LETTER

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An abundance of small exoplanets around stars with a wide range of metallicities

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The abundance of heavy elements (metallicity) in the photospheres of stars similar to the Sun provides a 'fossil' record of the chemical composition of the initial protoplanetary disk. Metal-rich stars are much more likely to harbour gas giant planets[1–4], supporting the model that planets form by accumulation of dust and ice particles[5]. Recent ground-based surveys suggest that this correlation is weakened for Neptunian-sized planets[4,6–9]. However, how the relationship between size and metallicity extends into the regime of terrestrial-sized exoplanets is unknown. Here we report spectroscopic metallicities of the host stars of 226 small exoplanet candidates discovered by NASA's Kepler mission[10], including objects that are comparable in size to the terrestrial planets in the Solar System. We find that planets with radii less than four Earth radii form around host stars with a wide range of metallicities (but on average a metallicity close to that of the Sun), whereas large planets preferentially form around stars with higher metallicities. This observation suggests that terrestrial planets may be widespread in the disk of the Galaxy, with no special requirement of enhanced metallicity for their formation.

In February 2011, the Kepler mission[10] announced its discovery of 1,235 planet candidates, of which more than half have radii smaller than that of Neptune[11]: $R_P < 4R_\oplus$, where $R_\oplus$ is the Earth radius. We used reconnaissance spectra obtained by the Kepler Follow-up Observing Program (FOP) to derive metallicities for several hundred of the brighter planet candidates, and used the results to explore the relationship between planet size and host-star metallicity. Metallicity, denoted [m/H], is defined as the proportion of a star's outer layers made up of chemical elements other than hydrogen and helium and expressed on a logarithmic scale where zero is the Sun's metallicity. Thousands of spectra have been gathered by the Kepler FOP, but the majority of the spectra have signal-to-noise ratios too low to extract precise stellar parameters using traditional methods. To take full advantage of this large observational effort, we have developed a tool (stellar parameter classification (SPC); see Supplementary Information) that uses a library of synthetic spectra to determine stellar parameters from spectra with modest signal-to-noise ratios (signal-to-noise per pixel >15). Using this approach, we derived metallicities in a consistent and homogeneous manner for the entire sample of Kepler FOP spectra, thus avoiding the systematic differences that can occur when comparing metallicities derived by different techniques. Only the most robust classifications are presented here (Supplementary Information), yielding precise stellar parameters for 152 stars harbouring 226 planet candidates mostly in orbits within 0.5 AU of the host star. We used the stellar parameters from SPC and the Yonsei–Yale stellar evolutionary models[12] to estimate the radii of the host stars, which we couple with the photometric data from the Kepler mission[11] to infer the planet radii (Supplementary Information).

Previous studies[4,6–9] have suggested that the observed correlation between metallicity and the likelihood that solar-type stars host gas giants is weaker for Neptunian-sized planets. However, it is unclear whether this correlation extends into the regime of terrestrial-sized planets, which is important for a better understanding of planet-formation processes. The number of host stars with planets smaller than Neptune in our sample (175 planets) is significantly larger than in earlier studies and includes much smaller planets (as small as Earth). This allows us to compare a statistically significant sample of homogenously derived spectroscopic metallicities of solar-type stars hosting small and large planets. By contrast, a recent study used metallicity indicators based on photometry[13]. In Fig. 1, we show that the average metallicity of stars hosting planets with radii smaller than that of Neptune ($R_P < 4.0R_\oplus$) is lower ([m/H] $= -0.01 \pm 0.02$) than that of the stars harbouring gas giant planets ([m/H] $= +0.15 \pm 0.03$). We find that smaller planets are observed at a wide range of host-star metallicities ($-0.6 <$ [m/H] $< +0.5$), whereas larger planets are detected preferentially around stars with higher metallicity (Figs 2 and 3). To investigate the statistical significance of the difference in metallicity, we perform the two-sample Kolmogorov–Smirnov test of the two subsamples of host stars and find the probability that the two distributions are not drawn randomly from the same parent population is 99.96% (over 3.5σ). An F-test shows that fitting the data in Fig. 3 with a metallicity that increases linearly, as opposed to being constant, as a function of radius yields a better fit with a confidence level of 99.99995% ($\sim 5\sigma$).

Figures 2 and 3 reveal that the population of small planets has a wide range of host-star metallicities, but on average the metallicity of the stars hosting the smaller planets is lower than that of the larger planets. The Kepler-11 system[14] demonstrates that small planets can possess a wide range of mean densities, much like their Jupiter-sized counterparts, and the low mean density of exoplanets Kepler-11d, e and f implies that these planets formed before the gas in the system dissipated completely. The metallicity of the protoplanetary disk may have a key role in how quickly planetary cores can form and, thus, in whether they are able to accrete a gaseous envelope before the gas in the system dissipates. However, additional data, including dynamical masses, are

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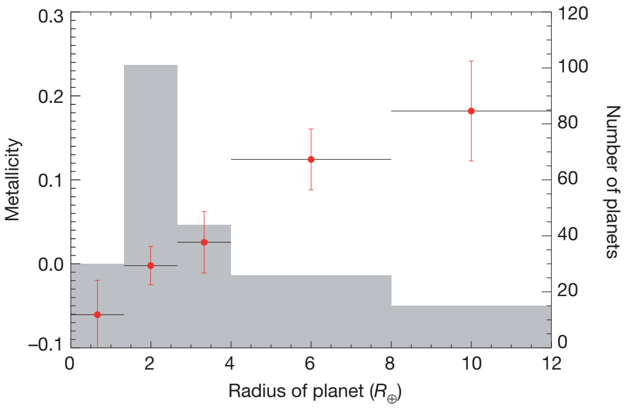

Figure 1 | Average host-star metallicities. Stellar metallicity is defined as $[\mathrm{m/H}] = \log_{10}(N_\mathrm{m}/N_\mathrm{H})_\mathrm{star} - \log_{10}(N_\mathrm{m}/N_\mathrm{H})_\mathrm{Sun}$, where N_m and N_H are respectively the number densities of metal atoms (all elements more massive than helium) and hydrogen atoms. Red points represent the average metallicity of the host stars with planets of different radii grouped in $1.33R_\oplus$ and $4R_\oplus$ bins. The bin size is indicated by the length of the horizontal line and the uncertainty in the average metallicity is given by the standard error. The shaded grey histogram shows the number of planets in each bin, and illustrates the large number of small planets in the Kepler sample. The average metallicity of host stars with smaller planets ($R_\mathrm{P} < 4R_\oplus$) is lower ($[\mathrm{m/H}] = -0.01 \pm 0.02$) than that of host stars with larger planets ($[\mathrm{m/H}] = +0.15 \pm 0.03$). Some of the planetary candidates in the Kepler sample are expected to be false positives that do not turn out to be transiting planets, such as occurs when the reduced signal from a background eclipsing binary is by chance contained within the photometric aperture of the foreground target star. The false-positive rate of the candidates that pass the standard vetting procedures applied by the Kepler team has been estimated to be less than 10% (ref. 26). Therefore, such a low false-positive rate is not expected to impact our results and interpretation. We have thus ignored possible contamination by false positives. We do not derive absolute probabilities or occurrence rates of planets and therefore do not attempt to eliminate the many strong bias and selection effects that, for example, completeness studies (for example ref. 27) must take into account. We have explored the possibility that correlations between planet size and parameters such as orbital semi-major axis are the source of the apparent dependence on metallicity, but find no evidence for such an effect (Supplementary Information).

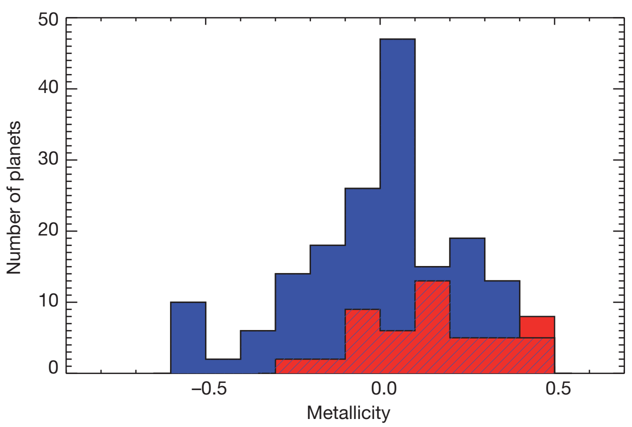

Figure 2 | Comparison of host-star metallicities for small and large planets. The histograms compare the metallicities of two samples of stars hosting planets by dividing the sample at $R_\mathrm{P} = 4R_\oplus$. The host stars of the gas giant planets ($R_\mathrm{P} \geq 4R_\oplus$; red histogram) are clearly more metal rich than those of the smaller planets ($R_\mathrm{P} < 4R_\oplus$; blue histogram), which have a much wider range of metallicities. The hatched area represents the area where the histograms overlap. A Kolmogorov–Smirnov test shows that the probability that the two distributions are not drawn randomly from the same parent population is greater than 99.96%; that is, the two distributions differ by more than 3.5σ. The average metallicity of the stars with small planets ($[\mathrm{m/H}] = -0.01 \pm 0.02$; blue histogram) differs by almost 5σ from that of the larger planets ($[\mathrm{m/H}] = +0.15 \pm 0.03$; red histogram).

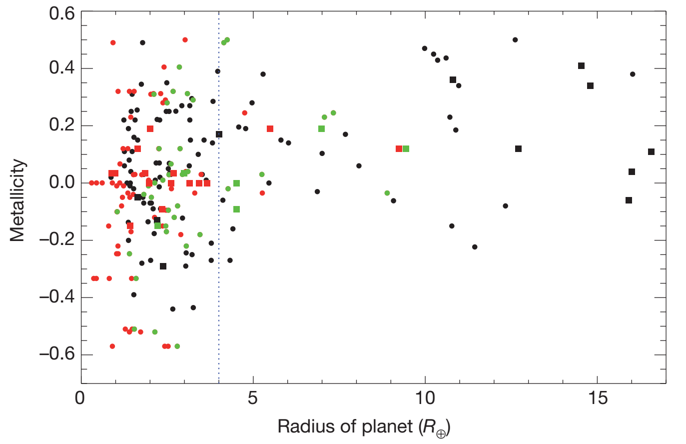

Figure 3 | Individual host-star metallicity as a function of planet radius. The black dots represent single-planet systems, whereas the green dots represent the largest planet and the red dots represent all the smaller planets in multiple-planet systems. The confirmed, published Kepler planets in our samples are plotted as squares with the same colour code as the dots. Planet candidates in multiple systems are each added to the sample with the same host-star metallicity. In Supplementary Information, we consider systems of planets as opposed to individual planets by neglecting all but the largest planet in each system. The vertical dotted line indicates the division of the sample at $R_\mathrm{P} = 4.0R_\oplus$. The data show that Kepler detects small planets around stars with a wide range of metallicities ($-0.6 < [\mathrm{m/H}] < 0.5$), and that larger planets are found preferentially around stars with solar metallicity or higher. The average uncertainty in the individual measurements in metallicity is 0.08 dex and that in planetary radius is 12%.

needed better to understand the seemingly diverse regime of small planets.

Our data show that the well-established correlation between metallicity and occurrence of giant planets[1–3] does not extend into the smaller planet regime below $R_\mathrm{P} < 4R_\oplus$, where the host stars instead have a wide range of metallicities. This observation implies that, by contrast with smaller planets, gas giants require exceptional conditions to trigger their formation. Our findings agree well with the core accretion theory for planet formation, whereby high-metallicity environments allow planetary cores to grow rapidly to reach approximately ten times the mass of the Earth, continue to accrete a gaseous envelope and evolve to gas giants of several hundred Earth masses[5]. Gas disks around young stars are observed to dissipate within a few million years[15], requiring the cores of their planets to reach ten Earth masses within that time if they are to become gas giants. Planets forming in low-metallicity environments, however, may not reach large enough core masses before the dissipation of the gas disk, which could explain why we find very few gas giants around low-metallicity stars. Planetary accretion cannot compete with gas dissipation around low-metallicity stars because the number density of planetesimals is low[16–18] and gas disks dissipate sooner around low-metallicity stars[19,20].

The semi-major axes of the orbits of the majority of the Kepler planets analysed in this work are less than 0.5 AU, so the detected gas giants in our sample were probably brought into orbits within 1 AU by migration[21]. A decreased efficiency of migration in low-metallicity disks could partly explain the observed deficiency of gas giants around the low-metallicity stars. The formation of gas giants late in the lifetime of the protoplanetary gas disk would reduce their subsequent migration because the gas disk is diluted at that stage. This could partly explain why we observe so few gas giants in close orbits. However, late planet formation will in itself suppress formation of gas giants because some cores are formed after the disappearance of the gas disk. Hence, migration cannot be the only reason for the small number of gas giants that we observe around low-metallicity stars.

During the initial stages of planet formation, dust grains collide to form planetesimals, which represent the kilometre-sized building blocks of planets. In some models, planetesimal formation is only possible in disks with metallicities greater than the solar value[17,18]. However, our results show that small planets are present around stars with a wide range of metallicities. The formation of planetesimals in low-metallicity environments can occur if the metallicity is enhanced by preferential evaporation of gas in the disk, for example by photo-evaporation processes associated with the central star or, alternatively, by external sources such as nearby massive stars. In both cases, the removal of gas by photo-evaporation is expected to occur early in the lifetime of the disk, possibly within one million years[22,23]. Such short timescales are consistent with radiometric age dating of meteorites suggesting that, in the Solar System, planetesimal accretion may have begun as early as a few hundred thousand years following formation of the Sun[24].

Finally, we note that some studies have proposed that a metallicity of at least half that of the Sun is required for the formation of terrestrial planets[25]. However, our analysis based on the Kepler planet candidates indicates that terrestrial planets can form at a wide range of metallicities, including metallicities almost four times lower than that of the Sun ($[m/H] \approx -0.6$). In addition, we find that the frequency of occurrence of small planets ($R_P < 4.0R_\oplus$) relative to that of large planets ($R_P > 4.0R_\oplus$) is $\sim$2.7:1 for stars of metallicity greater than that of the Sun but increases to $\sim$5.9:1 for stars of metallicity less than that of the Sun. Therefore, the formation of small, terrestrial planets does not require a metal-rich environment, suggesting that their existence might be widespread in the disk of the Galaxy.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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