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White paper in response to solicitation for alternate science investigations for the Kepler spacecraft

Transits of Lilliputian Worlds around Nearby Tiny Stars with Kepler

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Abstract

It is argued here that Kepler is still the best observatory to search for planet transits around nearby very low-mass (VLM) stars. This white paper lies out a plan to reveal transits of potentially habitable rocky planets around VLM dwarfs using the Kepler spacecraft. It is widely accepted in the scientific community that an unambiguous signature of the existence of life in the universe would be to find planets similar in size to the Earth, and to detect atmospheric signatures in their atmosphere that resemble that of the current Earth. Transits around nearby tiny dwarfs will provide candidates for infrared radial velocity follow-up, and for the characterization of the atmospheric constituents of potentially habitable planets by means of transmission spectroscopy with existing or planned telescopic facilities such as the James Webb Space Telescope or the new generation of extremely large ground-based telescopes.

Project Description (10 pages)

Section 1: Introduction

The potential to use the radial velocity (RV) and transit techniques to discover planets with masses similar to Jupiter, but much closer to their stars than in the solar system was first recognized by Otto Struve (1952). At that time, astrometry was the most popular technique to search for exoplanets because it was thought that giant planets might only exist at large separations from their host stars, and indeed there were some encouraging results (Strand 1944). However, those results were never confirmed and even to the present day planets detected by astrometry remain elusive even though astrometric precision keeps improving (Lazorenko et al. 2011).

The first high precision radial velocity search for substellar-mass companions to solar-type stars was reported by Campbell et al. (1988), and the first transit exoplanet survey around an eclipsing binary was published by Deeg et al. (1998).

In 1992 the first exoplanetary system around a pulsar was found at Arecibo Observatory (Wolszczan & Frail 1992); soon followed by the first unambiguous giant planet discovered around a solar-type star (Mayor & Queloz 1995). The first exoplanet revealed by a transit survey had to wait almost a decade longer (Alonso et al. 2004). Nowadays, the RV and transit techniques have been developed to become the most successful at discovering exoplanets, and it has been established that planets with masses similar to Jupiter do exist indeed very close to their host stars. These hot Jupiters are rare planets, but they were the first to be detected due to a bias effect in the RV technique.

The characterization of the atmospheres of transiting exoplanets has been achieved via spectrophotometric observations in and out of transits (Charbonneau et al. 2002; Gibson et al. 2012) mostly using space telescopes. The small radius of the host M dwarf of the transiting super-Earth exoplanet GJ1214b has made it possible to try to detect its transmission spectrum using the 2-meter class ground-based telescopes (de Mooij et al. 2012). So far, a detection of the atmosphere in this planet, which is thought of being an ocean planet or mini-Neptune, has not been coming forward, not even with the Hubble Space Telescope (Berta et al. 2012).

This white paper focues on an important niche that remains almost unexplored, namely the study of the planets around objects that bridge the gap in mass between solar-type stars and giant planets such as very-low mass (VLM) stars and brown dwarfs (BDs). BDs were elusive objects until they were revealed unambiguosly by Rebolo, Zapatero Osorio & Martín (1995). These objects fail to settle on the Hydrogen-burning main sequence because of the development of degenerate cores (Kumar 1963; Hayashi & Nakano 1963).

The last two decades have brought about a tremendous progress in the discovery and understanding of VLM dwarfs. Over 700 of these objects have been found all over the sky, including low galactic latitudes (Phan Bao et al. 2008, and references therein). Subclass M7 is considered to define the frontier between cool dwarfs and ultra-cool dwarfs (UCDs) because the strong TiO absorption bands that shape the optical spectrum of the former start to weaken and completely disappear for mid-L dwarfs. This behaviour is understood as a result of Ti atoms getting locked into dust grains (Jones & Tsuji 1997). M7 is also close to the boundary between VLM stars and BDs in the Pleiades cluster (Martín, Rebolo & Zapatero Osorio 1996). BDs can have late-M spectral types when they are young, i.e. LP944-20 (Tinney 1998), but they cool to very low temperatures as they shrink and lose gravitational energy. Discoveries of nearby BDs have prompted the addition of three new spectral classes to the Harvard system.

The L spectral class is defined by the disappearance of TiO bands from the optical spectrum due to condensation of metallic dust grains (Tsuji et al. 1996). The effective temperature domain of the L spectral class has been estimated to range from 2200 K to 1400 K (Golimowski et al. 2004). The T spectral class is defined by the onset of methane absorption in the near-infrared spectrum (Burgasser et al. 2006). The effective temperature domain of the T spectral class has been estimated to range from 1400 K to 500 K.

The discovery of transiting habitable exoplanets around VLM dwarfs will be a major step toward the understanding of habitability in rocky planets with sizes similar to Earth. Such planets will offer an opportunity to measure atmospheric constituents using large telescopes in the ground and from space. The Kepler mission has announced that rocky exoplanets are very common (Borucki et al. 2011). However, characterization of the atmosphere of most of the Kepler planets is not feasible with any existing or foreseen facility. We have recently used the Kepler Input Catalog (KIC) supplemented with ground-based imaging and spectroscopy to identify 41 UCD candidates in the Kepler FoV (Figure 1). We estimate that, given the photometric precision expected with Kepler, for their brightness and their small radii, a detection planet transits is feasible around most of them, although their faintness ($19 \leq I \leq 21$) makes the follow-up characterization of their atmospheres not feasible.

VLM dwarfs are fully convective, small (<0.3 solar radii), cool (spectral type later than M4) objects (Cassisi 2011). The last three decades have brought about a tremendous progress in the discovery and understanding of VLM stars. Even now, more VLM stars are still been identified in the immediate solar vicinity (Frith et al. 2013).

However, despite all the progress in the research on VLM objects, there are still no transiting planets, nor any eclipsing binaries known for which the primary has spectral type later than M6. The lowest-mass eclipsing binary known was found in the Orion Nebula Cluster (Stassun et al. 2005). Kepler has found some eclipsing binaries for which the secondary is a VLM object (e.g., Howell et al. 2010) but no spectra can be obtained for the secondary because of the high contrast with the primary.

Pinfield et al. (2003) estimate a VLM binary frequency of 50% +/- 10%, of which about 15% are resolved by HST in the separation range 7 to 12 AUs and mass ratios higher than about 0.5 (Martín et al. 2003). In star-forming regions, young open clusters and OB associations the frequency of infrared excess indicative to dusty disks around VLM objects is high (Harvey et al. 2012), and the disks show evidence for dust processing (Riaz et al. 2012).

Infrared radial velocity and ground-based transit surveys have started the search for giant planets around VLM dwarfs (Blake et al. 2010; Rodler et al. 2012; Kovacs et al. 2013). These studies and others suggest that the planet frequency among VLM dwarfs is likely to be high, and also that those planets tend to be smaller than around solar type stars.

Section 2: VLM dwarfs observed by Kepler

Recently we presented reconnaissance spectra for a sample of 18 VLM dwarfs observed by Kepler for at least 3 cycles. Despite of the presence of rotational modulation and flares in many of the light curves, we demonstrated sensitivity to planet transits with radii between 1 and 5 Earths (Martín et al. 2013). The best sensitivity was obtained for quiet VLM dwarfs with Kepler magnitude around 16th (see Figure 1).

With the Kepler GO4-0030 program, we more than doubled the number of VLM targets observed by Kepler, and we enhanced the sample in quarter 16 via a DDT proposal. All of these objects have been confirmed to be VLM dwarfs via low-resolution spectra. The Kepler light curves are under analysis.

Our Kepler VLM dwarfs have been identified using data from the Kepler Input Catalog (KIC), 2MASS, Poss I and II, DSS and the UKIDSS databases, supplemented by deeper imaging data obtained using the IPHAS filters at the 2.5-m Isaac Newton Telescope (the KIS survey; Greiss et al. 2012). Our team has participated in the KIS, and has experience in identification of VLM objects in large area surveys using Virtual Observatory tools (Aberasturi et al. 2011).

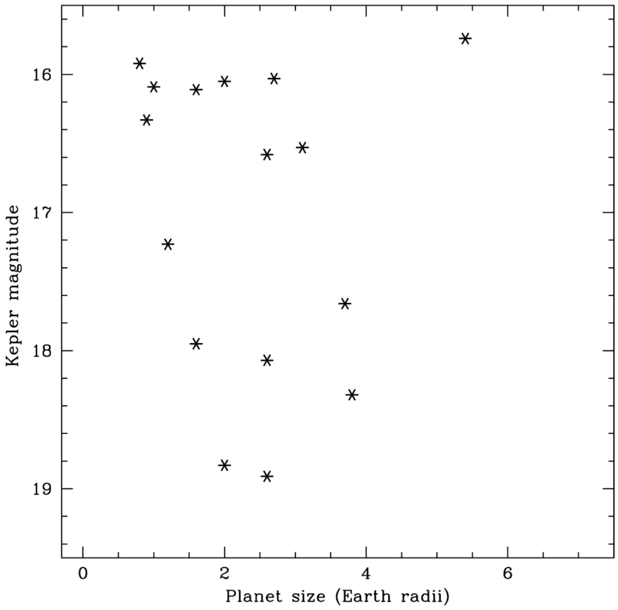


Figure1 *– A plot the Kepler sensitivity in units of Earth radii as a function of Kepler magnitude for the sample of VLM dwarfs studied by Martín et al. (2013). .*

Section 3. <u>Methodology</u>

Milli-magnitude photometric precision with small ground-based telescopes has been demostrated at optical wavelengths by several projects such as Mearth (Charbonneau et al. 2009), which has been successful at discovering a transiting super-Earth around the nearby M4.5 dwarf GJ1214.

The approach presented here is low-risk but potentially high-gain because transiting rocky planets in the habitable region around nearby VLM dwarfs offer the most cost effective opportunity to find targets to characterize the atmosphere of habitable planets. The distinguishing characteristics of the proposed Kepler survey that make it different to the MEarth or any other ground-based surveys are the following: (a) Cooler, fainter and smaller targets, but fewer of them (2000 M dwarfs in the case of MEarth, **150 nearby VLM dwarfs in the case of this Kepler survey**). (b) Large field of view so that many reference stars are observed simultaneously. (c) Quasi-continuous observations from space remove the large gaps and window effects that plague ground-based observations, particularly when they use only one site.

A description of the Kepler survey presented in this paper is the following:

(i) The targets are a sample of **150 VLM dwarf stars within 25pc from the Sun**. All of them are point sources and have low-resolution optical spectra available that yield spectral types from M6 to M9 (see appendix for detailed information about a subset of the selected targets). The cool end at M9 is determined by the limiting magnitude to get sufficient precision to detect Earth-sized planets given the estimated pointing stability performance of the Kepler spacecraft with 2 wheels. Cooler dwarfs are intrinsically fainter, and the planets within their habitable regions are likely affected by very strong tidal effects.

(ii) The targets will be observed with optimized apertures given their galactic latitude and the knowledge of the background stars. Typically the apertures will range between 10 and 20 Kepler pixels.

(iii) The integration times will be constant for each target and will range from 3 to 20 seconds depending on the target brightness.

(iv) The need for data storage is modest. The pixel images of the target plus 300 additional stars in the field will be requested (calibration stars plus other VLM dwarfs in the same field).

(v) Data reduction and analysis will be carried out in a similar way as presented in Martín et al. (2013), but with a modified version of the algorithm to take into account trailed images.

(vi) The duration of the observation on each target will be 3 days to cover the expected planet orbital periods within the habitable regions. **The total duration of the survey is 450 days.**

(vii) The main scientific impact of the proposed survey will be to determine the frequency of habitable planets around VLM stars, and to monitor the evolution of surface features in their atmospheres (Martín et al. 2001, 2013). Besides the main nearby VLM dwarf target in each field, we will also detect and study the Kepler light curves of around 50 additional fainter VLM dwarfs in each field. Those targets will be selected via a study of the spectral energy distributions.

Section 4. Habitable regions around VLM dwarfs and follow-up plan

Detailed calculations of the habitable zone for VLM dwarfs need to be done using real spectra of these objects, particularly at ultraviolet wavelengths. This work is part of a separate collaboration with the group of Lisa Kaltenegger, and it is just starting at the time of writing this paper. Preliminary results indicate that for an M9 dwarf the central part of the habitable region is located at an orbital period of 26 hours for a central mass of 0.08 solar masses and a planet with similar albedo as the Earth (0.29). In this particular example, the survey would cover almost 3 orbital periods.

Multi-wavelength observations of transit candidates will be carried out to weed-out false-positives because the amplitude of planetary transits almost does not change with wavelength (Borucki & Summers 1984). These follow-up observations will be done at other space telescopes, such as the Hubble and Spitzer. Adaptive optics or lucky imaging observations of the hosts of transit planet candidates will also be performed to check for the presence of background eclipsing binaries that may induce false positives. Radial velocity follow-up of transiting rocky exoplanet candidates to derive masses or set upper limits will be obtained with the CARMENES instrument at Calar Alto Observatory (Quirrenbach et al. 2010). Even though the RV precision may not be enough to detect the signal of some habitable transiting exoplanets around VLM dwarfs, an upper limit would be placed on the mass, and the density could be estimated as in the case of Kepler-22b (Borucki et al. 2012). It will also be very important to carefully determine the properties of the VLM hosts using spectral synthesis (e.g., del Burgo et al. 2009).

The frequency of transiting rocky planets (sizes less than about 1.5 Earth radii) found by the Kepler mission is about 15%, and it appears to increase toward lower primary masses. If there is continuity in the planetary properties we estimate that the expected yield of this survey is larger than 10 transits of rocky planets orbiting the habitable region around 150 VLM dwarfs within 30 pc. A null result in this survey would place stringent constraints on models of rocky planet formation. This result is consistent with the estimates provided by Belu et al. (2011). They found that within 10 pc distance from the Sun the number of transiting habitable planets is 5 times the number of habitable planets per star. 90% of those transiting habitable planets are expected to occur around M-type dwarfs, and particularly around the latest M dwarfs because they have closer-in habitable zones and smaller radii. Four thousand million years ago there were 3 rocky planets in the habitable region around the Sun (Selsis et al. 2007). Planetary systems around VLM dwarfs are likely more tightly packed than around solar-type stars, and hence the chances of having more than one planet in the habitable region is higher.

Appendix: The sample (due to the page limit of this proposal, information is provided here only for a subset of the 150 targets selected for this survey, the full list of targets is available upon request)

Target name: GJ 3517 = LHS 2065 = LP 666-9 = 2MASSW J0853361-032931

Published spectral types: M9.0 (Kirkpatrick et al. 1991)

Photometric magnitudes from Simbad:
V 18.80 [~] J 11.212 [0.026] H 10.469 [0.026] K 9.942 [0.024]

Eq. J2000 Coord.: **08 53 36.19 -03 29 32.11** Parallaxes *mas*: **116.8 [1.5]**

Notes:

No lithium detection and faint luminosity constrain its mass to the range 0.08 – 0.06 solar masses (Reid 1987; Henry & McCarthy 1993; Martin, R. Rebolo, A. Magazzu 1994).

Rotation and activity data: (Reiners & Basri 2010)

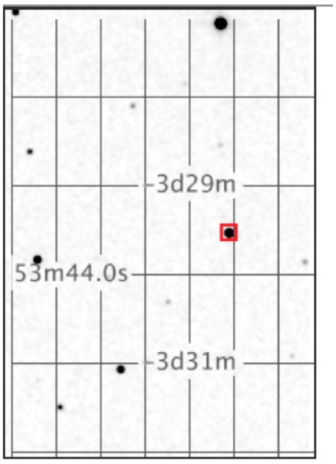
Projected rotational velocity (vsin i) = 13.5 +/- 2.0 km/s

Halpha equivalent width = 31.8 A

Log LHalpha/Lbol = -3.93

Average magnetic field Bf = 2900 G

Optical flare reported in Martin & Ardila (2001).



2mass-atlas-981226s-j0800162_sub.fits

Finder chart for GJ3517 from 2MASS J-band image. The FoV is 5 x 5 square arcminutes. Courtesy of NASA/IPAC Infrared Science Archive.

Target name: LHS 2090 = LP 368-128 = 2MASS J09002359+21500543

Published spectral types: M6.5 (Scholz et al. 2001).

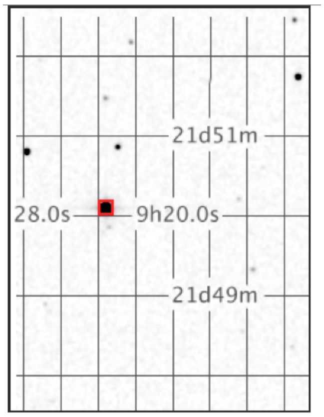
Photometric magnitudes from Simbad:
V 16.10 [~] J 9.436 [0.020] H 8.836 [0.023] K 8.437 [0.021]

Eq. J2000 Coord.: **09 00 23.59 +21 50 05.43** Parallaxes *mas*: **156.87 [2.67]**

Notes:

Rotation and activity data: (Jenkins et al. 2009)

Projected rotational velocity (vsin i) = 20.0 +/- 0.6 km/s



2mass-atlas-981106n-j1390173_sub.fits

Finder chart for LHS2090 from 2MASS J-band image. The FoV is 5 x 5 square arcminutes. Courtesy of NASA/IPAC Infrared Science Archive.

Target name: GJ 644C = LHS 429 = LP 368-128 = 2MASS J16553529-0823401 = VB8

Published spectral types: M7.0 (Kirkpatrick et al. 1991).

Photometric magnitudes from Simbad:

V 16.70 [~] **J 9.776 [0.029]** **H 9.201 [0.024]** **K 8.816 [0.023]**

Eq. J2000 Coord.: **16 55 35.29 -08 23 40.11** Parallaxes *mas*: **153.96 []**

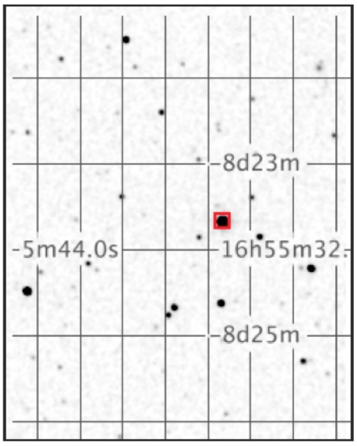
Notes:

Physically associated to GJ 644 (Separation 1500 AU)

Rotation and activity data: (Jenkins et al. 2009)

Projected rotational velocity (vsin i) = 9.0 km/s

Optical flare reported by Martin (1999).



2mass-atlas-990411s-j1150115_sub.fits

Finder chart for GJ644C from 2MASS J-band image. The FoV is 5 x 5 square arcminutes.

Target name: 2MASS J1835379+3259545 = LSR J1835+3259

Published spectral types: M8.5 (Reid et al. 2003)

Photometric Magnitudes from Simbad:

V 18.27 [~]	**J 10.270 [0.022]**	**H 9.617 [0.021]**	**K 9.171 [0.018]**

Eq. J2000 Coord.:

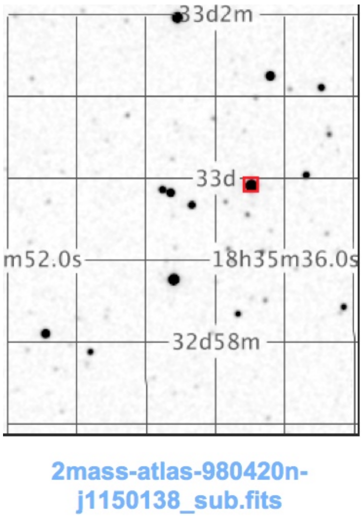
18 35 37.90 +32 59 54.59 Parallaxes *mas*: **176.5 [0.5]**

Notes: Rotation and activity data: (Reiners & Basri 2010)

Projected rotational velocity (vsin i) = 44.0 +/- 4.0 km/s

Halpha equivalent width = 3.2 A

Log LHalpha/Lbol = -4.85



Finder chart for LSR1835+3259 from 2MASS J-band image. The FoV is 5 x 5 square arcminutes. Courtesy of NASA/IPAC Infrared Science Archive.

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