The 16th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun
ASP Conference Series, Vol. 448, Electronic Edition
Christopher M. Johns-Krull, Matthew K. Browning, and Andrew A. West, eds.

The WFCAM Transit Survey: A Search for Rocky Planets Around Cool Stars

Jayne Birkby,[1] Simon Hodgkin,[1] David Pinfield,[2] and the WTS consortium and members of the EC funded RoPACS initial training network

[1]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK*

[2]*Centre for Astrophysics Research, Science and Technology Research Institute, University of Hertfordshire, Hatfield, AL10 9AB, UK*

Abstract. We report on the WFCAM Transit Survey which is a near-infrared photometric monitoring campaign designed primarily to test the predictions of planet formation theory. We monitor a statisically significant sample of $\sim 6,000$ M-dwarfs ($M<0.6M_{\odot}$) across 6 sq. deg of the sky, by taking advantage of the highly-efficient queue-scheduled operational mode of the 3.8m United Kingdom Infrared Telescope. Our light curves have RMS $<1\%$ between $13 < J < 16$ magnitudes and preliminary simulations indicate the survey is sensitive to at least Jupiter-like transits of M-dwarfs. The survey is approximately 25% complete and within this dataset we find i) no planet-like transit events, despite thorough and extensive follow-up this summer and ii) 32 new M-dwarf eclipsing binaries. We do not speculate on the planet fraction of M-dwarfs at this incomplete stage of our survey, but once we achieve 1,000 epochs of observation on our entire M-dwarf sample, we will have a significant observational constraint to place on occurrence of planets around M-dwarfs. We report masses and radii for three of our newly discovered eclipsing binary, with errors of $3-7\%$, which all show inflated radii when compared to stellar evolution models (e.g. Baraffe et al. (1998)). Our results support the growing body of observations with inflated M-dwarf radii, which may be caused by increased magnetic activity inhibiting the convection efficiency or increased star spot coverage (e.g. Chabrier et al. (2007); Jackson et al. (2009)). Finally, we present preliminary mass and radius estimates of a fourth new eclipsing binary, which is one of the lowest mass binary systems ever discovered and will provide a calibrating point in the desert of observations between 0.1-0.2$M_{\odot}$.

1. Introduction

The theory of planet formation via core accretion makes an intriguing and observable prediction that the formation of rocky and icy planets is common around M-dwarfs but that hot-Jupiters are extremely difficult to produce. This report details the ongoing WFCAM Transit Survey which was designed to test this prediction.

The core accretion paradigm is, briefly, as follows: Phase 1 - an initial core build up of mostly solid material that experiences a runaway accretion until it depletes the feeding zone; Phase 2 - the accretion of solid material and gas at relatively small rates and it is this phase that determines the overall time-scale for planet formation; Phase 3 - when the masses of accreted solid material and gas are approximately equal, the planet experiences a runaway gas accretion, creating gas giant planets as it continues (Perri &

Cameron 1974; Mizuno et al. 1978; Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996). Pollack et al. (1996) suggest that it can take ~ 8Myrs to reach Phase 3 but the models are sensitive to assumed grain opacities and the density of the solids in the disc. More recent work by Laughlin et al. (2004) shows that Jupiter mass objects can form around a solar mass star in just over 3Myrs. However, for M-dwarf systems, this process can take considerably longer due to less angular momentum, which leads to slower disc dynamics. Observations of specific age stellar populations show that the fraction of stars with discs rapidly decreases with time. The effects of disc dispersal mechanisms, such as X-ray photo-evaporation (Owen et al. 2010), leave < 5% of stars with surviving gas discs after 10Myrs. Ida & Lin (2005) performed core accretion based Monte Carlo simulations to study the distribution of planet mass as a function of star-planet separation. Their results, which allowed for migration and disc evolution, indicated that for increasingly lower mass host stars, the existence of Jupiter mass objects wanes for all separations, and at $0.2M_{\odot}$ the pile up of objects close to their host star, where numerous 'Hot Jupiters' have been detected around solar type stars, becomes limited to icy cores i.e. 'Hot Neptunes'. However, there are a few detections of more massive planets around M-dwarfs, notably the microlensed system OGLE-06-109L (Gaudi et al. 2008), which is a $\sim 0.5M_{\odot}$ host star with two planets of $\sim 0.71M_J$ and $\sim 0.27M_J$ at separations of ~ 2.3AU and ~ 4.6AU. Gaudi et al. (2008) suggest that the detection of this system from only six confirmed microlensing planet detections indicates these scaled down solar system analogues could be common.

2. The Survey

It is clear that we need a large, statistically significant sample of M-dwarfs to fully address the predictions of planet formation theory, and to provide observations of a key physical process in discs, which is essentially unconstrained (Alexander & Armitage 2009). For this purpose, we have designed a photometric monitoring campaign, called the WFCAM Transit Survey (WTS), to search for transiting planets around M-dwarfs, with the aim of populating the observational gap in the M-dwarf mass regime ($< 0.6M_{\odot}$).

M-dwarfs are ideal targets for transit surveys. A Jupiter radius object transiting a mid M-dwarf will cause a relative flux decrease of ~ 10%, an order of magnitude more than if it transited a solar radius star. A flux decrease of 10% is easily detected with relatively small ground-based telescopes (< 4m) and we can readily achieve 1% precision photometry from the ground, meaning one can also detect the transits of Neptunes and large rocky planets around mid M-dwarfs. For very late type M-dwarfs ($0.1M_{\odot}$), the stellar radius is equal to the radius of Jupiter allowing the detection of a transit of an Earth-size object orbiting an M8 dwarf from the ground (see figure 1). In addition, a transiting planet provides the inclination angle needed to break the sin(i) degeneracy in its mass measurement, along with a measurement its density, the opportunity to study the planetary atmosphere via transmission spectroscopy, and the contrast ratio between M-dwarfs and planets compared to solar type stars is much more favourable for direct imaging.

There is one caveat in determining the properties of planets transiting M-dwarf stars. Exoplanet properties derive from the mass and radius of their host star however, the mass-radius relationship below $1M_{\odot}$ is not well-calibrated (see e.g. Morales et al. (2010)). The best calibrators for this relationship are double-lined eclipsing binaries

(EBs), whose masses and radii can be measured very precisely (~ 2%, Torres et al. (2009); Andersen (1991)) in a model- and distance- independent manner. But, there are only ~ 10 M-dwarf EBs with sufficient precision to constrain the mass-radius relationship and those measurements significantly disagree with current state-of-the-art stellar evolution models, such as the models of Baraffe et al. (1998), which under-predict the radii of M-dwarfs by $5 - 10\%$ (López-Morales & Ribas 2005). Recent work has attempted to relate the discrepancies to increased magnetic activity which could inhibit convective efficiency or increase star spot coverage (Chabrier et al. 2007; Jackson et al. 2009). When this error in the host star radius is propagated to any exoplanet parameters, it can mean the difference between an ocean planet or a planet enshrouded in an H/He envelope (see Charbonneau et al. (2009) for an example). Fortunately, in a transit survey, M-dwarf eclipsing binaries are easily detected and essentially provide a means of self-calibration. The precise measurement of a significant sample of M-dwarf eclipsing binaries is a further science goal of the WFCAM Transit Survey.

2.1. Survey design

Existing transit surveys, with the exception of the MEarth project (Nutzman et al. 2009), do not go faint enough to include a statistically significant sample of low mass stars. We attempt to maximise our sensitivity to the M-dwarf population by observing a large area (many stars) in the J-band (the peak of a cool star's spectral energy distribution) with a large aperture telescope. The United Kingdom InfraRed Telescope with the Wide-Field Camera (UKIRT+WFCAM) offered a unique opportunity thanks to the highly efficient queue-scheduled operational mode of the telescope. We noted that there was room for a flexible proposal in the queue, which did not require the very best observing conditions. Most of the ongoing UKIRT programmes ask for good seeing and a photometric sky, they also do not have uniform coverage in Right Ascension. We realised that we could design an observing campaign that would always have a target visible, and could handle mediocre seeing and thin cloud cover. We chose four target regions to give us year-round visibility, each passing close to the zenith at Mauna Kea (within 15 degrees). We decided to stay reasonably close to the galactic plane to increase the numbers of early M-dwarfs. We restricted ourselves to $b > 5$ degrees to avoid the worst effects of overcrowding. WFCAM's pixels ($0.4''$/pix) are significantly smaller than those of most small aperture ground-based transit survey instruments, such as SuperWASP. This has the useful advantage of reducing the numbers of blended targets, and therefore the numbers of transit mimics. Also, our M-dwarf targets automatically protect us from the common transit mimic where an M-dwarf eclipses a much hotter F-star. The secondary eclipse signal is often undetectable and thus appears as a transiting event, but as we are focusing on M-dwarf primaries, we do not encounter such mimics. Our most pernicious mimics are grazing or equal depth M-dwarf eclipsing binaries which can be shallow events. However, as mentioned, these EBs can still be useful for calibrating the mass-radius relationship. Finally, we combined 2MASS photometry and the Schlegel maps to select fields that maximised the ratio of dwarfs to giants (Cruz et al. 2003), while maintaining E(B-V)<0.1. Each WTS field covers 1.5 sq. degrees of sky and consists of eight pointings of the WFCAM paw print, exposing for a 9-point jitter pattern with 10 second exposures at each position, and tiled to give uniform coverage across the field. It takes 15 minutes to observe an entire field once, resulting in 4 data points per hour. The survey aims to observe each of the four fields one-thousand times in order to have enough data to reliably detect transiting and eclipse-like events.

2.2. Data quality

We follow the data reduction steps outlined by Irwin et al. (2007) to perform variable aperture photometry on all the time-series images. The procedure flags objects that have overlapping isophotes as blends and a morphological image classification flag highlights non-stellar objects (Irwin & Lewis 2001). We achieve a per data point photometric precision of 3-4mmag for the brightest objects, with RMS scatter $< 1\%$ for $J \lesssim 16$, which is sufficient to detect transiting planets around mid M-dwarfs (see figure 1). Saturation occurs at $J \sim 12.8$. We are currently working to increase our precision through improved background subtraction techniques and by removing signatures of correlated noise from the light curves. Preliminary simulations of the sensitivity of the WTS light curves, based on the recovery rates for fake transits injected into our real data, indicate that the data are sensitive to Jupiter-sized objects and we are awaiting the results for Neptune-sized objects.

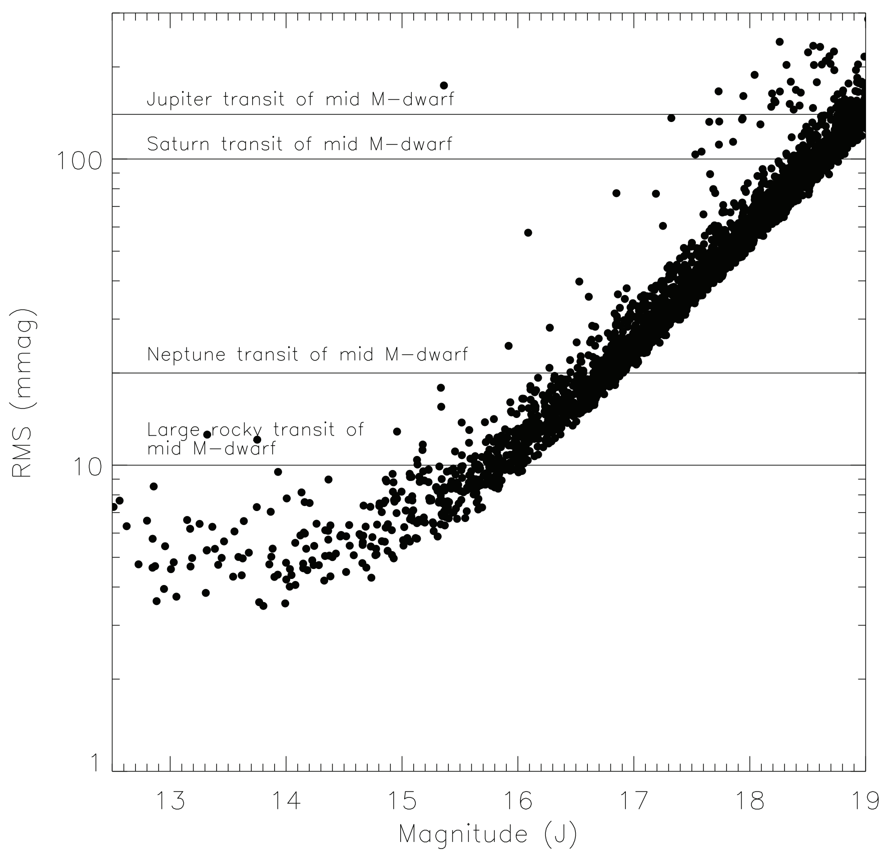

Figure 1. The RMS scatter per data point of the WTS light curves as a function of J-band magnitude, for all unblended objects in the 19hr field with stellar morphological classification. We achieve a per data point photometric precision of 3-4mmag for the brightest objects, with RMS scatter $< 1\%$ for $J \lesssim 16$. The solid horizontal lines mark the change in flux caused by the transits of various sized objects around mid M-dwarfs.

2.3. The M-dwarf Sample

Two of the WTS fields overlap with SDSS coverage and thus we combine the u, g, r, i and z photometry of SDSS with our WFCAM Z, Y, J, H and K magnitudes to fit initial SEDs to classify the stars in the field-of-view. To date, one of our fields (at RA∼ 19hrs) has 1,000 epochs of observation. For now, we use details from this field to extrapolate the numbers of M-dwarfs in the entire WTS. We limit our transit search to $J \leq 16$ mags due to the lack of current instrumentation that could follow-up objects fainter than this. Across the entire survey, we have $\sim 6,000$ M-dwarfs between $13 < J < 16$ with spectral type M0V-M4V.

3. New M-dwarf eclipsing binaries on the mass-radius relationship

We report here on the results from one field from the WTS, i.e. the quarter of the survey that contains $\sim 1,000$ epochs of observation. In this field alone, we have identified 32 new M-dwarf eclipsing binary systems, all with estimated primary masses $< 0.6\mathrm{M}_\odot$. Figure 2 shows three of the EBs in our sample that we were able to follow-up spectroscopically this summer using the intermediate resolution spectrograph, ISIS on the William Herschel 4-m telescope in La Palma (WHT). Despite their relative faintness, we still achieve an RMS of $\sim 2-3$km/s for the radial velocity measurements, which translates to mass and radius errors between $3-7\%$. The positions of our new objects in the mass-radius plane are denoted by the open red, green and blue squares in figure 3. All theses objects appear to be inflated when compared to the 5Gyr isochrone from the Baraffe et al. (1998) models. Low-resolution spectra of the binaries showed Hα emission implying magnetic activity in the chromosphere. Our results give weight to the theory that increased magnetic activity plays an important role when determining the radii of M-dwarfs and it is clear from this growing body of evidence and from discussion at the Cool Stars 16 meeting that evolutionary models must attempt to account of magnetic activity in this mass regime (see I. Baraffe's report in these proceedings). Note that the periods of the WTS EBS range from 1.5-5.0 days (green squares correspond to the 5-day orbital period binary). While we expect tidal circularisation to have occurred in all of these objects (Zahn 1977), one might expect that at increasing orbital separation, the effect of increased magnetic activity and therefore inflated radii may decreases however, we do not see evidence for this in our small sample of WTS EBs so far.

We attempted to measure RVs for one further EB with the WHT but due to the small luminosity ratio, we were unable to extract the secondary component lines to measure the mass ratio. However, by combining information from the light curve, photometry and primary RV curve, we estimate that this binary has component masses of $\sim 0.2 + 0.1\mathrm{M}_\odot$, making it one of the lowest mass EBs ever discovered. The object is approaching the theorised limit for binary formation via fragmentation and could serve as a useful benchmark as well as providing a calibration point in the desert of observations in the mass-radius relationship (see open purple squares in figure 3).

4. Where are the hot Jupiters?

Only one-quarter of our survey currently contains enough epochs in which to reliably search for planets and to-date we have detected no transit-like events, despite a thor-

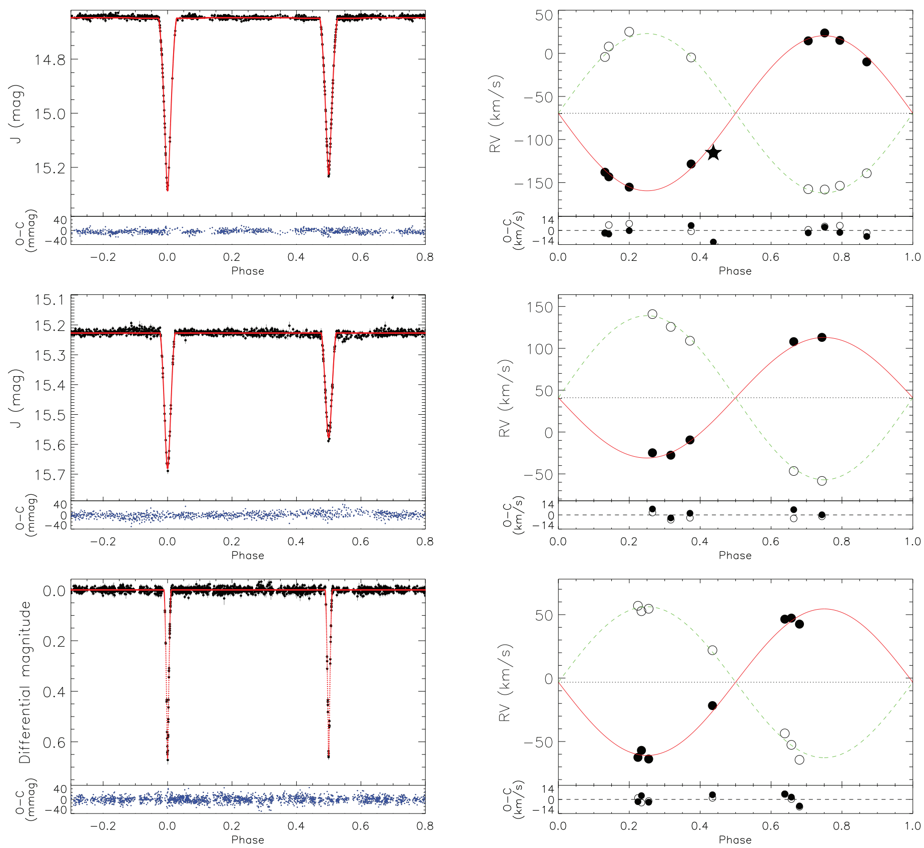

Figure 2. Light curves (left) and RV curves (right) for three newly discovered eclipsing binaries in the WFCAM Transit Survey. Model light curves from jktEBOP (Southworth et al. 2004) are shown with a solid red line and their residuals are shown in blue below the light curve, note change in y-axis scale. In the RV plots, the solid red line denotes the primary component model and the dashed green curve shows the secondary RV model variation. The RMS for the radial velocity measurements is $\sim 2 - 3$km/s and the model residuals are shown in the lower panels on a zoomed-in scale. The horizontal dotted line shows the systemic velocity of the system.

ough and extensive follow-up of candidates this summer with the Isaac Newton 2-m Telescope (INT). While our preliminary simulations show that we are sensitive to hot Jupiter-like objects in the survey, it would be wrong to speculate at this early stage on the hot Jupiter or hot Neptune fraction for M-dwarfs, because only $\sim 1,800$ of our M-dwarfs have undergone investigation. However, once the survey is complete, we will have a significant constraint to place on the occurrence of planets around M-dwarfs.

5. Conclusions

We have reported on the WFCAM Transit Survey, which is an near-infrared photometric monitoring campaign designed to i) place constraints on the occurrence and formation of planets (rocky and gas) around low-mass stars and ii) provide a large sample of

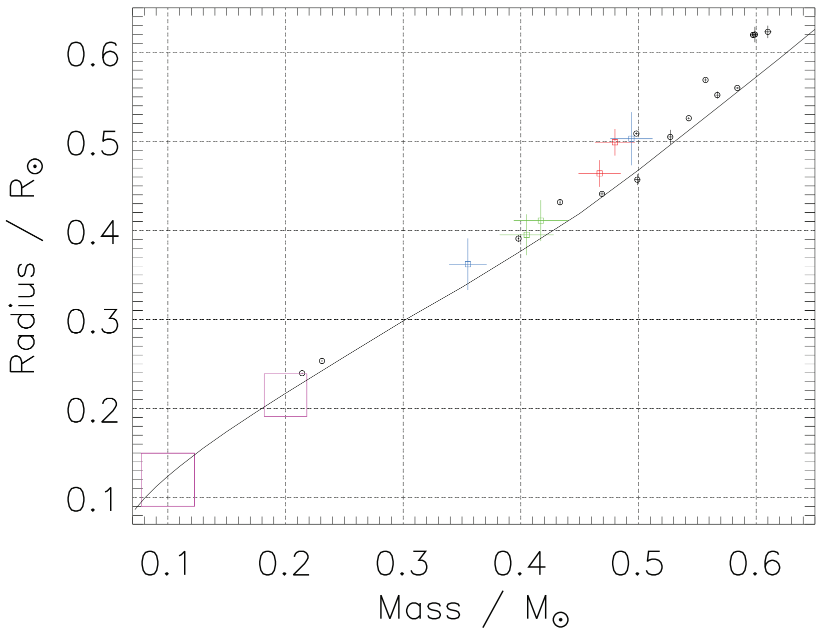

Figure 3. The mass-radius relationship for M-dwarfs. Shown with black circles are all know EB measurements with reported errors $\leq$ 7%. The newly discovered WTS EBs with measured masses are shown by the red, green and blue open squares, where the colours tie together the primary and secondary components of each system. The larger purple open squares mark the approximate masses and radii for a further WTS EB which occupies a desert in EB measurements. The black solid line is the 5Gyr isochrone from the Baraffe et al. (1998) stellar evolution models. The WTS EBs have orbital periods ranging from 1.5-5.0 days (the green open squares show the system with a 5-day period). Note that all the WTS EBs sit significantly above the isochrone. (This plot has been updated to include the results of Kraus et al. (2010) which were released after the meeting.)

M-dwarf eclipsing binaries with which to calibrate the poorly constrained mass-radius relationship below $1M_\odot$. We monitor $\sim 6,000$ M-dwarfs between $13 < J < 16$ magnitudes with stellar type M0-M4. So far, we have 1,000 epochs of observations in a quarter of the survey area, from which we identify no planetary transit events and 32 new M-dwarf eclipsing binaries. Follow-up observations of three of these EBs with a 4-m class telescope this summer give masses and radii, with $3-7\%$ errors, that indicate the components have inflated radii when compared to current stellar evolution models. This is in agreement with a growing body of observations and support theories that assign the inflated radii to the affects of increased magnetic activity. We have also reported preliminary mass and radius estimates for a further new M-dwarf EB which is one of the lowest mass binaries ever discovered and which occupies a sparsely populated region of the mass-radius plane. Although our preliminary simulations indicate that we are capable of detecting Jupiter-like transit events from the WTS data, we do not speculate on the planet fraction for M-dwarfs at this stage of the survey because we only have sufficient epochs for $\sim 1,800$ M-dwarfs. Once our survey is complete, with 1,000 epochs of observations for $\sim 6,000$ M-dwarfs, we will be able to place a significant constraint on the numbers of planets formed around M-dwarfs. The survey relies on the continued operation of UKIRT until at least April 2012 for which we are optimistic, and we envisage that observations for the WTS will increases as other UKIRT large scale programs (such as UKIDSS) approach completion.

Acknowledgments. We extend special thanks to all the staff at UKIRT. J. Birkby acknowledges the support of an STFC PhD studentship.

References

Alexander, R. D., & Armitage, P. J. 2009, ApJ, 704, 989. 0909.0004
Andersen, J. 1991, A&A Rev., 3, 91
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403. arXiv:astro-ph/9805009
Bodenheimer, P., & Pollack, J. B. 1986, Icarus, 67, 391
Chabrier, G., Gallardo, J., & Baraffe, I. 2007, A&A, 472, L17. 0707.1792
Charbonneau, D., Berta, Z. K., Irwin, J., Burke, C. J., Nutzman, P., Buchhave, L. A., Lovis, C., Bonfils, X., Latham, D. W., Udry, S., Murray-Clay, R. A., Holman, M. J., Falco, E. E., Winn, J. N., Queloz, D., Pepe, F., Mayor, M., Delfosse, X., & Forveille, T. 2009, Nat, 462, 891. 0912.3229
Cruz, K. L., Reid, I. N., Liebert, J., Kirkpatrick, J. D., & Lowrance, P. J. 2003, AJ, 126, 2421. arXiv:astro-ph/0307429
Gaudi, B. S., Bennett, D. P., Udalski, A., Gould, A., et al. 2008, Science, 319, 927. 0802.1920
Ida, S., & Lin, D. N. C. 2005, ApJ, 626, 1045. arXiv:astro-ph/0502566
Irwin, J., Irwin, M., Aigrain, S., Hodgkin, S., Hebb, L., & Moraux, E. 2007, MNRAS, 375, 1449. arXiv:astro-ph/0612395
Irwin, M., & Lewis, J. 2001, New Astronomy Reviews, 45, 105
Jackson, R. J., Jeffries, R. D., & Maxted, P. F. L. 2009, MNRAS, 399, L89. 0908.1406
Kraus, A. L., Tucker, R. A., Thompson, M. I., Craine, E. R., & Hillenbrand, L. A. 2010, ArXiv e-prints. 1011.2757
Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004, ApJ, 612, L73. arXiv:astro-ph/0407309
López-Morales, M., & Ribas, I. 2005, ApJ, 631, 1120. arXiv:astro-ph/0505001
Mizuno, H. 1980, Progress of Theoretical Physics, 64, 544
Mizuno, H., Nakazawa, K., & Hayashi, C. 1978, Progress of Theoretical Physics, 60, 699
Morales, J. C., Gallardo, J., Ribas, I., Jordi, C., Baraffe, I., & Chabrier, G. 2010, ApJ, 718, 502. 1005.5720
Nutzman, P., Charbonneau, D., Irwin, J., Burke, C., Berta, Z., & Falco, E. E. 2009, in AAS/Division for Planetary Sciences Meeting Abstracts, vol. 41 of AAS/Division for Planetary Sciences Meeting Abstracts, 08.02
Owen, J. E., Ercolano, B., & Clarke, C. J. 2010, ArXiv e-prints. 1010.0826
Perri, F., & Cameron, A. G. W. 1974, Icarus, 22, 416
Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzweig, Y. 1996, Icarus, 124, 62
Southworth, J., Maxted, P. F. L., & Smalley, B. 2004, MNRAS, 351, 1277. arXiv:astro-ph/0403572
Torres, G., Andersen, J., & Giménez, A. 2009, A&A Rev., 13. 0908.2624
Zahn, J. 1977, A&A, 57, 383