Mem. S.A.It. Vol. 89, 332

Memorie della

The status of the research on exoplanets

G. Micela

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Palermo, Piazza del Parlamento 1 I-90134 - Palermo, Italy, e-mail: giusi@astropa.inaf.it

Abstract. In the last years a significant technological effort has led to new sophisticated instruments devoted to the measurements of masses (manly from ground) and radii (mainly from space) of exoplanets. These important developments allowed us the discovery of a large number of exoplanets around stars in the solar neighborhood. Thanks to these discoveries, today we know that most solar-like stars host at least one planet. A fraction of them, mainly those around red dwarfs, may have characteristics similar to the Earth (equilibrium temperature, mass, average density) and therefore could sustain an atmosphere and permit the set up for the conditions of life development, even if their "Suns" are much redder and active than our's. New instruments, as ESPRESSO and PLATO will allow us in the near future to find planets even more similar to the Earth, around stars of one solar mass and JWST, ARIEL and ELT will permit studying their atmospheres.

Key words. Planets and satellites: detection – Planets and satellites: terrestrial planet

1. Introduction

In the last twenty years, after the discovery of 51 Peg b, the research on exoplanets has grown very quickly, and today (May 2018) we have identified about 3800 confirmed planets belonging to more than 2800 planetary systems. During the early years, it was possible to detect only massive/hot planets but, more recently, thanks to the new instrumentations and the optimised observing strategy, many smaller/light planets have been discovered. Fig. 1 shows the mass (fig. 1a) and the radius (fig. 1b) of the confirmed planets as a function of the discovery year. Plots show clearly how, in the last years, we have been able to identify lighter (smaller) planets, comparable with the Earth. The sudden increase of the number of planets smaller than Jupiter, evident in Fig. 1b, is due to the launch of the Kepler satellite in 2009 that is the main provider of transiting planets (Borucki et al. 2010).

The today known thousands of planets span a huge range of masses, size, orbits. The new instruments and observing strategy enable us to further extend the interval of physical parameters to the small planets regime, that up to few years ago was impossible to explore due to the limited capabilities of instruments.

2. Detection methods

Several methods are currently used to identify new planets. Each of them is adequate for detecting planetary systems with specific characteristics and therefore has is own biases. The most used techniques include:

– Radial velocity measurements. This method measures the reflex motion of the host star through high precision,

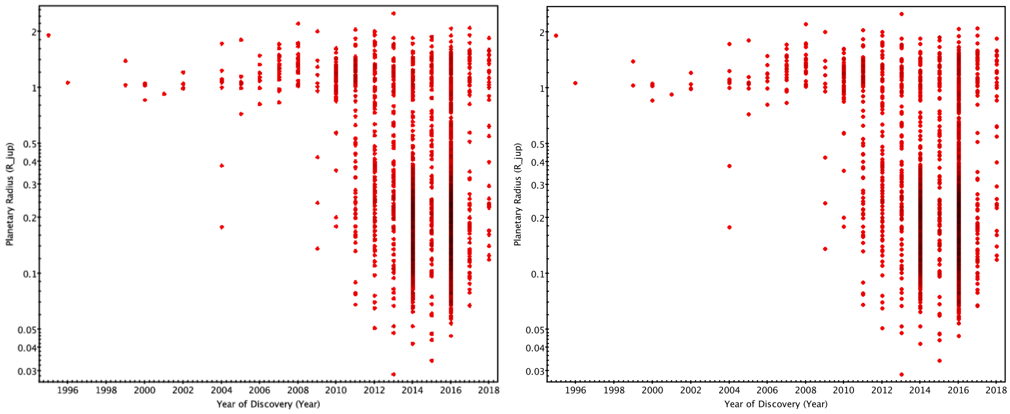

Fig. 1. Panel a), on the left: Projected mass of confirmed exoplanets as a function of discovery year; Panel b), on the right: Measured radius of confirmed exoplanets as a function of discovery year. (Data from Explanet.eu database).

high accuracy spectroscopy, providing the projected mass of the planet. Planets discovered with this method are typically within a few of astronomical units (AU) from their host stars;

- Transit photometry. This technique is based on the observation of the (small) eclipse of the stellar light due to the transit of the planet in front of the star. Although the transit probability is very small, the method is very efficient thanks to the large fields of view - and therefore large observed samples - of the observing campaigns. The transit method allows measuring planetary radii and is strongly biased toward close-in planets, typically within a fraction of AU from the host;
- Direct images of planets. The technique has been used only recently, with the advent of very accurate optics and coronographs and, up to now, has discovered a limited number of planets. It can be effective in detecting giant planets very distant (several AUs) from the star, preferentially young, when the planet is still contracting and, therefore, more luminous.

One of the most astonishing results of the research on exoplanets is the huge diversity of their characteristics, unexpected based on our knowledge of Solar System, the only known planetary system until the discovery of 51 Peg b (Mayor and Queloz 1995). For example, our system does not present Hot Jupiters or super-Earths that, instead, are very common around other stars. The goal of the research for new planets is not finalised just to the increase of the number of known planets, but to build a comprehensive view of the possible architectures and configurations of planetary systems in order to answer to broader questions as: How do planets and planetary systems form and evolve? Is our Solar System special or are there other systems like ours? Are there potentially habitable planets?

In order to face these questions we need to determine the frequency of planets and their architecture, derive their structure and the properties of atmospheres in a large range of physical configurations; we expect also that such properties depend on environment (i.e. metallicity) and on host star properties.

The current observations indicate that almost every solar-like star has one or more planets (i.e. Howard et al. 2010, Mayor et al. 2011), and that, when observation biases are appropriately taken into account, small or light planets are more common than larger or more massive counterparts.

3. The nature of exoplanets

In order to characterise the physical properties of the planets, we need to determine their average density, with the goal to discriminate their nature (gaseous, ocean or rocky). Unfortunately, we know both mass and radius only for a subsample of planets (today - May 2018 - only 711 out of confirmed 3969 planets), therefore we may derive information on their structure only for this fraction. The difficulty to measure both quantities for the majority of planets, is that the radius may be obtained only for transiting planets. The most prolific provider of transiting planets, up to now, has been the Kepler satellite, whose targets are often too faint to allow a spectroscopic follow up to measure masses.

The mass-radius relation is shown in Fig. 2. At a given mass, planets have a large range of radii, with the bulk of more massive planets spanning at least a factor of two - corresponding to about one order of magnitude in density - with several outliers with higher density. The spread of density is even larger in the lower mass regime. The origin of this large range is only partially explained by measurement errors and evolution of planetary radius due to the natural contraction of the planets and irradiation from the star (e.g. Fortney et al. 2013). The observed spread suggests that in the super-earth regime mini-gas, ocean, and rocky planets with density from less than 1 g/cm^3 to 5 g/cm^3 may coexist .

Observations have several consequences: first of all we can state that the Solar System planets are not the only possible realisation and that other types of planets can exist. Then, small planets are not necessarily rocky, and gaseous planets are not necessarily large. In particular small exoplanets are very diverse, including Earth-like to mini-gas planets in the same mass regime. Mini-gas planets are unlikely to be habitable, and therefore silicate-iron planets will be the prime targets for follow up spectroscopy dedicated to the search of terrestrial "twins" and biosignatures.

As explained above we may determine both radius and mass only for planets transiting around bright stars and therefore only

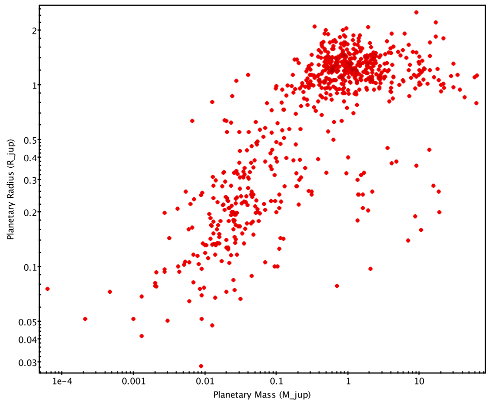

Fig. 2. Mass - radius relation for the known 711 exoplanets with both parameters measured. (Data from Exoplanet.eu database).

for a fraction of the known exoplanets. If we limit ourself to super-earths we obtain the sample shown in fig. 3, where we report the orbital distances as a function of mass of the host of the super-earth with measured radius and mass. The plot includes also planetary masses derived through TTV method (e.g.Lithwick et al. 2012) and therefore more uncertain that those measured from radial velocity. The more striking characteristics of the plot is that these super-earths orbit very close to the host stars and only few around low-mass stars, fall marginally in the formal habitable zone. This fact is a direct consequence of the observation bias towards short period planets introduced by the transit method.

In order to populate the most interesting part of this plot, the new transit missions are focused on bright stars, for which will be possible to measure planetary mass through spectroscopic follow up from ground. In particular TESS (Ricker et al., 2014) is a NASA mission launched on April 18 2018 with the goal to perform a full sky survey, with average exposure time of ~ 80 days. CHEOPS (Broeg et al., 2013) is a small mission of the ESA Cosmic Vision programme; it will be launched at the beginning of 2019, and will be a follow up mission with the main goal to search for transits of planets detected with radial velocity and to refine the orbit parameters and transit depth of known transiting planets. Finally PLATO (Rauer et al., 2014), is the M3 mission of the ESA Cosmic Vision programme, that will be launched in 2026. It will observe a large fraction of the sky, some part with exposure time of three years. It will detect and characterise (e.g. density, age) terrestrial planets around bright solar- like stars up to the habitable zone. All together these instruments, complemented by spectroscopic measurements, will cover a large fraction of the plot reported in fig. 3 . An added value of the transiting surveys from space is given by the continuous high precision light curves that will be obtained. They will allow us to derive accurate stellar parameters (through asteroseismic analysis) as stellar mass, radius, stellar type, temperature, luminosity and age. This will permit determining accurate planetary parameters and evolutionary status of the entire planetary systems.

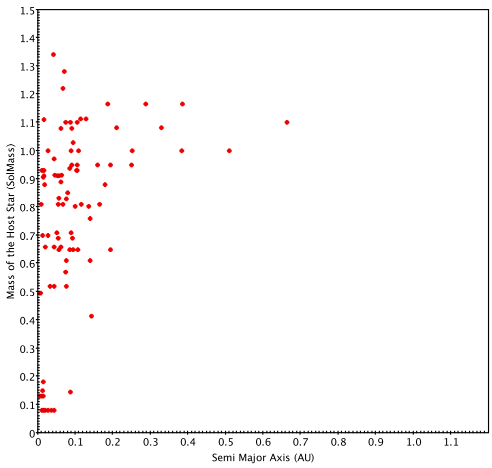

Fig. 3. Host mass versus orbital distance for the super-earths with both mass and radius measured (Data from Exoplanet.eu database).

4. Exoplanetary atmospheres

Having identified a significant sample of exoplanets, it is possible to study the atmospheres of a fraction of them. With the available technology, today it is possible to observe the atmospheres of transiting, therefore mainly hot/warm, planets around bright stars, through differential spectroscopy, and of young massive planets orbiting far away from their hosts, through direct imaging.

Studies of atmospheres may give several information on planet properties. The detection of the presence of an atmosphere and its properties break the intrinsic degeneracy in the interpretation based on measurements of average density. In fact, planets with a moderate uniform density and planets with a dense core and a more rarefied atmosphere have indistinguishable average density but very different structure. The observation of the atmosphere allows distinguishing these two scenarios.

Chemical composition of an atmosphere traces the history of a planet. In fact the today composition is the result of the chemistry of the original nebula, but also of the migration path followed by the planet, since its atmosphere captures the chemical species present in the regions of the disc crossed by the planet. By observing the abundances of such elements it is possible to reconstruct the migration path of a planet and go back to its birthplace. Furthermore it is possible to obtain information on the evolution of the atmospheres identifying planets with primary and secondary atmospheres. Atmospheres have an important role in determining habitability conditions and time- resolved observations may allow to study the dynamics and therefore climate in exoworlds.

The atmosphere of a planet is the result of several complex phenomena. Beyond the initial conditions and following migration path, also history of impacts has a role; a fundamental ingredient is the stellar radiation that in extreme cases may originate gas escape from the upper layers of the atmosphere. Furthermore the atmosphere is not static but evolves as a consequence of tectonic activity and volcanism; finally also the development and evolution of life may modify in relevant way the atmosphere composition.

One of the most challenging aspects of this studies is the search for *habitable* planets. The first problem is the definition of *habitability*. Usually it is defined through the simple condition that the temperature has to allow the presence of liquid water. On the one hand, this definition is too conservative, given that on the Earth there are organisms, the so-called extremophiles, that survive in apparently proibitive conditions. On the other hand, a condition on the temperature alone is not sufficient since other factors play a crucial role. One of the most important is certainly the presence of an atmosphere: only planets with a gravity sufficient to avoid its complete evaporation can reach the habitability conditions. The presence of a planetary magnetic field has the important role of shielding the surface of the planet from the impacts of cosmic rays and particles coming from space. High energy stellar radiation, including flares, should not be too intense, this condition makes difficult to have habitable planets around dM stars, the most common stars in the solar neighborhood, since they are on average more active than the Sun. Furthermore, around these small stars, the stellar habitability zone - defined as the distance from the star where the equilibrium temperature allows the liquid water - is close to the star. The short orbital period and the favourable contrast make the identification of planets in the habitability zone easier than around more massive stars. However they are subjected to intense irradiation due to the stellar activity and are in most cases in synchronous orbits, with one face continuously illuminated by the star and the other always in shadow with huge temperature gradients on the surface. In this configuration it is probable that the planet can be habitable only at the terminator where extreme temperatures are not reached.

Observations of planetary systems are dominated by the stars, even in the most favourable cases. Therefore we need very high signal to noise observations, a very good control of systematics, and, of course, an optimal observational strategy. Today we may use three different methods to observe the atmospheres, each with specific advantages and disadvantages: direct imaging of the planet spectra, differential spectroscopy in and out transit, and radial velocity monitoring. Direct imaging may be used to observe wide-separation systems. It allows to determine elemental composition, temperature profile and to identify the presence of clouds and hazes. In and out transit/occultation spectroscopy is well suited to observe close-in planets, it provides information on composition, thermal profile, photochemistry, cloud and hazes, evaporation and dynamics. Radial velocity monitoring helps in determining composition, dynamics, winds and in observing the stratosphere. These two latter methods can be used in principle also out of transits, taking advantage of the phase modulation of the emission reflected by the planet.

A number of atmospheres have been observed, in particular using transit spectroscopy, with ground and space instruments (Hubble and Spitzer). Data are still sparse and hard to interpret but, in a number of cases, the most abundant species have been detected and the atmospheric thermal structure derived (e.g. Charbonneau et al., 2002; Redfield et al., 2008, Sing et al., 2016). The visible band allows to observe the reflection spectrum close to the occultation, while in the infrared spectrum there are many intense molecular bands. Moreover the infrared is less affected by the cloud presence that masks the spectral features (e.g. Knutson et al., 2007; Majeau et al., 2012; Stevenson et al., 2014, Tinetti, Encrenaz, Coustenis, 2013). One the most frequently detected feature is the water vapour (e.g. Barman 2007, Beaulieu et al. 2010; Birkby et al., 2013; Burrows et al. 2007, Charbonneau et al. 2008; Crouzet et al. 2012, 2014; Danielski et al. 2014; Deming et al. 2013; Grillmair et al. 2008; Kreidberg et al., 2014b, Line et al., 2016; McCullough et al. 2014; Swain et al. 2008, 2009; Tinetti et al. 2007, 2010), CO (Snellen et al., 2010) and methane, (Swain et al. 2008). Similarly, some water-rich hot-Neptune has been observed (Fraine et al., 2014), while warm Neptunes seem to be dominated by clouds that prevent the observation of molecular features (e.g. Knutson et al. 2014; Morello et al., 2014; Fukui et al. 2013). UV observations with HST indicate that some transiting planets have unstable atmosphere, with hydrodynamic escape phenomena due to intense irradiation from their host star (e.g. Vidal-Madjar et al., 2003; Linsky et al., 2010; Fossati et al, 2010).

There are also observations of super-Earths, for which is difficult to define a clear scenario, with a variety of situations and often dominated by clouds (e.g. Bean et al. 2010; Kreidberg et al., 2014a).

In general, data are still sparse but very suggestive of a rich scenario. Clearly a broader wavelength range in the infrared will help in disentangling some ambiguities present in the spectra interpretation (Swain et al., 2009; Madhusudhan and Seager, 2009; Lee et al., 2012; Line et al., 2013; Waldmann et al., 2015a,b). The upcoming JWST, with its large effective area and suite of instruments, will give a decisive contribution to the study of well selected targets, while a dedicated mission will observe a sample of planets covering the relevant parameters of star-planet systems, to shed light on the origin of the observed diversity. In order to fulfil this needs, ESA has selected the ARIEL mission as M4 mission of the cosmic vision programme for a launch in 2028 (Tinetti et al. 2018). ARIEL will observe a sample of about 1000 transiting planets, including giants, Neptunes, super-Earths and Earth-size planets around stars of several spectral types. It will observe in a large range of wavelength from 0.5 to $\sim 7.8\ \mu$ with a mix of photometry (in the visible) and low resolution spectroscopy. Working with transiting planets, ARIEL will observe preferentially hot and warm planets, that have the advantage of well-mixed atmospheres, with most of elements in gaseous phase; therefore, the atmosphere composition of these planets is representative of the "true" composition. ARIEL will study in detail individual planets deriving, among others properties, chemical composition, atmospheric circulation and cloud pattern, it will distinguish equilibrium and non-equilibrium chemistry, will explore the coupling interior-atmosphere and will evaluate the relevance of stellar environment and evolution of the planetary system. At the same time ARIEL will study the planet population, exploring their chemical diversity, the correlation between the temperature, presence of clouds and the stellar-type, the evolution of the atmospheres and of the coupling of the atmosphere with the planet interior, the correlation between the elemental composition and planet birthplace, and the transition between terrestrial planets and sub-Neptunes.

A different method to study the planetary atmospheres is through radial velocity monitoring at very high spectral resolution ($\Delta\lambda/\lambda \geq 100,000$). At such high resolution molecular bands are resolved in tens of individual lines and the strong doppler effect due to orbital motion of the planet (up to >150 km/sec for hot Jupiter) allows to distinguish moving planetary lines from stationary telluric and stellar lines. Of course, in order to obtain high signal to noise, high spectral resolution observations, large aperture telescopes and very stable spectrographs are needed. The method has been used in few cases (Snellen et al. 2010). Data analysis is very challenging and requires very careful methods to subtract the dominant stellar spectrum and the telluric lines: the goal is to measure flux variations less than 10^{-3-4} as a function of λ over 1-5 hour time scales, in presence of variations of turbulence, seeing, absorption, scattering and thermal sky emission of the Earth atmosphere and of gravity vector, field rotation and temperature of instrument.

Using this technique, Snellen et al. (2010) have revealed the transmission spectrum of CO in the atmosphere of the hot Jupiter HD209458 b observed with CRIRES at VLT. Such detection has allowed to observe directly the planet orbital velocity, to solve for masses of both planet and star, and, to suggest (at 2σ level) from some blue shift evidences, the presence of high altitude winds.

The method can be applied also to observations with GIARPS (Claudi et al. 2016), the observing mode that allows to use simultaneously HARPS-N and GIANO at TNG, obtaining high resolution VIS-NIR spectra and high precision radial velocities. In this way, a large wavelength coverage is obtained (HARPS-N in the $0.38\mu < \lambda < 0.69\mu$ range, and GIANO from $0.95\mu < \lambda < 2.45\mu$). GIARPS is already on duty at TNG. Using GIANO at TNG, Brogi et al. (2018) have detected the H_2O molecule in HD18973 b, determining a volume mixing ratio of$H_2O \approx 10^{-4}$.

The full exploitation of this technique will be obtained with HIRES at ELT (Marconi et al. 2016). The high resolution and the stability of the instrument, together with the huge effective area of the telescope, will allow to study the atmospheres of a large number of planets. Simulations show that it will be possible to detect the O_2 molecule in the atmospheres of terrestrial planets in habitable zones around nearby late dM stars (Snellen et al. 2014).

Acknowledgements. This work has been supported by the "Progetto Premiale WOW (A Way to Other Worlds) funded by Italian Ministry of Education and Research. The author acknowledges useful discussions with her colleague L. Affer.

References

Barman, T. S. 2007, ApJ, 661, L191
Bean, J. L., et al. 2010, Nature, 468, 669
Beaulieu, J.-P., et al. 2010, MNRAS, 409, 963
Birkby, J.L., et al. 2013, MNRAS, 436, L35
Borucki, W. J., et al 2010, Science, 327, 977
Broeg, C., et al. 2013, in Hot Planets and Cool Stars, ed. R. Saglia (EDP Science, Les Ulis), EPJ Web of Conf., 47, 03005
Brogi, M., et al. 2018, A&A, 615, A16
Burrows, A., et al. 2007, ApJ, 661, 502
Charbonneau, D, et al. 2002, ApJ, 568, 377
Charbonneau, D., et al. 2008, ApJ, 686, 1341
Claudi, R., et al. 2016, Proc. SPIE, 9908, 99081A
Crouzet, N., et al. 2012, ApJ, 761, 7
Crouzet, N., et al. 2014, ApJ, 795, 166
Danielski, C., et al. 2014, ApJ, 785, 35
Deming, D., et al. 2013, ApJ, 774, 95
Fortney, J. J., et al. 2013, ApJ, 775, 80
Fossati, L., et al 2010, ApJ, 714, 222
Fraine, J., et al. 2014, Nature, 513, 526
Fukui, A., et al. 2013, ApJ, 770, 95
Grillmair, C. J., et al. 2008, Nature, 456, 767
Howard, A. W., et al. 2010, Science, 330, 653
Knutson, H. A., Nature 2007, 447, 183
Kreidberg, L., et al. 2014a, Nature, 505, 69
Kreidberg, L., et al. 2014b, ApJ, 793, L27
Lee, J.-M., Fletcher, L. N., Irwin, P. 2012, MNRAS, 420, 170
Line, M.R., Yung, Y. 2013 , ApJ, 779, 6
Line, M.R., et al. 2016, AJ, 152, 203
Linsky, J. L., et al. 2010, ApJ, 717, 1291
Lithwick, Y., Xie, J., Wu, Y. 2012, ApJ, 761, 122
Madhusudhan, N., Seager, S. 2009, ApJ, 707, 24
Majeau, C., Agol, E., Cowan, N. B. 2012, ApJ, 747, L20
Marconi, A., et al. 2016, Proc. SPIE, 9908, 990823
Mayor, M., Queloz, D. 1995, Nature, 378, 355
Mayor, M., Marmier, M., Lovis, C. 2011, ArXiv:1109.2497
McCullough, et al. 2014, ApJ, 791, 55
Morello, G., et al. 2014, ApJ, 786, 22
Rauer, H., et al. 2014, Exp. Astr., 38, 249
Redfield, S., et al. 2008, ApJ, 673, L87
Ricker, G. R., et al. 2014, Proc. SPIE, 9143, 20
Sing, D. K., et al. 2016, Nature, 529, 59
Snellen, I. A. G., et al. 2010, Nature, 465, 1049
Snellen, I. A. G., et al. 2014, Nature, 509, 63
Stevenson, K. B., et al. 2014, Science, 346, 838
Swain, M. R., Vasisht, G., Tinetti, G. 2008, Nature, 452, 329
Swain, M. R., et al. 2009, ApJ, 690, L114
Tinetti, G., et al. 2007, Nature, 448, 169
Tinetti, G., et al. 2010, ApJ, 712 L139
Tinetti, G., Encrenaz, E., Coustenis, A. 2013, A&A Rev., 21, 63
Tinetti, G., et al. 2018, Exp. Astron., submitted
Vidal-Madjar, A., et al. 2003, Nature, 422, 143
Waldmann, I.P., et al. 2015a, ApJ, 802, 107
Waldmann, I.P., et al. 2015b, ApJ, 813, 13