Resolving the Multiplicity of Exoplanet Host Stars in Gemini/NIRI Data

Kim Miskovetz, Trent J. Dupuy, Jessica Schonhut-Stasik, and Keivan G. Stassun

1Department of Physics and Astronomy, University of Hawai‘i at Hilo, Hilo, HI 96720, USA
2Gemini Observatory, NSF’s OIR Lab, Hilo, HI 96720, USA
3Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
4Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA
5FRIST Center for Autism, 2414 Highland Avenue, Suite 115, Nashville, TN 37212, USA

ABSTRACT

The majority of stars have one or more stellar companions. As exoplanets continue to be discovered, it is crucial to examine planetary systems to identify their stellar companions. By observing a change in proper motion, companions can be detected by the acceleration they induce on their host stars. We selected 701 stars from the Hipparcos–Gaia Catalog of Accelerations (HGCA) that have existing adaptive optics (AO) imaging data gathered with Gemini/NIRI. Of these, we examined 21 stars known to host planet candidates and reduced their archival NIRI data with Gemini’s DRAGONS software. We assessed these systems for companions using the NIRI images as well as RUWE values in Gaia and accelerations in the HGCA. We detected three known visible companions and found two more systems with no visible companions but astrometric measurements indicating likely unresolved companions.

Keywords: Astrometric binary stars(79), Direct imaging(387), Planet hosting stars(1242), Visual binary stars(1777)

The majority of stars have one or more stellar companions (e.g., Moe & Di Stefano 2017), so our understanding of how planetary systems form and evolve is incomplete without accounting for multiple-star systems. Developing such an understanding is an ongoing challenge (e.g., Moe & Kratter 2019) that relies on comprehensive observational evidence over a wide range of separations, ranging from inside the scale of the solar-system (<50 AU; e.g., Kraus et al. 2016) to much wider (~10⁴ AU; e.g., Ngo et al. 2016).

Gaia observations present an opportunity to examine the multiplicity of planetary systems on both of these scales (Gaia Collaboration 2018). Near or inside the angular resolution limit of Gaia (~0′′1), poor astrometric fit as quantified by the Renormalised Unit Weight Error (RUWE) can indicate unresolved multiplicity (e.g., Halley Vrijmoet et al. 2020). At wider separations, a discrepancy in proper motions at different epochs can be used to identify massive bodies by the acceleration they induce on the primary star (e.g., Kervella et al. 2019). Combined, these methods probe close-in multiples (1–10 AU) and wide companions on long-period orbits (~30–10⁴ yr, corresponding to ~10–100 AU) for the many known planetary systems within ~10–100 pc. AO imaging can then be used to visually investigate wider companions that astrometry may not detect.

Gemini Observatory’s Near InfraRed Imager (NIRI) is capable of imaging wavelengths from 1.0–5.5 µm with a typical field of view of 20″ × 20″ (Hodapp et al. 2003). Gemini Observatory’s ALTitude conjugate Adaptive optics for the InfraRed (ALTAIR; Christou et al. 2010) further improves the quality of these observations, allowing NIRI to resolve both close binaries down to the diffraction limit of the 8-m Gemini telescope, and wider binaries.

We used the Hipparcos–Gaia Catalog of Accelerations (HGCA; Brandt 2018) for target selection, as it contains a uniform analysis of astrometric acceleration for bright stars. The HGCA is a cross-calibration of the Hipparcos (Perryman et al. 1997) and Gaia missions (Gaia Collaboration et al. 2016a,b,c, 2018).

Corresponding author: Kim Miskovetz
kmiskove@hawaii.edu
We performed an automated search of the Gemini Observatory Archive (GOA; Hirst & Cardenes 2016) in a 10″ radius around the Equinox J2000 Epoch 2000.0 right ascension and declination values of all stars in the HGCA catalog, and selected those that had NIRI data. We cross-matched a list of the resulting 701 stars to the list of known or suspected exoplanets from exoplanets.org (Han et al. 2014), resulting in 23 stars of interest, five of which are known multiple systems. HD 19994 is a triple system with a circumpimary exoplanet and a binary pair orbiting the primary at ≈2″ (Wieght et al. 2016). KELT-2 and WASP-33 also have visual companions at ≈2″ (Beatty et al. 2012; Mugrauer 2019). HD 89744 has an L-dwarf companion 63.1″ away (Wilson et al. 2001), and HD 125612 has a stellar companion ≈1.5″ away (Mugrauer & Neuhäuser 2009), both well outside NIRI’s field-of-view.

We used Gemini Observatory’s data reduction software DRAGONS (Data Reduction for Astronomy from Gemini Observatory North and South) to reduce imaging data from NII R (AURA Gemini Observatory-Science User Support Department 2018). Data we used was taken in one of five different filters: $K_{cont}$ ($\lambda_c = 2.097$ μm; FWHM= 0.031 μm), $H$ ($\lambda_c = 1.649$ μm; FWHM= 0.291 μm), $CH_{4}$s ($\lambda_c = 1.595$ μm; FWHM= 0.115 μm), Brγ ($\lambda_c = 2.168$ μm; FWHM= 0.034 μm), and $H_{cont}$ ($\lambda_c = 1.576$ μm; FWHM= 0.022 μm) (Rodrigo & Solano 2020). We reduced 21 of 23 stars of interest and visually examined them for companions. $\varepsilon$ Tau and HD 218396 could not be reduced because $\varepsilon$ Tau had insufficient frames, and HD 218396 was highly saturated.

We recovered all three companions expected to be in the NII R data (WASP-33, KELT-2, and HD 19994). We found background stars that were not co-moving with HD 17156, HD 168443, and HAT-P-11. Four targets had data taken in angular differential imaging mode, such that DRAGONS failed to properly rotate the images while stacking, resulting in primary stars with well-defined diffraction spikes but any companions smeared by sky rotation. For GJ 436, HD 130322, and GJ 876, we found no such smeared companions. For HD 19994, we estimated an approximate separation of 2.3 ± 0.1″ from the curved smear left by its known companion.

For systems with visible companions, we computed their angular separations and position angles. These data were taken with NII R’s f/32 camera with a pixel scale of 21.9 mas pixel$^{-1}$. We assumed a global uncertainty of 0.05 mas pixel$^{-1}$ on the pixel scale and 0.1° on the orientation of NII R (Beck et al. 2004). For KELT-2, we used NII R data from 2013 Apr 9 UT to measure an angular separation of 2.433 ± 0.006° and a position angle of 332.7 ± 0.1°, where the calibration uncertainties dominate over relative pixel position uncertainties. For comparison, Beatty et al. (2012) found an angular separation of 2.29 ± 0.05″ and a position angle of 328.6 ± 0.9° on 2012 Apr 10 UT. The disagreement between these measurements is larger than expected for orbital motion of a ≈300-AU binary, indicating that the measurement uncertainties are likely somewhat underestimated. Using Gaia data from 2015, we computed an angular separation of 2.3792″ and a position angle of 332.140°, which is between our measurement and that of Beatty et al. (2012). We also found an angular separation of 1.980 ± 0.005″ and a position angle of 277.0 ± 0.1° for WASP-33. Ngo et al. (2016) found a position angle of 276.4 ± 0.2° on 2010 Nov 29, a position angle of 276.247 ± 0.045° on 2013 Aug 19, and an angular separation of 1.940 ± 0.002.

Additional criteria that may indicate a system as a potential binary include HGCA $\chi^2$ values above 11.8 ($> 3\sigma$) or RUWE values above 1.2 (Stassun & Torres 2021). By combining information on these systems’ HGCA $\chi^2$ values, Gaia RUWE values, and Gemini/NII R imaging, we can obtain a nearly complete view of these systems. Our sample included only one system with high RUWE, $\iota$ Dra. This star is very bright ($G = 2.8471 ± 0.0037$ mag; Gaia Collaboration 2018), so its high RUWE is most likely due to saturation in Gaia. Our sample also included two systems with significantly high HGCA $\chi^2$ values: 14 Her ($\chi^2 = 439.78$) and HD 168443 ($\chi^2 = 34.02$). Though the NII R images for these systems show no companions, these $\chi^2$ values suggest that they may be worth investigating with higher-contrast data. For 14 Her, Wittgenmyer et al. (2007) found evidence of a long-period outer companion, which likely explains its very high $\chi^2$. Likewise, the massive outer brown dwarf in the HD 168443 system (Pilyavsky et al. 2011) may explain its high $\chi^2$.

REFERENCES
Adams, A. D., Boyajian, T. S., & von Braun, K. 2017, Monthly Notices of the Royal Astronomical Society, 473, 3608–3614, doi: 10.1093/mnras/stx2367
AURA Gemini Observatory-Science User Support Department. 2018, DRAGONS: Gemini Observatory data reduction platform. http://ascl.net/1811.002
Beatty, T. G., Pepper, J., Siverd, R. J., et al. 2012, The Astrophysical Journal, 756, L39, doi: 10.1088/2041-8205/756/2/139
Beck, T. L., Schaefer, G. H., Simon, M., et al. 2004, The Astrophysical Journal, 614, 235, doi: 10.1086/423418
Table 1. Gemini NIRI Observations of Planet Hosts

| Name     | HIP ID  | Method | HGCA $\chi^2$ | RUWE | $d$ (pc) | Date              | Filter     | $N_{\exp} \times t_{\exp}$ (s) | $K_S$ (mag) | $N_{\text{comp}}$ | Program ID | PI   |
|----------|---------|--------|----------------|------|---------|-------------------|------------|-------------------------------|--------------|-----------------|------------|------|
| WASP-33  | 11397   | Transit| 0.48           | 0.88 | 121.9 ± 1.0 | 08/29/2012       | Kcon(209)_G0217 | 9x10.4           | 7.468 ± 0.024 | 1            | GN-2012B-Q-118 | Quinn     |
| HD 17156 | 13192   | RV     | 1.38           | 1.00 | 78.09 ± 0.24 | 09/05/2012       | Kcon(209)_G0217 | 9x5.6            | 6.763 ± 0.024 | 0            | GN-2012B-Q-118 | Quinn     |
| HD 19994 | 14954   | RV     | 1.67           | 1.13 | 22.52 ± 0.10 | 08/31/2005       | PK50_G0201      | 148x30           | 3.75 ± 0.24   | 1            | GN-2005B-Q-4   | Doyon    |
| ε Eri    | 16537   | RV     | 1.56           | 0.92 | 3.203 ± 0.005 | 09/08/2005       | PK50_G0201      | 20x30            | 1.601 ± 0.060 | 0            | GN-2005B-Q-4   | Doyon    |
| HD 34445 | 24681   | RV     | 0.43           | 1.05 | 46.09 ± 0.10 | 02/23/2010       | H$_{\text{2}2}$0203 | 16x0.5           | 5.790 ± 0.023 | 0            | GN-2010A-SV-101 | Engineering |
| KELT-2   | 29301   | Transit| 1.67           | 0.96 | 134.06 ± 0.80 | 04/09/2013       | Kcon(209)_G0217 | 9x7.2            | 7.346 ± 0.031 | 1            | GN-2013A-Q-54 | Quinn     |
| HD 50499 | 32970   | RV     | 0.95           | 0.98 | 46.28 ± 0.06 | 03/06/2008       | CH4(short)       | 6x25             | 5.836 ± 0.016 | 0            | GN-2008A-Q-95 | Croll    |
| HD 89744 | 50786   | RV     | 1.54           | 0.65 | 38.64 ± 0.11 | 06/23/2005       | Brgamma_G0218   | 9x10             | 4.454 ± 0.021 | 0            | GN-2005A-Q-22 | Thomas   |
| GJ 433   | 56528   | RV     | 6.20           | 1.11 | 9.065 ± 0.004 | 05/10/2009       | PK50_G0201      | 4x50             | 5.623 ± 0.021 | 0            | GN-2009A-Q-94 | Dieterich |
| GJ 436   | 57087   | RV     | 2.00           | 1.18 | 9.75 ± 0.01  | 03/23/2008       | CH4(short)       | 11x25            | 6.073 ± 0.016 | 0            | GN-2008A-Q-95 | Croll    |
| HD 102195| 57370   | RV     | 0.25           | 0.82 | 29.34 ± 0.05 | 03/18/2006       | CH4(short)       | 9x30             | 6.151 ± 0.018 | 0            | GN-2006A-Q-5  | Doyon    |
| HD 125612| 70123   | RV     | 1.39           | 1.02 | 57.62 ± 0.16 | 03/23/2006       | PK50_G0201      | 5x25             | 6.838 ± 0.026 | 0            | GN-2008A-Q-95 | Croll    |
| HD 130322| 72339   | RV     | 2.37           | 1.03 | 31.88 ± 0.07 | 05/15/2006       | PK50_G0201      | 10x30            | 6.234 ± 0.023 | 0            | GN-2006A-Q-5  | Doyon    |
| HD 134987| 74500   | RV     | 1.40           | 0.89 | 26.18 ± 0.05 | 03/24/2008       | PK50_G0201      | 4x25             | 4.882 ± 0.016 | 0            | GN-2008A-Q-95 | Croll    |
| ε Dra    | 75458   | RV     | 1.09           | 1.46 | 31.65 ± 0.30 | 03/22/2008       | H-con(157)       | 6x25             | 0.701 ± 0.041 | 0            | GN-2008A-Q-95 | Croll    |
| 14 Her   | 79248   | RV     | 439.78         | 0.98 | 17.93 ± 0.01 | 03/24/2008       | CH4(short)       | 11x25            | 4.714 ± 0.016 | 0            | GN-2008A-Q-95 | Croll    |
| HAT-P-2  | 80076   | Transit| 1.70           | 1.01 | 127.77 ± 0.40 | 07/12/2012       | Kcon(209)        | 4x11.22          | 7.603 ± 0.020 | 0            | GN-2012A-Q-99 | Quinn    |
| HD 168443| 89844   | RV     | 34.02          | 0.94 | 39.62 ± 0.12 | 02/26/2012       | H$_{\text{2}2}$03 | 10x60            | 5.211 ± 0.015 | 0*           | GN-2012A-Q-51 | Wahhaj   |
| HAT-P-11 | 97657   | Transit| 9.61           | 0.98 | 37.76 ± 0.03 | 07/07/2012       | Kcon(209)        | 4x6.15           | 7.009 ± 0.020 | 0*           | GN-2012A-Q-99 | Quinn    |
| GJ 849   | 109388  | RV     | 0.74           | 0.85 | 8.800 ± 0.004 | 06/19/2008       | CH4(short)       | 11x25            | 5.594 ± 0.017 | 0            | GN-2008A-Q-95 | Croll    |
| GJ 876   | 113020  | RV     | 2.01           | 1.13 | 4.675 ± 0.002 | 08/21/2005       | CH4(short)       | 9x30             | 5.010 ± 0.021 | 0            | GN-2005B-Q-4  | Doyon    |

*There are no physically associated companions, but there are other stars in the NRI field-of-view.

Note—The following programs have had their data published previously: GN-2005B-Q-4 and GN-2006A-Q-5 (Galicher et al. 2016), and GN-2009A-Q-94 (Dieterich, Sergio Bonucci 2013).

References—All $K_S$ values are from Cutri et al. (2003), with the exception of those of ε Eri and ε Dra, which are from Adams et al. (2017).