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Daniel Rouan and Anne-Marie Lagrange

Detection of exoplanets: exploiting each property of light

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Guest editors: Anne-Marie Lagrange (LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.) and Daniel Rouan (LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.)

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Exoplanets / *Exoplanètes*

Detection of exoplanets: exploiting each property of light

Détecter les exoplanètes en exploitant chacune des propriétés de la lumière

Daniel Rouan [*, a] **and Anne-Marie Lagrange** [a]

[a] LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université Paris-Cité, 5 place Jules Janssen, 92195 Meudon, France

E-mails: daniel.rouan@obspm.fr (D. Rouan), Anne-marie.Lagrange@obspm.fr (A.-M. Lagrange)

Abstract. Up to now and probably for still a long time, the only support of information used to detect exoplanets has been the analysis of light, either visible or infrared. In the vast majority of cases it is the light from a star and not the light from the planet itself which is used, because the huge contrast in brightness between the star and a planet orbiting it as well as the extremely short angular distance between them makes direct imaging a real challenge. It is then a subtle effect detected on the starlight that in general indicates the planet's presence and provides information on some of its characteristics: mass, radius, distance to the star, temperature, etc. As an introduction to the different contributions appearing in this volume, this article proposes a kind of brief review of the various methods imagined by astronomers to exploit one of the properties of the light to succeed in detecting and characterizing exoplanets. We'll show that even direct detection became a reality and contributes to the more than 5000 exoplanets detected today.

Résumé. Jusqu'à présent et probablement pour encore longtemps, le seul support d'information utilisé pour détecter les exoplanètes est l'analyse de la lumière, qu'elle soit visible ou infrarouge. Dans la grande majorité des cas, c'est la lumière d'une étoile et non celle de la planète elle-même qui est utilisée, car l'énorme contraste de luminosité entre l'étoile et une planète en orbite autour d'elle ainsi que la distance angulaire extrêmement courte qui les sépare font de l'imagerie directe un véritable défi. C'est alors un effet subtil détecté sur la lumière de l'étoile qui indique en général la présence de la planète et fournit des informations sur certaines de ses caractéristiques : masse, rayon, distance à l'étoile, température, etc. En guise d'introduction aux différentes contributions figurant dans ce volume, cet article propose une sorte de brève revue des différentes méthodes imaginées par les astronomes pour exploiter une des propriétés de la lumière afin de parvenir à détecter et caractériser des exoplanètes. Nous montrerons que même la détection directe est devenue une réalité et contribue aux plus de 5000 exoplanètes détectées aujourd'hui.

Keywords. Transit, Direct imaging, Velocimetry, Coronagraphy, Interferometry, Astrometry, Gravitational lensing.

Mots-clés. Transit, Imagerie directe, Vélocimétrie, Coronographie, Interférométrie, Astrométrie, Lentille gravitationnelle.

Note. This article is an adaptation in English of a part of one Chapter of the forthcoming book "Les 150 ans de la Société Française de Physique Panorama historique et scientifique" published by EDP-sciences (Les Ulis, France), with their kind permission.

* Corresponding author

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1. Introduction

There are an infinite number of worlds, some similar to this one, others dissimilar. For atoms being infinite in number [...], there is nothing to hinder the infinity of worlds. Almost 2300 years passed between this remarkable insight of Epicurus in a letter to Herodotus and the discovery of the first exoplanet orbiting an ordinary star by Michel Mayor and Didier Queloz in 1995 [1], a discovery that earned them the Nobel Prize in Physics in 2019. This idea, formulated in the epoch of the Greek philosophers, was taken up by several thinkers over the centuries, including Giordano Bruno in the 16th century : *There are therefore innumerable suns and an infinite number of earths revolving around these suns* [2], who was sent to the stake for this iconoclastic thought, but also, closer to us, Bernard le Bovier de Fontenelle [3]: *I put it into my head that each star could well be a world. Nothing is so beautiful to imagine as this prodigious number of whirlpools, the middle of which is occupied by a Sun that makes the planets revolve around it.* In the 19th century, with astronomy having been enriched by large catalogues of stars and distance measurements revealing the immensity of the stellar population, the idea took hold, at least among astronomers, of the probable existence of these worlds orbiting stars other than the Sun.

Since then, several discoveries have made this idea even more widely accepted. From a simple statistical point of view, if we consider the observable Universe[1], it must contain about 100 billion galaxies, each of which harbours an average of 100 billion stars, i.e. a total of 10^{22} stars: it is hardly admissible that our sun is the only one to have acquired a planetary entourage. Especially since, even before the actual detection of planets, the genesis of the solar planetary system was well understood from a theoretical point of view as one of the slags of the formation of the Sun. The admitted scheme is the following (see [4] for a complete description): the collapse of a gigantic galactic cloud of gas (hydrogen and some helium) containing small sub-micron solid particles (1% of the mass of the gas for this component) happens under the effect of self-gravitation; it results in a flattening of the matter along the initial rotation axis of the cloud under the effect of the centrifugal force which slows down the collapse in the perpendicular direction[2]. At the end, the process results in a huge central over-density, the protostar, within which soon nuclear reactions will ignite, and, surrounding the protostar, an extended rotating disc that contains gas and solid particles. In a short time the gas dissipates under the radiative pressure of photons emitted by the newborn star while the play of collisions and the agglomeration of particles in successive stages will give rise successively to grains of sand, pebbles, rocks, planetesimals up to solid planets (or planetary nuclei for giant gaseous planets). Such proto-planetary disks are observed in star-forming regions of the Milky Way as dark, oblong silhouettes [5], projected onto a uniform luminous background specific to these regions[3]. The consistency between model and observations was thus well established and the generality of planetary systems became extremely likely.

But how easy actually detecting an exoplanet is?

[1] i.e. the Universe less than 13.8 billion light years away.

[2] In terms of physics it is the conservation of angular momentum that is responsible for this flattening.

[3] This background is created by the fluorescence of hydrogen ionised by the intense UV radiation produced by the most massive and hottest stars. Those luminescent galactic clouds are called HII regions.

2. Direct detection: a very difficult task

The estimates that we are able to make, based on known data on the distances of stars and the size of the solar system, point to the extreme difficulty of direct detection. Even for a nearby star its potential planetary system is not only completely swamped in the image spot of the star at the telescope focus, which is far from point-like, but also presents itself with a terribly low contrast compared to the brightness of the star. Let us examine these two effects: the first one results both from an effect of fundamental physics and the role of the atmosphere. Diffraction dictates that the image of a point object at infinity will have a finite angular size proportional to the wavelength of observation and inversely to the diameter of the telescope. In the unit of angle that astronomers like to use, the arcsecond, we have approximately the relation : $\theta('') = 0.2\lambda(\mu\text{m})/D(\text{m})$. For a very nearby star, at say 4 light years away[4], a planet in an Earth-like orbit is angularly at $0.75''$ from its star. In the visible ($\lambda = 0.5\mu$m), this means that a telescope of one metre diameter would in principle be able to separate the planet, since the diffraction spot size is $0.1''$. But alas, this hope is ruined by the atmosphere which, animated by turbulent movements at different levels, mainly near the ground and at an altitude of around 12 km, introduces small random variations in the refractive index which, over the ten km or so of the effective thickness of the atmosphere, will disturb the final image. This one will reach an angular size between 0.7 and $3''$ in diameter, depending on the quality of the observation site. The second difficulty is that of contrast. To illustrate this, it is sufficient to realise that the Earth seen from a distance has a brightness ten billion times weaker than that of the Sun in the visible range! The two combined effects of the small angular distance between the star and the planet and the high contrast thus make the challenge of direct detection terribly difficult. This challenge is often illustrated by the image of a firefly that one would try to distinguish at night as it flits around a marine lighthouse 20 km away. Several articles in this issue prove however that there has been huge progresses to overcome those technical difficulties, as demonstrated in [6] and that several cases of direct imaging of both planets and disks have indeed been possible, as detailed in [7] and [8].

3. Indirect methods vs light properties

This explains why astronomers initially searched for exoplanets by indirect methods, i.e. by measuring on a star itself some quantities that could be affected by the presence of one or several planets in orbit. Astronomers have shown a great deal of imagination, as illustrated in the diagram in Figure 1, which summarises this abundance of ideas, although not every branch of the tree has necessarily borne fruit. In this volume the reader will discover in much more details the various methods that have been indeed productive, while I'll give in the following just a flavour of those techniques.

From the point of view of a physicist, we may examine these methods by looking at the different properties of light that each methods rely on. These properties are summarised in the Table 1, adopting in two different columns a particle (photon) or wave (electromagnetic wave) point of view, but linked to the same property.

[4] Distance to Proxima Centauri, the closest star to the Sun.

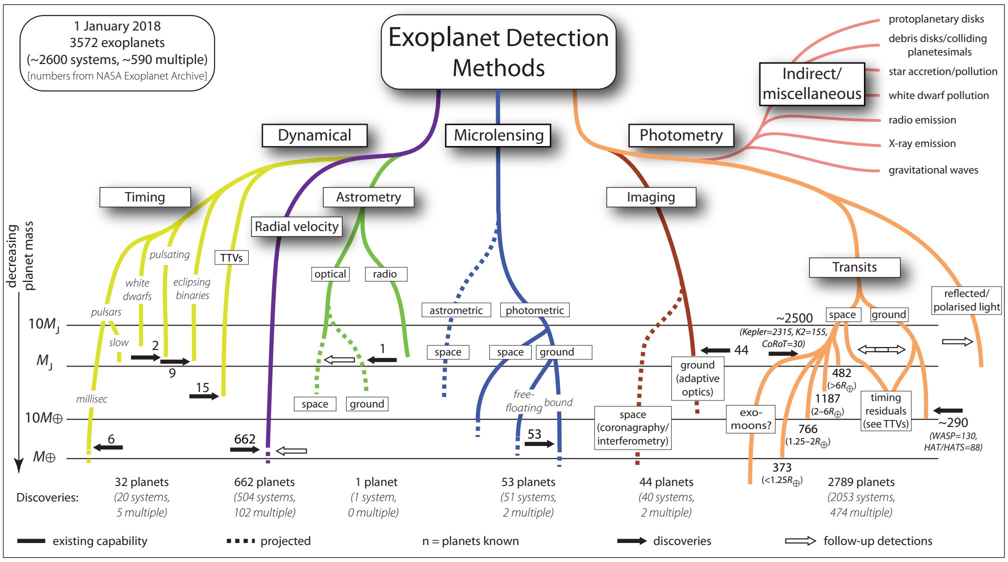

Figure 1. The tree of methods devised for the detection of exoplanets (copyright: Perryman, 2018).

Table 1. The different properties of light listed either from the point of view vue of light as particles or as a wave. Le last column indicate the type of instrument installed on a telescope that can measure a quantity linked to this property.

Photon	Electromagnetic wave	Instrument
Energy ($h\nu$)	Wavelength (λ)	Spectrograph
Number of photons	Light intensity	Photometer
Coherence	Spectral purity	Interferometer
Spin state	Polarisation	Analyzer/Polarizer
Constant speed, deflection by a mass		Photometer
Direction of momentum	Direction of propagation	Astrometry

It is worth noting that each of these properties gave rise to an effective method that has contributed to the present impressive list of over 5000 exoplanets detected (see the site www.exoplanet.eu). Introducing briefly the physics which is behind each of the methods of direct or indirect exoplanet detection is the purpose of this article which acts then as an introduction to the several papers of this special issue that detail in a much more complete way those various techniques.

It should be mentioned that the difficulty inherent to the problem of detecting exoplanets has required in all cases the use of cutting-edge techniques, and often the development of new ones. Here are a few examples: ultra-sensitive and very fast two-dimensional detectors, adaptive optics (initiated in France for astronomical applications), nano-technologies, frequency combs, very large and pretty soon extremely large telescopes (10 m and 40 m in diameter respectively), multi-telescopes interferometry. A research work as fundamental as that on discovering and characterizing exoplanets will thus have generated new know-how in companies and laboratories, a source of innovations, with often indirect but effective spin-offs for society.

4. Exploiting wavelength of light: the Doppler velocity method

The method is presented in much more details in [9] and [10] of this issue. Let's first highlight what is called the reflex motion of the star. This is nothing less than the motion of the star around the centre of gravity (c.o.g.) of the star-planet system, which is not confused with the centre of the star although it is close to it. For example, for the Sun it situated at a distance within about two solar radii, mainly due to the effect of Jupiter. The star then moves on a very tight orbit around the c.o.g. and it is this motion that one tries to detect. The velocimetry-Doppler method aims at measuring along the line of sight the component of the star's velocity on this trajectory. A single planet (or one that is more massive than the others in the system) will induce a periodic variation in the velocity, the analysis of which will give not the exact mass of the planet, but a lower value. It is this type of measurement that was used for the first detection of an exoplanet orbiting a "normal" star[5] by Michel Mayor and Didier Queloz.

The measurement is based on the Doppler–Fizeau effect, i.e. the small shift in wavelength of the detected starlight, either towards the red when the star is moving away from the observer on its orbit, or towards the blue when the star is approaching. The main difficulty is that one is looking for velocities as low as one m/s[6]. The instrument involves several techniques simultaneously but is mainly based on spectroscopy at very high spectral resolution, i.e. capable of discriminating in the spectrum of the star, patterns that are very close in wavelength. In addition to high spectral resolution, one wishes to benefit from the very large number of spectral lines[7] present in the spectrum to obtain what is known as a multiplex gain, so the spectrum must be obtained in the largest possible spectral range, in other words in a range of wavelengths covering as many colours as possible of the rainbow and beyond. This dual requirement for very good spectral resolution and a wide spectral range is achieved by a special spectrograph, known by the barbaric name of the cross-scale échelle spectrograph. In this instrument, a large diffraction grating produces the high spectral resolution and is associated with a second dispersive component (prism or grating) of lower resolution which will separate, along a direction perpendicular to that of the main dispersion, independent spectral regions. On the two- dimensional detector (a CCD), the entire spectrum will be formed, arranged somewhat like the successive lines of a text. Figure 2 illustrates the appearance of such a stellar spectrum produced by HARPS[8] one of the most performing instrument of this kind. The spectrum indeed exhibits a very large number of lines. For the detection of 51 Peg-b Mayor and Queloz [1] Exoplanet science with SPIRou: near-infrared precision velocimetry and spectropolarimetry benefited from the superb performances of the ELODIE spectrograph installed at the focus of the 193 cm telescope of the Haute-Provence Observatory.

To determine the Doppler shift, which can be as small as $\Delta\lambda/\lambda_{\emptyset} = 10^{-10}$, a very fine comparison of the observed spectrum with a known spectrum of the same type of star is used. This involves determining the amount of shift along the λ axis of one spectrum relative to the other that

[5] Three years earlier, a system of three planets, including a Moon-like one, had been discovered by A. Wolszczan and his collaborators around a pulsar, i.e. a rapidly rotating neutron star, the residue of the supernova explosion of a massive star.

[6] This is to be compared to the much higher velocity of 30 km/s of the Earth on its orbit which indeed is added to the Doppler shift

[7] A spectral line manifests itself as a narrow, dark band in the spectrum, i.e. the decay of light, at a very specific wavelength position, which is specific to a particular chemical element present in the star's atmosphere.

[8] High Accuracy Radial velocity Planet Searcher an instrument installed on a 3.60 m telescope operated by ESO in Chile.

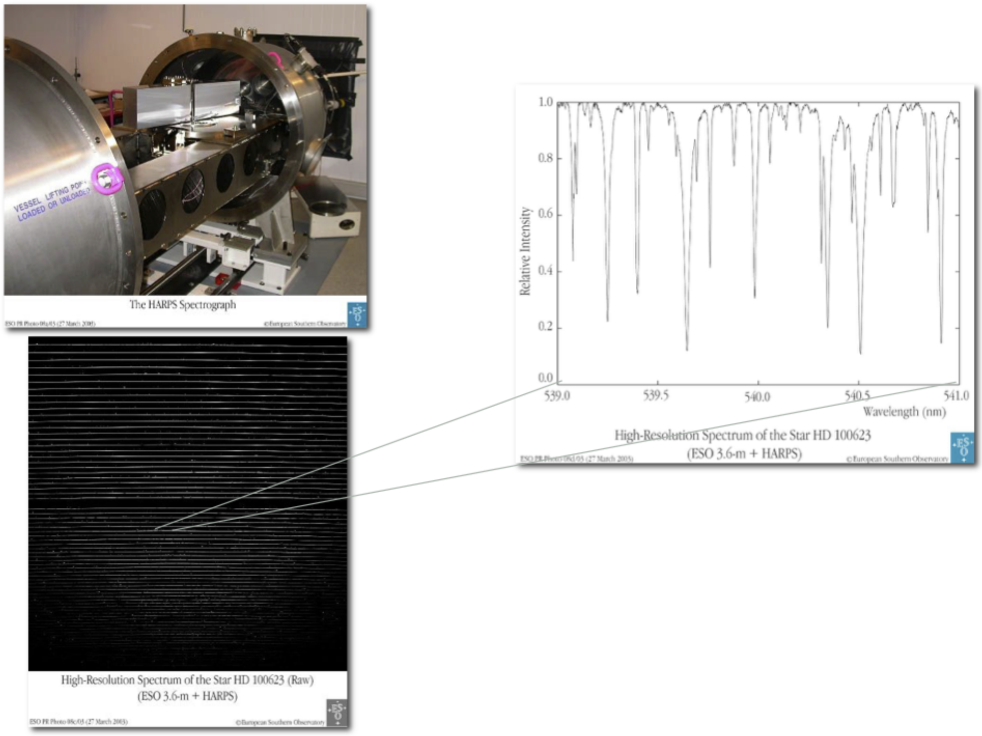

Figure 2. Top left: ESO's HARPS instrument installed on a 3.60 m telescope in Chile, which has discovered many extrasolar planets. The large diffraction grating and the tank that insulates it from vibrations and temperature or pressure variations are particularly noticeable. Bottom left: the cross-scale spectrum formed on the CCD detector. Right: zoom in on a small region of the spectrum illustrating the large number of absorption lines that can be observed.[9]

gives the best line-to-line correspondence and results in a maximum in a mathematical function[10] involving the two digitised spectra. After various improvements, including the introduction of a frequency comb as a wavelength calibrator and access to very large telescopes (8-10m), one has gone from a detectable speed of a few tens of m/s[11] to a fraction of m/s, allowing the detection of exoplanets of only a few Earth masses.

5. Exploiting light intensity: the transit method

The luminous power (or equivalently, the number of photons per second) that we receive from a star is generally very stable. Therefore, if we measure periodic and short decreases in this power (known as the star's brightness), we can suspect that an object is regularly passing in front of the star and masking part of its surface for a privileged observer. The phenomenon is well known for so-called eclipsing binary star systems that exhibit such regular decreases in brightness. The idea that such a phenomenon, named a transit, could be observed for planets passing in front of a

[9] High Accuracy Radial velocity Planet Searcher.

[10] This is the cross-correlation coefficient, an integral of the product of the two spectra, one being shifted with respect to the other

[11] 51 Peg-b, the first planet detected by M. Mayor and D. Queloz, corresponds to 128 m/s of speed variation

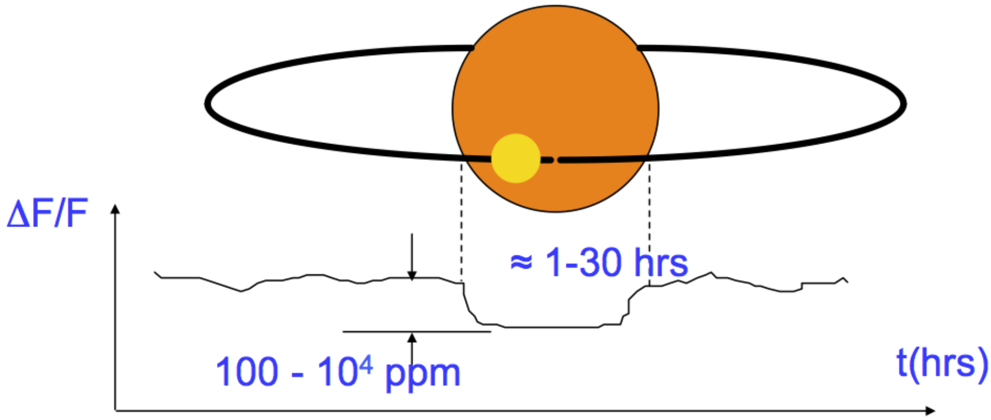

Figure 3. Principle of exoplanet detection by transits. The curve corresponds to the measured flux of the star, the central decrease corresponding to the transit of a planet in front of the stellar surface. Typical values of quantities related to the event are shown (ppm is short for parts per million).

stellar disc had been proposed for decades, but it was only in 2000 that such a detection was made for the first time by Charbonneau and his collaborators [11] by targeting a star already known to host an exoplanet, detected by the Doppler velocimetry method. The parameters derived from such a detection are the period (and at least three identical transits must be detected to be certain of the periodic nature of the phenomenon), its orbit by applying the Kepler–Newton laws, and the radius of the planet since the decrease in brightness is proportional to the planet's surface.

The main characteristics of the transit phenomenon are a duration of a few hours, a relative amplitude of between one hundred and ten thousand ppm and a periodicity of between a few days for planets with very close orbits and a few years. Figure 3 illustrates these characteristics. Note that the transit is only detectable if the observer is practically in the orbital plane of the planet[12] which corresponds to probabilities between 10 % and 0.1% typically (1% for the Earth around the Sun). It is therefore necessary to observe a very large number of stars simultaneously for very long periods of time in order to have the chance to detect a transit on a star that will subsequently become the object of special surveillance. Space missions are particularly well suited to this type of research because they benefit from a very stable environment compared to ground based measurements where the atmosphere disturbs the measurement and, above all, because they allow quasi-continuous monitoring of star fields over long periods. This was the case with the COROT space mission. The CNES satellite, the first of its kind, has been able to monitor a dozen stellar fields and detect three dozen extrasolar planets over several years. Among these, its crowning achievement is the detection of COROT-7 b [12], the first planet to be confirmed as small (radius of 1.7 Earth radius), with a solid surface and a density almost equal to that of the Earth (Figure 4).

Launched a few years after COROT, NASA's KEPLER satellite had size and field-of-view characteristics that made it much more powerful, so it is still the instrument that has obtained the highest number of detections of exoplanets (2 662 up to 2019, when the mission ends). ESA's future PLATO mission[13] has the goal to detect and characterise Earth-like planets by transit and

[12] One shows that the probability for any observer to be in this situation for a planet orbiting a star of radius R* at a distance a from the star is p = R* / a

[13] ESA: European Space Agency

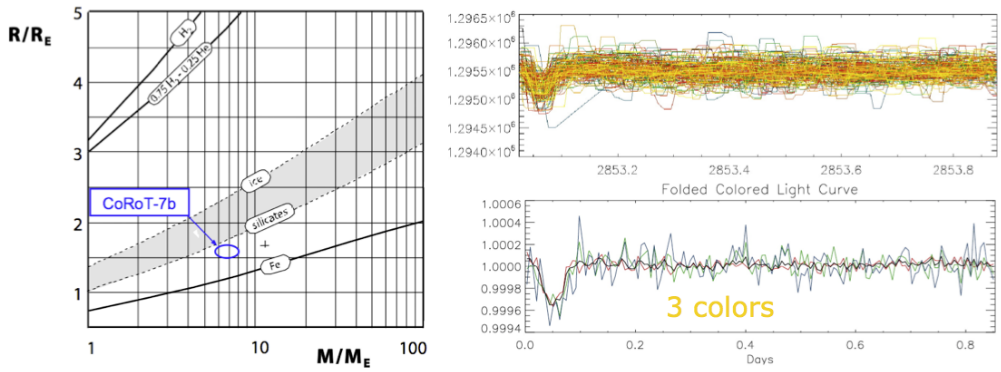

Figure 4. Right upper panel: stacked sequences of observations of the star COROT-7, revealing a small flux decrease of 0.035 days. Right lower panel: the sum of all sequences in three colours, revealing the same transit depth, which excludes for example the passage of a dark spot on the star's surface. Left: Position of COROT-7b in a Mass/Radius diagram that conducts to a density close to that of the Earth, probably indicating a composition dominated by silicates.

is scheduled for launch in 2026 [13]. Finally the ESA mission ARIEL [14] aims at performing a chemical census of a sample of transiting exoplanets[14]

6. Exploiting the coherence of light: direct detection

Although particularly difficult as stated in the introduction, the direct detection of exoplanets has nevertheless been possible in a few dozen cases: they correspond to the particular situation of young and hot planets, and involve specific techniques using the property of coherence of light. Only brief elements of the progresses done in this field are given here. We refer the reader to the exhaustive article in this issue by Galicher and Mazoyer [6].

In very young systems (a few million years after the formation of the star), the planets of the cortege are still in a phase of contraction which releases a very large amount of gravitational energy in the form of heat: the planetary surfaces can reach several thousand degrees and as a result their emission in the infrared range becomes very important, approaching this time a notable fraction (up to one ten thousandth to fix ideas) of the stellar emission which, as for itself, decreases with the wavelength. The contrasts, although still high, then become accessible to very specialised instruments. This is especially true when looking for the outermost planets in the system where the angular separation from the star becomes compatible with the angular size of the stellar spot at the telescope focus. Two important advances have made it possible to reduce the harmful effects of the star (photon noise, image spot width and/or diffraction pattern feet) very significantly: firstly, the development of adaptive optics and secondly of devices known as coronagraphs[15], which are capable of extinguishing the star very effectively while preserving its immediate environment. In the first case, the effects of atmospheric turbulence, which has distorted the light wavefront, are corrected in real time by acting a thousand times a second on a deformable mirror which "debump" the wavefront and restores it to practically the same state as

[14]This is done by spectroscopically analysing their atmospheres at the time of transit when light from the star travelling in observer's direction crosses the planetary atmosphere.

[15]The word coronograph comes from the Latin corona, the crown. It was proposed by the astronomer B. Lyot, who built such a device to observe for the first time the solar corona, outside an eclipse.

when it approached the Earth. The coherence of the light is then restored and can be exploited. The measurement of the wavefront deformations is carried out by a wavefront analyser that uses part of the star's light and distributes it over a matrix of micro-lenses, each of which produces an image giving information on the local slope of the wavefront. Developed in the early 1990s, particularly in France, this technique now achieves remarkable performance in the near infrared and reproduces the telescope's diffraction spot, which is all the finer the larger the telescope, as mentioned in the introduction. The second advance in coronagraphs has been the subject of intense, very dynamic research, which has led to numerous concepts, most of which use the coherence property that the light wave has re-appropriated thanks to adaptive optics. One such coronagraph is the four-quadrant phase coronagraph shown in Fig. 5. As its name suggests, it consists of a transparent plate cut into four quadrants, two of which are offset in thickness by a small amount, the half-wavelength of observation: if the star image is formed exactly at the centre of the device, then each quadrant will allow 1/4 of the wave amplitude to pass through, but with a delay for two of them that will ultimately produce a destructive interference of the star light. A planet whose image is located laterally does not suffer from this effect and its light is transmitted in full. Three of these devices have been installed on the MIRI infrared camera, one of the four instruments of the James Webb Space Telescope, which was launched at the end of 2021 and which has among its objectives, the detection and characterisation of extra-solar planets. A few specialised instruments equipped with different types of coronagraphs have been designed for very large telescopes of 8-10m in diameter and thus attempt, thanks to the conjunction of adaptive optics and coronography, to directly detect young and hot exoplanets. The SPHERE instrument is one of them: installed on one of the 8m telescopes of the VLT, it was developed by a European consortium. It is recognised as the most efficient of them. The direct detection of exoplanets is a success, as images of about 75 such objects and a large number of proto-planetary disks, such as the one shown in Fig. 5, have now been obtained.

It should be noted that another technique still in a pioneering phase and which also exploits the coherence property of light is multi-telescope interferometry, as detailed in this issue by [15]. In particular, this is the case of the VLTI[16] in Chile, which corresponds to the coherent recombination of the four 8m diameter telescopes of the VLT, giving it in principle an angular resolution power equal to λ / B where B is the distance separating the most distant telescopes (180 m), i.e. = $0.003''$! The VLTI's GRAVITY instrument, which uses this advanced technique, has thus been able to confirm, spectroscopically characterize and accurately follow astrometrically on their orbits a hand of planets, already known by Doppler velocimetry [16], [17]. The spectrum obtained is by far the most resolving, spectrally speaking, thanks to the precise localisation and delimitation allowed by interferometry.

7. Exploiting the direction of arrival: astrometry

Again, in this indirect technique, it is the reflex motion invoked for Doppler velocimetry that is at stake. This time the question is of measuring the apparent motion of the star on the sky, as it progresses along the small orbit around the centre of gravity of the star / planet system. It should be noted that the angular amplitude of this movement is extremely small: to give an idea of the magnitude, let us say that the effect of an Earth around a star like the Sun, located 30 light-years away, corresponds to 0.3 micro arcseconds, i.e. one ten-millionth of the diameter of the image spot of a star at the focus of a telescope at a standard site. This is still out of reach for the moment, but the effect of a Jupiter around the same Sun reaches 500 micro arcseconds, which, while still tiny, is now accessible to a dedicated instrument. Such an instrument does exist

[16]Very Large Telescope Interferometer.

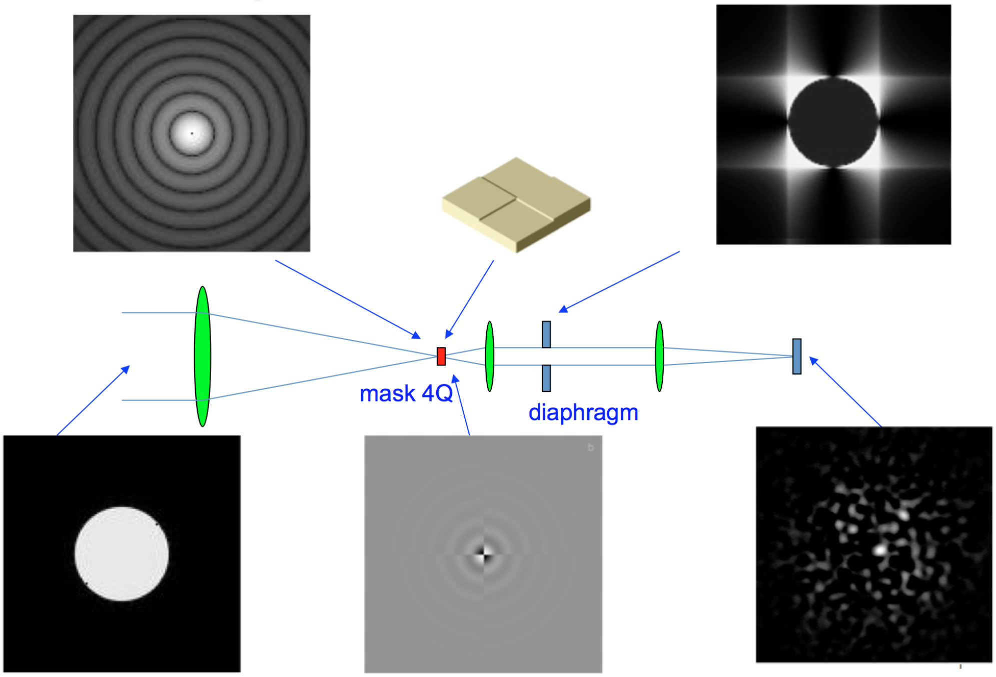

Figure 5. Principle of the four-quadrant phase mask coronagraph. The different panels, from left to right, show respectively the telescope pupil, the amplitude of the diffraction spot at the focus of the telescope, the phase mask, the amplitude after the phase mask, the image of the pupil where all the light is rejected outside and finally a final image of the focal plane where only residual light from the star remains, while a planet can be discerned.

and has been observing more than a billion stars since December 2013. It is GAIA, the global astrometry satellite built and operated by Europe, which, placed around the Lagrange point L2, is in the process of defining the most accurate absolute reference point ever built, as described in details in [18], in this issue. To do this, it is measuring very precisely the angle between two stars aimed in two very different directions (106.5°) by a pair of telescopes and this on tens of billions of indefinite pairs of stars. It is with respect to this absolute reference frame that the scalloped[17] trajectory of a star is observed, as illustrated in Fig. 7. If deviations from the regular motion are observed, then from these deviations one can deduce the displacement between the centre of gravity of the planetary system and the position of the photo-centre of the star and thus derive the masses and orbital radii of the planets in the system. Of course, there is a strong bias towards the most massive planets and those furthest from their star, as they dominate the position of the centre of gravity. At this time, the GAIA consortium has not yet announced any detections using this method, as it has been decided to wait until the end of the mission to exploit the full 100 terabyte data set for this particular scientific purpose, but projections based on actual

[17] The festoon is due to the motion of the Earth around the Sun, which produces a regular variation in the apparent direction of the star, the so-called parallax, which is directly related to the distance of the star, while the straight path around which the festoon wraps corresponds to the star's proper velocity in the Galaxy.

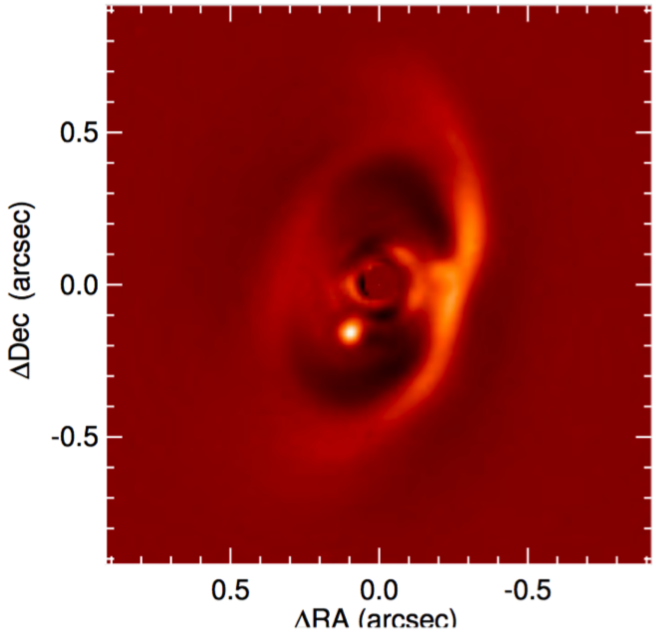

Figure 6. The proto-planetary disc around the star PDS-70, in which a planet has clearly formed a wide groove. Near-infrared image obtained with the SPHERE instrument at the VLT.

performance give a number of detections as impressive as 21 000, or more than four times the number of exoplanets currently detected by all methods[18].

8. Exploiting the constant speed of light: gravitational lensing amplification

Here we rely on an effect of Einstein's General Relativity which was used very early on to validate this theory experimentally[19]. For the detection of exoplanets, one has in fact benefited from programmes launched in the 1990s that aimed to identify whether the famous dark matter – that observations of star velocities in galaxies required – could be due to brown dwarf objects, i.e. compact, very faint objects that were grouped together under the acronym MACHO[20]. The method aimed at detecting an amplification of the brightness of a distant star when such a MACHO passed exactly on its line of sight. The mass of the MACHO behaves like a lens that concentrates the light rays coming from the distant star and passing in its vicinity towards the observer's telescope: this one measures then a significant increase in brightness over a period of a few weeks until a maximum is reached, followed by a symmetric decrease. Such events have been indeed detected but in insufficient numbers to attribute the dark mass component to this sought population of MACHOS. On the other hand, in a number of cases, one or more short-lived over-amplifications have been observed, consistent with the presence of massive planets

[18] It should be noted that GAIA is also capable of detecting planets by the transit method despite the non-continuous monitoring of the stars: 6500 additional planets should thus be added to GAIA's list of achievements.

[19] It was the British astronomer Arthur Eddington who, in 1919, only four years after Albert Einstein had set out the principles of GR, by observing an apparent displacement of the position of stars close to the Sun during a total eclipse, was able to confirm experimentally one of the essential predictions of this theory, the deviation of light passing close to a large mass.

[20] For Massive Astronomical Compact Halo Objects.

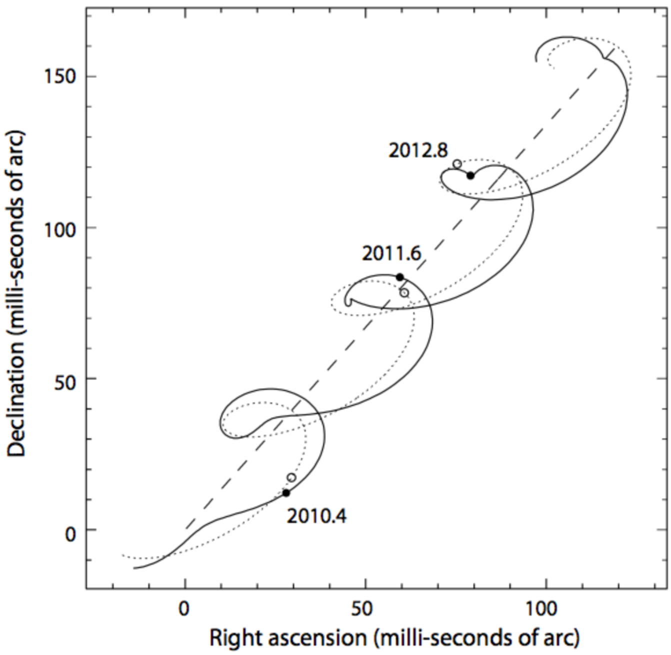

Figure 7. Apparent trajectory on the sky of a star whose position would have been measured with great accuracy by the astrometric mission GAIA. The solid line describes the actual trajectory, and the dotted line the expected trajectory if the apparent displacement were due to only two effects: the difference of the proper velocities of the star and the Sun in the Galaxy (dashed straight line) and the scalloped periodic variation due to the motion of the Earth in orbit around the Sun. We note a non- regular gap between the two curves, which reflects the expected effect of one or more planets, i.e. the gap between the centre of gravity of the star-planet system and the photo-centre of the star. Note that the latter effect has been greatly amplified on this curve for clarity. Taken from Perryman [19].

in orbit around the lens star. The paper by J.P. Beaulieu in this issue [20] describes in details this method. Tracing the mass and orbital distance of the planet(s) is an inverse problem that is not always easy to solve and can lead to very large uncertainties, but in many cases the derived parameters are quite reliable, as in the example given in Fig. 8, where two planets with masses of 0.3 and 0.7 Jupiter masses could be identified on orbits of a few astronomical units. This is one of the interesting characteristics of this method, which favours planets in a range of orbital radii between 1 and 10 astronomical units, which is otherwise poorly covered by the methods mentioned above, since the radial velocity method and the transit method are clearly biased towards tight orbits, which are easier to detect, whereas astrometry and direct detection are methods favoured by very wide planetary orbits.

9. Exploiting polarisation

The latter technique will be briefly discussed, as it has not yet yielded spectacular results, but the point is to be complete when illustrating how each property of light has given rise to thought and attempts to exploit it in the quest of detecting exoplanets. The starting point is to note that light from a star is essentially unpolarised, with no physical mechanism in the stellar photosphere that

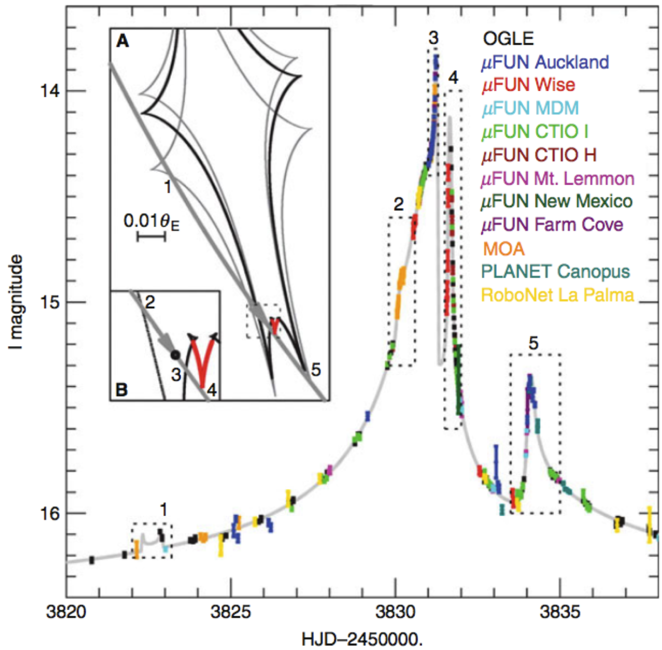

Figure 8. Example of the detection of two planets orbiting the star OGLE-2006- BLG-109L, which produced accidents on the light curve of a distant gravitationally amplified star. Without a planet, the curve would have been regular and symmetrical in a bell shape. The inserted diagram describes the secondary (caustic) amplification zones cut by the apparent trajectory of the distant star, derived as a result of long calculations. The estimated masses and orbital radii of the two planets are 0.73, 0.27 $M_{Jupiter}$ and 2.3, 4.5 Astronomical Unit, respectively.

can a priori orient the electric field vector. On the other hand, since the light from an exoplanet is the result of reflection or scattering of starlight by the planet's surface or atmosphere, polarisation becomes the rule, as illustrated in Fig. 9. One would then expect the degree of polarisation of purely planetary light to be between 5 and 50%. Of course, when mixed with the unpolarised light coming directly from the star, this quantity drops to a much lower fraction, directly proportional to the star/planet contrast.

Despite this handicap, it is this property of polarisation that a group from the University of Zürich [21] proposed to exploit by using a clever differential method to separate two orthogonal components of the electric field vector and detect the expected minute difference between them. The ZIMPOL[21] instrument developed for this purpose achieves this goal by rapidly modulating the polarisation state of the incident light[22], then analysing it with a conventional polariser and receiving it on a CCD whose charges are transferred synchronously with the modulation by going back and forth behind masked lines of pixels. The performances obtained is remarkable, already enabled to resolve the polarimetric signatures of circumstellar disks, and could in theory allow the detection of the reflected light of exoplanets orbiting around bright, nearby stars.

[21] Zurich Imaging Polarimeter.

[22] In practice, the components of the electric field are rotated alternately between 0° and 90°.

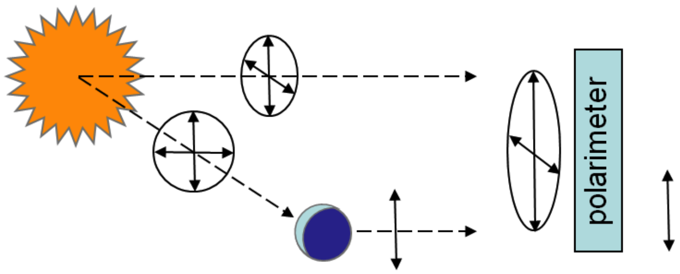

Figure 9. The light that reaches us from a star is essentially unpolarised, whereas the component reflected or scattered by the surface or atmosphere of an orbiting planet is partially polarised. This is illustrated by the set of vertical and/or horizontal arrows showing the electric field carried by the two types of components. When they arrive, mixed together, at the observer, he will use an analyser to measure the proportion of polarised light.

10. Conclusion

As rapidly depicted in this review, each of the various aspects of the physics of light have been examined as a possible entry in the ever more active search for exoplanets. As usual, the first step is imagination and we can be convinced by examining Fig. 1 that it is indeed fully the case. Of course, not all the methods imagined have yet proved to be fruitful, but they may become so when new technologies or access to space open the right window of opportunity. This will probably be the case with the soon coming European Extremely Large Telescope which, both in terms of angular resolution power and photon collection capacity, will allow a prodigious leap, a source of inspiration for instrumentalist physicists hunting planets.

The reader should have now some keys to go deeper in the state of the art of planet detection, characterization and understanding, as proposed in the various articles of this special issue. They are written by worldwide recognized specialists of the field and constitute an almost complete and reliable sum of the present knowledge in this field.

Conflicts of interest

The authors have no conflict of interest to declare.

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References

[1] M. Mayor, D. Queloz, "A Jupiter-mass companion to a solar-type star", *Nature* **378** (1995), no. 6555, p. 355-359.

[2] B. Giordano, *De l'infinito universo et Mondi (The Infinite, the Universe and the Worlds)*, 1584.

[3] B. Le Bovier de Fontenelle, *Entretiens sur la pluralité des mondes (Talks on the plurality of worlds)*, 1686.

[4] A. Crida, "Planetary formation and early phases", *C. R. Physique* **24** (2023), no. S2, p. 233-248.

[5] C. R. O'dell, Z. Wen, X. Hu, "Discovery of New Objects in the Orion Nebula on HST Images: Shocks, Compact Sources, and Protoplanetary Disks", *Astrophys. J.* **410** (1993), p. 696.

[6] R. Galicher, J. Mazoyer, "Imaging exoplanets with coronagraphic instruments", *C. R. Physique* **24** (2023), no. S2, p. 69-113.

[7] A. Boccaletti, "Observations of circumstellar disks in scattered light with SPHERE at the VLT", *C. R. Physique* **24** (2023), no. S2, p. 151-169.

[8] G. Chauvin, "Direct Imaging of Exoplanets: Results & Perspectives", *C. R. Physique* **24** (2023), no. S2, p. 129-150.

[9] M. Mayor, "Doppler cross-correlation spectroscopy as a path to the detection of Earth-like planets", *C. R. Physique* **24** (2023), no. S2, p. 27-36.

[10] C. Moutou, J.-F. Donati, F. Debras, "Exoplanet science with SPIRou: near-infrared precision velocimetry and spectropolarimetry", *C. R. Physique* **24** (2023), no. S2, p. 37-44.

[11] D. Charbonneau, T. M. Brown, D. W. Latham, M. Mayor, "Detection of Planetary Transits Across a Sun-like Star", *Astrophys. J.* **529** (2000), no. 1, p. L45-L48.

[12] A. Léger, D. Rouan, J. Schneider *et al.*, "Transiting exoplanets from the CoRoT space mission. VIII. CoRoT-7b: the first super-Earth with measured radius", *Astron. Astrophys.* **506** (2009), no. 1, p. 287-302.

[13] H. Rauer, C. Aerts, M. Deleuil *et al.*, "The PLATO Mission", in *European Planetary Science Congress*, EPSC Abstracts, vol. 16, 2022.

[14] G. Tinetti, P. Drossart, P. Eccleston *et al.*, "A chemical survey of exoplanets with ARIEL", *Experimental Astronomy* **46** (2018), no. 1, p. 135-209.

[15] S. Lacour, "Astrometry of directly imaged exoplanets with optical interferometry", *C. R. Physique* **24** (2023), no. S2, p. 115-128.

[16] M. Nowak, S. Lacour, A.-M. Lagrange *et al.*, "Direct confirmation of the radial-velocity planet β Pictoris c", *Astron. Astrophys.* **642** (2020), article no. L2.

[17] S. Lacour, J. J. Wang, L. Rodet *et al.*, "The mass of β Pictoris c from β Pictoris b orbital motion", *Astron. Astrophys.* **654** (2021), article no. L2.

[18] A. Sozzetti, "Gaia astrometry and exoplanetary science: DR2, (E)DR3, and Beyond", *C. R. Physique* **24** (2023), no. S2, p. 45-56.

[19] M. Perryman, "The History of Astrometry", *Eur. Phys. J. H* **37** (2012), p. 745—792.

[20] J.-P. Beaulieu, "Hunting for Cold Exoplanets via Microlensing", *C. R. Physique* **24** (2023), no. S2, p. 57-68.

[21] H. M. Schmid, A. Bazzon, R. Roelfsema *et al.*, "SPHERE/ZIMPOL high resolution polarimetric imager. I. System overview, PSF parameters, coronagraphy, and polarimetry", *Astron. Astrophys.* **619** (2018), article no. A9.