Paths of Discovery
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THE DISCOVERY OF EXTRASOLAR PLANETS

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In the fall of 1995, a question which had been haunting astronomers and philosophers for twenty-five centuries found its first clear answer, given by the undisputable observation of the first planet around a star other than the Sun, 42 light-years away: 51 Pegasi had a planetary companion, orbiting in 4.2 days and at least half as massive as Jupiter. The astronomers Michel Mayor and Didier Queloz, from the Geneva Observatory, had made this extraordinary discovery[1] at the Observatoire de Haute-Provence, in France, after ten years of efforts, concluding a quest which had begun 50 years earlier and opening a radically new era in astronomy.

Since this first observation, 155 exoplanets (also called *extrasolar planets*)[2,3] have been discovered around stars more or less similar to the Sun, with 120 cases where a single planet is known, and 13 cases of multiple systems formed of 2 or 3 planets (see Fig. 1, page 282). To take the month of September 2004 alone, 11 planets were published! The least massive planet known to date orbits around the star μ Arae, with a mass of 14 times (lower limit) the mass M of the Earth.

A QUESTION RAISED TWENTY-FIVE CENTURIES AGO

This discovery deserves careful attention for two reasons. First, contrary to many discoveries which seem to come unexpected or were hard-

[1] Mayor, M., Quéloz, D., 'A Jupiter-mass companion to a solar-type star', *Nature*, 378, 355 (1995).

[2] For a presentation of up-to-date discoveries in this field, see the remarkable site by Schneider, J. *Encyclopédie des planètes extrasolaires*, www.obspm.fr/encycl/f-encycl.html.

[3] Marcy, G., *et al.*, http://exoplanets.org.

ly guessed even a few decades before their outburst, the question of other worlds has been present since the dawn of philosophy and science in humanity. Raised implicitly or explicitly by anyone who contemplates the sky at night, it deals with the very place of man in the Universe, as it was admirably put forward by Blaise Pascal when he writes in his *Pensées*:

> Que l'homme contemple donc la nature entière dans sa haute et pleine majesté, qu'il éloigne sa vue des objets bas qui l'environnent... Mais si notre vue s'arrête là, que l'imagination passe outre; elle se lassera plutôt que de concevoir. Tout ce monde visible n'est qu'un trait imperceptible dans l'ample sein de la nature. Nulle idée n'en approche... Que l'homme, étant revenu à soi, considère ce qu'il est au prix de ce qui est; qu'il se regarde comme égaré dans ce coin détourné de la nature; et que de ce petit cachot où il se trouve, j'entends l'univers, il apprenne à estimer la terre, les royaumes, les villes et soi-même à son juste prix. Qu'est-ce qu'un homme dans l'infini?[4]

The second reason is the following: the quest for exoplanets has succeeded because of the intrication between a deep, long-lasting interrogation over centuries and the development of observational techniques and instruments in astronomy, an intrication which is outstanding in this case but far from being typical of discovery in general. As I have devoted a great deal of my professional life to the latter, it is for me a good motivation to present this contribution to the 2004 Session *Paths of Discovery* of the Pontifical Academy of Sciences.

Probably, the question was first explicitly raised by Democrites and restated by Epicure, who immediatly related it to the infinity of the world:

> Il n'y a donc rien qui empêche l'existence d'une infinité de mondes ... On doit admettre que dans tous les mondes, sans exception, il y a des animaux et tous les autres êtres que nous observons ...[5]

The theological implications, especially on the Incarnation, of such a speculative statement made it a matter of dispute in Christianity, with positive (Albert the Great, 1206-1280) and negative (Etienne Temple) views on its pertinence. It certainly reached its most dramatic climax in 1600 with the death sentence pronounced against Giordano Bruno. As

[4] Pascal, B. *Pensées*, Fragment 72 (classification Brunschvicg), Lattès, Paris, 1988.
[5] Epicure, *Lettre à Hérodote*.

Nicolas de Cues (1401-1464) before him, Bruno refers to the omnipotence of God when considering the likelihood of other 'worlds':

> [Dieu] ne se glorifie pas dans un seul, mais dans d'innombrables Soleils, non pas en une seule Terre et un monde, mais en mille de mille, que dis-je? En une infinité de mondes.[6]

Certainly Bruno was a philosopher and a theologian, not a scientist as was Galileo: even so, his rehabilitation, as one prominent 'carrier in history' of an idea which has recently proven so fruitful, could be a recognition, by the Catholic Church, of the sinuous paths of discovery.

Emergence of a Scientific Problem

During the 19th and first half of the 20th centuries, the physical theories and the progress of astronomical observations helped to transform the previous speculations into a real scientific problem. Newton's theory of gravitation had proven its power to describe the stellar motions, especially in double or multiple systems of stars, which are extremely frequent in our Galaxy. It is indeed the gravitational perturbations of the planets in the solar system which led to the discovery of Neptune (LeVerrier 1846) and Pluto (Lovell 1936). It soon appeared that the discovery of exoplanets could only be indirect, and would result from tiny perturbations eventually measured on the star itself, i.e. on the change of its position on a sky photograph with respect to background 'fixed' stars appearing in its neighbourhood. Indeed, observing directly an utterly faint planet around a star with the telescope remained impossible: a companion B, only a thousand times fainter than the bright star Sirius A, was detected in 1862 by Alvan Clark on a photograph, but had previously (1844) been proposed by Friedrich Bessel on the basis of perturbations observed on Sirius' motion. It is interesting to observe that in the cases of Neptune or Pluto, the qualification of *discoverer* may refer to the person who predicted the existence and position of the object, or to the one who provided an observation proving directly an image or indirectly its presence. Arago said of LeVerrier:

> In the eyes of all impartial men, this discovery will remain one of the most magnificent triumphs of theoretical astronomy ...

[6] Bruno, G., *De l'infini, de l'univers et des mondes*, trans. J.-P. Cavaillé, Belles-Lettres, Paris, 1995.

Progress of Observations

By the mid-20th century, the performances of telescopes, associated with photography, began to make possible the detection of tiny perturbations in stellar motions, despite the continuous trembling of stellar images due to the presence of the Earth's atmosphere, which reduces the accuracy of astrometry and was already well-described by Newton.[7] From now on, the eventual *discovery* of an exoplanet would result from a *search* of these hypothetical objects, on the basis of quantitative predictions of their potential effects. Several astronomers (Strand in Philadelphia on the star 61 Cygni, Reuyl and Holmberg in Virginia on 70 Ophiuchi, Van de Kamp in Philadelphia on the Barnard star) did interpret their astrometric measurements as the proof of a planet in orbit. Since by then the well-established stellar theory allowed to establish the mass of stars, the mass of the assumed perturbator could then be deduced from the amplitude of the perturbation and its classification as a planet result from a comparison with Jupiter or Saturn's masses. Unfortunately for their authors, none of these claimed detections of planets were confirmed, and the Barnard candidate was definitively proclamed inexistant[8] in 1973. Would the classical astrometry method ever succeed in detecting planets?

But another question lays in the background of the search for exoplanets: how confident can one be that they simply exist elsewhere? could the Solar system be an absolute unique phenomenon in the Galaxy? – Detecting planetary systems in other galaxies was, and still is, entirely out of reach. Modern astronomers are all Copernicans in a generalized manner, in the sense that they refuse to give any privileged character to our present position as observers of the universe: in this respect, there *ought* to be other planetary systems, a statement which is not so far, although comforted by centuries of science, from the position of Epicure! But, in addition to this act of belief, understanding the history and formation of our solar system made great progress since the formulation of the *nébuleuse primitive* hypothesis by Pierre Simon de Laplace[9] in 1796. In 1902, Sir James Jeans proposed a scenario of gravitational accretion, which along with the formation of a star, would lead to the formation of a disc of gas and dust, and later to orbiting

[7] Newton, I., in *Optics*.

[8] Gatewood, G., Eichhorn, H., 'An unsuccessful search for a planetary companion of Barnard's star (BD +4 3561)', *Astron. J.*, 78, 769-776 (1973).

[9] Pierre-Simon de Laplace, *Exposition du système du monde*, 1st edn., Paris, 1976.

planets, a scenario which is now fully recognized in the light of precise simulations (see Fig. 2 and 3, pages 283-4, ref.[10]). This scenario would remain hypothetical if observation had not progressively confirmed it: in the last decade, tens of protoplanetary discs have been observed by the *Hubble Space Telescope* or ground based telescopes, giving a firm basis for the search of their last stage of evolution, namely the formation of planets.

Modern Times and Discoveries

The discovery of exoplanets could obviously rely on a small indirect effect on their parent star, but which effect should one detect, and with which instrument? During the period 1975-1990, the techniques of optical astronomy were making immense progresses. Because the progress of observation, which in astronomy is the source of discovery, required better images and better spectra, all the resources of optics, helped by the newborn and powerful computer capability, were explored by astronomers. It is important to point out here the weight of tradition and human models. In France for example, it is a long chain of physicists or opticians, who all showed an interest in astronomy, which led to the success of the last generation: there is a continuity of methods, traditions and open-minded exploration of the 'virtually impossible' from Fresnel, Biot, Fizeau, Chrétien, Lyot, Françon, Jacquinot, Maréchal, Connes, to finally Labeyrie who recreated optical interferometry,[11] abandoned since the prowess of Albert Michelson (1920), the first one to have directly measured stellar diameters. Similarly, it is in these years (1989) that adaptive optics emerged, beating for the first time in history the trembling of stars observed by ground-based instruments at visible or infrared wavelengths, and allowing to conceive and build new generations of giant telescopes, such as the European *Very Large Telescope* in Chile or the *Keck Telescopes* in Hawaii.

In 1970, a rudimentary but incredibly powerful spectrograph was built in Cambridge (UK) by Roger Griffin, exploiting ideas of multiplexing the light, which were put forward in the optics community at this time, both in England and in France: instead of measuring one spectral line among the ten thousands present in a stellar spectrum, one cumu-

[10] Artimovicz, P., www.astro.su.se/~pawel/.

[11] Labeyrie, A., 'Interference fringes obtained on Vega with two optical telescopes', *Ap.J.*, 196, L71-L75 (1975).

lates all the information common to these lines, improving enormously – by a factor of 10^3 – the sensitivity of the instrument to Doppler shifts. It is exactly what the people looking for variations of stellar velocities in multiple systems needed, and this did not escape the young Michel Mayor, who was nurtured by the long tradition of precise radial velocities measurements carried by the Observatoire de Genève, where he worked, and by the Observatoire de Marseille where a bright optician named André Baranne was conceiving new instruments. The first spectrograph they built entered operation in 1977, and was focused on the search for low mass stars in multiple systems.

In fact, stimulated by David Latham (Cambridge, USA) who was working along the same tracks, they jointly discovered with him in 1988 the object[12] HD114762, which was finally classified as a brown dwarf, i.e. an object of intermediate mass between a star and a planet: this result, coming after several false hopes of previous detections of these objects, was to lead to a list, in 2004, of several tens of brown dwarfs. By the end of the 1980s, the theory of star formation had placed fairly strict mass limits on the possible ignition of nuclear reactions in the core of an object to produce a real star (above 0.08 M_{sun}) or briefly on its surface to produce a brown dwarf (between 13 $M_{Jupiter}$ and 0.08 M_{sun}= 80 $M_{Jupiter}$), a mass of 13 $M_{Jupiter}$ thus defining the maximum mass of a planet. The brown dwarf quest is in itself another fascinating discovery story, which is connected to, but distinct from, the search for exoplanets, given the proximity of masses and detection techniques. The mass of HD114762 seems to make it a brown dwarf and not a planet, but doubt remains permitted.

At this point, Mayor comments that he became 'ouvertement un chasseur de planètes'[13] and a second generation of instruments was built, with Swiss accuracy, with all the available technology and the sensitivity required to detect the effect of a jovian planet on the parent star: this sensitivity can simply be expressed as the capability to measure, in the radial velocity of the star, temporal variations of the order of a few metres per second (a Doppler-Fizeau relative effect of roughly 10^{-8}). His team is not alone, as in California with Geoffrey Marcy and Paul Butler, as well as in Canada with Gordon Walker and Bruce Campbell, two other groups are on the

[12] Latham, D.W., Stefanik, R.P., Mazeh, T., Mayor, M., Burki, G., 'The unseen companion of HD114762 – A probable brown dwarf', *Nature*, 389, 38 (1989).

[13] Mayor, M., Frei, P.-Y., *Les nouveaux mondes du cosmos*, Seuil, Paris, 2001.

track: the potential discovery is nearly on hand, the technology is readily available, it all becomes a matter of tenacity, good weather... and luck.

The search made by these astronomers focused on the periodic fluctuations of the stars radial *velocity*, which, as a direct consequence of Kepler laws, is apparently caused by an orbiting planet and would allow the determination of its period and mass. But in the late 1970s, the old astrometric method, based on the measurement of periodic fluctuations in the star's *position*, was becoming possible at the requested accuracy (a fraction of a millisecond of an angle) thanks to the new but difficult technique of optical interferometry, reborn in 1975 and slowly developing. The astronomer Michael Shao, from the *Jet Propulsion Laboratory* in United States – a leading place in the exploration of the Solar system since the *Voyager* missions to Jupiter and Saturn in the 1970s and 1980s –, developed, in the 1980s on the historical Mt. Palomar in California, a remarkable astrometric interferometer to measure the orbit of close binary stars. He succeeded, but he soon realized that this indirect detection technique would only be really successful if carried in space by unmanned telescopes unaffected by atmospheric perturbations, and he initiated long-term projects in this direction, yet to come (see Fig. 4, page 284).

The odds were therefore in favor of the spectroscopists, and indeed, always needed at some point for a discovery to happen, was with the Geneva group. Luck seemed even more needed after an unsuccessful search, published in 1994 by the two other active groups in America, who found no companions on their sample of 20 stars: they were indeed looking for long orbital periods (years) as expected for objects comparable to Jupiter in mass a mass set by the limited sensitivity of the instruments – and far away from the star, where many theorists predicted the massive planets ought to be.

What follows is Mayor's description of the final run. In November 1994, he and his young collaborator Didier Quéloz hinted at an oscillation on one of their reference stars, 51 Pegasi. Having eliminated instrumental effects, they remained puzzled by the measured period of 4.2 days, which, given the known mass of this star, led to mass lower limit of half a Jupiter and an orbit situated at 0.05 astronomical units, i.e. extremely close to the star, a distance at which (almost) no one would imagine such a large planet to be present. At Saint-Michel-de-Haute-Provence Observatory, the star is no longer observable until July 1995, and they spend their time establishing the ephemerids of the planet in order to *predict* where it should be when it will be reobserved. This is an exact reminder of Le Verrier predicting, from celestial mechanics, the position where Galle in Berlin would observe Neptune. On July 6, 1995, the observation confirms precisely the prediction (see Fig. 5, page 285). The two astronomers prepare their publication in *Nature*, but in the meantime try to assess the physical possibility for an orbit to remain stable with such a close periastron, where tidal effects could quickly destroy the planet: their American colleague Adams Burrows, a specialist, is consulted and accepts with fair play to run his computer code without asking questions. Fortunately, his verdict does not rule out the stability and the discovery is announced and applauded at a scientific meeting in October in Florence. The discovery not only confirmed by their competitor Geoffroy Marcy at Lick Observatory, but the Lick group reviewed the data and searched them for short period planets, for which indeed they were not looking: they found two other planets (orbiting the stars 70 Virginis and 47 Ursae Majoris).

The entire astronomical community would soon understand that an entirely new field was open, and was forced to think over its prejudices against massive planets being so close to the star. In fact, one soon realized that a far-reaching analysis had been published[14] as early as 1986, analysis which could have led to focus the search on orbital periods of the order of days or weeks, rather than of years or decades. This analysis was showing that massive planets can indeed only be formed in the protoplanetary disc at a distance of several astronomical units of the star, such as Jupiter and Saturn's orbits, but can migrate inwards because of interactions of the young planet with the remaining gaseous disc.

Before drawing general conclusions from this splendid adventure, it is interesting to discuss briefly what the word *discovery* exactly means here, as the only proof at this moment was only indirect, i.e. the gravitational action of the planet on the star. No one had yet *seen* this planet, as Galle saw Neptune through his telescope. In 2000, the astronomer Henry, looking at the by then detected planets, found that one of them was regularly passing in front of its star because of the inclination of its orbit with respect to the line of sight from Earth. He observed a measurable 2% decrease of the star's brightness: not only this measurement gave a reasonable density of the planet, but it was adding another indirect proof of its presence. Five more such *transits* have since been detected.

Although in 2005 no one doubts the reality of the 155 discovered exoplanets, a real image of an exoplanet, as the one Galle obtained of Neptune, is much wanted, but indeed extremely difficult to obtain, as the planet is

[14] Lin, D.N.C., Papaloizou, J., 'On the tidal interaction between protoplanets and the protoplanetary disk. III – Orbital migration of protoplanets', *Ap.J.*, 309, 846 (1986).

buried into the much more intense light of the star. The detection of actual photons from an exoplanet would open the way to spectroscopy, i.e. to a detailed analysis of its composition, its atmosphere, etc.

Here comes another story, involving again a radical technological breakthrough, in which I was fortunate to play a direct role during the period 1981-1998: namely the advent of adaptive optics[15] to beat the deleterious effects of the Earth's atmosphere on astronomical images, which I mentioned above. To make a long story short, ground-based telescopes can be equipped with an active deformable mirror, controlled by a computer, which almost exactly compensates the effects of the atmosphere and restores the resolution capability the telescope would have if placed in space. This enormously helps the detection of faint stellar companions and the system we built for the European telescope *Yepun* (one of the four VLT telescopes) allowed Anne-Marie Lagrange and Gaël Chauvin to publish[16] in September 2004 the (likely) first *direct detection* of an object of planetary mass (approximately 5 M_J), orbiting around the brown dwarf 2M1207 (see Fig. 6, page 285): some caution is still exercized by the authors as absolute proof, eliminating the unlikely chance of a line-of sight coincidence with a background object, will only be given when the motion of the planet is directly observed.[17]

In this story of exoplanets, one important step is missing, which I should have emphasized in due time: it is the totally unexpected discovery of planetary mass objects around pulsars in 1992, with an entirely different method. Pulsars are neutron stars, left over after the explosion of a supernova: extremely compact and carrying most of the angular momentum of the parent star, they rotate as fast as 1 kHz, and are detected by their modulated radio or optical emission at this frequency. Radiofrequency measurements can be extremely precise (down to 10^{-12}) in relative accuracy, a performance which incidentally led to the first observational proof of gravitational waves, as predicted by general relativity. Because of the violent events which led to the formation of a pulsar, no one really believed that eventual planets existing around the parent star could survive the explosion, until successive hints of detections as early as 1970, only 3 years after

[15] Rousset, G., Fontanella, J.C., Kern, P., Gigan, P., Rigaut, F., Léna, P., *et al*., 'First diffraction-limited astronomical images with adaptive optics', *Astron. & Astrophys.*, 230, L29-32 (1990).

[16] Chauvin G., Lagrange A.-M., Dumas C., Zuckerman B., Mouillet D., Song I., Beuzit J.-L. & Lowrance P., 'A giant planet candidate near a young brown dwarf', *Astron. & Astrophys.*, 425, L29 (2004).

[17] In 2005, the proof was fully given of the physical association of both objects, and the planet confirmed.

the discovery of the pulsars, although disproven later, stimulated theorists to think over the problem.

Any massive body orbiting around a pulsar will affect periodically the measured frequency, and become detectable. In 1992, the young Polish astronomer Alexander Wolszczan published the discovery of two planets, a third one being later added, orbiting around the pulsar PSR 1257+12: their masses are respectively 0.09, 3.9 and 4.3 times the mass of the Earth.[18] They are indeed, and will probably remain for some time, the least massive single objects ever detected at this distance from us: there is no dispute about the fact they are most likely the residual of a planetary system which survived the explosion of the supernova. Yet, they were and still are quite apart in the quest for other planetary systems, like ours, as the extremely strong radiation (γ and X rays) emitted by the pulsar does not leave any possibility for these objects to evolve towards complexity, as our system did. Despite many efforts, the list has not much increased in the ten last years, as it only counts another case as for 2004.

Conclusion

The story of exoplanets is in its infancy, and we should learn more in the coming years. As usual, the discovery is opening a kind of Pandora box, where many old questions suddenly become revitalized, the question of possible life emergence and evolution in *other worlds*, to use Epicure's expression, being the central one in the years to come.

The path of discovery has been long but quite straight. The initial question was fairly simple, as possibly the one which led to the concept of atom. The progress became significant by the mid-1900s, only when the observing tools reached the level of accuracy and sensibility required by the expected effects of an exoplanet. But to get an order of magnitude of these effects, a fairly large body of theory and extrapolation from our own solar system was needed at the same moment, and accompanied every step towards the final discovery. On the other hand, some of these predictions were taken too seriously and led to question the discovery, when the first exoplanet was found at such an odd close distance to its star.

[18] Wolszczan, A. & Frail, D., 'A Planetary System around the Millisecond Pulsar PSR1257+12', *Nature*, 255, 145 (1992).

One should note that this major discovery, opening a scientific revolution, is not the result of a radical change of paradigm, as its foundation has been laid down for centuries. Although the detection of the pulsar planets in 1992, for which no one was looking for, or the extreme proximity of the 51 Peg planet to its star, were both entirely unexpected, they could quickly be understood without a major revision of theories or models.

There is here an interesting point, namely the connection between discovery and *threshold* effects. Clearly Mayor's result came at a time where technology had suddenly reached the level or sensitivity needed for the detection. This may seem a self-fulfilling affirmation, but one may point out that several other paths with different instruments (e.g. astrometric measurements on the parent star, or transits measured from satellites), could as well lead to a similar discovery. Another threshold lay in the statistics involved:[19] the discovery could only result from a systematic and lengthy search on many stars... but no one knew a priori the size of a relevant sample. Walker, one of Mayor's competitors, worked unsuccessfully on a sample of 23 stars: with a now known probability of 4 to 5% for these stars to have a massive planet but studyng double stars, his chances to find one where dim. Mayor, who initially was not looking for planets, worked on a sample of hundreds of stars.

The long chain of astronomers who carried the issue and invented instruments by drawing on all the resources of optics available during their time has certainly been a key for success, and will likely remain so in the future. This continuity of efforts, the kind of *rage* to reach a result which seemed vanishing for so long, illustrates again the words of Bernard de Chartres[20] (†1130), quoted by John of Salisbury:

> Bernard de Chartres disait que nous sommes comme des nains juchés sur des épaules de géants [les Anciens], de telle sorte que nous puissions voir plus de choses et de plus éloignées que n'en voyaient ces derniers. Et cela, non point parce que notre vue serait puissante ou notre taille avantageuse, mais parce que nous sommes portés et exhaussés par la haute stature des géants.

In this respect, the final discoverer has the immense merit of the last step, of the tenacity to reach it, of the ability to seize the chance which is always needed, but is the heir of a long story.

[19] As pointed out by Jean Schneider, with whom the author had fruitful exchanges.

[20] Newton, to which this metaphor is often but wrongly attributed, used it in a letter to Robert Hooke in 1676, where he wrote: 'If I have seen farther than others, it is because I was standing on the shoulder of giants'.

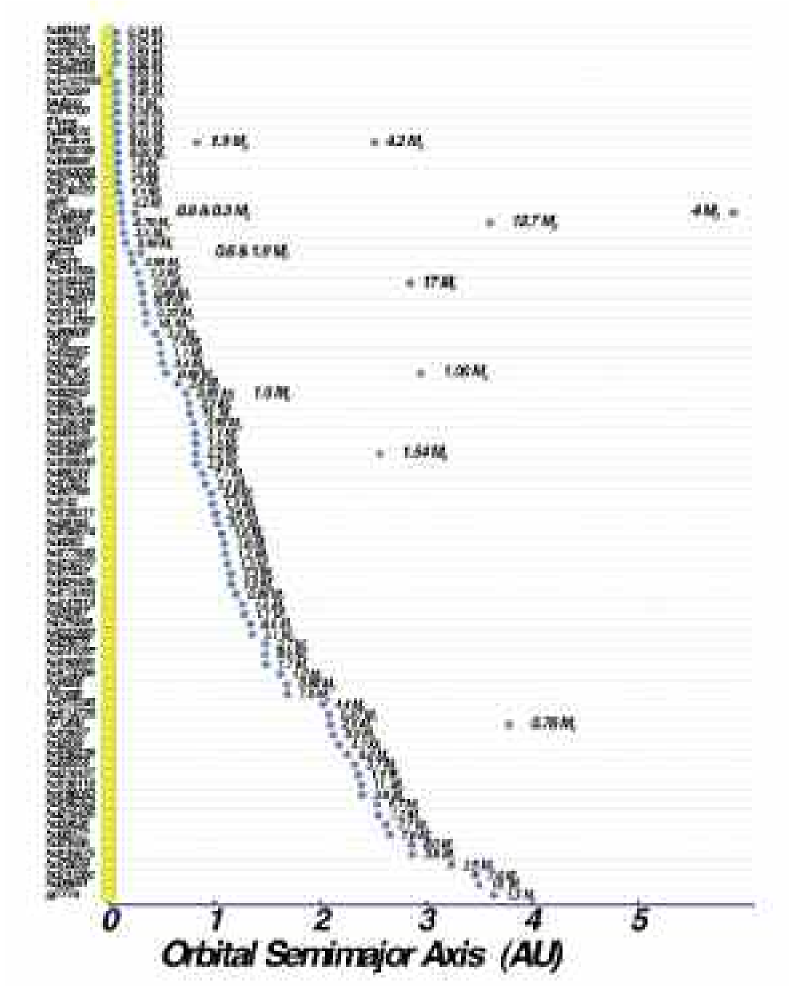

Figure 1. An overall view of the exoplanets known at the date September 2004 (Marcy *et al.*, Ref.[3]). Star names are on the left, distance to the star (semi-major axis of elliptical orbit) is in abcissa, measured in astronomical units (1 a.u. = 150 millions kilometers = distance Sun-Earth), planets are labeled with their mass, measured in units of the Jupiter mass M_J (1 M_J = 1/1000 M_{Sun} = 326 M_{Earth}). Except in a few cases (transiting planets), these masses are lower limits, because of the uncertainty, due to the spectrometric detection method, on the inclination of the planetary orbit w.r.t. the plane of the sky.

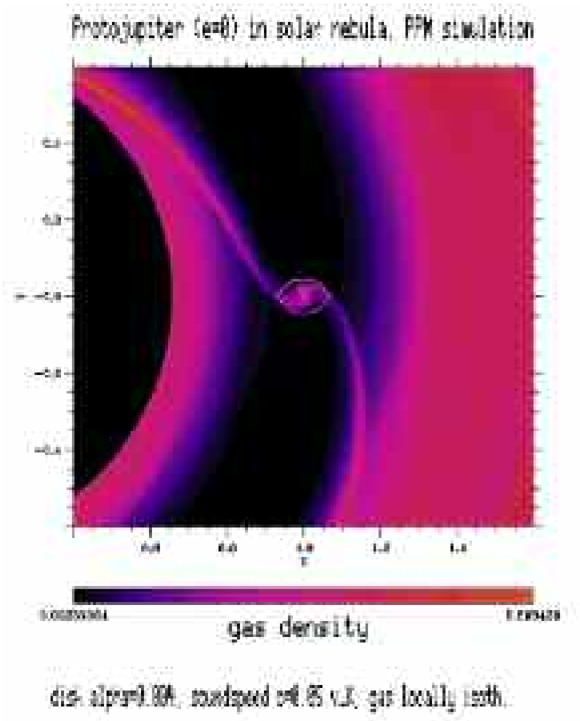

Fig. 2. A simulation of the formation of a planet in a protoplanetary disc, resulting from accretion of matter. From Ref.[9].

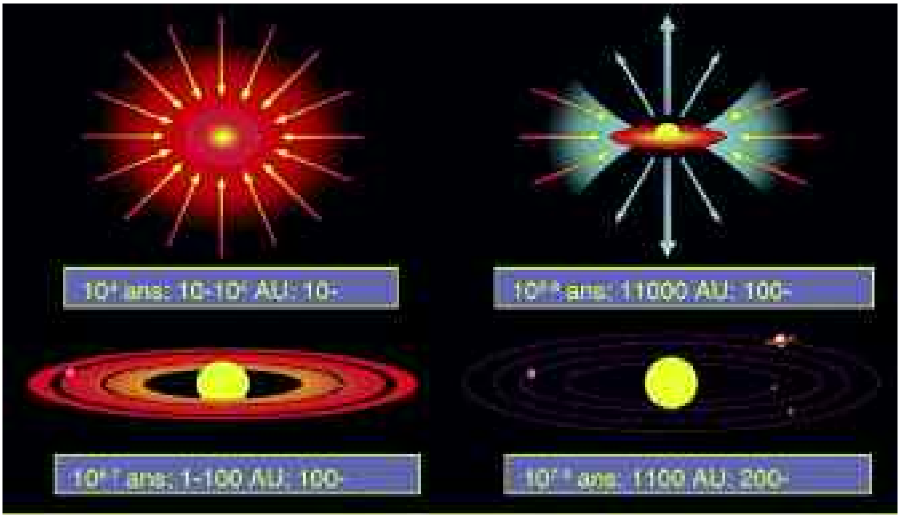

Fig. 3. The various stages of star and planet formation shown schematically, as they are now understood. Duration of each phase is in years, scale is in astronomical units (AU), and the temperature of the accreting gas in Kelvin.

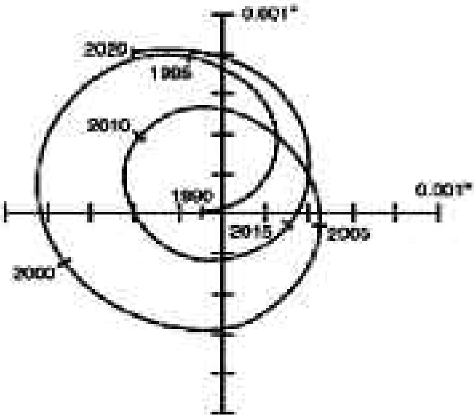

Fig. 4. The proposal of Michael Shao to detect the planet existence by measuring the reflex motion of its star during the orbit. This simulation shows the apparent motion the Sun would have on the sky, if observed 10 pc away, due to the presence of its planets (mostly Jupiter and Saturn). The amplitude is less than 1 milliarcsec, hence can only be detected with the angular resolution of an optical interferometer, located either in space or on the surface of the Earth.

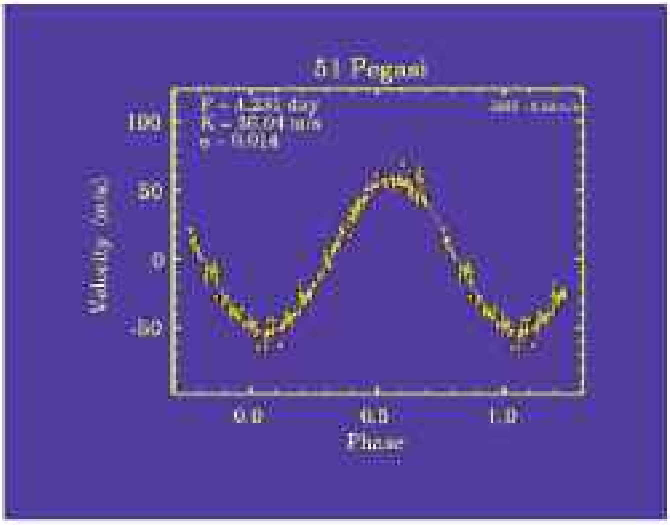

Fig. 5. The detection of the first planet by the induced motion of its star 51 Pegasi. The apparent velocity of the star in the direction of the observer is modulated with time (here labeled 'phase') at the rate of the orbiting period of 4.23 days (Source: M. Mayor, Geneva Observatory).

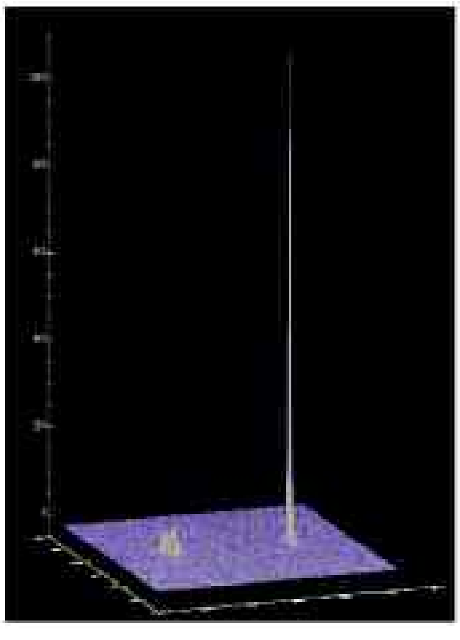

Fig. 6. The extraordinary performance of an adaptive optics correcting system on a large telescope, here on the European *Very Large Telescope*. The graph shows the distribution of the intensity of light at the focal plane of the telescope without (left) and with (right) the correction: the concentration is increased by more than one order of magnitude, allowing the telescope to practically reach its diffraction limit. This instrument is used for the observation shown on Fig. 7. (Source: ESO).

Fig. 7. The *direct* detection of a planetary mass object, in orbit around the brown dwarf 2M1207 at a distance of 55 astronomical units. The objects are situated 70 pc away from Earth, and are observed at the near-infrared wavelengths by the VLT telescope Yepun, equipped with adaptive optics (Ref.[16]). The second graph shows the planet position in comparison with the Solar system. (Source: A.-M. Lagrange & G. Chauvin, CNRS-INSU and ESO).