Nobel Lecture: Plurality of worlds in the cosmos: A dream of antiquity, a modern reality of astrophysics[*]

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It is amazing to consider that the question of the plurality of Worlds in the universe was already discussed in the Antiquity by Greek philosophers. In a very famous letter of Epicurus (341–270 BC) we can read, "Worlds are in an infinite numbers some of them similar to our own one, some others being different… living species, plants and all the other visible things could exist in some worlds and could not in others."

The question of the plurality of worlds in the universe has been continuously present during the last two millennia. We can, for example, quote this sentence by the philosopher and theologian Albertus Magnus (circa 1200–1280), "Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature."

In 1277, Etienne Tempier, Bishop of Paris, with the agreement of the pope Jean XXI, asked that the question of plurality of worlds be taught at the Sorbonne. We can also mention the two major contributions of Emmanuel Kant (1755) in his *Universal Natural History and Theory of Heaven* and Pierre-Simon Laplace in his *Exposé du système du Monde*. Both contributions introduce the notion of protoplanetary nebula, having noticed that all planets are moving in the same plane and sense of rotation.

I. CHANGE OF PARADIGM DURING THE SECOND HALF OF THE 20TH CENTURY

How many planets are there in the Milky Way; see Fig. 1? How many planets are similar to Earth? It is interesting to look at the astronomical literature of the twentieth century for estimations of planetary systems in the Milky Way. Before 1943, the estimations were between zero and at most a few. It was supposed that the formation of the protoplanetary nebulae results from the close encounter of two stars. The very low probability of such an event (close to zero!) is at the origin of these pessimistic estimates. In the early 1940s, claims of planet discoveries around some of the closest stars to the Solar System (claims which were later found to be erroneous) produced a complete paradigm shift, with estimates of planetary systems in our Galaxy as large as hundreds of billions [see Dick (1991)]. It is interesting to note that this shift in paradigm was actually the result of spurious detections of planetary systems!

During the past three decades, improvements in astronomical instrumentation and the development of new observational techniques made it possible to transform the old philosophical concept of "plurality of worlds" in the universe into an active field of modern astrophysics.

Today, more than 4000 exoplanetary systems have been detected, and we are beginning to discover planets in the so-called habitable zones of host stars. These Earth-like

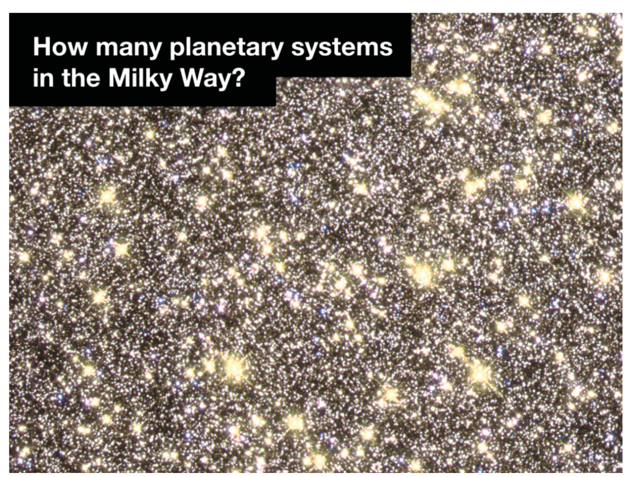

FIG. 1. 200 billion stars, but how many planetary systems are there in the Milky Way? This photo illustrates the huge number of stars seen in a very small fraction of the disk of our Galaxy. How do we detect planetary systems hosted by these stars?

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FIG. 2. 1995, images of protoplanetary disks: The Hubble Space Telescope reveals protoplanetary disks around very young stars of the Orion Nebula. From McCaughrean and O'dell, 1996.

exoplanets have physical conditions suitable for the development of the complex chemistry of life. In the last 25 years these discoveries have completely transformed our understanding of planetary populations and the process of planetary system formations; see Fig. 2.

Young stars formed by gravitational collapse of turbulent giant molecular clouds should have extremely large rotational velocities. However, the observed rotational velocities of stars at the bottom of the main sequence (stellar masses less than about 1.2 times the solar mass) are extremely small. Otto Struve suggests that the excess of angular momentum, if not present in the stars themselves, should be present in the protoplanetary nebulae. Consequently, protoplanetary disks are byproducts of the stellar formation itself and we can anticipate that most of stars (if not all of them) should host planetary systems.

In the 1970s, an excess of infrared luminosity in the spectra of very young stars finally revealed the presence of protoplanetary disks. Then in 1995, direct imaging of very young stars moving out of the Orion Nebula showed that most them are surrounded by disks of dust and gas [see McCaughrean and O'dell (1996)].

No doubt at all, most (if not all) stars should host planetary systems.

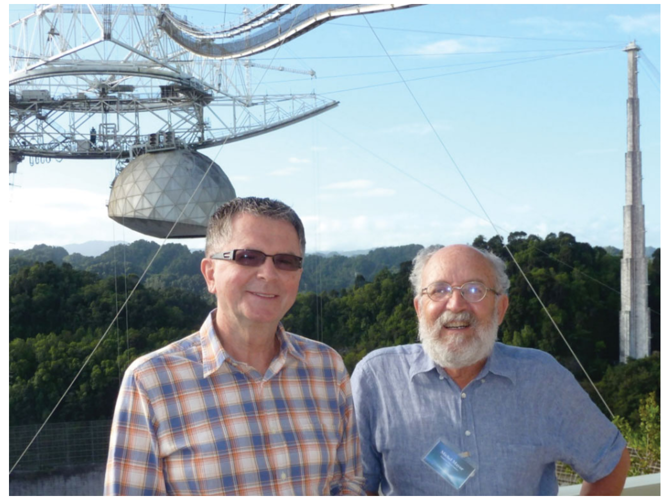


FIG. 3. Alex Wolszczan and Michel Mayor in front of the secondary mirror of the Arecibo radiotelescope in 2002 (twenty year celebration of the discovery of the planetary system hosted by the neutron stars PSR B1257+12).

How can we detect these systems?

Before discussing our contribution to the detection of planets, I would like to mention an extraordinary discovery made by Alex Wolcsczan and Dale Frail in 1992 (Wolcsczan and Frail, 1992; Wolcsczan, 1994). By measuring the anomalous arrival times from the neutron star PSR B1257+12 (see Fig. 3), they deduced the presence of two planets with masses only a few times the mass of our Earth. More recently, an additional planet was discovered orbiting the same pulsar. It may be possible that these planets, whose orbits are almost circular like most low-mass planets around normal stars, were formed from the debris of the destruction of a small stellar companion, although other formation scenarios are possible.

II. DOPPLER SPECTROSCOPY AS A PATH TO THE DETECTION OF EARTH-LIKE PLANETS

The possibility of detecting the gravitational influence of orbiting planets on the radial velocities of stars was suggested long before the Doppler technique was precise enough to allow such measurements (Belorizky, 1938; Struve, 1952).

In the eighties, several teams explored the possibility to developing spectrographs with the goal of achieving a precision better than about 15 m/s, a precision requested for the detection of gaseous giant planets. Among these different approaches, only a few were used in a systematic search to detect gaseous giant planets: in 1979, Campbell and Walker (1979) introduced a HF absorption cell in front of the spectrograph in order to achieve internal precise wavelength calibration, while in 1992, Marcy and Butler (1992) designed an iodine cell for the same purpose.

III. THE PERMANENT QUEST FOR HIGHER AND HIGHER PRECISION: THE FIRST STEP WITH CORAVEL

We started to build instruments at the Haute-Provence Observatory in the South of France. Our first cross-correlation spectrometer CORAVEL, installed in 1977 on our 1-m

FIG. 4. The CORAVEL template used to determine the radial velocity of states by cross-correlation 40 years ago! To be seen at the Nobel Museum. From Baranne, Mayor, and Poncet, 1979.

telescope, achieved a precision of 300 m/s; see Fig. 4. It was a very exciting period of my life. The efficiency of CORAVEL was amazing, about 4000 times the efficiency of the ancient spectroscopic technique using photographic plates (Baranne, Mayor, and Poncet, 1979). With such efficiency, it was easy to revisit many areas of astrophysics. CORAVEL was used for a diverse range of studies including: the dynamics of globular clusters as for example Omega Centauri, and the pulsation of Cepheids in the Magellanic Clouds (small galaxies some 150 000 light years from the Earth).

The majority (about 2/3) of solar type stars have a stellar companion. Together, Antoine Duquennoy and I in 1991 made a 15 year-survey of several hundred stars relatively close to the Solar System to determine the statistical properties of double stars: the distributions of their characteristics are seen as fossil tracers of stellar formation mechanisms. While CORAVEL was not designed to search for exoplanets, by 1989 we had discovered an $m \sin i = 11$ Jupiter mass companion after combining our measurements with similar ones by David Latham (Latham *et al.*, 1989).

Recent astrometric measurements made by the *Gaia* satellite (Kiefer, 2019) reveal a very small inclination of this system to the line of sight, in turn revealing the true mass of the companion to be that of a very low mass M star. Nevertheless this early detection demonstrates that the spectrograph precision was approaching the level needed to detect real planets.

IV. A SMALL TECHNICAL NOTE

What is the principle of a cross-correlation spectrograph? I would like to illustrate the key point of this technique. Stars at the lowest part of the main sequence have thousands of atomic absorption lines in their spectra. When you disperse stellar luminosity into its different wavelengths, these absorption features appear as narrow lines in their spectra. Stars are moving in the sky relatively to our Solar System. The component of the velocity along the line of sight is called the *radial velocity*. Due to the motion of a star, you will see a small change in the position of lines resulting from the Doppler effect. If you measure the wavelength shift of an atomic transition, you will have the possibility to get the radial velocity of that star. At the level of precision needed, this is a difficult task, although the basic idea of the instrument is quite simple.

To precisely measure the positions of the absorption lines, we need a lot of photons … but stars are faint. The central feature of the cross-correlation technique is an instrumental design allowing one to use thousands of atomic lines simultaneously. The first demonstration of its feasibility appeared in 1967 by Roger Griffin (see Fig. 5), while the first proposal had been made by Peter Fellgett (1955). To detect planets, we have to measure extremely small changes of the stellar wavelengths. Our spectrograph HARPS (Mayor *et al.*, 2003) is able to detect changes of velocities of 0.3 m/s. This velocity corresponds to a Doppler shift of only a billionth of the wavelength … a shift of only a few silicon atoms on our detector. A planet hosted by a star will induce a small wobble of its velocity. For example, the velocity of our Sun is affected by the gravitational influence of Jupiter and as a result moves at 12 m/s around the gravity center of the Solar System. The Earth also induces a wobble of the Sun's velocity, but of only at 8 cm/s—the discovery of Earth-type planets is a real challenge.

It is easy to understand the cross-correlation technique and its capability to *concentrate all the Doppler information* when we have a look at the first CORAVEL spectrometer. The stellar spectra obtained by a cross-dispersed optics (echelle grating and grism) is projected on a template (see Fig. 4). This template is a glass plate coated with chromium, except on the position of atomic absorption lines. When the stellar lines match the holes in the template, the transmitted light is minimum. On the other hand if the stellar spectrum is Doppler shifted, matching will not be perfect and the amount

FIG. 5. Roger Griffin was the first to demonstrate, already in the early sixties, that radial-velocity measurements can be efficiently made by a cross-correlation spectrograph (Griffin, 1967).

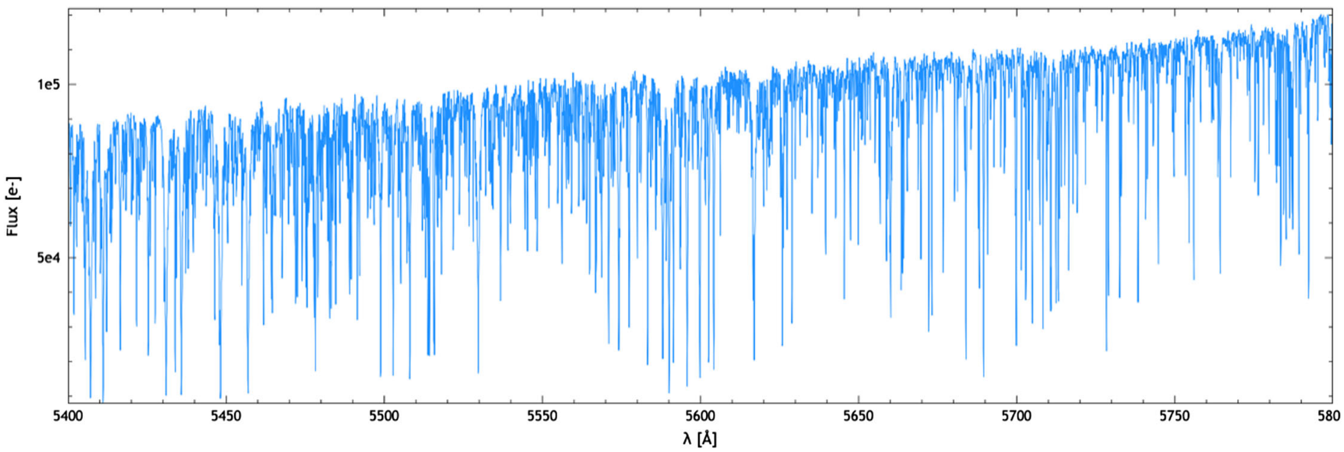


FIG. 6. Spectrum of HD 85512 obtained with the ESPRESSO spectrograph installed at the ESO Paranal Observatory (Chile). Only 400 Å appear in the figure while the true spectral window of ESPRESSO is about 10 times larger. With ESPRESSO we can measure the important Doppler information contained in the spectra of solar-type stars or colder. The cross-correlation technique allows one to concentrate Doppler information from several thousand absorption lines to measure precise stellar radial velocities.

of transmitted light will be larger. An optical device allows one to determine how much the stellar spectrum must be shifted in order to minimize the transmitted therefore the mean radial velocity from several thousands of atomic lines. With CORAVEL, the cross-correlation is made optically. In our subsequent instruments (ELODIE, CORALIE, HARPS and ESPRESSO), the stellar spectra (see Fig. 6) are registered with a low noise, large CCD and the cross-correlation is done numerically with a digital template. However, the principle is exactly the same.

It is interesting to note that several other processes which have a global effect on atomic lines can benefit from the cross-correlation technique and its capability to concentrate diluted physical information. For example the stellar rotation velocity is easily determined as the Doppler broadening affects all the stellar atmospheric lines (Benz and Mayor, 1981) while the measurement of Fe/H gives the mean stellar metallicity (Mayor, 1980). As a result of the huge efficiency of cross-correlation spectroscopy, the technique is frequently used today to determine stellar radial velocities, rotational velocities as well as stellar metallicities.

V. THE QUEST FOR A HIGHER PRECISION: THE SECOND STEP WITH ELODIE

By the end of the 1980s, the evolution of technology allowed for the development of a new spectrograph. In 1988, the director of the Haute-Provence Observatory asked André Baranne and myself to design a cross-correlation spectrograph adapted to the 1.93-meter telescope at that Haute-Provence Observatory. Two significant technological developments were critical to improve the precision of the spectograph: the possibility of having a large CCD detector and the existence of optical fibers of high quality. Here is not the place to present the technical details.

I would just mention that we needed to have a very, very stable illumination of the optics of our instrument to achieve the desired precision and to maintain it over several years. Optical fibers offer that possibility, guiding the stellar light from the telescope to the spectrograph in a stable environment in a thermally controlled enclosure below the telescope.

One crucial aspect provided by our computer-controlled spectrograph CORAVEL, was the possibility of immediately having the fully reduced stellar radial velocity in a few seconds after the end of the measurement. We wanted to conserve that unique characteristic with the new spectrograph. The situation was not straightforward with the new instrument and at the end of his graduate studies, in 1990, Didier Queloz took in hand this important part of the software.

In science, it is only in exceptional cases that you can do things by yourself—at least in the field of modern astronomical instruments. I have to thank all the technicians and engineers of Haute-Provence and Geneva for their contribution to the success of the ELODIE instrument. Special thanks are especially due to André Baranne (Fig. 7), our Chief Optician. ELODIE (see Fig. 8) was a big success from 1993 onwards, immediately resolving velocity variations down to

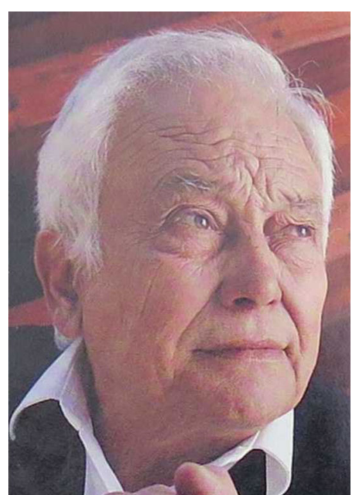


FIG. 7. André Baranne, the father of the optics of CORAVEL, ELODIE and CORALIE.

FIG. 8. The ELODIE instrument installed on the 1.93-meter telescope at the Haute-Provence Observatory (OHP) was built by the technical staffs from OHP and Geneva Observatory. A special mention is due to André Baranne (Optical Engineer at Marseille Observatory). André is in the second row, just below the word OHP. He discovered the white pupil mounting, broadly used today in many astronomical spectrographs. (Alain Vin is missing from this photo!)

FIG. 9. Antoine Duquennoy.

10–15 m/s (a factor of 20 to 30 better than CORAVEL) and providing a precision which allowed for the detection of exoplanets (Baranne *et al.*, 1996).

VI. SEARCHING FOR EXOPLANETS

How could we detect a planet? A planet does not produce any luminosity. It just reflects a small part of the luminosity of a star it received. Let us look at our Solar System. Jupiter reflects one billionth of luminosity of the Sun. In 1995, it was not possible to directly get images of exoplanets due to this large luminosity contrast between the host star and planets. Therefore, we were obliged to use an indirect technique. As a result of the gravitational influence of a planet, the host star moves around the gravity center of the system. We could then measure shifts of wavelength caused by the Doppler effect.

During the spring of 1994, my two young collaborators Antoine Duquennoy (Fig. 9) and Didier Queloz and I began a program with the new ELODIE instrument to search for possible brown dwarfs or gaseous giant planets orbiting solar-type stars. Antoine and I wanted to extend our study concerning double stars (Duquennoy and Mayor, 1991) to explore the domain of very small mass ratios. But I had no *a priori* expectation of what we would find. At that time, brown dwarfs, stars which are not massive enough to have nuclear reactions in their core, were still undetected. The lower limit for their masses was estimated to be only a few times the mass of Jupiter, overlapping the domain of gaseous giant planets.

Observing time on a telescope is only given on a competitive basis. We got seven observing nights every second month. Unfortunately, in June 1994, Duquennoy died in a car accident and then we were only two to do the observations. That search, among a sample of 142 solar-type stars, began during the spring of 1994, and already at the end of our first season of observations (see Fig. 10), we noted that the velocity of the star 51 Pegasi showed a periodic variation, which could be interpreted as being caused by the influence of a planet: a planet with a smaller mass than that of Jupiter. We observed an orbital period of 4.2 days, which disagrees with theoretical predictions. We had found a gaseous giant planet with an orbital period of four days rather than the 10 years (or more) than every one expected—a factor of 1000 out!

There had been many claims of discoveries of planets in the past, which were found to be wrong later. That is one of the reasons why we decided to postpone the publication of our finding for an additional season. We were certain of the quality of all of our measurements, but there was a risk of bad interpretations. We could be misled by other physical processes, such as those related to stellar magnetic activity.

A very interesting example of the confusing effect of magnetic activity is given by the star HD 166435. A periodic variation (with a period of 3.8 days) was observed during

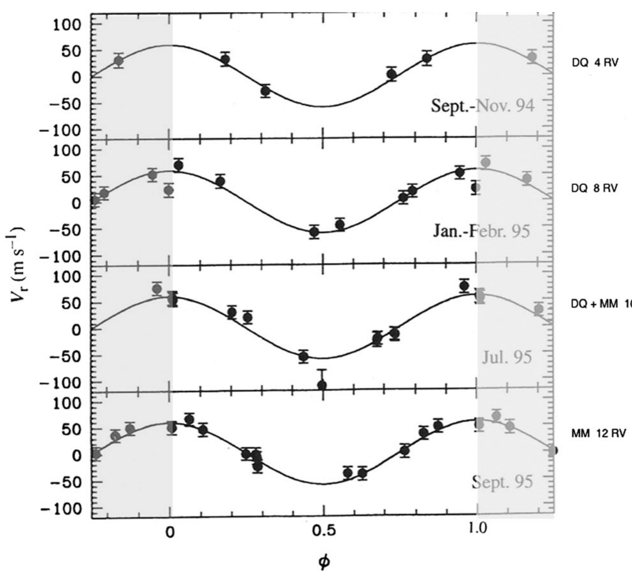


FIG. 10. Radial velocity measurements of 51 Pegasi obtained during four observing runs from September 1994 to September 1995. Adapted from Mayor and Queloz, 1995.

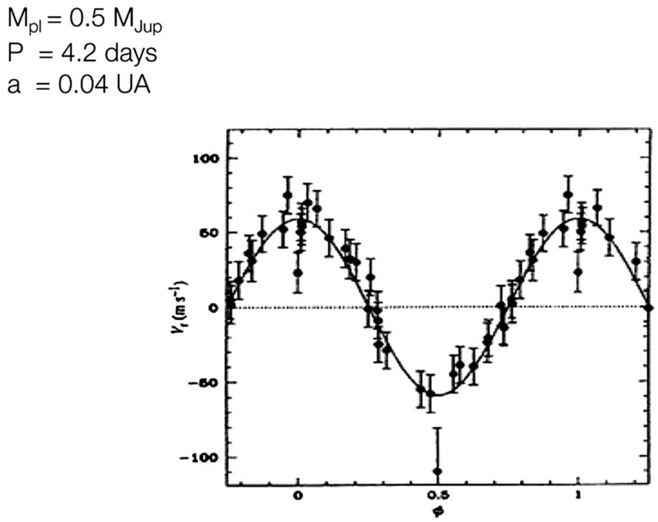


FIG. 11. The first exoplanet hosted by a solar-type star: 51 Pegasi b (October 1995). From Mayor and Queloz, 1995.

several observing periods in 1998. However, a photometric variation of the luminosity and color indicates an intrinsic cause of that variability resulting from a very large magnetic spot with a rather long lifetime (Queloz *et al.*, 2001). We conclude that the radial-velocity variations were not due to gravitational interactions with an orbiting planet but, instead, originated from line-profile changes stemming from star spots on the surface of the star. The quasi-coherence of the radial-velocity signal over more than two years, which allowed a fair fit with a binary model, makes the stability of this star unusual among other active stars. It suggests a stable magnetic field orientation where spots are always generated at about the same location on the surface of the star.

Another concern came from the existing scenario for the formation of giant planets in the nineties. As the quantity of dust is limited in an accretion disk, the formation of gaseous giant planets requires the agglomeration of ice particles. Ice particles only exist at sufficiently large distances of solar-type stars … and the formation of gaseous giant planets could only

FIG. 12. Exoplanet pioneers at the Wyoming conference 2011. From left: Alex Wolczscan, Michel Mayor, Nathalie Bathalia, William Borucki, David Charbonneau and Geoff Marcy.

exist at distances larger than about five astronomical units and have orbital periods larger than 10 years (Boss, 1995)!

The period of the companion of 51 Pegasi, 4.2 days, was much too short; see Fig. 11. We did not understand how it was possible to produce a planet with such a short period, but by July 1995, our data were so consistent that we ventured to announce the discovery of the first extrasolar planet orbiting a Sun-like star (Mayor and Queloz, 1995).

The discovery of this first planet with its very short orbital period made it necessary to take into account the orbital migration of planets during the formation period in an accretion disk. This mechanism had already been studied 15 years before the discovery of 51 Pegasi b by Goldreich and Tremaine (1980) [see also Papaloizou and Lin (1984), Lin and Papaloizou (1986), and Ward (1986)]. However, the prediction of the migration of exoplanets had never been used to build observing strategies! See Fig. 12 for an image of exoplanet pioneers.

Soon after the discovery of 51 Pegasi b, Lin, Bodenheimer, and Richardson (1996) showed that a short-period gas giant could result from the gravitational interaction of the young planet with the accretion disk.

Since 1995, the observational evidence for orbital migration has deeply changed every scenario of planetary formation.

A few months after the discovery of 51 Peg b, the detection of several short period planets was announced by the Californian team (Butler and Marcy, 1996; Marcy and Butler, 1996; Butler *et al.*, 1997). Clearly, 51 Peg b, the first

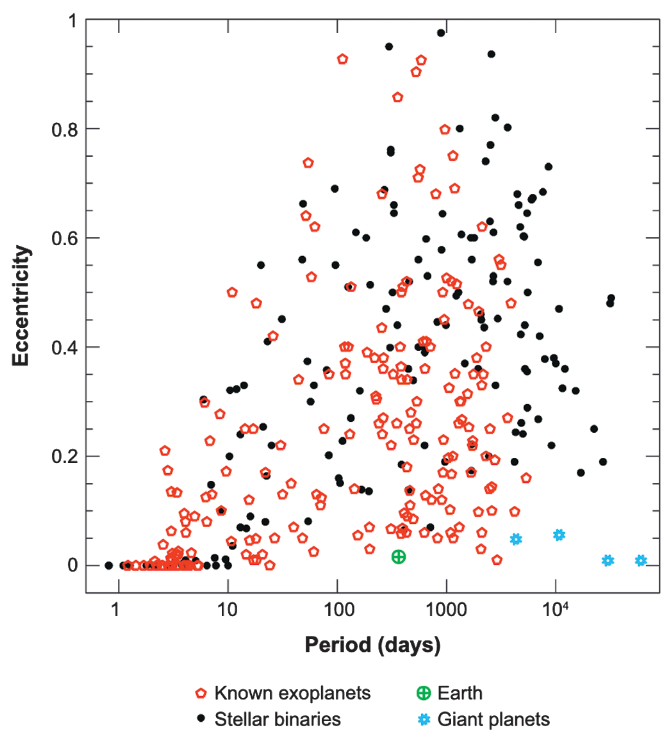


FIG. 13. The observed diversity of planetary systems shows (i) orbital periods as short as a few hours and (ii) orbits with a large range of eccentricities. Period-eccentricity diagram for the sample of known exoplanets (in 2007!) in comparison with stellar binaries. The Earth and giant planets of the Solar System are indicated as well. From Udry and Santos, 2007.

FIG. 14. M. Mayor and D. Queloz at La Silla Observatory (ESO, Chile) in front of the 1.2-meter EULER telescope and in the distance, the 3.6-meter telescope. These two telescopes have made significant contributions to the detections of exoplanets since 1998 and 2003, respectively.

"Hot Jupiter" is not a unique object with exceptional characteristics.

We continued the search of planets in the northern sky. We moved to the southern sky and started observations at La Silla Observatory (ESO) located in Chile. Firstly with CORALIE, a slightly improved copy of the ELODIE spectrograph. Then, with the HARPS spectrograph on the ESO 3.6 meter telescope at La Silla.

We may wonder why we continue to search for planets when we have already found more than 4000 of them. In fact, the goal is not simply to detect an additional planet. It was probably the case at the beginning, but today we want to have a global view of planetary systems and to understand their formation and evolution.

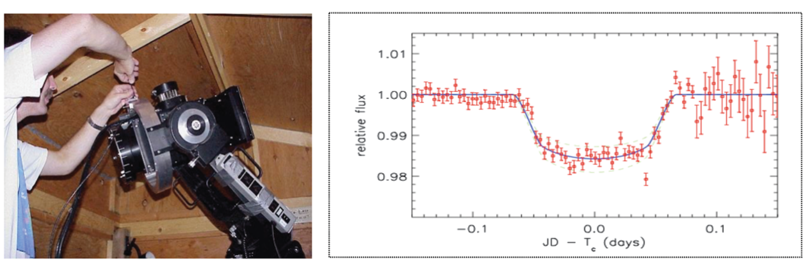
The formation and evolution of planetary systems involves a very broad spectrum of physical process: orbital migration, lifetime of accretion disks, detailed mechanisms of planetary formation, interaction between planets, chemical composition of host stars, etc.

The observation of the diversity of planetary systems (see Figs. 13 and 14) has been used to constrain theoretical models of their formation. Several teams explored the relative importance of these different processes. Our understanding of planetary formation results from the dialogue between theory and observations (Benz *et al.*, 2014).

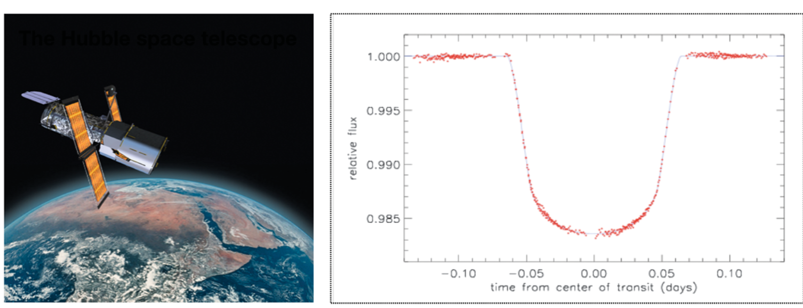
Another very nice possibility exists for planet detection. If a planet passes between a star and an observer's line of sight, it blocks out a tiny part of the star's light. As a result, we can observe a periodic diminishing of the stellar luminosity due to the transit of the planet. The depth of the depression is directly proportional to the relative size of the planet compared to its host star. Before the announcement of the discovery of 51 Pegasi b, we immediately tried to detect possible planetary transits … but the inclination of the orbital plane was not adequate.

Upon detecting another short period planet in the summer of 1999 ($P = 3.5$ days), we were able to predict the exact time when it might transit in front of its star HD 209458. At the predicted time, on September 9 and 16 of that year, the first planetary transit was observed (see Fig. 15), which proved that indeed, we were observing gas giant planets such as Jupiter or Saturn (Charbonneau *et al.*, 2000). The bulk density of that giant planet is as low as 0.3 grams per cubic centimeter. This planetary transit was independently measured in November 6, 1999 by the Californian team (Henry *et al.*, 2000).

Soon after we were able to measure the Rossiter-McLaughlin effect for a planet: a spectroscopic transit, which allows the measurements of the projected angle between the stellar spin axis and the planet's orbital axis (Queloz *et al.*



(a)



(b)

FIG. 15. September 9 and 16, 1999. A first planetary transit. Hot Jupiters are gaseous giant planets: density $= 0.3\,\mathrm{g/cm^3}$. (a) From Charbonneau *et al.*, 2000. (b) From Brown *et al.*, 2001.

2000). New results show a large variety of angles, with occasionally very inclined orbits and in few cases even retrograde orbits. These cannot be explained solely by planetary migration. The evolution of planetary systems becomes even more complicated with the possible dynamical influence of distant stellar companions (via the Kozai effect).

About twenty years after the discovery, we finally succeeded in detecting the reflected light from 51 Pegasi b (Martins *et al.*, 2015) thereby obtaining a direct estimate of 0.46 (+0.06, −0.01) M_{Jup} for the mass of the planet.

The observation of an exoplanetary transit opened the door to the study of the internal composition of planets, therefore creating a new field of astronomy: exoplanetology. This first detection of a planetary transit also played a crucial role in the decision to build space missions devoted to detect exoplanetary transits.

VII. CHEMICAL CLUES FOR STARS WITH PLANETS

The chemical composition of a planet, including both its interior and atmosphere, is likely to be related to the chemical composition of the protostellar cloud, and this will be reflected in the composition of the stellar atmosphere. The precise determination of the stellar chemical abundances provides important constraints on the mechanisms of planetary formation.

The very first detections of exoplanets immediately leads to the suspicion that there should be a relation between the stellar metallicity and the occurrence of giant planets. Systematic surveys of the metallicity of large stellar samples have confirmed the strong positive correlation between the frequency of giant planets and the chemical composition of the host stars (Santos, Israelian, and Mayor, 2001, 2004; Fischer and Valenti, 2005; Sousa *et al.*, 2011). See Figs. 16 and 17.

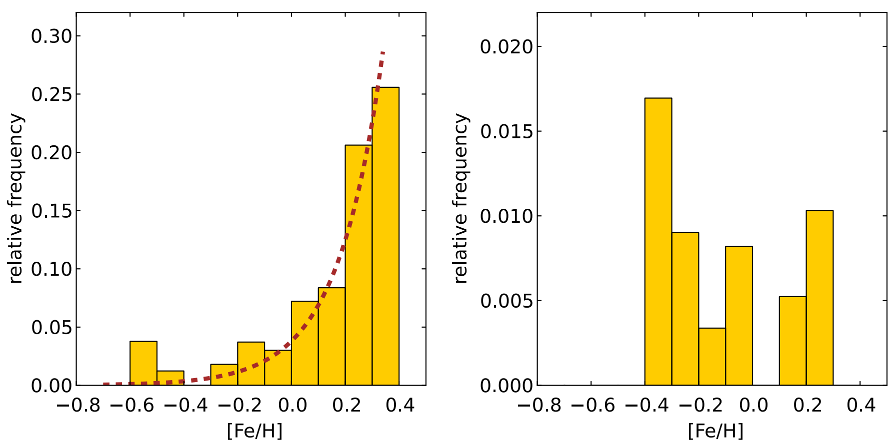


FIG. 16. Metallicity distribution of planet hosting stars (Mayor, Lovis, and Santos, 2014). Left panel: the frequency of giant planets as a function of stellar metallicity is shown based on results from the HARPS planet search program. In the right panel, we illustrate the same plot for stars that host only Neptune- or Super-Earth-like planets. These plots shows a clear correlation between the presence of giant planets and the metallicity of the star. This trend is not seen for stars hosting a lower-mass planet.

FIG. 17. Garik Israelian and Nuno Santos: two colleagues having contributed so much to the study of the chemical composition of stars with or without planets.

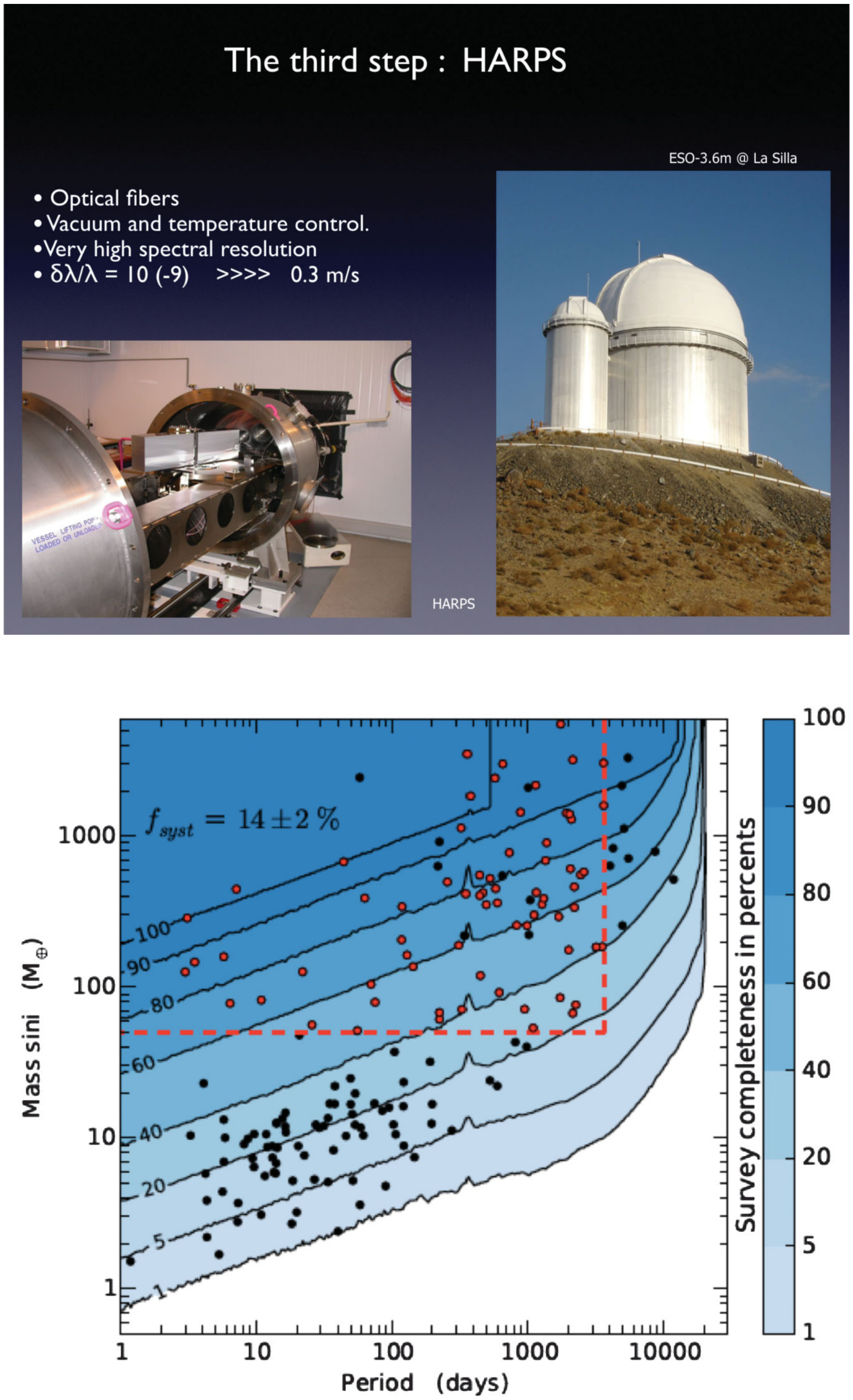


FIG. 18. After 16 years we continue to conduct a large and systematic survey of stars in the southern hemisphere with the CORALIE spectrograph on the EULER telescope and the HARPS spectrograph on the 3.6-meter telescope. We try to design surveys with controlled detection bias in order to obtain distributions of planetary systems as functions of mass, orbital period, host star metallicity, etc., These distributions provide constraints on planet formation scenarios and tell us (for example) that planets more massive than 50 Earth-masses are hosted by about 14% of solar-type stars. We also remark that "hot-Jupiters," while being the first planets detected are rare (about 1%), most giant planets have larger orbital periods from several months to several years. We can also remark on the extreme abundance of planets with masses between a few Earth-masses and 20 Earth-masses (Super-Earth).

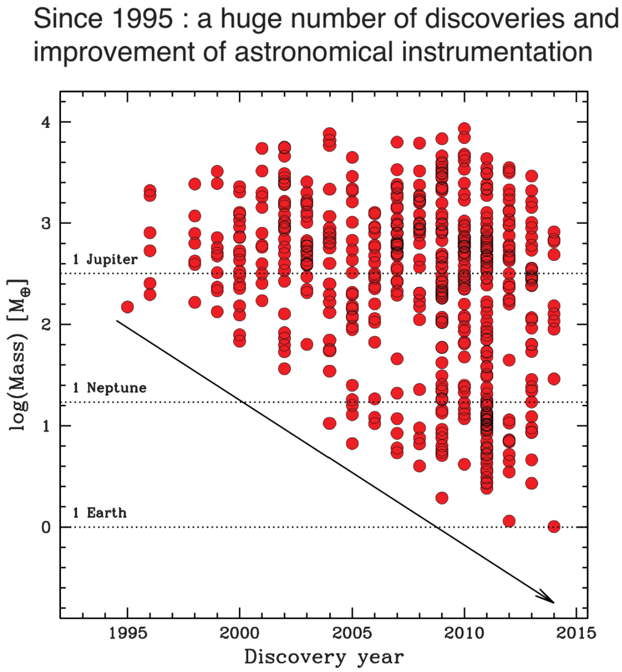


FIG. 19. Since 1995: A huge number of discoveries and improvement of astronomical instrumentation. After the discovery of 51 Pegasi b, we have observed an amazing number of planet discoveries. We can also remark on the result of the improvement of the sensitivity of Doppler spectrographs allowing today the detection of planets with masses as small as the Earth mass (at least for relatively tight orbits!).

VIII. HARPS, THE THIRD STEP TOWARDS HIGHER PRECISION AND THE PATH TO THE DETECTION OF ROCKY PLANETS

The sensitivity of the HARPS spectrograph has improved to the point where it now allows us to detect much lower mass planets. This can be considered as part of the quests for rocky planets. Recall that while Jupiter induces a change of velocity of the Sun at the level of 12 m/s, the Earth induces a change of only 8 cm/s. High precision is required in order to detect rocky planets.

We were able to design a new, much more sophisticated instrument that works in vacuum with temperature controlled at the level of a few milli-Kelvin degrees during the night. In 2000, I took the lead of the construction of a new spectrograph called HARPS (see Fig. 18), which was fully optimized to search for very low mass planets (Mayor *et al.*, 2003). That new spectrograph, installed at La Silla in Chile in 2003, was sensitive enough to detect velocity changes smaller than 1 m/s and therefore to discover even lighter planets, right down to the mass of the Earth. Francesco Pepe played a major role in the development of that instrument as project engineer.

Our obsessional search for higher and higher velocity precision has been rewarding (Fig. 19). With the HARPS spectrograph, we have detected a new population of Super-Earth and Neptune mass planets: a population of extremely common planets orbiting solar-type stars (planets with masses between 1 and 20 Earth-masses; see Fig. 19(Mayor and Udry,

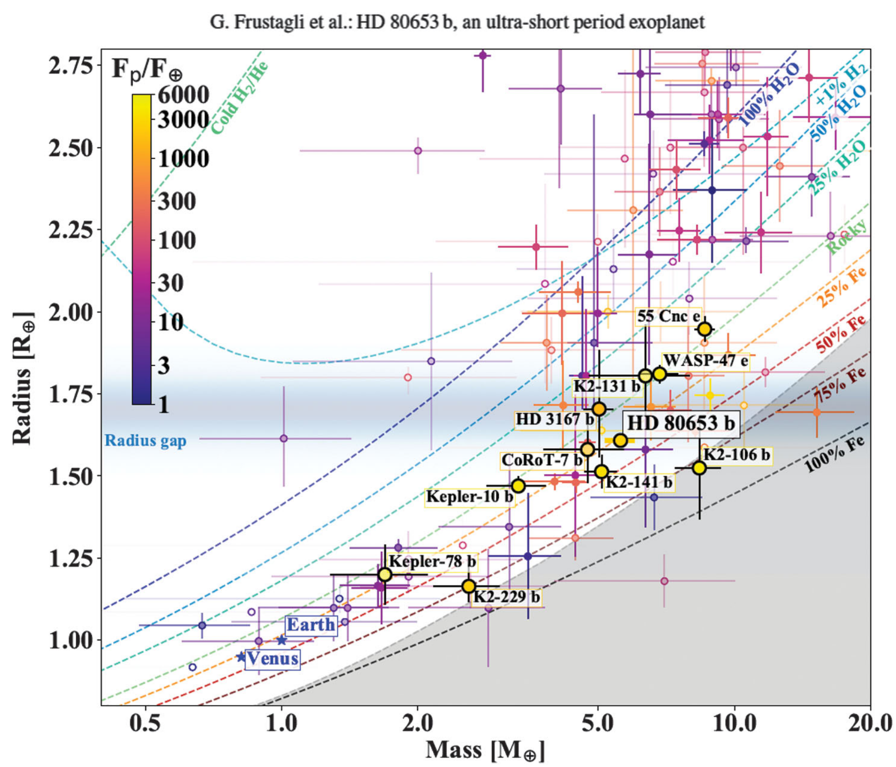


FIG. 20. Mass-radius diagram of planets smaller than 2.8 Earth radii (Frustagli *et al.*, 2020). The dashed lines show planetary interior models for different compositions as labeled (Zeng *et al.*, 2019). Planets are color-coded according to the incident flux F_p, relative to the solar constant received on the Earth [for the full description see Frustagli *et al.* (2020)].

SPECTRO	year	precision	Telescope	
CORAVEL	1977	300 m/s	1 m	OHP
ELODIE	1994	13 m/s	1.9 m	OHP
CORALIE	1998	6 m/s	1 m	ESO Chile
HARPS	2003	1 m/s	3.6 m	ESO Chile
HARPS-N	2013	1 m/s	3.5 m	IAC La Palma
ESPRESSO	2018	0.1 m/s	8.2 m (x4)	ESO Chile

FIG. 21. Increasing the precision. Radial velocity via cross-correlation spectroscopy: A path to the detection of Earth-type planets. Over the last 40 years the precision for the different generations of cross-correlation spectrographs has been increased by a factor 3000! This gain of sensitivity allows for the discovery of planets with smaller masses. Francesco Pepe (Fig. 22) is the PI of the team having built ESPRESSO.

2008). That rich sub-population has been beautifully confirmed by the Kepler Space mission.

The Kepler space mission with its harvest of several thousand planetary transits has provided planetary radii for a large number of Earth-type planets. We need to know the mass of these planets to constrain the bulk density of their composition. As Kepler candidates are in the northern sky we have been obliged to develop a copy of HARPS, presently installed at La Palma Observatory on the Galileo 3.5 meter telescope. We devoted an extremely large number of observing nights to study the inner composition of planets having only a few times the mass of our Earth.

FIG. 22. Francesco Pepe, the principal investigator of the ESPRESSO spectrograph. This instrument, installed at Cerro Paranal (ESO Chile) can feed by one either one or four 8.2 meter unit telescopes of the VLT, achieving thus a collecting power equivalent to a 16-meter telescope! ESPRESSO represents the latest generation of the series of our cross-correlation spectrographs and was designed to achieve a precision of 0.1 m/s.

The combined data from HARPS radial velocities and planet diameters derived from planetary transits are of special interest for planets with masses less than 20 Earth masses. These measurements, for example, allow the study of the transition from rocky to Neptune-like planets [see a recent radius-mass diagram from Frustagli *et al.* (2020)], derived from combined radial velocities and diameters for transiting planets and reproduced below; see Figs. 20 and 21.

The huge harvests of detections made by space missions like CoRoT, Kepler, TESS as well as ground based experiments like SuperWasp have demonstrated the potential of the transit technique. The present focus is to detect Earth twins. We know that we have a huge number of rocky planets in the galaxy. The problem is to detect planets as close as possible to us for follow-up studies and especially planets which are located in the so-called habitable zone of the star, that is, the zone at a distance from the star where the complex chemistry for life development has had the chance to emerge. We already have the possibility to detect Earth twins with the present instrumentation.

One of our current projects in Geneva is to build a small catalogue of bright stars with rocky planets in the habitable zone. We need such an input catalogue for the next generation of instruments to explore planets like Earth. If we are ever to build an ambitious space mission, we want to have a list of likely stars to look at.

More than 2000 years ago, Greek philosophers were already discussing the plurality of worlds in the universe, and speculating on the possibility that some of these worlds could have living species. Today, exobiology emerges as a new multidisciplinary domain of science.

Do we have living organisms outside the Solar System?

I do not know how many years will be necessary to give an answer to that fundamental question. However, I am certain that it will remain on the agenda of all scientific agencies. Today we are close to having the technology to detect biomarkers in the atmospheric spectra of exoplanets. For more than 2000 years, humanity has been waiting for an answer to the possible existence of life on other worlds, so we can afford to wait a few decades.

> Do there exist many worlds, or is but a single world?
> This is one of the most noble and exalted questions
> in the study of Nature.
> Albertus Magnus (1200–1280)

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