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The polarization of HD 189733

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ABSTRACT

We present linear polarization observations of the exoplanet system HD 189733 made with the HIgh Precision Polarimetric Instrument (HIPPI) on the Anglo-Australian Telescope (AAT). The observations have higher precision than any previously reported for this object. They do not show the large amplitude polarization variations reported by Berdyugina et al. Our results are consistent with polarization data presented by Wiktorowicz et al. A formal least squares fit of a Rayleigh–Lambert model yields a polarization amplitude of 29.4 ± 15.6 parts per million. We observe a background constant level of polarization of ∼55–70 ppm, which is a little higher than expected for interstellar polarization at the distance of HD 189733.

Key words: polarization – techniques: polarimetric – planets and satellites: atmospheres – planets and satellites: individual: HD 189733b.

1 INTRODUCTION

The characterization of exoplanet atmospheres, particularly with ground-based telescopes, is a difficult task. Polarimetry offers a useful approach, providing a strong contrast between the star and planet as the star's light is typically unpolarized (Seager, Whitney & Sasselov 2000). Large and tightly orbiting hot Jupiter planets scatter enough light to potentially produce a polarization signal dependent largely upon the composition of the atmosphere (Hough & Lucas 2003). The detection of linearly polarized light from an exoplanet system can provide information about a planet's orbital orientation and about the properties of the particles that scatter the light in its atmosphere. The technique therefore provides complementary information to other characterization techniques such as transit and eclipse spectroscopy.

Seager et al. (2000) modelled the expected polarization levels for hot Jupiter-type systems and predicted that linear polarization varying over the orbital cycle at the tens of parts-per-million level might be present in the combined light of the star and planet. Since Sun-like stars are thought to generally have low polarizations (Bailey, Lucas & Hough 2010; Cotton et al. 2016) this technique provides good contrast and should be achievable from ground-based observations. Past attempts at polarized light detection such as those described in Lucas et al. (2009) have not detected significant planetary polarization signals.

The HD 189733 hot Jupiter system (Bouchy et al. 2005; Torres, Winn & Holman 2008) is one of the brightest and best-studied transiting exoplanet systems. Observations of transits and eclipses of HD 189733b using the *Hubble Space Telescope* have shown strong evidence for a Rayleigh scattering haze in its atmosphere, which shows up as increasing absorption towards shorter wavelengths in the transit spectrum (Pont et al. 2008, 2013) as well as reflected light seen in the secondary eclipse at blue wavelengths (Evans et al. 2013). This makes HD 189733b a promising target for polarimetric observations.

However, polarization observations of this system to date have produced conflicting results. Berdyugina et al. (2008) reported an unexpectedly high level of polarization variation of ∼200 ppm (parts per million) from the HD 189733 exoplanet system using the DIPol instrument (Piirola et al. 2005) at La Palma's KVA (Royal Swedish Academy of Sciences) telescope. Subsequently Wiktorowicz (2009) reported no polarization variation with an upper limit of 79 ppm (99 per cent confidence) using the POLISH instrument. Further observations (Berdyugina et al. 2011) using TurPol (Piirola 1973) on the Nordic Optical Telescope in three bands showed a polarization signal in the *U* and *B* bands but not in the *V* band. They argued that the non-detection by Wiktorowicz (2009) was due to the use of too red a band. The amplitude reported in the *B* band was 100 ± 10 ppm. The polarization was attributed to Rayleigh scattering from the planet's atmosphere.

More recently Wiktorowicz et al. (2015) have reported *B*-band polarization measurements of HD 189733 using the POLISH2 instrument on the Lick Observatory 3-m telescope. They set a limit

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on the *B*-band polarization amplitude of 60 ppm (99.7 per cent confidence).

This Letter presents the most sensitive measurements of the system to date using a blue broad-band filter in an attempt to distinguish between these conflicting results.

2 OBSERVATIONS

HD 189733 was observed during three observing runs on the 3.9-m Anglo-Australian Telescope (AAT) at Siding Spring Observatory, New South Wales, Australia. The observations were made with the HIgh Precision Polarimetric Instrument (HIPPI; Bailey et al. 2015). The dates of observations were 2014 Aug 28–31, 2015 May 23, 26 and Jun 26. HIPPI is an aperture polarimeter using a ferroelectric liquid crystal (FLC) modulator, a Wollaston prism analyser and two photomultiplier tubes (PMT) as detectors. The FLC provides a 500 Hz primary modulation which is used together with two additional stages of slower modulation obtained by rotation of the Wollaston prism and detectors, and finally by rotating the whole instrument to four position angles (0°, 45°, 90°, 135°) using the AAT's Cassegrain rotator.

HIPPI has been shown from repeat observations of bright low polarization stars to deliver a precision of 4.3×10^{-6} (4.3 ppm) or better (Bailey et al. 2015). This is comparable to or better than the precisions reported from polarimeters based on photoelastic modulators such as the Pine Mountain Observatory polarimeter (Kemp & Barbour 1981), PlanetPOL (Hough et al. 2006), POLISH (Wiktorowicz & Matthews 2008) and POLISH2 (Wiktorowicz & Nofi 2015; Wiktorowicz et al. 2015).

HIPPI uses Hamamatsu H10720-210 PMT modules that have ultrabialkali photocathodes with a peak quantum efficiency of 43 per cent at 400 nm. The HD 189733 observations were made through a 500 nm short pass filter (referred to as 500SP) to exclude any red light from the K 1.5 V star. The overall bandpass covers 350–500 nm (the polarization optics cut off light below 350 nm) and the effective wavelength calculated from the bandpass model described by Bailey et al. (2015) is 446.1 nm. This is a similar but somewhat broader band than the *B* band used by Berdyugina et al. (2011) and Wiktorowicz et al. (2015).

The moonlit sky can contribute a significant polarized background signal within our 6.7 arcsec diameter aperture. The 2014 August observations were all made with lunar illumination phases less than 35 per cent but with the Moon near 90° seperation from HD 189733b where Rayleigh scattering is at a maximum. The 2015 observations were all made after the Moon had set. Any residual background signal is subtracted from the data using a sky observation made immediately after each science observation at each Cassegrain rotator position.

The telescope introduces a small polarization (telescope polarization or TP) that must be corrected for. As described in Bailey et al. (2015) we determine the TP using observations of a number of stars we believe to have very low polarization either based on previous PlanetPol observations (Hough et al. 2006; Bailey et al. 2010) or because of their small distances and expected low levels of interstellar polarization (see Bailey et al. 2010; Cotton et al. 2016). The telescope polarization has been found to be stable during each run, and between the 2015 May and June runs, but changed signficantly from 2014 to 2015, probably as a result of the realuminization of the AAT primary mirror in early 2015. Determinations of TP in the SDSS g' filter are reported in Bailey et al. (2015) and Cotton et al. (2016) giving values of 48 ± 5 ppm in 2014, and 36 ± 1 ppm in 2015.

Table 1. Low polarization star measurements to determine telescope polarization (TP) in the 500SP filter. The adopted TP for the 2014 August and 2015 May runs use only measurements acquired on that run. The 2015 June run uses measurements from both 2015 May and June.

Star	Date	p (ppm)	θ (°)
β Hyi	Aug 29	60.7 ± 4.4	109.3 ± 2.1
β Hyi	Aug 30	63.6 ± 4.3	110.0 ± 2.0
BS 5854	Aug 31	60.6 ± 4.7	111.4 ± 2.2
β Hyi	Aug 31	51.9 ± 4.6	112.4 ± 2.6
Adopted TP	2014 Aug	59.1 ± 2.2	110.7 ± 1.1
BS 5854	May 22	38.7 ± 5.3	83.3 ± 3.9
Sirius	May 23	44.8 ± 0.9	87.2 ± 0.6
β Hyi	May 26	49.8 ± 11.7	88.4 ± 6.9
Adopted TP	2015 May	44.3 ± 3.4	86.5 ± 2.3
BS 5854	Jun 26	50.2 ± 4.8	97.2 ± 2.8
Adopted TP	2015 Jun	45.8 ± 2.8	86.7 ± 1.8

Table 2. The data before binning and efficiency correction. The datum marked with a † is believed to be a physical outlier and is not binned with the other data.

UT Date and Time	Q/I (ppm)	U/I (ppm)
2014:08:28 11:25:52	64.2 ± 14.0	11.5 ± 20.2
2014:08:28 12:29:38	− 14.3 ± 22.3	18.0 ± 21.2
2014:08:28 13:31:19	28.3 ± 21.6	54.0 ± 22.3
2014:08:29 10:18:49	11.9 ± 19.2	29.0 ± 19.0
2014:08:29 11:25:24	9.9 ± 19.0	− 8.1 ± 19.1
2014:08:29 12:29:08	30.0 ± 19.3	29.9 ± 20.7
2014:08:30 10:53:57	39.5 ± 21.1	14.9 ± 21.8
2014:08:30 12:00:11	38.9 ± 19.2	15.1 ± 21.8
2014:08:30 13:05:23	51.5 ± 19.5	21.4 ± 19.3
2014:08:31 10:18:26	58.0 ± 18.6	17.4 ± 19.0
2014:08:31 11:24:40	33.1 ± 19.0	44.4 ± 18.4
2014:08:31 12:11:13	42.4 ± 25.0	72.3 ± 25.0
2014:08:31 12:47:49 †	77.0 ± 26.7	85.2 ± 26.6
2015:05:23 16:50:38	22.1 ± 22.8	5.1 ± 23.1
2015:05:23 17:50:59	45.0 ± 20.9	40.1 ± 20.9
2015:05:23 18:50:20	38.7 ± 20.6	18.6 ± 20.9
2015:05:26 16:30:20	54.0 ± 19.7	21.6 ± 19.7
2015:05:26 17:32:55	57.4 ± 19.1	47.9 ± 19.3
2015:05:26 18:32:07	69.5 ± 21.2	28.5 ± 21.4
2015:06:26 16:33:18	− 6.2 ± 18.8	45.5 ± 18.9
2015:06:26 17:30:07	37.4 ± 19.3	63.7 ± 19.2

We have also made a smaller number of TP observations directly in the 500SP filter used with HD 189733 as listed in Table 1. These observations consistently show telescope polarizations of 22–25 per cent higher values than the more extensive g' band observations.

Full details of the observation, calibration, and data reduction procedures with HIPPI can be found in Bailey et al. (2015).

3 RESULTS

The unbinned polarization results before efficiency correction on HD 189733, corrected for telescope polarization using the values in Table 1, are listed in Table 2. Each of these measurements is the result of approximately one hour of total observation (half this for the last two points on 2014:08:31). We list the mid-point time and the normalized Stokes parameters Q/I and U/I are given in ppm on the equatorial system. One further correction is required to the

Table 3. Nightly means of the linear polarization of HD 189733.

UT Date and Time	HMJD	Phase	Q/I (ppm)	U/I (ppm)
2014:08:28 12:28:56	56897.52397	0.30255	31.7 ± 13.8	33.8 ± 14.9
2014:08:29 11:24:27	56898.47916	0.73309	21.0 ± 13.4	20.6 ± 13.8
2014:08:30 11:59:50	56899.50369	0.19488	52.6 ± 14.0	20.8 ± 14.3
2014:08:31 11:07:29	56900.46731	0.62923	54.5 ± 14.3	47.6 ± 14.2
2015:05:23 17:50:39	57165.74522	0.20064	42.8 ± 15.1	25.8 ± 15.2
2015:05:26 17:31:47	57168.73232	0.54704	73.2 ± 14.0	39.7 ± 14.1
2015:06:26 17:01:43	57199.71313	0.51133	19.0 ± 16.4	66.3 ± 16.4
Average			42.7 ± 5.4	35.4 ± 5.5

data and this is for the wavelength dependent modulation efficiency of the instrument. This is calculated using the bandpass model described by Bailey et al. (2015) specifically for each observation. The value is close to 82.4 per cent for all of these observations.

The nightly means of the corrected observations each consisting of approximately two to three hours total observing time are given in Table 3. One point (2014:08:31 12:47:49) has been omitted from the binned data as it is believed to be affected by variable sky background due to the Moon setting mid observation.

Orbital phase is calculated according to the ephemeris (Triaud et al. 2009) where zero phase corresponds to mid-transit.

$$T = HMJD\,53988.30339 + 2.21857312\,E. \quad (1)$$

The errors of our nightly means are typically 13–16 ppm. This can be compared with errors of typically 20–40 ppm for the nightly means of POLISH2 observations (Wiktorowicz et al. 2015)

4 DISCUSSION

4.1 Comparison with previous results

Our results differ significantly from those reported by Berdyugina et al. (2011). While we see consistently positive values of Q/I and U/I, Berdyugina et al. (2011) show near zero values at phases 0.0 and 0.5, with a strong negative excursion around phases 0.3 and 0.7, reaching an amplitude of nearly 100 ppm in Q/I. Even if we allow an arbitrary zero-point shift, our data are not consistent with such a large amplitude variation in Q/I.

Our data are in much better agreement with the results of Wiktorowicz et al. (2015). This data set shows generally positive Q/I and U/I with average values (from data in their table 3) of Q/I = 19.2 ± 4.1 ppm and U/I = 40.3 ± 3.5 ppm, which are in reasonable agreement with our averages of Q/I = 42.7 ± 5.4 and U/I = 35.4 ± 5.5 ppm. The differences can probably be understood as due to uncertainties in the telescope polarization of the Lick telescope which Wiktorowicz et al. (2015) report is variable at the 10 ppm level.

4.2 Rayleigh–Lambert model

We have fitted our data with a Rayleigh–Lambert model for the expected polarization variation. This is a simple analytic model which calculates the intensity according to the expected phase variations for a Lambert sphere, and assumes the polarization follows the phase function for Rayleigh scattering (see: Seager et al. 2000 and Wiktorowicz 2009). To find the best fit we use a Levenberg–Marquardt non-linear least squares algorithm (Press et al. 1992) with five parameters: the polarization zero-point offsets in Q/I and U/I (Z_q and Z_u), the polarization amplitude p which allows the effects of depolarization processes such as multiple scattering to be taken into account, the position angle of the major axis of the projected orbit ellipse on the sky PA and the orbital inclination i. The fitted parameters and their uncertainties (determined from the covariance matrix of the fit) are listed in Table 4. The fitted model is shown by the red curve on Fig. 1.

Table 4. Parameters of Rayleigh–Lambert fit to HIPPI linear polarization observations of HD 189733.

Parameter	Value	Units
Z_q	53.7 ± 9.6	ppm
Z_u	45.1 ± 9.5	ppm
p	29.4 ± 15.6	ppm
pa	114.4 ± 19.0	degrees
i	87.6 ± 6.6	degrees

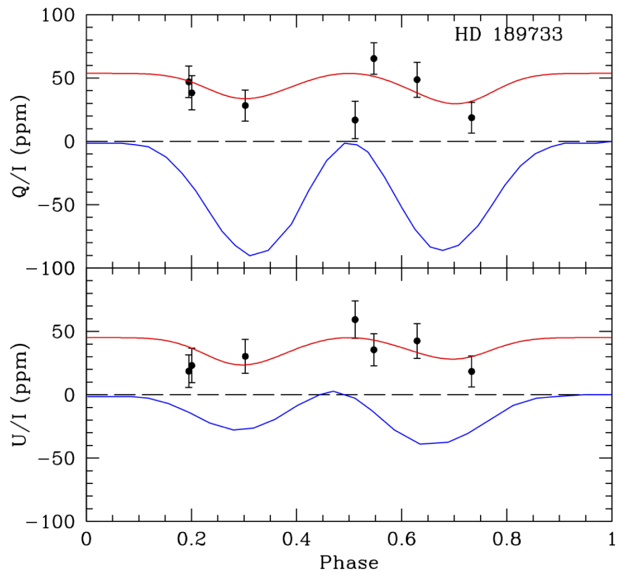

Figure 1. HIPPI measurements of the polarized light from the HD 189733 system. The binned measurements from Table 3 are shown. The red curve is a least squares fit of a Rayleigh–Lambert model as described in Section 4.2. The blue lines show the best-fitting curves for the data of Berdyugina et al. (2011).

The less than 2σ uncertainty on the polarization amplitude means that this cannot be considered as a detection of polarized light from the planet. A model with no polarization variation due to the planet is still an acceptable fit to the data. However, it is interesting that our best-fitting polarization amplitude of 29.4 ± 15.6 ppm is at a level that is in agreement with plausible values for Rayleigh scattering from the planet. For example Lucas et al. (2009) estimate an amplitude of 26 ppm for a Rayleigh-like multiple scattering model with a single scattering albedo of 0.99. This is an optimistic model because in reality we would expect a modest reduction in the amplitude due to (i) atomic and molecular absorption features and (ii) the Rayleigh depolarization factor of 0.02 (Penndorf 1957; Hansen & Travis 1974) which reduces the polarization at each scattering event. Considering the geometric albedo from a fractional eclipse depth of ∼126 ppm from 290–450 nm reported in Evans et al. (2013), and the Rayleigh scattering model grid of Buenzli & Schmid (2009) which would place an upper limit to the amplitude of the polarized light contribution at about 30 per cent of the geometric albedo, we can estimate an upper bound for a Rayleigh scattering atmosphere to be ∼37.8 ppm.

A more extensive set of observations with an instrument like HIPPI on a 4-m class telescope might be capable of detecting the expected planetary signal in this and other bright hot Jupiter systems. Putting a similar instrument on an 8-m class telescope should enable the measurement uncertainties to be halved from ∼14 ppm to ∼7 ppm, making detection of the expected signals at levels of ∼20 ppm possible.

4.3 Constant polarization

A clear result of our observations, is that in addition to any polarization from the planet, there is a constant background level of polarization from HD 189733. Depending on what we assume about the planetary signal, this ranges from around 55 ppm, if we use the values given in Section 4.1 for no planetary signal, to 70 ppm for the best-fitting model of Table 4. Interstellar polarization is the most likely source of polarization in typical solar-like stars (Bailey et al. 2010; Cotton et al. 2016).

Extrapolating from the trends in fig. 4 in Cotton et al. (2016), we would expect a star at ∼19 pc (Koen et al. 2010), in the Northern hemisphere and in the Galactic plane to have a polarization between 15 and 40 ppm. This is rather less than the values we find for HD 189733.

Circumstellar dust can also produce a constant offset for the polarized light signal from a system. However, Bryden et al. (2009) found HD 189733 was unlikely to have circumstellar dust substantial enough to affect polarization measurements based upon measurements of infrared excess. The effect of circumstellar dust on a system's polarized light measurements would be an addition to the offsets Z_q and Z_u which would not vary over the time-scale of the planet's orbit.

4.4 Effect of starspots on system polarimetry

There are other possible sources that could be contributing to polarized light in the system. HD 189733A is an active BY Draconis type variable star: a star whose brightness varies due to star spots moving across its surface. Star spots can cause linear polarization by breaking the circular symmetry of the limb polarization (Moutou et al. 2007). However Berdyugina et al. (2011) found that starspots would only cause a maximum of 3 ppm contribution to polarized light based on the photometric transit curve deviations from Winn et al. (2007). Similarly, Kostogryz, Yakobchuk & Berdyugina (2015) estimated the contribution of starspots on the polarized light signal to be only $\sim 2 \times 10^{-6}$. The interplay between the planet and starspot symmetry breaking can produce detectable effects during the planet's transit. However none of our observations are taken during transit.

The linearly polarized light from the starspots themselves, is negligible (Afram & Berdyugina 2015) under most circumstances. Magneto-optical effects such as the transverse Zeeman effect (Huovelin & Saar 1991) or the Faraday effect (Calamai, Landi Degl'Innocenti & Landi Degl'Innocenti 1975) could introduce noise to the linear polarization measuements if enough lines were present within our bandpass or if significant starspot coverage is present along with extended ionized gases from the planet's atmosphere respectively.

The rotational period of HD 189733A is known to be longer, at 11.8 d (Moutou et al. 2007), than the orbital period of HD 189733b (2.2 days, Triaud 2010). With additional observations it should be possible to determine whether the magnitude of activity associated with starspots is significant, and disentangle it from that due to reflection from clouds in the planetary atmosphere. Regardless, in any analysis focused on the orbital period, starspot effects will average out over time.

4.5 Effect of Saharan dust on La Palma observations

The large polarization amplitudes for HD 189733 reported by Berdyugina et al. (2011) are not seen in the other three data sets now reported for this object, Wiktorowicz (2009), Wiktorowicz et al. (2015) and this work.

The strongest evidence for polarization variation found by Berdyugina et al. (2011) was in the *B* band TurPol data from the Nordic Optical Telescope on La Palma obtained on dates of 2008 Apr 18–24, and 2008 Aug 2–9. They note that the August data was affected by Saharan dust but argue that this should not cause any effect on the results as '*TurPol enables exact compensation of any background polarization that is not variable...*'. This statement misunderstands how airborne dust impacts on precision polarimetry. It is not a background sky polarization that could be automatically subtracted by the instrument's sky-subtraction capability. The dust introduces a spurious polarization into starlight passing through the dust. The effects were studied in detail by Bailey et al. (2008) using observations of a Saharan dust event observed with PlanetPol in 2005.

Data from the Carlsberg Meridian Telescope[1] on La Palma show a substantial Saharan dust event over 2008 Aug 2–9 with the r' band extinction ranging from 0.212 to 0.377 throughout this period (compared with a normal clear sky level of ∼0.09). This is a larger and more extended event than the one observed in 2005 by Bailey et al. (2008) which led to spurious polarization effects up to 48 ppm at 56° zenith distance. It seems highly likely that the HD 189733 data reported by Berdyugina et al. (2011) are significantly affected by this dust. As the individual observations are not reported, it is not possible to judge the extent of the problem. However, without exclusion or correction of affected data, this cannot be regarded as a reliable data set for precision polarimetry.

5 CONCLUSIONS

We have reported new polarization observations of the hot Jupiter exoplanet system HD 189733. The observations have higher precision than any previously reported for this object. We do not detect the large polarization amplitude (100–200 ppm) planetary signals previously reported (Berdyugina et al. 2008, 2011). Our results agree reasonably well with the results of Wiktorowicz et al. (2015)

[1] http://www.ast.cam.ac.uk/~dwe/SRF/camc_extinction.html

showing generally positive polarization values in Q/I and U/I, and at most a small planetary polarization signal.

A least-squares fit of a Rayleigh–Lambert model gives a polarization amplitude of 29.4 ± 15.6 ppm. While this signal has less than 2σ significance and cannot be claimed as a detection of planetary polarization, it is at a level consistent with a plausible polarization amplitude from the planet. It is consistent with a multiply scattering atmosphere which could produce the albedo measurements taken by Evans et al. (2013). This suggests that a more extensive series of observations, or observations on a larger telescope should enable the planetary polarization to be detected and measured.

HD 189733 has a significant constant background level of polarization that is a somewhat higher than would be expected for interstellar polarization. This could be due to the non-uniformity of the Local Hot Bubble interstellar medium.

We suggest that the polarization data of Berdyugina et al. (2011), which shows a large polarization amplitude inconsistent with that reported by other groups, may be unreliable as a result of spurious polarization due to a Saharan dust event over the La Palma observatory in 2008 August.

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REFERENCES

Afram N., Berdyugina S. V., 2015, A&A, 576, A34
Bailey J., Ulanowski Z., Lucas P. W., Hough J. H., Hirst E., Tamura M., 2008, MNRAS, 386, 1016
Bailey J., Lucas P. W., Hough J. H., 2010, MNRAS, 405, 2570
Bailey J., Kedziora-Chudczer L., Cotton D. V., Bott K., Hough J. H., Lucas P. W., 2015, MNRAS, 449, 3064
Berdyugina S. V., Berdyugin A. V., Fluri D. M., Piirola V., 2008, ApJ, 673, L83
Berdyugina S. V., Berdyugin A. V., Fluri D. M., Piirola V., 2011, ApJ, 728, L6
Bouchy F. et al., 2005, A&A, 444, L15
Bryden G. et al., 2009, ApJ, 705, 1226
Buenzli E., Schmid H. M., 2009, A&A, 504, 259
Calamai G., Landi Degl'Innocenti E., Landi Degl'Innocenti M., 1975, A&A, 45, 297
Cotton D. V., Bailey J., Kedziora-Chudczer L., Bott K., Lucas P. W., Hough J. H., Marshall J. P., 2016, MNRAS, 455, 1607
Evans T. M. et al., 2013, ApJ, 772, L16
Hansen J. E., Travis L. D., 1974, Space Sci. Rev., 16, 527
Hough J. H., Lucas P. W., 2003, in Fridlund M., Henning T. Compiled by Lacoste H., eds, ESA SP-539: Proceedings of the Conference on Towards Other Earths: DARWIN/TPF and the Search for Extrasolar Terrestrial Planets. ESA, Noordwijk, p. 11
Hough J. H., Lucas P. W., Bailey J. A., Tamura M., Hirst E., Harrison D., Bartholomew-Biggs M., 2006, PASP, 118, 1302
Huovelin J., Saar S., 1991, ApJ, 347, 319
Kemp J. C., Barbour M. S., 1981, PASP, 93, 521
Koen C., Kilkenny D., Van Wyk F., Marang F., 2010, MNRAS, 393, 229
Kostogryz N. M., Yakobchuk T. M., Berdyugina S. V., 2015, ApJ, 806, 1, 97
Lucas P. W., Hough J. H., Bailey J. A., Tamura M., Hirst E., Harrison D., 2009, MNRAS, 403, 1949
Moutou C. et al., 2007, A&A, 473, 651
Penndorf R., 1957, J. Opt. Soc. Amer., 47, 176
Piirola V., 1973, A&A, 27, 383
Piirola V., Berdyugin A., Mikkola S., Coyne G. V., 2005, ApJ, 632, 576
Pont F., Knutson H., Gilliland R. L., Moutou C., Charbonneau D., 2008, MNRAS, 385, 109
Pont F., Sing D. K., Gibson N. P., Aigrain S., Henry G., Husnoo N., 2013, MNRAS, 432, 2917
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, Numerical Recipes in FORTRAN: The Art of Scientific Computing. Cambridge Univ. Press, Cambridge
Seager S., Whitney B. A., Sasselov D. D., 2000, ApJ, 540, 504
Torres G., Winn J. N., Holman M. J., 2008, ApJ, 677, 1324
Triaud A. H. M. J. et al., 2009, A&A, 506, 377
Triaud A. H. M. J. et al., 2010, A&A, 524, A25
Wiktorowicz S. J. Matthews K., 2008, PASP, 120, 1282
Wiktorowicz S. J., 2009, ApJ, 696, 1116
Wiktorowicz S., Nofi L. A., 2015, ApJ, 800, L1
Wiktorowicz S., Nofi L. A., Daniel J.-T., Kopparla P., Laughlin G. P., Hermis N., Yung Y. L., Swain M. R., 2015, ApJ, 813, 48
Winn J. N. et al., 2007, AJ, 133, 4

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