$

$$\times \left( \frac{\alpha_{\text{mri}}}{0.02} \right)^{-1/5} \left( \frac{k_D}{1 \text{cm}^2 \text{g}^{-1}} \right),$$

(5)

where $k_D$ is the grain opacity.

Considering the disk depletion, the gas density profile can be modified to be

$$\Sigma_g = \frac{M}{3\pi \nu(a)} \exp \left( -\frac{t}{\tau_{\text{dep}}} \right),$$

(6)

where $\tau_{\text{dep}}$ refers to the disk depletion timescale, which is observed as a few million years (Haisch et al. 2001). We adopt $\tau_{\text{dep}} = 10^6$ yr in the simulations, where $t$ is the time of evolution.

Because of the stellar magnetic field, the gas disk is truncated at $a_{\text{mstr}}$ (Koenigl 1991),

$$a_{\text{mstr}} = \left( 1.06 \times 10^{-2} \text{AU} \beta' \left( \frac{R_*}{R_\odot} \right)^{12/7} \left( \frac{B_*}{1000 \text{G}} \right)^{4/7} \right)^{1/3}$$

$$\times \left( \frac{M_*}{M_\odot} \right)^{-1/7} \left( \frac{M}{10^{-7} M_\odot \text{yr}^{-1}} \right)^{-2/7},$$

(7)

where $R_*$, $R_\odot$, and $B_*$ refer to the radius of the star, the radius of the Sun, and the magnetic field of the central star, respectively. $\beta' \leq 1$ is a free parameter. Herein, we choose $\beta' = 1$ corresponding to a typical Alfvén radius in the way of spherical accretion. Hereafter we use $P_{\text{crit}}$ and $P_{\text{mstr}}$, the Keplerian orbital period, instead of $a_{\text{crit}}$ and $a_{\text{mstr}}$, for convenience. Combining the effect of the magnetic field, the gas density profile is substituted by

$$\Sigma_g = \frac{M}{3\pi \nu(a)} \exp \left( -\frac{t}{\tau_{\text{dep}}} \right) \eta,$$

(8)

where

$$\eta = 0.5 \left[ \text{erf} \left( \frac{a - a_{\text{mstr}}}{0.1 a_{\text{mstr}}} \right) + 1 \right]$$

is induced by the truncation of the magnetic field.

Based on Equation (8), we find that $\Sigma_g \propto r^{-3}$ and there are generally two maxima in the gas density profile. Figure 1 shows the density profile with various star accretion rates (see the top panel (a)). We label the inner maximum density location as DM1, and similarly the outer one as DM2. The locations of DM1 and DM2 change with the star accretion rate. In Figure 2 we show the density versus star accretion rate. From Figure 2 (the top panel (a)), we notice that, with a decrease of star accretion rate, the values of DM1 and DM2 approach each other until they merge into one; the combination occurs at $\sim M = 5 \times 10^{-9} M_\odot \text{yr}^{-1}$, corresponding to a maximum density at an orbital period of 13 days. Herein, we choose $a_{\text{dead}} = 0.001$, $a_{\text{mri}} = 0.01$, and $B_* = 0.5$ K, respectively, where the bottom panel (b) displays the values of the density at DM1 and DM2, respectively.

2.2. Planetary Migration and Eccentricity Damping

For the planets in KOI-152 system, their masses are estimated to be less than 100 $M_\oplus$. From classical planetary formation theory, they may undergo type I or type II migration during their evolution.

Type I migration is induced by angular momentum exchange between gas disk and planets. Based on linear analysis, the net momentum loss on a planet causes an inward migration (Goldreich & Tremaine 1979; Ward 1997; Tanaka et al. 2002). Under this assumption, the speed of type I migration is very fast. In such a situation, it is difficult to produce terrestrial planets. Recently, several new theories have been developed on reducing the speed of type I migration or even reverse the migrating direction (Baruteau & Masset 2008; Kley & Crida 2008; Kley et al. 2009; Paardekooper & Papaloizou 2008; Wang & Zhou 2011).

Considering the uncertainty of type I migration, we adopt a reduction of the migration speed, taking a timescale of type I migration of an embryo with mass $m$ as (Tanaka et al. 2002)

$$\tau_{\text{migI}} = \frac{1}{f_1 \tau_{\text{linear}}} = \frac{1}{f_1 (2.7 + 1.1 \beta) \left( \frac{M_*}{m} \right) \left( \frac{M_\odot}{\Sigma_\alpha^2} \right) \left( \frac{M}{10^{-7} M_\odot \text{yr}^{-1}} \right)^{2/7}} \times \left( \frac{h}{a} \right)^2 \left[ \frac{1 + \left( \frac{r}{M_{\odot}} \right)^{5/3}}{1 - \left( \frac{r}{M_{\odot}} \right)^5} \right] \Omega^{-1} \text{yr},$$

(10)

where $e$, $r$, $h$, and $\Omega$ are eccentricity, distance from the central star, scale height of the disk, and the Keplerian angular velocity, respectively. $\tau_{\text{linear}}$ is the timescale of linear analysis result; $f_1$ is the reduction factor. Herein, we choose $f_1 = 0.03, 0.1, 0.3$, respectively, and $\beta = -d \ln \Sigma_\alpha/d \ln a$. $\Sigma_\alpha$ means the gas density profile of the disk expressed in Equation (8). As the value of $\beta$ is related to the density profile, the speed of type I migration may be slowed down or even reversed at some special areas. In addition, Figure 1 shows the values of $\beta$ using $M = 2 \times 10^{-8} M_\odot \text{yr}^{-1}$ as an example (see the bottom panel (b)). According to Equation (10), if $\beta < -2.45$, the timescale of type I migration will transfer from positive to negative. Furthermore, we notice that when embryos run across DM2 and DM1, the migration speed will decrease, which may lead to the trapping of the embryos there.

When it grows massive enough, a planet will start to experience type II migration, as the strong torque caused by the planet will open a gap in the gaseous disk (Lin & Papaloizou 1993). The timescale of type II migration for a planet with mass $m$ is
(a)

(b)

Figure 1. Density profile of the gas disk and the values of $\beta$. The upper panel (a) shows the gas density profile with star accretion rate ($\dot{M} = [1 \times 10^{-9}, 5 \times 10^{-8}] M_\odot$ yr$^{-1}$), $\alpha_{\text{dead}} = 0.001$, and $\alpha_{\text{mri}} = 0.01$. The parameters of the star are set to be $B_* = 0.5$ KG and $R_* = 2.5$ R$_\odot$, except the red line for the cases in Group 4 with high magnetic field $B_* = 2.5$ KG. The bottom panel (b) illustrates the values of $\beta$, taking $\dot{M} = 2 \times 10^{-8} M_\odot$ yr$^{-1}$ as an example. Two maximum densities are located at $\sim 3.6$ days and 26 days, respectively, where $\beta$ changes from positive to negative at DM2 and the region inside DM1.

(A color version of this figure is available in the online journal.)

(Ida & Lin 2008)

\[
\tau_{\text{migII1}} \simeq 5 \times 10^5 \frac{f_g}{g} \left( \frac{C_2 \alpha}{10^{-4}} \right)^{-1} \left( \frac{M_\star}{M_J} \right)^{1/2} \left( \frac{a}{1 \text{AU}} \right) \left( \frac{M_\star}{M_\odot} \right)^{-1/2} \text{yr},
\]

\[
\tau_{\text{migII2}} = \frac{a}{|\dot{a}|} = 0.7 \times 10^5 \left( \frac{\alpha}{10^{-3}} \right)^{-1} \left( \frac{a}{1 \text{AU}} \right) \left( \frac{M_\star}{M_\odot} \right)^{-1/2} \text{yr},
\]

where $\alpha$ is the efficiency factor of angular momentum transport.

When the mass of planet is comparable to that of the gas disk, a fraction ($C_2 \sim 0.1$) of total angular momentum will transfer between the planet and the disk in the evolution. In this case, $\tau_{\text{migII1}}$ applies. Herein, we adopt $\alpha = \alpha_{\text{dead}} = 0.001$, $C_2 \alpha = 10^{-4}$. If the mass of the gas disk is larger than that of the planet, it will migrate with the gas disk over the timescale of $\tau_{\text{migII2}}$. We emphasize that the timescale of type II migration is larger than that of type I.

A gap will form in the gas disk when the planet grows to massive enough ($m > M_{\text{crit}}$) (Ida & Lin 2008),

\[
M_{\text{crit}} \simeq 30 \left( \frac{\alpha}{10^{-3}} \right) \left( \frac{a}{1 \text{AU}} \right)^{1/2} \left( \frac{M_\star}{M_\odot} \right) M_\oplus.
\]

In this work, we assume that the planet will undergo type II migration when its mass is greater than $M_{\text{crit}}$. Additionally, we consider the eccentricity damping induced by the interactions between the gas disk and the embryo (Goldreich & Tremaine 1979). The damping timescale for an embryo with mass $m$ is described as (Cresswell & Nelson 2006)

\[
\tau_e = \left( \frac{e}{\dot{e}} \right)_{\text{edamp}} = \frac{Q_e}{0.78} \left( \frac{M_\star}{m} \right) \left( \frac{M_\star}{M_\odot} \right) \left( \frac{h}{r} \right)^4 \Omega^{-1}
\times \left[ 1 + \frac{1}{4} \left( \frac{e}{\dot{e}} \right)^3 \right] \text{yr},
\]

Figure 2. Relationship between the gas density and star accretion rate. The upper panel (a) shows the orbital period at the location of maximum density with various star accretion rates. The black dotted line represents the boundary of the dead zone and the active zone using Equation (5) while the purple line indicates the truncated location according to Equation (7). The bottom panel (b) displays the values of density at two maximum density locations.

(A color version of this figure is available in the online journal.)
where $Q_e = 0.1$ is a normalization factor consistent with hydrodynamical simulations. The meanings of other symbols are similar to those in Equation (10).

### 3. NUMERICAL SIMULATIONS AND RESULTS

To explore the secular evolution of the KOI-152 planetary system, we assume that three planets had formed in the outer region of the system and migrate toward the inner region due to the interactions with the gas disk. Thus, the acceleration of a planet with mass $m_i$ is given as

$$\frac{d}{dt} \mathbf{V}_i = -\frac{G(M_\odot + m_i)}{r_i^2} \mathbf{r}_i + \sum_{j \neq i}^N \frac{G m_j (\mathbf{r}_j - \mathbf{r}_i)}{r_j^3} \mathbf{r}_j + \mathbf{F}_{\text{damp}} + \mathbf{F}_{\text{migI}}(\text{or} + \mathbf{F}_{\text{migII}}),$$

where $\mathbf{r}_i$ and $\mathbf{V}_i$ mean the position and velocity vectors of the planet $m_i$ in the stellar-centric coordinates, and the external forces are defined as

$$F_{\text{damp}} = -\gamma(V_i \cdot \mathbf{r}_i)\mathbf{r}_i, \quad r_i^3$$

$$F_{\text{migI}} = -\frac{\mathbf{V}_i}{2T_{\text{migI}}},$$

$$F_{\text{migII}} = -\frac{\mathbf{V}_i}{2T_{\text{migII}}}.$$

Each planet is assumed initially to be in coplanar and near-circular orbit and suffers from mutual gravitational interaction and the effect exerted by the central star. The initial orbital elements of each planet were randomly generated: the argument of pericenter, longitude of the ascending node, and mean anomaly were randomly set between $0^\circ$ and $360^\circ$. In this way, we generate a set of 34 runs for simulation.

We numerically integrate the Equation (14) using a time-symmetric Hermit scheme (Aarseth 2003). If the distance from a planet to the central star is smaller than the radii of the star we originally set, we assume that the planet collides with the star. Each run evolved for $10^6$ years.

Based on Equation (12), for $\alpha = 10^{-3}$, if $a > 0.125$ AU, then we have $M_{\text{crit}} > 15 M_\odot$. Hence, if their initial locations are all without 0.125 AU, KOI-152.02 and KOI-152.03 will undergo type I migration, and the outermost one will experience type I or II migration. In this sense, two kinds of models are assumed in the simulations: for Model 1, we suppose that all planets will suffer type I migration; whereas for Model 2, we simply consider that KOI-152.02 and KOI-152.03 will go through type I migration but KOI-152.01 will undergo type II migration. According to the aforementioned analysis, one of the planets in this system may be captured at DM1 or DM2. In such a case, taking into account the range of the star accretion rate [1 $\times$ 10$^{-9}$, 5 $\times$ 10$^{-9}$] $M_\odot$ yr$^{-1}$, we find that the positions of DM2 are at ~13, 26, and 48 days, respectively, in three groups for Model 1. In addition, the conditions of the density profile of various groups and models are summarized as follows.

**Model 1**

**Group 1.** For $M = 5 \times 10^{-8} M_\odot$ yr$^{-1}$, the density profile $\Sigma_g$ is labeled as the blue line in Figure 1. DM2 = 48.039 days; KOI-152.01 is likely to be captured at $a_{\text{crit}}$.

**Group 2.** For $M = 2 \times 10^{-8} M_\odot$ yr$^{-1}$, $\Sigma_g$ is labeled as the black line (Figure 1). DM2 = 26.08 days; KOI-152.02 is likely to be captured at $a_{\text{crit}}$.

**Group 3.** For $M = 1 \times 10^{-9} M_\odot$ yr$^{-1}$, $\Sigma_g$ is labeled as the green line (Figure 1). DM2 = 51.9 days; KOI-152.01 is likely to be captured at $a_{\text{crit}}$.

**Group 4.** For $M = 1 \times 10^{-9} M_\odot$ yr$^{-1}$, $\Sigma_g$ is labeled as the red line (Figure 1). DM2 = 51.9 days; KOI-152.01 is likely to be captured at $a_{\text{crit}}$.

**Model 2**

Comparison with Group 2 of Model 1: for $M = 2 \times 10^{-8} M_\odot$ yr$^{-1}$, $\Sigma_g$ labeled as the black line in Figure 1. DM2 = 26.08 days, KOI-152.02 is likely to be captured at $a_{\text{crit}}$. However, KOI-152.01 will undergo type II migration.

**3.1. Model 1: All Planets Undergo Type I Migration**

In order to understand the influence of the star accretion rate and the speed of type I migration, we perform four groups of simulations. Table 2 lists the detailed information for the dominant results of each group, where the last column shows the Keplerian orbital periods at the locations of DM1 and DM2.

**3.1.1. Group 1: KOI-152.01 Captured at $a_{\text{crit}}$**

In this group, DM1 and DM2 occur at ~2.4 days and 48 days, separately, with $M = 5 \times 10^{-8} M_\odot$ yr$^{-1}$. From the profile of gas density, we note that, if Planet 01 is likely to be trapped at DM2, the resulting configuration may be analogous to KOI-152. In total, we performed five runs to examine how the planets come into the resonant region, where Table 2 reports typical outcomes in our simulations. For example, in a typical run, Planet 02 or 03 will continue to move inward until reaching DM1 in cases where they have been kicked inside of DM2. Subsequently, Planet 01 is trapped at ~60 days as shown in Figure 3 and the two inner planets are eventually captured into 2:1 MMR. From Figure 1, we show that if a planet is pushed into the region inside DM2, the value of $\beta$ changes from negative to positive before it approaches DM1. The change in sign of $\beta$ is the reason that the two inner bodies migrate toward DM1. However, no matter...
Table 2
Detailed Information of Five Groups in the Simulations

| ID    | $M$ ($M_\odot$ yr$^{-1}$) | Initial Periods (days) | $f_1$ | Terminal Periods (days) | Terminal Period Ratios ($P_{01}/P_{02}, P_{02}/P_{03}$) | $P_{\text{crit}}, P_{\text{inst}}$ (days) |
|-------|-----------------|----------------------|------|----------------------|-------------------------------------------------|----------------------------------|
| Group 1 | $5 \times 10^{-8}$ | 120, 320, 850 | 0.1  | 2.58, 5.2, 60.5       | 11.63, 2.02                                    | 48.039, 2.443                   |
| Group 2-1 | $2 \times 10^{-8}$ | 120, 320, 850 | 0.03 | 3.8, 7.75, 32.83      | 4.24, 2.04                                     | 26.08, 3.618                    |
| Group 2-2 | $2 \times 10^{-8}$ | 120, 320, 850 | 0.1  | 1.899, 12.19, 24      | 1.97, 6.42                                     | 26.08, 3.618                    |
| Group 2-3 | $2 \times 10^{-8}$ | 120, 320, 850 | 0.3  | 3.8, 7.67, 32.85      | 4.28, 2.02                                     | 26.08, 3.618                    |
| Group 2-4 | $2 \times 10^{-8}$ | 120, 320, 20012 | 0.03 | 31.72, 64.23, 6960.77 | 108.37, 2.02                                   | 26.08, 3.618                    |
| Group 2-5 | $2 \times 10^{-8}$ | 120, 320, 20012 | 0.1  | 3.82, 7.7, 32.85      | 4.27, 2.01                                     | 26.08, 3.618                    |
| Group 2-6 | $2 \times 10^{-8}$ | 120, 320, 20012 | 0.3  | 3.78, 5.72, 32.83      | 5.74, 1.51                                     | 26.08, 3.618                    |
| Group 3-1 | $1 \times 10^{-9}$ | 120, 320, 850 | 0.1  | 3.5, 7.12, 14.73      | 2.07, 2.03                                     | 13.067                          |
| Group 3-2 | $1 \times 10^{-9}$ | 70, 150, 320 | 0.03 | 13.78, 27.87, 57.07   | 2.05, 2.02                                     | 13.067                          |
| Group 3-3 | $1 \times 10^{-9}$ | 220, 500, 1400 | 0.1  | 11.71, 23.56, 47.64   | 2.02, 2.01                                     | 13.067                          |
| Group 4  | $1 \times 10^{-9}$ | 220, 320, 850 | 0.1  | 14.17, 28.56, 58.54   | 2.05, 2.01                                     | 51.9                            |
| KOI-152 | $1 \times 10^{-9}$ | 134.8, 27.40, 52.09 | 0.1  | 13.067                   | 1.90, 2.03                                     | 13.067                          |

Notes. Terminal periods are the orbital periods of three planets at the end of run. $P_{\text{crit}}$ and $P_{\text{inst}}$ represent Keplerian orbital periods in association with the regime of DM1 and DM2.

In this scenario, a planetary configuration is finally created, which consists of two planets trapped into a 2:1 MMR or 3:2 MMR at DM1 and the outermost one resided inside DM2, far away from DM1.

3.1.2. Group 2: KOI-152.02 Captured at $a_{\text{crit}}$

By adopting $M = 2 \times 10^{-8} M_\odot$ yr$^{-1}$, we have DM1 and DM2 located at $\sim$3.6, 26 days, respectively. In this group, we performed six runs in total. The results of all runs are reported in Table 2. From Table 2, we observe that, similar to the cases of Group 1, Planet 03 is quickly captured at DM1 as it is thrown into the region inside DM2. In Runs 1–3, we utilize the same initial conditions but choose a variational migration speed. In these runs, Planet 02 cannot stay at DM2 but is kicked into the inner region by the perturbation of Planet 01, and then it falls into MMR with Planet 01 (Run 2) or Planet 03 (Runs 1, 3). In Runs 4–6, Planet 01 is initially well separated from the other two, by placing the outer planet in a starting location much more distant from the central star. The results of Runs 5 and 6 are analogous to that of Runs 1–3. The variation of $\beta$ is the governing reason for the evolution of Runs 1–3 and 5–6. However, owing to slow migration speed, Run 4 differs from other runs, where three planets cannot pass through DM2. Here, one may notice that it is impossible for three planets to form a configuration resembling to KOI-152. From the analysis of six runs, we summarize the simulation outcomes, where Planets 02 and 03 are in a 2:1 MMR for four runs and in one run they are captured into a 3:2 MMR, whereas in another special case Planets 01 and 02 become trapped into a 2:1 MMR over the evolution.

The created configuration in Group 2 varies with the value of $f_1$. The inner planet is always trapped in the boundary of the inner hole unless they undergo a lower speed of type I migration and the outermost planet is formed farther simultaneously. Thus, in such a scenario, a configuration similar to KOI-152 cannot be created.

3.1.3. Group 3: KOI-152.03 Captured at $a_{\text{crit}}$

In the simulations, we assume the star accretion rate to be equal to $1 \times 10^{-9} M_\odot$ yr$^{-1}$. From the density profile shown in Figure 1, we see that DM1 and DM2 tend to combine into one position at $\sim$13 days. In this group, we totally carried out 10 runs. Details of three runs are also shown in Table 2. If we examine the type I migration considering $f_1 \geq 0.1$, the results of evolution then bear resemblance to the case of Group 3-1, where KOI-152.01 is trapped at $\sim$14 days and in the meantime the other two planets jump into the inner region at $P < 10$ days, unless we started them at distant orbits from the star or slow down the speed of type I migration. In Group 3-2, we lower the migration speed and the result is shown in Figure 4, where Planet 03 is capable to being trapped at $\sim$14 days. The simulation results are consistent with the current observational values of KOI-152. When Planets 02 and 01 keep pace with Planet 03, two pairs are fully captured into 2:1 MMRs. Group 3-3 simulates the condition related to a high speed of type I migration and distant initial orbits. Figure 5 displays that Planets 01 and 02 are locked into 2:1 MMR in the dynamical evolution as well as Planets 02 and 03. In conclusion, according to our evaluation, three planets are eventually captured into Laplace resonance, with the resonant angles in a libration about 180° for Groups 3-2 and 3-3. When the planets are trapped into MMRs, their eccentricities are excited during the evolution; but due to strong gas damping, they cannot be pumped up to large values.

Taking $f_1 \leq 0.1$ into account, a configuration similar to KOI-152 is formed, where two pairs of planets are in the 2:1 MMRs.

3.1.4. Group 4: High Magnetic Field Star

Herein we consider that the star bears a high magnetic field of $B_\star = 2.5$ KG. In comparison with Group 3, for a high magnetic field star, the truncation of the inner hole is at $\sim$50 days, farther than that for a low magnetic field star as shown in Figure 6. Herein we carried out three runs. Figure 7 illustrates the results of a typical run, where the middle and bottom panels (c–f) show the resonant angles for the planets. From the figure, we note that three planets are captured into a 4:2:1 MMR at
Figure 4. Results of the evolution for Group 3-2. The two upper panels (a and b) show the evolution of orbital periods and eccentricities. The middle and bottom panels (c–f) are indicative of the resonant angles of three planets. In this run, they are captured into 4:2:1 MMR over much shorter timescale. In the end of this run, a planetary configuration similar to KOI-152, which consists of three planets, is formed.

(A color version of this figure is available in the online journal.)

Figure 5. Results of the evolution Group 3-3. The two upper panels (a and b) show the evolution of orbital periods and eccentricities. The middle and bottom panels (c–f) exhibit their resonant angles. In this run, they are captured into 4:2:1 MMR within a shorter timescale. A planetary configuration analogous to KOI-152, consisting of three planets, is generated.

(A color version of this figure is available in the online journal.)
because of the fast speed of type I migration, the system is totally destroyed. In another run, the produced planetary configuration is quite analogous to the typical Laplacian geometry, with the resonant angles librating at 180°. For $f_1 \leq 0.1$, we have a planetary configuration similar to KOI-152.

3.2. Model 2: KOI-152.01 Undergoes Type II Migration

According to our analysis above, Planet 01 may perform type II migration. In this model, we set Planets 02 and 03 to undergo type I migration but Planet 01 suffers from type II migration. We carry out 10 runs for Model 2 by varying the initial position of the outermost planet. But owing to a slow speed of type II migration, Planet 01 cannot reach its nominal position even if it is placed at the orbit with a period of 70 days in the beginning. Figure 8 shows a typical run of the simulations. In this run, the density profile is the same with that in Model 1 of Group 2, $f_1 = 0.1$ for Planets 02 and 03. In the end, the simulation results show that three planets migrate to 31.72, 63.86, and 211.13 days, respectively. However, Planet 01 is a little deviated from the present-day observation.

Under this scenario Planet 01 cannot approach its estimated position regardless of the initial location of the outermost planet. In addition, the two inner planets are always trapped into 2:1 MMR at DM2. In summary, we cannot generate a Laplacian configuration for three planets from Model 2.

4. CONCLUSIONS AND DISCUSSIONS

In this work, we have extensively investigated the formation of the configuration for the KOI-152 system using numerical
gas disk will migrate into the regime much closer to the central simulations. We assume that three planets formed in a region far away from the time evolution of the semimajor axes and eccentricities, respectively. (A color version of this figure is available in the online journal.)

Figure 8. Orbital evolution for Model 2. Two inner planets undergo type I migration while the outer one suffers from type II migration. The upper panel (a) shows the density profile, and the middle and bottom panels (b and c) exhibit migration while the outer one suffers from type II migration. The upper panel

$\frac{P_{01}}{P_{02}} = 2 \times 10^{-8} \frac{M_{\odot}}{\text{yr}}$. respectively, where $Q'$ is the tidal dissipation factor and we adopt $\rho = 3 \text{ g cm}^{-3}$ for them. Meanwhile, the semimajor axes are also decreasing over the timescales of $\tau_{\text{tide}}/(2e^2)$. In that case, the orbits of the planets will become a little closer to the star than those without considering of tidal effects. Owing to shorter timescales, the inner planets migrate faster, driving all of them out of MMR. Then, the configuration of KOI-152 forms and three planets are near MMRs. This scenario may be suitable to account for the formation of other systems with planetary configurations like KOI-152.

Among the 16 month data of *Kepler*, 242 target stars host two planet candidates, 85 with three Planets, 25 with four planets, 8 with five planets, and 1 with six (Fabrycky et al. 2012). We examine all candidates and find that 10 systems may have two pairs of the planets involved near 2:1 MMRs, e.g., a near Laplacian resonance configuration. The orbital periods and their ratios are shown in Table 3. The ratios of the orbital periods are all in the range of [1.83, 2.18], which may imply that they are likely to bear a formation scenario similar to KOI-152. In addition, the configuration of KOI-148 is close to the outcomes of Groups 2-1 and 2-3 where two planets are simply trapped in 2:1 MMR, which demonstrates that the system may be formed when the star is younger than the case of KOI-152 with $M = 2 \times 10^{-8} \frac{M_{\odot}}{\text{yr}}$.

Marcy et al. (2001) revealed that there were two giant planets involved in a 2:1 MMR orbiting the star GJ 876. However, after the fourth planet was discovered in the GJ 876 system, the previously known 2:1 MMR configuration then becomes a Laplacian resonance configuration, where three planets are trapped into a 4:2:1 MMR with the resonant angles librating at $0^\circ$, respectively, differing from the Galilean moons of Jupiter in a libration at $180^\circ$ (Rivera et al. 2010). In such configurations, a planetary system will remain stable for at least one billion years. A great many of previous works have investigated the dynamics and stability of the system consisting of three planets at that time (Ji et al. 2002, 2003; Zhou et al. 2005; Zhang et al. 2010). From the former results, we learn that the migration scenario may be responsible for the formation of two giants locked into 2:1 MMR. Thus, under the same formation scenario for KOI-152, three planets may also be trapped into a 4:2:1 MMR, showing a

Table 3
| ID  | $P_{01}$ (days) | $P_{02}$ (days) | $P_{03}$ (days) | $P_{04}$ (days) | $P_{01}/P_{02}$ | $P_{02}/P_{03}$ | $P_{03}/P_{04}$ |
|-----|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| KOI | 152            | 52.09119       | 27.40415       | 13.484         | ...            | 1.9009         | 2.0323         |
|     | 571            | 13.34331       | 7.26733        | 3.886758       | ...            | 1.8361         | 1.8698         |
|     | 665            | 5.867973       | 3.07154        | 1.611912       | ...            | 1.9104         | 1.9055         |
|     | 733            | 11.34917       | 5.924992       | 3.133968       | ...            | 1.9155         | 1.8912         |
|     | 829            | 38.5596        | 18.64904       | 9.75222        | ...            | 2.0676         | 1.9123         |
|     | 898            | 20.08923       | 9.70579        | 5.16991        | ...            | 2.0561         | 1.8899         |
|     | 899            | 15.36813       | 7.1388         | 3.306569       | ...            | 2.1603         | 2.1514         |
|     | 1426           | 150.0341       | 74.91443       | 38.87641       | ...            | 2.0027         | 1.9270         |
|     | 1860           | 12.2094        | 6.3194         | 3.0765         | ...            | 1.9321         | 2.0541         |
|     | 1895           | 32.1349        | 17.2812        | 8.4575         | ...            | 1.8595         | 2.0433         |
|     | 935            | 87.6464        | 42.6329        | 20.85987       | 9.6168         | 2.0558         | 2.0438         |
|     | 148            | 42.89554       | 9.67374        | 4.777978       | ...            | 4.4342         | 2.0247         |

Note. $P_{01}$, $P_{02}$, $P_{03}$, and $P_{04}$ are, respectively, the orbital periods of the planets in the systems.

http://archive.stsci.edu
resemblance to those of GJ 876. Hence, we may safely conclude that the near Laplacian configurations are quite common in planetary systems as also revealed by Kepler, and our work may provide some substantial clues to the formation of such intriguing systems.

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