

Exoplanets Doppler method

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1

Indirect Methods: gravitational perturbation of the stellar motion

$$a_* = a \frac{M_p}{M_*}$$

The reflex motion of the star is proportional to M_p/M_*

This introduces an observational bias
that favours the detection of massive planets around low-mass stars

Indirect methods based on the perturbation of the stellar motion:

Radial Velocity (or Doppler)

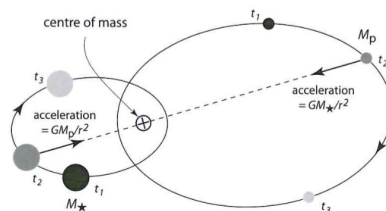
Timing

Astrometric

3

Indirect Methods: gravitational perturbation of the stellar motion

- The star and the planet orbit around their common barycenter
 - The stellar motion, induced by the gravitational perturbation of the planet, is called “reflex motion”



Exercise:

show that the Jupiter-Sun barycenter lies outside the volume of the Sun,
by 7% of the Sun's radius

2

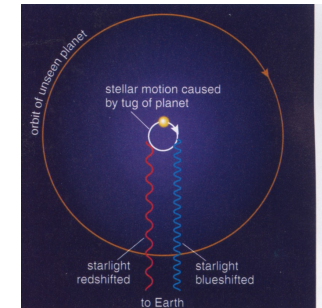
Doppler method

- Spectroscopic measurement
 - Based on the measurement of the radial velocity of the stellar reflex motion at different epochs

The stellar radial velocity contains a variable term, $V_* \sin i$, due to the projection of the reflex motion along the line of sight

Thanks to the Doppler effect, the variable term $V_* \sin i$ induces a periodic shift of the photospheric lines of the stellar spectrum

- Requires high resolution spectroscopy
 - e.g., Echelle spectroscopy



$$\Delta\lambda = \lambda_{\text{obs}} - \lambda_{\text{em}}$$

$$v_r \simeq \left(\frac{\Delta\lambda}{\lambda_{\text{em}}} \right) c$$

4

Masurement of the stellar radial velocity

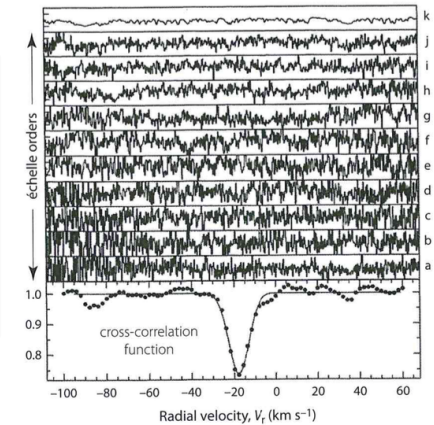
- Based on the measurement of the centroid of stellar absorption lines
- The central position of the absorption line, λ_c , can be measured with line-fitting methods
- For unblended, unsaturated lines, a Gaussian fit generally provides an accurate determination of the centroid
- The centroid λ_c is compared with the laboratory wavelength of the electronic transition responsible for the absorption, λ_o
- In this way we calculate the radial velocity: in the non-relativistic case, the radial velocity is

$$V_r = c (\lambda_c - \lambda_o) / \lambda_o$$

5

Doppler method: Cross correlation spectroscopy

Example cross-correlation function for a K0 III star with $S/N \sim 1$. Observations at $R=40000$ in 10 echelle orders, each covering ~ 4 nm. About 1000 lines match the template. The resulting cross-correlation function is shown at the bottom. (Queloz 1995)



7

Doppler method: Cross correlation spectroscopy

Information on the instantaneous Doppler shift is contained in the many thousands of absorption lines present in the high-resolution optical spectra of solar-type stars

This information can be concentrated into a few parameters by cross-correlation with a template of the expected stellar spectrum

In practice, one has to determine the value of ϵ minimizing

$$C(\epsilon) = \int_{-\infty}^{+\infty} S(v) M(v - \epsilon) dv$$

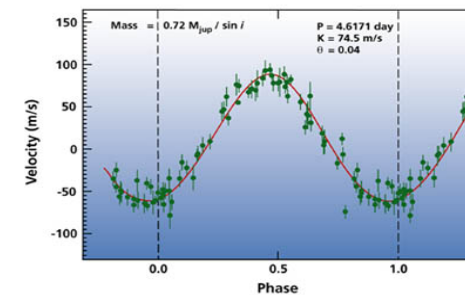
where S is the spectrum, M is the mask (i.e. a numerical template), both expressed in velocity space v

Thanks to the use of thousands of absorption lines, the cross correlation is efficient even at low signal-to-noise ratio

6

Radial velocity curves

- By plotting the stellar radial velocity as a function of time we build a radial velocity curve
- Once the periodicity is determined, data taken at different epochs can be rescaled as a function of orbital phase

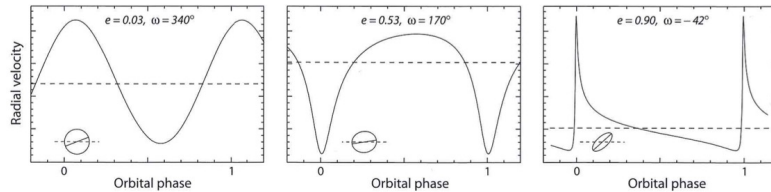


Radial velocity curve of 51 Peg b,
the first exoplanet detected with the Doppler method (Mayor et al. 1995)

8

Radial velocity curves

- For circular orbits with $M_p \ll M_*$ the Keplerian radial velocity curves are sinusoidal
- In general, radial velocity curves can have different shape, depending on the eccentricity, e , and the argument of the pericenter, ω



Examples of radial velocity curves
left: HD73256 - center: HD142022 - right: HD4114
dashed lines: radial velocity of the barycenter

9

The above expression for K can be used to estimate the expected effect for the Solar System planets

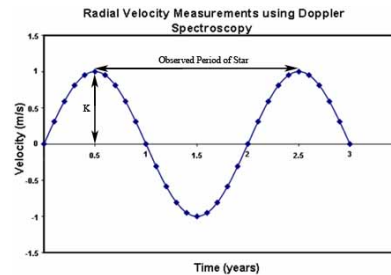
W. D. COCHRAN AND A. P. HATZES

Table I
Radial Velocity Signals of the Planets

Planet	M_p (M_J)	R (AU)	P (years)	Θ_* at 10 pc (mas)	K (ms^{-1})
Mercury	1.74E-4	0.387	0.241	6.4E-6	0.008
Venus	2.56E-3	0.723	0.615	1.8E-4	0.086
Earth	3.15E-3	1.000	1.000	3.0E-4	0.089
Mars	3.38E-4	1.524	1.881	4.9E-5	0.008
Jupiter	1.0	5.203	11.86	0.497	12.4
Saturn	0.299	9.54	29.46	0.273	2.75
Uranus	0.046	19.18	84.01	0.084	0.297
Neptune	0.054	30.06	164.8	0.156	0.281
Pluto	6.3E-6	39.44	247.7	2.4E-5	3E-5

11

- Parameters that can be derived from the radial velocity curve
 - Semi-amplitude, K , and period, P
- The amplitude corresponds to the variation of $V_* \sin i$ during one orbital period



- The semi-amplitude is given by

$$K = \left(\frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin i}{(M_* + M_p)^{2/3}} \frac{1}{(1 - e^2)^{1/2}}$$

10

Doppler method: selection effects

For a given stellar mass, the amplitude of the reflex motion scales as $M_p P^{-1/3}$
Easier to detect massive planets with short orbital period (i.e., small semimajor axis)

For a given planetary mass, the amplitude of the reflex motion scales as $M_*^{-2/3}$
Easier to detect planets around low-mass stars (e.g. M type stars)
However, low-mass stars are intrinsically fainter than stars of higher mass

The amplitude of the reflex motion is larger when the line of sight is aligned with the orbital plane ($\sin i \approx 1$)

If orbits are oriented at random, this selection effect does not introduce a bias on the physical properties of the planetary systems

12

- **Derivation of orbital and planetary parameters with the Doppler method**
 - The radial velocity curves provides the period, P , from which the semimajor axis a is inferred using the third Kepler's law
 - The mass of the star is derived from a spectroscopic study combined with a model of stellar structure
 - By fitting the radial velocity curve one can obtain the eccentricity, e , and the argument of the pericenter, ω
 - In this way, from the semi-amplitude K one can infer a lower limit on the planet mass

$$M_p \sin i = K \left(\frac{P}{2\pi G} \right)^{1/3} (M_* + M_p)^{2/3} (1 - e^2)^{1/2}$$

13

Doppler method

- **Technological requirements**

Extremely stable spectrograph

- Long term stability in temperature (possibly years)
- The spectrograph is closed in a separate room/container, fed by optical fibres

High accuracy of wavelength calibration

- Control of the optical paths of the stellar and wavelength calibration spectra
- Thorium-argon calibration

Classic observations

- Laser frequency combs

Cover the entire wavelength range of interest with a series of calibration lines of uniform spacing and intensity and accurately known wavelengths determined by fundamental physics

15

- **The orbital inclination**

- Systems with high inclination give a higher radial radial velocity signal and, in this sense, are more likely to be detected
- Statistically, the correction term $\sin i$ is not very large
- The statistical probability that the orbital inclination is within an arbitrary range (i_1, i_2) is (Fischer et al. 2014)

$$\mathcal{P} = |\cos(i_2) - \cos(i_1)|$$

- There is roughly an 87% probability that random orbital inclinations are between 30 and 90, or equivalently, an 87% probability that the true mass is within a factor of 2 of the minimum mass $M_p \sin i$
- In any case, a safe determination of the mass requires an independent measurement of the orbital inclination, i

14

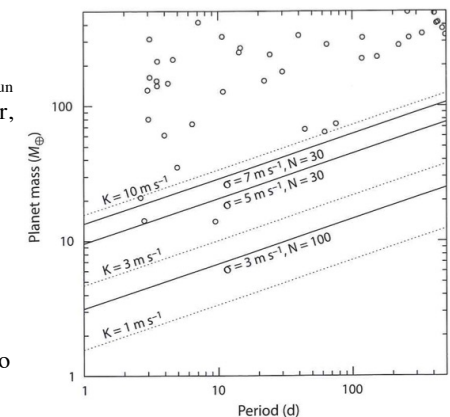
- **Mass limit of detectability**

Minimum mass limit for a 50% detection threshold as a function of the number of observations, N , and the combined error, σ , for $M_* = 1 M_{\text{sun}}$

In addition to the measurement error, the “stellar jitter” (activity in the stellar atmosphere and stellar oscillations) contributes to the combined error σ

With increasing measurement accuracy, stellar jitter becomes the most severe limit of application of the method

Current limits ~ 0.4 m/s; the aim is to attain ~ 0.1 m/s to detect and Earth-like planet around a solar-like star



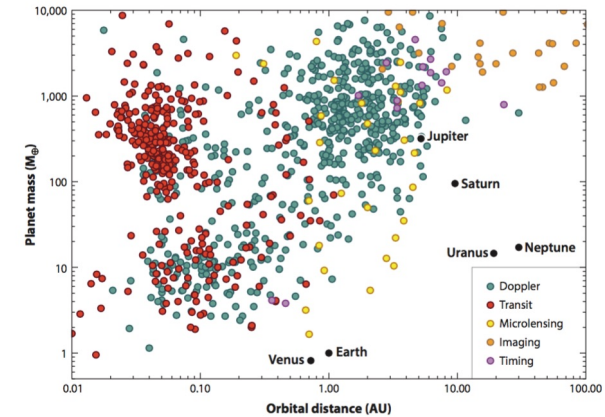
16

Doppler method the HARPS spectrographs

- **HARPS**
 - High Accuracy Radial velocity Planet Searcher
 - Telescope: ESO 3.6m La Silla (Cile)
 - <http://www.eso.org/sci/facilities/lasilla/instruments/harps/>
 - Has played a pioneering role, and is still effective, in the search for extrasolar planets
 - Extremely stable, with current limits of radial velocity accuracy ~ 40 cm/s for planets orbiting relatively bright stars ($V \sim 12$)
- **HARPS-north**
 - Based on the HARPS spectrograph, installed in 2012 at the Italian national telescope TNG (3.5m, La Palma, Spain)
 - Extends the capabilities of HARPS to the northern hemisphere

17

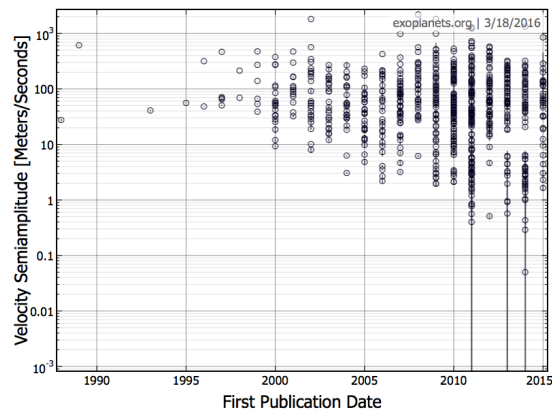
Doppler method comparison with other methods



19

Doppler method

- **Very effective method**
 - Between 1995 and 2012 most exoplanets have been discovered with the Doppler method
 - Currently (January 2018) detected 743 planets in 553 planetary systems



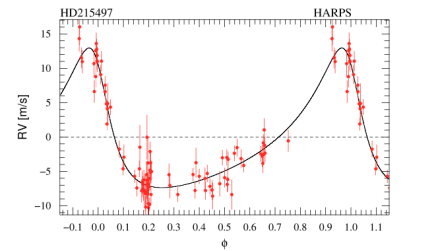
18

Detection of multiple planetary systems with the Doppler method

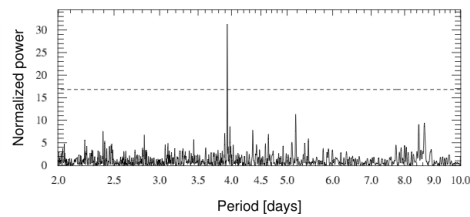
- The total radial velocity signal due an orbiting system of n_p planets is assumed to result from the independent reflex motions due to each planet separately
- **Procedure:**
 - Make a Keplerian fit of the most intense signal of the radial velocity curve
 - Subtract the Keplerian fit to the experimental data and search for more periodic signals in the residuals
 - If the periodogram (Fourier transform) of the residuals shows a peak above the noise level, a further Keplerian fit is performed
- The procedure can be iterated if the periodogram of the residuals shows additional significant peaks

Example:
Two-planet system orbiting HD215497 (Lo Curto et al. 2010)

Detection of the planet
that yields the main
signal ($P=568$ d)

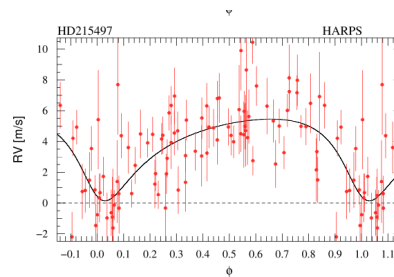


The periodogram of the
residuals shows a peak
at $P=3.93$ d, well above
the noise level



Example:
Two-planet system orbiting HD215497 (Lo Curto et al. 2010)

Keplerian fit of the
residuals, using the
orbital parameters
determined from the
previous step



Final results

Parameter	HD 215497b	HD 215497c
P [days]	3.93404 ± 0.00066	567.94 ± 2.70
T [JD-2 400 000]	$54\,858.95 \pm 0.37$	$55\,003.48 \pm 5.15$
e	0.16 ± 0.09	0.49 ± 0.04
ω [deg]	96 ± 34	45 ± 4
K [m s $^{-1}$]	2.98 ± 0.34	10.10 ± 0.65
V [km s $^{-1}$]	49.3107 ± 0.0006	
$m \sin i$ [M_{Jup}]	0.02	0.33
$m \sin i$ [M_{Earth}]	6.6	104.3
a [AU]	0.047	1.282

Doppler method New projects

• Espresso

- Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations
 - <http://www.eso.org/sci/facilities/develop/instruments/espresso.html>
- Extremely stable, recently installed at the combined focus of the ESO VLT (8m x 4)
 - Radial velocity accuracy: < 10 cm/s
 - Fainter stars than observable with HARPS
- Should allow detection of terrestrial-type planets at ~ 1 AU around solar-type stars

• Future limits of application of the method

- Jitter produced by stellar activity and variability
- Stellar pulsation, magnetic variability (spots, flares)

23

Doppler method future projects

• CODEX

- Instrument concept for the European ELT (Extremely Large Telescope)
- It aims to detect the expansion of the Universe directly, by measuring the Doppler shift of high-redshift quasar Ly- α absorption lines as a function of time
- The experiment targets a Doppler accuracy of ~ 0.02 m/s maintained over several decades
- The design has developed from HARPS and will incorporate all the state-of-the-art technology (e.g. laser comb, etc.)
- CODEX will have direct application to exoplanet studies
- Stellar jitter would definitely become the major limitation

24