The MEarth-North and MEarth-South Transit Surveys: Searching for Habitable Super-Earth Exoplanets Around Nearby M-dwarfs

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Abstract. Detection and characterization of potentially habitable Earth-size extra-solar planets is one of the major goals of contemporary astronomy. By applying the transit method to very low-mass M-dwarfs, it is possible to find these planets from the ground with present-day instrumentation and observational techniques. The MEarth project is one such survey with stations in both hemispheres: MEarth-North at the Fred Lawrence Whipple Observatory, Mount Hopkins, Arizona, and MEarth-South at Cerro Tololo Inter-American Observatory, Chile. We present an update on recent results of this survey, for planet occurrence rates, and interesting stellar astrophysics, for which our sample of 3000 nearby mid-to-late M-dwarfs has been very fruitful. All light curves gathered during the survey are made publicly available after one year, and we describe how to access and use these data.

1. Introduction

It is now widely recognized that M-dwarfs are extremely advantageous targets to search for transiting exoplanets, due to their small sizes, which greatly enhance transit depths, and their low luminosities, which mean the habitable zones are at much shorter orbital periods than for solar-type stars (e.g. Kasting et al. 1993; Charbonneau & Deming 2007; Kopparapu et al. 2013). For mid-to-late M-dwarfs, these factors are sufficient to allow mini-Neptune, super-Earth and potentially even Earth-size planets to be detected from the ground, and followed up to characterize the planetary atmospheres spectroscopically using present day and near-future facilities such as HST, *Spitzer*, JWST, and ground-based large and extremely large telescopes.

MEarth is a dedicated ground-based transit survey designed to take advantage of these properties, operating from two sites: the Fred Lawrence Whipple Observatory on Mt Hopkins, Arizona, and Cerro Tololo Inter-American Observatory, Chile. Each site has eight 0.4m robotic telescopes. MEarth-North has been fully operational since 2008 September, and MEarth-South since 2014 January. MEarth has discovered one transiting planet so far, the mini-Neptune GJ 1214b (Charbonneau et al. 2009), which orbits an M4.5 dwarf (Reid et al. 1995) at 14.6pc (Anglada-Escudé et al. 2013). This is the smallest exoplanet for which atmospheric transmission spectra have been obtained (e.g. Kreidberg et al. 2014) by virtue of its small (approximately 0.2 $R_\odot$) and nearby host star.

2. Target stars

The MEarth survey strategy and MEarth-North target selection have been described in detail by Nutzman & Charbonneau (2008). All of the targets for MEarth-North were drawn from the Lépine-Shara Proper Motion catalog (LSPM; Lépine & Shara 2005), specifically a subset of these stars with colors (and where available, astrometric, photometric or spectroscopic distance estimates) consistent with being M-dwarfs within 33 pc from Lépine (2005).

The target list for MEarth-South is still expanding at the time of writing. The initial set of targets were drawn from the sample of stars with measured astrometric parallaxes from the Research Consortium on Nearby Stars (RECONS) parallax program[1], the Palomar/Michigan State University (PMSU) spectroscopic survey (Reid et al. 1995; Hawley et al. 1996), and the LSPM-South catalog (Lépine, private communication). For the LSPM-South, candidate nearby M-dwarfs were selected using the color and reduced proper motion criteria from Lépine & Gaidos 2011, except without the J magnitude limit (applying it would severely limit the number of mid-to-late M-dwarfs selected). The 33 pc volume limit of the North was duplicated in the Southern target selection.

Unlike most other surveys searching for planets around M-dwarfs, MEarth *exclusively* targets mid-to-late types with estimated radii $< 0.33\ R_\odot$ (approximately M3 or later) because these are by far the most advantageous targets to search for small planets near the habitable zone. The distribution of estimated stellar radii and magnitudes for the MEarth targets is compared with the *Kepler* M-dwarf sample in Figure .1. Light curves are also available for a handful of earlier stars which lie in the same field of view as one of our targets, or due to revisions in the stellar parameter estimates since the original target selection.

There are approximately 2000 targets meeting our selection criteria in the Northern sample, and 1000 in the current Southern sample.

[1] `http://www.recons.org/publishedpi.2012.1016`

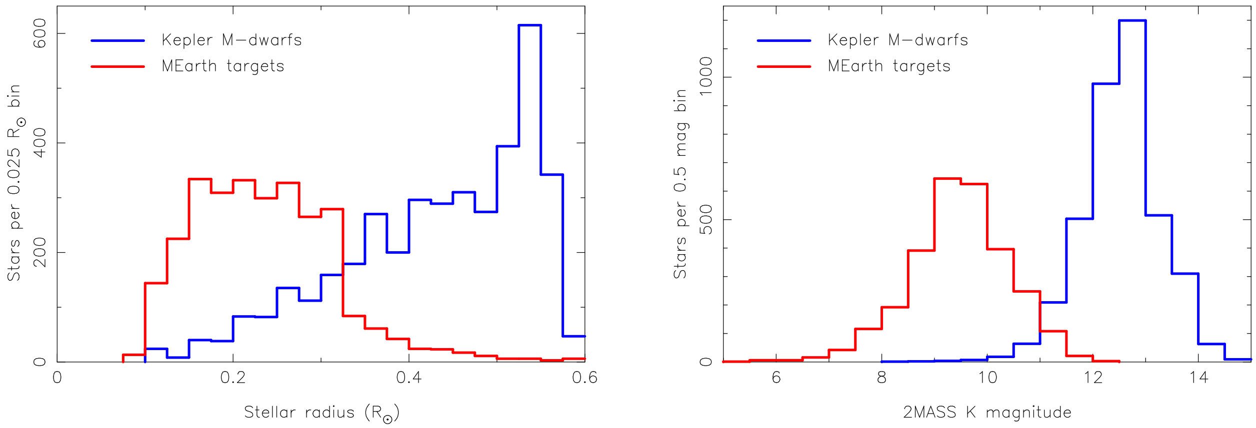

Figure .1: Comparison of the properties of the MEarth target stars with the *Kepler* M-dwarfs (parameters for the latter are from Dressing & Charbonneau 2013). **Left:** Distribution of estimated stellar radii. **Right:** 2MASS K magnitudes.

3. Observational strategy

The MEarth targets are spread over the entire sky, meaning most of them have to be observed individually. During normal survey operations, each telescope cycles around a set of target stars, returning to each star at a cadence of $20 - 30$ minutes. Exposure times are set individually to achieve sensitivity to a desired planet size, taking multiple exposures per visit where necessary.

Transits last $0.5 - 2$ hours given the estimated parameters of our target stars, so only a few data points would be gathered during each transit with this strategy. Instead, the data are analyzed in real time, and followup observations taken immediately on any star showing a candidate transit, while the event is still in progress (see Figure .2). This results in a substantial improvement in sensitivity to long orbital periods, and maximizes use of our telescope resources by allowing a lower cadence to be used to observe more targets simultaneously. Our methods for transit detection are detailed in Berta et al. (2012).

4. Planet occurrence rates

Results from the *Kepler* mission indicate planets are extremely common around early-M dwarfs (Dressing & Charbonneau 2013). Our results for mid-to-late M-dwarfs have been shown to be consistent with the *Kepler* results by Berta et al. (2013), who also examined methods to improve the survey yield by probing smaller planets at longer orbital periods. These methods are undergoing trials at MEarth-North.

5. Stellar astrophysics

The MEarth data and real-time transit detection system are extremely sensitive to low-mass eclipsing binaries (EBs), out to quite long orbital periods. So far, 6 new low-mass EBs have been discovered: 4 in the Northern hemisphere (Irwin et al. 2009, 2010, 2011b, and one

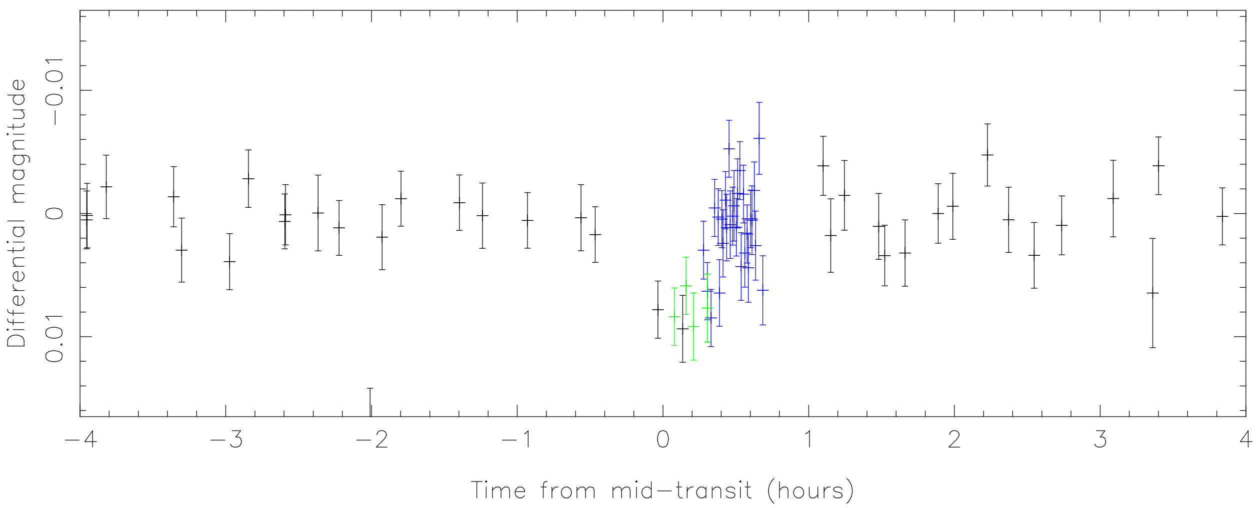

Figure .2: Example phase-folded light curve of a transiting planet candidate discovered using our real-time detection method at MEarth-South. Points taken in response to the real-time detection of the transit are shown in green and blue, and consist of two separate events on different nights. These greatly amplified the significance of the detection and provided an estimated orbital period of approximately 8 days.

further new system), and 2 in the Southern hemisphere (Dittmann et al., in preparation). These systems help to constrain models of low-mass stars by providing valuable empirical benchmarks at a wide range of orbital periods ($0.77 - 41$ days).

Rotation periods for 41 Northern stars with existing astrometric parallaxes, based on 2 years of MEarth photometry, were used to study rotational evolution in the fully convective domain (Irwin et al. 2011a). Additional data taken since the preparation of this original sample, the expansion to the Southern hemisphere, and recent improvements in the availability of astrometric parallax measurements allow this type of analysis to be extended to a much larger sample of stars, which is in progress (Newton et al., in prep.).

A spectroscopic followup program has targeted many of the objects with measured rotation periods, both in the optical to measure activity indicators (West et al., in prep.) and the near-infrared to measure metallicities (Newton et al. 2014). These observations have also been used to develop an empirical method based on equivalent widths of atomic lines in the near-infrared to estimate fundamental stellar properties such as radii, calibrated using observations of stars with interferometric angular diameter measurements (Newton et al., in prep.).

Astrometric parallaxes were measured from MEarth data for 1507 Northern hemisphere mid-to-late M-dwarfs (Dittmann et al. 2014), using the transit survey data where available, and a dedicated observing program covering all other target stars at a cadence of approximately 10 days for 3 years. Many of these stars did not have previous astrometric parallax measurements.

6. Data releases

Public releases of the MEarth target star light curves are made annually on September 1, with data being released one year after being taken. At the time of writing, Data Release 3 is in the late stages of preparation, and combined with the existing Data Release 2 (released 2013 September 1) will include all light curves from the start of the Northern survey to 2013 July (the end of our 2012-2013 observing season), a total of 5 years of data. All release materials are placed on a public web page[2].

These releases are intended to be accessible and as straightforward as possible to use. Light curves and summary tables of target star properties are provided in ASCII format, including tar files containing the entire release for those desiring to analyze large numbers of objects. Details of the content and production of the light curves (including how the data were processed) are included.

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[2] `http://www.cfa.harvard.edu/MEarth/Data.html`

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