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[redacted] most of them in [redacted] own solar system. The [redacted] at planetary systems are [redacted] properties. As the number of [redacted] of exoplanets and their host stars [redacted] ical and chemical processes leading to

[redacted] the [redacted] our own [redacted] around the p [redacted] ter years of false st [redacted] nouncements, it was th [redacted] ve evidence had finally b [redacted] aller orbiting bodies in dis- ta [redacted] onments. At the same time, [redacted] e no [redacted] anything like our own Sun, and [redacted] planets orbiting them would not be expected to harbor life as in our solar system. For this reason, researchers had long been eager to observe planets in orbit around Sun-like stars, and in 1995, a first planet was detected around the star 51 Pegasi (2, 3). Since then, more than 150 other planets [redacted] these discovered, or at least confirmed, with radial-velocity techniques (4), in which the stellar wobble of the star moving about the center of mass of the star-planet system is measured with spectral Doppler information. These discoveries have advanced our understanding of planet dynamics and planet formation.

The increase in precision and continuity of the current radial-velocity surveys has given astronomers the possibility of unveiling a large variety of planets. In less than 10 years, the lowest known detectable planetary mass has decreased by more than one order of magnitude (Fig. 1), reflecting the jump in measurement precision from ~10 m s^{-1} to ~3 m s^{-1} at the end of the century (5), and more recently crossing the barrier of 1 m s^{-1} precision with state-of-the-art spectrometers such as the High Accuracy Radial Velocity Planet Searcher (HARPS) (6).

About 10% of the discovered exoplanets have an orbital period of less than 5 days. These planets are easier to detect because they require le
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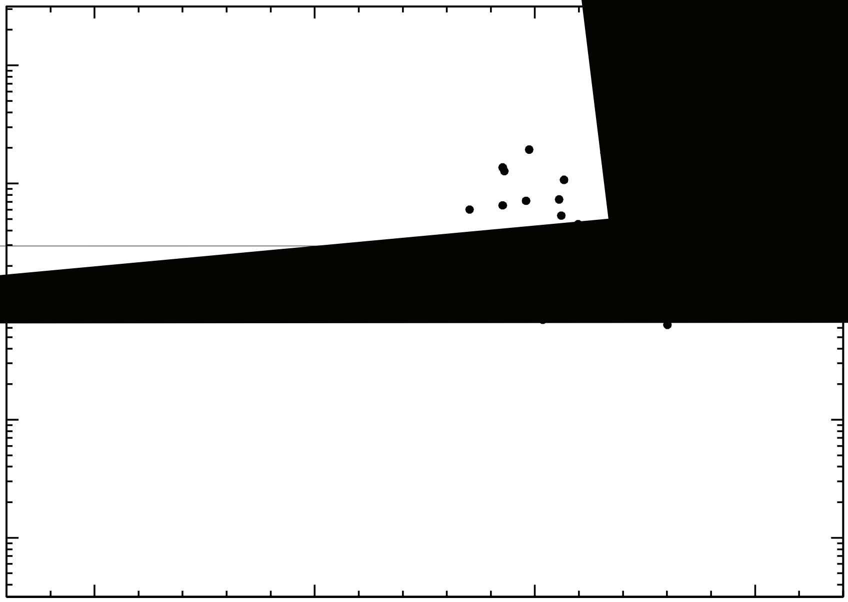

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*To whom correspondence should be addressed. E-mail: nuno.santos@oal.ul.pt centric orbits (*10*) more typical of some comets in the solar system, whereas others are in multiple planet systems (*11*). Finally, although the most recently discovered planets have masses only one order of magnitude larger than Earth (*11–13*), some behemoths have more than 15 times the mass of Jupiter (*14*). It is not clear whether the more massive of these companions should be classified as planets at all. According to the pre-1995 planet formation theories, none of these objects were supposed to exist.

To understand the meaning of these observations, models of planetary system formation and evolution are required. One giant planet formation scenario is the core accretion model. In this model, a solid core is first formed by the accretion of planetesimals. As the core grows, it eventually becomes massive enough to gravitationally bind some of the nebular gas, thus surrounding itself with an envelope. The subsequent evolution of this core-envelope structure has been studied in detail (*7*), and it has been shown that the solid core and the gaseous envelope grow in mass, the envelope remaining in quasistatic and thermal equilibrium. During this phase, the energy radiated by the gas is supplied by energy released from the accretion of planetesimals. As the core mass reaches a critical value [of the order of 15 Earth masses ($M_{\oplus}$) at 5 astronomical units (AU), but depending on different physical parameters, such as the solid accretion rate onto the core], radiative losses can no longer be offset by planetesimal accretion and the envelope starts to contract. This increases the gas accretion rate, which in turn raises the radiative energy losses, causing the process to accelerate, leading to the very rapid buildup of a massive envelope.

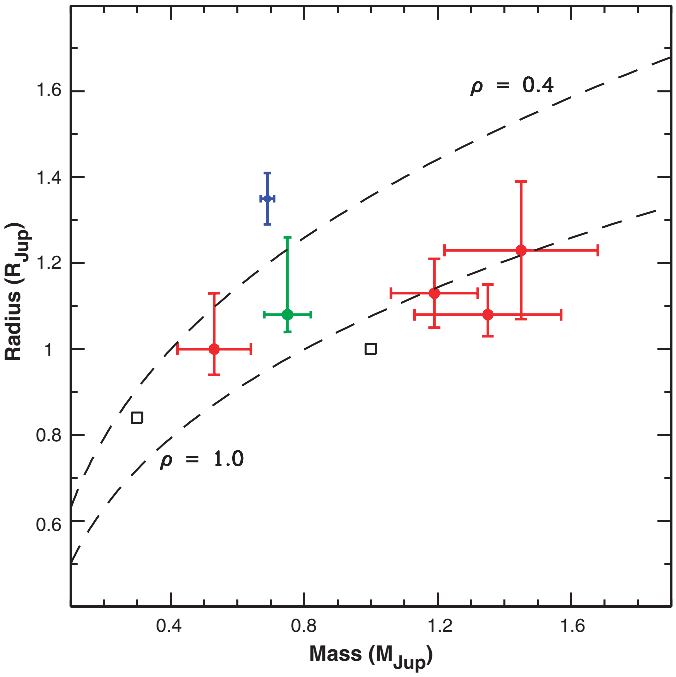

Fig. 2. Mass-radius diagram for the giant planet companions for which a transit event has been detected. Red symbols denote planets discovered by the OGLE survey (*8*, *40*, *48*), the green symbol denotes the planet orbiting the star TrEs-1 (*49*), and the blue symbol denotes HD 209458 b (*46*). The positions of Jupiter and Saturn are also marked (black open squares). Two isodensity curves, with densities ρ of 0.4 and 1.0 g cm^{-3}, are also shown for comparison. The planet orbiting HD 209458 presents the most anomalous (low) mean density.

Paramount to this model is the growth of a critical core before the disappearance of the protoplanetary disk. The lifetime of these disks can be estimated from astronomical observations by relating the total mass of the disks (*15*) to the mass accretion rate (*16*). This yields a lifetime for these objects of 1 to 10 million years, in agreement with the frequency of disks in open clusters of different ages (*17*). Because this lifetime is of the same order, if not smaller, than the planet formation time scale, a fast growth of the core beyond the critical mass is essential. Calculations by Pollack *et al.* (*7*) showed that this formation time scale is extremely sensitive to the assumed disk surface density and that only relatively high values will yield giant planets within the disk's lifetime. Recent extensions of the core accretion model, including disk evolution and planet migration (*18*), have shown that, provided the planet survives, migration speeds up core growth, resulting in giant planet formation well within the inferred disk lifetimes.

In the direct collapse scenario (*19*), giant planets form directly from the gravitational fragmentation and collapse of the protoplanetary disk within a few dynamical time scales. Although this is an appealing feature that greatly simplifies a number of complicated processes, this model has its own difficulties as well. For example, high-resolution simulations of this process show that planets tend to form on elliptical orbits at distances of several astronomical units and masses between 1 and 7 Jupiter masses (M_{Jup}). Smaller mass planets would result from the evaporation of these objects by nearby hot type O and B stars (*20*). Furthermore, the enrichment in heavy elements as measured in the atmospheres of Jupiter and Saturn might be difficult to explain, as massive bodies eject many more planetesimals than they actually accrete (*21*). Finally, any sizable inner core will have to be built by the accretion of very large objects, because smaller ones will invariably be destroyed while plunging through the envelope.

In summary, two formation paradigms are currently being critically examined. The core accretion model is sufficiently advanced to begin to allow quantitative calculations to be made and thus permits a direct comparison with giant planets in (*22*) and outside (*21*) our solar system. The direct collapse model is in a state where only qualitative statements can be made without the possibility to compare quantitatively with observations.

Having at first painfully exposed our still sizable lack of understanding, the growing number of exoplanets discovered is now allowing a statistical analysis of their properties (*10*, *23–26*) as well as those of their host stars (*27*, *28*), thereby providing invaluable constraints on the physical and chemical processes involved in the formation of these systems.

Statistical Properties of Exoplanets

Before 1995, all our understanding of planet formation was based on studies of one system, the solar system. The failure of our theories to explain the diversity of the more than 150 exoplanets has markedly shown the necessity for further observational guidance. In the case of the solar system, this guidance is provided by in situ measurements that allow a detailed study of structure, composition, isotopic abundances, and often time scales. In the case of the exoplanets, this guidance is provided by a careful statistical analysis of the distribution of masses, periods, and orbital eccentricity, as well as of the chemical properties of the host star. Both approaches are needed.

The existence of giant planets with orbital periods of less than ~10 days, the so-called "hot Jupiters," poses important difficulties to conventional as well as unconventional giant planet formation scenarios. The most important is related to the high temperatures in these regions, which either prevent the condensation of enough solids to form a core capable of accreting several hundred Earth masses of gas during the lifetime of the disk or simply inhibit direct collapse. To circumvent this, migration of planets over relatively large distances is often invoked. Close-in planets may have formed at large distances and then migrated inward. Thus, the existence of "hot Jupiters" has forced on us the concept that the current locations of planets may have little to do with their birthplaces.

Migration can be due to several physical processes such as gravitational scattering in multiple systems (*29*) or gravitational interactions between the gaseous and/or the planetesimal disk and the planet (*30*, *31*). These two mechanisms must necessarily occur, and interactions between an embedded planet and a gaseous disk were discussed before the discovery of the first exoplanet (*32*). The question is therefore not whether migration takes place or not but rather what its direction and amplitude are.

Two types of migration modes have been identified, depending on whether the planet is massive enough to open a gap in the disk (type II migration) or not (type I migration) (*30*, *33*–*35*). All these migration models conclude that planets are migrating mostly inward toward the star, over large distances and fast. In fact, migration time scales obtained so far are so short (especially for type I migration) that, in almost all cases, planets should not survive but should fall into their host star (*36*, *37*). Because planets are actually observed in large numbers and at various distances to their stars, two conclusions can be drawn: Either our migration theory is still incomplete or core accretion is not the way most planets form. Because new ideas for slowing down migration are emerging (*21*) and because core accretion models based on a slower rate are capable of meeting quantitative tests (*22*), we rather favor the first hypothesis.

Evidence of a mechanism halting the inward migration of planets at short distances may be deduced from the observed overabundance of systems with periods around 3 days, whereas for smaller orbital periods, only a few cases exist (*38*). This result contrasts with the period distribution of stellar companions for which periods much shorter than 3 days exist.

The physical mechanism responsible for halting and parking the planet at short distances from the host star is still being debated. Possible mechanisms include the existence of a central cavity in the disk, tidal interaction with a fast-spinning host star, or even Roche lobe overflow (*36*). Another possibility is that planets venturing closer are photoevaporated by the radiation field emitted by the host star, thus becoming too small to be detected or vanishing altogether (*39*). The case of the few new OGLE (Optical Gravitational Lensing Experiment) transiting planets (*8*, *40*) having orbital periods of less than 2 days may in this context be interpreted as the tail of the short-period planets distribution (*38*).

Although these stopping mechanisms are relevant at short distances, they do not explain why giant planets are found at intermediate distances (e.g., with periods around 1 year) nor why Jupiter, for example, has apparently remained beyond 5 AU. In fact, the recent addition of disk evolution and planetary migration mechanisms into the core-accretion models suggests that planets essentially migrate until the disk disappears (in fact, until the disk becomes much less massive than the planet) (*18*, *21*). In this picture, the diversity results from the distribution of parameters such as the disk masses, lifetimes, disk processes, photoevaporation, and number of planets formed. Unfortunately, none of these parameters are precisely known, and it may even be that planetary formation itself is providing a feedback mechanism (*41*).

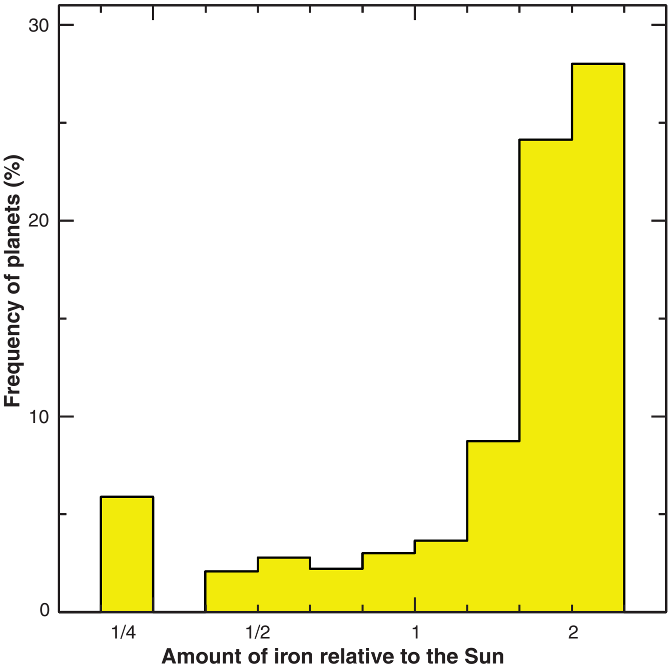

Fig. 3. Percentage of stars that were found to have planets among the Geneva planet search survey sample as a function of the relative amount of iron (i.e., metallicity) with respect to the Sun. This figure shows that ~25% of the stars with twice the solar metallicity harbor a planetary mass companion, whereas this percentage decreases to below 5% for stars with the same metal content as our Sun (*53*).

The observed period distribution of planetary companions may be telling us something about these issues (*23*, *25*). There seems to be a paucity of high-mass planetary companions with orbital periods shorter than ~40 days. Current statistical analysis suggests that the migration of a planet may be strongly related to its mass or even to the presence of other stellar companions (*24*, *25*).

The analysis of the mass distribution of companions to solar-type stars with orbital periods shorter than 3000 days indicates that although the radial-velocity technique is more sensitive to massive companions, the frequency of discovered planets increases as a function of decreasing mass (*42*). Furthermore, this distribution falls to a value close to zero for masses between about 10 and 20 times the mass of Jupiter. From 20 to 60 M_{Jup}, there is then a scarcity of companions to solar-type stars. This gap, usually called the brown dwarf desert (*43*), separates the lower mass planetary companions from their higher mass stellar counterparts, including brown dwarfs, considered to be failed stars. Together with the shape of the mass distribution, this suggests a different formation mechanism between low-mass companions to solar-type stars and planetary systems.

The analysis of the orbital eccentricity distribution also indicates that the measured values range from ~0 to more than 0.9, a range similar to the one found in binary stars. However, recent analysis (*10*) suggests that planetary systems have on average a lower eccentricity than multiple stellar systems. Although this might be interpreted as the signature of a different formation mechanism, it is worth pointing out that these high eccentricities cannot be accounted for in the standard formation model of giant planet formation. Eccentricity pumping mechanisms such as interactions in multiple systems (*44*, *45*) or the interactions between the planet and the disk of planetesimals (*45*) have to be invoked to explain these high eccentricities.

Transiting Planets: Probing the Planet Structure

So far, most of the known extrasolar planets have been detected with radial-velocity techniques. Alone, this gives us information only about the orbital parameters of the planets and their minimum masses but nothing about their physical properties such as radius or mean density. Fortunately, the recent detection of several cases (*8*, *40*, *46*–*49*) of photometric transits as the planets pass in front of their host stars, thus blocking part of the stellar light, has provided us with additional information to derive these quantities (Table 1).

These discoveries have also raised further interesting and troubling issues. For example, among the six confirmed transiting planets, HD 209458 has a mean density much smaller than that of the others (Fig. 2). Furthermore, the planets with shorter orbital periods are also the most massive ones, indicating that there might be a relation between planet mass and orbital period (*50*).

In addition to the internal structure, the detection of transiting planets opens a new possibility to study planetary atmospheres.

When a planet crosses the stellar disk, its upper atmosphere acts as a filter, absorbing the light coming from the star at preferential wavelengths that correspond to atomic or molecular transitions occurring in its atmosphere. Because of this effect, sodium absorption features were detected in the atmosphere of the planet orbiting HD 209458 (*51*). Further observations have also recently suggested that this giant planet is evaporating, as carbon and oxygen atoms are blown away along with its hydrodynamically escaping hydrogen atmosphere (*52*).

The Stars Hosting Planets

The study of the stars hosting planets has also found an unexpected correlation, the importance of which to planet formation is recognized even though its full implications have not yet been understood. Host stars have, on average, a higher metal content than stars with no planetary companions detected (*27*, *28*). In other words, these stars have a higher ratio of heavy elements to hydrogen than that observed in average solar-type field stars. The most recent studies have confirmed this correlation and shown that the observed trend cannot be due to any sampling or observational bias (*53*). More than 20% of stars with metallicity greater than two times the solar metallicity harbor a planet, whereas only ~3% of stars with solar metallicity have a giant planet (Fig. 3) (*28*, *53*, *54*). However, this does not imply that giant planets cannot be formed around more metal-poor stars. Rather, it suggests that the probability of formation in such a case is substantially lower (*55*). Indeed, there is a hint that, for lower metallicity values, the frequency of planets may remain relatively constant (*53*) as a function of the stellar metallicity. Whether this reflects the presence of two different regimes of a low metallicity tail is currently under debate, and more data will be needed before this question can be answered.

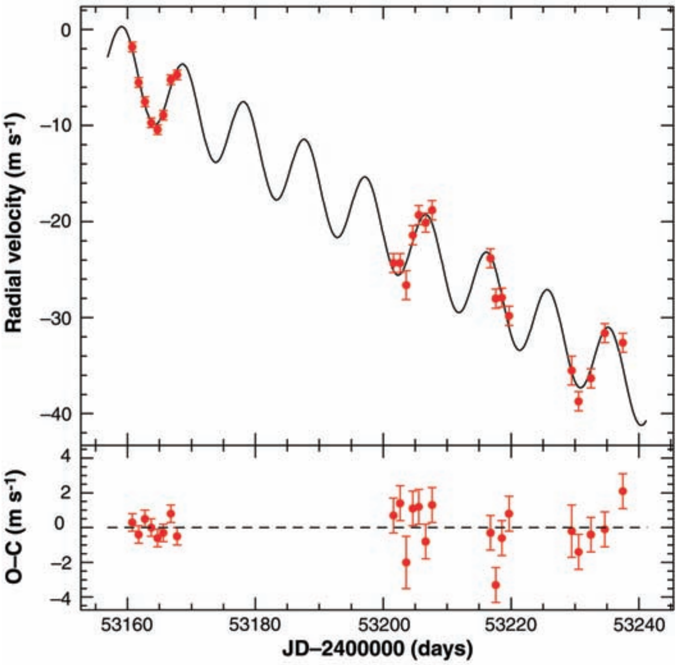

Fig. 4. Radial-velocity measurements of μ Ara as a function of time, as obtained with the HARPS spectrograph (*6*). The solid line represents the best fit to the data, obtained with the sum of a Keplerian function and a linear trend. This latter represents the effect of the long-period companions to the system (one, or possibly two other giant planets are known to orbit this star). The residuals of the fit, with a root mean square of only 0.9 m s^{-1}, are shown in the lower panel. [Adapted from Santos *et al.* (*12*)]

Although pollution of the star by infalling planetary material has been suggested to explain the higher metallicities (*27*, *56*), it is now believed that the stellar surface abundance is a relic of the original elemental abundance in the gas clouds that gave birth to the stars and the planets (*57*). In other words, this implies that planetary formation, at least for the kind of planets that have been discovered so far, is far more likely in a metal-rich environment. Alternatively, the metallicity could be increasing the migration rates of the giant planets. In such a case, we could be simply discovering those planets with periods that are relatively short, and thus, those bodies orbiting metal-rich stars. This possibility receives some support from the possible (weak) correlation found between the stellar metal content and the orbital period of the planets (*27*, *58*). However, recent models suggest that such an influence is probably not strong enough to effectively change the migration rates (*59*), which are already much faster than the traditional planet formation process itself.

More heavy elements should, in principle, lead to faster core growth and therefore to an easier formation of giant planets in the core accretion scenario. Models have been proposed that claim to explain quantitatively this correlation (*55*), even though many details are still not clearly accounted for. In the direct collapse model, the connection would need to be a more subtle one in which metallicity affects the ability to collapse, that is, to radiate energy. So far, calculations (*19*) indicate that collapse is insensitive to metallicity. Therefore, in this formation scenario, the observed correlation between stellar metallicity and likelihood of hosting a planet would have to be due to pollution by ingested planetary material. As a consequence, it seems that current results support core accretion as the main process leading to the formation of the now-discovered planets. However, disk instability is not excluded as a viable way to form planets, in particular around metal-poor stars.

After All, What Is a Planet?

All these odd properties of the exoplanets have contributed to a change in the definition of planet. The answer to the question ''what is a planet?'' is not even clear at this moment. For example, the dividing line between low-mass stars (e.g., brown dwarfs) and planets seems to be rather uncertain, and it may be that bodies formed as planets may have a mass in the brown-dwarf regime (≥13 M_{Jup}) (*60*), and vice versa.

Although no consensus exists, and a clear definition of planet has not been agreed on, the International Astronomical Union (IAU) has proposed a working definition (*61*), based on three major points: (i) Objects with masses below the limiting mass for thermonuclear fusion of deuterium, currently calculated to be near 13 M_{Jup} for objects of solar metallicity (*60*), that orbit stars or stellar remnants are planets (no matter how they formed). The minimum mass or size required for an object to be considered a planet should be the same as that used in the solar system. (ii) Substellar objects with masses above the limiting mass for thermonuclear fusion of deuterium are brown dwarfs, no matter how they formed or where they are located. (iii) Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not planets but are sub–brown dwarfs (or whatever name is most appropriate).

We should mention that, according to this definition, a very low mass object formed by the gravitational collapse of a molecular cloud, separated by ~50 AU from a low mass star, should be considered a planet. These kinds of objects have been found, and if we take this definition strictly, the first image of a planet orbiting another star may have been obtained (*62*). However, it seems unlikely that a giant planet could have been formed in a low mass disk at such a large distance from its host star, in this case (*62*) a brown dwarf itself, in a reasonable time scale (*7*). The 13-M_{Jup} limit also seems to us to be no more than an arbitrary limit used as a possible ''definition'' and is probably not related to the planetary/stellar formation physics.

Toward Other Earths

The discovery of numerous giant planets orbiting other solar-type stars has demonstrated that planet formation is a common process. By extension, these detections suggest that Earth-like planets might be just as common. Although the detection of an Earth-like planet is probably beyond the reach of current techniques, the discovery in August 2004 of two planets (*11*, *12*) with a minimum mass of $\sim$14 $M_\oplus$ orbiting Sun-like stars (μ Ara c and 55 Cnc e) (Fig. 4), as well as of a slightly more massive exoplanet orbiting the M dwarf GJ 436 (*13*) (with a minimum mass of 21 $M_\oplus$), implies that we are only a factor of 10 in mass away from this goal. The former two of these planets have short-period (10-day) orbits and circle metal-rich solar-type dwarfs. Their orbital characteristics and masses, together with state-of-the-art models of planet formation (*18*), suggest that there might be two channels to account for their existence: one in which a large mass object has been evaporated to the present mass and another one in which the object never grew larger. In the latter case, because these objects probably could not have migrated too far, the exact location of the ice line during their accretion, which might be closer to the star than previously thought (*63*), is required to infer their composition.

μ Ara and 55 Cnc were the only two stars that were surveyed with high enough precision to allow the detection of such low-mass bodies around a ''solar mass'' star. This may imply that low-mass short-period planets are common. Very low mass planets like the ones orbiting μ Ara c and 55 Cnc e will be the prime targets for satellites like Convection Rotation and Planetary Transits (COROT) and Kepler (*64*).

Once Earth-like planets orbiting in the habitable zone are known, the search for life in these systems will undoubtedly follow. The question of the existence of life is too important to be ignored even if the technology required and the cost involved are currently still staggering. Hence, future space missions will have to be launched that are capable of remotely sensing the presence of life. The space interferometers Darwin (ESA) and the Terrestrial Planet Finder (NASA) are precisely such missions. Using optical coronography and nulling interferometry techniques (to remove the light from the target stars, leaving only the photons coming from the planet), these missions will be capable of detecting the spectroscopic signatures of life in the atmospheres of these planets.

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