Who am I?

Height

5σ outlier

Normal (puny) human

Width

me
Outline

- RV Method Review
- Astro 2010 Report & NSF Portfolio Review
- RV SAG goals
  - Survey Science Drivers and Wavelength
  - Ongoing and Upcoming Surveys / Facilities
  - Instrumentation Approaches
RV Method Review

Radial Velocity
Transits
Microlensing
Imaging
Pulsar Timing

Number of Detections

Discovery Year
Doppler Shift due to Stellar Wobble
RV Method Review
RV Method Review
RV Method Review
Echelle Spectrum
RV Method Review – a single order of a spectrum

1 m/s ~1/3,000th of a resolution element
wavelength shift ~ 1 nm
RV Method Review – a single order of a spectrum

1 resolution element ~ 30 km/s

1 m/s ~ 1/3,000\textsuperscript{th} of a resolution element
wavelength shift ~ 1 nm

→ Precision RVs are firmly in the systematic noise regime
RV Method Review

Radial Velocity
Transits
Microlensing
Imaging
Pulsar Timing
The unseen companion of HD114762: a probable brown dwarf

DAVID W. LATHAM, TSEVI MAZEH, ROBERT P. STEFANIK, MICHEL MAYOR & GILBERT BURKI

BROWN dwarfs are substellar objects with too little mass to ignite hydrogen in their cores. Despite considerable effort to detect brown dwarfs astrometrically\textsuperscript{1–4}, photometrically\textsuperscript{4–9}, and spectroscopically\textsuperscript{10–12}, only a few good candidates have been discovered. Here we present spectroscopic evidence for a probable brown-dwarf companion to the solar-type star HD114762. This star undergoes periodic variations in radial velocity which we attribute to orbital motion resulting from the presence of an unseen companion. The rather short period of 84 days places the companion in an orbit similar to that of Mercury around the Sun, whereas the rather low velocity amplitude of about 0.6 km s\textsuperscript{-1} implies that the mass of the companion may be as low as 0.011 solar masses, or 11 Jupiter masses. This leads to the suggestion that the companion is probably a brown dwarf, and may even be a giant planet. However, because the inclination of the orbit to the line of sight is unknown, the mass of the companion may be considerably larger than this lower limit.
Latham, Stefanik, Mazeh, Mayor, Burki -- CfA speedometer & CORAVEL (1989)

**HD 114762** F9 V $m_V=7.3$  $m_2 \sin i = 11 \, m_J$

280 obs  \(\sigma_{RV} = 0.42 \, \text{km/s}\)  \(e = 0.26\)
51 Peg  Mayor & Queloz  1995

$P = 4.23$ d

$m \sin i = 0.47$ J

$\sigma_{RV} \sim 13$ m/s
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- Water-worlds & Super-Earths
- Direct RV detection (Tau Boo b; Rodler et al 2012; NIR)
New Worlds, New Horizons
in Astronomy and Astrophysics

Report Release e-Townhall
Keck Center of the National Academies
August 13, 2010
Astro 2010 Report

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- The charge from the decadal survey is to “discover planets within a few times the mass of Earth as potential targets for future space-based direct-detection missions.” (e.g. JWST) This is listed as a “Mid-Scale Innovations Project” top three priority for ground-based work in the $12 million to $40 million range.
NSF Portfolio Review

- Below we list the rank-ordered technical capabilities in AST-supported areas that are needed to address the highest-ranked PSSF (Planetary Systems & Star Formation) scientific priorities from NWNH...
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- Critically needed technical capabilities to address this research question are high precision (≤1 m/s) radial velocity programs for Doppler planet detection and Kepler follow-up (of larger, higher mass planets), high resolution spectroscopy to characterize the properties of host stars, small-to-moderate telescopes for photometric follow-up of microlensing events/ground-based transit surveys, and instrument development for extreme-precision optical spectrometers (to reach 10 cm/s) and high-resolution near-IR spectrographs to detect planets orbiting cool stars (later than M4V).
RV SAG Goals

Assess the State of Precision RV measurements for Planetary census –

Planet detection and characterization via precision radial velocity measurement has been the workhorse technique in the exoplanet field. This group will consider the important continuing role of RV measurements, both scientific and programmatic.
RV SAG Goals

Key science questions include:
RV SAG Goals

Key science questions include:

- What are the near-term, medium-term, and long-term needs for Doppler measurements to support NASA science objectives - how many stars of what magnitudes and spectral types?
Primary Science Driver

Find the nearby Earth-like planets in habitable zone orbits around a Sun-like star, corresponding to a 10 cm/s edge-on orbit RV K semi-amplitude for a one solar mass-star.
Fig. 4.— The time (seconds) to detect ($\sigma_v = K$) a 5 $M_\oplus$ planet in the habitable zone of its parent star, 10 parsecs away, for a range of observing wavelengths and stellar effective temperatures. The hashed regions correspond to wavelengths where the infrared absorption is too high for ground-based observations to be effective.
Habitable Zone as a Function of Spectral Type

Kasting et al. (1995)
55 Cnc system

55. Cnc

Scale = 3.16 AU
Inner HZ = 0.67 AU
Outer HZ = 1.32 AU

Habitable Zone

GJ 1214

hzgallery.org
Habitable Zone RV amplitude

![Graph showing the relationship between planet mass, star mass, and mean habitable zone distance](graph.png)

- Planet in habitable zone RV amplitude (m/s)
- Mean habitable zone distance (AU)
- M_{star}/M_{sun}

Approximate visible limit
The smallest planets in the Kepler sample are predominantly found around low-mass stars.

Howard et al. (2010)
The M Dwarf Opportunity

- 70% of main sequence stars are M dwarfs
  - Abundant within 10 pc
  - Until recently, neglected compared to FGK stars
The M Dwarf Opportunity

- Span a factor of ~5 in Mass/Radius, \( \sim 10^3 \) in Luminosity
  - For comparison, all of AFGK stars span a factor of \( \sim 2.5 \) in Radius, ~5 in mass, ~300 in Luminosity
- M dwarfs are red, V-K > ~3.5
  - Only 4 >M4 with V<12
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Key science questions include:

- What are the near-term, medium-term, and long-term needs for Doppler measurements to support NASA science objectives - how many stars of what magnitudes and spectral types?
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- How does this precision vary as a function of stellar type and wavelength?
- What are the implications of these limitations for new ensemble survey science goals and for finding the nearest low-mass exoplanets for future characterization?
Astrophysical Sources of RV Noise (Dumusque et al. 2011)

- P-mode oscillations ~ Minutes → Integrate over oscillations
- Granulation, Plages ~ Hours → multiple visits / night
- Spots ~ 30 Days → wavelength dependent
- Activity Cycle ~ Decade → Activity indicators, baseline
- Rotational broadening
  in younger stars → less RV content / line
Astrophysical Sources of RV Noise (Dumusque et al. 2011)

Dominant RV variability may not be a planet.

But is this a problem?

Example & Counter-Example: Kepler light curves show most solar type stars are on average more active than the Sun.

Valeri Makarov’s talk later today, plus Andrew Howard’s talk from previous EXOPAG meeting
Single Star Spot RV Noise Toy Model

\[ \Delta T_{\text{spot}} = 200 \text{ K} \]

- \( T_\ast \): 2800 K
- \( T_\ast \): 3700 K
- \( T_\ast \): 5700 K

RV signal [m/s]

Wavelength [nm]
Single Star Spot RV Noise Toy Model

\[ T_\ast: \]
- 2800 K
- 3700 K
- 5700 K

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*Does this result extend to earlier spectral types and/or longer wavelengths?*
RV SAG Goals

Programmatic questions to be considered include:
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- What are the benefits or disadvantages of increased investment in telescope time (and for which class of telescope)?
Telescope cost vs. Aperture
Telescope cost vs. Aperture

MINERVA concept: Array of smaller telescopes can achieve better cadence and same light gathering power compared to a larger telescope, and at a much lower cost.
RV SAG Goals

Programmatic questions to be considered include:

- What are the benefits or disadvantages of increased investment in telescope time (and for which class of telescope)?
- What competitive opportunities exist in the short and long term in the context of existing and planned US and European facilities?
An incomplete list of current and upcoming visible RV facilities:

<table>
<thead>
<tr>
<th>Facility</th>
<th>RV Precision</th>
<th>Observing Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIRES/eta Earth</td>
<td>1.5 – 2.0 m/s precision RV</td>
<td>~ 20 nights per year</td>
</tr>
<tr>
<td>Future: SHREK?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HARPS-N&amp;S</td>
<td>Sub-1 m/s precision</td>
<td>~ 80-100 nights per year</td>
</tr>
<tr>
<td>(N first light 2012)</td>
<td></td>
<td></td>
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<tr>
<td>APF</td>
<td>1.5 – 2.0 m/s precision RV</td>
<td>~ year-round</td>
</tr>
<tr>
<td>Currently inactive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHIRON</td>
<td>Sub-1 m/s precision</td>
<td></td>
</tr>
<tr>
<td>LCOGT</td>
<td>– similar to MINERVA, also funded</td>
<td></td>
</tr>
<tr>
<td>EXPRESSO/VLT, G-CLEF/GMT, CODEX/E-ELT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>etc…</td>
<td>See also Dave Latham’s talk</td>
<td></td>
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</tbody>
</table>
## The future of NIR PRVs:

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Facility</th>
<th>Wavelength Range</th>
<th>Resolution</th>
<th>Lead Authors</th>
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<tbody>
<tr>
<td>CARMENES</td>
<td>Calar Alto</td>
<td>0.5-1.8 microns</td>
<td>R~80k</td>
<td>Andreas Quirrenbach</td>
</tr>
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<td>CRIRES</td>
<td>VLT</td>
<td>5 m/s @ K</td>
<td>R~100k</td>
<td>Bean et al. 2010</td>
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<tr>
<td>CSHELL</td>
<td>IRTF</td>
<td>~7 m/s @ K</td>
<td>R~46k</td>
<td>Anglada-Escude, Plavchan et al. 2012</td>
</tr>
<tr>
<td>ESPaDOnS</td>
<td>CFHT</td>
<td>0.3-1 micron</td>
<td>R~70k</td>
<td>Jean-Francois Donati</td>
</tr>
<tr>
<td>HZPF</td>
<td>HET</td>
<td>~3 m/s @ YJH (~10 m/s w/ PATHFINDER)</td>
<td>R~50k</td>
<td>Suvrath Mahadevan</td>
</tr>
<tr>
<td>iSHELL</td>
<td>IRTF</td>
<td>~2-3 m/s @ K</td>
<td>R~75k</td>
<td>John Rayner</td>
</tr>
<tr>
<td>iGRINS</td>
<td>Harlan Smith @ McDonald</td>
<td>HK</td>
<td>R~40k</td>
<td>Dan Jaffe</td>
</tr>
<tr>
<td>NIRSPEC2</td>
<td>Keck</td>
<td>JHKLM</td>
<td>R~50-100k?</td>
<td>Ian McLean</td>
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RV SAG Goals

Programmatic questions to be considered include:

- What are the benefits or disadvantages of increased investment in telescope time (and for which class of telescope)?
- What competitive opportunities exist in the short and long term in the context of existing and planned US and European facilities?
- How should we prioritize increased investment in existing telescope resources versus investment in new, dedicated facilities and/or technology development for precision calibration/stabilization?
NASA Programmatic Investment

- Historically NASA has not invested in ground-based RV research at the program level, with the exception of PI-based grant programs such as Origins, and Kepler team RV followup.
- As part of the RV SAG in line with the Decadal Survey, should this possibility be on the table?
- NASA investment in ground-based astronomy (e.g. Keck Interferometer, LBTI, IRTF) must have clear and explicit ties to current or planned space-based missions.
  - JWST precursor science surveys (target identification)
  - Kepler follow-up
  - RVs in space?
Gordon Walker, PRV meeting @Penn State in 2010:

the future?

space

4-m at L2 – Strehl ~ 0.5

spectrograph

$R > 250,000$

$\lambda$ 0.3 to 2 μm

→ No telluric absorption, relatively more stable PSF!
RV SAG Goals

Instrument/technical questions include:
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- What potential exists for red/near-infrared radial velocity precision?
Techniques for Precision RVs

- Essentially there are two instrumentation philosophies
  - Gas cells + fiber scrambler (HIRES)
    - Correct for systematics from imperfect spectrographs in data processing with common optical path wavelength calibration
Gas Absorption Cell

Absorption cell

Orders separated

Many interference orders overlapped

High incident angle

Grating

Prism
Iodine Cell
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Philosophies not mutually exclusive
Velocity RMS

2–3.5 m/s

1–3 m/s

HIRES
GK stars in Eta-Earth Survey
Known planets removed

HARPS
Mayor and Udry, 2008,
Phys. Scr. T130, 014010

Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the "large" rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.
PRVs in the NIR and Visible

- Current and future efforts span ~4 orders of magnitude in precision:
  - Telluric lines: ~25 – 100 m/s in NIR (Bailey et al. 2010, Crockett et al. 2011);
    ~10 m/s in the visible (Figuera et al.)
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PRVs in the NIR and Visible

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Keck Fiber Scrambler

Julien Spronck - Yale
PSF Stability (Centroid)

Spronck et al. 2011 – Visible fiber scrambler with circular core fiber

Position of the center of the PSF normalized by FWHM

Fiber: 0.007
Slit: 0.1

=> Improvement in PSF stability by a factor 10 or more
Credit:
Andy Szentgyorgyi’s group at CfA.
Fiber Scrambler First Light @1.6 microns, May 2012

Limiting RV Noise Source:
PSF stability, ie the illumination of echelle and detector in both the far and near field respectively
→ Replace starlight with stable output from a fiber
→ FIBER SCRAMBLER:
  • Improves PSF centroid and FWHM stability by factors of >10
  • Improves corresponding LSF stability
  • Easier to model LSF and improves resulting RV precision

Compact! 3” of beam travel

SV Peg with fiber scrambler & gas cell in tandem

Raw spectra taken with a 50x100 micron rectangular non-circular core 10 m agitated fiber.
Conclusion

Several groups are actively pushing the frontiers in RVs in terms of wavelength, precision and data analysis, as we will hear in the rest of this session, to potentially fulfill the bold predictions of the decadal survey.

Want to join the RV SAG and help contribute to the report we will prepare?

Talk to Peter Plavchan (plavchan@ipac.caltech.edu) & Dave Latham (latham@cfa.harvard.edu)