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Stellar Metallicities in Circumbinary Planet and Single-Host Star Systems

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ABSTRACT

The primary characteristic of a star is its mass. However the chemical composition of a star, known as the metallicity, is also an important parameter. In this investigation we examine the metallicities of the confirmed exoplanet host stars from the NASA Exoplanet Archive collection, NExScI. We examine the metallicities of circumbinary planet host stars and compare these against single-star planets. We find the metallicity of the circumbinary planet sample tends to favor values lower than zero dex, although these are small sample statistics which are subject to change as the sample size increases. We also find the metallicity of stars with single planets is lower than that stars that have more planets.

1. INTRODUCTION

The metallicity of a star is defined as the fraction of a star that is not hydrogen or helium. In this investigation we examined the metallicities of the host stars of Kepler-Mission confirmed transiting planets and the also the radial velocity-discovered planets (Borucki et al. (2010)).

Detecting a planet via the transit method requires observation of a star as its planet crosses the path between us and the star. This leads to a decrease of the star's total light we receive. The size of the planet determines how much the apparent brightness of the star will dim. The depth of light that is blocked by the planet ΔF is proportional to the squared radius of the planet R_p.

$$\Delta F \propto R_p^2$$

The RV method requires high-precision observations of a star's radial velocity. This method depends on the motion of the star as it is influenced by the planet. As a result, radial velocity observation is effective at detecting short orbital period planets with small orbital radii since these have a greater influence on their host star. These short period planets are often referred to as "Hot Jupiters" because they have high mass, very high temperatures, and are close to their host stars. The typical mass and period of a Hot Jupiter planet is within 0.36—11.8 Jupiter masses and 1.3—111 Earth days. When combined with radial velocity data, a transit can also provide a good estimate of the planet's mass and density. This is possible as radial velocity measurements give the planet mass and inclination parameter and transit observation gives inclination and radius.

2. CIRCUMBINARY HOST STARS

Circumbinary planets are planetary systems where the planets orbit two host stars instead of one. The first circumbinary planet system discovered was Kepler-16b, then Kepler 34b and 35b demonstrated that circumbinary systems are not all that rare (Doyle et al. (2011); Welsh et al. (2012)). The circumbinary planet sample used is Kepler-16b (Doyle et al. (2011)), Kepler-34b and Kepler-35b (Welsh et al. (2012)), Kepler-38b (Orosz et al. (2012)), Kepler-47b and c (Orosz et al. (2012)), Kepler-64b/PH1 (Schwamb et al. (2013); Kostov et al. (2013)) Kepler-413b (Welsh et al. (2012)), Kepler-1647b (Kostov et al. (2016)) for a total of 9 systems. Because of their triple body configuration, circumbinary host stars have some of the most most precisely known masses and radii. Our goal is to determine whether the metallicity of circumbinary planetary systems differs from single star planet systems

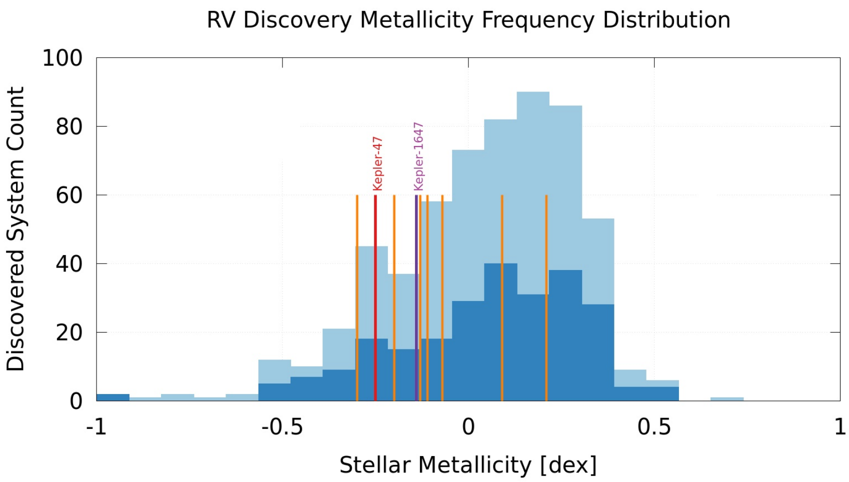
We find the average metallicity of the circumbinary stars examined is -0.166 ± 0.256 dex. We inspect Kepler-47 and Kepler-1647 as these have interesting characteristics. Kepler-47 has the shortest period eclipsing host stars in the sample as well as being a multi-planet system. On the other hand, Kepler-1647 has the longest period and largest radius planet.

3. ARCHIVAL DATA

We obtained our data from the NASA Exoplanet Archive database, NExScI. In order to minimize systematic bias, we created separate metallicity profiles for the transit and radial velocity confirmed planets. Planets discovered by eclipse, pulsar, and transit timing variations, as well as gravitational microlensing events and direct imaging were removed from our sample; these comprised a small percentage of the data available. We then took the circumbinary stars and compared these to the single-star systems. The remaining transit and radial velocity data include 2911, and 672 data points.

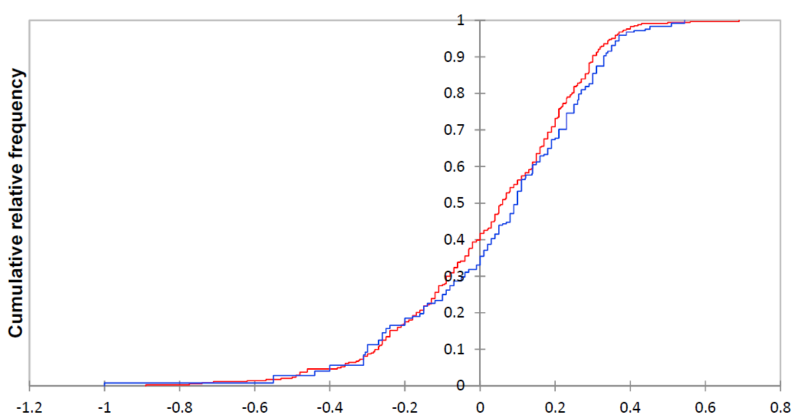
4. RADIAL VELOCITY SAMPLE

Figure 1. RV sample metallicity for single planet (light blue) and multi-planetary systems (dark blue). Vertical bars locate circumbinary star metallicities.



We compared the metallicities for stars witn one vs. multiple planets. In figure 1 we show histograms of the metallicity distributions for the radial-velocity-discovered exoplanets. The metallicities of the 9 circumbinary planets are overlayed on the histograms. Given the small sample size, it is hard to say if there is a significant difference. We find the circumbinary planet stars are less metal rich with an average of -0.166 ± 0.256 dex. The radial velocity sample has an average of 0.033 ± 0.241 dex for single planet systems and 0.053 ± 0.254 dex for stars with more than one planet. In the red and purple bars are the metallicities of Kepler-47 and Kepler-1647. The metallicities of these two stars are lower than the sample peak at about 0.2 dex. An interesting feature in the radial velocity profile is a local peak occurring at -0.26 dex. The metallicity of Kepler-47 falls in this region (-0.250 ± 0.080 dex).

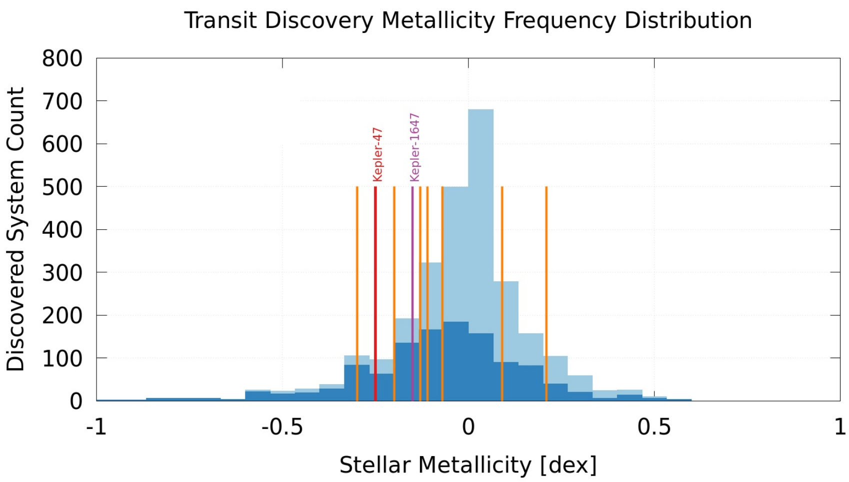
Figure 2. Radial velocity sample cumulative histogram for single planet (red) and multi-planetary systems (dark blue)



We determined the two radial velocity populations follow the same distribution via the Kolmogrov-Smirnov test (figure 2). Utilizing the K-S test we found a p-value < 0.216 at an alpha of 0.05. As the computed p-value is higher than the significance level alpha, we can say both samples follow the same distribution with a risk of rejection lower than 0.01%.

5. TRANSIT SAMPLE

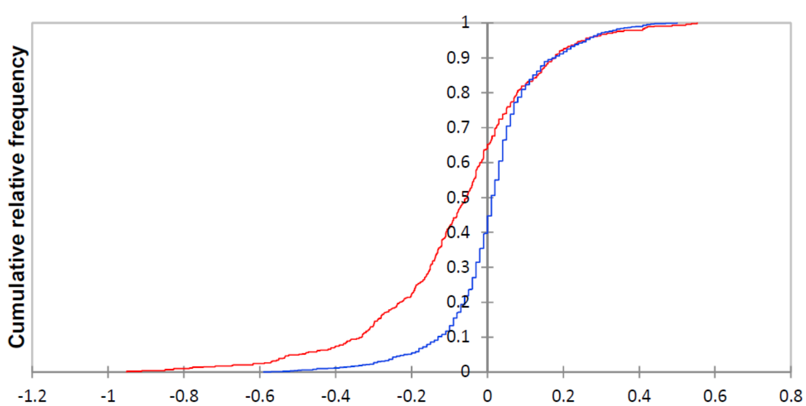
Figure 3. Transit sample metallicity for single planet (light blue) and multi-planetary systems (dark blue). Vertical bars locate circumbinary star metallicities.



We complete the same tests for the transit planets in our sample. In figure 3 we show histograms of the metallicity distributions and the circumbinary planet stars for the transit-discovered exoplanets. Once again, given the small sample size, it is hard to say if there is a significant difference. We find the circumbinary planet stars are less metal rich with an average of -0.166 $\pm$ 0.256 dex. The transit sample average is 0.015 $\pm$ 0.137 dex for single planet systems and -0.077 $\pm$ 0.224 for stars with more than one planet. The metallicities of Kepler-47 and Kepler-1647 are lower than the sample peak.

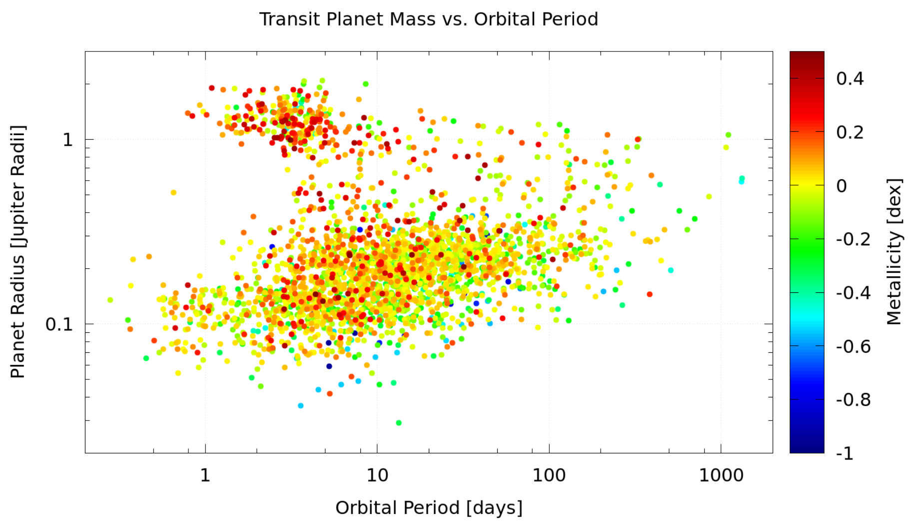
In figure 3 we show histograms of the metallicity distributions for the Kepler-discovered exoplanets. Surprisingly, we determined the metallicity populations for stars with one planet vs. multiple planets are in fact different. We confirm the visual impression with the K-S test on figure 4 The KS test demonstrated this as the p-value, $p < 0.0001$ computed from the sample was lower than the significance $a = 0.05$; the distributions of the two samples are different with a risk of rejection lower than 0.01%.

Figure 4. Transit velocity sample cumulative histogram for single planet (red) and multi-planetary systems (dark blue)



It has been know for a while that Hot Jupiter planets tend to be in single-planet systems and also have higher metallicity than smaller planets (Thorngren et al. (2016)). Figure 5 displays a metallicity color-map. The region with orbital periods of 1-100 days, and 0.7-3.55 Jupiter radii shows the typical location of Hot Jupiter planets. The red points on this region tend to have a higher average metallicity than the rest of the data population. We filtered out this sample and acquired an average of -0.0191 $\pm$ 0.182 dex which is higher than the total set average of -0.0251 $\pm$0.185 dex. We recovered the already known effect Hot Jupiter planets have on their host stars (Thorngren et al. (2016)). The presence of Hot Jupiter planets has been found to raise the overall metallicity of stars.

Figure 5. Transit sample population.



6. CONCLUSIONS

This investigation determined the following:

- A slight preference for slightly metal poor circumbinary host stars (-0.166 $\pm$ 0.256 dex), but the small amount of data do not allow any firm conclusion.
- In the Kepler data, the metallicities of stars with multiple planets seem to have slightly lower metallicity (-0.077 $\pm$ 0.224 dex) than single-planet stars (0.015 $\pm$ 0.137 dex)
- For radial velocity discovered systems, there is no planet multiplicity-metallicity relation. The single planet sample average is 0.033 $\pm$ 0.241 dex, and 0.053 $\pm$ 0.254 dex for multiple planet systems.

Given the small sample of circumbinary planets discovered thus far, it is not possible to determine a precise metallicity distribution. Nevertheless, we can still compare the metallicity of these systems to their single star counterparts. The circumbinary planet sample does not appear to significantly differ from the Kepler sample, neither in mean nor in spread (standard deviation). However, seven out of the nine observed metallicities favor a metallicity less than zero. Given the available metallicity data for circumbinary stars, these appear to be 'metal-poor'.

There seems to be a fundamental difference in stars that have one transiting planet to those with multiple transiting planets. During this investigation we determined on average the metallicity of a star is lower if it has multiple planets. We ruled out Hot Jupiters as the culprits for this result. This trend was only present in the Kepler data sets. This could indicate stars with multiple planets have a lower metallicity as the protostellar metals tended to accumulate into the planets rather than the star.

7. FUTURE ANALYSIS

The significance of the single-vs-multi planet metallicity difference is interesting and needs to be independently verified. If the trend is found to persist, an explanation needs to be found. Given the small sample of circumbinary planets it appears as if the metallicity of multi-star systems is lower as well; however, the sample must be much larger in order to verify this. The Kepler transit metallicity distribution seems more peaked than the radial velocity sample, and it would be good to know why. Something interesting that we noticed from the radial velocity sample is a non-Gaussian asymmetric distribution with a second, small, local peak occurring at metallicities of -0.26 dex in figure 1. Changing the bin size left the region unaffected. This was not present in the Kepler data set. Further research can be made to understand why the distribution looks the way it does

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