Validation of the exoplanet Kepler-21b using PAVO/CHARA long-baseline interferometry

Daniel Huber,1,2*† Michael J. Ireland,1,3,4 Timothy R. Bedding,1 Steve B. Howell,2 Vicente Maestro,1 Antoine Mérand,5 Peter G. Tuthill,1 Timothy R. White,1 Christopher D. Farrington,6 P. J. Goldfinger,6 Harold A. McAlister,6 Gail H. Schaefer,6 Judit Sturmann,6 Laszlo Sturmann,6 Theo A. ten Brummelaar6

1Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia
2NASA Ames Research Center, Moffett Field, CA 94035, USA
3Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia
4Australian Astronomical Observatory, PO Box 296, Epping, NSW 1710, Australia
5European Southern Observatory, Alonso de Cordova 3107, Casilla 19001, Vitacura, Santiago 19, Chile
6Center for High Angular Resolution Astronomy, Georgia State University, PO Box 3969, Atlanta, GA 30302, USA

Accepted 2012 February 22. Received 2012 February 22; in original form 2011 December 19

ABSTRACT
We present long-baseline interferometry of the Kepler exoplanet host star HD 179070 (Kepler-21) using the Precision Astronomical Visible Observations (PAVO) beam combiner at the Center for High Angular Resolution Astronomy (CHARA) Array. The visibility data are consistent with a single star and exclude stellar companions at separations ~1–1000 mas (~0.1–113 au) and contrasts <3.5 mag. This result supports the validation of the 1.6 R⊕ exoplanet Kepler-21b by Howell et al. and complements the constraints set by adaptive optics imaging, speckle interferometry and radial-velocity observations to rule out false positives due to stellar companions. We conclude that long-baseline interferometry has strong potential to validate transiting extrasolar planets, particularly for future projects aimed at brighter stars and for host stars where radial-velocity follow-up is not available.

Key words: techniques: interferometric – planets and satellites: individual: Kepler-2lb – stars: individual: HD 179070.

1 INTRODUCTION
The NASA Kepler mission aims to find extrasolar planets in the habitable zones of solar-type stars through the detection of brightness dips as planets cross the stellar disc. While Kepler has been highly successful in finding exoplanet candidates, ground-based follow-up observations are important to confirm the detections. The most common astrophysical false positives for Kepler involve stellar companions that remain unresolved due to Kepler’s large pixel size (~4 arcsec). False positives can be divided into companions that are physically bound to the target star (hierarchical triple systems) and companions that are either in the foreground or the background of the target due to chance alignment (blends). In both cases, a transit-like shape can be mimicked by eclipses of a stellar companion or transits of a planet around the secondary companion.

For large (Jupiter- and Neptune-sized) planets, candidates can often be confirmed using radial velocity observations, giving a direct estimate of the planet’s mass (see e.g. Borucki et al. 2010, Koch et al. 2010, Latham et al. 2010; Cochran et al. 2011), while transit timing variations can be used to confirm planets in multiple systems (see e.g. Fabrycky et al. 2012; Ford et al. 2012; Steffen et al. 2012). For many super-Earths and Earth-sized planets, however, the Doppler signature is typically too small compared to the intrinsic stellar variability, and transit timing variations might not be detected. In these cases, candidates are validated by excluding as many false-positive scenarios as possible. The first stage in this process uses the Kepler data to detect signatures of stellar companions through photocenter shifts and the comparison of transit depths (see e.g. Batalha et al. 2010; Bryson et al. 2010), followed by statistical modelling of potential blending scenarios (see e.g. Fressin et al. 2011; Morton & Johnson 2011; Torres et al. 2011). These constraints are then combined with ground-based follow-up observations such as spectroscopy, speckle interferometry and adaptive optics imaging (see e.g. Gautier et al. 2010; Howell et al. 2011). High-angular-resolution observations using long-baseline interferometry offer a powerful tool to complement these methods and extend the parameter range that can be excluded, particularly for close-in (both bound and unbound) companions.

*E-mail: daniel.huber@nasa.gov
†NASA Postdoctoral Program Fellow.
2 OBSERVATIONS

We have observed HD 179070 as part of our interferometric follow-up campaign of Kepler stars using the PAVO beam combiner (Ireland et al. 2008) at the CHARA Array (ten Brummelaar et al. 2005). PAVO is a three-beam pupil-plane beam combiner optimized for high sensitivity and angular resolution, recording visibilities over a spectral bandpass of ∼650–800 nm with a limiting magnitude in typical seeing conditions of R ≲ 8 mag. Using baselines reaching up to 330 m, PAVO/CHARA is capable of resolving angular sizes down to ∼0.3 mas. For more details on the instrument and data reduction, we refer to Ireland et al. (2008).

HD 179070 was observed on 2011 July 2 in two-telescope mode using the S1-W1 (278 m) baseline in excellent seeing conditions. Two scans were obtained, which were interleaved with observations of three different calibrator stars. Using various catalogues available in the literature, calibrators are typically chosen to be single field stars in close vicinity (<10") to the target star. Table 1 lists the spectral types, photometric properties and expected sizes of all stars in this study. The predicted sizes were calculated using the (V − K) relation given by Kervella et al. (2004). V magnitudes have been extracted from the Tycho catalogue (Perryman & ESA 1997) and transformed into the Johnson system using the calibration of Bessell (2000). K magnitudes have been obtained from the Two Micron All Sky Survey (2MASS) catalogue (Cutri et al. 2003) from the Two Micron All Sky Survey (2MASS) catalogue (Cutri et al. 2003, Skrutskie et al. 2006). We have tested the photometry for reddening by comparing the observed (B − V) colours with a list of intrinsic colours as a function of spectral type given by Schmidt-Kaler (1982). The observed colours have been found to be compatible with the spectral types for all stars except for the calibrator HD 178591, which is classified as an ellipsoidal variable by Hipparcos. We have accounted for this by adding a systematic uncertainty corresponding to the observed variability amplitude (∼0.05 mag) to the statistical photometric uncertainty in the V band. Note that the potential companion of HD 178591 can be expected to have a negligible influence on the interferometric measurements. The final uncertainties for the predicted angular diameters were calculated by adding a conservative 5 per cent calibration uncertainty in quadrature to the uncertainty calculated from the photometry.

Figure 1 shows the raw squared visibility measurements across the PAVO passband for the target and the calibrators. As expected from their predicted sizes, the visibility levels of the calibrators are very similar. Note that the raw measurements are considerably lower than the expected visibilities (∼0.9) due to atmospheric turbulence and optical aberrations. HD 179070 remains practically unresolved in our observations, with raw visibilities at very similar levels to the calibrator stars, and no significant visibility change as a function of wavelength. Moreover, the similarity between target and calibrator scans shows that the visibility curve of HD 179070 is consistent with a single star. For any companion for which the interference patterns (fringe packets) of the two stars overlap in delay space, a periodic visibility modulation would be observed, while any incoherent flux from companions at larger separations would cause a drop in the observed visibility (see e.g. Monnier 2003; ten Brummelaar 2007). The interferometric field of view for each case depends on the coherence length and the projected baseline (ten Brummelaar 1995), and for our observations corresponds to <30 and 30–1000 mas, respectively.

To illustrate this more clearly, Fig. 2 shows the calibrated squared visibility data of HD 179070 as a function of spatial frequency. Visibilities were calibrated by dividing the calibrator data by the predicted sizes to obtain a system visibility, which was then used to

| HD     | Spec. type | V     | K     | θ_{V−K} (mas) |
|--------|------------|-------|-------|---------------|
| 179070 | F6IV       | 8.262(11) | 6.945(18) | 0.169(09) |
| 174260 | B8V        | 7.323(05) | 7.465(18) | 0.103(05) |
| 178591 | B5V        | 7.130(57) | 7.191(24) | 0.119(06) |
| 183204 | A0V        | 7.425(07) | 7.386(21) | 0.110(06) |

Table 1. Spectral types, photometry and expected angular sizes of stars in this study. Brackets indicate the last two digits of the 1σ uncertainties.

HD 178591 is an ellipsoidal variable with an amplitude of ∼0.05 mag.

© 2012 The Authors, MNRAS 423, L16–L20
Monthly Notices of the Royal Astronomical Society © 2012 RAS
Figure 2. Calibrated squared visibility versus spatial frequency for HD 179070. The red solid line shows the best-fitting single-disc model with a diameter of $\theta_{\text{LD}} = 0.13 \pm 0.02$ mas. The areas marked by blue dashed, dash–dotted and dash–triple-dotted lines show the range of minimum squared visibilities expected for companions $>1$ mas with contrasts of 1.5, 3 and 4.5 mag, respectively. The inset shows a close-up of the data.

correct the target visibility. We then fitted the limb-darkened disc model given by Hanbury Brown et al. (1974) to the data using the method described by Derekas et al. (2011). We used a linear limb-darkening coefficient for the $R$ band of $\mu_R = 0.5197$, derived from the closest matching grid point of Claret & Bloemen (2011) to the stellar parameters presented by Howell et al. (2012). The red line in Fig. 2 shows the best-fitting single-disc model, yielding a diameter of $\theta_{\text{LD}} = 0.13 \pm 0.02$ mas with a reduced $\chi^2 = 1.4$. This diameter agrees with the diameter of $0.15 \pm 0.01$ mas constrained from the asteroseismic radius ($R/R_\odot = 1.86 \pm 0.02$; Howell et al. 2012) and Hipparcos parallax ($\pi = 8.86 \pm 0.58$ mas; van Leeuwen 2007). The areas marked by blue dashed, dash–dotted and dash–triple-dotted lines illustrate the minimum squared visibilities expected for a stellar companion with a contrast of 1.5, 3 and 4.5 mag compared to HD 179070. Deep minima correspond to close-in companions (1–30 mas) which will show a periodic variation across the PA VO and hence an overall drop in visibility would be observed. Fig. 2 suggests that the PA VO observations rule out any companion at contrasts of $\lesssim 3$ mag. Note that for stellar companions at even closer separations ($\lesssim 0.1$ au), the PA VO data would solely exclude companions along the baseline vector at the time of observation, which in this case spans only one epoch. We also note that the faint $\sim 14.5$ mag companion at $\sim 0.7$ arcsec detected by Howell et al. (2012) has negligible influence on our measurements.

To establish the magnitude limit more quantitatively, we performed $10^5$ simulations as follows. For each iteration, we used the spatial frequencies of our observations to generate a synthetic binary model consisting of a primary with the expected size of HD 179070 and an unresolved secondary, with a separation and contrast drawn from uniform distributions between 1–50 mas and 1–6 mag, respectively. We then added white noise to each data point with a standard deviation corresponding to our estimated relative measurement uncertainties. For each simulated data set, we then fitted a binary model to the data and compared the $\chi^2$ value to the one calculated from a single-disc model with the expected size of HD 179070. The simulations showed that in $>99$ per cent of all cases, the binary model yielded a significantly ($>3\sigma$) better fit for contrasts below 3.6 mag. This limit has been found to be only weakly dependent on the separation, dropping to $\sim 3.4$ mag for wide (50–1000 mas) binaries. To confirm the limit, we performed a Bayesian model comparison by calculating the odds ratio between both models. Equal prior probability of each model was assumed (hence simplifying the problem to the calculation of the Bayes factor). The marginal likelihood (evidence) for each model was calculated using nested sampling (Skilling 2004). We assumed a Gaussian prior probability for the primary diameter, and a uniform prior for the separation and contrast of the binary model. Due to computational reasons the calculation was performed for 150 simulations and restricted to a smaller range of close-in (1–10 mas) companions. The computed Bayes factors consistently favoured the binary model over the single-star model for contrasts $<3.5$ mag. As expected, this value is more conservative than the limit inferred from the likelihood ratio, since the Bayesian model comparison penalizes the binary model for its added complexity. Based on these results, we conclude that our data would have revealed a stellar companion at separations $\sim 1$–1000 mas ($\sim 0.1$–113 au) and contrasts $<3.5$ mag.

We note that the above simulations assume that our measurement uncertainties are well characterized. Previous PA VO observations of the same star over multiple nights showed that night-to-night variations in $V^2$ are at the 2–3 per cent level (Huber et al., in preparation), while the $\sim 5$ per cent uncertainties in the calibrator sizes (see Table 1) translate to a 1 per cent uncertainty in $V^2$ (van Belle & van Belle 2005). Both these contributions are considerably smaller than our measurement uncertainties (estimated from the scatter of individual data frames integrated over each scan), which are on average 13 per cent. Combined with the low reduced $\chi^2$ of our fit, we therefore argue that our measurement uncertainties are a good estimate of the total uncertainty in our data.

© 2012 The Authors, MNRAS 423, L16–L20
Monthly Notices of the Royal Astronomical Society © 2012 RAS
We have presented high-angular-resolution observations of the exoplanet host star HD 179070 (Kepler-21) using the PAVO beam combiner at the CHARA Array. Our data clearly rule out stellar companions at separations between ~1 and 1000 mas (~0.1–113 au) with contrasts of <3.5 mag. This complements and extends the validation efforts by Howell et al. (2012), and supports the conclusion that the detected transit is due to a 1.6 R⊙ extrasolar planet in an orbit around HD 179070.

The results shown here demonstrate the potential of PAVO/CHARA to validate transiting exoplanet candidates, and complement the existing efforts using long-baseline interferometry to characterize exoplanet host stars (see e.g. Baines et al. 2009; van Belle & von Braun 2009; von Braun et al. 2011). Using a recent compilation of detected exoplanets in the NASA Exoplanet Archive,1 we estimate about half a dozen host stars with transiting exoplanets to be accessible to observations with PAVO/CHARA. Furthermore, there will be a considerable overlap with the target sample of the planned Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2009), which is aimed at finding planets around nearby (V < 12) stars. While the contribution of PAVO to the validation effort of Kepler-21b is relatively modest, it can be expected that long-baseline interferometry will play a significant role in validating transiting extrasolar planets, in particular for future missions aimed at bright stars and for cases where precise RV follow-up may not be available.

ACKNOWLEDGMENTS

DH, TRB and VM acknowledge support from the Access to Major Research Facilities Programme, administered by the Australian Nuclear Science and Technology Organisation (ANSTO). DH is supported by an appointment to the NASA Postdoctoral Program at Ames Research Center, administered by Oak Ridge Associated Universities through a contract with NASA. The CHARA Array is funded by the National Science Foundation through NSF grant AST-0606958, by Georgia State University through the College of Arts and Sciences, and by the W. M. Keck Foundation. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

REFERENCES

Baines E. K., McAlister H. A., ten Brummelaar T. A., Sturmann J., Sturmann L., Turner N. H., Ridgway S. T., 2009, ApJ, 701, 154
Baraffe I., Chabrier G., Allard F., Hauschildt P. H., 1998, A&A, 337, 403
Batalha N. M. et al., 2010, ApJ, 713, L103
Bessell M. S., 2000, PASP, 112, 961
Borucki W. J. et al., 2010, Sci, 332, 216
Cutri R. M. et al., 2003, in Cutri R. M. et al., eds, The 2Mass All-Sky Source Catalog. NASA/IPAC Infrared Science Archive
Derekas A. et al., 2011, Sci, 332, 216
Fabrycky D. C. et al., 2012, ApJ, in press (arXiv:1201.5415)
Ford E. B. et al., 2012, ApJ, in press (arXiv:1201.5409)
Fressin F. et al., 2011, ApJS, 197, 5
Gautier T. N., III et al., 2010, preprint (arXiv:1001.0352)

1 http://exoplanetarchive.ipac.caltech.edu/index.html

© 2012 The Authors, MNRAS 423, L16–L20
Monthly Notices of the Royal Astronomical Society © 2012 RAS
Hanbury Brown R., Davis J., Lake R. J. W., Thompson R. J., 1974, MNRAS, 167, 475
Howell S. B., Everett M. E., Sherry W., Horch E., Ciardi D. R., 2011, AJ, 142, 19
Howell S. B. et al., 2012, ApJ, 746, 123
Ireland M. J. et al., 2008, in Schöller M., Danchi W. C., Delplancke F., eds, Proc. SPIE. Vol. 7013, Optical and Infrared Interferometry. SPIE, Bellingham, p. 701324-701324-10
Kervella P., Thévenin F., Di Folco E., Ségransan D., 2004, A&A, 426, 297
Koch D. G. et al., 2010, ApJ, 713, L131
Latham D. W. et al., 2010, ApJ, 713, L140
Monnier J. D., 2003, Rep. Progress Phys., 66, 789
Morton T. D., Johnson J. A., 2011, ApJ, 738, 170
Perryman M. A. C., ESA, eds, 1997, ESA Special Publication. Vol. 1200, The Hipparcos and Tycho Catalogues. Astrometric and Photometric Star Catalogues Derived from the ESA Hipparcos Space Astrometry Mission. ESA, Noordwijk
Ricker G. R. et al., 2009, American Astron. Soc. Meeting, 213, 403.01
Schmidt-Kaler T., 1982, Stars and Star Clusters, Landolt-Börnstein, Group VI, Vol. 2b. Springer, Berlin
Skilling J., 2004, in Fischer R., Preuss R., Toussaint U. V., eds, AIP Conf. Proc. Vol. 735, Entropy Methods in Science and Engineering. Am. Inst. Phys., New York, p. 395
Shrutskie M. F. et al., 2006, AJ, 131, 1163
Steffen J. H. et al., 2012, MNRAS, in press (arXiv:1201.5412)
ten Brummelaar T. A., 1995, Appl. Opt., 34, 2214
ten Brummelaar T. A., 2007, in Hartkopf W. I., Guinan E. F., Harmanec P., eds, Proc. IAU Symp. 240, Binary Stars as Critical Tools & Tests in Contemporary Astrophysics. Cambridge Univ. Press, Cambridge, p. 178
ten Brummelaar T. A. et al., 2005, ApJ, 628, 453
Torres G. et al., 2011, ApJ, 727, 24
van Belle G. T., van Belle G., 2005, PASP, 117, 1263
van Belle G. T., von Braun K., 2009, ApJ, 694, 1085
van Leeuwen F., 2007, A&A, 474, 653
von Braun K. et al., 2011, ApJ, 729, L26
This paper has been typeset from a \TeX/\LaTeX file prepared by the author.