Tenth Anniversary of 51 Peg-b : Status of and prospects for hot Jupiter studies

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Preface

During the fall of 1995, Michel Mayor and Didier Queloz from Geneva Observatory announced the discovery of the first extrasolar planet, 51 Peg-b, based on observations performed on the 193-m telescope of the Observatoire de Haute Provence equipped with the ELODIE spectrograph. In 2005, we decided to celebrate this discovery, which triggered a flood of new studies in this research field, during an international colloquium. This colloquium was held from August 22th to 25th, 2005 in the quiet and warm place of Observatoire de Haute Provence, in the South of France. It gathered about eighty international astronomers, specialists in the field of extrasolar giant planets. It has been the opportunity to review the success of past discoveries on extrasolar planets similar to 51 Peg-b, the so-called "hot Jupiters". The detection of 51 Peg-b at Observatoire de Haute Provence has indeed raised a number of questions and created the new research domain of "exoplanetology". Its impact on the astrophysical community and well beyond has been huge. This is mostly due to the unexpected short orbital distance of the planet in the 51 Peg system, 0.05 astronomical unit, which implies different formation and evolution mechanisms than those at play in the solar system.

During the meeting, most recent observational facts were presented, as well as the state-of-the-art on the sample of 170 known extrasolar planets – among which about 30 are hot Jupiters. Then, the discussions focused on theoretical explanations about the physics at play in the atmospheres of irradiated giant planets and in planetary systems including hot Jupiters: formation, evolution, dynamics. Finally, part of the discussion was devoted to future developments of instrumentation and expectations in this field for the next decade. Papers include invited reviews, regular talks and posters. They are organised in this book as during the meeting, in seven thematical sections.

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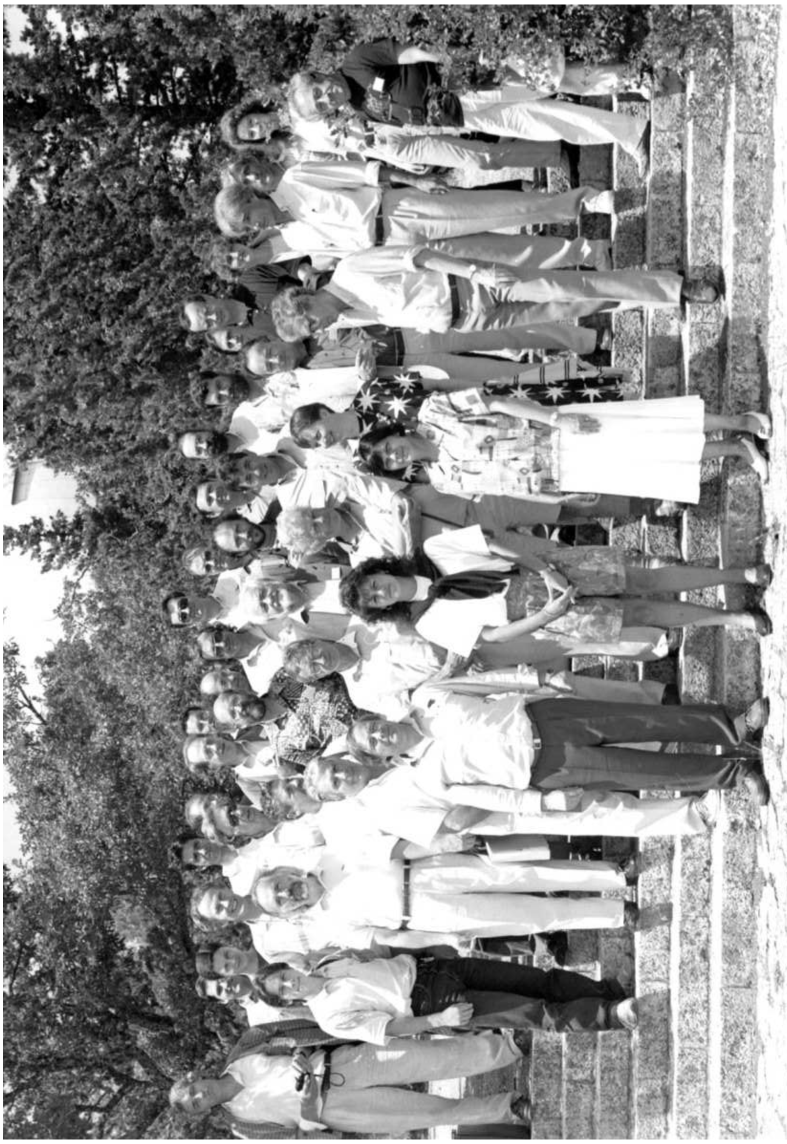

A conference about ground-based detection of extrasolar planets was held at OHP in July 1995, only four months prior to the announcement of the 51 Peg-b discovery. At that time, no participant (except perhaps one) could have imagined that a meeting dedicated to hot Jupiters would be held at OHP 10 years later !

Opening speech


OHP
CNRS
En 1995, sur le télescope de 193cm
équipé du spectrographe ELODIE,
Michel Mayor et Didier Queloz
découvraient la première planète
extrasolaire 51 Peg-b autour
d'une étoile autre que le Soleil.

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The discovery of 51 Pegasi at Haute-Provence Observatory – The quest for precise radial velocity

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Abstract. The discovery of 51 Pegasi at OHP is part of the continuous improvements of correlation spectrographs, in order to measure more and more precise radial velocities. Three generations of instruments developed over 30 years have allowed to increase the radial-velocity precision by a factor 500, from 250 $\mathrm{m\,s^{-1}}$ in the seventies to better than 0.5 $\mathrm{m\,s^{-1}}$ at present times.

1. CORAVEL - A first taste of the cross-correlation technique

At the time of the 10^{th} anniversary of the discovery of the first extra-solar planet orbiting a star similar to our Sun, we would like to place that discovery in context with the several consecutive steps done over almost three decades to improve the precision of radial velocities. The discovery of 51 Peg b has been the first result of intensive instrumental developments.

In 1953 already, P. Felgett proposed the principle of the cross-correlation technique to derive radial velocities. The cross-correlation of an ad-hoc template and the stellar spectrum provide a very efficient way to extract the Doppler information which is distributed over several thousands of stellar absorption lines. A first demonstration of the feasibility of that idea has been made in 1967 by R. Griffin using one single order of a diffraction grating limiting the wavelength domain to 500 Angström. The use of echelle grating combined with a cross-disperser offered later the possibility to enlarge considerably the optical bandwidth. The optical cross-correlation on the spectrum delivered by a cross-dispersed echelle spectrograph is however not a completely obvious task. In order to perform the optical cross-correlation on several spectral orders, one needs to correctly reproduce a Doppler shift at any position of the focal plane.

In 1977, we began our radial-velocity survey with the CORAVEL spectrograph on the 1-meter Swiss telescope at OHP (Baranne et al. 1979). With this computer-controlled spectrograph, the determination of radial velocities became a real pleasure. The efficiency of deriving radial velocities increased by much more than 3 orders of magnitude compared to the old photographic technique. The revolutionary precision of 250 $m\,s^{-1}$ jointly with the remarkable optical efficiency, have been at the basis of numerous studies in stellar kinematics carried out with this instrument.

Together with Antoine Duquennoy, we got interested in the statistical properties of solar-type binary stars. We have been naturally driven to search for very low-mass companions as part of our study of the mass-function of secondaries. Among the many stars used to permanently monitor the stability of CORAVEL, we have acquired quite a lot of velocity measurements of the star HD114762. In 1988, David Latham, when using his own measurements on that star, noticed a small periodic variation of the velocity of HD114762 with a period of 84 days. On the request from Dave, we investigated our own measurements and discovered immediately the same 84 days variation confirming the presence of a companion of $m_2 sini$ as small as 11 Jupiter-mass (Latham et al. 1989). Despite the modest precision compared to present spectrographs, that discovery demonstrated at that time the possibility to explore the domain of substellar companions such as brown dwarfs (Figure 1).

Our discussion of the multiplicity of solar-type stars in the solar vicinity (Duquennoy & Mayor 1991) suggested (wrongly) that the eccentricity-mass diagram could be used to distinguish a massive giant planet from a brown dwarf in the domain of a few Jupiter masses. Quite evidently the recent discoveries have revealed the existence of extrasolar planets on very eccentric orbits, contradicting finally our initial guess.

The CORAVEL cross-correlation was made optically with a physical template corresponding to given conditions of air temperature and pressure. Due to the air refractive index depending on ambient conditions, this template could not be perfect and induced therefore some wavelength mismatch and was thus a source of error on the velocity. Another precision limitation was set by the entry slit of the spectrograph, which had an equivalent width when projected in the focal surface of 8 $km\,s^{-1}$! Despite a very good automatic telescope guiding, a residual centering error was unavoidable. These two effects probably explain most of the limitation to 250 $m\,s^{-1}$ on the observed precision.

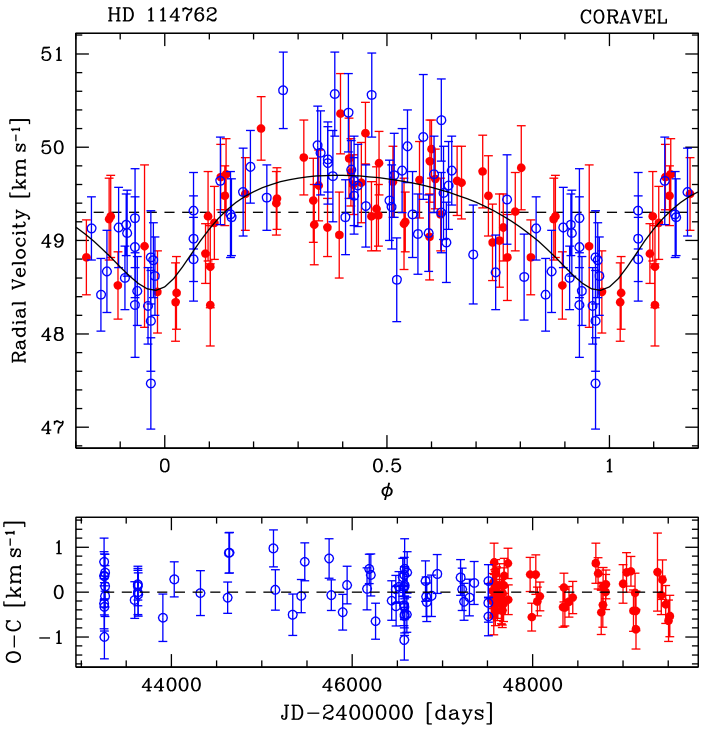

Figure 1. *CORAVEL radial-velocity measurements of HD 114762 obtained at OHP on about 6500 days. The orbital elements of the very-low mass companion (Latham et al. 1989) have been derived from combined Oak Ridge and CORAVEL data.*

2. ELODIE - The instrument which made the discovery of 51 Peg possible

The two weaknesses of CORAVEL have been removed on ELODIE by two hardware changes: First, the use of a CCD recording the full visible spectrum allowed us to replace the optical cross-correlation by a numerical cross-correlation. Second, the spectrograph is now fed by an optical fiber. The fiber considerably stabilizes the PSF. This effect is improved further by adding a "double-scrambler" on the optical path of the fiber. With such a light injection, the guiding and focus influence is decreased by at least a factor one hundred compared to the slit spectrograph. Calibration exposures with a thorium-argon lamp allow to permanently determine the dispersion equation in all the grating orders, removing thus any possible mismatch between spectrum and template. In addition a second optical fiber fed with a thorium lamp provides the possibility to measure and correct for any spectrograph drift during the scientific exposure itself.

The ELODIE spectrograph, with its spectral resolution of 42000, was connected to the 1.93-m telescope of OHP in 1994 (Baranne et al. 1996). Soon during the first observing nights, a precision on the radial velocities of 13 to 15 $\mathrm{m\,s^{-1}}$ was demonstrated; an improvement by a factor 20 compared to CORAVEL! This precision was comparable to the level achieved by the different teams searching for planets at that time (Table 1, from Walker et al. 1995).

Table 1. *Comparison of radial-velocity precision obtained by different teams (from Walker et al. 1995, last line added according to ELODIE characteristics).*

Group	Technique	σ_{RV} [$\mathrm{m\,s^{-1}}$]	N_*	Δt [yrs]	Detections
UBC Vic	HF	15 $\mathrm{m\,s^{-1}}$	21	12	–
Texas	O_2, I_2	15 $\mathrm{m\,s^{-1}}$	27	6	–
Lick	I_2	15 $\mathrm{m\,s^{-1}}$	26	3	–
Arizona	FP	30 $\mathrm{m\,s^{-1}}$	16	8	–
OHP	Th, Ar	15 $\mathrm{m\,s^{-1}}$	142	1	1

As with CORAVEL, the software of the ELODIE spectrograph provides the full reduced velocity in the few minutes after the end of the exposure. The goal of the observing programme led by M. Mayor, A. Duquennoy and D. Queloz was to determine the mass function of substellar companions (brown dwarfs and giant planets) to solar-type stars. 142 stars were selected among the single stars of the Duquennoy and Mayor (1991) survey. The rhythm of measurements was imposed by the time allocated to our survey (one week every two months). After a few months, at the end of 1994, the periodic variability of 51Peg became evident and a first ephemeris determined. If due to a companion, the mass of it would have been about half that of Jupiter. With an orbital period as short as 4.2 days, this object was so surprising in respect to the parameters expected for giant planets (Boss 1995), that some level of prudence was recommended. On the following season, at the beginning of July 1995, the periodic variation was still present and showed the same period, phase and amplitude. The hypothesis of a planetary companion on a very tight orbit became stronger (Mayor & Queloz 1995). The residuals around the variation curve (13 $\mathrm{m\,s^{-1}}$) were comparable with the typical precision available in 1995. The ELODIE cross-correlation template used at that time was not completely free of weak telluric lines. A new and "clean" template, free from these perturbing telluric absorption lines, as well as the implementation the double scrambler on the optical fiber, allowed a significant improvement in precision, achieving 6 $\mathrm{m\,s^{-1}}$ (as an example see the residuals around the orbit of 70 Virginis (Naef et al. 2004). At about the same time, progresses were made with the iodine cell technique, which allowed, in combination with much larger telescopes, to attain even better radial-velocity precision, with residuals as small as 3 $\mathrm{m\,s^{-1}}$ (Butler et al. 1996).

CORALIE, located on the EULER 1.2-m telescope at la Silla Observatory, is a spectrograph similar to ELODIE but with a slightly higher resolution of 50000. Despite the very modest size of the telescope, CORALIE has been one of the most productive instruments in that domain, having discovered some 40 exoplanets. After a few minor improvement of the software this instrument achieves nowadays the level of 3 $\mathrm{m\,s^{-1}}$ (Pepe et al. 2002) for bright stars. Unhappily, the size of the EULER telescope limits the precision for most of the stars of our southern survey to a photon noise of 8 -10 $\mathrm{m\,s^{-1}}$.

3. HARPS - Radial velocities better than 1 $\mathrm{m\,s^{-1}}$

HARPS is the most recent spectrograph we have built to search for exoplanets. Once again, this spectrograph is fed by two optical fibers, one for the star, the second for the simultaneous thorium. Some improvements have been made compared to ELODIE and CORALIE:

- The optical resolution has been raised to R=115000 . The Doppler information is increased due to the sharper absorption lines.
- HARPS is a vacuum-operated spectrograph with outstanding temperature control ($\delta T \sim 10^{-3}\,\mathrm{K}$ on one night; $\delta T \sim 10^{-2}\,\mathrm{K}$ on the long term).
- The sampling of the spectrum is 3.5 pix/resolution element and thus better than many other instruments.
- A full thermal and mechanical decoupling of the spectrograph and the vacuum tank has been implemented. High mechanical stability has been achieved by placing the instrument in the Coude room and by completely avoiding moving functions.
- The reduction software has been improved with regards to many aspects, in particular for a more precise and robust dispersion relation determination and barycentric velocity correction. A new and more precise table of the thorium lines has been produced (Lovis et al. 2006).

– Due to the higher resolution and the new thorium-line catalog, more than 6000 stellar absorption lines are now involved in the calibration and cross-correlation processes (from 3800 to 6900 Angström).

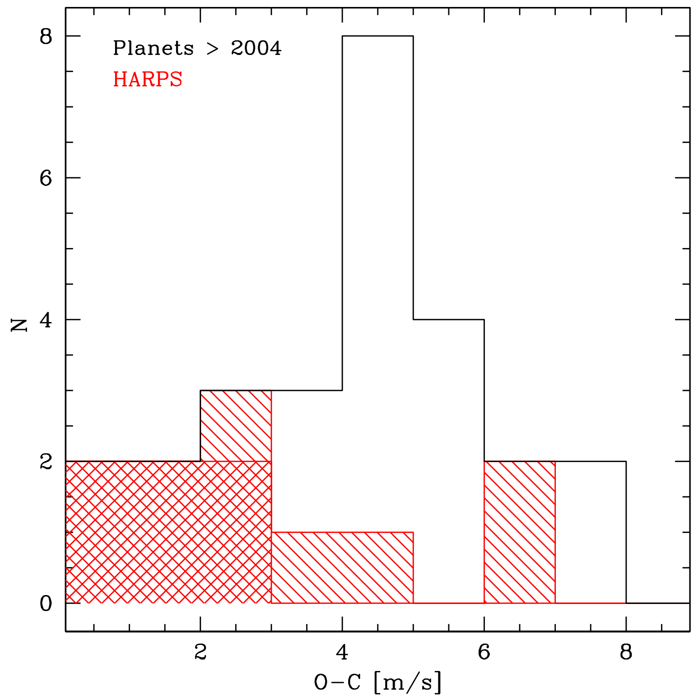

Figure 2. *O-C residuals of the radial-velocity measurements for exoplanets submitted for publications after 2004 (a few very large O-C corresponding to planets orbiting giant stars have been omitted). The dashed area shows orbits discovered with HARPS and the cross-correlation technique. Orbits obtained with HARPS using a special observing strategy adapted to detect very-low mass planets are represented by the double-dashed region. The white area is used for orbits detected by other radial-velocity teams.*

HARPS is an ESO instrument fed by the 3.6m telescope at la Silla Observatory (Mayor et al. 2004). A rather large survey to search for exoplanets on the Southern sky is made by the Consortium having developed that instrument (500 observing nights in five years). The full potential of cross-correlation spectrograph has been revealed by HARPS.

A large number of radial-velocity curves of discovered exoplanets have residuals smaller than 1 $m\,s^{-1}$. The superb precision achieved with HARPS becomes evident if we compare the residuals on orbital solutions published over the past 2 years (Figure 2). Already several planets with masses comparable to Neptune's mass have been discovered with this instrument: Mu Ara (Santos et al. 2004), HD4308 (Udry et al. 2005), Gl581 (Bonfils et al. 2005).

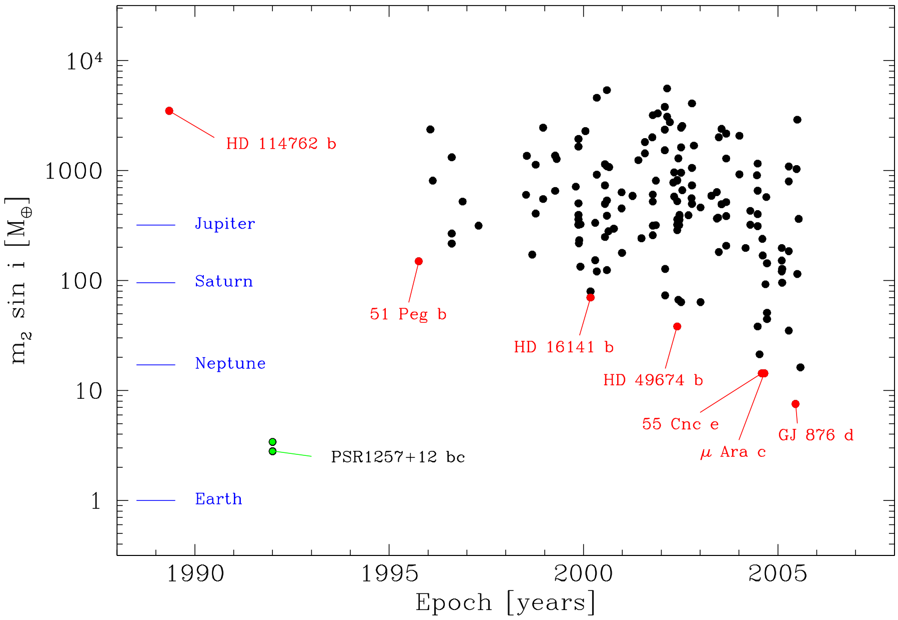

Figure 3. *Minimum mass of the known extrasolar planets orbiting solar-type stars, in Earth masses as a function of the year of the discovery. The masses of Jupiter, Saturn, Neptune, and the Earth are marked for comparison. A few benchmark cases are labelled, as well as the masses of the two planets orbiting the pulsar PSR 1257+12 (Wolszczan & Frail 1992).*

The number of exoplanets discovered during the past few years is impressive. It must be pointed out that the lower mass-limit of detected planets has decreased a lot in the last ten years (Figure 3). The detection of smaller-mass planet of only a few earth masses is evidently the direct result of the huge improvements made on the precision of radial-velocity measurements during the same period. The presently achieved precision level is best illustrated by HARPS: On the time scale of one night a precision level of 0.2 $\mathrm{m\,s^{-1}}$ could be demonstrated. Over several nights, the precision stays still better than 0.5 $\mathrm{m\,s^{-1}}$. Over several seasons, our estimation of the HARPS precision is limited by our poor knowledge of the intrinsic stability of stars, but observed dispersion values on many stars clearly indicates that the performance is better than 1 $\mathrm{m\,s^{-1}}$ (Lovis et al. 2005).

4. Radial velocity measurements better than 0.1 $\mathrm{m\,s^{-1}}$?

Very large telescopes will be very probably developed in the coming 10 to 15 years with diameters ranging from 30 to 100 meters. It is interesting to investigate the scientific questions to be addressed by these giant telescopes by including adequate instrumentation in the discussion. Already today, we are investigating the possibility of building spectrographs which should provide high sensitivity and a precision level between 0.1 and 0.01 $\mathrm{m\,s^{-1}}$ over time scales of several years. The scientific goals, which can be addressed at that level of precision, concern mainly the cosmology, e.g. with the possibility to have a direct measurement of the expansion of the Universe. Nevertheless, a closer look to the technical possibilities reveals that the search for terrestrial planets will become accessible (Pasquini et al. 2005).

Acknowledgements. The impressive progresses achieved during the last ten years to discover exoplanets are, to a large extend, the direct result of the progress made in instrumentation. It is a pleasure to acknowledge the most important contribution to the search for exoplanets provided by the technical staff of Haute-Provence and Geneva Observatories, as well as ESO. All along these decades we have benefited of a continuous financial support by the Swiss National Science Foundation (SNSF). The success of our planet-search programmes at OHP and ESO have only been possible thanks to the generous allocation of observing time by these observatories. So many colleagues have been involved in this long-term programme, and it is always very difficult to thank only few of them. Nevertheless, we would like to specifically express our gratitude to André Baranne, François Bouchy, Christophe Lovis, Francesco Pepe and Stéphane Udry for their outstanding contribution to that quest for highest precision.

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