Exoplanets
Doppler method

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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

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

\[ \Delta \lambda = \lambda_{\text{obs}} - \lambda_{\text{em}} \]

\[ v_r \sim \left( \frac{\Delta \lambda}{\lambda_{\text{em}}} \right) c \]
High resolution spectroscopy
“echelle” spectra

The Echelle spectrograph uses a plane grating at high angles of incidence and diffraction, essentially at very high orders, to take advantage of the consequent high resolution and dispersion.

To separate the different free spectral ranges (Echelle orders) on the detector, the Echelle spectrograph uses a second dispersion element of lower dispersion (a “cross-disperser”).

High resolution:
\[ R \sim 10^4 – 10^5 \]

Data reduction of stellar spectra

Main steps of the data reduction procedure

‘bias’ subtraction
‘flat field’ calibration
- required to correct different efficiencies of individual CCD pixels
- performed using a calibration lamp that illuminates the CCD uniformly

Extraction of the spectrum
- From bidimensional to unidimensional
- 'Merging' of the orders of the Echelle spectrum

Wavelength calibration
- Transforms the pixel space into wavelength space
- Requires a comparison emission spectrum of a calibrating lamp with emission lines at known wavelength positions

Example
Emission spectrum of an Ar-Th calibration lamp
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 $\epsilon$ 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 relatively low signal-to-noise ratio.

Example cross-correlation function for a K0 III star with
S/N ~ 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)

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 curves

- For circular orbits with $M_p << M_*$ 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, $\omega$.

Examples of radial velocity curves
left: HD73256 - center: HD142022 - right: HD4114
dashed lines: radial velocity of the barycenter.
• Parameters that can be derived from the radial velocity curve
  – Semi-amplitude, $K$, and period, $P$
    The amplitude corresponds to the variation of $V_\ast \sin i$ during one orbital period
  – The semi-amplitude is given by
    \[ K = \left( \frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin i}{(M_\ast + M_p)^{2/3}} \left(1 - e^2\right)^{1/2} \]

Doppler method: selection effects

For a given stellar mass, the amplitude of the reflex motion scales as $M_\ast P^{1/3}$
  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 $M_p^{-2/3}$
  Easier to detect planets around low-mass stars (e.g., M type stars)
However, one should take into account that 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 ($\sin i = 1$)
  This selection effect does not introduce a bias on the physical properties of the planetary systems if orbits are oriented at random

• 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, $\omega$
  – In this way, from the semi-amplitude $K$ one can infer a lower limit on the planet mass
    \[ M_p \sin i = K \left( \frac{P}{2\pi G} \right)^{1/3} \left( M_\ast + M_p \right)^{2/3} \left(1 - e^2\right)^{1/2} \]
• The orbital inclination

– Systems with high inclination give a higher 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)

\[
P = |\cos(i_2) - \cos(i_1)|
\]

– 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, \(i\)

Indirect estimate of the orbital inclination \(i\)

For young stars with stellar activity and rotation

• In principle, one could determine the inclination \(i_{rot}\) between the stellar equatorial plane and the line of sight from a detailed study of the star:
  – From the analysis of photospheric absorption profiles one obtains \(V_{rot} \sin i_{rot}\)
  – From the photometry of activity indexes one obtains the rotation period
  – From a detailed spectroscopic study of the star combined with models of stellar structure one obtains the stellar radius
  – From the radius and rotation period one obtains \(V_{rot}\)

• If the planet’s orbital plane is coplanar with the star equatorial plane, \(i = i_{rot}\)
  – This hypothesis is generally true for the Solar System planets
  – For extrasolar planetary systems the hypothesis could be tested through the Rossiter-McLaughlin effect (treated in a subsequent lesson)

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
– 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

• Limits of detectability

Minimum mass limit for a 50% detection threshold as a function of the number of observations, \(N\), and the combined error, \(\sigma\), for \(M_p=1 M_{\odot}\).

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

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

Current limits \(\sim 0.4 \text{ m/s};\) the aim is to attain \(\sim 0.1 \text{ m/s}\) to detect an Earth-like planet around a solar-like star
Doppler method
the HARPS spectrographs

- **HARPS**
  - High Accuracy Radial velocity Planet Searcher
  - Telescope: ESO 3.6m La Silla (Chile)
  - 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~12)

- **HARPS-north**
  - Based on the HARPS spectrograph, installed in 2012 at the Italian national telescope TNG (3.5m, La Palma, Spain)
  - Has started to provide important results, extending the capabilities of HARPS to the northern hemisphere

Doppler method

- Very effective method
  - Until 2012 most exoplanets have been discovered with the Doppler method (~700 planets in ~560 planetary systems)

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.

Keplerian fit of the residuals, using the period determined from the previous step.

Final results

Doppler method

Future projects

- **Espresso**
  - Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations
    - [http://www.eso.org/sci/facilities/develop/instruments/espresso.html](http://www.eso.org/sci/facilities/develop/instruments/espresso.html)
  - Extremely stable, to be 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)

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