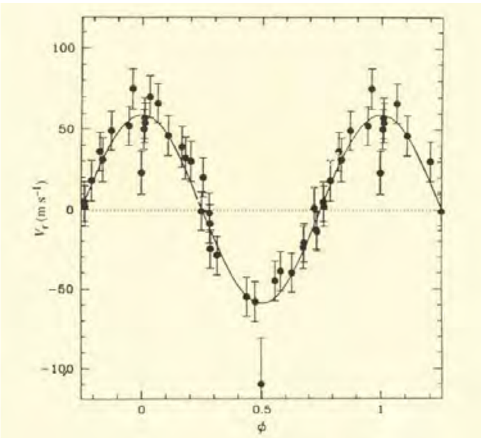
THE FIRST DETECTION OF AN EXOPLANET THAT OPENED A NEW FIELD IN PLANETOLOGY

Michel MARCELIN[1], Isabelle BOISSE[1], Marc FERRARI[1,3], Guillaume HEBRARD[2,3], Emmanuel HUGOT[1]
[1] Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France
[2] Sorbonne Université, CNRS, IAP, Paris, France
[3] Aix Marseille Univ, CNRS, OHP, France
***michel.marcelin@lam.fr**



Periodic Radial Velocity oscillations of the star 51 Pegasi measured at OHP (Observatoire de Haute-Provence) in 1995 revealed a planet orbiting around it. This first detection of an exoplanet had been expected for a long time, since everyone was convinced that most of the stars were surrounded by planets. This success, leading to the Nobel Prize of physics in 2019, is the result of the evolution of technics for the measurement of radial velocities of stars during half a century at OHP.

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RADIAL VELOCITIES FROM SLIT SPECTROGRAPH TO OBJECTIVE PRISM

The measurement of radial velocities of stars has been the main activity at the Observatoire de Haute-Provence (OHP) since the 1950s. The first spectrograph used for such observations was built by Raymond Tremblot who measured radial velocities early in 1934 with a telescope of 80 cm diameter at *Forcalquier* in the south of France before being installed at OHP in 1945 a few kilometers away. This instrument consisted of four prisms, providing a large dispersion of light. Two eyepieces enabled to see the field of view projected onto a slit, but also behind the slit by looking at the entrance face of the first prism. It had been used until 1954 and produced a large number of scientific papers, still cited in the 80's.

In the classical objective prism, invented by Edward Pickering (Harvard) in 1882, a large prism is placed in front of the objective lens or mirror of a telescope, allowing the simultaneous acquisition of the spectra of many stars. This technique was widely used in many observatories during the first half of the 20th century, allowing to classify a large number of stars with respect to their spectrum.

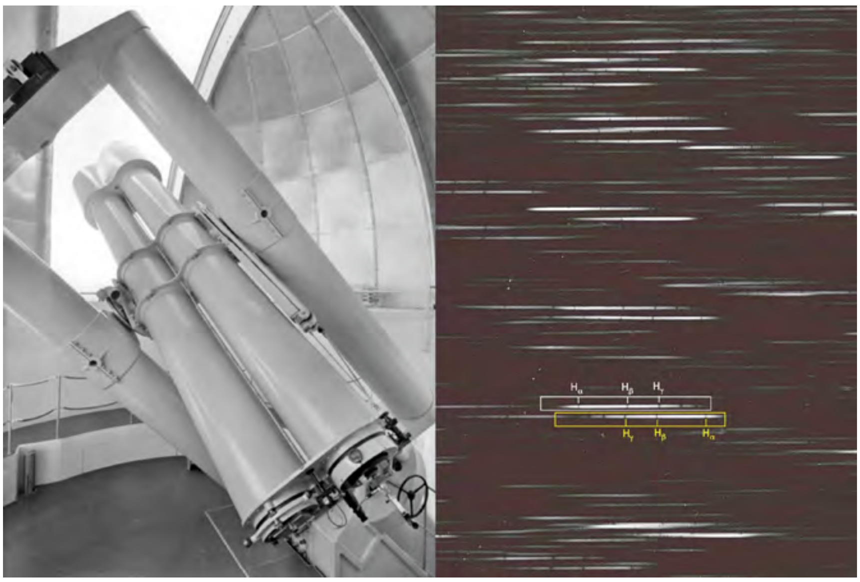
In 1947 Charles Fehrenbach invented a specific objective prism for the radial velocity's measurements [1]. The idea was to replace the ordinary prism by two head-to-tail prisms composed of different materials, Flint for one and Crown Baryum for the other. These two prisms have the same angle and refraction index for a given wavelength, so that the deviation of light induced by one prism is compensated by the other one. As a result, each spectrum is located at the place where the star should be without any prism. More precisely, the coincidence is obtained at the wavelength for which the two prisms have the same refraction index. In order to measure the radial velocity of stars, two successive exposures of a stellar field are made on the same photographic plate and the prism is rotated by 180° between the two exposures. For each star of the observed field, it thus provides a set of two spectra with inverted dispersion. The radial velocity of a star is estimated by measuring the shift between the two spectra and by applying the Doppler-Fizeau effect.

In the 1950s, the Observatoire de Haute-Provence commissioned two objective prisms, the PPO (Petit Prisme Objectif), 17 cm in diameter, and the GPO (Grand Prisme Objectif), 40 cm in diameter. These instruments are in the form of twin astronomical telescopes (Figure 1), one carrying the prism while the other was used for guiding light during the photographic exposure. For about thirty years, these two instruments provided numerous images on which were recorded hundreds of star spectra. The radial velocities measurement accuracy was about 5 km/s, depending on the spectral type of star and its apparent luminosity. These measurements have been used to study the kinematics and structure of our Galaxy, the Milky Way.

CORAVEL, A TECHNOLOGICAL BREAKTHROUGH

A breakthrough in the measurement of star radial velocities was proposed by Peter Fellgett in 1953 by making the correlation of the observed spectrum with that of a reference star. First trials are done in 1955 by Horace Babcock but the first instrument providing results is built by Roger Griffin in 1967 [2]. This instrument projects the spectrum of a star obtained with the 90 cm Coudé spectrograph at Cambridge onto the negative plate of the spectum of Arcturus (bright star in Boötes constellation, offering a large number of absorption lines) obtained with the same instrument. This negative plate consists of a mask with 240

Figure 1. (Left) Picture of the Large Objective Prism (GPO) at OHP. (Right) Part of a photographic plate with pairs of head-to-tail stellar spectra obtained with this instrument. The first spectral lines of the Hydrogen Balmer series for the two recorded head-to-tail spectra of one star are highlighted. The separation between the same Balmer line on the two spectra varies as a function of the radial velocity of the star. © Collection Photothèque OHP/CNRS.



holes corresponding to the position of the absorption lines of Arcturus. This method is limited to stars of the same spectral type as Arcturus, or close to it, otherwise the measurement accuracy quickly drops.
In 1979 a French-Swiss team builds the CORAVEL instrument (COrrelation Radial VELocity) [3] on the same principle, with the spectrum of Arcturus replicated on a mask where holes replace the absorption lines. An optical device projects the spectrum of the observed star directly onto that mask so that, when two spectra coincide, a minimum of light is detected. The light transmitted by the instrument is converted into an electric current with a photometer and the signal is displayed on a cathodic oscillograph. The mask is laterally displaced using a micrometric screw, in order to precisely know the mask displacement needed to obtain the coincidence of the two spectra. This displacement in wavelength is related to the radial velocity of the star by a simple constant of proportionality. The astronomer can therefore obtain the value of the radial velocity in real time, which is a true revolution! Of course, the use of computers enables to control the instrument but also to perform data analysis and calculation in real time. The technological breakthrough is therefore marked with the advent of the CORAVEL instrument.
The dispersion of light in CORAVEL is obtained by combining a prism with a grating and covers the wavelengths from 360 nm to 520 nm. The grating reflects the light and is optimized for observing large diffractiv orders (typically between 50 and 100) thus providing a large dispersion. The dispersion of light by the grating is perpendicular to that of the prism - each band corresponding to a specific diffractive order of the grating - which enables to separate the different orders and produce a spectrum with some twenty parallel bands, covering a compact format.
The wide spectral range of CORAVEL enables to use about 1500 absorption lines produced by different elements in the atmosphere of stars with types comparable to that of Arcturus (notably iron). The precision of the radial velocity achieved with this instrument is about 0,3 km/s (average dispersion of measurements for the same star over several nights). The calibration for finding the instrumental zero is provided by an Iron Hollow Cathode Lamp.
CORAVEL was installed in 1977 on the Swiss 1 m diameter telescope at OHP (Fig. 2), and was used until 1996 by astronomers from Geneva's and Marseille's Observatories as well as by Roger Griffin (who built a copy for this telescope in Cambridge) producing about 200 000 measurements of star radial velocities. CORAVEL

Figure 2. CORAVEL attached at the Cassegrain focus of the 1 m Swiss telescope at OHP.
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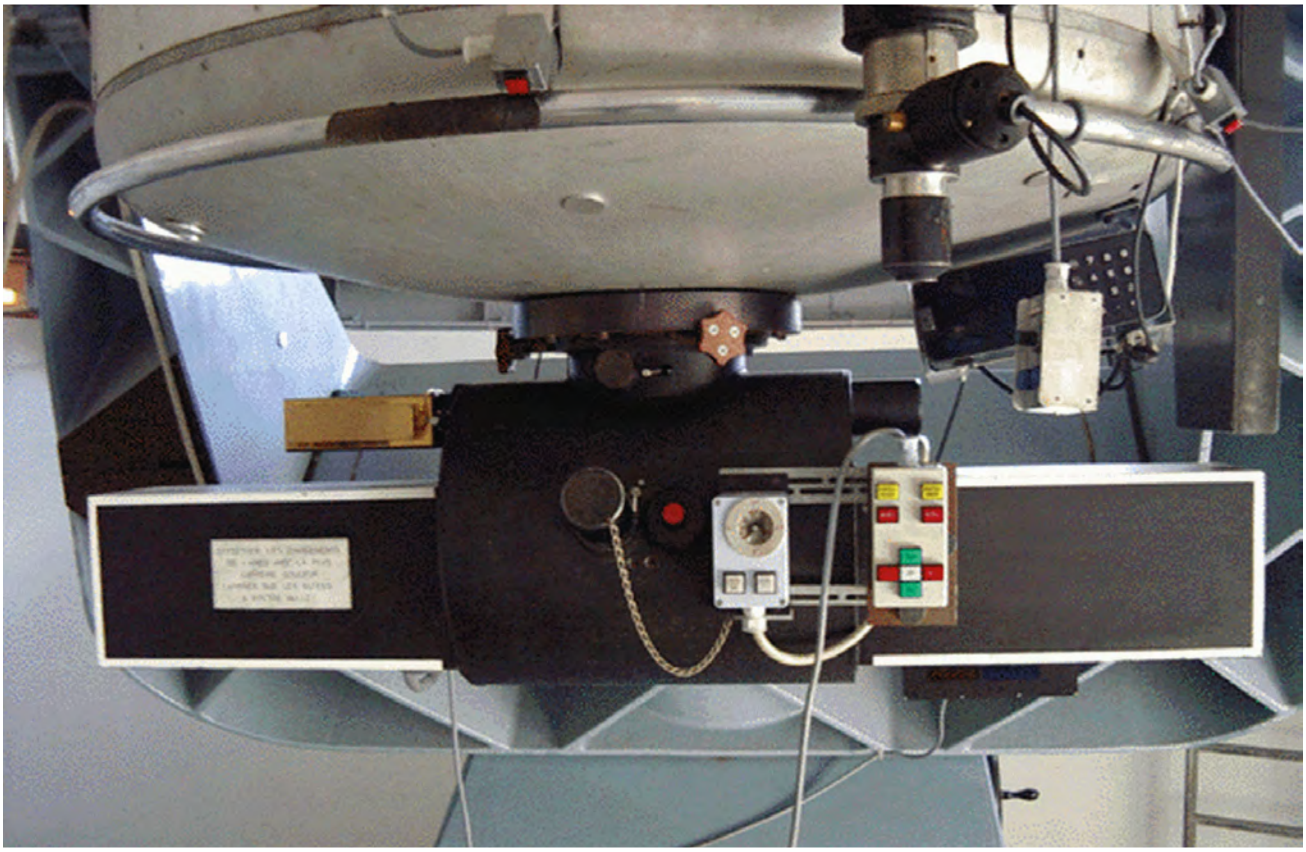

was in particularly used by Duquennoy and Mayor to publish a widely used, unbiased study of stellar multiplicity in the solar neighborhood. A second CORAVEL operated between 1981 and 1994 on the Danish 1.54m diameter telescope at ESO (La Silla, Chile) to measure the radial velocities of stars in the southern hemisphere.

ELODIE AND THE FIRST DETECTION OF AN EXOPLANET

The measurement accuracy obtained with CORAVEL makes it possible to study the orbital motions of double stars as well as the pulsation of Cepheids which are giant stars that can be observed in nearby galaxies and which are used to measure distances since the period of their pulsation is directly related to their intrinsic luminosity.

A planet orbiting a star will produce a periodic change in radial velocity of the star as it orbits around it, provided that the orbital plane is not seen from the front, hence the idea of using an instrument like CORAVEL for detecting the presence of planets around other stars. But the accuracy required is much higher. If we consider the example of Jupiter, the giant planet in the solar system, the disturbance caused on the speed of the Sun is only 12 m/s, where the accuracy of CORAVEL is typically 300 m/s. Therefore, the big leap is to gain a factor 20 in accuracy to be able to detect planets as large as Jupiter around stars similar to the Sun. This is a huge gap and this is almost the same gain obtained by switching from the objective prism (5 km/s accuracy) to CORAVEL (0.3 km/s accuracy).

In 1990, in response to a request from the Observatory of Haute-Provence, Michel Mayor (Observatory of Geneva) and André Baranne (Observatory of Marseille) embarked on the construction of the CORAVEL successor. In order to gain in accuracy, it was decided not to attach the spectrograph to the telescope but to place it in an isolated room, at constant temperature, and to guide the light through an optical fiber. This is a major technological breakthrough, that will be used later for many instruments fed by optical fibers. Another novelty is the use of a CCD sensor (Charge Coupled Device) with 1024 x 1024 pixels of 24 µm. The instrument was first named SuperCORAVEL but finally named ELODIE and, as with CORAVEL, the optical design was entrusted to astronomer André Baranne. To solve stability problems, the device is equipped with two optical fibers. The first brings to the spectrograph the light of the star observed while the second provides the brightness of the neighboring sky which can then be subtracted from the measurements to improve the quality of the measured velocity. However, this step is complicated to operate and represents a potential source of errors. The OHP's computer engineer, Alain Vin, then proposed a technical improvement which consisted in coupling the second fiber to a thorium-argon calibration lamp. This trick, which proved to be worthwhile, allows at any time to subtract from the measurements the minute movements linked to the intrinsic instability of the instrument and revealed in real time by the calibration lamp.

The data reduction part is once again a major challenge, especially since the physical mask used in CORAVEL is now a digital mask. Didier Queloz (Michel Mayor's PhD student) spent three years developing the software to process ELODIE's data. The improvements made to the data reduction software improved the efficiency of the device by a factor of three.

The ELODIE instrument (Figure 3) was mounted in 1993 under the dome of the 1.93 meter telescope at OHP and started its routine observations in 1994, reaching an accuracy of 15 m/s for the measurement of radial velocities, twenty times better than CORAVEL. After just a few months of operation, the first exoplanet was identified, orbiting star 51 in the Pegasus constellation. Michel Mayor and Didier Queloz were awarded the Nobel Prize in Physics in 2019 for this discovery.

A twin of ELODIE, named CORALIE, was mounted on April 1998 at the Swiss 1.2-metre Leonhard Euler Telescope at ESO's La Silla Observatory (Chile) for measuring radial velocities of stars in the southern hemisphere.

In 2003, the OHP launched the study of SOPHIE to succeed ELODIE by •••

offering better performances. This new instrument aims at continuing the detection and the characterization of extrasolar planets by measuring radial velocities, but also at studying the vibration of stars (asteroseismology) for studying stellar activity and the physical conditions inside stars. Whereas ELODIE only allowed this type of study to be carried out on a handful of objects, SOPHIE made it possible to probe stellar interiors on a significant sample of bright solar-type stars.

Fun fact: this suite of instruments has been named after the daughters of some OHP staff, Élodie, Coralie and Sophie. Sophie eventually became a real acronym at the end (Spectrographe pour l'Observation des PHénomènes des Intérieurs stellaires et des Exoplanètes).

There is no technological breakthrough associated with the transition from ELODIE to SOPHIE, as this is still a cross-dispersion spectrograph, installed in an isolated room and fed by optical fibers. The optical concept is however a bit more sophisticated (double-pass Schmidt chamber) and the best of existing technologies has been implemented to optimize the performance of the spectrograph: 1) the instrument is designed to be as bright as possible; 2) its precision mechanics ensure improved stability; 3) the optical elements that scatter light are enclosed in a sealed tank filled with pure nitrogen; 4) the thermal regulation of the instrument is carried out to the hundredth of one degree; 5) it is fed by four optical fibers allowing observations in different configurations. Compared to ELODIE, SOPHIE has a spectral resolution 1.6 times greater, a ×20 luminous efficiency (which therefore makes it possible to observe stars 20 times less bright) and the accuracy on the measurement of the radial velocity is 2 m/s, which is 6 times better. Finally, SOPHIE has 10 times less stray light than ELODIE. It should also be noticed that the image sensor is a CCD, as for ELODIE, but larger and more efficient (2k × 4k pixels of 15 µm against 1k × 1k pixels of 24 µm).

Figure 3. The ELODIE instrument in the insulated room under the dome of the 1.93 m telescope at OHP. © Michel MARCELIN.

The SOPHIE spectrograph was commissioned at OHP in 2006 [5]. ELODIE made it possible to discover some twenty exoplanets by the radial velocity method over a dozen of years, between 1994 and 2006. In fifteen years of operation, SOPHIE has discovered and studied more than 300 exoplanets and brown dwarfs and continues its harvest today. SOPHIE has been regularly improved and updated since 2006. In particular, octagonal-section fibers were implemented in 2011 for improving the radial velocity accuracy thanks to a better scrambling. SOPHIE was the first spectrograph to use this technology, hereafter used on other instruments like HARPS, HARPS-N or ESPRESSO.

TOWARDS THE FUTURE

More than 5000 exoplanets have been discovered since the first detection of 51 Pegasi b in 1995. However, only about a thousand of them have been detected through the measurement of radial velocities. Almost 4000 have been detected by the method of transit, much easier to apply since it is based on a simple photometry to monitor the periodic dimming of a star when a planet passes in front of it (2662 exoplanets have been thus detected by NASA's Kepler satellite alone). Detecting an exoplanet with the two methods is the only way to estimate both the mass and size of this exoplanet, hence its density, which is all the more interesting for characterizing it. Another method of detection is direct imaging, much more difficult than the two previous ones, explaining why only two hundreds have been imaged with this method to date. At the beginning, most of the exoplanets discovered were Jupiter class planets. Techniques are improving continuously and planets down to telluric ones are detected now. Some earthlike exoplanets have already been identified, and there is no doubt that many other ones are going to be discovered in a near future.

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