From Hot Jupiters to Hot Neptunes ... and Below

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Since the discovery of the first Hot Jupiter around 51 Pegasi in 1995, the field of exoplanet detection has been driven by the improvements in the precision of radial velocity measurements. Reaching accuracies lower than 10 m s\(^{-1}\) on Doppler measurements has allowed to explore the domain of gas giants like Jupiter and Saturn. Now, the domain of 1 m s\(^{-1}\) accuracy has been reached, opening the realm of Neptune-mass planets and lower. In parallel, the transit method has come of age, with six detections in the past two years. Transiting planets offer a direct view into planet structure and composition. Planetary size, density, and even the composition of their atmosphere can be measured during the transit. Several elements have already been detected in the transiting planet HD209458, which seems to be slowly evaporating. In the coming few years, the combination of space-based transit surveys and dedicated radial-velocity spectrograph will open the domain of terrestrial exoplanets.

§ 1. The quest for radial velocity precision

Since the first discovery of an extrasolar planet around a solar-type star ten years ago,\(^{1}\) the research in this field has been very productive and has led to the detection of more than 140 exoplanets. The vast majority of these discoveries have been made with the radial-velocity (RV) technique, i.e. the precise measurement of the RV wobble that a planet induces on its parent star due to its orbital movement.

The saga of the detection of exoplanets has been constantly driven by the ever-increasing accuracy of the radial velocity determination. Until the end of the eighties, the most accurate radial velocities were obtained with cross-correlation spectrographs like CORAVEL with a precision on individual measurements of about 300 m s\(^{-1}\). The nineties witnessed a quantum leap in the precision, down to the level of 10 m s\(^{-1}\), allowing the detection of 51 Peg in 1995 with velocity residuals of 12 m s\(^{-1}\). Since then, the accuracy of radial velocity measurements has increased by another order of magnitude. A few landmark planets are shown on Fig. 1 to illustrate this improvement from the time of the first low-mass brown dwarf candidate, HD114762b, through 51 Peg to HD16141 and \(\mu\) Ara c (Table I).

<table>
<thead>
<tr>
<th>Year of discovery</th>
<th>Name</th>
<th>(m_2\sin i) ([M_\odot])</th>
<th>(k) ([\text{m s}^{-1}])</th>
<th>(O - C) ([\text{m s}^{-1}])</th>
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<td>1989</td>
<td>HD 114762 b</td>
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<td>616.7</td>
<td>500</td>
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<td>150</td>
<td>57.3</td>
<td>13</td>
<td>ELODIE/OHP</td>
</tr>
<tr>
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<td>HD 16141 b</td>
<td>70</td>
<td>10.8</td>
<td>3.2</td>
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<tr>
<td>2002</td>
<td>HD 49674 b</td>
<td>38</td>
<td>14.0</td>
<td>5.6</td>
<td>HIRES/Keck</td>
</tr>
<tr>
<td>2004</td>
<td>55 Cnc c</td>
<td>14</td>
<td>6.7</td>
<td>5.4</td>
<td>HRS/HET</td>
</tr>
<tr>
<td>2004</td>
<td>(\mu) Ara c</td>
<td>14</td>
<td>4.1</td>
<td>0.9</td>
<td>HARPS/ESO-3.6</td>
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</table>
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Fig. 1. The minimum mass ($M \sin i$) of exoplanet plotted as a function of their date of discovery. A few landmark objects are labeled. (cf. Table I)

The passage from accuracies of hundreds of m s$^{-1}$ to tens of m s$^{-1}$ was mainly due to the advent of CCD cameras and to improved dedicated spectrographs.$^{2)-4}$ The crucial ingredient controlling the radial velocity accuracy is the stability of the wavelength calibration and the precision of the tracking of the variations in this calibration. There are two main ways to push the radial velocity uncertainties to the level of a few m s$^{-1}$. The first is to obtain a spectrum of a Thorium lamp at the same time as the star’s spectrum is measured. The Thorium emission lines provide a fixed wavelength reference.$^{3}$ The second is to interpose a cell containing iodine gas in the path of the star’s light before spectroscopic dispersion.$^{4}$ The absorption spectrum of iodine is superimposed on the star’s spectrum and provides the fixed wavelength reference.

Out of the 140 presently known exoplanets, about 70 were detected with the thorium technique.

1.1. Hot Jupiters

The vast majority of these exoplanets are gas giants like Jupiter and Saturn, many of them orbiting very close to their star. These two characteristics are a consequence of the limits of the detection technique — heavier and close planets producing a larger radial velocity wobble — and do not necessarily reflect the real distribution of planet characteristics. The statistical properties of giant planets
derived from the present sample have been studied in a series of papers to which we refer the reader for details.

The most outstanding statistical features are the presence of gas giants on very short orbits, down to orbital periods close to 1 day, the scarcity of very heavy planets (in the 2–10 Jupiter mass range), and the clear increase in the quantity of planets around stars with more heavy elements than the Sun.

1.2. Hot Neptunes

In 2001, a consortium led by Geneva Observatory started to build for ESO an instrument capable of achieving the 1 m s$^{-1}$ precision level. For that purpose, a thorough understanding of the instrumental factors limiting the RV precision was mandatory. It was recognized that atmospheric pressure and temperature variations are the main causes of instrumental drifts during an observing night. In numbers, a RV drift of 1 m s$^{-1}$ corresponds to a pressure change of only 0.01 mbar, or a temperature change of 0.01 K. Although these drifts can be accurately corrected with the simultaneous ThAr reference, minimizing these influences is necessary to further improve the RV accuracy. Therefore, the new instrument HARPS was put under vacuum in a strictly temperature-controlled environment. Another critical point was the stability of the spectrograph illumination. A fiber link to the spectrograph with high light-scrambling properties, coupled to a dedicated guiding software, was found to be the best solution to avoid spurious wavelength shifts due to changing illumination or varying instrumental profile. Further requirements to reach the desired precision included a large spectral coverage, high spectral resolution, high pixel sampling (3–3.5 pixels FWHM) and the possibility to obtain high S/N data for a large number of stars to maximize the Doppler information content of the spectra. All these constraints led to the construction of an echelle spectrograph spanning the whole visible range (3800–6900 Å) at a resolution $R = 115,000$, mounted on the ESO-3.6 m telescope at La Silla Observatory (Chile), operational since October 2003.

First results from HARPS included some asteroseismological time series demonstrating the unprecedented accuracy of this instrument (see Ref. 9)). Figure 2 shows the oscillations in radial velocity due to acoustic p-modes in 4 different stars, as observed with HARPS during the commissioning period. The amplitude of these modes depends on spectral type and evolution stage, early-G and evolved stars having the largest amplitudes (up to 10 m s$^{-1}$ peak-to-peak) whereas late-K dwarfs show only weak modulations (1–2 m s$^{-1}$). Periods also vary along the main sequence, ranging from $\sim$4 to $\sim$15 minutes between K and early-G stars. These RV measurements have an accuracy better than 40 cm s$^{-1}$ (including photon noise and guiding errors), demonstrating the extraordinary capabilities of HARPS. Long-term stability is found to be at the level of 1 m s$^{-1}$ or better (see Ref. 10) for a detailed analysis).

Up to last year, the accuracy of the radial velocity searches limited the planet detection to gas giants like Jupiter and Saturn. More than one hundred planets had been discovered, but all were gas giants of much larger mass than the Earth, and even than the so-called “Ice giants” in our Solar System, Uranus (15 Earth masses) and Neptune (17 Earth masses).
Then in the summer of 2004, three planets were detected in quick succession, with masses comparable to that of Neptune.

A 14 earth-masses extrasolar planet was detected around $\mu$ Ara (HD 160691).\textsuperscript{11)\textsuperscript{11)} The faint signal of this planet was first detected during an asteroseismological run on this star. Apart from the expected, short-period ($\sim$8 min, see Ref. 12)) p-mode oscillations, another modulation was clearly present, with a period at least as long as the span of the asteroseismological data (see Fig. 3). Follow-up observations confirmed the presence of a periodic signal with period $P = 9.5$ days and RV amplitude $k = 4.1$ m s$^{-1}$, which is best explained by the Keplerian movement of an exoplanet with a minimum mass of $14 M_\oplus$ (see Fig. 4). $\mu$ Ara was already known to host one giant planet and another substellar companion,\textsuperscript{13)\textsuperscript{13)} making this star extremely interesting for planet formation theories and dynamical studies. Further high-precision observations are needed to better constrain the orbital parameters of this system.

The detection of $\mu$ Ara c was made simultaneously with two other important discoveries, the very low-mass planets 55 Cnc e\textsuperscript{14)\textsuperscript{14)} and Gl 436 b.\textsuperscript{15)\textsuperscript{15)} All three objects have probable masses between 14 and $\sim$25 $M_\oplus$, making them the first members of a new class of exoplanets, the Hot Neptunes. The question about their composition and internal structure is still open. In the core accretion model of planet formation, these objects might actually have started their formation within the ice boundary,
Fig. 3. RV time series of $\mu$ Ara obtained during an asteroseismological run (8 nights). The p-modes oscillations are responsible for the high-frequency RV variations, but cannot explain the night-to-night RV changes.

Fig. 4. Phased radial velocities for $\mu$ Ara after removing the long-term trends due to the giant planets in the system. The remaining signal has a period $P = 9.5$ days and a semi-amplitude $k = 4.1$ m s$^{-1}$, corresponding to a minimum mass of only $14 M_\oplus$ for the hot Neptune.

accreting mainly solid materials and becoming “super-Earths”. Alternatively, these planets might have formed further away in the disk, starting with a solid core and then going through the gas accretion phase. Migration would have simultaneously brought them closer to the star before they become too massive. The gaseous envelope could then have been evaporated by the strong stellar radiations, provided the
semi-major axis became sufficiently small.

From the observational point of view, the detection of such objects turns out to be challenging, but not impossible. It requires a large number of measurements and some care in dealing with the stellar oscillations. Asteroseismological “noise” can be greatly reduced by integrating long enough to cover one or more typical oscillation periods. Furthermore, evolved and early-type stars should be avoided as they exhibit large-amplitude, long-period oscillations which are more difficult to average out. With the accumulation of high-precision observations in the coming months and years, we should be able to tell whether hot Neptunes are very common or rather rare, bringing important new constraints on planet formation theories.

1.3. Detecting planets down to a few Earth masses

As the spectrograph dedicated to radial velocity planet searches keep improving, and the telescopes keep getting bigger, the accuracy of the wavelength calibration is on its way to getting past the 1 m s$^{-1}$ level. Accuracies of a few centimeters per second are conceivable with a HARPS-like instrument installed on the VLT, for instance.

However, at this level of accuracy, other difficulties arise. The photosphere of a Solar-type star is a turbulent, boiling surface in constant motion and with constant local temperature variations. These effects induce changes in the measured mean radial velocity to the level of a few m s$^{-1}$, variations on all time scales, from a few minutes for intrinsic vibration modes to several days for rotation starspots.

Therefore, to push the accuracy below the m s$^{-1}$ and obtain the precision necessary to detect planets Earth-like planet will require not only further improvement in the stability of the wavelength calibration, but also careful subtraction of the intrinsic variations due to the star. An example of the possible methods to deal with the stellar noise was given above in the context of the discovery of $\mu$ Arae.

1.4. What do the Neptunes tell us?

Moving from the domain of hot Jupiters towards that of Neptune-mass planets will address three questions:

- Are the current models of formation and evolution of planets correct?
- What is the density and composition of Neptune-mass planets?
- What is the mass dependence of the abundance of planets?

The distribution of the masses of planets discovered up to now is observed to be steeply increasing down to the detection limit. There appears to be more light planets than massive planets, down to masses comparable to Saturn (see Fig. 6). However, there is no particular reason to assume that this mass function keeps increasing indefinitely. The capability of detection Neptune-mass planet will tell us whether most planets orbiting close to normal stars are large gas giants, or whether smaller planets are even more abundant.

Theoretical models of planet formation can be used to predict the planet distribution in the mass-period diagram. We consider here in particular the models recently proposed in Ref. 16). Figure 5, taken from their paper, shows the expected distribution of planets as a function of orbital period and mass. Interestingly, the newly discovered planets fall in a region of these diagrams that seems difficult to pop-
ulate by models. The reason is to be found in the fast and efficient core accretion and migration processes. Indeed, after the formation of a solid core of about $10 \, M_\oplus$, the runaway gas accretion phase should lead very rapidly to the formation of a gas giant with a mass above $\sim 0.5 \, M_{\text{Jup}}$. On the other hand, interactions with the disk will make the planet migrate inwards to distances below $0.05$–$0.1$ AU, and thereby become a hot Jupiter. As a result, there will be a planet desert in the mass-period diagram, as explained in Ref. 16).

The discovery of planets in this desert and the obtention of statistically meaningful numbers on planet occurrence in this region will therefore represent a very important test for planet formation theories, especially for the standard core-accretion and migration scenarios. The increasing sensitivity of radial-velocity surveys will bring strong constraints on that issue in the near future.

Some of the Neptune-mass planets will be transiting (see §2). The measurement of the transit will allow a measurement of their radius and their density. Theoretical

Fig. 5. Mass-period diagrams taken from Ref. 16), showing the prediction of a “desert” at intermediate distances for masses between $0.05$ and $0.5 \, M_{\text{Jup}}$. The bottom left panel shows the actual detections. Five planets recently detected with HARPS do fall in this area of the diagram, raising questions about their formation history.
considerations indicate that Neptune-mass planets could have almost any imaginable composition, from Hydrogen-Helium gas, to ice, to rock, or even to carbon rich rock ("diamond planets",\(^{17}\)). Only measurements of their density will tell us which of these is realised more often in reality.

1.5. Super-Earths

Detecting planets even lighter than Neptune would be feasible in principle in the near future, but it will be very difficult with the present strategy of radial velocity surveys. After all, most stars do not have close-in planets, so that exoplanet detection requires the monitoring of a large sample of targets. But planets of a few times the mass of the Earth produce wobbles of the order of a few m s\(^{-1}\), which require a large number of measurements to be detected. The amount of telescope time available is simply not sufficient to search for Earth-mass planets in this way.

There is, however, another detection method, the transit method, that will be the subject of the next section and has only recently come into its own. Future satellite missions like Kepler could be able to detect transiting candidates down to the size of the Earth. Since the target is given by the transit search, and the period and phase of the radial velocity orbit can be known from the transit signal, measuring the radial velocity orbit becomes much easier. Planets with masses only a few times
that of the Earth will be detectable in this way (see §2.5 and Fig. 10).

§2. Transiting exoplanets

2.1. Detecting planets by transits

If a planetary orbit happens to be seen perfectly edge-on from Earth, the planet *transits* in front of its host star every orbit. The light of the host star undergoes a dimming proportional to the surface of the transiting planet. This offers a very straightforward means of detecting exoplanets and measuring their size. Further radial velocity monitoring can then reveal the other orbital parameters and the planet mass. Detecting transiting exoplanets is therefore not only useful to increase the collection of known planets. It is the easiest way to measure the exact size, mass and density of exoplanets.

The probability of transit decreases with increasing size of the orbit. For planets like the Solar System giants, the probability of exact alignment of the orbit is less than 1/1000. For this reason, transit searches were initially thought impractical for planet searches. The discovery of 51 Pegasi, with its 4-day period, changed this. “Hot Jupiters” like 51 Peg are so close to their parent stars that the transit probability is about 10%. They are also relatively abundant (about 1% of solar-type stars harbours a hot Jupiter). Therefore, monitoring a few thousand stars in photometry — a routine undertaking with the advent of large CCD cameras — should be sufficient to detect several transiting exoplanets.

In 1999, the Hubble Space Telescope monitored several thousand stars in the globular cluster 47 Tuc for eight days on end with exactly this purpose. To everybody’s surprise, no planets were found, a result that is now attributed to the paucity of planets around metal-poor stars.

The hot Jupiters discovered by radial velocity were also closely monitored in photometry, hoping that sooner or later one of them would have the correct inclination to transit its host star.

The first confirmed planetary transit is the transit of the extrasolar planet HD 209458b in front of its parent star. This so-called “hot Jupiter” planet has been discovered by radial velocity searches. It has a mass of 0.699±0.007 Jupiter masses and a period of about 3.52 days. The discovery of the transit (~1.6% absorption in the visible) was a strong confirmation that the planets detected by radial velocity were indeed planets. This transit gave the first estimate of the radius of an extrasolar planet (~1.42±0.10*R_Jup) confirming it to be a gas giant. *A posteriori*, rediscovery of this planet photometric transits was found in the Hipparcos data collected from the beginning of 1990 to the end of 1993. Together with more recent measurements, this allows to obtain a very accurate estimate of the period which is now known to be \( P = 3.5247542 ± 0.0000004 \), that is with an uncertainty of less than 4 seconds per year.

The discovery of HD209458b, apart from firmly establishing the reality of extrasolar planets, led to a flurry of interesting results (see §3). It also motivated many groups to pursue ground-based searches for planetary transits, now numbering more
than two dozen.*

Fig. 7. The evolution of the HD 209458 visible light curve during transits as observed with the STIS instrument on board HST.\textsuperscript{28} The excellent photometric accuracy of few $10^{-4}$ reveals not only the depth of the absorption ($\sim 1.6\%$) but also from the shape at the bottom of the profile, the limb darkening expected to be present over that solar-like stellar disk.

Fig. 8. Light curve of the transiting planet OGLE-TR-132. Top: lightcurve subsequently obtained at ESO with the VLT.\textsuperscript{29} Bottom: detection light curve by the OGLE collaboration.\textsuperscript{30}

\* See http://cfa-www.harvard.edu/planets/searches.html for a complete list.
2.2. *Ground-based transit surveys*

These transit searches have met unexpected difficulties. Initial projections, based on idealized assumptions, predicted many dozens and even hundreds of detections in the first years. In reality, only two of the surveys have produced any detection at all up to now. Atmospheric conditions and the technical difficulties associated with surveying a large area of the sky on a single camera, have marred most survey to the level of being unable to reach the necessary photometric accuracy of a few thousandths of magnitude.

The main exception is the OGLE survey. Building on their long experience in the search for gravitational micro-lensing,\(^{31}\) which requires stable monitoring of millions of sources, the OGLE team started in 2001 a survey for planetary transits in the Galactic disc.\(^{32}\) Contrarily to most other ground-based surveys, they used a rather large telescope (1.3 m) and focused on smaller fields down to fainter magnitudes. This proved to be a good strategy, because the large number of sources in the field allowed more precise differential photometry, and the large field magnification allowed a better sampling of each source on the camera.

Six transiting planets have now been discovered by photometric transit surveys, five of them by the OGLE survey (see references in Table II). The sixth one was found by a combination of three small coordinated telescopes on both sides of the Atlantic.

Another difficulty in the detection of transiting exoplanet turned out to be more severe than initially anticipated: the contamination by eclipsing binaries. Several configurations of eclipsing binaries can mimic a planetary transit signal. In particular, small M main-sequence stars with \(M \sim 0.1 \, M_\odot\) can also reach sizes as small as Jupiter, and produce transit signals indistinguishable from planets. Recently, a transiting M-dwarf was discovered among the OGLE survey candidates, OGLE-TR-122,\(^{33}\) that was actually smaller than some exoplanets. Only a radial velocity monitoring can tell the difference by revealing the amplitude of the orbital motion, and therefore the mass of the transiting companion.

2.3. *Radial velocity follow-up*

Radial velocity follow-up of photometric transit surveys is essential to measure the masses of the detected planets. Spectroscopic measurements are necessary in a more fundamental way for the confirmation of the planetary nature of the transiting body, because the vast majority of exoplanet transit candidates in existing surveys turn out to be eclipsing binaries. Finding planets by transits is therefore not only a large undertaking in stellar photometry, but also in spectroscopic follow-up.

For instance, the radial velocity follow-up of OGLE transiting candidates has required an important effort with the largest telescopes in the world. It has lead to the characterisation of many eclipsing binaries, in a very varied array of configuration. A few of the corresponding orbits, from Ref. 34), are shown in Fig. 9. The confusion cases include grazing equal-mass binaries, transits by small M stars, eclipsing binaries in a triple system and even a quadruple system of two close binaries!
2.4. The known transiting planets

The characteristics of these six objects are given in Table II. They are all gas giants of mass and size comparable to Jupiter. This is expected because smaller planets cause transits too shallow to be detected at present, and heavier planets are not found on tight orbits. These objects offer many interesting indications on the physics of hot Jupiters and, also, a number of surprises.

The foremost of these surprises is that three of the transiting gas giants have extremely short periods, shorter than 2 days (the so-called “very hot Jupiters”). This is in apparent contradiction with the fact that among the two dozen hot Jupiters
Fig. 10. **Mass-radius relation from stars to planets.** The position of the seven known transiting exoplanets is shown, as well as the giants planets of the Solar System. In the stellar domains, the data comes from interferometric measurements and from eclipsing binaries, many from the OGLE planetary transit survey. The lines show the stellar evolution models of Refs. 35) and 36). **Insert:** simulated data and radial velocity curve for the confirmation of an imaginary transiting “hot super-Earth” detected by the Kepler mission.

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Table II. Characteristics of known transiting exoplanets.

Known from radial velocity, none has a period shorter than 2.5 days. On closer inspection, it turns out that very short periods are strongly favoured by detection biases in the OGLE transit survey. When this is taken into account, the two results are found to be marginally compatible with each other if about 10% of hot Jupiters have periods shorter than two days.

Another surprise is visible in the mass-period diagram (Fig. 11) for the transiting planets: “very hot Jupiters” are about twice heavier than the “usual” hot Jupiters with periods in the 3–4 day range. It even seems that the planets show a unique relation between mass and period. Since these planets are thought to have migrated inwards from much wider orbits, this mass-period discrimination is surely related to...
the processes that determines where the migration stops. How are they related? At present there is no convincing scenario. The basic mechanism stopping migration has itself not yet been clearly identified. It could be related to the magnetic cavity that young stars excise around themselves, or to the tidal interactions of the star with the migrating planet.

The central result from transiting planets is the determination of the size and density of exoplanets. This is crucial to understanding their internal structure and composition. Figure 12 shows the mass-radius plot for the known transiting planets. For three years, HD209458b was the only available data in this plot, and it seemed to indicate that hot Jupiters could be much larger than Jupiter, and therefore much less dense. The low density of HD209458b, about a third of Jupiter, was difficult for models to explain. It was assumed to be related in some way to the proximity of the planet to its host star. The transit surveys showed that most hot Jupiters actually have sizes nearer to Jupiter itself, and therefore that their structure is less perturbed by the proximity to the star. This may seem surprising for “very hot Jupiters”, because they are even nearer to the star. But it makes sense if one recalls that they are also heavier, so that tidal and evaporation effects can actually be lower for them than for normal hot Jupiters.\footnote{50}

2.5. Ground based surveys: The near future

We can expect the resounding success of the OGLE survey in 2004 to lead to an increased rate of detection from transit surveys in the near future. The OGLE survey itself is going on with new fields in the Galactic disc. Other surveys are drawing the lessons of their difficulties and re-defining their strategies. Transit search telescopes team up in networks such as TrES (3 telescopes in the USA and
the Canary Islands) and HATnet to provide more continuous coverage of the same fields (for a list of transit surveys and their characteristics see http://star-www.st-and.ac.uk/~kdh1/transits/table.html). New instrumental tricks are being developed to reach millimagnitude accuracy on wide fields in realistic conditions (e.g. Ref. 51)). Plans are made to use Antarctica as an observing base for season-long continuous monitoring.

2.6. Space missions: CoRoT and Kepler

Soon, however, the focus will shift to space missions, with the launch of several space missions dedicated to the search for extrasolar planets by transits, in particular the CoRoT mission, planned for 2006, and the Kepler mission, in 2007.

CoRoT is a French-European mission that will monitor, during 2 1/2 years, a set of about 60,000 stars in the Galactic disc in search for planetary transits. Its sensitivity will be sufficient to detect planets of about double the radius of the Earth. Because of the relatively modest size of its main mirror, CoRoT will only detect such “super-Earths” around its brightest targets, if they are relatively close to their star ($P < 10$ days). The recent detection of three very light planets in tight orbits (see §1.2) seems to indicate that such planets could be abundant enough. A transit would establish their size, density, and therefore composition. Contrarily to hot Jupiters, for which a H-He gas giant nature was practically certain from the start, the precise nature of planets like $\mu$ Ara c is highly uncertain. They could be dense telluric planets, rock-ice planets, or the remnant of evaporated giants. Figure 10 shows the domain of the planetary mass-radius plane that CoRoT is going to explore, the domains of “hot neptunes” and “super-earths”. CoRoT will measure several hot Jupiter transits very precisely, will fish up intermediate size close-in planets — if
they exist — and may get a few transiting super-Earths. Luckily, recent progress in very high-precision Doppler spectroscopy has brought the detectability of the radial velocity orbit on par with the transit sensitivity of CoRoT, so that mass determinations should be available for most transiting planets that it will detect.

The Kepler mission is expected to go much further. It will monitor more than 100,000 stars during at least four years, and with a higher accuracy. Nominally, it will be able to detect the transit of an Earth-like planet orbiting at 1 AU — fulfilling the old dream of finding a twin of the Earth somewhere in the cosmos. If it reaches its objectives, the Kepler mission will populate the mass-radius diagram with all sorts of planets, thus opening the field of the nature and structure of exoplanets down to Earth masses. Note that the Solar System contains no planet of mass between Uranus (14 Earth masses) and Earth, and no “hot” planet ($A < 0.1$ AU) at all, so that the physics of close-in, intermediate-size planets is completely unexplored. Like main-sequence stars, gas giant planets are basically balls of gas whose properties are only weakly dependent on mass and composition. But this smooth dependence breaks down at smaller masses, and for lighter planets one can expect a startling variety of structure. The possible variety of such planets is mind-boggling, from “Ocean planets”, to charred remains of gas giant cores, to large telluric planets with extremely active plate motion, to evaporating comet-like gas or ice giants.

§3. Extrasolar planets atmospheres

Transiting exoplanets provide even more benefits. Indeed, the spectrum of the host star during the transit is rich in information. At the simplest level, one can evaluate the radius of the occulting body as a function of broad wavelength spectral domains, which is the first step towards the observation of the extrasolar planets atmospheres. As an example, the atmosphere of the Earth being opaque below 3000 Å, it would look larger by about 60 km if observed at shorter wavelengths. It is, of course, more difficult to observe transits in spectroscopy than in photometry simply because the number of photons available in a limited spectral domain is lower while the required accuracy has to be higher. The increased fraction of the stellar disk occulted by a typical extrasolar planetary atmosphere is of the order of $10^{-4}$ to $10^{-8}$, depending upon the atmospheric scale height and the species searched for. This requires for a positive detection large instruments, spaceborne telescopes being a priori better adapted according to their higher intrinsic stability. Indeed at the moment, there are no successful extrasolar atmospheric detections from any ground based instrumentation.

3.1. HD209458b

The first known transiting exoplanet, HD 209458b, is transiting a bright star ($m_v = 7.65$). This allows detailed observations of the transit light curve and of the effects of the transit on the star’s spectrum. First, the limb darkening effect is seen in details in the data collected with the Hubble space Telescope (Fig. 7). In addition, a careful analysis of the light curve and timing gives constrains on potential satellites or rings: the upper limits on satellite radius and mass are $1.2 R_{\text{Earth}}$ and
3 $M_{\text{Earth}}$, respectively; opaque rings, if present, must be smaller than 1.8 planetary radii in radial extent.\(^{28}\)

Despite the numerous searches for exoplanetary atmospheric signatures,\(^{52)–57)}\) only very few positive detections were completed, in the atmosphere of HD209458b: neutral sodium in the dense lower atmosphere,\(^{58)}\) and atomic hydrogen, oxygen and ionized carbon in the upper exosphere.\(^{59), 60)}\)

3.2. The lower atmosphere of HD 209458b

From the first model calculations it was shown that the lower atmospheric layers of the “hot Jupiters” should be at effective temperatures of the order of 1000 K or more\(^{61)–67)}\) and in the case of HD 209458b of about 1250 K. The corresponding atmospheric scale height being of the order of 800 km, it shows that an expected additional absorption from some species present in a planetary atmosphere, detected over one scale height, should be of the order of 0.03%. This is an extremely weak signature. However since it has to be detected in relative terms from the comparison with nearby spectral bands over an extremely stable stellar photospheric emission, this observational challenge was successfully achieved. Indeed an additional absorption of (0.0232±0.0057\%) in the Na\(_i\) doublet at 5890Å has been detected.\(^{58)}\) This signature of the atmosphere is less than predicted.\(^{68)}\) This could be interpreted in terms of atomic sodium depletion into molecules or grains, or more likely photoionization or clouds in the atmosphere,\(^{58)}\) this last hypothesis being consistent with the non-detection of CO.\(^{55), 57)}\)

This first detection of an extrasolar planetary atmosphere triggered a lot of effort to properly model exoplanetary spectra, the physical structure of their atmospheres and their possible evolution.\(^{69)–71)}\)

Additional model calculations were developed in order to evaluate the time dependent behavior of the lower planetary atmospheres.\(^{72), 73)}\) In particular the change with time of the stellar energy input on the top of the atmosphere (even under tidal locking of the planetary rotation), showed that zonal winds could be present. Their impact on the atmospheric distribution could give additional possible explanations for the observed too low sodium content.\(^{74), 75)}\) These last studies show that when sampling the atmosphere via absorption signatures produced through the planetary limb, one should consider in fact that two distinct regions of the atmosphere are studied: one over the “morning” limb and the other over the “evening” one. Atmospheric observations during transits thus only give access to atmospheric parameters averaged over two possibly very different regions of the atmosphere. This shows that in such a new field of research both the observations and the interpretations are certainly very difficult.

3.3. The upper atmosphere of HD 209458b

It has long been considered that the upper atmospheric signatures should not be more important than the first detection reported, simply because the atmospheric model predictions were not taking into account a possible very efficient heating of the upper atmospheric layers as it is well known to be the case in all solar system upper atmospheric planetary atmospheres. Note however that some attempts were
made to mention that the upper atmosphere behavior could be quite different from the one suggested from the lower atmospheric models, underlining in particular that some escape could be expected.\cite{54,61,68,76,78}

The most abundant, and lighter, element present in the upper atmosphere being atomic hydrogen, the first successful attempt\cite{59} to search for an atmospheric signature was made in the UV domain, at the Lyman $\alpha$ wavelength (1216\,Å), corresponding to the strongest resonant atomic hydrogen transition. The observed Lyman $\alpha$ spectrum of HD209458 is typical for a solar-type star, with a double peaked emission originating from the stellar chromosphere. It also shows a wide central absorption feature due to neutral hydrogen in the interstellar medium. The absorption signature was thus searched for on top of that complex profile.

The surprise came from the fact that the absorption over the stellar H\,$\!$\,i Lyman-$\alpha$ line was of about 15\,$\pm\,$4\%. This absorption signal is clearly larger than the visible planetary disk ($\sim$1.6\% of the star) showing that the upper atmosphere extends at least at several planetary radii. Although the small distance (8.5 stellar radii) between the planet and the star results in an extended Roche lobe\cite{79} of about 2.7 planetary radii (i.e. 3.6 Jupiter radii) size, the filling up of this lobe gives a maximum absorption of $\sim$10\% during each planetary transit. Since a more important absorption is detected, hydrogen atoms must cover a larger area: a drop of 15\% corresponds to an occultation by an object of 4.3 Jupiter radii. The hydrogen atoms are thus clearly beyond the Roche limit, i.e. beyond the planetary gravitational influence.

Furthermore this absorption signature was detected mainly between $-130$ and $+100\,$km\,s$^{-1}$ in terms of radial velocity of hydrogen atoms relative to the planet. This velocity is explained by the radiation pressure on the hydrogen atoms.\cite{78} Both the H\,$\!$\,i cloud geometrical extension beyond the Roche limit and the atoms velocity exceeding the escape one show that hydrogen atoms are escaping the planet.

3.4. Interpretation: An extended planetary exosphere

To evaluate the evolution of the H\,$\!$\,i atoms once they are free in the planet’s exosphere, a particle simulation in which hydrogen atoms are sensitive to the stellar radiation pressure inside and outside the Roche lobe was developed. Taking into account both the planetary and stellar gravities as well as the Lyman $\alpha$ radiation pressure over hydrogen atoms ($\sim$0.7 times stellar gravity) and the neutral hydrogen atoms lifetime (a few hours due to stellar EUV ionization) it was possible to show that escaping hydrogen atoms should expand in an asymmetric cometary-like tail before progressively being ionized when moving away from the planet.\cite{59} This scenario is consistent with the observations since the evaporating coma and tail cover a large area of the star, and most atoms absorptions are blueshifted because of the radiation pressure repelling them away from the star. The detection of more absorption in the blue part of the line is also consistent with these escaping atoms.

To account for the observed absorption depth, the particle simulation implies a minimum escape flux of $\sim 10^{10}$ g s$^{-1}$.

This evaporation rate is in agreement with theoretical calculations of the upper atmospheric structure, as long as some mechanism indeed heats up the upper layers of the planetary atmosphere. One of the heating mechanism could be related to
the important energy input in the upper layers produced by the absorption of the far UV stellar photons. Indeed in the far UV the number of spectral transitions due to many abundant species increases so much that all the stellar energy in that spectral domain could be deposited in the upper atmosphere. From different more or less sophisticated model evaluations\(^ {78} - ^ {83}\) it is shown that the upper atmospheric temperature could rise to about 10000 K. The scale height thus increases rapidly with altitude, making atmospheric detection certainly easier at the wavelengths where atmospheric absorption is very efficient, i.e. in the UV and far UV. In addition, this rise in the atmospheric temperature with altitude could indeed explain the escape of hydrogen atoms, the different estimates ranging from a minimum value\(^ {81}, ^ {83}\) of about \(\sim 10^{10}\) g s\(^{-1}\) to possibly 100 times more.\(^ {80}\)

It is important to note here that along these model calculations developed to explain the loss of hydrogen atoms, other theoretical calculations were completed in order to evaluate in the lower atmospheric regions the corresponding source. It was shown that the source of atomic hydrogen was essentially due to H\(_2\)O photolysis and the reactions of OH with H\(^ {84}, ^ {85}\). The consequence is that the “hot Jupiters” have a 3 orders of magnitude higher H concentration than in Jupiter itself.\(^ {86}\)

3.5. Detection of carbon and oxygen

Although the atmospheric detection could seem to be easier at UV wavelengths according to the larger absorption signature expected, the stellar flux being there much weaker and more variable than in the visible, the atmospheric detections at these wavelengths remain a real challenge.

Carbon and oxygen being among the abundant elements in the planetary atmospheres as well as being relatively light, they represented the natural next candidates for atmospheric detection signatures. Their strongest accessible spectroscopic resonance transitions being: for oxygen, O\(_i\), O\(_i^*\) and O\(_i^{**}\) at 1302.17, 1304.86 and 1306.03 Å and for ionized carbon, C\(_{\text{II}}\) and C\(_{\text{II}}^*\) at 1334.53 and 1335.69 Å. In the case of HD 209458b, the stellar UV flux was still high enough to allow the search for those species although the corresponding stellar UV lines are about 100 times weaker than the Lyman-\(\alpha\) one.

From simple model calculations it was however clear that even within an atmosphere at 10000 K, these species are too heavy to escape under Jeans escape mechanism since their thermal velocity peaks at only about 3 km s\(^{-1}\). A velocity of at least 10 km s\(^{-1}\) is needed to escape even from the higher thermospheric altitudes where they could be transported through thermal diffusion. Under such an atmospheric hydrostatic scenario, these species scale heights being extremely small (12 and 16 times less than in the case of hydrogen) they are not even expected to move up in the thermosphere and thus remain far from being potentially escaping or even detected.

Surprisingly again an absorption signature during the transits at a level of about 10% was observed,\(^ {60}\) showing that both carbon and oxygen atoms do reach the Roche limit and thus also escape away from the planet. The escape being clearly not the thermal Jeans process, it has to be a hydrodynamic escape mechanism in which hydrogen atoms moving at the sound speed transport in their flow many, if
not all, of the other species. This hydrodynamic escape mechanism,\textsuperscript{87} also known as planetary “blow-off”, is for the first time directly observed in the case of an extrasolar planetary atmosphere. From these new observations both the total volume density (from the population of the oxygen and carbon metastable levels, \( \sim 10^6 \text{cm}^{-3} \)) as well as the atoms average velocity (from the width of the carbon and oxygen absorptions, \( \sim 10 \text{ km s}^{-1} \)) at the level of the Roche lobe were evaluated, leading to a new and independent estimation of the escape rate: it has to be of the order of \( \sim 10^{10} \text{g s}^{-1} \) in agreement with the previous estimate obtained from the H\textsubscript{I} observation.

Because the HD 209458b planet is losing mass, the nickname “Osiris” has been suggested for it\textsuperscript{78} (the Egyptian god who also lost some mass).

3.6. Evaporation of “hot Jupiters” and the future of exoplanetary atmosphere studies

The transit observations of HD 209458b showed that “hot Jupiters” could evaporate and that, under certain circumstances, they could be significantly modified by

![Figure 13](image.png)

Fig. 13. Plot of the domain where the planet life time against evaporation is shorter than \(10^9\) years as a function of the initial mass and orbital period. In the grey region, the time to evaporate the full hydrogen envelope of a planet with a 15 Earth mass solid core is shorter than \(10^9\) years. This calculation uses the planets radii evolution\textsuperscript{88} with time, mass and effective temperature. The time variations of the FUV/EUV stellar flux are also taken into account, but it is found to have a negligible effect compared to the assumed planet radii. The squares show the position of the known planets. The three planets with mass between 14 and 21 Earth mass have been plotted with triangles. Figure from Ref. 89).
this evaporation process. In addition to the understanding of the specific HD 209458b case, by taking into account the tidal forces and the heating of the upper atmospheres by UV and EUV stellar fluxes, the escape rates of “hot Jupiters” as a function of their mass and orbital period have been evaluated\(^\text{89}\) (Fig. 13). From this evaluation, it turns out that even “very hot Jupiters” can be stable against evaporation if they are massive enough like OGLE-TR-56, OGLE-TR-113 or OGLE-TR-132 (see §2). On the other hand, planets with an orbital period shorter than about 3 days and less massive than about \(\sim 0.5\) Jupiter mass should be the subject of intense evaporation. If this takes place, most of the atmosphere must disappear on short time scale leaving the remaining central core of about \(\sim 15\) Earth mass of heavy material, with a shallow atmosphere or no more atmosphere at all. The state of the surface of these putative bodies is still to be determined and could be similar to the lava surface of Io with its 1500 K temperature. The emergence of the inside cores of former and evaporated “hot Jupiters” may constitute a new class of planets, for which the name “chthonian” planets were proposed,\(^\text{83}\) in reference to the Greek god of the Earth: Khthon ("chthonian" is used to name the Greek deities who come from hot infernal underground).

This suggestion of the existence of evaporated planet remnants has been recently emphasized by the discovery of three planets with short periods and low mass from \(m\sin i \sim 14\) to \(\sim 21\) Earth mass. In one case, \(\mu\) Arae,\(^\text{90}\) the orbital period of 9.55±0.03 day and the orbital distance of 0.09 AU seem not favorable for an evaporation scenario. However, the initial planetary mass and radius, and early evolution of the X, UV and EUV flux from the star are still to be evaluated to draw a firm conclusion. In the two other cases, 55 CnC\(^\text{91}\) and GJ 436\(^\text{92}\) having orbital periods of 2.81 and 2.64 days, both these planets fall exactly within the mass-period range predicted for most of the evaporation-modified (“chthonian”) planets.\(^\text{83}\) In conclusion, the nature, origin and history of these newly discovered planets are still to be clarified, but they appear to be possibly the result of the evaporation mechanism which has been uncovered thanks to spectroscopic observations of the transit of HD 209458b. If evaporated planet remnants are numerous, they will also be uncovered by the future space programs dedicated to the search for planetary transits. We have to wait for the coming deep transit surveys with dedicated space missions to understand the properties, distribution and evolution of these low mass planets which we start to discover.

3.7. Planetary transits: A first direct vision of extrasolar planetary atmospheres

As we have seen, planetary transits offer a first direct vision of extrasolar planets. They will give unprecedented capabilities to probe the extrasolar planets characteristics, composition and environment. As a last demonstration of these capabilities, we have plotted in Fig. 14 the image of the HST-STIS detector on which the signatures of all three species, H\(_i\), O\(_i\) and C\(_{\text{II}}\) were observed.\(^\text{60}\) The stellar spectrum is the bright horizontal line on top of which the absorptions during transits were recorded (but not seen directly here). Because the long slit of the HST-STIS instrument was also covering the sky, above and below the stellar spectrum are recorded the Earth geocoronal emissions. Both the H\(_i\) Lyman \(\alpha\) and the O\(_i\) 1302Å ones
Fig. 14. The STIS-MAMA detector over which were recorded the absorptions during the transits of the planet nicknamed “Osiris”. The star was placed in the entrance slit and its spectrum is spread horizontally as a bright line over which were recorded the different spectral emission lines related to the H\textsc{i}, O\textsc{i} and C\textsc{ii} transitions. Absorptions were observed over all three lines during transits. The Earth airglow was also recorded along the slit producing vertical signatures related to the presence of the corresponding atoms within the Earth upper atmosphere, above the HST observatory. Clearly high altitude hydrogen and oxygen atoms are present while no carbon ions could be seen. This demonstrates directly that if an Earth-like planet was one day discovered and observed during transits, a very different spectral signature from the one observed in the case of Osiris should be found since no C\textsc{ii} absorption would be then observed.

are clearly observed while obviously no C\textsc{ii} terrestrial airglow is detected at 1335Å. This directly demonstrates how powerful this observing technique will be since obvious differences will be found between Earth-like planets and other ones. Thanks to transiting planets, the search for life in other planetary systems via the signature of potential biomarkers may start much earlier than expected.

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