Challenges and Opportunities of M Dwarf Planet Hosts

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Outline

• Why M dwarfs?
• M dwarf challenges for planet detection and characterization
• Ongoing projects and highlights
• Future prospects
What are M dwarfs?

$0.07 < \text{mass} < 0.6 \, M_{\odot}$

G2
$M = 1 \, M_{\odot}$
$R = 1 \, R_{\odot}$
$T = 5800 \, K$

M3
$M = 0.45 \, M_{\odot}$
$R = 0.45 \, R_{\odot}$
$T = 3500 \, K$

M6
$M = 0.15 \, M_{\odot}$
$R = 0.2 \, R_{\odot}$
$T = 3000 \, K$

Earth

---sizes to scale---
The shortcut to habitable planets

#1 Low-mass advantage for dynamical methods

RV signal $\propto M_*^{-2/3}$
Transit depth $\propto R_*^{-2}$
Transit Spectroscopy $\propto R_*^{-2}$
The shortcut to habitable planets

#1 Low-mass advantage for dynamical methods

#2 Low-mass brings in habitable zone (Kasting et al. 1993)

RV signal $\propto a^{-1/2}$
Transit probability $\propto a^{-1}$
Transit frequency $\propto a^{-3/2}$

(Selsis et al. 2007)
The shortcut to habitable planets

#1 Low-mass advantage for dynamical methods

#2 Low-mass brings in habitable zone

#3 Low-mass stars most numerous

In the solar neighborhood:
75% M dwarfs, of which
50% $M_* < 0.2 \, M_{\odot}$

![Histogram showing distribution of star masses within 10 pc](image)
The shortcut to habitable planets

#1 Low-mass advantage for dynamical methods
#2 Low-mass brings in habitable zone
#3 Low-mass stars most numerous

Best chance to find a transiting habitable planet around a nearby star, and study its atmosphere

(Deming et al. 2008)
M dwarf firsts

- Planet–planet interactions (GJ876, Marcy et al. 2001)
- Firm astrometric detection (GJ876, Benedict et al. 2002)
- 1 of 3 RV Neptunes (GJ436, Butler et al. 2004)
- RV super–Earth (GJ876, Rivera et al. 2005)
- Transiting Neptune (GJ436, Gillon et al. 2007)
- Atmospheric study of a Neptune (GJ436, Demory et al. 2007, Deming et al. 2007)
- Coplanarity in a normal system (GJ876, Bean & Seifahrt 2009)
- RV 2 $M_{\text{Earth}}$ planet (GJ581, Mayor et al. 2009)
- RV 4:2:1 resonance (GJ876, Rivera et al. 2010)
- Atmospheric study of a super–Earth (GJ1214, Bean et al. 2010)
M dwarf challenges

- Faintness
- Activity
- Difficult to measure/estimate accurate stellar parameters
M dwarf challenges: faintness

PHOENIX models courtesy P. Hauschildt et al.
M dwarf challenges: faintness

PHOENIX models courtesy P. Hauschildt et al.
M dwarf challenges: faintness

normal RV and transit measurements

@ 10 pc
Sun V=4.8
M0 V=9.0
M8 V=18.7

PHOENIX models courtesy P. Hauschildt et al.
M dwarf challenges: faintness

normal RV and transit measurements

more flux in the red/NIR

but more challenging…

PHOENIX models courtesy P. Hauschildt et al.
M dwarf challenges: faintness

The (coupled) technical challenges of the NIR

- For RVs: spectrograph design, calibration, detectors, & tellurics
- For transits: few bright stars in a single pointing, bigger telescopes, detectors, RV follow-up
M dwarf challenges: activity

Leads to larger RV and photometric jitter

West et al. 2004
M dwarf challenges: activity

Partial solution is the NIR for RV

See also:
Prato et al. 2008
Huelamo et al. 2008
Figueira et al. 2010

LP 944–20

$V_{\text{rad}}$ (km s$^{-1}$)

$\Phi$

Martin et al. 2006
M dwarf challenges: activity

**NIR RV**

- Depends on spot temperature
- Maximum reduction reached around 1 µm
- Contemporaneous photometry a good diagnostic – e.g., GJ674 (Bonfils et al. 2007)

Reiners et al. 2010

See also Barnes et al. 2011
M dwarf challenges: activity

Photometry: occulted spots in transit

GJ1214b in r’ band

Carter et al. 2011b
M dwarf challenges: activity

Photometry: occulted spots in transit

GJ436b with Spitzer IRAC

Knutson et al. 2011
M dwarf challenges: activity

Photometry: unocculted spots in transit

GJ1214b simulation

Carter et al. 2011b
M dwarf challenges: activity

Photometry: long-term variability

GJ1214b

Berta et al. 2011
The MEarth Project

Oct. 2010 – Apr. 2011

Number of Stars

1σ Photometric Precision (Earth radii)

after removing systematics + stellar variability

before

systematics and stellar variability can be corrected by decorrelation and filtering; simulations show the cost is 10-20% suppression of transit depth

slide from Z. Berta
It is very difficult to estimate the masses, radii, and metallicities of field M dwarfs!

Impacts estimates of M and R for planets, study of correlations, and transit planet validation

The number one problem is the presence of significant abundance of molecules in their photospheres.

Enhanced activity and the fully convective nature of the latest objects are likely important secondary issues.
M dwarf challenges: parameters

The problem with mass

Delfosse et al. 2000
Models from Baraffe et al. 1998
M dwarf challenges: parameters

The problem with mass and radius

Carter et al. 2011a

Models from Baraffe et al. 1998
M dwarf challenges: parameters

The problem with radius – activity?

Single Stars!

See also: Lopez–Morales 2007

Demory et al. 2009

Models from Baraffe et al. 1998
M dwarf challenges: parameters

GJ1214b as an example

• Empirical M–L relationship + light curve:
  \[ \rho_* = 24.1 \pm 1.7 \text{ g/cm}^3, R_p = 2.65 \text{ R}_{\text{earth}} \]

• Theoretical isochrones + light curve:
  \[ \rho_* = 38.4 \pm 2.1 \text{ g/cm}^3, R_p = 2.27 \text{ R}_{\text{earth}} \]

Resolution would require eccentricity at least 0.1

More work clearly needed!
M dwarf challenges: parameters

The problem with metallicity

- Molecular features dominate the optical spectrum and prohibit clean equivalent width measurements
- Cool temperatures limit the range of atomic lines available, few are observable in the Sun
- Unreliable models mean that the objects must be fully characterized using photometry/spectroscopy and empirical relationships

Spectra from Pickles 1998
M dwarf challenges: parameters

Spectral synthesis to 0.1 dex accuracy?

GJ876: [M/H] = -0.12

Improved model atmospheres and spectral analysis code

Bean et al. 2006a & Bean et al. 2006b based on Valenti et al. 1998
Subsequent work by Chavez & Lambert 2009 & Schmidt et al. 2009
M dwarf challenges: parameters

Photometric calibration of metallicity

Functions of $V-K$ and $M_K$:
Bonfils et al. 2005
Johnson & Apps 2009
Schaufman & Laughlin 2010

Accuracy is 0.2 dex

GJ876: [M/H] = +0.03, +0.37, +0.23

Schaufman & Laughlin 2010
M dwarf challenges: parameters

Low-res NIR indices

GJ876: [M/H] = +0.43

Accuracy is 0.15 dex

see related poster Rojas–Ayala et al. 2010
M dwarf challenges: parameters

Final thoughts on metallicity

• Optical measurements should be re-visited with newly developed empirical calibrations of $T_{\text{eff}}$ and avoidance of problem areas

• Investigating the NIR at high-resolution and using more sophisticated analysis techniques have a great potential, but beware NLTE effects

• Increasingly important as more planet surveys focus on these stars
Ongoing projects and highlights
Ongoing projects and highlights

Optical radial velocity

- Discovery or confirmation of approximately 25 M dwarf planets
- Dearth of gas giants around M dwarfs: Endl et al. 2006, Johnson et al. 2007, Johnson et al. 2010
- Searches sensitive to very low-mass planets in the habitable zone around a few M dwarfs e.g., Endl & Kurseter 2008
- Very difficult to probe below 0.2 $M_{\text{sun}}$
Ongoing projects and highlights

NIR radial velocity

- Current state of the art is 5 m/s with VLT + CRIRES and ammonia cell
- CRIRES planet search running since 2009, 31 stars with $M < 0.2 \, M_{\text{sun}}$ so far, proposed to continue and add 30 more
- New northern hemisphere survey using Subaru + IRCS since late 2010, 20 m/s precision, 23 additional stars (PI: Andreas Seifahrt)
- Other surveys with precision $\geq 50$ m/s
  - Gemini + Phoenix + telluric calibration, Blake et al. 2007 – L Dwarfs!
  - Keck + NIRSPEC+ telluric calibration, Blake et al. 2010 – more L dwarfs!
  - Palomar + TEDI + ThAR and fibers, Muirhead et al. 2011
  - IRTF + CSHELL + telluric calibration, Crockett et al. 2011
- Plus new gas cell development – see next talk
- Results: No planet detections, some candidates, no giant planet for VB10
- Limitation is tellurics, new level of precision will require new instruments
Ongoing projects and highlights

NIR radial velocity

CRIRES ammonia gas cell

wedged windows to eliminate fringing

fixed pressure of 50 mbar at T=20 C

18 cm

5 cm
Ongoing projects and highlights

NIR radial velocity

CRIRES ammonia cell radial velocities

GJ699
rms = 4.8 m s\(^{-1}\)

GJ551
rms = 5.2 m s\(^{-1}\)

GJ406
rms = 5.1 m s\(^{-1}\)

GJ442B
rms = 5.2 m s\(^{-1}\)

Bean et al. 2010b
Ongoing projects and highlights

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• Other surveys with precision \( \gtrsim 50 \, \text{m/s} \)
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Ongoing projects and highlights

NIR radial velocity

VB10  VLT/CRIRES + ammonia cell

Radial Velocity (m s$^{-1}$)

$N = 12$  rms = 10.6 m s$^{-1}$

2009.2  2009.4  2009.6  2009.8

VLT/CRIRES + ammonia cell

Bean et al. 2010a
Ongoing projects and highlights

NIR radial velocity

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Ongoing projects and highlights

MEarth transit search

Charbonneau et al. 2009

GJ 1214b

Désert et al. 2011

Croll et al. 2011

Crossfield et al. 2011

Also stellar astrophysics!

MEarth South coming soon

Optimized for characterization!

Bean et al. 2010c

Charbonneau et al. 2009

Désert et al. 2011

Croll et al. 2011

Crossfield et al. 2011

Also stellar astrophysics!
Ongoing projects and highlights

Howard et al. 2011
Select future projects
Future projects

CARMENES: optical and NIR RV to 1 m/s precision

Will enable the large-scale detection of planets down to a few times the mass of the Earth in the habitable zones of nearby M dwarfs.

Telescope: Calar Alto 3.5m

Spectral coverage: 0.5 – 1.7µm with two stabilized spectrographs

Precision: 1 m s⁻¹ in 15 min for J = 8.5 M6 dwarf

Survey 300 stars in a 600 night / 5 yr GTO program

PI: A. Quirrenbach, Heidelberg

Operational in 2014

see related poster
Future projects
All-sky transit surveys from space

Proposed NASA Explorer-class missions:

**TESS** – PI. George Ricker

**ELEKTRA** – PI. Chas Beichman
see related poster
Summary

The first potentially habitable planet that we will have a hope of studying the atmosphere of will be found around an M dwarf.

Significant advances in the characterization of M dwarfs will have an important impact on the field and will most likely not be driven by stellar theorists, but rather exoplaneteers with a bigger motivation.