OXYGEN FUGACITIES OF ROCKY EXOPLANETS FROM POLLUTED WHITE DWARF STARS. A. E. Doyle[1], E. D. Young[1], B. Zuckerman[2], B. Klein[2], and H. E. Schlichting[1], [1]Department of Earth, Planetary, and Space Sciences, UCLA (a.doyle@ucla.edu, eyoung@epss.ucla.edu), [2]Department of Astronomy and Physics, UCLA.

Introduction: White Dwarf (WD) stars are the last stages of stellar evolution for stars where $M_{star} < 8$ M_{solar}. Because of the extraordinary gravity associated with these electron degenerate stars, elements heavier than He sink rapidly below their surfaces. Spectroscopic studies show that ¼ to ½ of cool WDs (<25,000 K) exhibit elements heavier than He and are deemed "polluted" [1, 2, 3]. The source of these heavy elements in WDs is accretion of exogenous rocky debris from parent bodies that previously orbited the WDs [4, 5, 6, 7, 8, 9]. Consequently, we now possess a unique and powerful method for measuring the elemental constituents of extrasolar rocky bodies with a level of detail and precision unattainable by any other exoplanet observation technique. Generally speaking, the compositions of the bodies polluting WDs resemble those of rocky bodies in our own solar system (Figure 1).

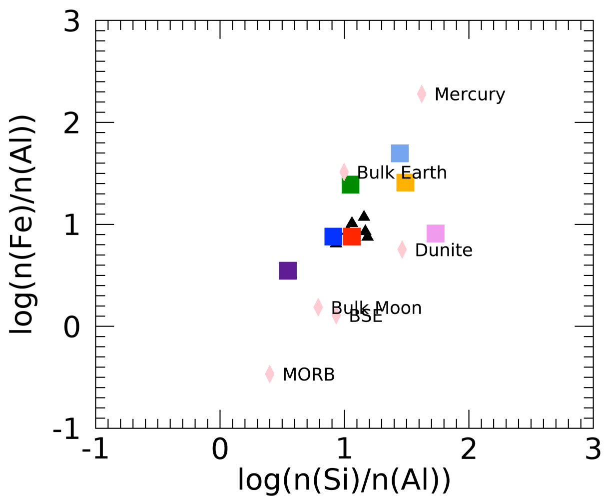

Figure 1. n(Fe)/n(Al) vs. n(Si)/n(Al) (by number) for the seven white dwarfs in this study (colored squares). For comparison, we also display abundance ratios for solar-system chondrites as black triangles and other solar system igneous materials as pink diamonds.

The non-ideal partial pressure of oxygen, oxygen fugacity (fO_2), provides a thermodynamic measure of the degree of oxidation. Oxidation states for planetary systems are often expressed relative to the Iron-Wüstite (IW) equilibrium Fe + ½ O_2 = FeO (Wüstite) such that ΔIW = log(fO_2) – log(fO_2)IW (~ independent of temperature). The bulk oxidation state of a rocky body with a metal core is therefore recorded by the concentration (or more accurately, activity) of oxidized iron ("FeO") in the rock and the concentration (activity) of Fe in metal:

$$\Delta IW = 2\log\left(\frac{x_{FeO}^{silicate}}{x_{Fe}^{metal}}\right) + 2\log\left(\frac{\gamma_{FeO}^{silicate}}{\gamma_{Fe}^{metal}}\right) , \quad (1)$$

where x_i^k are mole fractions of the species i in phase k and γ are activity coefficients for the species. Equation (1) refers to the fO_2 defined by silicate and metal at the time the planet or planetesimal formed. Subsequent processing (e.g., partial melting) will lead to local variations in fO_2 (e.g., terrestrial basalts vs. mantle) but will not generally alter the oxygen fugacity recorded by application of Equation (1).

The oxidation state of a planet determines its geophysics. For example, the relative size of the metallic core of a body or even the existence of a core is determined by oxygen fugacity (e.g. [10]). The intrinsic oxygen fugacity of the Earth is constrained by the 8 weight percent FeO in its mantle and its Fe-rich core to a ΔIW value of about −1 to −2 (depending upon activity coefficients used). Studies of meteorites reveal that, like the Earth, most rocky bodies in the solar system formed with oxygen fugacities approximately five orders of magnitude higher than that defined by a hydrogen-rich gas of solar composition (Figure 2; e.g. [11]). The enhancement in oxygen fugacity during rocky body formation may be attributable to the sublimation of water-rich and/or rock-rich dust at high dust/gas ratios. We wish to understand whether the processes that led to oxidation of rocks in the solar system are typical of other planetary systems.

Method: The ability to measure all four major rock-forming elements in a polluted WD affords the opportunity to use the abundance of "FeO" as a measure of the oxidation state of exoplanetary materials [12]. Polluted WDs with quantifiable concentrations of at least O and Fe, and all or a subset of Si, Mg, Al, and Ca, can be used to calculate oxygen fugacities from Equation (1) assuming that there was some metal during the formation of the body.

The basic methodology is as follows: the oxide components SiO_2, MgO, FeO, CaO and Al_2O_3 describe the compositions of the major minerals comprising the impacting rocks. Oxygen in excess of that needed to balance Si, Mg, Ca and Al is assigned to FeO. Oxygen in excess of that needed to balance all of the major rock-forming elements very likely came in the form of water (e.g., water ice on the parent body asteroid or planetary fragment; [13, 14]).

We propagate measurement uncertainties in the polluted WDs using a Monte Carlo approach. We repeat the calculation of FeO concentration ~10,000 times using random draws from the probability distributions for the abundances of each element. We tested this method on solar system bodies by converting the chemistry of these bodies into fictive polluted white dwarfs, as if the bodies (e.g., Earth, Mercury) had accreted onto a WD. We used typical WD measurement uncertainties for these calculations.

Having successfully recovered the oxygen fugacities for Earth, Mercury, and various modifications of chondritic bodies with prescribed fO_2 values, we then calculate the oxygen fugacities for the seven polluted WDs. The WDs used in this study include: SDSSJ1043+0855 [15], WD1226+110 [7], WD1929+012 [7, 16], WD1536+520 [17], GD40 [12, 18], SDSSJ0738+1835 [19], and WD1145+017 [20]. These WDs were chosen because they have detections of six major rock-forming elements.

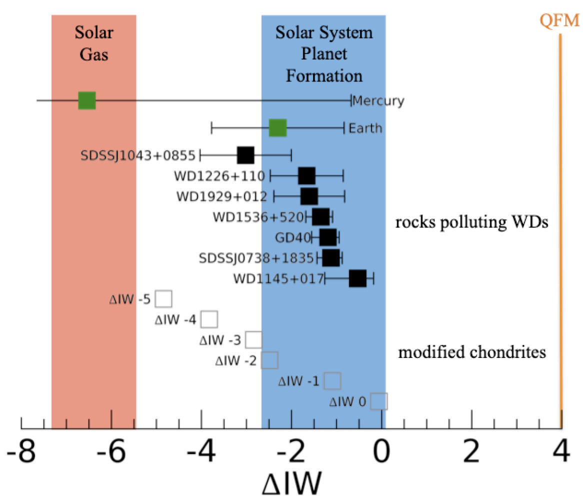

Figure 2. Calculated ΔIW for the rocky debris that polluted the seven white dwarfs in this study (black). The green symbols represent Mercury and Earth as recovered in our Monte Carlo simulations. The open symbols represent the recovered fO_2 values for the various test-case modified chondrites with prescribed fO_2 indicated. Error bars are from propagation of measurement uncertainties. The range of relative oxygen fugacities for a gas of solar composition (red), for solar-system rocky bodies (blue), and fO_2 relative to the ΔQFM (Quartz-Fayalite-Magnetite) buffer (orange) are shown for comparison. There is an additional uncertainty in ΔIW of about 0.2 due to plausible concentrations of elements other than Fe in the metal.

Results and Discussion: The ΔIW values we obtain for the rocks assimilated by the polluted WDs are all similar to those of the terrestrial planets and asteroids in our solar system, excluding Mercury (Figure 2). This indicates that the parent objects that polluted these WDs had intrinsic oxidation states similar to rocks in our solar system. It is therefore likely that the process that oxidized rocky bodies in the solar protoplanetary disk was also at work oxidizing extrasolar rocky bodies.

If dust/gas ratio is the primary control on oxidation state during rock formation, one would conclude that the dust/gas ratios during formation of the rocks that polluted these WDs were similar to those that formed rocks in the solar system. This in turn implies that high dust/gas ratios are intrinsic to rock formation in protoplanetary disks in general. Additionally, it is thought that the parent bodies that polluted the WDs are similar in mass to the largest asteroids in our asteroid belt. This would mean that rocky planets constructed from these planetesimals have intrinsic oxygen fugacities, and thus cores, similar to those of Earth.

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