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Migration & Extra-solar Terrestrial Planets: Watering the Planets

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Abstract. A diverse range of terrestrial planet compositions is believed to exist within known extrasolar planetary systems, ranging from those that are relatively Earth-like to those that are highly unusual, dominated by species such as refractory elements (Al and Ca) or C (as pure C, TiC and SiC) (Bond *et al.* 2010b). However, all prior simulations have ignored the impact that giant planet migration during planetary accretion may have on the final terrestrial planetary composition. Here, we combined chemical equilibrium models of the disk around five known planetary host stars (Solar, HD4203, HD19994, HD213240 and Gl777) with dynamical models of terrestrial planet formation incorporating various degrees of giant planet migration. Giant planet migration is found to drastically impact terrestrial planet composition by 1) increasing the amount of Mg-silicate species present in the final body; and 2) dramatically increasing the efficiency and amount of water delivered to the terrestrial bodies during their formation process.

Keywords. planetary systems, planets and satellites: formation.

1. Introduction

Migration of gas giant planets is believed to have occurred in numerous planetary systems, possibly including our own Solar System (eg. Armitage 2007, Walsh *et al.* 2011a). This migration is primarily driven by a coupling between the gas disk and the giant planet, resulting in the giant planet migrating inwards towards the host star as the gas itself viscously evolves and also flows inward. This type of migration is referred to as "type II" (Papaloizou & Lin 1984, Lin *et al.* 1996) and results in migration of the giant planet on the order of $\sim 10^{5-6}$ years.

During this migration, small bodies in the path of the giant planet are gravitationally scattered onto exterior orbits or shepherded inward by mean motion resonances (Mandell *et al.* 2007, Fogg & Nelson 2005, Fogg & Nelson 2007, Raymond *et al.* 2006), effectively redistributing vast quantities of solid material within the disk. This redistribution directly impacts the composition of any terrestrial planets forming within the system as planetary feeding zones are no longer composed of material immediately adjacent to the growing planetary body. Instead, they are composed of solid material from throughout the entire disk and are composed of a much more diverse range of materials.

Despite the fact that numerous studies has examined terrestrial planet formation and survival during giant planet migration (e.g. Walsh *et al.* 2011b, Raymond *et al.* 2009, Mandell *et al.* 2007, Gaidos *et al.* 2007, Raymond *et al.* 2006, Fogg & Nelson 2007, Fogg & Nelson 2005), few have considered the impact of migration on the composition of the resultant terrestrial planet and none have considered the issue in depth. Similarly, studies of potential terrestrial planet compositions (e.g. Bond *et al.* 2010a, Bond *et al.* 2010b, Elser *et al.* 2012) have neglected giant planet migration, focussing solely on late-stage planetary accretion with giant planets in fixed orbits. Given the apparently common occurrence of giant planet migration, coupled with its ability to drastically alter the distribution of planetary building blocks, and hence the composition of the planets themselves, it is necessary to extend our previous modeling work and incorporate migration to obtain a more realistic image of terrestrial planet formation.

2. Terrestrial Planet Formation

In order to quantify the effect of giant planet migration on extrasolar terrestrial planet compositions, we selected four specific dynamical scenarios to represent the various degrees of migration observed within known planetary systems. N-body dynamical simulations were run for (1) a Jupiter-mass planet located at 1AU and not migrating (hereafter referred to as in-situ); (2) a Jupiter-mass body migrating from 5AU to 1AU (JD_{5-1}); (3) a Jupiter-mass body migrating from 5AU to 0.25AU ($\mathrm{JD}_{5-0.25}$); and (4) a Jupiter-mass body migrating from 5AU to 0.25AU with an additional Saturn-mass body stationary at 9.5AU ($\mathrm{JSD}_{5-0.25}$). The $\mathrm{JD}_{5-0.25}$ were previously presented in both Raymond *et al.* (2006) and Mandell *et al.* (2007) (as JD and JSD, respectively) and the $\mathrm{JSD}_{5-0.25}$ simulations were previously reported in Mandell *et al.* (2007). Migration of the giant planet occurs over a timespan of 10^5 years and the simulations were run for a total of 50 Myr (for in situ and JD_{5-1}) or a total of 200 Myr (for $\mathrm{JD}_{5-0.25}$ and $\mathrm{JSD}_{5-0.25}$). Four simulations were run for each scenario.

Detailed chemical compositions were obtained the same way as was previously done by Carter-Bond *et al.* (2012), Bond *et al.* (2010a) and Bond *et al.* (2010b). Stellar photospheric abundances of the 14 most abundant elements (C, N, O, Na, Mg, P, Al, Si, S, Ca, Ti, Cr, Fe and Ni) (Gilli *et al.* 2006, Beirão *et al.* 2004, Ecuvillon *et al.* 2004, Ecuvillon *et al.* 2006) were utilized to obtain condensation sequences via the HSC Chemistry (v. 5.1) software, in conjunction with midplane profiles from Hersant *et al.* (2001). Photospheric abundances were adopted for five known planetary host stars - Solar, Gl777, HD4203, HD19994 and HD213240. These systems were selected for study as they span the full range of potential condensation sequences, as determined by the stellar Mg/Si and C/O value (see Figure 1). These two ratios exert the greatest control over the compositions of solids forming within a given system. A stellar C/O value below 0.8 implies that Si will be present within the system in the solid form primarily as either the $\mathrm{SiO_4}^{4-}$ or $\mathrm{SiO_2}$ building block. The exact form of this silicate is controlled by the Mg/Si value, ranging from pyroxene ($\mathrm{MgSiO_3}$) (for Mg/Si<1) to olivine ($\mathrm{Mg_2SiO_4}$) (for Mg/Si>2). If the C/O value is greater than 0.8, then carbide phases (C, SiC and TiC) will be present along with silicate species, resulting in C-rich planetary building blocks (Kuchner & Seager 2005, Gaidos 2000). Phase changes and outgassing by the bodies during migration are neglected, as is planetary outgassing and differentiation. It is important to note here that although we do use the chemical composition of specific planetary host stars, the n-body simulations are not intended to replicate the dynamics of any particular system. They are demonstrative only.

3. Migration and Terrestrial Planet Compositions

The inclusion of giant planet migration has profound effects on the composition of extrasolar terrestrial planets. The two primary impacts are 1) giant planet migration increases the amount of Mg-silicates incorporated into a terrestrial planet, resulting in the production of an increased number of Earth-like planets (as opposed to C-rich or refractory dominated bodies); and 2) giant planet migration results in the delivery of large amounts of hydrous phases to the terrestrial planet during the accretion process. Each of these is discussed in turn below.

Increased number of Earth-like planets. The most pronounced effect of giant planet migration on terrestrial planet compositions is that the relative abundance of Mg, Si and O increases, resulting in the increased production of Earth-like planets. This increase reflects the composition of material initially located interior to the giant planet and thus shepherded inwards into the terrestrial planetary feeding zone during the migration process.

No Earth-like planets (i.e. a Mg-silicate and metallic Fe planet with minimal trace elements and bulk elemental abundances for the major elements (O, Fe, Mg, Si) within

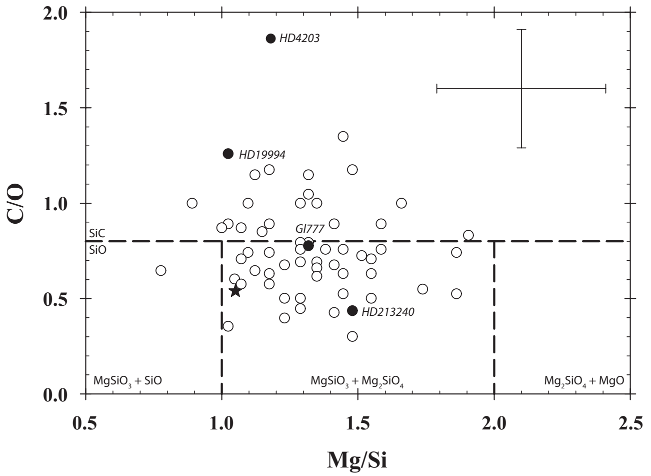

Figure 1. Mg/Si vs. C/O for known planetary host stars with reliable stellar abundances. Filled circles represent those systems selected for this study with their identifiers in italics. Stellar photospheric values were taken from Gilli *et al.* (2006)(Si, Mg), Beirão *et al.* (2004)(Mg), Ecuvillon *et al.* (2004)(C) and Ecuvillon *et al.* (2006)(O). Solar values are shown by the black star and were taken from Asplund *et al.* (2005). The horizontal dashed line indicates a C/O value of 0.8 and marks the transitions between a silicate-dominated composition and a carbide-dominated composition at 10^{-4} bar. The vertical dashed lines indicate the transition between the various Mg/Si regions. Dominant solid state composition for each region is shown. Average 2-σ error bars for the observational estimates are shown in upper right. Taken from Carter-Bond *et al.* (2012b).

±25% of the bulk Earth elemental abundances of Kargel & Lewis 1993) were produced in the in-situ scenario considered here. Earth-like planets were produced for the JD_{5-1} scenario (Jupiter-mass planet migrating from 5AU to 1AU) for Solar, HD213240 and Gl777 composition disks. Earth-like planets were produced for all disk compositions considered for both the $\mathrm{JSD}_{5-0.25}$ and $\mathrm{JD}_{5-0.25}$ scenarios. These results indicate that Earth-like planets are likely to be common within extrasolar planetary systems. That is not to say that the more "exotic" C-rich planets of Bond *et al.* 2010b are unlikely to exist. Numerous simulations produced both Earth-like planet and C-rich bodies within the same system. Instead we expect to see an increase in the proportion of Earth-like planets in those systems which have undergone giant planet migration.

This result is in agreement with current observational data. Polluted white dwarfs have recently been shown to be an effective tool in analyzing the composition of solid bodies present in a planetary system orbiting the precursor star. The atmosphere of a white dwarf is exclusively composed of H and/or He. As such, any other elements present in the atmosphere must be the result of accretion of solid material by the white dwarf itself (Jura 2008, Jura 2006, Jura 2003). Several observations (e.g. Jura & Xu 2012, Jura *et al.* 2012, Gänsicke *et al.* 2012, Zuckerman *et al.* 2011) have reported the detection of pollution indicative of accretion of material comparable in composition to that of Earth and CI chondrites. Additionally, C abundances have also been reported to be depleted compared to Solar. These observations further support the results of this study in that Earth-like terrestrial planets appear to be common within planetary systems and, although they may exist, more exotic planetary compositions (such as C-dominated bodies) are unlikely to be the planetary norm.

Efficient water delivery. The second key impact of giant planet migration on terrestrial planet composition is the delivery of significant quantities of hydrous phases (water ice and serpentine ($Mg_3Si_2O_5(OH)_4$)) to the terrestrial planets during their formation. In all of the in-situ simulations, no hydrous phases are accreted by the terrestrial planets. The inclusion of giant planet migration results in the delivery of water to all planetary bodies, with the $\mathrm{JSD}_{5-0.25}$ scenario producing some of the largest planetary water contents. Water abundance is highly dependent on disk composition, with higher C/O systems having less water ice available (Gaidos 2000). As a result, predicted planetary water contents range from 895 Earth oceans for a HD4203 composition disk ($C/O = 1.86$) up to 4492 Earth oceans for a HD213240 composition disk ($C/O = 0.44$). Although these values are a significant increase on previous water abundance estimates, these predictions should be considered to be upper limits only as we do not currently consider outgassing, hydrodynamic escape, or loss during collisions. Based on observed elemental depletions in ordinary chondrites with respect to the 50% condensation temperature (Davis 2006), we expect to lose up to 97% of the delivered water, resulting in a more probable maximum planetary water retention of just 27 - 135 Earth-oceans of water (depending on disk composition) for the scenario with the largest extent of giant planet migration ($\mathrm{JSD}_{5-0.25}$).

In addition to the many biological consequences of water delivery, water also exerts great influence on many planetary processes, including mantle rheology, differentiation and atmospheric composition. The presence of surface water has been found to be a crucial factor for plate tectonics (van Heck & Tackley 2011, Korenaga 2010), with the presence of water serving to lower the yield strength of olivine, decreasing the force needed to instigate slippage and possible subduction along a fault line. Furthermore, if significant amounts of water are present in the planetary interior, the total amount of melt produce may increase, along with a possible increase in crust thickness (Asimow &

Langmuir 2003). Combining these effects together, we can conclude that the Earth-like planets simulated here are likely to have both increased melt production as well as an increased likelihood of active plate tectonics.

4. Conclusions

By redistributing vast quantities of solid material within a planetary disk, giant planet migration can dramatically influence the composition of terrestrial planets forming within a planetary system. Although a wide variety of extrasolar terrestrial planets may exist within known planetary systems, giant planet migration is found to increase the occurrence of Earth-like planets, while simultaneously increasing the amount of hydrous phases delivered to a terrestrial planet during accretion. These effects will not only influence planetary processes such as plate tectonics but may also impact planet detectability and habitability.

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