From exoplanets to exocomets

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Abstract. To date (June 2017), more than 3610 planets orbiting other stars than our Sun are known. We shall briefly review the main detection methods, together with some of the big surprises which arose since the discovery of the first exoplanet around a solar type star in 1995. It is now also possible to characterize the atmospheres of few extrasolar planets and exocomets become detectable.

1. Introduction

In November 1995, an article published in Nature \cite{1} puts planetary sciences not only as a new hot field in both observational and theoretical astrophysics but also as a topic with a large impact toward the layman. This article was reporting the first discovery of a planet orbiting a star beyond our Sun, namely the solar-type star 51 Pegasi. Nearly four centuries since Giordano Bruno was publicly burnt in Rome partly for having intuitively claimed the plurality of worlds, we are entering the extraordinary epoch in which one of the oldest inquiries of mankind – are we alone in the Universe? – can be tackled with the scientific method, leaving aside centuries of endless speculations.

2. Direct detection

The recording of a picture of an extrasolar planet is of course a major goal, but very difficult to achieve for two main reasons.

First, the angular separation between a planet and its parent star, as seen from the Earth, is very tiny. For instance, Sun-Jupiter at 4 light-years corresponds to 4 arcsec (or 1/900\(^\circ\)), and at 100 light-years, to 0.15\(^\prime\); Sun-Earth at 100 light-years is only 0.03\(^\prime\), well beyond the present ground-based standard instrumental capabilities which are limited by the seeing conditions. However, the largest telescopes in the best sites which are equipped with the sophisticated adaptive optics technique aiming at correcting for the atmospheric turbulence, are now able to provide better angular resolution; for instance, the ESO Sphere instrument at the VLT with extreme adaptive optics \cite{2} can reach the diffraction limit in the near infrared (20 mas in the R band); the VLT Interferometer is intended to do much better. In space, the European Space Agency (ESA) GAIA mission will reach an end-of-mission standard error around 15\(\mu\)as for stars brighter than \(\sim 13\) mag \cite{3}.

Second, there is a huge contrast between the planet and the star, the latter can be up to 10 billion times brighter than the former. To image an Earth around a Sun at 10 pc (1 pc = 3.26 light-years)
would be equivalent to image from Paris a glow-worm located at 30 cm from a lighthouse in Marseille (about 800 km away)! This is still impossible with the present day ground-based optical instrumentation. However, in the near infrared the contrast can be reduced to about 10 million, and it is feasible to register the thermal emission of sub-stellar objects (not yet Earth-like planets) around stars, thanks again to adaptive optics. As of June 2017, more than 80 exoplanets have been imaged in infrared light and some in the visible thanks to the Hubble Space Telescope (HST) (see for examples [4-8] and references in the catalog of extrasolar planets maintained at the URL: www.exoplanet.eu).

3. Indirect detection: dynamical effects
A solution to overcome the above difficulties is to apply the method used by Le Verrier for discovering Neptune, namely the gravitational perturbation induced by the planet. As a matter of fact, in a star-planet system, it is both the planet and its parent star that are orbiting the centre of mass of the system. For instance, the centre of mass of the system Sun-Jupiter is only at 0.005 AU from the centre of the Sun (just beyond the solar surface), and Jupiter is inducing a small orbital motion of the Sun of about 12 m.s\(^{-1}\) amplitude around this centre of mass, with a period of 11.9 years which is the orbital period of Jupiter at a velocity of 13 km.s\(^{-1}\). We describe the three different ways for detecting these dynamical effects.

3.1. Astrometry
An obvious way to detect the small stellar wobble around the centre of mass of the star-planet system is to monitor the star position on the plane of the sky. Some astronomers dedicated most of their professional life to that goal, but they never succeeded because the angular scale of the stellar motion is extremely small, even at short distances. For example, the solar motion as seen from 10 pc away is of the order of 100 μas, yet unreachable with the present day ground-based optical astrometric techniques, but now within reach of GAIA in operation since 2014, and with the VLTI. The detection of an Earth mass planet around a one solar mass star at 100 pc would require an astrometric accuracy better than 30 nas, still several hundred times below the final accuracy foreseen with GAIA.

Although the astrometric detection can be used with all types of stars and gives access to the exact mass of the planet, it is more sensitive to long periods (or large separations) and is inversely proportional to the distance of the star.

3.2. Timing
Another way is to make use of the enormous precision reachable when measuring time. Suppose a rapidly rotating star emitting a very well focused electromagnetic radio signal, like a lighthouse. The stellar motion induced by a putative planet around it can be detected by monitoring the arrival times of the signal when it passes in the wake of the Earth. Such a celestial extremely regular lighthouse is a pulsar, or neutron star. As of June 2017, 24 exoplanets have been detected around pulsars, including one planet not much more massive than the Moon. Also, only a few seconds accuracy on the time of the eclipses has been sufficient to identify a three Jupiter mass planet around an eclipsing binary star [9]. Six other planets have thus been detected.

Although the timing method allows the detection of very small masses and even satellites, and is insensitive to the distance of the system, it mainly applies to very peculiar stars – pulsars – which are million times less numerous than solar type or cooler stars. As a matter of fact, objects around pulsars were the very first to be discovered in 1992 [10], before 51 Pegasi in 1995, but pulsars are not standard "burning" stars on the Main Sequence like our Sun.

3.3. Velocimetry
Again to detect the small motion of the parent star around the center of mass, the third way makes use of spectroscopy. If one records the spectrum of the star when it is approaching the observer, the stellar lines are shifted towards shorter wavelengths because of the Doppler-Fizeau effect; on the contrary, when the star is receding from the observer, stellar lines are redshifted. Then, by reconstructing the
periodic stellar radial velocity curve as a function of time, it is possible to derive an upper limit to the mass of the planet: \( m \sin i \) with \( i \) the inclination angle of the orbital plane of the system with respect to the line of sight (for a system seen face-on from the Earth, there is no more Doppler-Fizeau effect, thus no possible detection). Furthermore, from the shape of the radial velocity curve it is possible to infer the eccentricity of the planetary orbit.

The challenge was to reach an accuracy better than 10 m.s\(^{-1}\) on radial velocity measurements in order to detect Jupiter-mass planets. This has been successfully performed in 1995 [1] by two Swiss astronomers – Michel Mayor and Didier Queloz – who were observing at the 1.93 m telescope of the CNRS Observatoire de Haute Provence (OHP) the star 51 Pegasi with the spectrograph Elodie. The semi-amplitude of the radial velocity curve was 59 m.s\(^{-1}\), which led to a 0.47 Jupiter mass planet. Besides being the first exoplanet detected around a solar type star, the huge surprise was the period of the planet: 4.2308 days, which corresponds to a semi-major axis of 0.052 AU, to be compared to the period of Jupiter 11.9 years. This was the first example of hot Jupiter.

Although the radial velocity method gives access to the planetary mass and other orbital parameters, it is limited to stars showing very many spectral lines in order to increase the measurement precision. Fortunately, this is the case of solar type and cooler stars, the most abundant ones in the Galaxy. As of June 2017, more than 710 extrasolar planets were discovered with this method. Of course, at the beginning the method was biased towards short period planets, i.e. hot Jupiters, but with time longer periods are found. The method is also biased towards more massive planets which induce larger velocity shifts, easier to detect. In order to detect an Earth around a Sun, an accuracy of the order of few cm.s\(^{-1}\) would be required, at the limit of the present instrumental capabilities. Furthermore, the method presents some limitations inherent to the star itself. For instance, photospheric activity related to spots at the stellar surface, chromospheric or seismic activity, can very well mimic radial velocity variations. Also, confusion cases can arise from stellar blends such as grazing binaries, small stellar companions or eclipsing binaries in a triple stellar system.

A specific spectroscopic signature in the radial velocity curve is interesting to note. If a planet is passing in front of its parent star (a transit, as seen from the Earth; see below), distortions of the stellar line profiles arise, due to the small fraction of the rotationally Doppler-shifted stellar disk occulted during the transit [11]. When this so-called Rossiter – McLaughlin effect is observed, it allows the determination of the angle between the orbital plane and the stellar equatorial plane – the obliquity – as well as the rotation velocity of the star.

### 4. Photometric detection

Stellar photometry provides two main ways for detecting extrasolar planets: one related to a relativistic effect, the other to a simple geometrical configuration.

#### 4.1. Gravitational microlensing

In 1936, Einstein computed [12] the gravitational lensing effect caused by the alignment of a background source star, an observer and a massive object in between, acting as a gravitational lens bending the light coming from the source star. The observer will perceive the source as a ring of light (the so-called Einstein ring, too small to be measured), if the three points (the source, the lens and the observer) are perfectly aligned; otherwise, he will register an amplification of the source light which can be very large depending on the impact parameter (the “degree” of the misalignment; amplification factors of 100 have been observed). Since the three points are moving, the observer will see an increasing amplification followed by a decreasing one, symmetrically with respect to a maximum and independently of the observed wavelength, perfectly well calculable if the source and the lens are assumed to be point-like.

If there is a planet orbiting the lens star, in specific geometrical configurations either caustic effects or an additional amplification superposed to the main one can be produced. The challenge is to follow precisely enough the main amplification due to the lens, which lasts weeks or months, in order to record the secondary planetary amplification, which lasts only hours or so. As of June 2017, 56 planets
have been detected through microlensing. One of them, 5.4 Earth masses with a period of 9.6 years, could have been the first ever detected cool rocky-icy exoplanet [13].

Without any photons from the lens system, the microlensing approach can identify terrestrial planets; however, any follow-up is impossible today. The probability to have an alignment of the three points is of the order of $10^{-6}$ or less. This is why light amplifications are searched for in surveys of millions of stars, in order to alert worldwide networks of photometric telescopes able to accurately register the expected planetary amplifications [14].

4.2. Occultation or transit

If the Earth is more or less in the plane of the orbit of an exoplanet around its parent star, it is possible to observe the passage of the planet in front of the star. Assuming random orientation of the orbit, the probability to observe such a planetary transit is close to the ratio of the stellar radius over the distance between the star and the planet. For instance, for a far-away observer the probability to observe a transit of Mercury in front of the Sun is about 1 % (planetary periods of the order of 100 days), while it drops down to 0.1 % for Jupiter (planetary periods of the order of 10 years). The tiny occultation of the stellar light during the transit (which can last few hours) depends of course upon the radii of the star and the planet. For example, the decrease of the solar flux during a Jupiter transit would be of the order of 1 %, which is quite easily detectable. The shape of the transit curve can be affected by the limb darkening effect which rounds both sides of the transit photometric profile.

The first confirmed planetary transit was due to the extrasolar planet HD209458 b [15], also nicknamed Osiris; it was recorded with a small aperture ground-based telescope in 1999 (~ 1.4 % absorption depth in the light curve), and subsequently very accurately studied with HST. The measured radius is 1.38 Jupiter radius (recall that detection of Earth size planets requires a photometric accuracy better than $10^{-4}$). This hot Jupiter has a period of 3.5247542 +/- 0.0000004 days, or a semi-major axis of 6.7 million km (Mercury is 8.6 times farther from the Sun). It was previously discovered by radial velocity searches [16] which derived a mass of 0.699 +/- 0.007 Jupiter mass. Combining mass and radius, one obtains an average density of 0.34 g.cm$^{-3}$. This was definitively proving that Osiris is indeed a gas giant.

As of June 2017, about 2720 transiting exoplanets are known. Although several ground-based transit surveys are on-going, this large number is in part due to the NASA KEPLER mission launched in March 2009, a little bit more than two years after the similar French CoRoT satellite; the original KEPLER mission and the CoRoT one are dead since ~2014; KEPLER is still operating (mission K2) but in a very degraded mode. Nearly 4750 candidate planets have been extracted from Kepler observations, but only less than half of them have been confirmed as exoplanets after deriving their masses from radial velocity measurements. It has to be noted that the KEPLER data archives are freely available on internet and usable in the framework of the so-called citizen science projects (see e.g. the URL: www.nasa.gov/kepler/education/citizen)

Besides the radius of the planet which is directly proportional to the transit depth, accurate light curve measurements can provide other parameters including period, inclination, limb darkening, and can reveal effects produced for instance by planetary phases, by gravitational modulation due to the stellar shape, by activity from stellar spots, by the presence of satellites, rings or companions (through shape and timing of transits).

5. Exoplanetary systems

As of June 2017, more than 3610 extrasolar planets are known, about 17 % being located in multiple systems (more than one planet around the same star, the record being 7 planets around the cool star Trappist-1 [17]). The complete interactive catalog of extrasolar planets is maintained at the URL: www.exoplanet.eu. The different methods for detecting exoplanets are up to now more or less limited to sufficiently bright stars in order to reach the needed accuracies, i.e. stars within roughly a thousand parsecs from the Sun, except microlensing which is only sensitive to more distant stars. If one extrapolates the present overall results to the whole Milky Way, one can conclude that billions of stars...
are hosting Jupiter-like planets; statistical studies even tend to indicate that most stars could have at least one planet, perhaps more frequently smaller planets (for more precise statistics, see e.g. [18,19]).

5.1. Some properties
The mass distribution of the detected exoplanets peaks around 1 Jupiter mass; however, this does not mean that lighter planets are less abundant; they are merely more difficult to detect. Nevertheless, it seems there is a lack of planets around 0.1 Jupiter mass (roughly 40 Earth masses).

The radius distribution also shows a desert of sub-Jupiter size exoplanets (roughly within 3–8 Earth radii) with orbital periods below ~3 days (i.e. hot planets), which could be the signature of an extreme mass loss leading to a complete evaporation leaving naked cores (see section 6 below).

As a matter of fact, there is an extreme diversity in the exoplanetary parameters that is not reflected in the Solar System. For instance, large eccentricities are known (up to 0.93), contrary to our System. The Extrasolar Planets Encyclopaedia (www.exoplanet.eu) allows to plot many different histograms or scatter plots.

5.2. Mass – radius relation
Knowing both planets sizes and masses, one has access to information on the interior structure of exoplanets, and ultimately on their formation process. One of the latest observational mass-radius plot for known transiting planets can be found in [20]. Theoretical curves can be built, assuming different composition from pure iron to 100% water planet through different % in silicates. Again, diversity wider than in the Solar System is noticeable: while some exoplanets follow the Earth composition, others are closer to ocean planets.

5.3. Secondary transit
For transiting planets, the light emitted by the exoplanets themselves can be identified during the secondary transit, i.e. while the planet is passing behind its star (as seen from the Earth), the opposite location of the primary eclipse. When the planet is hidden by the star, the observed flux comes from the star alone; when the planet is next to the star, the flux is coming from both the star and the planet; by subtraction, one then records photons from the planet itself. This has been done for few hot Jupiters in different infrared bands by the Spitzer Space Telescope. From this planetary thermal emission, one can derive the effective temperature of the planet and its albedo. Temperatures above 1000 K are deduced, even ~1150 K for Osiris [21,22]. Moreover, the phase-dependent modulation of the infrared brightness has also been observed [23].

6. Spectroscopic transits
A most valuable technique is transmission spectroscopy, i.e. identification of exoplanetary atmospheres as additional tiny absorptions during a transit, as supplementary spectral signatures over stellar spectra recorded during transits, i.e. when stellar light is going through the atmospheres. The planet will then appear larger when observed at a wavelength strongly absorbed by its atmosphere.

6.1. Osiris
The first detection of an extrasolar planet atmosphere was performed soon after the discovery of the transit of Osiris: using very high precision spectro-photometric HST data, an additional very weak absorption (0.023%) was detected within the neutral sodium doublet at 589 nm [24]. Still with HST but in the far-ultraviolet, the Osiris atmosphere has thus been also detected in other species: neutral hydrogen, oxygen and magnesium, singly ionized carbon and silicon III [25,26,27].

The first surprise came from the amount of additional absorption measured in the Lyman α H I line: 9.8 (+/- 1.8) %, which corresponds to a hydrogen cloud more extended than the Roche lobe of the planet. In this extended exosphere, H I is seen at radial velocities exceeding 100 km.s⁻¹. The presence of atoms beyond both the Roche lobe and the planetary escape velocity (54 km.s⁻¹), proves that hydrogen is escaping the planet. In order to produce such a large mass-loss signature, numerical
simulations show that a rate of the order of $10^{10}$ g.s$^{-1}$ is needed. This is in agreement with theoretical modelling of the upper atmosphere structure when taking into account tidal forces and heating by UV and extreme-UV radiations [28].

Another surprise was the detection of O I, C II and Si III, which are producing roughly 8-10% additional absorption. The mere presence of these heavier elements indicates that the atmosphere is not under the regime of Jeans escape, but is hydrodynamically escaping in a "blow-off" state [26]. Through the evaluation of the total density at the level of the Roche lobe ($\sim 10^6$ cm$^{-3}$), the escape rate can be independently estimated around $10^{10}$ g.s$^{-1}$, in agreement with the value derived from the H I observations.

Extensive observations with HST have revealed the presence of several layers of sodium [29] and the Rayleigh scattering by molecular hydrogen [30]. Sodium is less abundant at high altitude because of its ionization by stellar radiations or its condensation into molecules. This was the first time that variations in composition were detected in an exoplanet. Temperature and pressure profiles as a function of altitude have been derived [31]. At low altitude, temperature should be above $\sim$1700°C; then it seems to decrease below 500°C, allowing thus sodium condensation; in a higher stratospheric layer, temperature increases again. Analysis of neutral magnesium [32] has led to a 3D modelling of the Osiris’s extended, escaping atmosphere [33].

6.2. Evaporation of hot Jupiters

The evaporation phenomenon has been subsequently observed for three other exoplanets, sometimes with even larger mass-loss rate. For instance, the atmospheric absorption in H I reaches about 50% for the warm Neptune GJ436 b [34], which corresponds to $\sim$10% of the planet mass lost since its formation. Still in H I, the transit absorption depth was measured around 14% in 2011 for HD189733 b; but in this case, surprisingly no absorption was detected in 2010. By chance, a stellar flare has been observed in X-rays 8 hours before the studied transit of 2011, exactly the time needed for reaching the planet [35]. This supports the idea that the observed changes within the upper atmosphere of the planet can be caused by variations in the stellar wind properties, or by variations in the stellar energy input to the planetary escaping gas (or a mix of both effects). It is the first indication of interaction between the exoplanet's atmosphere and stellar variations, the start of exoplanetary space weather.

The atmospheric escape can modify the evolution of hot Jupiters. From the computation of an energy diagram (potential energy – related to the planetary mass – versus energy input from the star – related to the planet’s distance), it is possible to discuss life-time of exoplanets [36]. It turns out that even very hot Jupiters can be stable against evaporation if they are massive enough. However, Neptune-mass planets with period shorter than about three days (like GJ436 b) can be substantially affected by evaporation. Some of these must contain a large fraction of solid/liquid material; for instance, to survive evaporation GJ876 d must have a density larger than $\sim$ 3 g.cm$^{-3}$ (to be compared to the Earth density 5.5 g.cm$^{-3}$). In some cases, most of the planetary atmosphere could possibly disappear on a timescale shorter than the star’s life time, leaving a remaining rocky central core of several Earth masses, perhaps with a "boiling" lava surface similar to the one of Io in the Solar System. These putative remnants from evaporated hot Jupiters, might form a new class of planets, still to be confirmed.

Last, together with species reported above, few others have been detected such as K I, Si IV, and oxides like TiO, VO, MgSiO$_3$, Al$_2$O$_3$, either in the UV or the visible. Transmission spectroscopy in the near infrared with Spitzer has also given access to important atmospheric molecules, in particular methane, carbon oxide and dioxide, and water which is now robustly measured in a number of planets (see e.g. [37] and references therein). Again, a large diversity of atmospheres is revealed.

7. Exocomets

Beta Pictoris is a very bright, very young star in the southern hemisphere, which is known since 1984 to show a circumstellar dusty disk seen edge-on from the Earth. Soon after, the gaseous counterpart of the disk has been discovered through absorption lines in the star’s spectrum. Intensive observations in
the visible and the UV have revealed i) an absorption component stable in time at the radial velocity of the star, ii) many absorptions variable in time and velocities (although most of the time at velocities more or less larger than the stellar one), regardless of the ionization (large number of lines from neutral to highly ionized species like Al III and C IV). As early as 1987 [38], these behaviours were interpreted in terms of falling evaporating bodies – at that epoch, it was a “nonsense” to call them exocomets.

Through numerical simulations, this exocomets scenario succeeded to explain all the main characteristics of the variable gas, namely: narrow absorption lines at small velocities result from the vaporization of comets “falling”/transiting toward the star at large periastrons, while broad absorption lines at large velocities come from comets at small periastrons. It was regularly confirmed, for instance through the observation of the Mg II doublet proving that the absorbing gas clouds are optically thick but smaller than the star. The beta Pictoris disk is the prototype of “debris” disk around a young star (~ 22 Myrs), constantly replenished in both gas and dust through evaporation and collisions (see [39] and references therein).

From a statistical analysis of more than 1000 spectra of the Ca II doublet collected from 2003 to 2011, which provide a sample of about 6000 variable absorption signatures arising from about 500 exocomets transiting the disk of the parent star, two populations of exocomets have been identified [40]: i) one family producing shallow absorption lines, composed of old exhausted comets (that is, strongly depleted in volatiles) trapped in a mean motion resonance with a massive planet, ii) another family of young comets on a single orbit producing deep absorption lines, which is likely related to the recent fragmentation of one or a few parent bodies.

Recall that a massive Jupiter has already been imaged around beta Pictoris [41], with a period of about 36 years. Furthermore, a photometric variation of the star has been recorded during the night of November 10th, 1981 [42] – much before any exoplanet was discovered – which can be interpreted by the transit of a giant planet. In that case, the next transit of the Hill sphere of beta Pictoris b should occur in 2017 [43], thus providing an exciting, unprecedented opportunity for intensively observing an exoplanetary transit in front of a very bright star.

8. Concluding remarks

The extrasolar planets field of research is moving forward extremely rapidly, both observationally and theoretically. The number of exoplanets newly detected every year is steadily increasing together with both the instrumental accuracy improvements and the number of teams involved worldwide. The Extrasolar Planets Encyclopaedia is listing not less than 75 ground-based extrasolar planets global searches in the world and 24 space-based searches (both ongoing programmes and futures projects).

Four centuries after being burnt in Rome by the “fundamentalists” of that time, one can say Giordano Bruno was right. By accumulating studies of many extrasolar systems, it will be possible to better understand our own Solar System. However, the quest for an Earth-like exoplanet is another major motivation. Recently, a 1.3 Earth-mass planet has been detected by velocimetry around our closest star: alpha Centauri C b (Proxima b) [44]. It is not yet possible to decide its nature, between fully rocky or ocean planet, but its proximity makes some people dreaming…. More recently, seven transiting planets have been identified around the ultra-cool red dwarf Trappist 1, all with sizes similar or smaller than the Earth, and six of them having masses between 0.4 and 1.4 Earth mass [17]. All these seven planets show a synchronous rotation (always the same face toward the star), and three of them are located within the habitable zone of the star, the zone where water, if present, could be liquid at the planet's surface. Few tens of other exoplanets are in the habitable zone of their respective host stars, including Proxima b.

The ultimate goal will be to identify bio-signatures in those extrasolar planets. The signature of carbon dioxide is known to be present in the infrared spectra of the Earth, Mars and Venus; but only the spectrum of the Earth is also showing water and ozone/oxygen signatures. When we will be able to perform the spectrum of an exoplanet itself, if these three signatures appear, then astro-biologists say, nowadays, that it would be explainable only through photosynthetic processes, therefore life as we
know it on Earth. In order to prepare for this investigation, the Earth has been observed during a Moon eclipse, as if the Earth would be an extrasolar transiting planet. Oxygen, ozone and water vapour have been detected [45]. In principle, these species should be within reach of the European Extremely Large Telescope, presently under construction in Chile, for an Earth twin at 10 pc.

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