Overview of radial velocity surveys and planets discoveries

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Tuesday, March 30, 2010
Radial velocity surveys: an overview

Planets around low mass stars

An emerging population of low-mass planets
  - the HARPS survey
  - properties
  - comparison with giant planets

Perspectives
  -> Earth twin detection
    - RV search: finding new Earths (limitation of RV method)
The HARPS Search for Southern Extra-Solar Planets

The metal-deficient sample


Sample:
~100 FGK dwarfs with -0.5<[Fe/H]<-2.0

Goal:
Study giant planet frequency in metal-poor domain

Results:
- 3 new giant planets in long period (P>1.5 yr) orbits (HD171028b, HD181720b, HD190984b)
- Lower frequency rate than solar-metallicity stars
- Long period giant planets are not rare around moderately metal-poor stars?
- Still all planets in metal-rich tail of the sample

Future (now):
- Extend study to incidence of Neptunes/Super-Earths around moderately metal-poor stars
- Further test planet formation models
The Keck/HIRES Metal-Poor Planet Search
Sozzetti, PL Co-Is: Latham, Torres, Carney, Laird, Stefanik, Boss, Korzennik

**SURVEY OUTLINE**

1) 200 stars (Carney-Latham and Ryan samples), no close stellar companions, 2.0 < [Fe/H] < -0.6, Teff < 6000 K, V < 12
2) Reconnaissance for gas giant planets within 2 AU, to gauge the role of competing models of giant planet formation
3) Campaign duration: 3 years
4) Typical RV precision achieved: 5-10 m/s

**MAIN FINDINGS**

A) No giant planets (K > 100 m/s) within 2 AU of metal-poor stars: confirmed and extended previous findings

B) Can say very little on low-mass (K < 30 m/s) planets

C) ~6% of the stars have long-period companions (follow-up with direct IR imaging to ascertain their nature)

D) Average giant planet frequency is \( f_p < 0.67\% \) (1σ)

E) \( f_p \) (-1.0<[Fe/H]<-0.5) a factor of several lower than \( f_p \) ([Fe/H]>0.0), but indistinguishable from \( f_p \) (-0.5<[Fe/H]<0.0).

G) \( f_p ([\text{Fe/H}] ) \) appears bimodal, but no clear conclusion can be made. Need better statistics!

Where to go from here?

1) Expand the sample size;
2) Lower the mass sensitivity threshold;
3) Search at longer periods.
The HARPS Search for Southern Extra-Solar Planets
The volume limited sample

PI: G. Lo Curto  Cols: W. Benz, F. Bouchy, G. Hebrard, C. Lovis, M. Mayor, C. Moutou, D. Naef, F. Pepe,
D. Queloz, N. C. Santos, D. Segransan, S. Udry

Sample
Non-active, slowly rotating dwarf stars, from F2V to M0V, within 57.5pc.

Goal
Obtain high accuracy orbital elements of Jupiter-mass planets in a volume limited sample of the solar neighborhood.

Strategy
Large survey, aiming to high detection rates with moderate RV precision. Fast observations, with a required SNR of 40 and a RV precision of 2-3m/s.

Results
We have detected 32 extra-solar planets, 7 of them in multiple systems.
Many of our targets have yet insufficient measurements.
The survey is continuing…
Searching for Planets around Evolved Intermediate-Mass (1.5-5M☉) Stars

- Okayama 1.88m, Japan (B. Sato et al.)
  - 300 GK giants (V<6), since 2001
  - 10 planets and 1 brown dwarf
- Xinglong 2.16m, China (Y.-J. Liu et al.)
  - 100 GK giants (V~6), since 2005
  - 1 planet and 1 brown dwarf
- Bohyunsan 1.8m, Korea (I. Han et al.)
  - 190 GK giants (V<6.5), since 2005
  - 1 brown dwarf
- Subaru 8.2m, Japan (B. Sato et al.)
  - >200 GK giants (6.5<V<7), since 2006
  - Tens of candidates
- RTT 1.5m, Turkey (S. Selam et al.)
  - 50 GK giants (V~6.5), since 2008

Understanding properties of planets (frequency, mass, orbit, etc.) as a function of stellar properties (mass, evolutionary stage, etc.)
**SOPHIE EXOPLANETS CONSORTIUM**

*Search for northern extrasolar planets*

F. Bouchy, S. Udry, G. Hébrard, X. Delfosse, A.M. Lagrange, D. Queloz,
C. Lovis, C. Moutou, F. Pepe, C. Perrier, A. Santerne, N. Santos, D. Ségransan, A. Vidal Madjar

1.93m OHP telescope + *SOPHIE* spectrograph
60-80 nights / semester since 2007
- High precision search for super-Earths [200*]
- Giant planets survey on a volume-limited sample [2000*]
- Search for exoplanets around M-dwarfs [180*]
- Search for exoplanets around early-type M.S. stars [300*]
- Long-term follow-up of *ELODIE* long periods [40*]

*Bouchy et al., 2009, A&A, 505, 853*
The SDSS-III MARVELS Exoplanet Survey, 2008-2014
PI: Jian Ge (Univ. of Florida)

- MARVELS Fibers
- Instrument Calibration box
- Control box

• A large-scale planet survey using multi-object Doppler instruments (60 objects in 08-10, 120 objects in 10-14)
• To monitor a total of 11,000 V=7.6-12 FGK dwarfs, subgiants & giants with minimal metallicity and age biases for detecting and characterizing ~150 new giant planets
Global Extremely High Precision Exoplanet Tracker Network

Jian Ge (UF), Tinggui Wang (China), Eduardo Martin (Spain)

- 0.39-0.70 µm, R=18,000, with dispersed fixed-delay interferometer approach
- 0.5-1 m/s in 30 min for V< 8 solar type stars with 2 m telescopes
- ΔP~2 mpsi, ΔT~4mK, <10m/s drifts per day
- Science operation: EXPER (Apr. 10), LiJET (Sept. 10), and SET (11?)
Florida IR Silicon immersion grating spectromeTeter (FIRST) & IR Exoplanet Tracker (IRET), Jian Ge (UF) & Steve Osterman (Colorado)

• FIRST mode with $R=\frac{55,000}{1.4-1.8 \text{ um}}$ simultaneously with $2k\times2k$ H2RG

• IRET mode, $R=\frac{25,000}{0.8-1.35 \text{ um}}$ with a dispersed fixed delay interferometer simultaneously with $2k\times2k$ H2RG

• Commissioning in Fall 2010, $\sim 2 \text{ m/s}$ for a H$\sim 8 \text{ M5V}$ dwarf in 20 min

• Primary targets: M dwarfs and young stars
The Penn State – Toruń Centre for Astronomy Planet Search (PTPS)

Current PTPS collaboration:
- Penn State: A. Wolszczan, S. Gettel
- TCfA: A. Niedzielski, M. Adamów, G. Nowak, P. Zieliński

Goal: A search of ~ 1000 GK-giants for substellar companions

Instrumentation:
- 9.2-m Hobby-Eberly Telescope (HET)
- High Resolution Spectrograph (HRS, R=60,000), I₂-cell

Highlights:
- the most compact planet orbit around a giant (0.6 AU)
- two brown dwarf – mass companions to a giant
The NASA-UC Eta-Earth Survey for Low-mass Planets From Keck Observatory
Andrew Howard & Geoff Marcy

- RV survey of 230 nearby GKM dwarfs
- Search for low-mass planets (Msini = 3–30 MEarth)
- Constrain population of low-mass planets and planet formation theory

Next Talk . . .
The HARPS Search for Southern Extra-Solar Planets
The M-dwarf sample

PI: X. Bonfils  Cols: Bouchy, Delfosse, Forveille, Gillon, Lovis, Mayor, Pepe, Santos, Udry, Queloz,

Sample:
~400 brightest M dwarfs < 20 pc

Goals:
Probe the dependance on stellar mass
Detect low-mass & habitable planets

Results:
- 11 planets (7 hosts)
- 9/10 of M-dwarfs planets w/ $m \sin i < 20$ Mearth
- lowest-mass planets (GJ 581e; $m \sin i = 1.9$ Mearth)
- first prototype of an habitable planet (GJ 581 d)
- statistical results:
  - few Jupiter-mass planets
  - super-Earth are common (>30%)

Future (now):
- 300/400 M dwarfs are screened for
  - short-period (P<15 d)
  - low-mass planets (>3 Mearth)
- Further test planet formation models

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2009
... a 4th planet

- planets have: 1.9, 16, 5 & 7 M⊕
- 3.2, 5.6, 13 & 67 d
- Gl581d’s period is revised: 83 d -> 67 d

Mayor et al. (2009)
**GJ 674**

### Parameters

<table>
<thead>
<tr>
<th></th>
<th>GJ 674 b</th>
<th>Spot</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (day)</td>
<td>4.7</td>
<td>35</td>
</tr>
<tr>
<td>$e$</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td>$w$ (deg.)</td>
<td>143</td>
<td>113</td>
</tr>
<tr>
<td>$K$ (m/s)</td>
<td>8.7</td>
<td>5.06</td>
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<tr>
<td>$m_2 \sin i$ (M$_\oplus$)</td>
<td>11.1</td>
<td>12.6</td>
</tr>
<tr>
<td>$a$ (AU)</td>
<td>0.039</td>
<td>0.147</td>
</tr>
</tbody>
</table>

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**2-planet Keplerian model**

**Bonfils et al. (2007)**
all planets

Around M dwarfs:

- radial velocity (Keck/Lick/AAT)
- radial velocity (HARPS/ELODIE)
- μ-lens
Sample distributions: Masses & Magnitudes

Signature of formation or selection bias?

Bonfils et al. (2010, in prep.)
The HARPS search for low-mass planets

- Sample of ~400 slowly-rotating, nearby FGK dwarfs from the CORALIE planet-search survey
- HARPS log(R’_HK) => ~250 good targets
- Observations ongoing since 2004
- Focus on low-amplitude RV variations
  => about 50% of HARPS GTO time

ESO-3.6m @ La Silla
Fig. 3.— The mass and semimajor axis distribution of extrasolar planets. Units of the mass ($M_p$) and semimajor axis ($a$) are earth mass ($M_\oplus$) and AU. (a) The results in disks without the $\Sigma_g$ bump due to the coupling effect of MRI activity and the ice line, (b) those with the bump in $\Sigma_g$ but without the $\Sigma_d$ enhancement, and (c) those with both the effects. The top panels are observational data of extrasolar planets (based on data in http://exoplanet.eu/) around stars with $M_*=0.8$–1.25$M_\odot$ that were detected by the radial velocity surveys. The determined $M_p \sin i$ is multiplied by $1/(\sin i) = 4/\pi \approx 1.27$, assuming random orientation of planetary orbital planes. The other panels are theoretical predictions with $M_*=0.8$–1.25$M_\odot$ for various values of $C_1$. The
HD 69830: A trio of Neptunes

P1 = 8.67 days  a = 0.078 AU  M sini = 10.2 M\textsubscript{Earth}
P2 = 31.6 days  a = 0.186 AU  M sini = 11.8 M\textsubscript{Earth}
P3 = 197 days  a = 0.63 AU  M sini = 18.1 M\textsubscript{Earth}

HARPS@3.6-m telescope, ESO La Silla

Lovis et al., Nature 2006
An emerging population of Hot Neptunes and Super-Earths


P_1 = 1024 days
e_1 = 0.23
m_1 \text{sini} = 0.72 \text{M}_{\text{Jup}}

P_2 = 9.37 days
e_2 = 0.40
m_2 \text{sini} = 7.5 \text{M}_{\oplus}

HD 181433
K3 IV
d = 26 pc
m = 8.4
[Fe/H] = +0.33

Another triple system
A system with a Saturn and a Hot Neptune

\begin{align*}
P_1 &= 1350 \text{ days} \\
e_1 &= 0.27 \\
m_1 \sin i &= 0.36 \, M_{\text{Jup}} \\
P_2 &= 4.08 \text{ days} \\
e_2 &= 0.0 \\
m_2 \sin i &= 23 \, M_{\oplus}
\end{align*}

HD 47186
G6 V
\(d = 38\) pc
\([\text{Fe/H}] = +0.23\)
\(O-C = 0.94\) m/s
66 measurements

A system with 3 Super-Earths

Mayor et al. A&A 2009

\( P_1 = 4.31 \text{ days} \)
\( e_1 = 0.02 \)
\( m_1 \sin i = 4.3 \, M_\oplus \)

\( P_2 = 9.62 \text{ days} \)
\( e_2 = 0.03 \)
\( m_2 \sin i = 6.9 \, M_\oplus \)

\( P_3 = 20.5 \text{ days} \)
\( e_3 = 0.04 \)
\( m_3 \sin i = 9.7 \, M_\oplus \)

HD 40307
K2 V
Dist 12.8 pc
[Fe/H] = -0.31

O-C = 0.85 m/s
135 observations
+ drift = 0.5 m/s/y
Observations:
small mass planets everywhere?
Multi-planet systems very common -> complex RV curves

Widely different timescales involved (3 orders of magnitude in period)

Optimal data sampling a priori unknown

Stellar low-frequency noise varies from star to star (~0.5-2 m/s)

- Best strategy: perform high-cadence measurements (7-10 consecutive nights)
- Less stars, but more measurements per star
- High frequency series of observations for > 250 stars
The quest for the low-mass population

Core-accretion models predict a significant increase in population below 20-30 $M_\oplus$

Ida & Lin 2008
Mordasini et al. 2009
Are we detecting this population?
Are we detecting this population?

Yes!
Are we detecting this population?

Yes!

Number of candidates with:
1) $m \sin i < 30 \ M_\oplus$
2) $P < 50-70$ days

Significance of periodogram peaks, F-test
HARPS
high-precision programme

a few 10’s of new candidates with mass<30M_{\text{Earth}} \text{ and } P<50-70\text{d}

> 30\% (+/- 10\%) of stars have Neptunes or super-Eaths
Some Candidates overview (2)

A 3-planet system with 2 Neptunes + 1 super-Earth

\[ e_1 = 0.16 \]
\[ m_1 \sin i = 5.4 \, M_\oplus \]

\[ e_2 = 0.09 \]
\[ m_2 \sin i = 18.5 \, M_\oplus \]

\[ e_3 = 0.27 \]
\[ m_3 \sin i = 15.9 \, M_\oplus \]

55 observations
\[ \text{O-C} = 0.8 \, \text{m/s} \]

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Some Candidates overview (4): 2 planet systems

\[ P_1 = 44.1 \text{ days} \]
\[ e_1 = 0.34 \]
\[ m_2 \sin i = 13.2 \, M_\oplus \]

\[ P_2 = 86.9 \text{ days} \]
\[ e_2 = 0.23 \]
\[ m_2 \sin i = 20.0 \, M_\oplus \]

\[ P_1 = 7.44 \text{ days} \]
\[ e_1 = 0.65 \]
\[ m_2 \sin i = 10.4 \, M_\oplus \]

\[ P_2 = 45.5 \text{ days} \]
\[ e_2 = 0.23 \]
\[ m_2 \sin i = 20.0 \, M_\oplus \]

\[ P_1 = 14.07 \text{ days} \]
\[ e_1 = 0.45 \]
\[ m_2 \sin i = 15.6 \, M_\oplus \]

\[ P_2 = 96.4 \text{ days} \]
\[ e_2 = 0.23 \]
\[ m_2 \sin i = 20.0 \, M_\oplus \]
Some Candidates overview (5)

single planets

\[ P_1 = 39.6 \text{ days} \]
\[ e_1 = 0.5 \]
\[ m_2 \sin i = 9.7 \, M_\oplus \]

\[ P_1 = 38.9 \text{ days} \]
\[ e_1 = 0.1 \]
\[ m_2 \sin i = 23.1 \, M_\oplus \]
Some Candidates overview (6)

P = 2.34 days
e = 0-0.2
m sin i = 5.8 M⊕

P₁ = 51.59 days
e₁ = 0.235
m₂ sin i = 8.4 M⊕

single-planet system

+ a drift
Some properties of close-in low-mass planets

3) eccentricity

- High eccentricities seem common, as for gas giants

Warning: Highly uncertain

\[
\begin{align*}
m < 10 \, M_{\text{Earth}} \\
10 < m < 20 \, M_{\text{Earth}} \\
m > 20 \, M_{\text{Earth}}
\end{align*}
\]
System with several giant planets: many resonances

Correia et al. 2008
P1 = 226 d  P2 = 334 d

Desort et al. 2009

Planetary multiplicity for systems with at least one Neptune/Super-Earth

resonances are not the rule!
Systems with Neptunes and super-Earths

Properties?

An emerging new population

comparison with giant planets?
Some properties of close-in low-mass planets

1) Mass distribution
Some properties of close-in low-mass planets

1) Mass distribution

- Mass distribution grows towards lower masses, as predicted by core accretion.

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Some properties of close-in low-mass planets

1) Mass distribution

- Mass distribution grows towards lower masses, as predicted by core accretion ( ).

![Graph 1](image1.png)

![Graph 2](image2.png)
Some properties of close-in low-mass planets

2) Period distribution

Udry, Mayor, Santos 2003

Preliminary

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Some properties of close-in low-mass planets

2) Period distribution

- For small-mass planets, no peak at ~3 days. Rise to >10 days? Different formation mechanism?
No host star metallicity correlation for low-mass planets?

CORALIE giant planets

Comparison sample

Santos et al. 2001
No host star metallicity correlation for low-mass planets?

CORALIE giant planets
Comparison sample

HARPS low-mass planets

Santos et al. 2001

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No host star metallicity correlation for low-mass planets?

CORALIE giant planets

HARPS low-mass planets

Comparison sample

Santos et al. 2001

m < 20 MEarth
No host star metallicity correlation for low-mass planets?

- CORALIE giant planets
- HARPS low-mass planets

Comparison sample

Santos et al. 2001

m < 10 MEarth

m < 20 MEarth
HARPS survey: Preliminary results
Systematic search for planets in a sample of non-active stars.

S/N and integration time chosen to decrease photon noise and acoustic noise to a global error smaller than about 0.5 m/s.

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HARPS survey: Preliminary $M_2sini$-$a$ distribution
A not too biased view below 0.2 AU
Synthetic planet population

Nominal Model: alpha= 7x10^-3, f_1=0.001, M=1 M☉

The variation of the initial conditions within the observed limits (protoplanetary disk properties) produces synthetic planets of a very large diversity.

- Mass: More than four orders of magnitude
- Distance: More than two orders of magnitude.
Harps: exploration of small-mass domain

“Completeness”
(P<100 d)

Normalization
(factor 8)
Detection of Earth twins in the HZ of solar-type stars?
Pulsation noise on $\alpha$ Cen B and other stars

Simulated

$\text{Eggenberger, 2006, priv. comm.}$

Measured

$\text{HARPS commissioning}$

$p$-modes average well on time $> \sim 1$ characteristic timescale
Pulsation noise on $\alpha$ Cen B and other stars

Simulated

Eggenberger, 2006, priv. comm.

Measured

HARPS commissioning

Choice of the target is important
Granulation?

- Granulation ($\tau \sim 6$ min)
- Mesogranulation ($\tau \sim 3$ h)
- Supergranulation ($\tau \sim 1$ day)
- Active regions ($\tau \sim 10$ days)

- Other sources of noise at lower frequencies
- Requires simulations

Stars

Kjeldsen et al. (2005)

Sun

Pallé et al. (1995)
Encouraging results....

Binning effect calculated on several HARPS stars

Warning: observation strategy not optimum + instrumental effect + photon noise
- only 1 observation per night
- sparse sampling (not every night)
3m/night each 3 nights, binning 1 day, $M = 2.5 \ M_\oplus$, $P = 200.0$, $sini = 1$, $\log(R''hk) = -4.9$

Dumusque et al. 2010
3m/night each 3 nights, binning 10 days, $M = 2.5 \, M_\oplus$, $P = 200.0$, $sini = 1$, $\log(R'hk) = -4.9$. 

Dumusque et al. 2010
3m/night each 3 nights, binning 10 days, $M = 2.5\, M_\oplus$, $P = 200.0$, $\sin i = 1$, $\log(R'\text{hk}) = -4.9$

Dumusque et al. 2010
The HARPS Search for Southern Extra-Solar Planets
Search for Earth-analogs around nearby stars


Sample
10 nearby, quiet, non-rotating, stars

Goal
Find a planet similar to the Earth in m and P

Strategy
- Observe with high time sampling (3x per night) and long exposures (15 min.) to average oscillations and granulation
- Obtain at least 50 data points per season
- Observe at least 2 - 3 seasons

Detectability
Detectable minimum planetary mass assuming $\varepsilon = 0$ and aiming at $K/rms > 2.5$
(for varying stellar magnitude and activity):

High expected and measured frequency of low-mass planets

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Planet discovered by Doppler spectroscopy
Planet discovered by Doppler spectroscopy