THE HEAVY-ELEMENT MASSES OF EXTRASOLAR GIANT PLANETS, REVEALED

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ABSTRACT

We investigate a population of transiting planets that receive relatively modest stellar insolation, indicating equilibrium temperatures <1000 K, and for which the heating mechanism that inflates hot Jupiters does not appear to be significantly active. We use structural evolution models to infer the amount of heavy elements within each of these planets. There is a correlation between the stellar metallicity and the mass of heavy elements in its transiting planet(s). It appears that all giant planets possess a minimum of \( \sim 10^{15} \) Earth masses of heavy elements, with planets around metal-rich stars having larger heavy-element masses. There is also an inverse relationship between the mass of the planet and the metal enrichment \( (Z_{pl}/Z_{\odot}) \), which appears to have little dependency on the metallicity of the star. Saturn- and Jupiter-like enrichments above solar composition are a hallmark of all the gas giants in the sample, even planets of several Jupiter masses. These relationships provide an important constraint on planet formation and suggest large amounts of heavy elements within planetary H/He envelopes. We suggest that the observed correlation can soon also be applied to inflated planets, such that the interior heavy-element abundance of these planets could be estimated, yielding better constraints on their interior energy sources. We point to future directions for planetary population synthesis models and suggest future correlations. This appears to be the first evidence that extrasolar giant planets, as a class, are enhanced in heavy elements.

Key words: planetary systems

Online-only material: color figures

1. INTRODUCTION

Transiting exoplanets are valuable for planetary characterization because they allow us to measure their masses through stellar radial velocity or other dynamical measurements, as well as their radii from the transit light curve. Together, these yield a planet’s bulk density. In principle, this information could be used to determine a planet’s composition as increasing the mass fraction of heavy elements increases the density. This apparently straightforward method has been difficult to implement, however. Transit observations have revealed that most of the highly irradiated “hot Jupiters” are inflated to large radii beyond what is expected from simple models. The reason for this effect has not been determined; a variety of additional in-...
elements are uniformly mixed with hydrogen and helium and the planet is fully convective (mixed model). The primary heavy-element composition is a mixture of 50% rock and 50% ice using the equation of state (EOS) ANEOS (analytic equation of state; Thompson 1990). By considering the two extreme cases of having all of the heavy-element masses in the core or envelope, we bracket possible interior models of giant planets. For Jupiter, models that match gravity field constraints generally find that most of its heavy elements are in the envelope while for Saturn most are in the core (Fortney & Nettelmann 2010).

A complete description of the thermal evolution model can be found in Fortney et al. (2007) and Miller et al. (2009). Briefly, planets are composed of up to three components: (1) an inert core, (2) an adiabatic convective envelope (where heavy elements may be mixed in), and (3) a solar-metallicity non-gray atmosphere model (Fortney et al. 2007) that includes the atmospheric extension to the transit radius. The primary effect of heavy elements either in the core or in the convective envelope is mainly to decrease the planet’s radius at every time.

For each planet, the amount of heavy elements is determined under the constraint that the predicted model transit radius agrees with the observed radius at the observed age and incident flux. The average incident flux that a planet receives is given by

$$\langle F \rangle = \frac{L_\star}{4\pi a^2\sqrt{1 - e^2}},$$

where $L_\star$ is the luminosity of the star, $a$ is the semi-major axis of the orbit, and $e$ is the eccentricity of the orbit. This analysis was performed on all planets that met our average incident flux cut $\langle F \rangle < 2 \times 10^8$ erg s$^{-2}$ cm$^{-2}$ and had a mass greater than 20 $M_\oplus$—since our model is primarily designed to describe giants with masses greater than Neptune.

Note that these heavy-element masses should be taken as minimum masses since if the planet is internally heated or if higher atmospheric opacities (due to metal-enhanced atmospheres) slow the cooling (Ikoma et al. 2006; Burrows et al. 2007), then a planet would have more heavy elements than found here.

The required heavy-element mass to fit the radius is determined as the average of the layered and mixed cases. Each of the observed system parameters ($R_p$, age, $a$, $M_p$) has an associated error on its published value. The propagated error on the heavy-element mass ($\sigma_H$) is given by

$$\sigma_H^2 = \left( \frac{\partial M_c}{\partial R_p} \right)^2 \sigma_{R_p}^2 + \left( \frac{\partial M_c}{\partial age} \right)^2 \sigma_{age}^2 + \left( \frac{\partial M_c}{\partial a} \right)^2 \sigma_a^2 + \left( \frac{\partial M_c}{\partial M_p} \right)^2 \sigma_{M_p}^2 + \left( \frac{M_c - M_{env}}{2} \right)^2,$$

where $\sigma_{R_p}$, $\sigma_{age}$, $\sigma_a$, and $\sigma_{M_p}$ are the observationally determined errors in planet radius, system age, semi-major axis, and planet mass respectively. The derivatives $\frac{\partial M_c}{\partial \chi}$ (calculated at the observed planet parameters assuming core heavy elements) describe the sensitivity of the predicted heavy-element mass with respect to changes in a given parameter, $\chi$. The final term of the expression is the uncertainty due to the unknown structure of the planet. $M_c$ and $M_{env}$ are the predicted heavy-element masses if the heavy elements are within the core or the envelope, respectively.

We use the metallicity of the star [Fe/H] as given in each paper in Table 1. For each system, we compute the heavy-element mass fraction $Z_{star} \equiv 0.0142 \times 10^{[Fe/H]}$—assuming that the total heavy-element composition of other systems scales with their iron abundance, normalized to the solar metallicity as in Asplund et al. (2009).

3. FINDINGS

In Figure 2, we plot the stellar metallicity, [Fe/H], against the planet heavy-element mass for each of these systems. Using a least-squares fit, we find that $\log M_Z = (0.82 \pm 0.08) + (3.40 \pm 0.39)[Fe/H]$ for stars with [Fe/H] $> -0.05$. The reduced $\chi^2$ value of 1.95 implies that not all of the scatter can be explained by observational error. We expect a fairly flat relation (the dotted line in Figure 2) at subsolar stellar metallicity if 10–15 $M_\oplus$ of heavy elements are needed to trigger planet formation. In Table 1 we list the planets and observed parameters used. For each
## Table 1
Planes with Low Incident Flux

| Number | Name          | Mass (MJ) | Radius (R_J) | Age (Gyr) | (F) (erg s\(^{-1}\) cm\(^{-2}\)) | [Fe/H] | Core Model (M_⊕) | Mixed Model (M_⊕) | Average Model (M_⊕) | Z_pl | Z_pl/Z_star | References |
|--------|---------------|-----------|--------------|-----------|-----------------------------------|--------|------------------|-------------------|-------------------|------|-------------|------------|
| 1      | HD 80606 b    | 3.940 ± 0.110 | 1.030 ± 0.036 | 7.0 ± 4.0 | 1.67 × 10\(^7\)                  | 0.390 ± 0.030 | 87.0 ± 62.6      | 84.5 ± 62.6       | 85.8 ± 62.6       | 0.068 ± 0.050 | 2.0 ± 1.4    | [A],[A'] |
| 2      | CoRoT-9 b     | 0.840 ± 0.070 | 1.050 ± 0.040 | 4.0 ± 3.0 | 6.58 × 10\(^6\)                  | -0.010 ± 0.060 | 11.1 ± 17.6      | 10.3 ± 17.6       | 10.7 ± 17.6       | 0.040 ± 0.066 | 2.9 ± 4.8    | [B]        |
| 3      | HD 17156 b    | 3.212 ± 0.007 | 1.087 ± 0.006 | 3.4 ± 0.4 | 1.96 × 10\(^8\)                  | 0.140 ± 0.080 | 38.4 ± 9.3       | 37.8 ± 9.3        | 38.1 ± 9.3        | 0.037 ± 0.009 | 1.9 ± 0.6    | [C]        |
| 4      | Kepler-9 b    | 0.252 ± 0.013 | 0.842 ± 0.069 | 3.0 ± 1.0 | 8.11 × 10\(^7\)                  | 0.120 ± 0.040 | 31.0 ± 9.4       | 25.0 ± 9.4        | 28.0 ± 9.9        | 0.349 ± 0.124 | 18.7 ± 6.9   | [D]        |
| 5      | Kepler-9 c    | 0.171 ± 0.013 | 0.823 ± 0.067 | 3.0 ± 1.0 | 3.14 × 10\(^7\)                  | 0.120 ± 0.040 | 20.6 ± 6.4       | 16.5 ± 6.4        | 18.5 ± 6.7        | 0.341 ± 0.127 | 18.2 ± 7.0   | [D]        |
| 6      | CoRoT-10 b    | 2.750 ± 0.160 | 0.970 ± 0.070 | 2.0 ± 1.0 | 5.38 × 10\(^7\)                  | 0.260 ± 0.070 | 192.0 ± 93.8     | 172.3 ± 93.8      | 182.1 ± 94.4      | 0.208 ± 0.109 | 8.1 ± 4.4    | [E]        |
| 7      | HAT-P-15 b    | 1.946 ± 0.066 | 1.072 ± 0.043 | 6.8 ± 2.2 | 1.51 × 10\(^8\)                  | 0.220 ± 0.080 | 22.6 ± 37.1      | 21.5 ± 37.1       | 22.0 ± 37.1       | 0.036 ± 0.060 | 1.5 ± 2.6    | [F]        |
| 8      | HAT-P-17 b    | 0.530 ± 0.018 | 1.010 ± 0.029 | 7.8 ± 2.8 | 8.91 × 10\(^7\)                  | 0.000 ± 0.080 | 16.9 ± 7.7       | 15.1 ± 7.7        | 16.0 ± 7.7        | 0.095 ± 0.046 | 6.7 ± 3.5    | [G]        |
| 9      | WASP-8 b      | 2.240 ± 0.080 | 1.038 ± 0.047 | 4.0 ± 1.0 | 1.79 × 10\(^8\)                  | 0.170 ± 0.070 | 76.6 ± 52.8      | 70.1 ± 52.8       | 73.4 ± 52.8       | 0.103 ± 0.074 | 4.9 ± 3.6    | [H]        |
| 10     | CoRoT-8 b     | 0.220 ± 0.030 | 0.570 ± 0.020 | 3.0 ± 2.0 | 1.22 × 10\(^8\)                  | 0.300 ± 0.100 | 55.2 ± 8.1       | 45.2 ± 8.1        | 50.2 ± 9.5        | 0.717 ± 0.167 | 25.3 ± 8.8   | [I]        |
| 11     | HAT-P-18 b    | 0.197 ± 0.013 | 0.995 ± 0.052 | 12.4 ± 4.4 | 1.18 × 10\(^8\)                  | 0.100 ± 0.080 | 6.8 ± 4.7        | 5.8 ± 4.7         | 6.3 ± 4.7         | 0.100 ± 0.076 | 5.6 ± 4.4    | [J]        |
| 12     | HAT-P-11 b    | 0.081 ± 0.009 | 0.422 ± 0.014 | 6.5 ± 5.1 | 1.31 × 10\(^8\)                  | 0.310 ± 0.050 | 23.5 ± 2.7       | 20.4 ± 2.7        | 22.0 ± 3.1        | 0.854 ± 0.154 | 29.5 ± 6.4   | [K]        |
| 13     | HAT-P-12 b    | 0.211 ± 0.012 | 0.959 ± 0.030 | 2.5 ± 2.0 | 1.90 × 10\(^8\)                  | -0.290 ± 0.050 | 17.7 ± 4.2       | 14.5 ± 4.2        | 16.1 ± 4.5        | 0.239 ± 0.069 | 32.9 ± 10.3  | [L]        |
| 14     | GJ 436 b      | 0.074 ± 0.005 | 0.377 ± 0.009 | 6.0 ± 4.2 | 4.03 × 10\(^7\)                  | -0.030 ± 0.200 | 22.1 ± 1.6       | 19.5 ± 1.6        | 20.8 ± 2.1        | 0.888 ± 0.108 | 67.0 ± 40.0  | [M]        |

References. [A] Hidas et al. 2010; [A'] Nordstrom et al. 2008; [B] Deeg et al. 2010; [C] Nutzman et al. 2011; [D] Holman et al. 2010; [E] Bonomo et al. 2010; [F] Kovács et al. 2010; [G] Howard et al. 2010; [H] Queloz et al. 2010; [I] Bordé et al. 2010; [J] Hartman et al. 2011; [K] Bakos et al. 2010; [L] Hartman et al. 2009; [M] = Torres et al. 2008.
the planet mass and heavy-element enrichment ratio is consistent with the solar system’s giants (Fortney & Nettelmann 2010). All of these planets are consistent with being enhanced in heavy elements relative to their parent star. This enrichment in heavy elements is a distinguishing characteristic between planets and low-mass brown dwarfs with more solar-like abundances (Chabrier et al. 2007; Leconte et al. 2009).

If this emerging relationship between stellar metallicity and planetary heavy elements continues to hold with additional data, then the relationship could be used to determine the amount of heavy elements in a given inflated hot Jupiter with some confidence, based only on the parent star metallicity and planet mass. This would be powerful as it would allow for a straightforward determination of the additional energy needed to explain a planet’s inflated radius. The additional energy source could then be derived for each inflated planet, as a function of planet mass and irradiation level, and could be compared to model predictions (Guillot & Showman 2002; Batygin et al. 2011).

As additional data accumulate, modifications to the relations presented here could be in order. Perhaps a spread in \( Z_{\text{pl}} / Z_{\text{star}} \) could be due to orbital period, which could tie into the planet’s dynamical environment (Guillot & Gladman 2000). These relationships may be interesting to analyze in systems with multiple transiting planets. Another aspect related to orbital evolution is possible: perhaps differences in heavy elements could be seen between planets that are well aligned or misaligned with their stellar spin axis, as measured by the Rossiter–McLaughlin effect (Gaudi & Winn 2007), as these planets may have taken different paths to their current orbits. The relationship to stellar mass could also be investigated.

The planet formation process and composition may also be a function of the types of heavy elements that are in a protoplanetary disk. Previously, Robinson et al. (2006) showed empirically that [Si/Fe] or [Ni/Fe] are correlated with the existence of planets for a fixed [Fe/H]. Theoretically, they also showed that ice-rich disks tend to form cores faster. Therefore, as the sample of cooler planets in this domain increases, it will also be interesting to test how these planet composition trends are a function of \([\alpha/H]\) or of \([\text{Si/Fe}], [\text{O/Fe}], \text{or } [\text{C/Fe}]\). It may be possible to constrain the composition of the planetary heavy elements from such studies.

In closing, we find evidence from a sample of 14 transiting giant planets that these planets, as a class, are enhanced in heavy elements. The large heavy-element abundances found indicate that all heavy elements cannot be found solely in a core. If the
solar system and planet formation models are a guide, then, in addition to their dense cores, the H/He envelopes of these planets will be enhanced in heavy elements as well, which can be tested by observations of the atmospheres of planets via transit or direct imaging spectroscopy (see, e.g., Marley et al. 2007).

The trends identified here, that independent of stellar metallicity, all giant planets have a heavy-element mass of $10M_\oplus$ or larger, that the abundance of heavy elements in giant planets increases steeply with stellar metallicity, that Jupiter-like enhancement over solar abundances are standard for gas giants, and that more massive planets tend to have lower enrichment, could be enhanced or refuted by additional detections of transiting planets with equilibrium temperatures less than 1000 K. These longer-period systems will continue to be detected from the ground and recently NASA’s Kepler spacecraft identified dozens of candidates for a potentially dramatically larger sample of these less-irradiated transiting giant planets (Borucki et al. 2011).

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