

TOWARD CHEMICAL CONSTRAINTS ON HOT JUPITER MIGRATION

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ABSTRACT

The origin of hot Jupiters—gas giant exoplanets orbiting very close to their host stars—is a long-standing puzzle. Planet formation theories suggest that such planets are unlikely to have formed in situ but instead may have formed at large orbital separations beyond the snow line and migrated inward to their present orbits. Two competing hypotheses suggest that the planets migrated either through interaction with the protoplanetary disk during their formation, or by disk-free mechanisms such as gravitational interactions with a third body. Observations of eccentricities and spin-orbit misalignments of hot Jupiter systems have been unable to differentiate between the two hypotheses. In the present work, we suggest that chemical depletions in hot Jupiter atmospheres might be able to constrain their migration mechanisms. We find that sub-solar carbon and oxygen abundances in Jovian-mass hot Jupiters around Sun-like stars are hard to explain by disk migration. Instead, such abundances are more readily explained by giant planets forming at large orbital separations, either by core accretion or gravitational instability, and migrating to close-in orbits via disk-free mechanisms involving dynamical encounters. Such planets also contain solar or super-solar C/O ratios. On the contrary, hot Jupiters with super-solar O and C abundances can be explained by a variety of formation–migration pathways which, however, lead to solar or sub-solar C/O ratios. Current estimates of low oxygen abundances in hot Jupiter atmospheres may be indicative of disk-free migration mechanisms. We discuss open questions in this area which future studies will need to investigate.

Key words: planetary systems – planets and satellites: general

Online-only material: color figures

1. INTRODUCTION

Gas giant planets are thought to form in one of two ways. Core accretion of gas onto a $\sim 10 M_{\oplus}$ solid core operates within ~ 1 –10 AU (Pollack et al. 1996; Lissauer & Stevenson 2007), while rapid collapse by gravitational instability may occur beyond a few tens of AU (Boss 2000; Gammie 2001; Boley 2009). Neither process is thought to form in situ the gaseous hot Jupiters seen on short-period orbits (e.g., Mayor & Queloz 1995), so some form of migration from their formation locations is required to explain their existence.

These migration pathways are poorly constrained. Migration may occur via the planet’s interaction with, and transport through, the protoplanetary disk (e.g., Papaloizou et al. 2007), but could occur later via scattering or secular interactions of the planet with other massive planetary or stellar components in the system (e.g., Rasio & Ford 1996; Fabrycky & Tremaine 2007). A significant number of large spin-orbit misalignments observed in hot Jupiter systems initially supported the role of migration by scattering phenomena (e.g., Winn et al. 2010), but such misalignments may also be caused by planet migration through disks that are themselves misaligned (Batygin 2012; Crida & Batygin 2014). Consequently, observed dynamical properties of hot Jupiters have been unable to conclusively constrain their migration pathways.

In the present work, we suggest that chemical abundances of hot Jupiters have the potential to constrain their migration mechanisms. Following initial constraints on elemental abundance ratios in hot Jupiters (e.g., Madhusudhan et al. 2011a; Madhusudhan 2012), several studies in recent years have attempted to explain high C/O ratios in their atmospheres based on the local chemical conditions in the protoplanetary disk where the planets formed (Madhusudhan et al. 2011b; Öberg et al.

2011; Mousis et al. 2011; Moses et al. 2013; Ali-Dib et al. 2014). We investigate the influence of both the formation conditions of hot Jupiters as well as their subsequent migration to close-in orbits on their elemental abundances.

2. MODELLING ACCRETION AND MIGRATION

We simulate the formation and migration of hot Jupiters under different scenarios and keep track of their chemical compositions. Our models comprise four key components: (1) a time-dependent protoplanetary disk, (2) planet growth by accretion of solids and gas, both under core accretion and gravitational instability, (3) planet migration, both within and without the disk, and (4) chemical evolution of the planet.

2.1. Protoplanetary Disk

The protoplanetary disk comprises solid and gaseous components. For the gaseous component, we use the time-dependent viscous thin disk model of Chambers (2009). We assume an initial gas-to-dust ratio of 100 to derive the surface density of solids in the disk, increasing this solid surface density by a factor of two at the “snow line” ($T_{\text{disk}} = 170$ K) to account for the additional solids from water ice. We fix the stellar mass to $1 M_{\odot}$, the viscosity α to 0.01, the initial disk mass to $0.15 M_{\odot}$, and the simulation start time to 1 Myr to allow for prior embryo growth. The disk accretion rate is the steady-state solution $\dot{M}_{\text{disk}} = 3\pi \nu \Sigma_{\text{g}}$.

2.2. Growth of Giant Planets

We consider giant planet formation by both core accretion and gravitational instability. Our core accretion simulations of hot Jupiters follow a population synthesis approach (e.g., Alibert et al. 2005; Benz et al. 2014). Our simulations begin with the

opening of a gap in the disk, i.e., at the onset of Type II migration (e.g., Papaloizou et al. 2007), which sets the initial planet mass. Gas accretion onto the planet in the Type II regime after gap opening is set using the scaling relation from Veras & Armitage (2004). We further multiply this rate by an efficiency factor f_{accr} to allow for the possibility that material flows past the planet at a greater rate than implied by this prescription (see also Lubow & D’Angelo 2006).

Growing planets also accrete solid material from the disk, for which we use the solid accretion rate given by Alibert et al. (2005), including the capture efficiency factor that allows for planetesimals to be accreted inefficiently when the planet’s escape velocity is large (Ida & Lin 2004). The solid material accreted onto the planet is removed from an annular disk region 8 Hill radii wide centered on the planet of mass M_{pl} at semi-major axis a_{pl} .

We model gravitational instability following the approach of Helled & Schubert (2008, 2009). The initial masses of such planets is in the gas giant regime (Boley et al. 2010), so significant subsequent growth (or disruption) cannot occur for these planets to be detected as $\sim 1 M_{\text{Jup}}$ hot Jupiters (and not brown dwarfs). The migration is therefore either very rapid relative to further growth (i.e., effectively $f_{\text{accr}} \approx 0$), or occurs after dispersal of the gas disk. Most of the planet mass is therefore acquired in situ, with some solids subsequently accreted after gravitational collapse to reach the final planet mass. Helled & Schubert (2008) neglect gravitational focusing, which probably underestimates the solid mass accreted so we compute models with this prescription and alternatively assume that all solids within 8 Hill radii of the planet are accreted. These extremes likely cover the actual mass in solids accreted in such a scenario. Once the mass of solids acquired by the planet is determined, the mass in gas is just the difference between the total mass of the planet (fixed to near $1 M_{\text{Jup}}$) and the mass in solids.

2.3. Giant Planet Migration

We consider giant planet migration both through interactions with the gas disk and via dynamical interactions with a third body. We model inward Type II migration of a planet through the disk, which occurs for planets with more than a few tens of Earth masses (e.g., Papaloizou et al. 2007). The planet accretes gas as it migrates, so the observable planet atmosphere is dominated by the mass accreted once Type II migration begins and earlier phases are of minor concern here (and we do not model them). The relative rates of gas/solid accretion and migration set the locations in the disk where the planet’s envelope came from, and hence the observable chemical properties of the planet.

We adopt the Type II migration rate used by Ida & Lin (2004), though other migration prescriptions are possible (e.g., Mordasini et al. 2009). Our model accounts for the possibility of different migration prescriptions by varying the accretion efficiency via the factor f_{accr} . Given the prescriptions for gas accretion and migration of a giant planet, an expression for planet growth during migration, which is independent of the disk properties, is

$$\frac{d \log M_{\text{pl}}}{d \log a_{\text{pl}}} \sim -5 f_{\text{accr}} \sqrt{a_{\text{pl}}/30 \text{ AU}}. \quad (1)$$

At large radii migration is slow relative to growth, but increases at small radii (i.e., 1 AU). This growth can be visualized in a plot of M_{pl} versus a_{pl} as shown in Figure 1, with

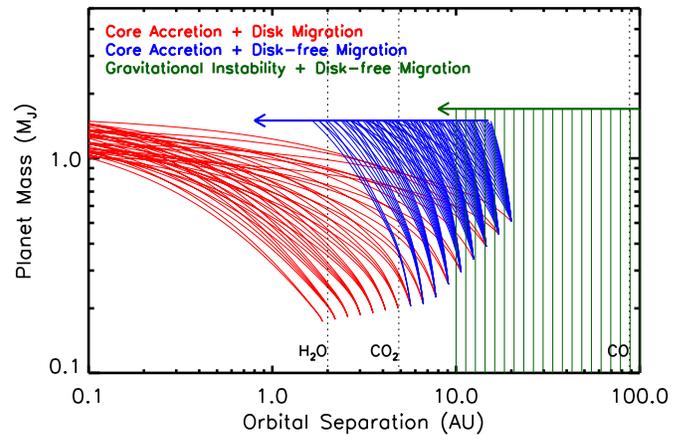


Figure 1. Evolutionary tracks showing the formation and migration of hot Jupiters under three different conditions. The planets start at the lower right and move to the upper left. Only a representative population is shown in each case. The red curves show evolution of hot Jupiters that formed via core accretion and migrated through the disk. The blue curves show evolutionary tracks of planets that formed by core accretion but migrated through disk-free mechanisms, e.g., dynamical scattering. The green curves show tracks of hot Jupiters that formed via gravitational instability and migrated disk-free. The black vertical dashed lines show snow lines of H_2O , CO_2 , and CO for a representative disk.

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

curves following the formation of planets with different initial conditions and f_{accr} (see also Mordasini et al. 2009; Rice et al. 2013).

Migration via scattering or secular perturbations (i.e., “disk-free” migration) is treated by truncating planet growth at the target mass of $1 M_{\text{Jup}}$. For core accretion and disk-free migration, the planet evolves via Type II migration until it reaches $1 M_{\text{Jup}}$ following which we assume the growth is truncated due to a scattering event or disk dispersal. For gravitational instability we simply assume in situ formation prior to scattering. In either case the planetary chemical composition is fixed when $1 M_{\text{Jup}}$ is reached, and the semi-major axis decreased to 0.1 AU without further accretion. In reality, the planet may continue to accrete during disk-free migration, the chemical implications of which in our models are similar to those involving Type II migration followed by scattering, as discussed in Section 4.

2.4. Chemistry

The dominant O and C bearing species in the disk mid-plane are H_2O , CO_2 , CO , CH_4 , silicates, and graphite grains. The volume mixing ratios of these species for a solar composition disk are derived based on chemical equilibrium in the disk mid-plane (Woitke et al. 2009) as well as from observations of protoplanetary disks (Öberg et al. 2011; Draine 2003; Pontoppidan 2006); our adopted values are shown in Table 1. The snow lines of H_2O , CO_2 , and CO govern the apportionment of C and O in gaseous versus solid phases, apart from minor fractions of C and O in refractory condensates such as silicates and graphite grains (Pontoppidan 2006). The mid-plane elemental composition of a representative solar abundance disk is shown in Figure 2. For separations closer to the star than the H_2O snow line, O and C are predominantly in gas phase with minor quantities in silicates and carbides. For larger separations, O is progressively depleted from the gas and moved into solid ices following the various snow lines starting with H_2O . C is predominantly in gas phase until the CO_2 and CO snow lines (also see, e.g., Öberg et al. 2011).

Table 1
Volume Mixing Ratios of Chemical Species in the Disk

Species	T_{cond} (K) ^a	Case 1 ^b : X/H	Case 2 ^c : X/H
CO	20	$0.45 \times \text{C/H}$ ($0.9 \times \text{C/H}$ for $T < 70$ K)	$0.65 \times \text{C/H}$
CH ₄	30	$0.45 \times \text{C/H}$ (0 for $T < 70$ K)	0
CO ₂	70	$0.1 \times \text{C/H}$ (0 for $T < 70$ K)	$0.15 \times \text{C/H}$
H ₂ O	170	$\text{O/H} - (3 \times \text{Si/H} + \text{CO/H} + 2 \times \text{CO}_2/\text{H})$	$\text{O/H} - (3 \times \text{Si/H} + \text{CO/H} + 2 \times \text{CO}_2/\text{H})$
Carbon grains	150	0	$0.2 \times \text{C/H}$
Silicates	1500	Si/H	Si/H

Notes.

^a The condensation temperatures for CO, CH₄, CO₂, and H₂O are adopted from Mousis et al. (2011), and those for silicates and carbon grains are adopted from Öberg et al. (2011).

^b Volume mixing ratios of the various species adopted based on theoretical computations for a solar composition disk (Woitke et al. 2009). For temperatures higher than the CO₂ condensation curve, i.e., at smaller orbital separations, the densities can be high enough for methane (CH₄) to be abundant in chemical equilibrium. Non-equilibrium chemistry could also lead to some CO production. CO₂ is less abundant than CO or CH₄, depending on the temperature regime (Madhusudhan & Seager 2011). We have assumed a CO₂ fraction to be 10% of C, and partitioned the remaining C between CO and CH₄. Farther out in the disk, beyond the CO₂ snow line, CO contains the majority of C and CH₄ is negligible (Woitke et al. 2009).

^c Volume mixing ratios of the various species following (Öberg et al. 2011) who adopted values based on ice and gas observations in protoplanetary environments. This set of compositions contains carbon grains leading to more solid carbon.

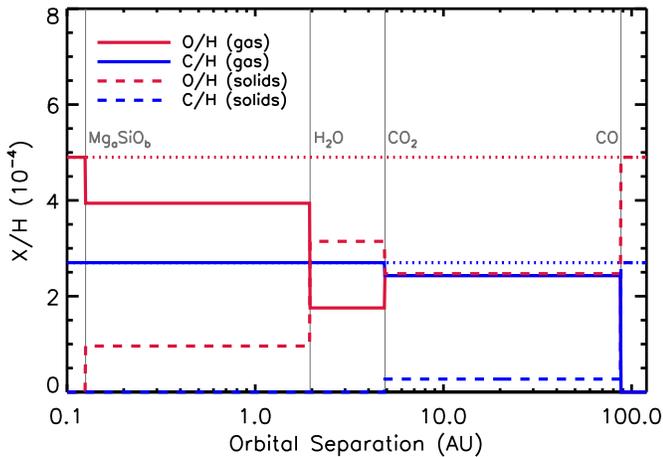


Figure 2. Partitioning of oxygen and carbon in the mid-plane of a model protoplanetary disk. The molecular mixing ratios correspond to case 1 of Table 1 for illustration. The solid red (blue) curves show the volume mixing ratio of oxygen (carbon) in the gas, and the dashed curves show the corresponding volume mixing ratios in solid planetesimals, in the form of ices or rocks. The dotted lines show the total abundances of O and C in gas and solids, which equal solar abundances. The condensation fronts of different molecular species are shown in the thin vertical lines.

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We perform the calculations for two assumptions of chemistry, one motivated by theoretical calculations of chemistry in H₂-rich environments (Woitke et al. 2009; Madhusudhan & Seager 2011), and another based on observations of ice and gas in protoplanetary environments (Öberg et al. 2011). In Table 1, we express the volume fractions of species in terms of elemental volume fractions for solar composition (Asplund et al. 2009): O/H = 4.9×10^{-4} , C/H = 2.7×10^{-4} , and Si/H = 3.2×10^{-5} . At each time step of the planet’s growth and migration, the mass fractions of the various chemical species in solids and gas accreted by the planet are determined based on the planet’s feeding zone, mid-plane temperature, and net mass accreted in solids and gas.

2.5. Accretion/Migration Scenarios

We now combine the above model components to investigate various formation–migration pathways that can lead to hot

Jupiters. Our goal is to form planets with $M_{\text{pl}} \approx 1 M_{\text{Jup}}$ and $a_{\text{pl}} \approx 0.1$ AU around Sun-like stars with solar abundances. We consider three broad formation–migration scenarios as shown in Figure 1, and explore a wide range of initial conditions in each: (1) planets formed via core accretion with initial separations at ~ 1 –20 AU and migrated to 0.1 AU through the disk, (2) planets formed via core accretion but migrated disk-free, (3) planets formed via gravitational instability in situ but migrated disk-free. We do not model gravitational instability followed by disk migration since this scenario results in planets more massive than the $1 M_{\text{Jup}}$ planets considered here. Other modeling aspects for future considerations are discussed in Section 4.

3. PLANETARY CHEMICAL COMPOSITIONS

For each of the three scenarios discussed in Section 2.5 and illustrated in Figure 1, the resulting elemental abundances in terms of the O/H and C/H ratios are shown in Figure 3.

For Jovian-mass hot Jupiters formed via core accretion and disk migration, the oxygen abundances range from solar to over $10\times$ solar values, whereas the carbon abundances range between solar and $\sim 5\times$ solar values. The solids in this separation range (~ 1 –20 AU) are dominated by O in the form of H₂O-ice between the H₂O and CO₂ snow lines, with additional contribution due to CO₂-ice beyond the CO₂ snow line, while some O is also present in silicates at all separations. The amount of carbon in planetesimals is sensitive to its assumed abundance in grains, as shown in Table 1. Assuming C is present only in volatiles (case 1 in Table 1), C in solids is only due to CO₂-ice and leads to a C/H of ~ 1 – $1.5\times$ solar. On the other hand, following case 2 if C is present as graphite grains (Öberg et al. 2011; Draine 2003), C abundances up to $\sim 5\times$ solar are possible. If carbon-based volatiles, e.g., CH₄ and/or CO, are locked into H₂O-ice forming clathrates (Mousis et al. 2011) the C abundance is further increased. Irrespective of the form of C, the C/O ratio is always sub-solar. Assuming Jupiter’s formation by core accretion and using its observed C/H (Atreya 2010), as shown in Figure 3, we predict its O/H to be ~ 5 – $8\times$ solar which is consistent with previous estimates (Mousis et al. 2012). Thus, hot Jupiters formed via core accretion and disk migration could contain solar or super-solar C/H and O/H, but would have

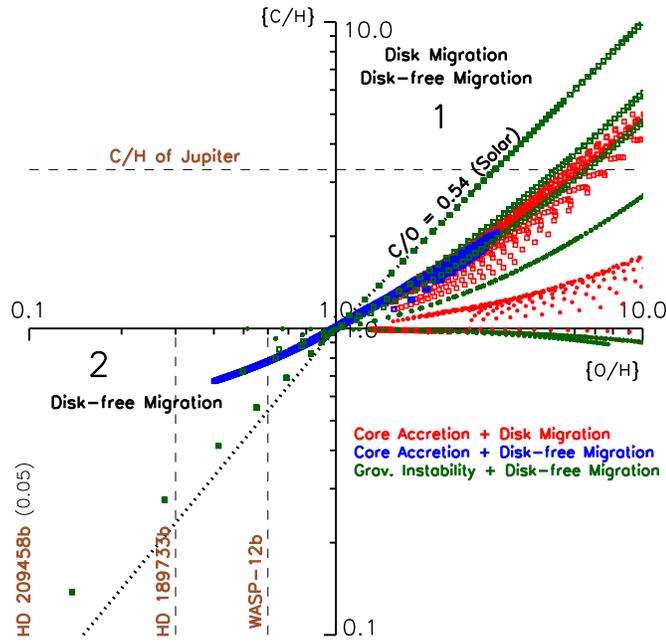


Figure 3. Oxygen and carbon abundances of hot Jupiters formed through different formation–migration pathways. The x - and y -axes denote O/H and C/H volume mixing ratios in the planetary envelope normalized to solar values. The red, blue, and green symbols show hot Jupiters that formed via different combinations of formation and migration mechanisms as shown in the legend. All the resulting planets largely occupy two quadrants in the C – O plane marked as regions 1 and 2. The circles and squares indicate different prescriptions for chemistry corresponding to the first and second cases, respectively, of Table 1. The vertical dotted lines in the lower left quadrant show O/H abundances derived from the sub-solar H_2O abundances reported for three hot Jupiters by Madhusudhan et al. (2014). The highest value within the uncertainties is adopted here; see Section 4.

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sub-solar C/O , and would occupy the lower half of the top-right quadrant (region 1) of the C – O plane in Figure 3.

Hot Jupiters that formed via core accretion but underwent disk-free migration, can have super-solar or sub-solar abundances, as shown in Figure 3. Planets that formed closer-in accrete solids more efficiently, resulting in super-solar abundances, before accretion is halted due to scattering. These planets also occupy region 1 of the C – O plane in Figure 3. Planets forming farther out tend to have sub-solar elemental abundances, due to an enhanced ability to eject rather than accrete at large separations as discussed in Section 2, and super-solar C/O ratios. For planets originating between the H_2O and CO_2 snow lines, the O/H is sub-solar whereas the C/H is nearly solar. Those originating beyond the CO_2 snow line result in sub-solar C/H as well as sub-solar O/H , thereby occupying the bottom-left quadrant of the C – O plane (region 2). The presence of C in graphite can further lower the C/H ratio for such planets, while still retaining a super-solar C/O ratio.

Planets that originated at large orbital separations ($\gtrsim 20$ AU), are likely to have formed in situ via gravitational instability followed by disk-free migration. As shown in Figure 3, such planets can have super-solar as well as sub-solar O and C while their C/O ratios depend on their formation location. For planets forming beyond the CO snow line (~ 80 AU), the C/O ratio is close to solar independent of the overall metallicity as the important volatiles are all in solid form. For planets forming in this region the metallicity and C/O ratio are inversely correlated; for super-solar abundances the C/O ratio is sub-solar whereas for sub-solar abundances the C/O ratio is super-solar, both

governed by the location of the planet with respect to the H_2O - and CO_2 -ice lines.

Overall, our results suggest a preliminary framework for placing chemical constraints on migration mechanisms of hot Jupiters. Super-solar O and C abundances are unlikely to yield conclusive constraints as they can result from a variety of formation–migration pathways. However, sub-solar O and C abundances and super-solar C/O ratios could be indicative of disk-free migration of hot Jupiters irrespective of whether they formed by core accretion or gravitational instability.

4. DISCUSSION

Recent observations suggest sub-solar H_2O abundances in several hot Jupiters, e.g., HD 189733b, HD 209458b, and WASP-12b (Madhusudhan et al. 2014; Stevenson et al. 2014). It is unclear if clouds are responsible for the muted H_2O features (Madhusudhan et al. 2014; McCullough et al. 2014), and the low H_2O may indeed represent the bulk atmospheric composition. A bulk sub-solar H_2O abundance could result either from a sub-solar bulk metallicity and/or a $C/O \geq 1$. If the bulk metallicity is sub-solar, the limits on the O/H in these planets are shown in Figure 3, which would suggest disk-free migration as a potential explanation for their origins. Alternatively, the C/O could be ≥ 1 as has been suggested for WASP-12b (Madhusudhan et al. 2011a; Stevenson et al. 2014), but the C/H ratio is presently unconstrained but observable in the future.

Future studies will need to investigate in detail several aspects of the present population study (also see Benz et al. 2014). In principle, a rigorous simulation of the chemical evolution of a planet while forming and migrating would include hydrodynamic disk evolution along with N -body planetesimal dynamics and self-consistent chemistry. Such next-generation models may predict a wider dispersion in elemental abundances than shown in Figure 3. We have assumed that no accretion happens after the onset of disk-free migration via a scattering event, while in reality the disk may still be present and accretion may continue especially at short orbital separations. In such cases, a higher elemental enhancement is possible, especially in oxygen, and some of the systems from region 2 of Figure 3 may move into region 1 analogous to our models with Type II migration followed by scattering. Conversely, the influence of “planetesimal shepherding” by the inward migrating hot Jupiter (Fogg & Nelson 2007a, 2007b) may result in lower solid accretion than we have assumed. Overall, however, hot Jupiters with sub-solar C/H and O/H will be hard to explain via disk migration as they would need to (1) form at large orbital separations beyond the CO_2 snow line ($\gtrsim 5$ AU), and (2) migrate through the disk all the way to close-in orbits without accreting any significant mass in solid planetesimals.

We have assumed that the bulk elemental abundances in the protoplanetary disk mimic those of the host star, in this case solar. However, future observations of protoplanetary disks could help provide a range of plausible chemical abundances and disk properties that could be used as inputs in modeling studies. New studies would also need to investigate the influence of the accreted solids on the atmospheric compositions of hot Jupiters. For hot Jupiters, the temperatures in the deep atmosphere, at ~ 100 – 1000 bar, can be $\gtrsim 2000$ K (Burrows et al. 2008) which is hotter than the sublimation temperatures of all ices and silicates. The interiors are even hotter and convective, because of which we have assumed the elements in solids accreted are well mixed in the planetary envelope.

Overall, our study presents a first attempt at investigating chemical constraints on the migration mechanisms of hot Jupiters. Future measurements of precise elemental abundances in hot Jupiter atmospheres and concomitant advances in theoretical work extending the ideas presented here might lead to new insights on the migration of hot Jupiters, which have thus far remained enigmatic based on dynamical constraints alone.

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