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The composition and mineralogy of rocky exoplanets: A survey of >4000 stars from the Hypatia Catalog

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Abstract

Combining occurrence rates of rocky exoplanets about sun-like stars, with the number of such stars that occupy possibly hospitable regions of the Milky Way, we estimate that at least 1.4×10^8 near-Earth-sized planets occupy habitable orbits about habitable stars. This number is highly imprecise to be sure, and it is likely much higher, but it illustrates that such planets are common, not rare. To test whether such rocky exoplanets might be geologically similar to Earth, we survey >4000 star compositions from the Hypatia Catalog—the most compositionally broad of such collections. We find that rocky exoplanets will have silicate mantles dominated by olivine and/or orthopyroxene, depending upon Fe partitioning during core formation. Some exoplanets may be magnesiowüstite- or quartz-saturated, and we present a new classification scheme based on the weight percent ratio (FeO+MgO)/SiO_2, to differentiate rock types. But wholly exotic mantle mineralogies should be rare to absent; many exoplanets will have a peridotite mantle like Earth, but pyroxenite planets should also be quite common. In addition, we find that half or more of the range of exoplanet mantle mineralogy is possibly controlled by core formation, which we model using $\alpha_{Fe} = Fe^{BSP}/Fe^{BP}$, where Fe^{BSP} is Fe in a Bulk Silicate Planet (bulk planet, minus core), on a cation weight percent basis (elemental weight proportions, absent anions) and Fe^{BP} is the cation weight percent of Fe for a Bulk Planet. This ratio expresses, in this case for Fe, the fraction of an element that is partitioned into the silicate mantle relative to the total amount available upon accretion. In our solar system, α_{Fe} varies from close to 0 (Mercury) to about 0.54 (Mars). Remaining variations in theoretical exoplanet mantle mineralogy result from non-trivial variations in star compositions. But we also find that Earth is decidedly non-solar (non-chondritic); this is not a new result, but appears worth re-emphasizing, given that current discussions often still use carbonaceous or enstatite chondrites as models of Bulk Earth. While some studies emphasize the close overlap of some isotope ratios between certain meteoritic and terrestrial (Earth-derived) samples, we find that major oxides of chondritic meteorites do not precisely explain bulk Earth. To allow Earth to be chondritic (or solar), there is the possibility that Earth contains a hidden component that, added to known reservoirs, would yield a solar/chondritic bulk Earth. We test that idea using a mass balance of major oxides using known reservoirs, so that the sum of upper mantle, metallic core, and crust, plus a hidden component, yields a solar bulk composition. In this approach, the fractions of crust and core are fixed and the hidden mantle component, F_h, is some unknown fraction of the entire mantle (so if F_{DM} is the fraction of depleted mantle, then $F_h + F_{DM} = 1$). Such mass balance shows that if a hidden mantle component were to exist, it must comprise >28% of Earth's mantle, otherwise it would have negative abundances of TiO_2 and Al_2O_3. There is no clear upper limit for such a component, so it could comprise the entire mantle. But all estimates from $F_h = 0.28$ to $F_h = 1.0$ yield a hidden fraction that does not match the inferred sources of ocean island or mid-ocean ridge basalts, and would be geologically unusual, having higher Na_2O, Cr_2O_3, and FeO and lower CaO, MgO, and Al_2O_3 compared to familiar mantle components. We conclude that such a hidden component does not exist.

Keywords: Exoplanets, Hypatia catalog, mineralogy, hidden mantle component, chondrite, bulk earth, meteorites