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Exoplanets / *Exoplanètes*

Doppler cross-correlation spectroscopy as a path to the detection of Earth-like planets

Spectroscopie Doppler par corrélation croisée : une possibilité pour détecter des planètes similaires à la Terre

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Abstract. In the middle of the 20th century, a paradigm shift appeared concerning the expected frequency of planetary systems in the galaxy . . . a shift induced by the observation of the rotational velocities of low main sequence stars (Struve 1952)!

At the same time, Fellgett (1955) proposed to concentrate the diluted Doppler information on several tens of thousands of absorption lines to allow the precise measurement of stellar velocities. This idea improved the efficiency of radial velocity measurements by a factor of over 1000. Gradually the accuracy of the new generation of spectrographs using cross-correlation is improved from 300 m/s to 0.1 m/s. . . . An idea that will contribute in an important way to the discovery of 51 Pegasi b and several hundreds of planetary systems.

Will visible or infrared cross-correlation spectrographs today be able to detect rocky planets in the habitable zone associated with their host star?

Résumé. Au milieu du 20ème siècle, un changement de paradigme est apparu concernant la fréquence attendue des systèmes planétaires dans la galaxie . . . un changement induit par l'observation des vitesses de rotation des étoiles de la séquence principale basse (Struve 1952) !

A la même époque, Fellgett (1955) propose de concentrer l'information Doppler diluée sur plusieurs dizaines de milliers de raies d'absorption pour permettre la mesure précise des vitesses stellaires. Cette idée a permis d'améliorer l'efficacité des mesures de vitesse radiale d'un facteur supérieur à 1000. Progressivement, la précision de la nouvelle génération de spectrographes utilisant la corrélation croisée est améliorée de 300 m/s à 0,1 m/s. . . . Une idée qui contribuera de manière importante à la découverte de 51 Pegasi b et de plusieurs centaines de systèmes planétaires.

Les spectrographes à corrélation croisée dans le visible ou l'infrarouge seront-ils aujourd'hui capables de détecter des planètes rocheuses dans la zone habitable associée à leur étoile hôte ?

Keywords. Astronomy, Planetology, Exoplanets, Exobiology, Velocimetry.

Mots-clés. Astronomie, Planétologie, Exoplanètes, Exobiologie, Vélocimétrie.

Note. Follows up on a conference-debate of the French Academy of Sciences entitled "Exoplanets: the new challenges" held on 18 May 2021, visible via https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.

Note. Fait suite à une conférence-débat de l'Académie des sciences intitulée « Exoplanètes : les nouveaux défis » tenue le 18 mai 2021, visible via https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.

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1. Change of paradigm during the 20th century

The last 25 years have seen this ancient dream of the “plurality of worlds” transformed into an exciting area of 21st century astrophysics.

In a famous letter, Epicurus in the 4th century BC already wondered about the possibility that some of these Worlds might contain living species. The hypothesis of the plurality of Worlds, and even the possibility that some of them shelter living species, has been present in philosophical thinking over the last two millennia.

However, the astronomers in the first half of the 20th century estimated that our planetary system was unique among the hundreds of billions of stars in our Galaxy. What was the origin of the nebulae required to explain the formation of planets with coplanar orbits and same direction of rotation? The erroneous assumption that the disk originated from tidal effects resulting from a very close passage of two stars (near-collision) was at the origin of these erroneous estimates of the frequency of planetary systems. Indeed, the probability of a near-collision, despite billions of years and hundreds of billions of stars, is close to zero.

The discovery in 1943 of planets hosted by stars in the solar vicinity led to a complete change in the estimate of the number of planetary systems ... for a wrong reason! These discoveries soon proved to be wrong (Dick [1]).

Struve [2] noted that the rotations of low main sequence stars are very small despite the large angular momentum expected from star formation by gravitational collapse of turbulent gas:

> *“I have suggested elsewhere that the lack of rapid axial rotation of normal solar-type stars ... suggests that these stars have converted their axial rotation to angular momentum from the orbital motion of the planets. Therefore, there can be many planet-like objects in the galaxy”* (Struve [2]).

Change of paradigm: the estimation of planetary systems in the galaxy jumps to billions or hundred of billions (Figure 1).

In the 1970s, the detection of strong infrared emission from very young stars revealed the presence of protoplanetary disks (see for example Beckwith [3]).

In 1995, the high angular resolution of the Hubble Space Telescope allowed McCaughrean and O’Dell [4] to obtain images of these disks surrounding most of the young stars in the Orion Nebula (Figure 2a).

And, more recently, the ALMA submillimeter interferometer has provided astonishing images of the accretion disks associated with very young T-Tauri stars (Figure 2b).

The structure of these disks, which exhibit dark rings, suggests the formation of planetary systems.

> *There is no longer any doubt that most stars must be hosts to multi-planetary systems: how can they be detected?*

2. Doppler spectroscopy

The ratio of stellar luminosity to the luminosity reflected by a possible planet made direct imaging beyond the possibilities of the instrumentation of the time. Indirect detection seemed more promising. Beloryzky [5] and Struve [2] had already mentioned the possibility of detecting the existence of planets by measuring the gravitational pull of the planet. This possibility was obviously beyond the accuracy of the spectrographs of that time. The years 1970–1990 saw a wide variety of instrumental developments to improve the sensitivity and stability of spectrographs. I will only mention here the approaches that led to exoplanet search programmes. On more than ten years, Campbell and Walker [6] using an HF calibration cell carefully measure the radial velocity of about 20 stars. Marcy and Butler [7] made a survey of a larger stellar sample using an iodine cell as calibration device. Baranne *et al.* [8, 9] developped cross-correlation Doppler spectrographs as the ELODIE spectrograph, Baranne *et al.* [10], installed on the 1.93 m telescope at Haute-Provence Observatory.

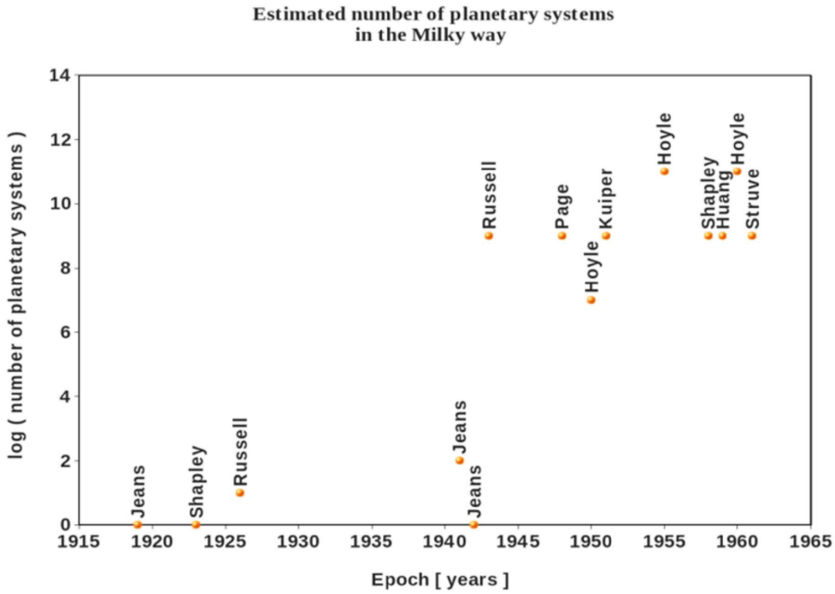


Figure 1. Estimated number of planetary systems in the Milky Way during the 20ith Century (adapted from Dick [1]).

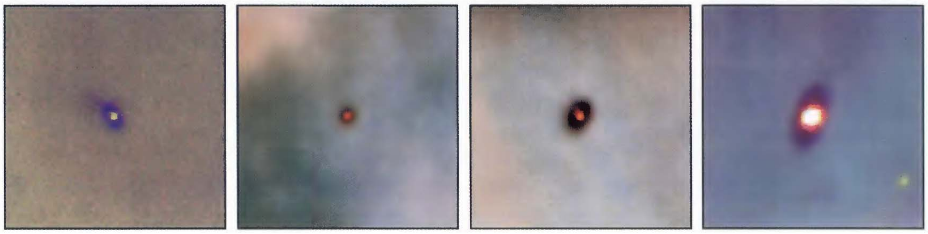
3. The discovery of 51 Pegasi b

But let's go back 27 years, to the beginning of this exciting phase of first discoveries.

Given the success of our CORAVEL instrument (Baranne *et al.* [8]) Philippe Véron, director of the Haute-Provence Observatory, asked André Baranne and myself to develop a cross-correlation spectrograph to be installed at the Cassegrain focus of the 1.93-m telescope. The technical possibilities of the 1980s offered decisive advantages: large CCD detector allowing the spectrum to be recorded and digitally correlated with a mask adapted to the variations in temperature and atmospheric pressure, optical fibers to improve the scrambling of the beams illuminating the optics, etc. In 1990 we obtained (with difficulty!) the financing of this instrument and in April 1994 it was possible to begin our survey to search for exoplanets. Our stellar sample consists of 142 solar stars selected to be simple, during a survey of more than ten years with the CORAVEL spectrograph (Duquennoy and Mayor [11]). Our periods of observation on the 1.93 m telescope were limited to one week every two months. Our radial velocity precision was better than 15 m/s.

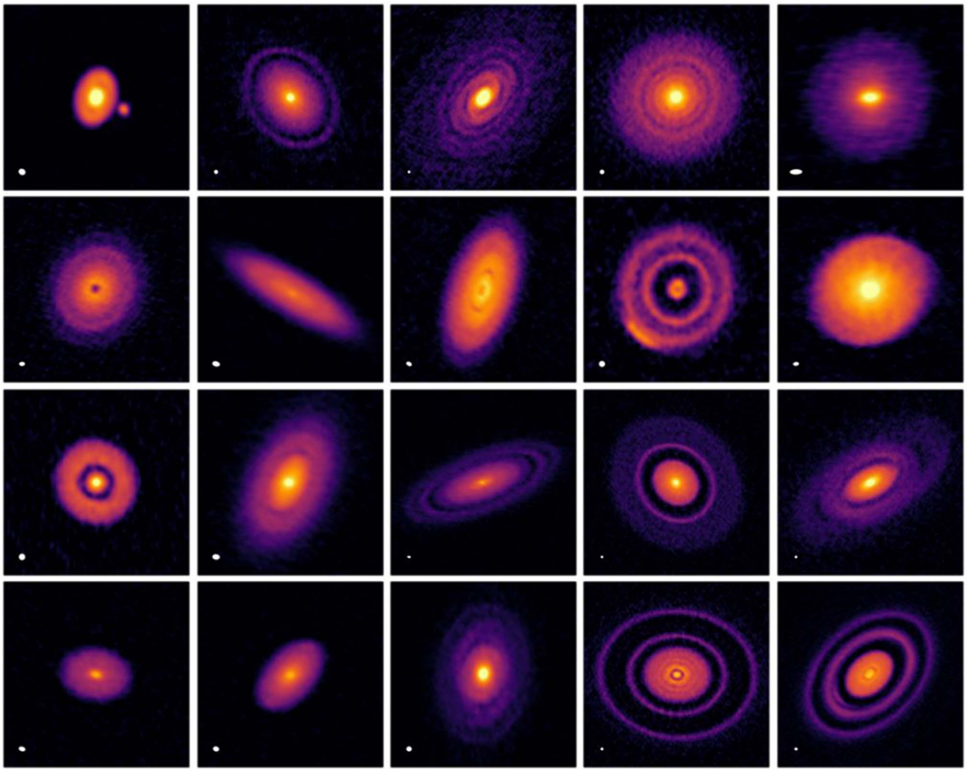
Our survey aims to extend the mass function of companions orbiting solar-type stars beyond the lower limit of hydrogen-burning (i.e., the domain of brown dwarfs and planets). In January 1995, several stars exhibit significant radial velocity variations, some with strong chromospheric activity have non-periodic variations. However, a G2V star appears to have a periodic velocity variation of only 4.2 days, maybe resulting from a planetary companion with a minimum mass (*msini*) of about half the mass of Jupiter (estimated from only 12 measurements).

The scenario of Jovian planet formation required the accretion of ice particles (Boss [13]), thus orbital periods greater than 10 years. Our planet candidate showed a disagreement of about a factor 1000 with this formation scenario!



(a)

Disk Substructures at High Angular Resolution Project (DSHARP)



This is the official Data Release webpage for the ALMA Cycle 4 Large Program *Disk Substructures at High Angular Resolution Project (DSHARP)*. DSHARP is a deep, high resolution (35 mas, or 5 au) survey of the 240 GHz (1.25 mm) continuum and ^{12}CO *J*=2-1 line emission from 20 nearby, bright, and large protoplanetary disks, designed to assess the prevalence, forms, locations, sizes, and amplitudes of small-scale substructures in the distributions of the disk material and how they might be related to the planet formation process.

(b)

Figure 2. (a) Accretion disks observed by the HST around young stars of the Orion Nebula (McCaughrean and O'Dell [4]). (b) Disks substructure at High Angular resolution measured with the ALMA submillimeter Interferometer (Andrews *et al.* [12]).

Periodic (or quasi-periodic) variations in stellar velocities can result from pulsations, stellar rotation associated with surface anisotropies induced by the stellar magnetic activity or due to the influence of a companion.

Radial velocity variations only allow the determination of a minimum mass (*msini*). If the proper rotation of the star was 4.2 days, one should have observed a very strong chromospheric

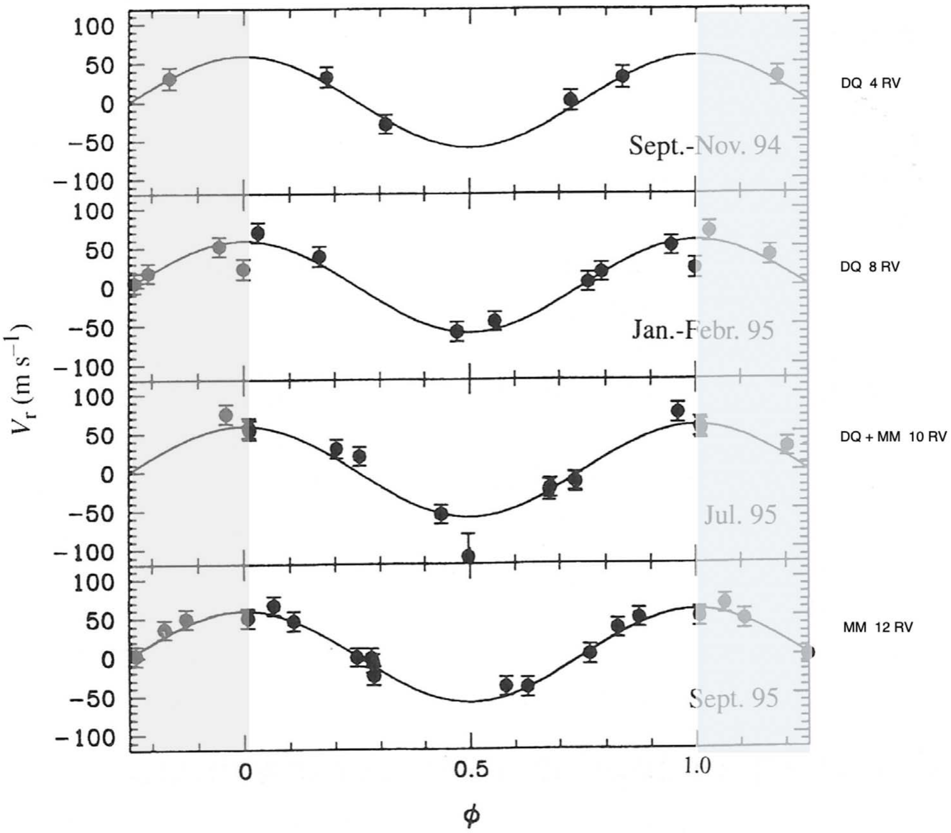


Figure 3. Measurements of the radial velocities of 51 Pegasi b made in 1994 and 1995 at the Haute-Provence Observatory, Mayor and Queloz [14]. The observations acquired at four different periods attest of the stability of the variation.

activity, whereas 51 Pegasi does not show such signs. The probability of having a very weak *sini*, orbiting almost perpendicular to the line of sight, is very low. The photometric stability was not consistent with a pulsation. In addition, gravity modes (with $n = 115$) do not pass through the convective zone, etc.

The following season allowed us to verify the stability of the period, the amplitude, and the phase of the radial velocity variation of 51 Pegasi: a test to exclude the hypothesis that the observed radial velocity variation results from the influence of the magnetic activity phenomena. The stability of the shape of the cross-correlation function also helps to reject the possibility of pulsation (also rejected on physical arguments and the observed photometric stability).

In July 1995, with Didier Queloz, at the Haute-Provence observatory, we were convinced of the interpretation of the influence of a planet of mass close to half a Jupiter. The announcement (Mayor and Queloz [14]) was based on 34 measurements (Figure 3).

The following year saw the announcement of the discovery of several planets, often also with short periods, typical of what were then called "hot Jupiters".

The origin of the short periods observed for these "hot Jupiters" was published immediately after the announcement of the discovery of 51 Pegasi b (Lin *et al.* [15]). During the formation of the planet, still immersed in the accretion disc, an angular momentum transfer induces an orbital migration. In fact, this effect had already been studied for 15 years . . . but not considered by planet researchers (Goldreich and Tremaine [16], Papaloizou and Lin [17], Lin and Papaloizou [18],

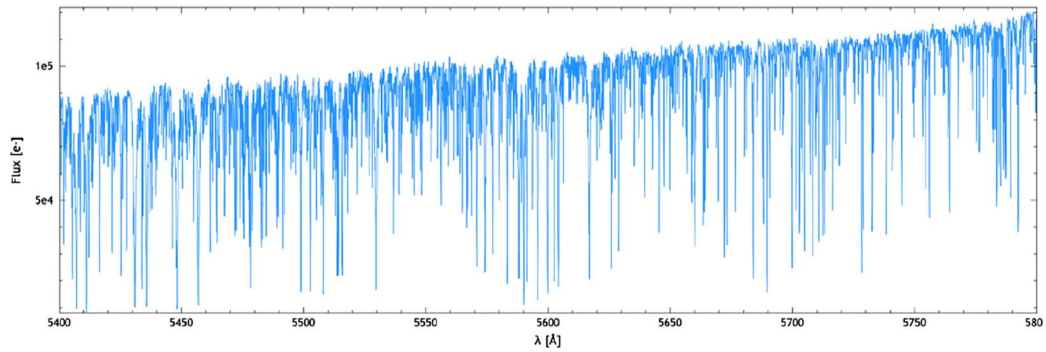


Figure 4. 10% of the bandwidth used by the ESPRESSO spectrograph (Pepe *et al.* [20]). This figure illustrates the richness of the Doppler information contained in the spectrum of cool stars. But it is interesting to note that the Doppler variation of the Sun induced by the gravitational influence of the Earth. About 0.1 m/s corresponds to less than a thousandth of the width of the thinnest of these spectral lines.

Ward [19]). The discovery of orbital migration through the discovery of short-period planets is a major physical phenomenon for the understanding of planetary system formation.

4. The cross-correlation spectroscopy

Several thousandth of absorption lines are present in the spectra of cold stars. Figure 4 illustrates a limited range (about 10%) of the spectrum obtained with the ESPRESSO spectrograph, recently installed on the VLT on Mount Paranal (ESO, Chile). The Doppler information is diluted on this large number of absorption lines, each one being determined by a limited number of photons.

Fellgett's [21] proposal was to concentrate the Doppler information by cross correlating a template typical of cold star spectra with the observed spectrum. The position of the correlation function provides the radial velocity derived from thousands of absorption lines.

A first correlation spectrograph by Griffin [22] demonstrated the efficiency of this concept, reaching an accuracy of 500 m/s and an efficiency relative to the old photographic technique of the order of a factor of 1000.

The progress made in improving the sensitivity and stability of cross-correlation spectrographs over the last 45 years has been exceptional.

Since 1971, I had the pleasure of collaborating with André Baranne, optics engineer, at the Marseille Observatory.

In 1977, our first instrument of this type, CORAVEL, allows a precision for radial velocities of 300 m/s (Baranne *et al.* [8, 9]), then with ELODIE it was possible to detect stellar wobble with an accuracy of 13 m/s in 1994 (Baranne *et al.* [10]), and for our third generation of cross-correlation instrument, HARPS in 2003, allows reaching 1 m/s (Mayor *et al.* [23]). Finally, ESPRESSO in 2018 reaches the exceptional accuracy of 0.1 m/s (Pepe *et al.* [20]). Note that this exceptional precision of 0.1 m/s corresponds approximately to the variation in the velocity of the Sun due to the presence of the Earth. This improvement in accuracy is the result of numerous improvements to the spectrograph (vacuum instrument, octagonal fibres to improve mode mixing, calibration unit with Fabry–Perot and lasercomb as calibration units, etc). Improvements also results from multiple modifications of the signal processing software (0.1 m/s corresponds to only one nanometer in the detector plane!).

However, the real limit of accuracy is dominated by the variation of the radial velocity induced by the various phenomena related to the magnetic activity in the atmosphere of cold stars. Many efforts are being made to reduce the influence of intrinsic stellar noise. Even for stars with low magnetic activity, such as our Sun for example, a variation in the measured radial velocity can be greater than one meter per second.

Since 2015, a small telescope of about 10 cm feeds the HARPS spectrograph installed on the 3.5 m Galileo telescope in La Palma (Canary Islands) with the sun integrated light. A time series of several years of the solar radial velocity has been obtained and allows various signal processing approaches to be tested (Dumusque *et al.* [24]). Signal processing using Gaussian processes (Collier-Cameron *et al.* [25]) or using deep learning allows a significant decrease in the rms (De Beurs *et al.* [26]).

Energy transport in the outer regions of the solar atmosphere results from convective motions. Depending on their depth of formation in the atmosphere, the absorption lines have a different sensitivity to the variations in the speed of convection. These velocity variations are themselves linked to variations in the magnetic field. Thus, a cross-correlation analysis considering the depth of the lines (Cretignier *et al.* [27, 28]) allows a major decrease of the solar radial velocity dispersion (Cretignier *et al.* [27]) and his PhD thesis, Geneva University (2022). Applied to the large number of stellar spectra acquired with HARPS this approach reveals a very large number of new planetary candidates with very small masses (Figure 5) (the global rms of this large sample decreases from 1.3 m/s to 0.75 m/s). A large fraction of the remaining rms results from the photon noise due to limited S/N of stellar measurements. We can expect a significant increase of the S/N in the future by using the ESPRESSO spectrograph connected to a VLT with a diameter of 8.2 m (and in some cases connected to the four VLT on top of Paranal).

Planets with minimum masses much smaller than the Earth-mass have previously been detected.

However, only for planets with quite short periods. The ESPRESSO spectrograph was able to detect a short-period sub-Earth planet orbiting Proxima Centauri (M = 0.26 Earth-mass, Period = 5.12 days, semi-amplitude of the radial velocity variation = 39 cm/s) (Faria *et al.* [29]) (Figure 6).

The radial-velocity detection of Earth-twins in the habitable zone of the one solar mass star is really challenging for solar-type stars. However the habitable zone (HZ) is much closer to M-host stars. Several planets have already been detected in the HZ of interesting low mass stars of the solar neighborhood (Proxima Centauri b, our closest neighbor (Anglada-Escudé *et al.* [30]); and seven planets hosted by Trappist 1, a very low mass M-star with 3 planets in the HZ (Gillion *et al.* [31]).

5. Earth-twins?

Can we detect rocky planets in the habitable zone of a star like our Sun?

Let us first note that a good dozen planets with masses comparable to that of our Earth have already been detected in the habitable zone of their host star. Most of them are hosts of very small mass stars, for which the habitable zone near the star corresponds to very short period orbits. The most promising are Proxima Centauri (having a planet with period 11 days, Anglada-Escudé *et al.* [30]) and Trappist-1 [31].

This last star of mass close to the lower limit of the main sequence is surrounded by seven rocky planets including three planets with a temperature compatible with the presence of liquid water on their surface (Gillon *et al.* [31]). These planets very close to their host star are synchronized and thus always present the same hemisphere facing the star. In addition, these planets are subjected to an intense flux of energetic particles.

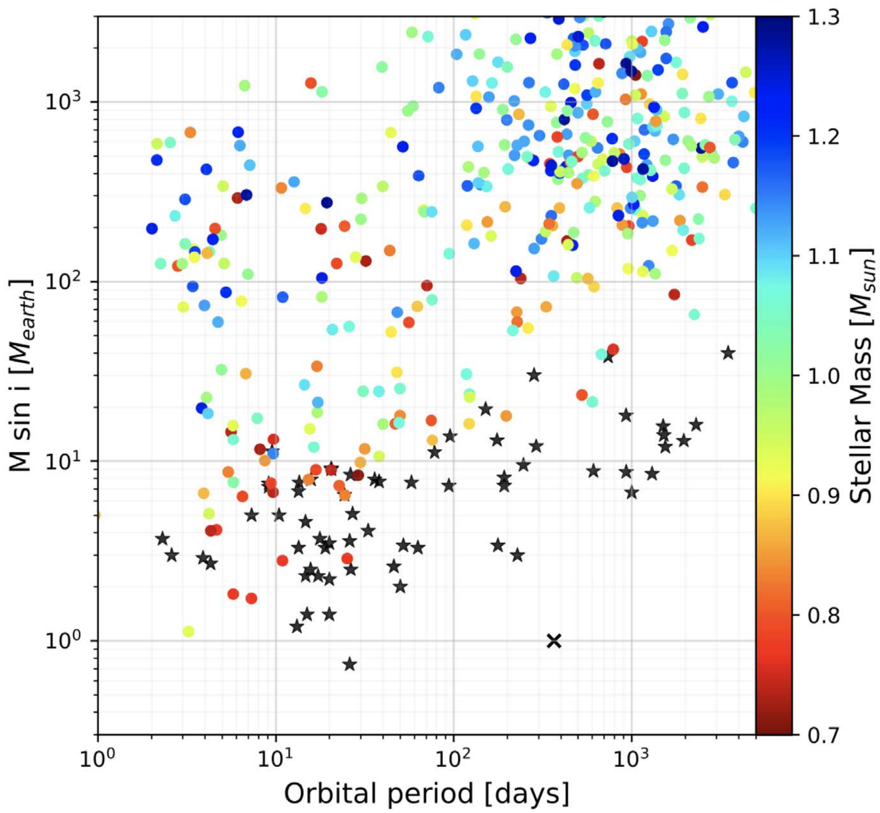


Figure 5. Minimum masses of planets detected by the radial velocity method as function of the orbital period. Black symbols have been used for the planetary candidates detected by the Yarara software (Cretignier *et al.* [28]). The masses of host stars are coded by different colors. A cross indicates the position of Earth.

The luminosity received at the surface of these planets close to low mass stars is in the infrared. Do these conditions allow the development of the complex chemistry involved in the development of life? Perhaps, but it is also interesting to ask the question of the detectability of rocky planets in the habitable zone of solar-type stars or even slightly less massive (spectral type K).

The detection of "habitable" planets is facilitated around low mass stars because the amplitude of the variations of the radial velocity is greater when the period is short and the mass of the star small. In addition, the probability of detection by the planetary transit technique also favors short periods.

These various factors do not act in favor of the detection of planets hosted by K or G stars.

We have seen the difficulty to detect a Doppler variation of 0.08 m/s hidden in the noise induced by the magnetic activity. The difficulty of detecting a transit with a period of 6 months to a year and a contrast of a few ten-thousandths is also delicate.

It is certain that the discovery of a planet through a transit will help considerably to constrain the measurement of the planetary mass required by cross-correlation spectroscopy. We can hope that the various space missions currently in progress or expected soon (TESS, CHEOPS, PLATO) may reveal some rocky planets in the habitable zone of nearby K or G stars.

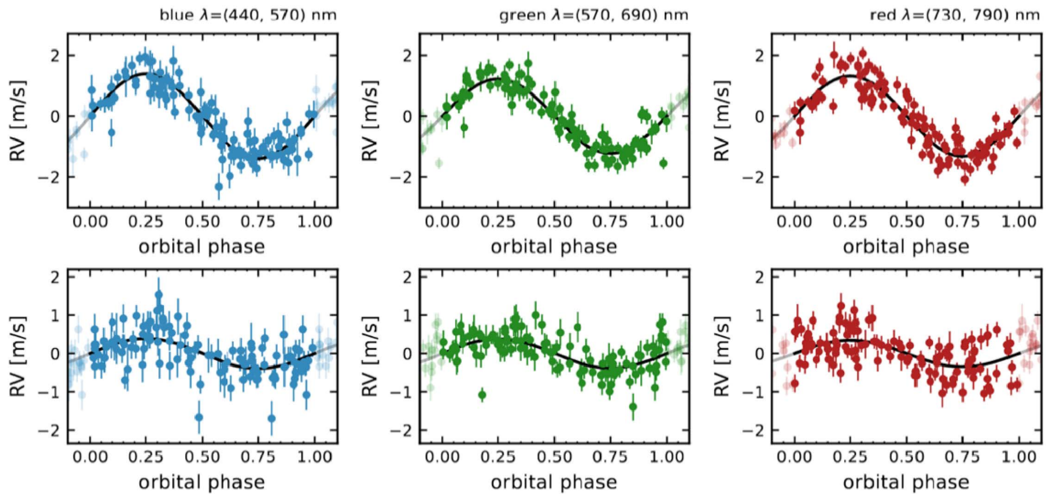


Figure 6. Radial velocity variations of Proxima Centauri due to its two closest planets (Faria *et al.* [29]).

Such objects will offer choice targets for the study of their atmosphere by transmission spectroscopy during transits (every 6 months or year!). But the atmosphere of a planet of mass comparable to our Earth is quite thin. The detection of its atmosphere and possibly of biomarkers will require very high signal/noise spectra for such measurements. The ESO telescope of 39 m diameter under construction on Mount Armazones and its spectrograph ANDES (Marconi *et al.* [32]) will be adapted to such measurements.

The frequency of rocky planets orbiting in the habitable zone of stars of spectral types G or K is not well constrained. Figures of the order of a few percent have been mentioned in various studies. Let us note that the surveys of stellar radial velocities (HARPS in the southern hemisphere and at HIRES at Keck for the north) indicate a strongly increasing curve of the frequency of planets when their mass decreases.

Let us also note that the numerical simulations of the planetary formation indicate the massive presence of rocky planets of period compatibles with their presence in the habitable zone (Benz *et al.* [33]).

Conflicts of interest

Author has no conflict of interest to declare.

Acknowledgements

I would like to dedicate these few pages to Roger Griffin and André Baranne who left us recently. This text highlights the role played by these two colleagues in the development of correlation spectroscopy.

From CORAVEL to ELODIE, HARPS and ESPRESSO, many friends, engineers, technicians, and astrophysicists have participated in this exceptional leap in precision from 300 m/s to 0.1 m/s, may they all be warmly thanked.

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