Doppler spectroscopy and the discovery of extrasolar planets

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Abstract

This paper aims to clarify how to use Doppler spectroscopy to detect extrasolar planets. Doppler spectroscopy is an indirect method for finding extrasolar planets and known as radial velocity method. Doppler spectroscopy was the first successful method for the detection of exoplanets. It is still the most effective method for detecting exoplanets from Earth. A star with a planet will move in its own small orbit in response to the planet's gravity. This leads to variations in the speed with which the star moves toward or away from Earth. When viewed from a distance, these slight movements affect the star's normal light spectrum. If the star is moving towards the observer, then its spectrum would appear slightly shifted towards the blue and if it is moving away, it will be shifted towards the red. The radial velocity can be deduced from the displacement in the parent star's spectral lines due to the Doppler Effect. The radial velocity method can detect such variation which be used to confirm the presence of the planet.

Key words: Doppler spectroscopy, extrasolar planets, spectrum, Radial velocity,

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Introduction

The Doppler technique is a good method for discovering exoplanets. It uses the Doppler Effect to analyze the motion and properties of the star and planet. Both the planet and the star are orbiting a common center of mass. This means that the star and the planet gravitationally attract one another, causing them to orbit around a point of mass central to both bodies. In our solar system, all bodies orbit a common center of mass, including the Sun, but the Sun is so large in comparison to the planets, the center of mass actually lies inside the Sun. This makes the Sun seem to wiggle back and forth, and the spectrum of the Sun shifts back and forth as well. We search for this spectral shift in other stars to determine if there are one or more planets orbiting that star. When the star moves toward us, the light emitted has a shorter wavelength, so we say its spectrum is blue shifted. When it is moving away from us, the light has a longer wavelength, so we say its spectrum is red shifted.

While the Doppler technique is most widely used for detecting extrasolar planets, it is best suited to look for very massive planets orbiting close to their parent star (http://lasp.colorado.edu.)

Methods

Radial velocity

1. The radial velocity of a star is ideally the component of the velocity vector of its center of mass that lies along the line of sight. Radial velocities are valuable for a variety of astrophysical investigations, including studies of the orbits of long period binary stars, and the distances to star clusters . "Barycentric" radial velocities, such as reported here, are measured relative to the barycenter, or center of mass, of the Solar System (David et. al. ,2002 p 503–522).

Radial velocities can be determined via the position of the maximum (peak) of cross correlation function between the spectra of object (star) with the spectrum of the standard object (star) known radial velocity ((Bailer - jones,2004 p 703–712).) (Fig. 1,2).

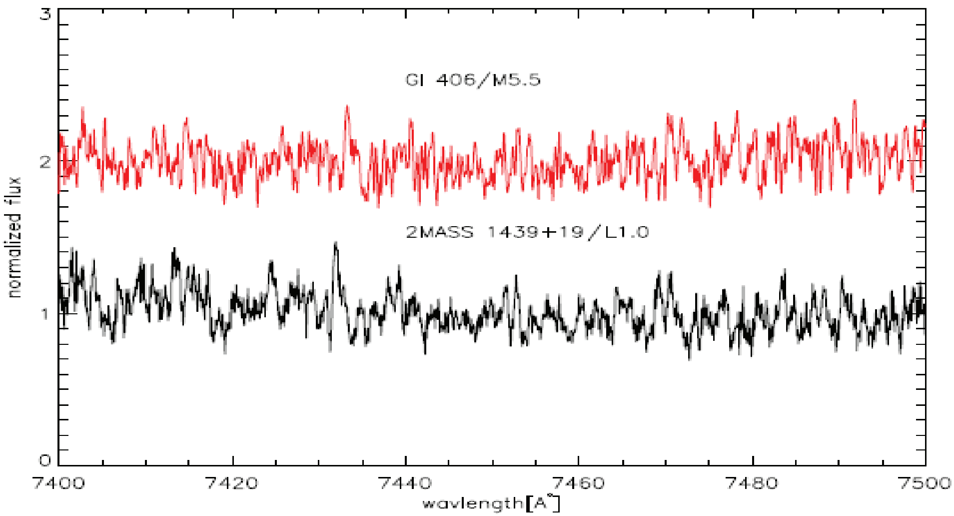

Fig. 1: Shows two spectra in the wavelength range 7400 -7500 ao (the red spectrum: Standard object, L and M spectral type).

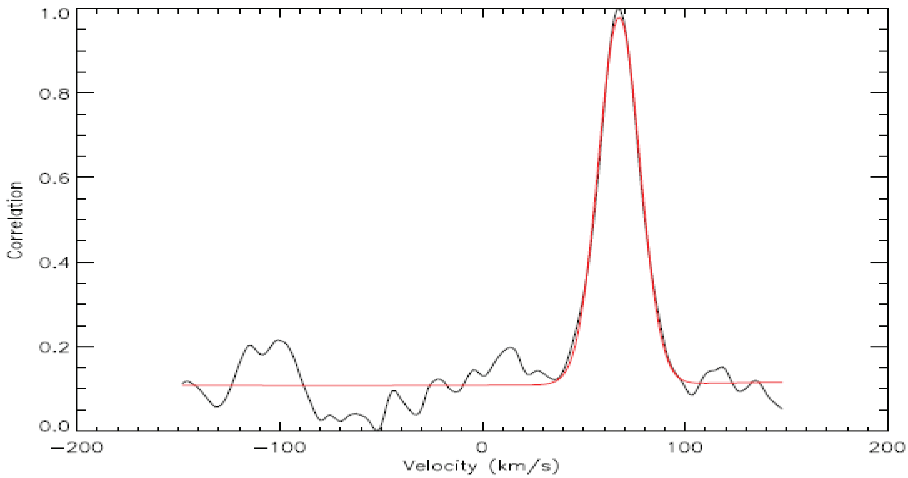

Fig. 2: Shows the cross correlation function between the two above Spectra (the red curve: Gauss function).The middle of the Gauss fits indicates the radial velocity.

Doppler spectroscopy

The Doppler Effect refers to the apparent shift in the wavelength (and frequency) of a wave when there is relative motion between the source of the wave and an observer. If an object such as a star moves away from us then the spectral lines will appear to shift towards the longer wavelength or redder part of the spectrum. Such a shift is termed a redshift. The amount of the shift would depends on the relative velocity between source and observer.

A comparison of position of spectral lines is presented in Fig.(3) which shows a source at rest (top), redshift where the source is moving away from the observer (middle) and blue shift where the source is moving towards the observer (bottom). Note that the motion between source and observer is relative.

Doppler spectroscopy detects periodic shifts in radial velocity by recording variations in the color of light from the star. The radial velocities can be calculated with the aid of the techniques of spectrography and the Doppler Effect.

$$V_r = c\,\frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0}$$

Where:

V_r : The radial velocity c : The speed of light

$\Delta\lambda$: The wavelength shift of light

λ_0: The wavelength of light

The sign radial velocity is defined: $+V_r$ blue shift and $-V_r$ red shift (4).

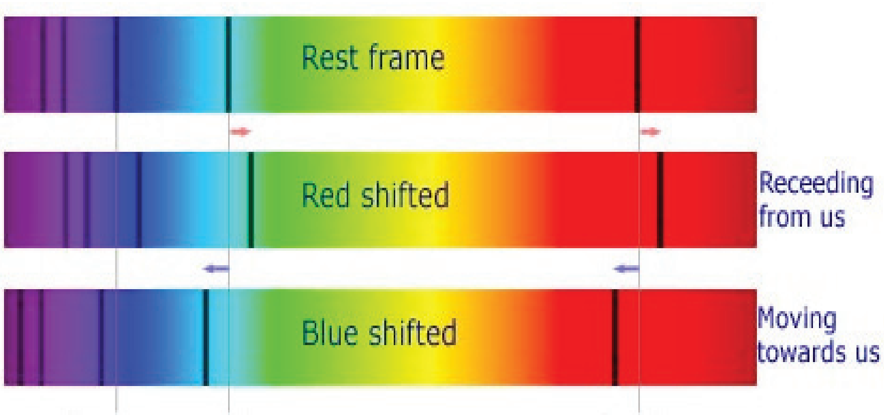

Fig. 3: Doppler shifting. (After www.atnf.csiro.au)

Instrumentation for Doppler Measurements

Instrumentation-HIRES, (High Resolution Echelle Spectrograph) at the Keck Telescope is a grating cross dispersed, Echelle spectrograph capable of operating between 0.3 and 1.0(μM). Observers can request one of two configurations, (HIRE Sb) or (HIRE Sr) using different cross dispersers and collimators fig(4), which are optimized for short and long wavelength observations, respectively. The efficiency of the two is equal at approximately 4200Angstroms (å).

Switching between the two is not possible during the night. Aside from the possible gaps in coverage at long wavelengths, the spectral span per exposure ranges from about 3000å for short wavelength settings, to about 4500 å at long wavelength settings (https://www2.keck.hawaii.edu).

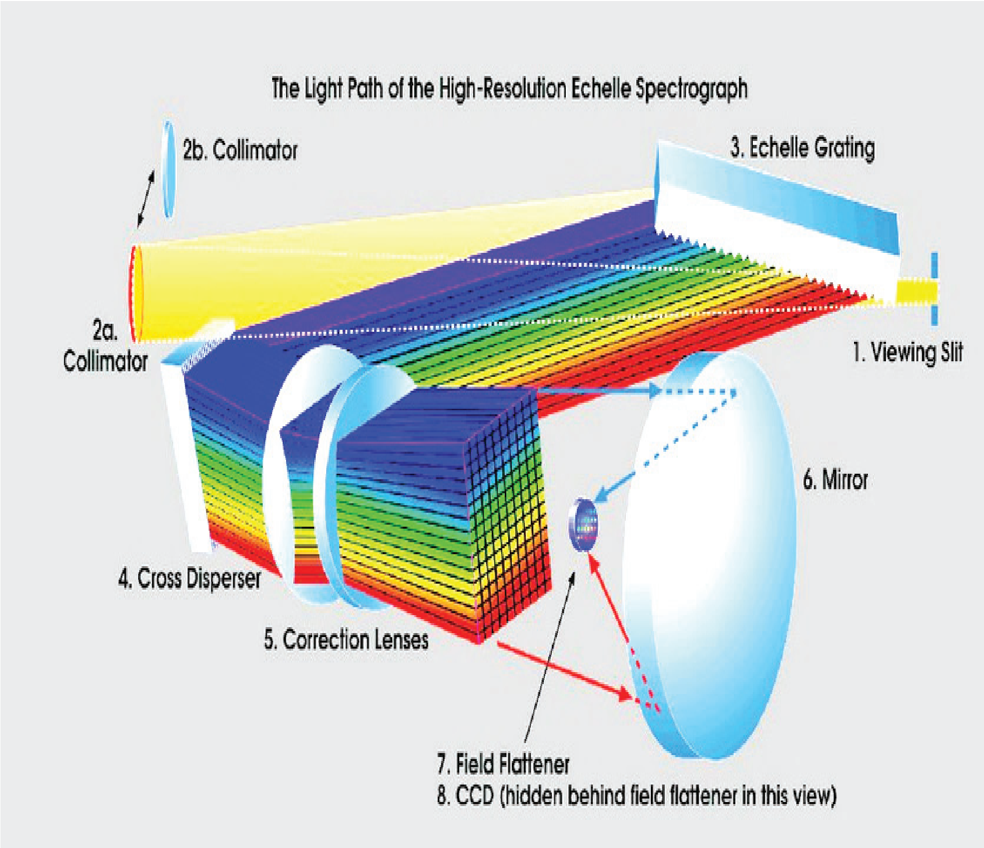

Fig. 4: shows the Light Path of High Resolution Echelle-Spectrograph.

(After www2.keck.hawaii.edu)

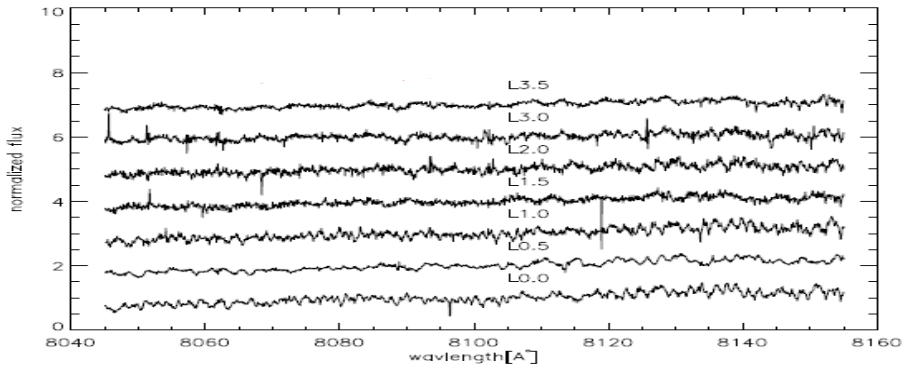

Fig. 5: Shows HIRES-spectra wavelength range (8040- 8160å).

Instrumentation-HARPS, the High Accuracy Radial velocity Planet Searcher at the ESO (European Southern Observatory) La Silla 3.6m telescope is dedicated to the discovery of extrasolar planets. It is a fiber-fed high resolution Echelle spectrograph. The instrument is built to obtain very high long term radial velocity accuracy (on the order of 1 m/s). To achieve this goal, HARPS is designed as an echelle spectrograph fed by a pair of fibers and optimized for mechanical stability (https:// www.eso.org).

This tiny shift in the star's spectral lines can be measured with a high precision spectrograph such as HARPS fig (6) and used to infer the presence of a planet. In 2011 the team behind HARPS reported the discovery of 50 exoplanets, including 16 new super-Earths (with a mass between one and ten times that of the Earth). HARPS, at that time, was responsible for two thirds of all the known exoplanets with masses less than that of Neptune (https:// www.eso.org).

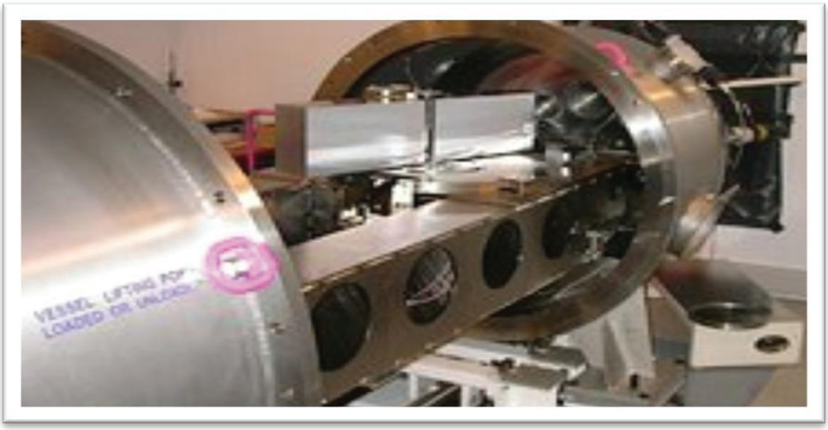

Fig. 6 Shows HARPS spectrograph. ((**After** https:// www.eso.org))

Finding exoplanets

The first confirmation of an exoplanet was made in 1995 by M. Mayor and D. A. Queloz (**https:// palereddot.org**). 51 Peg. B is the first exoplanet discovered orbiting fig(7) a main-sequence star and the first known hot Jupiter. It was classified as a hot Jupiter because it has orbital period of less than 10 days (4.23 days) and is similar in characteristics to the solar system's biggest planet with a mass of about 0.47 Jupiter masses (https:// phys.org/news/2017).

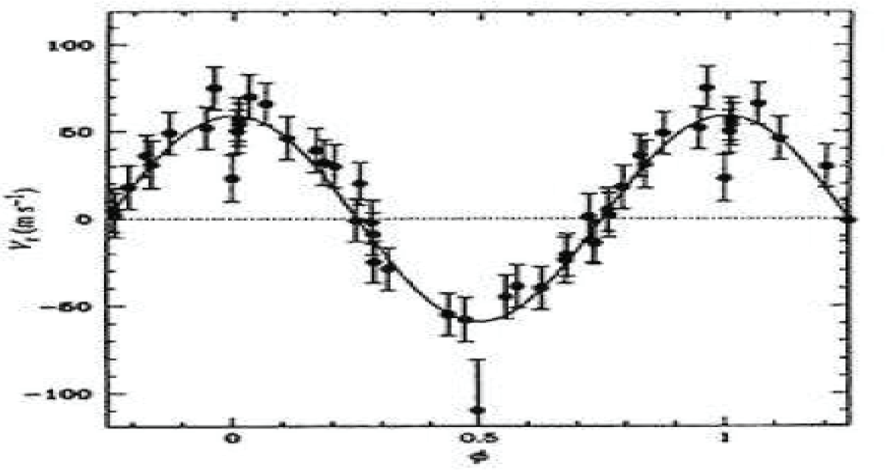

Fig. 7: Shows radial velocity curve of the Star 51 Peg. (ø: Orbital period). (After https:// palereddot.org)

Planets are very dim objects, and their direct observation is an extremely difficult task. The first direct observation of an exoplanet (GQ Lupi) only occurred in 2005 with VLT (Very Large Telescope). The observation of a Doppler shift of the spectral lines of a star indicates a change in the velocity of the star with respect to the observer. Since the observer himself is moving with a velocity ~3 0 kms^{-1} variable in direction, it is necessary to subtract this motion from the observational data and reduce it to the barycenter of the solar system (Beaugé et.al, 2008). The Doppler technique measures the reflex velocity that an orbiting planet induces on a star. Because the star-planet interaction is mediated by gravity, more massive planets result in larger and more easily detected stellar velocity amplitudes. It is also easier to detect close in planets, both because the gravitational force increases with the square of the distance and because the orbital periods are shorter and therefore more quickly detected.

Figure (8) shows an example of one of the lowest amplitude exoplanets, detected with HARPS. The orbital period for this is planet 58.43 days. The data was comprised of 185 observations spanning 7.5 years (Debra et.al, 2014, p.715-737).If an extrasolar planet is detected, a minimum mass for the planet can be determined from the changes in the star's radial velocity. To find a more precise measure of the mass requires knowledge of the inclination of the planet's orbit. A graph of measured radial velocity versus time will give a characteristic curve (sine curve in the case of a circular orbit), and the amplitude of the curve will allow the minimum mass of the planet to be calculated using the binary mass function.

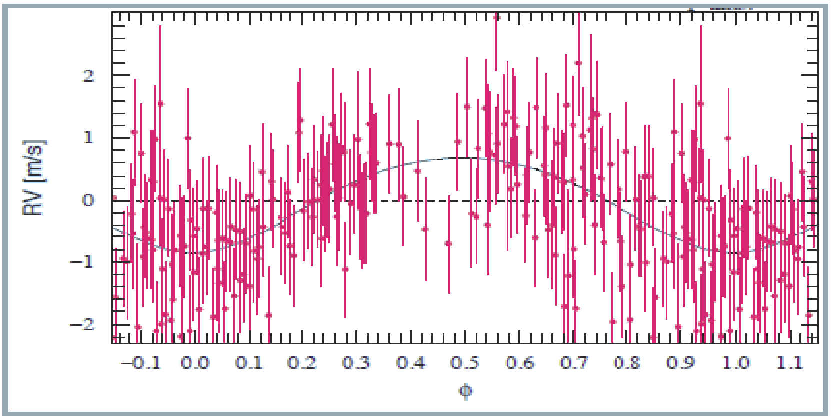

Fig. 8: Shows one of the lowest amplitude exoplanets detected with HARPS. (After Debra)

The Doppler technique gives information about the star's velocity toward or away from us, and from this we can find its mass. It is possible to calculate the planet's velocity using its orbital period and distance from its star. Using the law of conservation of angular momentum, the mass of the planet can be calculated.

The law of conservation of momentum says that in any closed system (that is, a system in which external forces are negligible), the total momentum of all the objects in the system cannot change so when objects within a closed system interact with one another, the momentum of an individual object may change, but the total momentum of all of the objects within the system must remain constant. The planet and the star must have equal magnitudes of momentum, and can be set equal to each other:

$$M_{Star}v_{Star} = M_{Planet}v_{Planet}$$

Where:

M_{Star} = is the mass of the star
M_{Planet} = is the mass of the and planet
v = is the velocity relative to the center of mass of the system.

The mass of the planet: can be calculated as following:

$$M_{Planet} = \frac{M_{Star}v_{Star}}{v_{Planet}}$$

The mass and velocity of the star can be determined from the Doppler technique. Though orbits are generally elliptical, we can use the circumference of a circle, for the distance traveled by a planet around its star. In this case, can be substituted (a), the semi major axis of the orbit, for(r) the planet's orbital period (p), is the time it takes the planet to travel around its star. The orbital period (p) can be determined from the Doppler technique.

$$v_{Planet} = \frac{2\pi a_{Planet}}{P_{Planet}}$$

Where is the planet's orbital period, is the semi-major axis of the planet's orbit and can be calculated using Kepler's Third Law. The planet's mass is given by (https:// lasp.colorado.edu):

$$M_{Planet} = \frac{M_{Star}v_{Star}P_{Planet}}{2\pi a_{Planet}}$$

Conclusion

The Doppler technique gives us information about the star's velocity. The observation of a Doppler shift of the spectral lines of a star indicates a change in the velocity of the star with respect to the observer. When the star moves toward us, the light emitted has a shorter wavelength, so we say its spectrum is blue shifted. When it is moving away from us, the light has a longer wavelength, so we say its spectrum is red shifted. This tiny shift in the star's spectral lines can be measured with a high precision spectrograph such as HARPS and used to infer the presence of a planet.

The radial velocities can be calculated. A graph of measured radial velocity versus time will give a characteristic curve (sine curve in the case of a circular orbit) and the amplitude of the curve will allow the minimum mass of the planet to be calculated using the binary mass function.

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