New Near-IR Techniques for Precision Radial Velocities

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<thead>
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<td>Rick Gerhart and Caltech glass shop, Thurston Levy and Glass Instruments Inc, Scot Howell and Mindrum Precision</td>
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The M Dwarf Opportunity

- 70% of main sequence stars are M dwarfs
  - Abundant within 10 pc
  - Habitable zones are closer in with shorter periods, but tidal locking an issue
  - Transits are deeper $\sim (R_p/R_\star)^2$
  - Radial velocity amplitudes are larger

- Span a factor of $\sim 5$ in Mass/Radius, $\sim 10^3$ in Luminosity
  - For comparison, all of AFGK stars span a factor of $\sim 2.5$ in Radius, $\sim 5$ in mass, $\sim 300$ in Luminosity

- M dwarfs are red, V-K > $\sim 3.5$
  - Only 4 >M4 with V<12
RV content of M dwarfs as a function of wavelength

3500 K ~ M3

2800 K ~ M6

Reiners et al. 2009
Why go to the Near-Infrared for RVs?

- Some non-exoplanet science:
  - With 10 cm/s long-term precision, can initiate a ~10 year survey to directly measure the expansion of the Universe with high-z galaxies
  - With a 30m telescope, can characterize non-Newtonian orbits at the Galactic Center

- “Unconventional” exoplanet science:
  - Embedded YSOs with high extinction → too red for the visible

Rho Oph
~ 2 Myr
A_J=5

DSS R  2MASS J  2MASS K_S
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- “Unconventional” exoplanet science:
  - Embedded YSOs with high extinction $\rightarrow$ too red for the visible
    - Constrain the formation epoch, dynamics, and migration of planets, which must take place before the primordial gas disk dissipates at $\sim$5 Myr, ie:

What is the youngest star with a hot Jupiter?
Why go to the Near-Infrared for RVs?

- Some non-exoplanet science:
  - With 10 cm/s long-term precision, can initiate a ~10 year survey to directly measure the expansion of the Universe with high-z galaxies.
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- “Unconventional” exoplanet science:
  -Embedded YSOs with high extinction → too red for the visible.
  -Young and/or active stars → Less stellar RV noise in the NIR.
  -Combine optical + NIR RVs → Characterize, identify, and perhaps remove sources of stellar RV noise for solar-type main-sequence stars.
Single Star Spot RV Noise Toy Model

Reiners et al. 2009

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

RV signal [m/s]

Posters by Isabelle Boisse, Andreas Quirrenbach
NRC 2010 Decadal Survey

“The first task on the ground is to improve the precision radial velocity method .... With a new generation of high-resolution spectrometers in the optical and near-infrared, a velocity goal of 10 to 20 centimeters per second is realistic.”

The US RV community response*: Yes, we can do that.

Signed by over 50 of the US attendees at Penn State RV Workshop, August 2010, representing a significant fraction of the US RV community.
Our Road-Map to Addressing the Decadal Survey Challenge

- We are using CSHELL on IRTF as a testbed for several NIR RV techniques, adapted from the visible
  - 17 years old
  - 256x256 detector
  - $R \sim 45k$
  - single order spanning 5 nm @ 2.3 $\mu$m ($\approx 13$ Å @ 600 nm)

→ Really not what we want to be using long term, but CSHELL an excellent instrument to try new things.
Our Road-Map to Addressing the Decadal Survey Challenge

- We are using CSHELL on IRTF as a testbed for several NIR RV techniques, adapted from the visible
- We plan to apply these techniques to CSHELL’s successor, iSHELL (~2014)
  - R~70k
  - cross-dispersed immersion grating
  - ~250 nm spectral grasp
Our Road-Map to Addressing the Decadal Survey Challenge

- We are using CSHELL on IRTF as a testbed for several NIR RV techniques, adapted from the visible
- We plan to apply these techniques to CSHELL’s successor, iSHELL (~2014)
- We are conducting a design study to upgrade NIRSPEC on Keck II
  - Leverage NIRSPEC’s existing hardware investment (~$8M in 1998)
  - Cross-dispersed, Quasi-Littrow Echelle, R~33K
  - Cryogenic, temperature, pressure, gravity stabilized
  - Can use a couple of tricks to get to R~47K and then R~95K
  - Replace the detectors with H2RG’s
    - RV precision currently limited by mid-90s detectors
  - Replace the calibration unit
Techniques for Precision RVs

- Historically, ‘precision’ spectroscopy in the NIR has been anything but precise, lagging behind visible work.
- Current and future efforts span ~4 orders of magnitude in precision:
  - Telluric lines: ~25 – 100 m/s (Chris Crockett’s talk)
  - Gas absorption cells: ~5 m/s (Bean et al. 2010, this work)
  - Fiber scramblers: non-circular fiber cores (visible to date, this work)
  - Stabilized Fabry Perot etalons: potential for ~10 cm/s (visible to date)
  - Laser combs: potential for ~1 cm/s (visible + H-band: Osterman et al. 2010)
  - Uranium-Neon emission lamps (PATHFINDER + Mahadevan et al.)
  - Adaptive Optics
Choice of gas: METHANE

Why has methane been missed?
- Telluric methane!
- By using an isotopologue or deuterated methane, the reduced mass changes.
  - The ro-vibrational lines shift by ~10 nm!
Choice of gas: METHANE

Why has methane been missed?
- Telluric methane!
- By using an isotopologue or deuterated methane, the reduced mass changes.
  - The ro-vibrational lines shift by ~10 nm!
  ➔ Effectively, a whole new gas.
- Can operate at room temperature!
- Greater line density than Ammonia
Gas Cell Spectra: K-band

![Graph showing NH$_3$ and $^{13}$CH$_4$ FTIR spectra over a range of wavelengths (nm) from 2200 to 2450.](image)
Gas Cell Spectra: H-band

- $NH_3$ FTIR spectrum
- $^{13}CH_4$ FTIR spectrum

Wavelength (nm)
Preliminary Data Analysis

\[ \sigma = 22 \text{ m/s} \]

Systematic Offset
40 m/s

Hours

RV (m/s)
Noise Floor?

Averaging N S/N ~ 200 RV measurements

RMS (m/s)

\[ \frac{1}{\sqrt{\text{S/N}}} \]

\sim 7.5 \text{ m/s}
Current Status

- Ongoing survey of young, low mass stars in nearby moving groups, previously neglected by visible RV surveys
- Technique & first light paper in prep.
- Data pipeline refinement ongoing
- Systematic RV jumps indicate we need to obtain better empirical stellar templates
  - 3 hr CRIRES proposal submitted
  - This is a solvable problem
- Once resolved, intra-night measurements point to long-term precision of ~20-40 m/s, given sufficient S/N, corresponding to sensitivity to sub-Jovian mass planets
- With ~250nm spectral grasp, iSHELL will improve the RV precision obtainable with our gas cell by a factor of ~7, to ~3-5 m/s
- Gas Cells and FTIR spectra available to the community to use!
Limiting RV Noise Source: PSF stability
Non-Circular Core Fibers

Efficient Modal Scrambling
Low Focal Ratio Degradation
Visible $\rightarrow$ NIR
Fiber Scrambler

- Negligible throughput loss with our scrambling technique
- Improves PSF centroid and FWHM stability by factors of >10
- Improves corresponding LSF stability without stabilizing the spectrograph
- Easier to model LSF and improves resulting RV precision
- Take to IRTF in ~fall 2011.
Summary

- There are a lot of interesting science cases enabled by a precision RV NIR spectrograph beyond looking for planets around M dwarfs.
- We can borrow a lot of the precision RV techniques developed in the visible, and adapt them to the NIR:
  - Gas cells, spectrograph stabilization, fiber scramblers, laser combs, etc.
- We are actively testing several of these techniques now.
- We have laid out an instrumentation roadmap for CSHELL → iSHELL → upgraded NIRSPEC that leverages existing hardware investments.