KEPLER-277 b : A SUPERMASSIVE TERRESTRIAL EXOPLANET IN THE KEPLER-277 PLANETARY SYSTEM.

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Introduction: Kepler-277 b is a sub-Neptune-sized exoplanet, which was discovered in 2013 by Kepler Space Telescope. The host star is a 4-Gyr-old main-sequence yellow dwarf star, having a mass of 1.12 M_{SUN} and a radius of 1.69 R_{SUN} [1], orbited by two known planets. Kepler-277 is 3276 light-years from the Sun and it can be observed in the constellation Lyra. The innermost known planet in the system is Kepler-277b orbiting the host stars with a period of 17.3 days. Based on the measured radius of 2.92 $R_\oplus$ and mass of 87.395 $M_\oplus$ [1], the main density of K-277 b is consistent with a terrestrial composition. Accordinghly, this planet can be belonged to the category of mega-Earths. Interestingly, the mass of the planet is 91.8 percent of the mass of Saturn, thus it is the one of the largest known rocky planet in the Galaxy.

The outermost known planet Kepler-277 c orbits the central star with a period of 33 days. The 0.67 Saturn-mass planet, having a radius of 3.36 $R_\oplus$ and a mass of 64.2 $M_\oplus$ [1], is mostly likely made of rock and metals, and it may have an atmosphere with a radius of ~ 5-10 percent of the total planetary radius. Thus, Kepler-277 is a so-called mega-Earth-system because it contains more terrestrial-like planetary bodies, which are more massive than super-Earths.

The one of the possible scenarios for the formation of K-277 b is that it could form as massive rocky planet with no significant gaseous envelope. According to an other scenario, the planet have originally formed as gas giants with substantial gaseous envelope, which had been eroded by photo-evaporation of its host star during the first ~ 1-2 billion years of the planetary system's lifetime. If K-277 b was a giant planet core then it was being compressed to a radius about 2.92 $R_\oplus$ inside a super-Jupiter with a mass of ~ 5-6 $M_{Jupiter}$.

This study focuses on a plausible planet model, which is based on that K-277 b have originally been formed as massive terrestrial planet with no substantial gaseous envelope.

Modeling the internal structure of Kepler-277 b: In the model the 1.22 Mg/Si ratio in bulk silicate mineral composition has been assumed. The upper mantle build up from olivine (ol), wadsleyite/ringwoodite (wdl/rwd), while the uppermost zone of lower mantle composed of silicate-perovskite (pv) and post-perovskite (ppv). In terms of the predictions of Umemoto et al. 2017 [2] and Wu et al. 2014 [3], three-stage dissociation of $MgSiO_3$ ppv occurs in the pressure range between 0.75-3.09 Tpa. At the pressure of 750 GPa, post-pv dissociates into I¯42d-type Mg_2SiO_4 + P21/c-type $MgSi_2O_5$ (UHP1). It transforms into Mg_2SiO_4 + Fe_2P-type SiO_2 (UHP2) by the second mineral phase transformation, which occurs at 1.31 TPa (UHP2). The UHP2 phase dissociated into CsCl-type MgO + Fe_2 P-type SiO_2 at 3.09 TPa (UHP3), which is the final-stage of the dissociation of $MgSiO_3$ ppv as expected.

For simplicity, the metallic core modeled by a bulk Fe composition, even though Fe, in general, alloyed with Ni or other metals and lighter elements, respectively.

Equations of state has been used to constrain a possible interior structure model for Kepler-277 b. Vinet EOS [4, 5] has been suited for computing the properties of materials in the upper mantle and in the pv belt in the lower mantle. Murnaghan equation of state [6] is being used for calculating the material properties in the ppv, in the UHP silicate mineral phases and for the case of the core. The utilized zero-pressure densities of fcc-Fe ^{1}, UHP silicate phases [7] ^{2} [8] ^{3},[9] ^{4}, MgO ^{5}, ppv^{6}, pv^{7}, wdl/rwd^{8} and olivine^{9} are 8.06^{1} [10], 3.67727^{5} (calculated for MgO by the data of Strachan et al. 1999)[11], 4.27^{6} [12], 4.152^{7}[13] , 3.644^{8}[13] and 3.347^{9} [13] g cm^3.

In terms of the predictions of Pickard and Needs (2009) fcc-structured iron transformed into body-centred-tetragonal (bct) phase at 34 TPa. The body-centered-cubic (bcc) structure also becomes stable than the hcp above 35 TPa [14]. The effect of ultrahigh-pressure on iron has been considered to constitute the structure model utilizing the relevant parameters of iron phases [14,15]. The present calculations shows that the innermost region of the core may be made of bct- and bcc-phase of iron due to the ultra-high central pressure of Kepler-277 b.

A plausible composition for Kepler-277b: The globally averaged surface gravity is more than ten times larger than on Earth, it is calculated to be 100.0797 m s -2. (10.2 g_{Earth}). The central pressure is being computed to be 37.52 TPa.

In terms of the modeling, Kepler-277 b has a relatively large core mass fraction (CMF) with a radius of 2.435 $R_\oplus$. A significant fraction of the metallic core has been found to be composed of fcc-iron owing to that it is being the stable iron phase over ~ 7 TPa. Above 34 TPa (~ 0.36 $R_\oplus$), bct-iron phase constitutes mostly the innermost region of the core. At 35 TPa (~ 0.26 $R_\oplus$), the bcc-structured Fe may also become stable than fcc-iron.

The relatively thin silicate mantle composed mainly of the ultrahigh-pressure phases of $MgSiO_3$. Above 750 GPa, ppv dissociates into $I\bar{4}2d$-type Mg_2SiO_4 + P21/c-type $MgSi_2O_5$ (UHP1). $I\bar{4}2d$-type Mg_2SiO_4 + Fe_2P-type SiO_2 (UHP2) constitutes the middle zone of the mantle by the further transition of $MgSiO_3$ ppv at the dissociation pressure of 1.31 TPa. CsCl-type MgO + Fe_2P-type SiO_2 (UHP3) consists of the lowermost mantle region at a depth range of 0 to ~ 2400 km above the core mantle boundary (CMB). If K-277 b had an Earth-like structure its total radius would be ~ 3.3-3.4 $R_\oplus$ depending mostly on the mineralogical composition of the mantle.

Revisiting the possible conditions of mantle convection in very massive rocky planets, it is likely that convection cannot occur in terrestrial planetary mantles above 5-6 $M_\oplus$ owing to the high viscosity contrast across the mantle. In contrast to previous suppositions [16,17], it is thought that a significant fraction of the mantle of mega-Earths may be a non-convective belt due to the strong adiabatic compression. The viscosity contrast is likely to be larger than 10^6 between the top and the bottom layer of their mantles. Moreover, they may have a thick lithosphere.

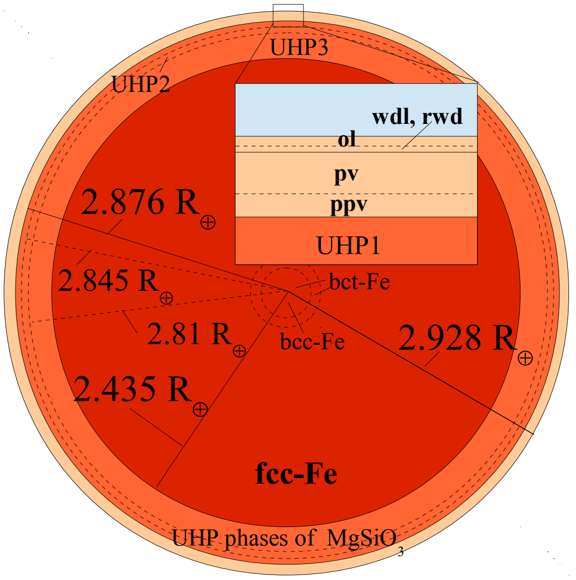

Figure 1. A plausible interior structure model for Kepler-277 b. The terrestrial-like mineral composition in the upper mantle and in the uppermost zone of the lower mantle have been assumed, while theoretically calculated ultrahigh-pressure (UHP) phases of $MgSiO_3$ constitute the largest volume fraction of the mantle. The bulk composition of the core consisted of different UHP iron phases.

Summary: K-277 b is an extremely massive rocky planet, which can be the one of the characteristic instance of terrestrial planets with a large CMF overlaid by a relatively thin and highly compressed mantle.

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