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Nobel Lecture: 51 Pegasi b and the exoplanet revolution[*]

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I. FOREWORD

> The worlds also are infinite, whether they resemble this one of ours or whether they are different from it.
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> Epicurus 300 BC (Laërtius, 1925; Long, 1972)

Scientific experiments panning out to a paradigm shift are rare and unexpected. It is the combined result of hard work, opportunity, technology readiness, and contributions by many people. With a bit of luck, all these elements play together in harmony and converge to create an exceptional moment where knowledge makes a step forward. Eventually, only a small number of key contributors get the chance to be rewarded for results that include the contributions and ideas of many others. I feel indebted to all these people. I would particularly like to express my deep gratitude to all engineers, technicians and collaborators of the Observatoire de Haute Provence (OHP) and Geneva Observatory that contributed to the construction and operations of ELODIE spectrograph and the 193 cm telescope of the OHP. Without their professionalism and unfailing motivation the discovery of the first exoplanet would have been different and my story as well.

This paper is about the story of the discovery of 51 Pegasis b, an exoplanet, a planet orbiting another star than our Sun. I will describe methods and challenges faced at that time. I will elaborate on the profound impact this discovery had on our general knowledge and understanding about planet formation and why it has been a seminal moment for the emergence of a new field of research in astrophysics, as well as a formidable incentive to kick-start the exploration of life in the universe.

II. PRECISE DOPPLER SPECTROSCOPY

An orbiting planet can be inferred by the observation of reflex motion of its parent star. The orbital trajectory of the host star around the center-of-gravity set by the star-planet system may be detected either through its astrometric orbit or periodic radial velocity changes. When by chance the geometry of the planetary orbital plane is such that the line of sight between the observer and the star is crossed by the planet a transit event occurs. Any of these "indirect" methods may be considered to detect a planet as an alternative to "direct" detection by spatially resolving a planet from its star, a formidable technical challenge still today.

In the 20th century, various exoplanet discovery claims by astrometric techniques have been made to be later dismissed on the basis of new data (Boss, 1998). For half a century, astrometry was essentially the only technique considered to detect a giant planet in an orbital configuration similar to Jupiter. Nobody had really considered searching for planets by measuring stellar radial velocities. They had a good reason for that. A giant planet orbiting at a few astronomical units away would produce a change of radial velocity of its parent star in the order of 10 $\mathrm{m\,s^{-1}}$. Detecting a variation of that order of magnitude with available technology at that time was an utopian perspective.

In 1952, Struve (1952) published a surprising visionary short note mentioning conducting "high-precision radial velocity work" to look for planets "much closer to their parent stars than is the case in the Solar System." This idea was way ahead of its time until a series of innovations would significantly reduce uncertainties on radial velocity measurements. Nobody considered seriously searching for planets using Doppler spectroscopy methods at the time for the next decade.

In 1967, the successful implementation of spectral matching techniques to derive stellar radial velocity by Griffin (1967), followed a few years later by a publication (Griffin and Griffin, 1973) "On the possibility of determining stellar radial velocities to 0.01 $\mathrm{km\,s^{-1}}$," changed the perspective. It opened a realistic prospect to reach the required performance to eventually detect planets by precise Doppler spectroscopy.

Campbell & Walker achieved the first successful implementation of ideas earlier sketched by Griffin & Griffin, a spectroscopic line reference source superimposed to the stellar light optical path, using an absorption cell located at the

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spectrograph entrance and filled with hydrogen fluoride (HF) gas (Campbell and Walker, 1979). Despite the safety and handling challenges to operate this equipment, they conducted, during 12 years, the first survey looking for "substellar companions to solar-type stars" using precise Doppler spectroscopy measurements (Campbell, Walker, and Yang, 1988; Walker *et al.*, 1995). The use of a gas cell as a self-reference to obtain precise radial velocities was later perfected by Marcy & Butler by replacing the meter-long lethally corrosive HF cell with a more compact and easy to handle cell fill with iodine (I_2) (Marcy and Butler, 1992). The ease and flexibility offered by the use of an I_2 cell would open the possibility for almost any existing high-resolution spectrograph to produce precise radial velocity measurements and to be used for a planet search survey. The apparent simplicity of this technical solution would however face the arduous challenge to deal with non-trivial data analysis inherent to the dense and blended forest of molecular line transitions of I_2 (Butler *et al.*, 1996).

The alternative to the self-calibration method with a gas cell is to operate a stable and precise spectrograph. In 1990, in a comprehensive review, Brown considered design optimization trade-offs needed to build such an instrument (Brown, 1990). Use of échelle spectrograph design is essential to produce, with the same exposure, spectra with high resolution and large wavelength range. These two characteristics allowed us to observe enough stellar spectral lines to precisely compute radial velocity from Doppler effect by cross-correlation with a match filter (correlation numerical mask) (Queloz, 1995) and to reach 10 $\mathrm{m\,s^{-1}}$ considering realistic observation sequences with existing telescopes (Bouchy, Pepe, and Queloz, 2001).

In the '90s, only a handful of instruments have been successfully developed along these guidelines reaching their design purpose to deliver high precision radial velocities. The successful ones (Brown *et al.*, 1994; Baranne *et al.*, 1996; Kaufer *et al.*, 1997) are essentially built with similar concepts. Optics are mounted on a static bench located in stable environment away from all kinds of telescope and dome mechanical, thermal and acoustic perturbations. They are using a multi-mode optical fiber to illuminate the spectrograph entrance (slit) with the image obtained by the telescope and another fiber to track instrument and air index variations in the spectrograph. In addition to removing the instrument away from the noisy telescope environment, optical fiber injection of the stellar image has the essential intrinsic property to scramble the intensity distribution of the telescope image and to produce a nearly uniform illuminated disk at the entrance slit almost suppressing guiding and seeing effects (Heacox, 1988).

A. ELODIE

The ELODIE spectrograph (see Fig. 1) started its scientific operation in 1994 on the 193 cm telescope of the Observatoire de Haute Provence (OHP). Its construction began in 1989 as a collaboration between the Observatoire de Haute Provence and the astronomy department of Geneva University. Its main purpose was to offer a new modern observation capability particularly for "bright time" period (when the Moon is visible) while at the same time, a twin copy (CORALIE) was built in parallel to be later mounted on the 1.2 m Swiss telescope at La Silla (ESO) in Chile (Queloz *et al.*, 2000).

FIG. 1. ELODIE spectrograph on display at OHP. On the left we see the échelle grating with the grooves facing us. On the left side, the optical fibers feeding the spectrograph are clearly visible (in orange). On the top sits the cryostat with inside the CCD detector. The "cross-dispersing" optic (not visible) is located in the vertical dark painted holding structure.

The spectrograph had been designed to achieve precise Doppler spectroscopy measurements. The optical concept was constrained by the requirement to have a compact, stable instrument and to maximize the use of all available area of the E2V 1024 × 1024 pixels CCD detector to obtain a recorded échelle spectra with the highest possible resolution over the whole visible range, from 390 nm to 681 nm. This was made possible by using a large and high angle of incidence diffraction échelle grating recently produced by Milton and Roy manufacture. To improve slit illumination stability an efficient double scrambler was included in the fiber-feed train. In addition ELODIE was uniquely equipped with a data reduction pipeline delivering radial velocity by numerical cross-correlation shortly after observation (Baranne *et al.*, 1996).

The development of an on-line data reduction pipeline, routinely delivering high precision radial velocities, was at that time a challenging task only made possible by the opportunity offered by the generous RAM and clock speed of newly available SPARC station mini computer by

FIG. 2. Middle cut of ELODIE image of a stellar spectra observed with simultaneous thorium recorded on the CCD. One clearly distinguishes the curved spectroscopic order of the stellar spectra from the interlaced emission spectrum due to simultaneous thorium lamp illuminating the second fiber.

Sun Microsystem. The ELODIE spectral information that is recorded on CCD is distributed over 67 curved and overlapping orders. This complex data structure of échelle spectra creates various software algorithmic challenges. For example, the spectroscopy resolution element was only about 10 $\mathrm{km\,s^{-1}}$, a thousand times bigger that the Doppler precision we were aiming at. Inspired by the work of Griffin Photometric Velocimeter and CORAVEL (Baranne, Mayor, and Poncet, 1979) implementation, software agorithms based on match filter (correlation mask) have been developed. These optimally combined together in an optimal way all of the Doppler spectroscopic information recorded on the spectra. The use of a reference fiber, fed by a thorium lamp during the exposure, produced a reference spectra the reduction pipeline was using to correct for mechanical variability and air index changes occurring between the time of wavelength calibrations and actual observations of stars (see Fig. 2). The implementation of "simultaneous referencing" was one of the cleverest tricks at the heart of data analysis to reach high precision in radial velocity measurements. The ELODIE spectrograph design and software development implemented with success a whole set of new concepts that have become standards in succeeding generations of stable spectrograph allowing further improvements in precision performances (Queloz *et al.*, 2001a; Plavchan *et al.*, 2015; Pepe *et al.*, 2018).

III. A PLANET THAT SHOULD NOT EXIST

A. 51 Pegasi

In spring 1994, with ELODIE barely operational, we started our survey. Our goal was to determine the occurrence of substellar companions in the solar neighborhood. Finding giant planets were not the only objective of the survey. It is worth recalling that in the '90s, the search for brown-dwarfs was a fashionable theme of research that stretched to the planet regime (Latham *et al.*, 1989; Marcy and Butler, 1994). Moreover our compelling need to make a convincing and realistic case for the Telescope Allocation Committee to obtain access to telescope observations could not be neglected.

The original target sample included 142 F,G,K main sequence stars Queloz *et al.* (1998) selected on the basis they were not spectroscopic binaries, located in a 25 pc neighborhood and—to our knowledge—not yet observed by another high precision Doppler survey. Our strategy was to start with a sample size significantly larger than the one previously observed by Campbell, Walker, and Yang (1988) that didn't succeed in detecting sub-stellar companions .

In autumn 1994, Michel Mayor (my Ph.D. advisor) literally left me keys of operation and went to Hawaii on sabbatical leave for a 6 month period. I was delighted and excited to be left in charge of the program, regularly going observing with ELODIE which I considered a bit as "my baby" and incidentally to gather more data for my Ph.D. which was due the year after.

In the original survey sample, we had previously identified 24 bright stars equally distributed in the sky. One would observe this subset a bit more frequently than others to serve us as precision validation. The star HD217014 known as 51 Peg was part of this group. We had an observing mission about every two months and they typically lasted one week.

In January 1995, it is fair to say that my first reaction was a moment of panic when I realized that the star HD217014 exhibited radial velocity variations larger than the sole effect of Doppler precision I expected from the spectroscopic information available. I thought something was going wrong in the spectrograph or with the data analysis. After days and nights anxiously spent alone checking any element, software step I could think about and gathering more data I eventually came to the only conclusion I could think about to explain the variability pattern: A planet of Jupiter mass is orbiting the star 51 Peg with a 4.25 d period corresponding to an orbital distance of 0.05 astronomical units. The planet is literally roasted and its atmosphere is 1000 K degrees hot. When retrospectively I think about it I realize how fearless and foolish this idea was, the privilege of an enthusiastic Ph.D. student.

When later I reported to Michel Mayor that I had found a planet, unsurprisingly he reacted with restrained enthusiasm. I think he couldn't believe it. That was fair enough. When we started the survey I still remember him telling me I should not expect to find any planets for my Ph.D., it would take years! He eventually changed his mind when additional radial velocity measurements collected in July 1995 confirmed my initial ephemerides based on previous observations.

We spent summer 1995 writing the paper to report our discovery. We had a fantastic challenge to overcome to convince our peers, considering our planet had no counterpart in the Solar System and no theoretical backup to explain a hot Jupiter configuration. Moreover ELODIE was a brand new challenger without yet any demonstrated results and the field was historically trapped with series of misjudgements and mistakes in data analysis. Finally, small changes in Doppler shift may potentially be due to stellar photosphere effects and explain our data as well. It was an impossible job! In the following years we would be confronted with a wave of skepticism. It would take years for the community at large to accept the reality of 51 Peg hot Jupiter and to modify of the paradigm about the universality of Solar System planetary architecture.

B. Alternative to planet hypothesis

The strongest resistance we faced about our interpretation was related to the fact that the measurement of radial velocity variation from stellar emerging spectra does not always imply the star is moving due to an orbiting planet. Convective transport of heat in Sun-like stars is carried out by about a million gas cells in motion with typical vertical velocities of kilometer-per-second. The resulting visible effect at stellar surface is described as "photosphere granulation." A magnetic field is generated from the sheer motion of the convection mechanism through the alpha-dynamo process, producing active regions on the photosphere that may display dark spots at the location of emerging strong magnetic field lines. Magnetic flux tubes form and decay on timescales typically comparable to the stellar rotation period and long-term magnetic cycles modify the convection patterns. The combined result of all these effects is to produce spectral lines of variable shape with underlying periodic and pseudo-periodic patterns. Practically, when measuring radial velocity, it is rather easy to observe variations produced by a combination of all these effects, in particular, when the star is young and active (Queloz *et al.*, 2001b).

In the discovery paper (Mayor and Queloz, 1995) we carefully addressed all possible ways to produce the observed changes in radial velocity by stellar atmospheric effects. We looked for records of photometric amplitude changes indicating a young and fast rotating star. We used the property of the correlation function to look for stellar line profile changes. We clearly ruled out all alternative origins by stellar atmosphere features but the idea of "hot Jupiter" planets was so awkward it had a hard time getting accepted. The main issue was that didn't fit in the planetary formation paradigm without seriously tweaking it. Changing a well established theory is rarely the first idea a physicist is considering out of an unusual experimental result. And yet the foundation of planet formation theory will need to be revised.

C. Challenging planetary formation

The process to form a planet is based on core accretion mechanisms in the disk. The underlying principle is a series of steps where a planet grows by stages by accreting material available in the disk. In early stages, proto-planetary disks are dominated by H and He gas. The disk also contains a small fraction of solids. Close to the star one finds refractory dust. In the outer part of the disk, "beyond snow lines" (Williams and Cieza, 2011), there is frozen ice originating from the solid phase transition of molecular gas (H_2O, CO, CO_2, CH_4,…).

In the disk, solid materials rapidly, dynamically decouple from the gas and settle down on the disk mid-plane where they agglomerate by sticking together. The result is a swarm of planetesimals that grow by collision amongst themselves to eventually form planetary embryos (Safronov and Zvjagina, 1969). The formation of giant planets proceeds from these embryos by accreting the gas left in the disk (Pollack *et al.*, 1996). The outcome depends on two competing processes: on one hand the dispersion of the gas disk, on the other hand the formation of a massive core big enough to efficiently accrete all the gas left around.

The fact that 90% of Jupiter's mass is made of H and He means that the core formed quick enough to accrete a significant amount of gas before it got dispersed. Such a favorable timing requires a high solid surface density of planetesimals available when the gas is still around. It is only encountered in the outer part of the disk at a few astronomical units (Lecar *et al.*, 2006). Therefore for the formation theory to account for the presence of close-in giant planets one must consider strong and efficient dynamical interaction with the disk (migration) and other massive bodies in the system to change the initial orbital configuration (Dawson and Johnson, 2018a). This element was never seriously considered or looked at by researchers working on planetary formation models despite being explicitly mentioned and computed fifteen years before (Goldreich and Tremaine, 1980). The '80s Goldreich &Tremaine paper prediction resurfaced at the time the first migration model was published (Lin, Bodenheimer, and Richardson, 1996), shortly after 51 Peg b was announced.

IV. A FEAST OF EXOPLANETS

I concluded my Ph.D. defence with a prophetic statement that the discovery of 51 Peg b exoplanet was just the tip of the iceberg and more planets of that kind would soon be detected. I simply couldn't believe we had by some extraordinary luck detected an extremely rare planetary configuration. I didn't have to wait long to be proven right.

A. Here comes the transit

A few months after the publication of 51 Peg b, two exoplanets detected by the radial velocity technique were announced (Butler and Marcy, 1996; Marcy and Butler, 1996). Three years later, eight exoplanets had been found, all with mass in the range of giant planets and three hot Jupiter planets (Marcy and Butler, 1998). Then in late 1999 a new hot Jupiter was found orbiting the star HD 209458 and luckily it happened to be transiting. This result, concluding on a similar interpretation from two independent techniques, had the final word and swept any reservations left on the reality of exoplanet discoveries (Charbonneau *et al.*, 2000; Mazeh *et al.*, 2000).

When the community realized that hot Jupiters truly existed, we saw blossoming dedicated exoplanet transit surveys (Pollacco *et al.*, 2006). A hot Jupiter exoplanet is 10 times smaller then our Sun and has a 10% chance to be seen with an orbital configuration aligned with its host star, making it a good target to look for transit by ground based differential photometry. The transit method provides us with an alternative to Doppler spectroscopy searches for planets. It allow us to derive the size of a planet instead of its mass.

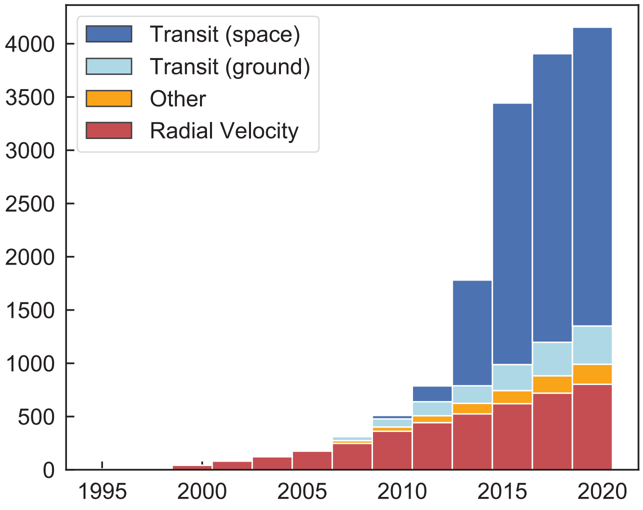

FIG. 3. Cumulative histogram of exoplanet discovery (Akeson *et al.*, 2013) trough time by various detection techniques. The spectacular growth of transit detection from space is due to the *Kepler* mission.

In 2006 the first exoplanet transit survey from space—COROT satellite—was launched and rapidly brought us evidence of the first rocky exoplanet COROT-7b (Leger *et al.*, 2009; Queloz *et al.*, 2009). The *Kepler* mission, launched three years later, eventually produced a stream of discoveries of small multi-planetary systems (Lissauer, Dawson, and Tremaine, 2014). In barely a decade, planet hunting activity went from repeated failures to an exoplanet gold rush, involving big survey and space missions carried out by large international consortiums. As a result of this rapid expansion of survey capabilities, the number of exoplanet detections spectacularly increased (see Fig. 3), lifting the veil on the extraordinary diverse exoplanet realm.

B. Change of perspectives

The discovery of the exoplanet 51 Peg b kick-started a new field of research of contemporary astrophysics. It acted as a stimulus to develop new instruments and observing facilities. A quarter century later, combined results from precise Doppler spectroscopy surveys, transit search space missions and wide field transit ground-based surveys have completely modified our perspective on the architecture and nature of planetary systems in the universe. We have learnt that our Solar System architecture is far from the norm. The wealth of diversity observed in exoplanet structures and orbital configurations (Fig. 4) is oddly contrasting with our Solar System.

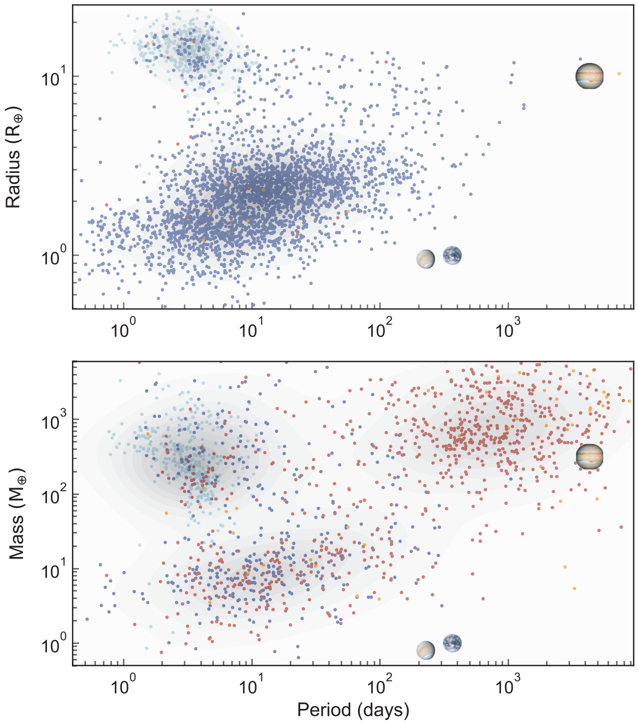

FIG. 4. Measured mass, radius and orbital period of all known exoplanets (Akeson *et al.*, 2013). Color code indicates techniques used to discover the planet (same as Fig. 3). For mass measured by Doppler spectroscopy $\sin i = 1$ is considered. Locations of Jupiter, Earth and Venus are indicated for the sake of comparison. A gray scale density map is overlaid to locate "cluster of similar exoplanets" on these diagrams

Transit and precise Doppler spectroscopic methods favor detection of exoplanets with short orbital period. The significant number of planets orbiting close to their star, so embarrassing for planetary formation theory, ironically turns out to be a fortunate situation from a detection point of view. It is fascinating to think that if the Solar System would be the norm, Fig. 4 would display few measurement points. The interest and spectacular growth of interested community would not be the same as what we see today.

Exoplanets with characteristics comparable to our Solar System planets are far more challenging to detect than most of the planets so far discovered. It explains the lack of an Earth-twin ("Goldilocks" planet) in current findings. By comparison to telluric planets a "Jupiter-twin" exoplanet is easier and within reach of Doppler surveys. It still needs a long term series of measurements and extensive telescope time access. In the near future, with the release of the *Gaia* mission the final catalogue (Fig. 4) is likely to display more data points in the mass-period region similar to Jupiter (Lattanzi and Sozzetti, 2010; Perryman *et al.*, 2014).

Measurement by transit method of the planet radius is efficient when the orbital period is short. For long period exoplanets, the probability to get the right geometrical alignment of line of sight is so negligibly low that it becomes impractical. This limitation is clearly visible in Fig. 4 by the increased scarcity of radius measurements gathered for exoplanets with orbital period typically longer than about 100 days.

In Fig. 4 three distinct groups of exoplanets are visible. The hot Jupiter population is the group of giant planets found in a short period (less than 10 days), with 51 Peg b its most emblematic member. On the colder end, farther out, one finds "classical" giant planets like our own Jupiter. Then one sees a cluster of smaller exoplanets mostly on short orbit, casually named "super Earth" or "mini-Neptune" compact systems. This group of planets is a mixed bag of anything fitting in a range defined on one side by Earth's physical characteristics and on the other side by Neptune.

Detailed statistical analysis of the occurrence of each group of exoplanets is not a trivial task. The apparent number of discoveries can't be simply converted to the occurrence of each type of exoplanet per star. Limitations of the techniques used to detect them and diversity of thresholds of each survey considered needs to be carefully taken into account to produce a robust result (Winn, 2018). Hot Jupiter planets, easy to detect by both techniques, are actually not that frequently found orbiting stars. An average occurrence rate of 1% is derived, with a tendency to be more frequently present when the host star's metallicity is higher (Santos, Israelian, and Mayor, 2001). The occurrence of cold Jupiters is about 10% for Jupiter analogs (Winn, 2018). If a broader definition is considered, including any exoplanet more massive than Neptune and up to 20 M_{j} planets, the occurrence rises almost to 50%. Note that this large group of exoplanets clearly distinguishes themselves from outer planets of our Solar System with a wider range of orbital eccentricities. The planetary configuration corresponding to the group of "super Earth & mini-Neptune" exoplanets seem to be the most commonly found configuration in our galaxy. One derives,

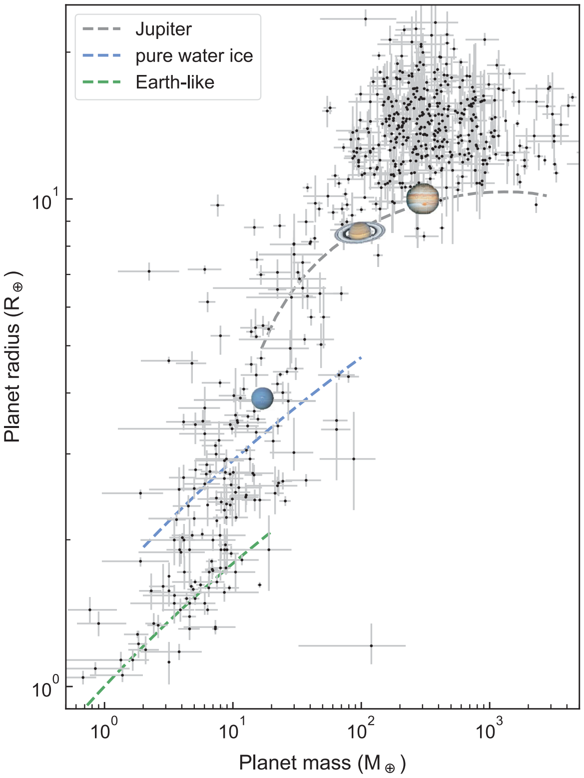

FIG. 5. All known exoplanets (Akeson *et al.*, 2013) with a measurement of their mass and radius. Hatched lines indicates model of bulk density for three different compositions. Jupiter, Saturn and Neptune are indicated for the sake of comparison.

on average, an occurrence of about 60% per star with orbital periods less than 100 days (Fulton and Petigura, 2018). The discovery of such a massive population of planets at short periods is a challenge to planetary formation theory. It is understood as a failure to properly account for dynamical effects occurring during the planet formation (Winn and Fabrycky, 2014). It raises as well the perplexing possibility that our Solar System's configuration may be far less common than expected.

C. Exoplanetary science begins

The exoplanet discovery bonanza not only unveiled the diversity of planetary orbital configurations but also a large range of physical structures. The combination of transit and precise Doppler spectroscopy allows us to measure exoplanet bulk density and to gain insights on the structure of planet interiors. The mass and radius measurement diagram in Fig. 5 displays all exoplanets for which these two physical parameters have been measured as well as a set of superimposed computed bulk density relations for different planet interiors (Fortney, Marley, and Barnes, 2007).

The computed bulk density for hydrogen-helium composition dominated planets, applicable to Jupiter, lies on the lower value boundary of observed giant exoplanet densities. The fact that most giant planet measurements displayed on this diagram indicate lower densities than Jupiter's is the consequence of a bias that favors short period exoplanet detections, and the fact that hot Jupiter planet diameters are observed to be inflated (Guillot and Gautier, 2009). Some exoplanets have been found with barely 10% Jupiter bulk density (Anderson *et al.*, 2010). Physical mechanisms at the origins of their bloated nature may be related to the combination of different effects due to their proximity to their host star and their formation process (Dawson and Johnson, 2018b).

In the case of exoplanets with mass smaller than Saturn, for any given range, computed bulk density shows a large dispersion, suggesting a mixture of planet interior structures. Some exoplanets have a bulk density that could be understood as a down-scaling extrapolation of Jupiter's interior. Others with denser values can be modeled by decreasing the value of H and He to 10% and increasing "heavy" elements (such as H_2O, NH_3, CO_2,…) in planet interiors like in the planet interiors of Uranus and Neptune for example. Going farther down in the sub-Saturn mass range one finds exoplanets having bulk density too high to be simply accounted by down-scaling Jupiter or Neptune planetary interiors. New structures without H and He should be considered.

The core accretion planet formation scenario produces a composite interior structure with schematically three distinct layers: core (densest component), envelope and atmosphere (visible part). The level of freedom that one can play with by balancing these three components produces naturally a confusing range of bulk density values. Practically a given bulk density can correspond to different ratios between these components. To simplify the interpretation in Fig. 5 is displayed a "pure ice" hypothetical planet model. It is revealing to compare it with Earth-like bulk structure extrapolated in the same mass range. The group of exoplanets in the super-Earth & mini-Neptune range (Fig. 5) exhibits a large dispersion suggesting an underlying diversity of planetary models. For example some planets with 5 $M_\oplus$ have been found compatible with Earth-like bulk density, while others with Neptune-like structures. This situation is reflected by the fact that for that group of planets we do not observe a direct relation between mass and radius. A careful inspection of this diagram would demonstrate the statistical significance of two groups of bulk density structures: One more "water-like" and the other more "Earth-like" (Fulton and Petigura, 2018). This suggests the super-Earth & mini-Neptune exoplanet category is potentially a group of mixed origins with different interior compositions (Neil and Rogers, 2019).

V. PROSPECTS

The fascinating diversity of bulk density encountered amongst compact super-Earth & mini-Neptune exoplanets and the fact they have no equivalent to be readily compared with Solar System planets is a challenge to model their interior as well as to trace their origins. Fortunately it is likely to change with the launch of the JWST space telescope and availability of large ground-based facilities currently in construction (like, for example, ELT). Using transit spectroscopy observations and occultation combined-light techniques, it will be possible to learn far more on these exoplanets (Winn, 2010). Insights about atmospheric and surface composition

(Demory *et al.*, 2016; Kreidberg *et al.*, 2019) will offer an exciting opportunity to clarify their nature and their origins.

The imminent prospect to measure atmospheric features of small transiting exoplanets opens the fascinating possibility to address the remote detection of life on these systems. The habitable zone that expresses a range of distances from its host star to maintain liquid water (Hart, 1978) is largely considered as a minimum condition for an exoplanet orbit to be of potential interest for the purpose to search for bio-markers (Kaltenegger, 2019).

Practically, the concept of habitable zones is a guideline for planning future observations. The habitable zone assumes an *ad hoc* atmosphere and planetary surface conditions (Kopparapu *et al.*, 2013) and scaled the illumination S_{eff} received by the planet to maintain liquid water (assuming water is present…). For small and cooler stars (M dwarfs) the inner boundary of the habitable zone gets close enough to overlap the range of short period small exoplanets discovered. Amongst them, the recent confirmation of rocky planets with a bulk density similar to the Earth (Gillon *et al.*, 2017; Grimm *et al.*, 2018), located in the habitable zone, reasonably questions the possibility of life on these systems. The prospect to eventually get insights on the atmosphere and geochemical conditions on these systems draws attention beyond the usual astronomy community.

Answering the big question about life on exoplanets will require a combined effort between astrophysics, planetary scientists, geophysicists, biochemists and molecular biologists. Recent developments on the origin of life on Earth (Sasselov, Grotzinger, and Sutherland, 2020) as a planetary phenomenon and its relevance to the search for life on another planet is steering us on a new exciting research route. Current efforts to identify true Earth-twin planetary systems on nearby stars (Hall *et al.*, 2018) will eventually lead to the development of a series of research programs and future facilities to look for bio-signatures and to address the origin, nature, and prevalence of life in the universe. Near us, Mars, Venus and satellites of giant planets in our Solar System are obvious locations to look closer for life signatures.

The discovery of the exoplanet realm is an extraordinary moment in mankind's pursuit of knowledge and natural inclination to be curious. It follows the steps of the Copernican revolution, extending it further out by placing our Solar System amongst countless planetary systems and by addressing the physical conditions conducive to the emergence of life. The large diversity and high occurrence of exoplanets orbiting stars in our galaxy offers so many opportunities for the chemistry of life to happen, eventually we shall detect it on another planet. It is just a matter of time.

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