Transiting Planets
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Precision Radial Velocities in the Near Infrared with TEDI

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Abstract. The TEDI (TripleSpec - Exoplanet Discovery Instrument) is a dedicated instrument for the near-infrared radial velocity search for planetary companions to low-mass stars with the goal of achieving meters-per-second radial velocity precision. Heretofore, such planet searches have been limited almost entirely to the optical band and to stars that are bright in this band. Consequently, knowledge about planetary companions to the populous but visibly faint low-mass stars is limited. In addition to the opportunity afforded by precision radial velocity searches directly for planets around low mass stars, transits around the smallest M dwarfs offer a chance to detect the smallest possible planets in the habitable zones of the parent stars. As has been the the case with followup of planet candidates detected by the transit method requiring radial velocity confirmation, the capability to undertake efficient precision radial velocity measurements of mid-late M dwarfs will be required. TEDI has been commissioned on the Palomar 200" telescope in December 2007, and is currently in a science verification phase.

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1. Planets around M dwarfs

The majority of the host stars of the planets detected to date lie in the range 0.7 to 1.4 $M_\odot$. Massive stars are generally not amenable to radial velocity studies due to featureless spectra from their hot atmospheres. Low-mass stars are cool and therefore faint in the green-visible where the Iodine cells provides absorption reference lines. Transit surveys similarly have been primarily sensitive to planets around solar-type stars, due to both the population probed by optical photometry over relatively narrow fields, and the requirement of radial velocity confirmation with optical spectrographs.

Even with the difficulty of detecting planets around cool stars, some of the most interesting examples have been discovered around M type stars: GJ 876 (Marcy *et al.* 2001) is a multiple planet system exhibiting resonant interactions and GJ 436 (Butler *et al.* 2004) is the lowest mass planet yet to be detected with transits. Bond *et al.* (2004) argue that the unusual binary microlensing event OGLE 2003-BLG-235/MOA 2003-BLG-53 is a $1.2^{+0.1}_{-1.2}$ $M_{\rm jup}$ planet orbiting a $0.36^{+0.3}_{-0.28}$ $M_\odot$ M2-M7 main sequence star. Perhaps the best candidate so far for an image of an extrasolar "planet" is the putative 5 $M_{\rm jup}$ companion to the $\sim$ 25 $M_{\rm jup}$ young M8 brown dwarf 2MASS J12073346-3932539 (Chauvin *et al.* 2004).

There are multiple reasons to focus on planets around low-mass stars. Low-mass stars and brown dwarfs dominate the stellar population in both number and mass. As the mass of the primary decreases, the radial velocity signature increases. Similarly, the radius of M dwarfs is favorable for transits: an Earth-radius planet orbiting a 0.08 $M_\odot$ star produces a transit of the same depth as a Jupiter-radius planet orbiting a sun like star (see Figure 1).

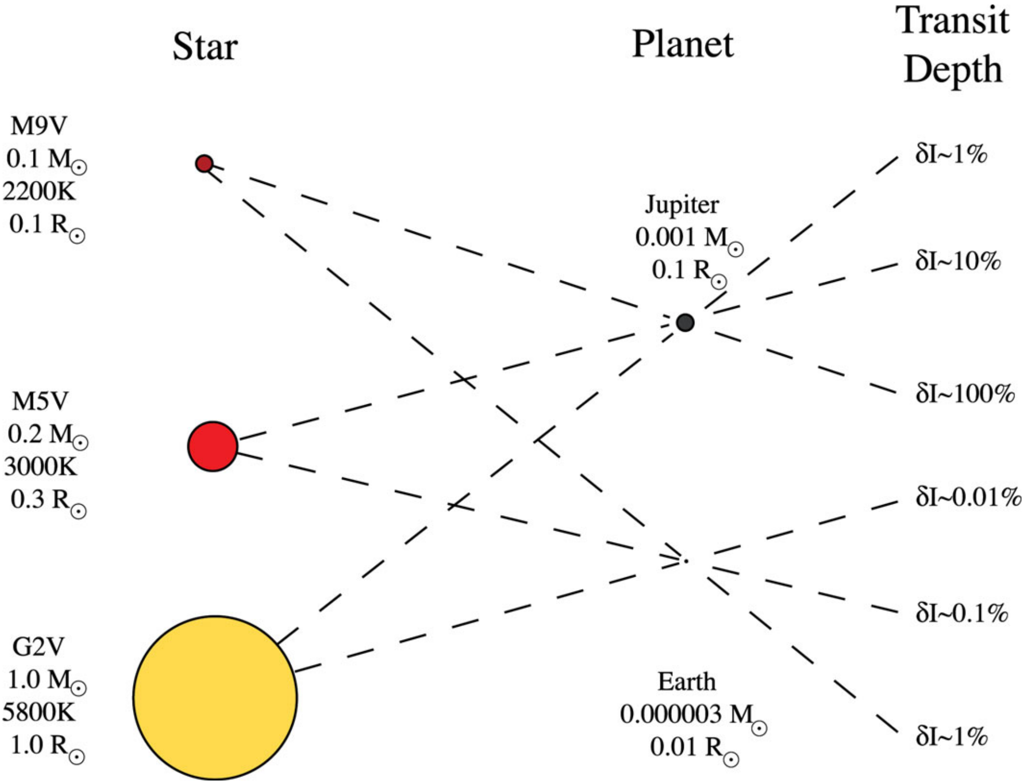

Figure 1. Transit depths for a variety of stars and planets (drawn to scale). An Earth-like terrestrial planet orbiting a low-mass star yields a comparable transit depth to the already detected combination of a gas giant orbiting a solar-type star.

Low-mass stars offer the best chance to detect low-mass planets. Furthermore, as cool stars are less luminous, the contrast is more favorable and the prospects for future direct imaging and spectroscopy of the planets themselves are greatly improved (e.g. the contrast in the Rayleigh-Jeans limit of a 300 K habitable zone planet around a 3000 K star is ∼0.1%, within a factor of a few of the detections already achieved with Spitzer (Deming *et al.* 2005). Of wider significance to the entire field of extrasolar and solar planetary science, Laughlin *et al.* (2004) predict that the core accretion mechanism of planet formation results in predominantly Neptune and terrestrial mass planets and few jovian mass planets around low mass stars. The study of the frequency and distribution of planets around M dwarf stars offers the possibility to discriminate between the two dominant theories of planet formation: core-accretion (Pollack *et al.* 1996) and gravitational instability (Goldreich & Ward 1973).

For these reasons, interest in focussing efforts on searching for planets around M dwarfs is rapidly intensifying (Gaidos *et al.* 2007). In addition to efforts to focus the current instruments on M dwarfs (e.g. Johnson *et al.* 2007; Forveille *et al.* 2008), a new generation of infrared optimized radial velocity spectrographs are under development (Ramsey *et al.* 2008; Oliva *et al.* 2006), as are M-dwarf targeted transit searches (Nutzman & Charbonneau 2008). The NASA/NSF Exoplanet Task Force Report emphasized targeting M dwarfs as the highest immediate priority within the exoplanet field. Even if transits are the primary method of detecting of planets around late M dwarfs, radial velocity capabilities with the sensitivity to verify planet candidates will be required.

Efficient Radial Velocities of M dwarfs

Past and current radial velocity surveys (e.g. Delfosse *et al.* 1998, 1999) have tackled small samples of M dwarfs ($\sim$ 100). The Keck Doppler survey of the California-Carnegie planet search includes 150 M stars, while the Keck Hyades program of Cochran *et al.* (2002) contains a sample of 20 M stars. Endl *et al.* (2003, 2006) have undertaken a dedicated M-star radial velocity survey with the HET. However, all of these surveys are limited to the earliest M stars, become rapidly incomplete beyond M2, and are not capable of extending into the coolest M spectral classes or the L and T dwarfs.

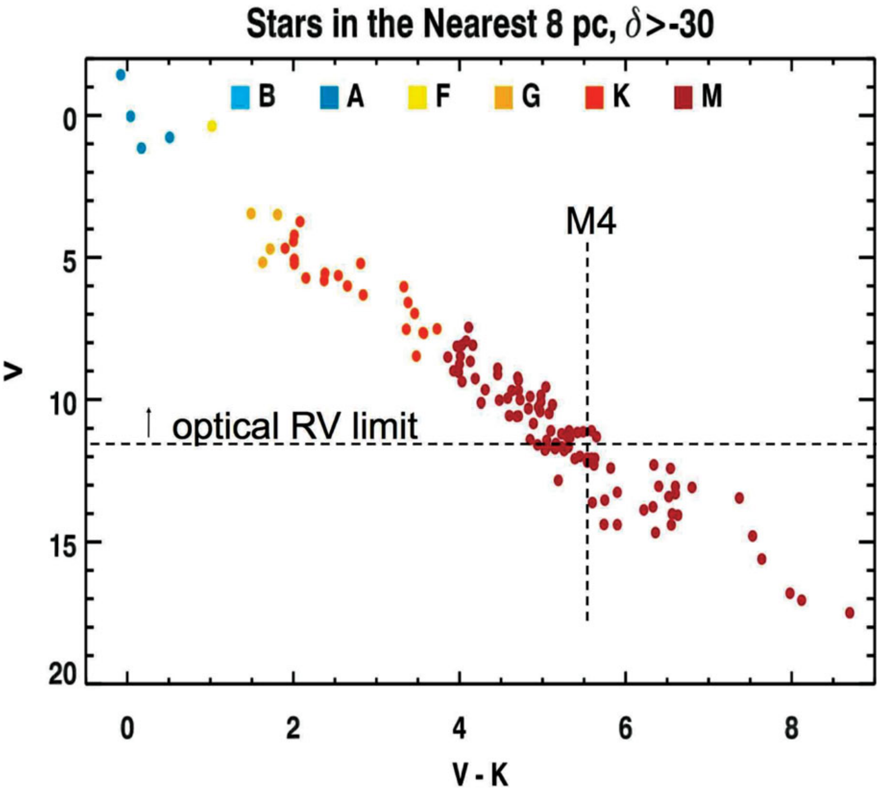

Figure 2. V-K vs V Color-Magnitude Diagram for the 8 parsec sample (Reid & Gizis 1997).

As shown in Figure 2, stars later than approximately M4 are beyond the $V \sim 12$ magnitude limit of optical precision RV instruments. However, with colors redder than $V - K > 5$ magnitudes, these are very favorable targets in the near infrared. Their rich molecular atmospheres offer a dense forest of lines in the infrared, ideal for precision Doppler measurements. The challenges of stabilizing and calibrating an infrared spectrograph are formidable. Accounting for the complex telluric absorption spectrum may prove difficult, though modelling suggests that this is not likely to limit precision at the 10 m/s level. Indeed the telluric absorption can be used as a calibrant (e.g. Blake *et al.* 2008, 2007).

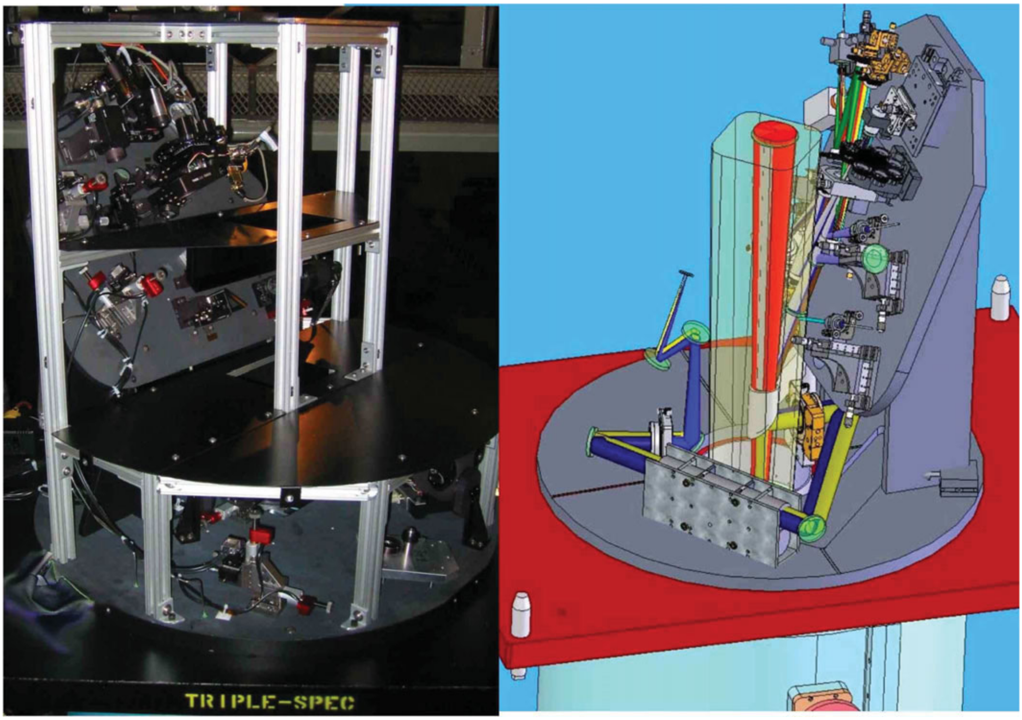

Figure 3. TEDI Instrument. On left is the TEDI interferometer mounted on the TripleSpec spectrometer. The solid model on the right shows the path of the starlight when the instrument is mounted on the cassegrain focus of the 200" telescope.

2. TEDI

We have recently been developing the "Externally Dispersed Interferometry" (EDI) for the TripleSpec spectrograph as an approach to achieve precision radial velocities in the near infrared without the need for a dedicated high -esolution spectrometer. TripleSpec (Wilson *et al.* 2004) is a facility spectrograph constructed by Cornell, Caltech and U. Virginia for the Palomar 200-inch telescope. TripleSpec covers the 0.8-2.5 μm wavelength range at $R \sim 2700$ in a single exposure. The EDI unit (see Figure 3) is placed ahead of TripleSpec to undertake radial velocity studies of the lowest-mass stars and brown dwarfs.

EDI (Erskine 2003) combines a Michelson interferometer with a moderate resolution spectrograph to achieve precision radial velocities. Additionally, it is possible to use the same instrument to synthesize a higher spectral resolution (Erskine *et al.* 2003).

TEDI has been developed over the last three years (Edelstein *et al.* 2007, 2006; Erskine *et al.* 2005, 2006), and saw first light on the Palomar 200" in December 2007/January 2008. Presently TEDI is undergoing a science verification phase, and will shortly begin a survey of late M dwarfs for planets.

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