Geophysical Research Abstracts
Vol. 16, EGU2014-9370, 2014
EGU General Assembly 2014

An Inversion Technique for Constraining the Interior Structure of Small Exoplanets

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Characterizing the interior structure of exoplanets is key to understand planet formation and to evaluate the probability of the existence of habitable planets outside our solar system. Several studies have been dedicated to examine effects of composition and temperature on exoplanet mass and radius, while few have tried to solve this as an inverse problem. Here we proceed along these lines and adopt an inverse approach based on a stochastic sampling algorithm to invert for physico-chemical structure of the interior of the planets given observations of mass, radius, and stellar photospheric Fe/Si abundances. With the inversion method employed here we are able to determine model parameter uncertainties, i.e., ranges in composition and core radius that are compatible with the observations.

For the inversions we make the following assumptions: (1) only rocky silicate exoplanets are considered, i.e., no oceans nor atmospheres; (2) bulk exoplanet composition is dictated by stellar photospheric abundance measurements (=CI-chondrites in the case of the Sun); (3) exoplanet cores are assumed to be made of pure iron.

We apply a Markov chain Monte Carlo (McMC) algorithm to constrain model parameters: core radius, mantle Mg/Si, Fe/Si ratios and Si-content. In order to predict data, or equivalently, solve for planetary mass and bulk composition, we use thermodynamic modeling methods to compute stable mantle mineralogy and density as a function of the considered composition, temperature, and pressure profile. For the core we employ an equation-of-state approach for pure iron to compute the density profile. We applied our method to a series of planetary bodies of masses between 0.1 and 10 M_E and radii between 0.4 and 2 R_E, assuming both specific stellar and unconstrained bulk compositions.

Overall, we find that core radius and mantle composition of rocky exoplanets can be constrained, although core radius appears to be better resolved because of increased sensitivity of data to the latter. However, the degree to which model parameters can be constrained depends critically on the observed mass and radius as well as their uncertainties. As an example, core radius is best constrained in the case of small massive bodies. Where no assumptions about bulk planetary composition are made, planetary mantle compositions generally appear to be unconstrained and only weakly so for large low-density bodies.

We have tested our integrated methodology on the terrestrial planets (Mercury, Earth, and Mars) and are able to reproduce their internal physico-chemical structure as inferred from independent data. We conclude that for exoplanets made of purely silicate mantle compositions and Fe-rich cores, we are indeed able to determine core radius, mantle composition and their uncertainties from observations of exoplanet masses, radii, and stellar Fe/Si abundance ratios. In the future we will extend the methodology to include hydrogen- and water-rich exoplanets, i.e., containing oceans and atmospheres. This study is a key step towards the analysis of low-density bodies, because the proposed scheme is formulated in a general manner and may be extended and/or adapted to other more general cases.