Exoplanet Search Techniques: Overview

PHY 688, Lecture 26
Mar 27, 2009
Outline

• Course administration
  – midterm exam: next Wednesday, April 1
  – review lecture: Monday, March 30
    • come with questions
  – final presentations
    • example topics on course website
    • select topic during class time on Monday

• Review of previous lecture:
  – hot Jupiter radii
  – Rossiter-McLaughlin effect

• Exoplanet search techniques
Example Presentation Topics

- Nearby young brown dwarfs (Josh Schlieder)
- Y dwarfs: empirical and theoretical expectations
- The 2MASS J0535–0546 brown dwarf eclipsing binary: why is the less massive component hotter?
- The substellar initial mass function: comparison among star forming regions and implications for the formation of brown dwarfs
- Non-equilibrium chemistry in substellar atmospheres
- Magnetic activity and rotation in low-mass stars and brown dwarfs
- Nemesis: Sun's hypothetical binary companion
- The origin of hot Jupiters
- The Kozai mechanism and the eccentricities of exoplanet orbits
- Searching for exo-earths through gravitational microlensing
- Planet formation through core accretion
- Planet formation through gravitational disk instability
- Planet migration and the architecture of planetary systems
- Extremely high contrast imaging of exoplanets: present and future
- Dynamical signatures of unseen planets in optically thin circumstellar debris disks
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Previously in PHY 688...
Sizes and Structure of Giant Planets: Very Hot Jupiters Are Larger

Fig. 3.— Cut-away diagrams of Jupiter, Saturn, and the two oddball extrasolar planets, drawn to scale. The observed radius of HD 149026b implies a massive core of heavy elements that makes up perhaps 70% of the planetary mass. In contrast, the radius of HD 209458b intimates a coreless structural model, as well as an additional energy source to explain its large value.

(Charbonneau et al. 2007)
Radii of Very Hot Jupiters

- some large radii cannot be explained by coreless planet models with high-altitude stratospheres:
  - extra internal power source?
    - stratospheric heat trap
    - tidal heating
    - damping or orbital eccentricity and apparent resetting of planet age?
      - host stars are giga-years old
  - preferential evaporation of neutral helium?

(Fortney et al. 2007)
Are Some Very Hot Jupiters Younger?

(Fortney et al. 2007)
Larger Radii through Evaporation of Neutral Helium

- material evaporated form planet carries both H and He
- H is ionized, He is not
  - this depends strongly in strength of EUV emission from host star
  - 10,000K temperature is in between ionization points
- strong planetary magnetic field could limit loss of charged H ions without affecting neutral He loss
- decrease of mean molecular weight at constant entropy: *larger radius*

*(Hansen & Barman 2007)*
Rossiter-McLaughlin Effect

- first detected in eclipsing binary stars
  - as in bottom panel

- effective Doppler shift of (absorption) line changes depending on the part of the host star that is occulted
  - stellar line profile may often be barely resolved spectroscopically

(Gaudi & Winn 2007)
RM Effect Geometry: Spin-Orbit Coupling

• seek to measure angle $\lambda$ between projected stellar rotation axis and planetary orbital axis

- note: $\Omega_s \sin I_s$ here is the same as $V_s \sin I_s$ and $V \sin I_s$ in the following slides, and indicates the projected stellar spin rate
RM Effect Geometry

- shape of deviation from normal radial velocity signature depends on $\lambda$

(Gaudi & Winn 2007)
RM Effect Magnitude

- depends on stellar rotation rate and planet-star radius ratio $\gamma = \frac{R_p}{R_s}$
  - photometric measurements of transit give precise and independent measure of $\gamma$

$$K_R \equiv V_S \sin I_S \frac{\gamma^2}{1 - \gamma^2}$$

$$= 52.8 \text{ m s}^{-1} \left( \frac{V_S \sin I_S}{5 \text{ km s}^{-1}} \right) \left( \frac{r}{R_{\text{Jup}}} \right)^2 \left( \frac{R}{R_{\odot}} \right)^{-2} \quad \text{(for } \gamma \ll 1)$$

(Gaudi & Winn 2007)
Observations of RM Effect Due to Planet Transits

- first observed in HD 209458b in 2000
- shown here for TrES-1
  - only third such observation
  - independent $V_s \sin I_s$ constrain from shape of stellar spectral lines

(Narita et al. 2007)

Fig. 2. Orbital plots of TrES-1 radial velocities and the best-fitting models, phased by $P = 3.0300737$ and $T_c(0) = 2453186.80603$. Top (marked with “a”): With the a priori constraint on $V \sin I_0$ (see text). Middle (marked with “b”): Without the constraint. Bottom (marked with “$\lambda = 0$ [deg]”): Without the constraint and assuming that $\lambda = 0^\circ$. Left panel: A radial velocity plot for the whole orbital phase. Right panel: A close-up of the radial velocity plot around the transit phase. The waveform around the central transit time is caused by the RM effect. Bottom panels: Residuals from the best-fit curve.
RM Effect in TrES-1: Measuring the Projected Spin-Orbit Angle

$V_s \sin I_s$ constrained from Doppler width of stellar line profiles

$V_s \sin I_s$ not constrained

Fig. 3. Contours of constant $\chi^2$ in ($V \sin I_s, \lambda$) space, based on simultaneous fitting of 32 radial velocity samples and 1333 photometric samples, with (left, marked with a) and without (right, marked with b) the a priori constraint on $V \sin I_s$. The solid line represents $\Delta \chi^2 = 2.30$ (inner) and $\Delta \chi^2 = 6.17$ (outer), while the dotted line shows $\Delta \chi^2 = 1.00$ (inner) and $\Delta \chi^2 = 4.00$ (outer), respectively.

(Narita et al. 2007)
Summary of RM Effect Observations for Transiting Planets

- measure projected spin-orbit angle $\lambda$
- infer constraints on actual spin-orbit angle $\psi$
- $\psi_{\text{peak}} < 22^\circ$ at 95% confidence
- broadly consistent with planet formation in a disk, no major orbital disturbance

Summary of RM measurements

<table>
<thead>
<tr>
<th>Exoplanet</th>
<th>Projected spin-orbit angle $\lambda$ [deg]</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 189733b</td>
<td>$-1.4 \pm 1.1$</td>
<td>1</td>
</tr>
<tr>
<td>HD 209458b</td>
<td>$0.1 \pm 2.4$</td>
<td>2,3,4,5,6*</td>
</tr>
<tr>
<td>HAT-P-1b</td>
<td>$3.7 \pm 2.1$</td>
<td>7</td>
</tr>
<tr>
<td>CoRoT-Exo-2b</td>
<td>$7.2 \pm 4.5$</td>
<td>8</td>
</tr>
<tr>
<td>HD 149026b</td>
<td>$1.9 \pm 6.1$</td>
<td>9,6*</td>
</tr>
<tr>
<td>HD 17156b</td>
<td>$9.4 \pm 9.3$</td>
<td>10,11*</td>
</tr>
<tr>
<td>TrES-2b</td>
<td>$-9.0 \pm 12.0$</td>
<td>12</td>
</tr>
<tr>
<td>HAT-P-2b</td>
<td>$1.2 \pm 13.4$</td>
<td>13*,14*</td>
</tr>
<tr>
<td>XO-3b</td>
<td>$70.0 \pm 15.0$</td>
<td>15</td>
</tr>
<tr>
<td>WASP-14b</td>
<td>$-14.0 \pm 17.0$</td>
<td>16</td>
</tr>
<tr>
<td>TrES-1b</td>
<td>$30.0 \pm 21.0$</td>
<td>17</td>
</tr>
</tbody>
</table>

Note: — References: (1) Winn et al. (2006); (2) Queloz et al. (2000); (3) Bundy & Marcy (2000); (4) Wittenmyer et al. (2005); (5) Winn et al. (2005); (6) Winn & Johnson (in prep.); (7) Johnson et al. (2008); (8) Bouchy et al. (2008); (9) Wolf et al. (2007); (10) Narita et al. (2008); (11) Cochran et al. (2008); (12) Winn et al. (2008); (13) Winn et al. (2007b); (14) Loeillet et al. (2008); (15) Hébrard et al. (2008); (16) Joshi et al. (2009); (17) Narita et al. (2007). Where multiple references are given, the quoted result is taken from the starred reference.

(Fabrycky & Winn 2009)
The RM Effect: Other Applications

- very sensitive to
  - $V \sin I_s$ (projected stellar rotation velocity)
  - $R_p$, $R_s$
  - $a$ (orbital semi-major axis)
  - $i$ (orbital inclination)

- shown is plot of change in stellar radial velocity due to RM effect

$$\delta \Delta v_s \equiv \lim_{dp \to 0} \frac{\Delta v_s(p + dp) - \Delta v_s(p)}{dp/p}$$

for various parameters $p$

- useful for
  - studying planet atmospheres
  - detecting/confirming wide planets

(Ohta et al. 2005)
Using the RM Effect to Probe Atmospheric Composition

- employ the strong $R_p/R_s$ dependence

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**Fig. 6.** Rossiter-McLaughlin-Effect (orbital motion subtracted) for the wavelength region 5840-5940 Å (100 Å bin centered around the NaD-doublet): Simulation with the wavelength-dependent radius for that wavelength interval (top panel, full line) versus a fixed radius $R_p = 1.31 R_{\text{jup}}$ (top panel, dashed line) and difference between the two (lower panel).

**Fig. 7.** Wavelength-dependent Rossiter-McLaughlin-Effect at the phase of maximum amplitude (-0.012): Top panel: Difference between the wavelength-dependent RME and the RME from the reference region 5000-5200 Å. Full line: Simulation with the wavelength-dependent radius, dotted line: Simulations with a fixed radius $R_p = 1.31 R_{\text{jup}}$. Lowe panel: The difference between the two simulations from the top panel.

(Dreizler et al. 2009)
Detecting Exo-Earth’s through the RM Effect

\[ K_O = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m \sin I}{(M + m)^{2/3}} \left(1 - e^2\right)^{-1/2} \]

\[ = 8.9 \text{ cm s}^{-1} \left(\frac{P}{\text{yr}}\right)^{-1/3} \left(\frac{m \sin i}{M_\odot}\right) \left(\frac{M}{M_\odot}\right)^{-2/3} \]

(latter equality true for \( m \ll M, e = 0 \))

\[ \frac{K_R}{K_O} = \left(\frac{PV^3}{2\pi Gm}\right)^{1/3} \left(\frac{\rho_*}{\rho_p}\right)^{2/3} \]

\[ \frac{K_R}{K_O} \sim 0.3 \left(\frac{m}{M_{\text{jup}}}\right)^{-1/3} \left(\frac{P}{3 \text{ days}}\right)^{1/3} \left(\frac{V}{5 \text{ km s}^{-1}}\right) \]

- note: \( i \) and \( I \) are the same variable in the top equation above
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From Lecture 2: Detection Techniques for Substellar Objects

brown dwarfs

• precision radial velocity monitoring
  – periodic Doppler shift of host star spectrum due to planet’s gravitational pull
• resolved imaging of binary systems
  – seeing-limited, speckle interferometry, adaptive optics
• unresolved photometry of hot stars
  – e.g., cool infrared excess in an otherwise much hotter white dwarf
• large-area sky surveys
  – extremely red objects

exoplanets

• precision radial velocity monitoring
• pulsar timing
  – apparent periodicity in pulsar rotation period due to planet’s gravitational pull
• transit photometry
  – ~1% dimming of star due to planet passing in front
• microlensing
  – gravitational lensing of light from background stars
• resolved imaging!
  – extremely high-contrast adaptive optics
Planet Detection Methods

(statistics as of Oct 2007)

(Perryman 2000)
Planet Detection History

- 318 radial velocity
- 58 transits
- 8 microlensing
- 7 pulsar timing
- 4 (11) imaging
Planet Detection: Direct Imaging

- 2MASS 1207–3932 B
  \( \sim 5 \, M_{\text{Jup}} \)

- primary is a young (~10 Myr) brown dwarf

- discovered with adaptive optics (AO) on the 8 m Very Large Telescope (VLT)

NACO Image of the Brown Dwarf Object 2M1207 and GPCC

(Chauvin et al. 2004)
Planet Detection: Direct Imaging

- Fomalhaut b
  \[ \sim 1 - 3 \, M_{\text{Jup}} \]
- discovered with the Hubble Space Telescope (HST)
Planet Detection: Direct Imaging

- HR 8799 bcd: $\sim 10–15 M_{\text{Jup}}$
- discovered with adaptive optics on the 10 m Keck telescope

(Marois et al. 2008)
Challenge of Direct Imaging: Star-Planet Contrast

- In the visible–near-IR
  - $F_{\text{Sun}} / F_{\text{Earth}} \sim 10^9$
  - $F_{\text{Sun}} / F_{\text{Jup}} \sim 10^8$
  - challenging wavefront control
  - small PSF
  - can observe from the ground

- In mid-IR
  - $F_{\text{Sun}} / F_{\text{Earth}} \sim 10^6$
  - $F_{\text{Sun}} / F_{\text{Jup}} \sim 10^4$
  - easier wavefront control
  - $>10 \times$ larger PSF
  - need to observe from space
Challenge of Direct Imaging: Star-Planet Contrast

Keck AO speckles at 2.2 µm

- high angular resolution, high-contrast imaging suffers from wavefront aberrations or order \( \sim \lambda \)
- aberrations manifested as “speckles” of size \( \sim \lambda/D \)
- speckles pose as “fake” planets

(Kalas 2005)
Planet Detection: Imaging

- **state of the art:** contrast of 9 mag at 0.5", 11 mag at 1" in the near-IR
- **benefits:** can perform atmospheric spectroscopy
- **limitations:**
  - hot (young), well-separated (>0.5") planets
  - no mass, radius information
- **false positives:** telescope speckles, distant background stars