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High-resolution images of Kepler Objects of Interest

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Abstract

Kepler announced 1235 candidate transiting planets earlier this year, most of them Neptune-sized or smaller [1]. High-quality follow-up observations are required both to confirm the planetary nature of each candidate and to accurately measure its characteristics. Here we focus on the efforts to obtain subarcsecond resolution images in order to detect close companion stars. Depending on their brightness and distance, nearby stars can dilute the transit signal from the target star, leading to an underestimate of the planetary radius, and in some cases a false positive detection. Additionally, since Earth-sized planets cannot currently be detected with radial velocity measurements, other means are vital to establishing accurate planetary sizes. Reconnaissance spectroscopy can rule out the presence of some types of companion stars, and high-resolution images provide complementary constraints, both critical components of efforts to validate planetary candidates.

Here we present adaptive optics (AO) images of several dozen Kepler Objects of Interest (KOIs). Roughly a third of the objects imaged in the near-infrared have a companion within 2" which are up to 4 magnitudes fainter in the Ks band. Additional stars dilute the light from the target star, causing the transit depth to be underestimated, and a dilution correction term must be applied to estimate the true object radius. If no companions are detected, we can place limits on the delta-magnitude and distance of any remaining potential companions. These limits are used in BLENDER analyses to constrain the phase space available for various background blend scenarios, which can place sharp limits on the false detection probability, allowing for candidates to be statistically validated [2].

1. Why images matter

The unprecedented level of precision achieved by the *Kepler* mission means that it is imperative that we understand the immediate neighborhood of each candidate planet. Stray light from nearby stars, even at very low levels, must be accurately accounted for in order to rule out false positives (due to background eclipsing binary stars and related scenarios), to determine accurate planetary sizes, and to support observations made with other instruments.

False positives. A variety of complementary methods are used to vet each *Kepler* candidate. For a few sufficiently bright stars whose candidates produce a detectable radial velocity motion in the star, high quality spectroscopy has been performed to determine planetary masses. Most candidates, however, do not yet have radial velocity measurements, particularly the smallest, most interesting objects that are also the hardest to detect. Other methods are used to rule out false positives for these systems. Reconnaissance spectroscopy is used to determine stellar parameters and search for spectroscopic binary signatures. The centroid motion of each candidate star is examined both in and out of transit to be sure the correct transit host has been identified. High resolution images have been taken for some objects to search for additional nearby stars, using multiple bands to provide additional color constraints on blend scenarios. All of these parameters are used in BLENDER analyses, a comprehensive approach that is used to validate the planetary nature of Kepler Objects of Interest, such as Kepler-9d [2]. The magnitude limits placed at a range of distances by high-resolution images are particularly important, since they are used to decrease the area in which background events can exist.

Accurate Sizes. Even if the object that transits is still a planet, the dilution caused by another star will make the planet appear smaller than it actually is. Accounting for even a little dilution could make a big difference in determining whether a planet is actually Earth-sized.

Observations with other instruments. Follow-up observations of *Kepler* candidates are being conducted with Spitzer. Most false-positive blend scenarios produce a color-dependent transit-like signature, so if a transit has the same depth both in the visible-range *Ke-*

pler bandpass and in the near-infrared with Spitzer, it is much more likely to be caused by a planet. However, if a nearby companion star happens to be very red, it might contribute negligibly in the *Kepler* bandpass but cause a noticeable dilution of the Spitzer light curve, leading to the false conclusion that the transit was caused by a blend. Thus, near-infrared images are very important to support Spitzer observations. In addition to primary transits, Spitzer is also looking for planetary occultations in order to derive planetary temperatures and albedoes, which also need to account for dilution from nearby stars [3].

2. Companion limits

For each star, we estimate the detection limits by assuming the companion has peak counts of at least 5 sigma greater than the background counts of an annulus at that distance. Though the exact field of view differs for each object, the region within about 5" of the KOI is imaged for all targets. Generally, we can find objects down to 4 magnitudes fainter at distances between 0.15-2", and down to 8 magnitudes fainter beyond 2" from the star, depending on the brightness of the target and the seeing. Approximately a third of all KOIs imaged have at least one companion within a distance of 2". For comparison, a *Kepler* pixel is 3.98" on a side.

3. Summary and Conclusions

Ground-based images, with spatial resolutions down to 0.1", are an important component of the *Kepler* follow-up efforts. These images reveal faint companion stars, which may dilute the observed transit depth, requiring a corrective term to calculate the true object radius. Limits placed on additional objects can help validate the likely planetary nature of candidates, particularly the least-massive objects that are difficult to detect with current radial velocity precision.

Acknowledgements

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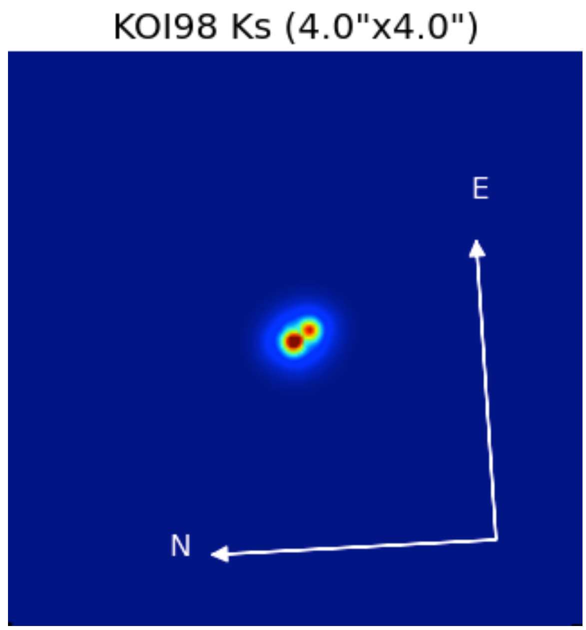

Figure 1: Image of KOI 98 observed with ARIES on the MMT in Ks in Nov 2009. A binary companion is located 0.2" away and is 0.5 mag fainter in Ks. The arrows show the size of the 4-point dither pattern and the approximate north-east orientation of the field.

References

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