Charge exchange in the colliding winds of Hot Jupiters and their host stars

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September 2, 2011

Abstract

This project investigates the charge exchange process between the atmospheric escape of a hot jupiter and the wind of its host star as a possible explanation for the Lyman α high-velocity absorption of the stellar spectrum observed during transits. We use 2D hydrodynamical simulation to follow the dynamic of the two fluids (shocks, compression layers...) and we implement a chemistry module to compute the quantity of neutral hydrogen produced by charge exchange. The simulations show that Kelvin Helmholtz instabilities develop at the interface between the two flows leading to a mixing that gives enough energetic neutral hydrogen to explain the observed absorption. However works still need to be done, especially the implementation of coriolis force due to the orbital motion of the planet, to achieve a steady state and get the correct geometry for the interface.

1 Introduction

Observations in the hydrogen Lyman-alpha transition of the extrasolar planet HD209458b with the Hubble Space Telescope (HST) have revealed that the planet is losing atomic hydrogen (Vidal-Madjar et al. 2003; Ben-Jaffel 2007). This mass loss is driven by photoionization heating of the planet's upper atmosphere by the host star (Garcia Munoz 2007; Murray-Clay et al. 2009). According to the HST observations, the hydrogen is Doppler shifted at surprisingly large velocities, A+/- 100 km/s, about an order of magnitude faster than the thermal wind velocities predicted by photoionization models. Holmström et al. (2008) Proposed that charge exchange between fast-moving ionized hydrogen in the host stellar wind and slow-moving neutral hydrogen in the planetary wind might explain the large Doppler shifts. This is a promising idea, but Holmström et al. (2008) did not include any hydrodynamics. This paper aims to model charge exchange in the shock interface between the stellar and planetary winds and attempt to reproduce the large Doppler velocities observed.

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2 Numerical methods

Our model includes three steps which we will describe in the following subsections: the hydrodynamic to follow the winds, the shocks and the compression zones; the chemistry to compute the charge exchange processes; the post-treated radiative transfer to compute the Lyman α absorption spectra.

2.1 Hydrodynamic

Our simulations are performed with the HERACLES code[1]. It is a grid-based code using a second order Godunov scheme to solve Euler equations (González et al. 2007). These equations are given in Eq. 1 with the advection equation for the abundances of the different species we are going to follow to compute the charge exchange reactions.

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) &= 0 \quad , \\ \frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot [\rho \mathbf{V} \otimes \mathbf{V} + pI] &= 0 \quad , \\ \frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\mathbf{V}] &= 0 \quad , \\ \frac{\partial \rho x_i}{\partial t} + \nabla \cdot (\rho x_i \mathbf{V}) &= 0 \quad . \end{aligned} \tag{1}$$

All the simulations presented are 2D cartesian. Murray-Clay et al. (2009) proposed a model for the atmospheric escape of a planet exposed to the UV radiation of its host star. This model is valid if the solar wind does not penetrate inside the sonic sphere which is at four planetary radii. Therefore we will inject the atmospheric escape of the planet through a disk of four planetary radii at the centre of the box with the parameters taken from Murray-Clay et al. (2009). The solar wind is assumed to be plane-parallel and is injected through a side of the box along the z direction. The speed and temperature are taken from LASCO and SOHO data (see Sheeley et al. 1997) and the density is computed from a typical solar mass loss of $2{\times}10^{-14}$ solar mass per year. Note that the atmospheric escape of the planet is almost fully ionized: only 20 % of neutral hydrogen remains unionized and can be used for the charge exchange processes. All these parameters are resumed in Table 1 as well as the three box size and resolution we will use in our study.

2.2 Charge exchange Process

The charge exchange process was first proposed by Holmström et al. (2008) to explain the absorption of the Lyman α spectrum of the star. It consists in the reaction given by equation 2: a ionized energetic hydrogem from the stellar wind gets a charge from a neutral cold hydrogen from the atmospheric escape of the planet.

$$H_h^+ + H_c^0 \rightarrow H_h^0 + H_c^+ \tag{2}$$

The cross section σ_{ce} of this reaction was studied in details by Lindsay & Stebbings (2005). They give a fit of the cross section in function of the energy of the incident particles E in (keV):

[1] http://irfu.cea.fr/Projets/Site_heracles/index.hmtl

Table 1: Parameters of the winds and the box used for the simulations

Solar wind	Atmospheric escape
$n_* = 6E3/cm^3$	$n_p = 2E6/cm^3$
$T_* = 1E6$ K	$T_p = 7000$ K
$v_* = 200$ km/s	$v_p = 12$ km/s
$f_*^+ = 1$	$f_p^+ = 0.8$
$c_* = 130$ km/s	$c_p = 10$ km/s
$M_* = 1.6$	$M_p = 1.2$
r direction	**z direction**
$L_x/R_p = 120, 120, 120$	$L_y/R_p = 120, 120, 240$
$n_x = 100, 1000, 1000$	$n_y = 100, 1000, 2000$

$$\sigma_{ce} = (4.15 - 0.531 \times ln(E))^2 (1 - e^{-67.3/E})^{4.5} \tag{3}$$

The chemistry step in the hydrodynamic simulation is computed using this cross section and assuming that the relative velocity between the two species can be approximated by $V_r = c_* - c_p$. The equations for the different abundances given in equation 4 are solved implicitely.

$$\begin{aligned} \frac{dx_h^+ n_H}{dt} &= -\sigma_{ce} x_h^+ x_c^0 n_H^2 V_r \quad , \\ \frac{dx_c^0 n_H}{dt} &= -\sigma_{ce} x_h^+ x_c^0 n_H^2 V_r \quad , \\ \frac{dx_h^0 n_H}{dt} &= +\sigma_{ce} x_h^+ x_c^0 n_H^2 V_r \quad , \\ x_c^+ &= 1 - x_h^+ - x_c^0 - x_h^0 \quad . \end{aligned} \tag{4}$$

2.3 Lyman α spectrum

The Lyman α spectrum corresponds to a transition between n=2 and n=1 levles of a hydrogen atom with a dumping constant $\Gamma = 6.365 \times 10^8/s$ which corresponds to the natural line width. The line centre frequency at rest is $\nu_{0r} = 2.466 \times 10^{15} Hz$ and the Doppler shifted frequency of an absorbing atom with a velocity v is given by $\nu_0 = \nu_{0r}(1 + v/c)$. The Doppler frequency width resulting from the thermal motion of the hydrogen atom corresponds to $\Delta\nu_D = (V_{th}/c)\nu_0$.

The Lyman α spectrum is computed using a voigt profile (Verhamme et al. 2006), the column density of neutral hydrogen N_H and the temperature of the hydrogen T_4 (in units of 1E4 K):

$$\tau_\nu = 1.041 \times 10^{-13} T_4^{-1/2} N_H \frac{H(\nu, a)}{\sqrt{\pi}} \tag{5}$$

in which $H(\nu, a)$ is given by:

$$H(\nu, a) = \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y^2} dy}{(y - x)^2 + a^2}$$

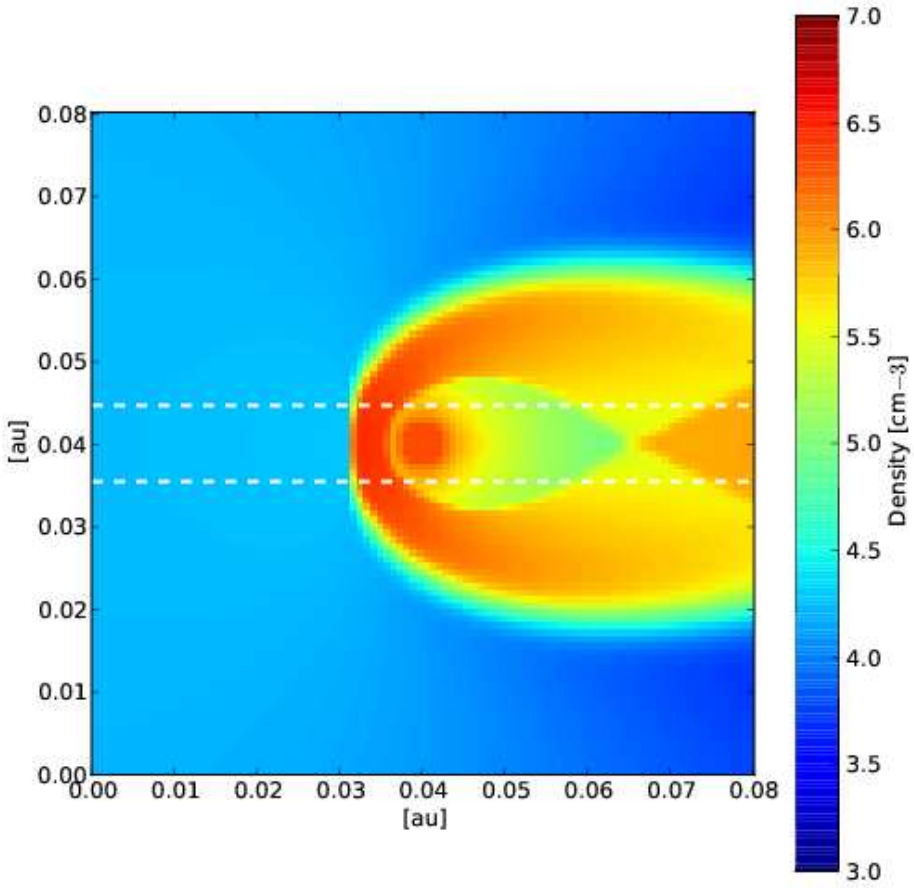

Figure 1: Density plot of the 100x100 simulation with the parameters of Table 1. The two dashed white line represents the line of sight of the stellar surface, the zone in which the presence of neutral hydrogen will absorb the Lyman α spectrum of the star.

$$\begin{aligned} x &= \frac{\nu - \nu_0}{\Delta\nu_D} \\ a &= \frac{\Gamma/4\pi}{\Delta\nu_D} \end{aligned} \tag{6}$$

The resulting profile highly depends on the thermal velocity of the neutral hydrogen, therefore it is sensitive to the temperature in the mixing layer.

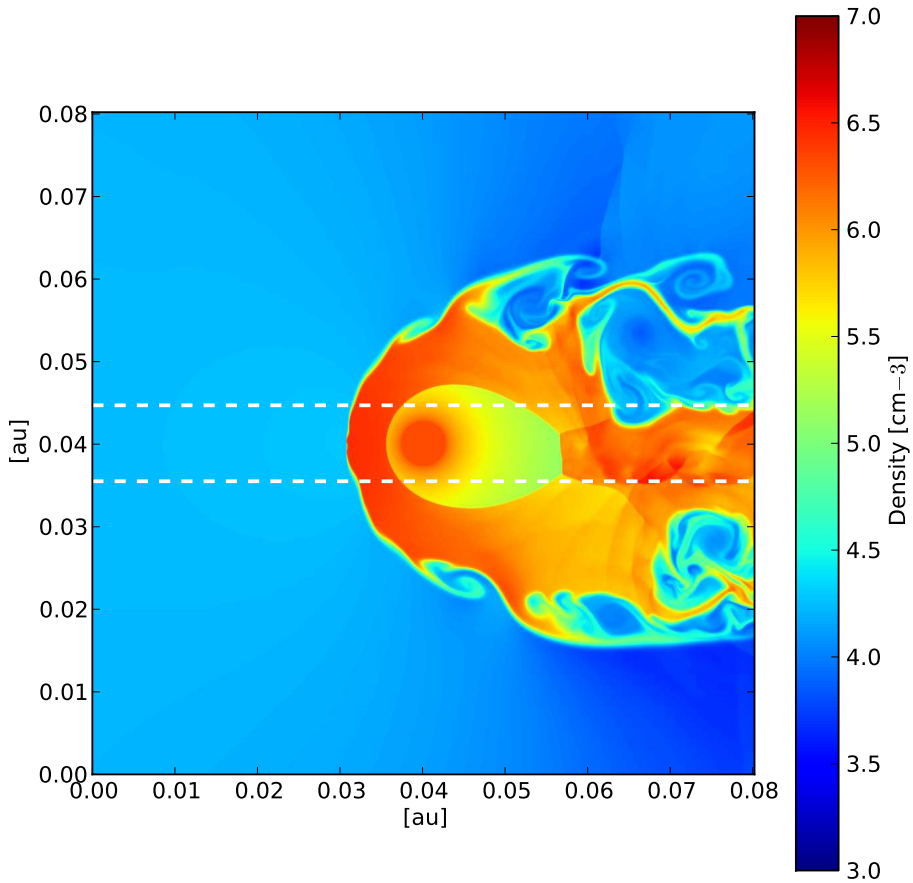

Figure 2: Same as figure 1 for the 1000x1000 simulation. Kelvin Helmholtz develops on the contact discontinuity between the two shock layers.

3 Results

In figure 1, we show a plot of the density in a low resolution simulation (100x100). The inner shock around the atmospheric escape is closing behind the planet, forming an X point. the contact discontinuity extend from a vertical front between the two shocked media to a horizontal spread interface at the back of the simuation. The outer shock is formed earlier in the simulation but escaped from the box at the front. This simulations was runned during 4E7 seconds (40 crossing time for the atmo-

spheric escape) achieving steady state. Most of the contact discontinuity lies out of the line of sight of the stellar surface, therefore no mixing in this zone will affect the absorption spectra.

However Kelvin Helmholtz instabilities are generated by increasing the resolution at 1000x1000, preventing the simulation to reach steady state. The same structure is present, the inner shock closes behind the planet, but the contact discontinuity is highly perturbed by the Kelvin Helmotz rolls. It can even get into the line of sight of the stellar surface, as shown in figure 2.

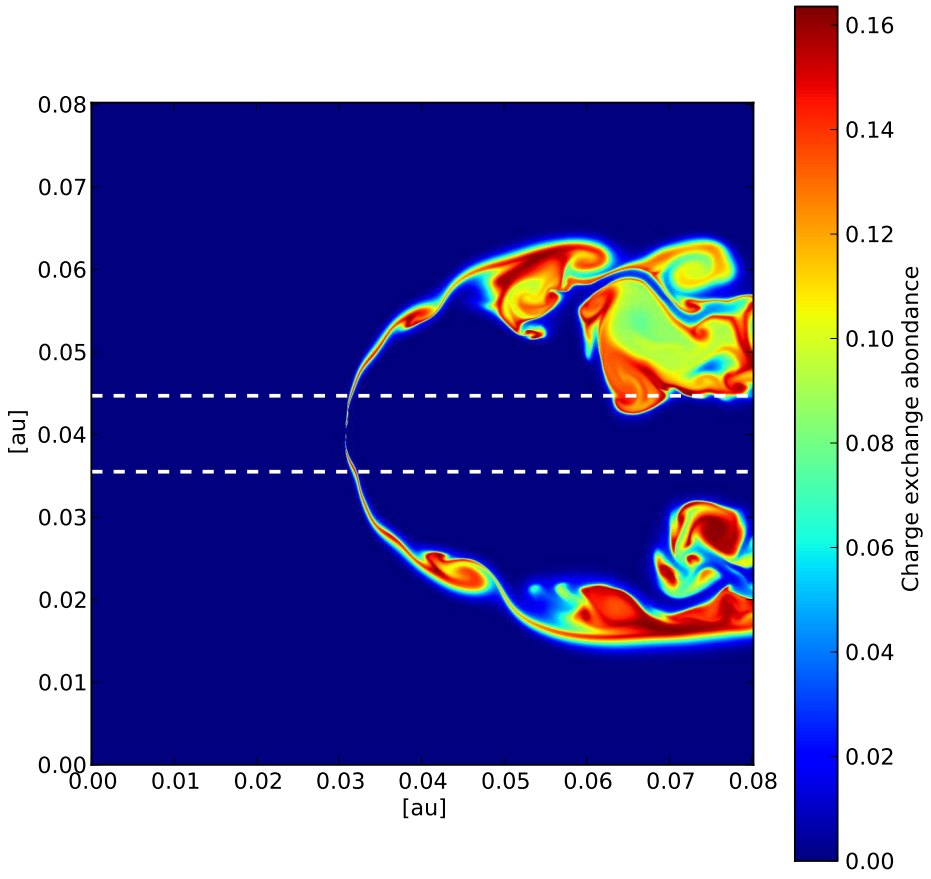

Figure 3: Abundance fraction of the charge exchanged neutral hydrogen produced in the 1000x1000 simulation.

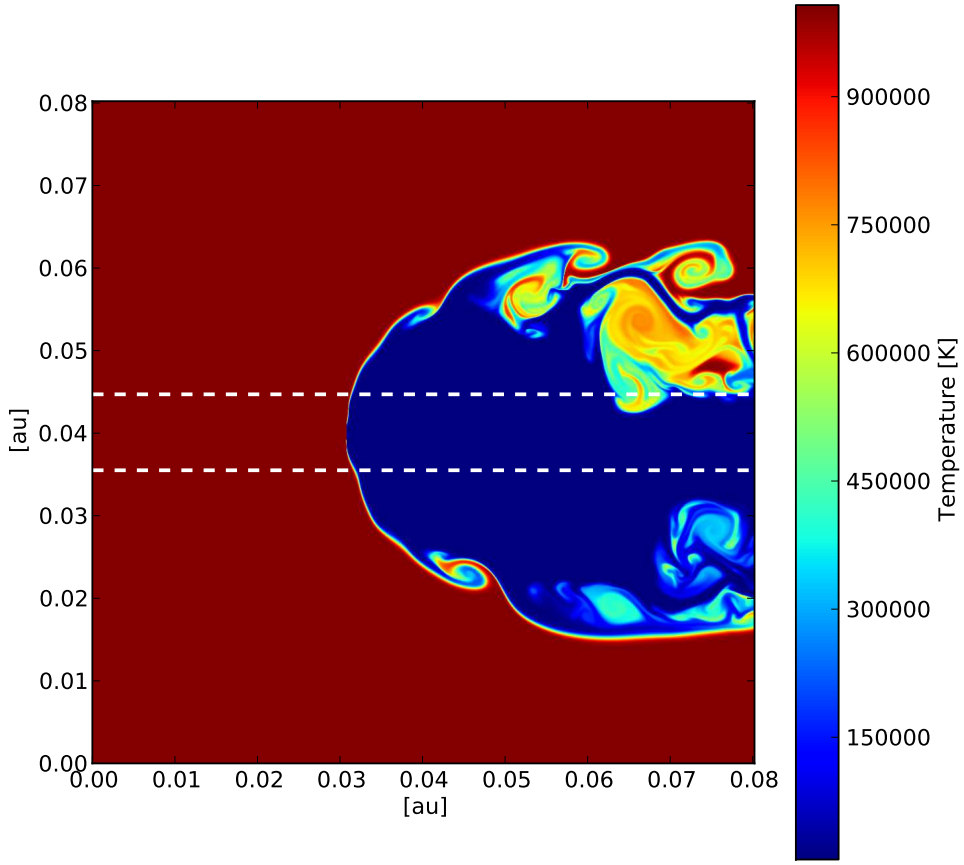

Figure 4: Temperature in the 1000x1000 simulation.

The abundance of neutral hydrogen produced by charge exchange is shown in figure 3 for the 1000x1000 simulation as well as the temperature in the mixing layer (Figure 4). As mentioned in section 2.3, the spectrum is highly dependant on the temperature of the neutral hydrogen produced by charge exchange. In these plots, the temperature is set to the temperature calculated in the simulation, however since we have a two temperature isothermal problem, this is not well defined and a better treatment of the temperature at the interface is needed.

The Lyman α spectra for the 100x100 and the 1000x1000 simulations are shown in figure 5. The effect of the Kelvin Helmholtz instability is clearly visible as it widden the absorption profile. Note

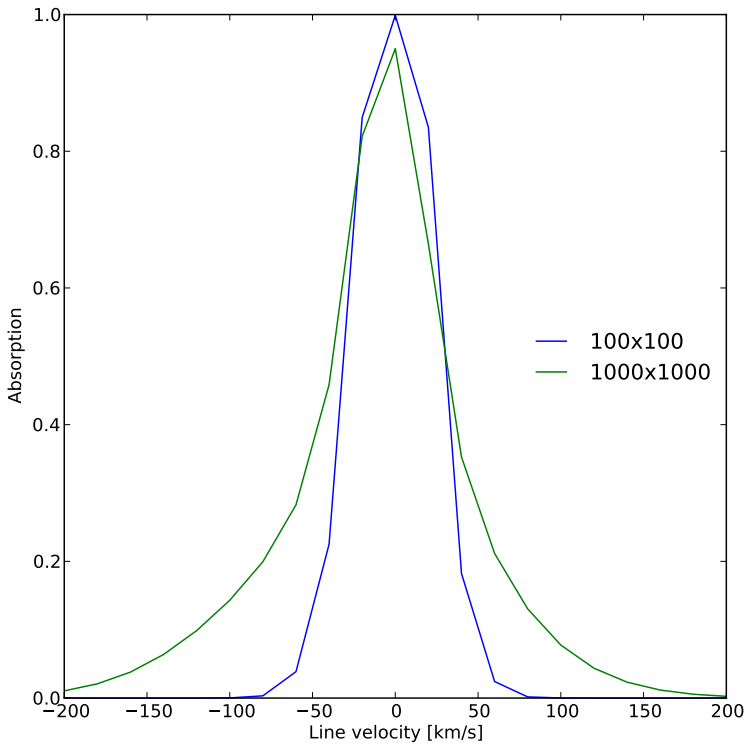

Figure 5: Absorption of the Lyman α spectra of the star by neutral hydrogen produced by charge exchange, in the 100x100 and 1000x1000 simulation.

that the absorption spectrum in the 100x100 simulation from the stagnation point is discutable since there should be no mixing in that zone. The resulting absorption at +/- 100 km/s is of order 10 % which is what we need to explain the observations. However this absorption is not a steady state since the Kelvin Helmholtz rolls can go away from the line of sight. Figure 6 shows that at large distance of the planet there will be a large fraction of mixing and thus of charge exchange behind the planet if we do not consider coriolis force dut to the orbital motion of the planet. Therefore it is important to implement it to have a stable tail going perpendicular to the line of sight (in the direction of the motion of the planet). If there is Kelvin Helmholtz rolls in such a tail, we could achieve a steady state for the absorption spectrum.

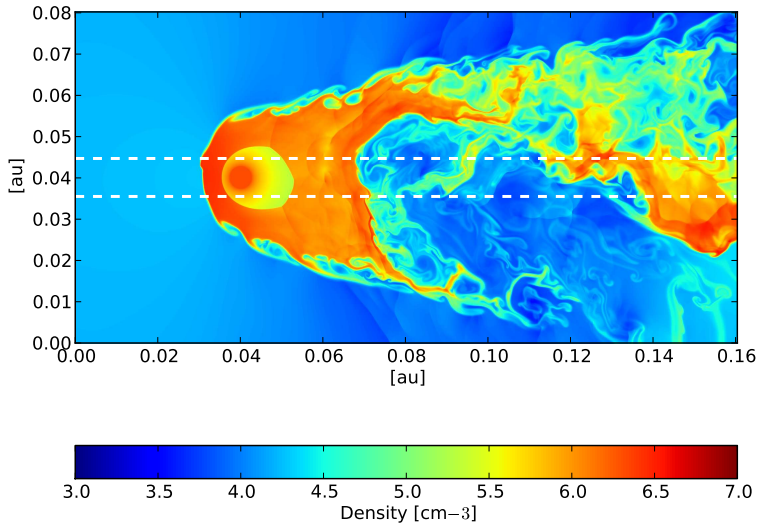

Figure 6: Same as figure 2 but the box is doubled at the back of the simulation. The Kelvin Helmholtz produced a lot of mixing behind the planet. An implementation of the Coriolis force is needed to know where the tail is going to turn and get out of the line of sight of the stellar surface.

4 Conlusion and Future Developments

We have shown that Kelvin Helmholtz instabilities occur at the contact discontinuity between the atmospheric escape of a hot jupiter and the stellar wind of its host star. These instabilities develop behind the planet and may explain with the charge exchange process, the observed absorption at high velocities of the Lyman α spectrum of the star.

In order to have robust results on the abundances of neutral hydrogen produced by charge exchange, we need to develop a better treatment of the temperature at the interface between the two flows. Besides we need also to implement the coriolis force in order to obtain a realistic shape for the contact discontinuityxs and get a steady state for the absorption spectrum.

We greatly thank the ISIMA 2011 summer program during which this project was initiated. ISIMA is funded by the American and Chinese National Science Foundation, the Center for the

Origin, Dynamics and Evolution of Planets, the center for Theoretical Astrophysics at Santa Cruz, the Silk Road Project and the Excellence Cluster Universe at TU Munich.

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