Finding and Characterizing SuperEarth Exoplanets Using Transits and Eclipses

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Abstract. We describe an approach to finding and characterizing superEarth exoplanets that is a natural extension of techniques that have succeeded for giant exoplanets. This dynamics-based approach exploits transits and eclipses, and radial velocities and Kepler's law, to measure the bulk properties of each planet (radius and mass). Space-borne infrared spectroscopy (i.e., from JWST) phased to mutual eclipses in transiting planet systems will yield the planet's emergent spectrum at modest resolving power. Applying this method to transiting superEarths requires finding the most favorable systems using a combination of ground- and space-based transit surveys. Lower main sequence stars offer several advantages in this approach, so transit surveys should pay particular attention to M-dwarfs. Extension of precision radial velocity techniques to the infrared will also be important, to measure masses for rocky planets orbiting M-dwarfs. The culmination of this path is the characterization (via JWST) of a habitable superEarth exoplanet orbiting a nearby lower main sequence star.

Motivation. Study of planets orbiting nearby, main-sequence stars has proceeded at a breakneck pace: Less than ten years elapsed from the first discovery of a sub-Jupiter-mass companion to a Sun-like star (Mayor & Queloz 1995) to the first direct detection of light emitted from an exoplanet (Charbonneau et al. 2005; Deming et al. 2005). This field of astrophysics is driven by observations. Progress in the past decade was initiated by precise radial velocity measurements, which continue to improve dramatically (e.g., Mayor et al. 2008, Howard et al. 2009). Recently, the combination of radial velocities with transit photometry is increasingly driving the field (Charbonneau et al. 2007). Measuring the radial velocity orbit and the transit light curve yield the mass and radius of an exoplanet, which in turn provide powerful constraints on its physical structure and bulk composition. However, the true power of a transiting geometry is that it permits the study of the planetary atmosphere without the need to spatially isolate the light of the planet from that of the star. It is this technique, which we term "occultation spectroscopy", that yielded the first emergent spectra of planets orbiting nearby Sun-like stars (Richardson et al. 2007; Grillmair et al. 2007, 2008; Swain et al. 2008).

The unifying feature of the exoplanet techniques that have succeeded for mature, Gyr-old stars is that they measure temporal changes in observable quantities phased to the planetary orbit. Charbonneau and Deming (2007) called these techniques "dynamics-based methods," because they allow the planet mass to be derived easily and accurately using Kepler's law. One of the great quests of astronomy is to obtain the spectrum of a terrestrial planet orbiting within the habitable zone of its star, and the dominant challenge in doing so is to isolate the light of the planet from that of the star. Dynamics-based methods separate these signals *temporally*, whereas imaging techniques do so *spatially*. The overwhelming dominance of the temporal methods over the past decade, and their success in measuring giant exoplanet spectra (e.g., Grillmair et al. 2008), show that obtaining spectra of nearby superEarths does not necessarily require extreme-contrast imaging. The recent announcement of the first transiting superEarth by CoRoT (Rouan et al. 2009) suggests that the era of superEarth characterization is already at hand.

We advocate that substantial resources be committed to improving the precision and extending the wavelength coverage of radial velocity measurements (e.g., extending them into the IR), extending transit surveys to the entire sky (especially for nearby stars such as M-dwarfs), and further developing occultation spectroscopy (i.e., emergent infrared spectra obtained at secondary eclipse). We believe these methods will yield the first detections and characterizations of superEarths orbiting within their stellar habitable zones, as well as the first observations of their spectra.

We see four broad advantages of a transit-based approach:

1. Transits obviate the demanding technological (hence, fiscal) requirement for extreme contrast ratio imaging at very small angular separations.
2. Much of the science may be accomplished with facilities that are either in operation, or general purpose observatories that are in advanced stages of planning or construction.
3. Occultation spectroscopy permits a direct estimate of the planetary surface flux with no degeneracy between temperature and emitting area.
4. Accurate masses and radii of planets studied by occultation spectroscopy will be determined from radial velocities and transit observations. Given accurate quantitative constraints on the physical structure and bulk composition, the inferences about the atmosphere from the observed spectra are likely to be far more penetrating than that for cases in which only the spectrum is available. Note also that advances in structural theory for superEarths have laid the foundation for optimal interpretation of the masses and radii (Seager et al. 2007, Valencia et al. 2007, Miller-Ricci et al. 2009).

The M-dwarf Opportunity. We see a particularly attractive opportunity in M-dwarfs. Such stars are by far the most common in the local solar neighborhood. The most recent results from the RECONS Survey (Henry et al. 2007) report 348 stars within 10 pc (as determined from trigonometric parallaxes), of which 239 are M dwarfs and only 21 are G dwarfs. Projecting these numbers by volume, we expect 10,000 M-dwarf stars within 35 pc. Whether these low-mass stars have the same rate-of-occurrence of planetary companions as Sun-like stars is an open question. Some authors (Butler et al. 2004) have stated that they find the rate of Jupiter-mass planets to be significantly suppressed for M-dwarf primaries, but others state clearly that the survey results do not yet permit this conclusion (e.g., Endl et al. 2006). Many of the least-massive known exoplanets orbit M-dwarfs (Butler et al. 2004; Rivera et al. 2005), but this reflects primarily a detection bias: A planet of a given mass and orbital period will induce a larger radial-velocity variation for a lower-mass star. Whether such stars have habitable Earth-mass planets is, of course, an open question. The habitability of such planets was recently revisited by Tarter et al. (2007), who found no compelling reasons that preclude life.

Throughout the remainder of this paper, we will quote numbers for an M4V primary (0.25 M_{Sun}, 0.25 R_{Sun}, 3200 K) and an M8V primary (0.10 M_{Sun}, 0.1 R_{Sun}, 2400 K). These two spectral types encompass that of most M-dwarfs. The dynamics-based path favors M-dwarfs, both for their low masses and radii (as we explain below) and the fact that their low luminosity places the habitable zone much closer to the star. For the M4V primary, the equilibrium temperature of the Earth (assuming the Earth's albedo) is obtained at 0.077 AU, and for the M8V primary, it lies at 0.017 AU. A small physical separation is troublesome for imaging, but desirable using transits. We see at least five advantages that favor the study of Earth-like planets of M-dwarfs:

1. Transits are more likely to occur (the habitable zone transit probability scales as T^{-2}_{star}). Assuming orbital planes randomly inclined to our line of sight, the transit probability for a planet at the orbital separations listed above is 1.5% (M4V) and 2.7% (M8V), significantly above the Earth-Sun value of 0.47%.
2. Transits are deeper and thus easier to detect. An Earth-sized planet induces transit depths

of 1.3 mmag (M4V) and 8.4 mmag (M8V), as opposed to 0.084 mmag (Sun).

3. Transits are more frequent, as the orbital periods for the semi-major axes listed above are only 15 days (M4V) and 2.5 days (M8V). This is favorable for detection, since fewer hours are required to ensure sufficient orbital phase coverage. This is also favorable for spectroscopic follow-up, since there are more events per unit time and thus more total hours spent in secondary eclipse. Per year, an Earth-Sun system in an equatorial transit would spend only 13 hours in secondary eclipse, whereas the total time in eclipse is 44 hours (M4V) and 84 hours (M8V).
4. The induced stellar radial-velocity variation is much larger and commensurate with current measurement precision in the optical. The peak-to-peak amplitude is 1.4 m/s (M4V) and 4.4 m/s (M8V), as opposed to 0.18 m/s for the reflex orbit of the Sun due to the Earth's orbit.
5. The planet-to-star contrast is much larger than that for the Earth-Sun system. In the Rayleigh-Jeans limit, this ratio depends upon the relative surface areas and brightness temperatures of the planet and star. This ratio is 0.012% (M4V) and 0.11% (M8V), compared to 0.00044% for the Earth-Sun system. This facilitates the measurement of the planetary spectrum by occultation spectroscopy.

We propose the following path for measuring the masses, radii, and emergent spectra for superEarths orbiting within the habitable zones of their stars:

I. Rocky planets shall be identified by transit photometry. The stellar sample should - at a minimum - be complete for the nearest 10,000 M-dwarfs.
II. Masses shall be measured by ground-based radial velocity follow-up.
III. Infrared spectra shall be measured using the technique of occultation spectroscopy.

We explore the practical aspects of these three steps in the following sections.

Step I. Transit Discovery. We advocate that the closest 10,000 M-dwarfs be surveyed photometrically with a precision and cadence sufficient to detect transits of Earth-sized planets in the habitable zone. This number is chosen so that the conclusions from a null result are of interest and commensurate with those of the *Kepler Mission*. If no such signal is found, then we would conclude that the rate of occurrence of such planets is less than 2.8% (3 sigma). However, if the rate of occurrence is only 5%, the expectation value would be 11 planets, a number worthy of the effort.

A survey targeted to M-dwarfs can be started from the ground. Ground-based photometric precision can be better than 1 milli-magnitude for at least some periods and sites. Using the Mt. Hopkins 1.2m telescope with KeplerCam (a thinned 4k x 4k CCD camera) in *z* band, the Transit Light Curve project (Winn et al. 2007, Holman et al. 2006) demonstrated a relative photometric precision of 0.20 mmag (15-minute bin) for time series observations of known transiting planets (see Figure 1). Although these observers implemented modest procedures to ensure high precision (for example, the images were mildly defocused), such precision could reasonably be anticipated for similar observatories, and further improvements were recently obtained by Johnson et al. (2009), using a PSF-shaping CCD camera on a larger telescope.

Unlike transit surveys that stare at fixed fields-of-view containing tens of thousands of stars, M-dwarf targets are spread uniformly over the sky and have to be observed sequentially. Already the MEarth project is monitoring the nearest 2000 M-dwarfs using a collection of robotic 16-inch telescopes on Mt. Hopkins (Nutzman and Charbonneau 2008). MEarth photometry is reduced in real time, permitting the identification of transits in progress. Once identified, the M-dwarf will be monitored intensively to observe a second transit and hence deduce the orbital period. In this mode, the number of hours required to survey each star is of order the orbital period, and accounting for weather losses roughly doubles this requirement. This is much less than current transit surveys, which phase-fold archived data and typically require more than 5 times as many hours to achieve their giant-planet detections. Note also that astrophysical false positives are not a significant source of distraction for a targeted survey of nearby M-dwarfs, since the targets will be well characterized with parallaxes, and it is extremely difficult to concoct a triple star system for which the eclipsing binary in hidden in the light of the intrinsically faint M-dwarf primary.

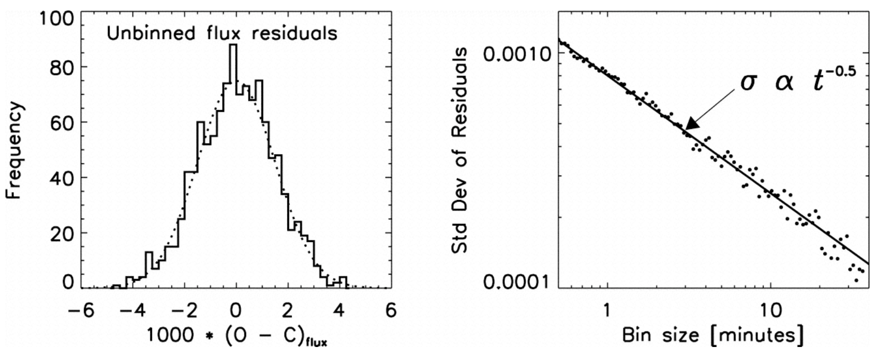
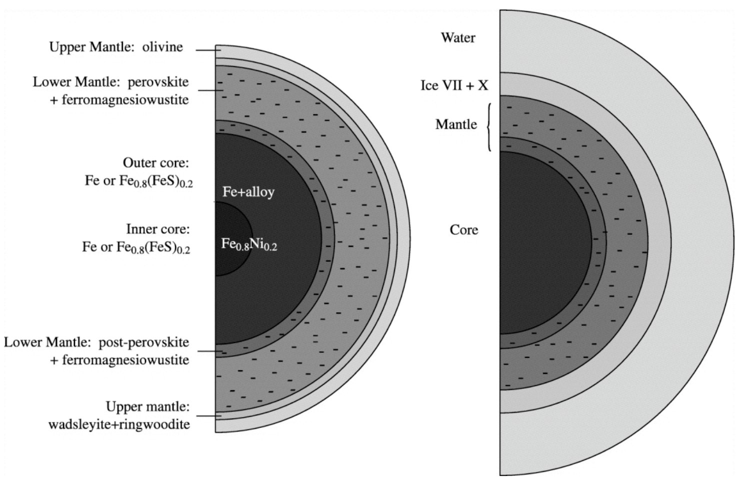


Fig 1. (Winn et al. 2007) Noise properties of flux residuals from time series photometry of TrES-1, gathered with the Mt. Hopkins 1.2-meter. Left: Distribution of unbinned residuals. The dotted line is a Gaussian function with a standard deviation of 0.15%. Right: Standard deviation of the residuals as a function of the size of the time-averaging bin size. The solid line represents the 1/sqrt(t) dependence that is expected in the absence of systematic errors.

Although MEarth will make significant progress toward a census of all planets transiting nearby M-dwarfs, more effort will be needed to complete the nearest 10,000 M-dwarfs. It is possible that such a survey will ultimately have to be space-based. We note that a significant fraction of the known radial velocity superEarths orbit FGK stars (Mayor et al. 2008). A space-based survey would have sufficient photometric precision to detect transits of rocky planets orbiting FGK-dwarfs, whose transits are too shallow to detect from the ground. Although these spectral types would be observed to greater distances, there are ample numbers that are close enough for superEarth characterization using occultation spectroscopy.

Step II. Mass Measurements. Precise radial-velocity monitoring of transiting planet candidates is required both to confirm their planetary nature and to provide precise estimates of the mass. When combined with the radius estimate, these measurements may be compared with structural models to determine the fractional composition of constituents such as iron cores, silicate mantles, and significant water envelopes (e.g., Valencia et al. 2007); see Figure 2. Transiting systems require an inclination near 90º, thus the mass of the planet may be determined directly. The peak-to-peak amplitude induced by an Earth-mass companion will be 1.4 m/s (M4V) and 4.4 m/s (M8V). Stars earlier than M5V emit sufficient flux shortward of 600nm that this signal may be measured with the well-developed optical radial-velocity techniques, either with extant facilities (such as HIRES or HARPS), or with spectrographs currently under construction (e.g., the New Earths Facility led by D. Sasselov). For later spectral types, or for fainter M-dwarfs of any spectral type, the spectral energy distribution requires spectrographs operating at near-IR wavelengths (e.g., TEDI, Edlestein et al. 2007). Such an instrument on an 8-m observatory could achieve the requisite precision for these targets with typical integration times of 0.5 hr. We believe that possible concerns about reduced precision due to variable telluric absorption, and the increased rotational velocities and spot coverage of stars at the bottom of the main-sequence are not insurmountable obstacles.



<u>Fig 2:</u> (from Valencia et al. 2007) Schematic representation of the structural model of a superEarth. To calculate the internal structure, the authors assumed a similar composition to that of Earth (left): a dense core of pure Fe or $Fe_{0.8}(FeS)_{0.2}$; a lower mantle composed of two silicate shells; and an upper mantle composed of two silicate shells. An ocean planet (right) will have an additional water/ice layer above the rocky core, and could be distinguished by its larger radius.

Step III. Transit and Occultation Spectroscopy. There are generally two opportunities per orbit to measure the spectrum of the planet: 1) the transmission spectrum can be measured during transit, and 2) the emergent spectrum due to the planet's thermal self-emission can be measured at secondary eclipse (occultation spectroscopy, e.g., Grillmair et al. 2008). We here concentrate on the case of occultation spectroscopy, but we note that transit spectroscopy will reveal significant information, especially for atmospheres having large scale heights.

Occultation spectroscopy for an M-dwarf terrestrial planet is best accomplished by space-borne cryogenic IR telescopes. We do not exclude the possibility that reflected light could be detected, particularly at the longest visible wavelengths. However, the paucity of visible light emitted by cool M-dwarfs motivates IR diagnostics. The *Spitzer Space Telescope* has proven the feasibility of occultation spectroscopy and photometry for the study of giant planets orbiting close to solar-type stars (e.g., Knutson et al. 2007, 2008, Deming et al. 2007, Grillmair et al. 2008). Here we summarize the *Spitze*r highlights, and project the scientific return from *JWST*.

Spitzer investigators have detected radiation from several hot Jupiters, in four (for many systems) to six bands (for the brightest systems), ranging in wavelength from 3.6 to 24 microns. These studies define the emergent spectra of these worlds at photometric resolution (Charbonneau et al. 2008, Knutson et al. 2008, 2009a, Machalek et al. 2008). Currently, over 10 hot Jupiters have been observed in this manner by Spitzer (much of the data are still under analysis), and the Warm mission will increase the number to over 20 for the 3.6 and 4.5 micron bands. *Spitzer* has detected day-night temperature contrasts on several hot Jupiters (Harrington et al. 2006, Knutson et al. 2007, 2009b), has measured spectra for two hot Jupiters at a resolving power of about 100 (Grillmair et al. 2007, Richardson et al. 2007, Swain et al. 2008, Grillmair et al. 2008), and has even measured time-dependent heating of a giant planet in a very eccentric orbit (Laughlin et al. 2009). The sensitivity of *Spitzer* to secondary eclipses in broad photometric bands extends to smaller planets such as exo-Neptunes (Deming et al. 2007) and to hot superEarths in favorable cases (Seager and Deming 2009).

Since *Spitzer* can in principle detect hot superEarths, it is not surprising that "warm superEarths" (300K) are within the grasp of *JWST*. The 6.5-m cold aperture, and its thermally benign environment at L2, are reasons to anticipate success (Green et al. 2007). We have calculated the S/N for occultation spectroscopy of a 290K terrestrial planet orbiting an M-dwarf, assuming that the planet emits as a blackbody in equilibrium with stellar radiation (Fig. 3). The calculation assumes parameters reasonable for *JWST*/MIRI spectroscopy. We include stellar and solar system zodiacal photon noise as well as the thermal background from the telescope and sun shade. Since the light from the host star will be dispersed, saturation will not occur in MIRI's minimum exposure time (3 s), and read noise will be dominated by the photon noise. We find that the S/N for spectra of the planet, at a resolving power of 40 (more than sufficient to detect molecular bands), is about 10 or greater for wavelengths ≥ 15 microns, in a 200-hour observing program (equally divided between in-eclipse and out-of-eclipse).

JWST photometry of warm Earth-like planets orbiting M-dwarfs will achieve S/N capable of measuring the day-night temperature difference, just as *Spitzer* has done for close-in giant planets. A traditional concern about the habitability of planets in the habitable zone of M-dwarfs is a large temperature difference caused by tidal-locking of their rotation. Tarter et al. (2007) have argued that this is not fatal for life, in part because atmospheric circulation efficiently re-distributes heat. *JWST* photometry could determine the degree of heat redistribution for these planets, just as *Spitzer* has done for hot Jupiters. Moreover, the mere detection of a small day-night temperature difference would be compelling evidence for the existence of an atmosphere (Seager and Deming 2009), even before spectroscopy was attempted.

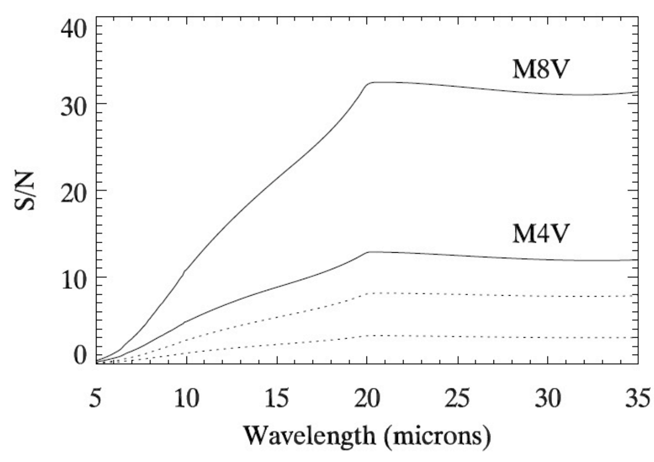


Fig 3: *S/N for our two cases, both having planets in the habitable zone (300 K). The spectral resolution is 40, as observed by the Mid-InfraRed Instrument (MIRI) on JWST. Planets with radii of 2R_{Earth} (solid lines) and 1 R_{Earth} (dashed lines) are shown. The total observing time in these simulations for each case is 200 hours.*

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