Chapter 10
The First Thousand Exoplanets: Twenty Years of Excitement and Discovery

Chris Impey

Abstract The recent "explosion" in the number of extrasolar planets, or exoplanets, is perhaps the most exciting phenomenon in all of science. Two decades ago, no planets were known beyond the Solar System, and now there are more than 770 confirmed exoplanets and several thousand more candidates, while the mass detection limit has marched steadily downwards from Jupiter mass in 1995 to Neptune mass in the early 2000s to Earth mass now. The vast majority of these exoplanets are detected indirectly, by their gravitational influence on the parent star or the partial eclipse they cause when they periodically pass in front of it. Doppler detection of the planet's reflex motion yields a period and an estimate of the mass, while transits or eclipses yield the size. Exoplanet detection taxes the best observatories in space, yet useful contributions can be made by amateur astronomers armed with 6-inch telescopes. The early discoveries were surprising; no one predicted "hot Jupiters" or the wild diversity of exoplanet properties that has been seen. It is still unclear if the Solar System is "typical" or not, but at current detection limits at least 10 % of Sun-like stars harbor planets and architectures similar to the Solar System are now being found. Over a hundred multiple planet systems are known and the data are consistent with every star in the Milky Way having at least one planet, with an implication of millions of habitable, Earth-like planets, and of which could harbor life. Doppler and transit data can be combined to give average density, and additional methods are beginning to give diagnostics of atmospheric composition. When this work can be extended to rocky and low mass exoplanets, and the imprint of biology on a global atmosphere can be measured, this might be the way that life beyond Earth is finally detected for the first time.

C. Impey (✉)
Department of Astronomy, University of Arizona, Tucson, AZ, USA
e-mail: cimpey@as.arizona.edu

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10.1 Introduction

The recent “explosion” in the number of extrasolar planets, or exoplanets, is perhaps the most exciting phenomenon in all of science. Two decades ago, no planets were known beyond the Solar System, and more than a few researchers had been burned by claims of detections that did not hold up, while many others had given up on the chase. When a planet with half the mass of Jupiter was found whipping around the star 51 Peg every 4 days, it was a stunning surprise (Mayor and Queloz 1995). We should, however, spare some surprise for the earlier discovery of planets around a pulsar, demonstrating that expectations are meant to be defied in astrobiology (Wolszczan and Frail 1992). Since 1995, the number of confirmed exoplanets has had a doubling time of 30 months. When the burgeoning number of candidates from NASA’s Kepler satellite is included, the number of exoplanets soared through a thousand early in 2012. Alongside these growing numbers is the steady downward March of the detection limit from Jupiter mass in 1995 to Neptune mass in the early 2000s to Earth mass now. History has not prepared us for what we have learned about distant planets (Raulin Cerceau 2013). The pace of progress and discovery has been dizzying even for experts in the field.

10.2 The Detection Problem

For centuries, scientists and philosophers speculated about the existence of planets around other stars (see other contributions in this volume). Once the Copernican revolution displaced the Earth from the center of the universe and it became one rocky body orbiting a normal star, the Principle of Mediocrity suggested that other Solar Systems should exist. By extension, this heuristic suggests the existence of planets similar to ours, and fuels expectations of life on beyond Earth and hence the whole subject of astrobiology.

To understand the challenge of exoplanet detection, consider a scale model. If the Sun is a glowing ball of plasma ten feet across, the Earth is a large blue-white marble 400 yards away and Jupiter is a pale yellow sphere the size of a beach ball just over a mile away. On this scale, the Solar System is 20 miles across, while the nearest Sun-like star would be another ten-foot glowing plasma ball 50–100,000 miles away. Looking towards that nearest Sun-like star, a giant planet like Jupiter would reflect a billionth of the star’s light and an Earth five times less, and both would be buried in the glare of the star, since their angular separation is less than the blurring of the star image seen through a telescope. Planets can also be detected by the reflex motion they induce on the star they orbit. In our Solar System, Jupiter causes the Sun to pirouette around its edge, a ten-foot wobble that would be imperceptible from thousands of miles away. The periodic Doppler motion induced on the star is also subtle, 11 m/s for Jupiter and 10 cm/s for the Earth, equivalent to a very slow walking speed. As fractions of the speed of light, these are four parts in a billion for Jupiter and a 100 times less for the Earth.

10.3 Failure and Frustration

Success in the search for exoplanets did not come easily or quickly. In the nineteenth century, unexplained motions of the binary star 70 Ophiuchus were attributed to a planet, and in the mid-twentieth century, Peter van de Kamp claimed to have detected a wobble of the nearby red dwarf Barnard's Star caused by a Jupiter-mass planet (van de Kamp 1969). That claim was discredited, although ironically, the Kepler team reported in 2012 the smallest exoplanets yet detected orbiting a red dwarf very similar to Barnard's Star. In 1988, Bruce Campbell and his collaborators published radial velocity evidence of a planetary companion to Gamma Cephei, though they used cautious language in their paper (Campbell et al. 1988). The interpretation of the evidence was called into question and it was 15 years before an exoplanet was confirmed in this system (Hatzes et al. 2003). An object times times Jupiter's mass was discovered in 1989 (Latham 1989), but uncertainty in its inferred properties mean that it might be a brown dwarf rather than a planet. In the second half of the 20th century, the stuttering progress in the search for exoplanets mirrored the development of astrobiology as a field (Dick 2013).

Pulsar timing provides an unusual window onto exoplanets. Pulsars are the collapsed, rapidly-spinning remnants of massive stars, and their rotation is so irregular that anomalies can be measured to a precision of one part in a trillion, allowing orbiting planets as slight as a tenth of the Earth's mass to be detected. A pulsar planet announced in 1991 received much publicity, but the claim was subsequently retracted. Yet the following year, Wolszczan and Frail (1992) found two Earth-mass planets around the millisecond pulsar PSR B1257+12, and that claim has stood the test of time, including the subsequent discovery of a third Moon-mass body. These radio astronomershad succeeded in find the first planet-mass objects beyond the Solar System, yet they experienced a strange kind of failure when the rest of the community seemed to relegate pulsar planets to the status of an exotic anomaly. Alan Boss (2009), Mike Perryman (2011) and Ray Jayawardhana (2011) have detailed at length the winding road that led to the first bona fide detection of a planet orbiting a main sequence star like the Sun. For interviews with many of the leading players, see Impey (2010).

10.4 The First Discoveries

The age of exoplanet discovery was formally ushered in on October 6, 1995, when Michel Mayor and Didier Queloz of the Geneva Observatory announced the discovery of an exoplanet half Jupiter's mass orbiting the G star 51 Pegasi (Mayor and Queloz 1995). While the exoplanet was unseen and only detected by the Doppler method, the 50 light years distant star was bright enough to be visible to the naked eye. News of the discovery must have been rather bittersweet for Geoff Marcy and Paul Butler, 5,000 miles away in California. Marcy had been running an experiment for 8 years and had removed 51 Pegasi from his sample due to an error in the star catalog. Within a week of the discovery, he and Butler had confirmed the Swiss discovery. They mined their data for similar objects and by the end of 1995 had found three more exoplanets (see Marcy and Butler 1998 for a snapshot of this rapidly emerging field of research). Mayor and Queloz had come to planet hunting from the perspective of binary star researchers, accustomed to orbital periods of hours or days, so they observed their candidates frequently. Marcy and Butler were taking data more sparsely and thought they had plenty of time to dig out planet signals, since Jupiter takes 12 years to orbit the Sun. Friendly competition drove them to push the limits of their spectrographs. These two groups have led the field in terms of Doppler detection ever since, with hundreds of new worlds to their names.

10.5 Surprise and Confusion

The detection of exoplanets had been anticipated for a long time, but the excitement of discovery was tinged almost immediately with confusion. 51 Peg b was a Jupiter-mass planet much closer its star than Mercury is to the Sun, whipping around a complete orbit in just over 4 days, at a scorching temperature of 1,000 °C (1,800 °F)! Discoveries were announced at a rate of about one a month for the first few years, accelerating to one a week in the early 2000s, and a current average of a new exoplanet daily. Properties of exoplanets are governed by an obvious observational truism: you can only detect planets that your technique allows you to detect. The statistical properties of the Doppler method sample have always been skewed in favor of high mass and short period, since those objects require less data of lower quality to be detected. But the first few dozen exoplanets were very surprising because they were so massive and so close to their parent stars, and most of them had orbital eccentricities larger than any of the planets in the Solar System. These "hot Jupiters" were unusual and completely unexpected.

In the absence of any other examples to test the paradigm with, planetary scientists had drawn as many inferences as possible from our Solar System. Locally, we see planets on nearly circular orbits within a few degrees of a single plane, with small rocky planets close to the Sun and rocky planets that have accreted large hydrogen and helium mantles far from the Sun. The underlying theory is based on the nebular hypothesis, which was proposed in 1734 by Emanuel Swedenborg and refined later in the 18th century by Immanuel Kant and Pierre-Simon Laplace. Problems with the nebular hypothesis were addressed by Victor Safronov in the 1970s and his work became the basis for the modern theory of planet formation. However, there had always been concerns that the theory might be overly tailored to the specific circumstances and history of one planetary system, making it a kind of "Just So" story. Planet formation is in some senses historical science, since its complexity cannot be captured either by a computer or by theory and evidence of the initial conditions might be unobtainable.

It was immediately clear that giant planets could not form so close to their stars; there simply isn't enough material at those distances in the proto-planetary disk and the temperature is too high (Lin et al. 1996). Rather, they migrate inwards due to interactions with each other and with material in the disk. This has to happen quickly since it only takes about a million years to grow by accretion from dust bunnies into planet embryos or planetesimals. These embryos are Moon- or Mars-sized in the inner regions and several times Earth's size beyond the snow line. One type of migration involves subtle resonance interactions between the embryo and gas in the disk and another happens after an embryo has grown to near Jupiter mass and it clears a gap in the disk, after which both the planet and the gap migrate to smaller distances. But that's not the whole story, as recent observations show that many hot Jupiters have highly included orbits and some even go around their stars in the opposite direction to the star's rotation! The details are complex, and planets interact violently with each other and can migrate in or out depending on the circumstances. Theory isn't yet mature enough to predict exoplanet properties.

10.6 Methods of Detection

For a decade after the discovery of 51 Peg b, the principle method for finding exoplanets was the Doppler method. It still yields the most confirmed exoplanets, but it has been "eclipsed" by Kepler in the number of exoplanet candidates. In a planetary system, planets and stars orbit a common center of gravity that is close to or inside the star but not as its center. The small reflex motion induced on the star by a massive planet is observable as a sinusoidal variation in velocity and that modest variation is detected with a series of high resolution spectroscopic observations. The radial velocity variation is inversely proportional to the square root of the orbital distance and proportional to the planet mass times the sin of the inclination angle of the orbit. Because of the uncertainty in inclination, a minimum mass is measured and for any sample of planet systems at random orientations the masses will on average be underestimated by a factor of two. Multiple planets can be detected with the same set of spectra; the most massive exoplanet is searched for first, then the best sinusoidal fit to the data is subtracted off, then a smaller signal is search for in the residuals. Each exoplanet contributes to the data as a harmonic of a particular strength and frequency, reminiscent of Kepler's harmony of the spheres.

The pioneering groups succeeded through exquisite experimental technique. Detecting a Jupiter mass planet involves measuring a long-term wavelength shift of a stellar absorption line by 0.1 % of its width. This requires a high dispersion spectrograph, high signal to noise spectra, and extremely accurate wavelength calibration. The second requirement is not too difficult to meet for the kind of bright stars targeted in the first radial velocity survey, many of which were visible to the naked eye like 51 Peg. The last requirement led to the innovation of passing light gathered by the telescope through an iodine cell, which imprinted a reference gird of thousands of narrow absorption lines on the spectrum. The first discoveries were made with a precision of 10 m/s and current accuracy is 1 m/s or slightly better. To see what a difference a decade can make, compare the *Annual Reviews of Astronomy and Astrophysics* summaries of Marcy and Bulter (1998) and Udry and Santos (2007).

When a planet passes in front of a star it dims it slightly and temporarily. For our Solar System seen edge-on from afar, Jupiter would dim the Sun by 1 % for 5 h every 12 years. The depth of the partial eclipse is just the ratio of the cross-sectional area of the planet to the cross-sectional area of the star. Observing exoplanet transits would seem like searching for needles in a haystack, but the prevalence of hot Jupiters improves the odds. For normal Jupiter-Sun systems with random orientations the odds of a transit alignment are one in a thousand but this rises to one in ten for systems with hot Jupiters. In 1999, the first transit was detected, of HD 209458b (Charbonneau et al. 2000). Since then, the number of exoplanets with transit detections has grown steadily to become about a third of the total sample. The combination of size from a transit and mass from radial velocity variation gives mean density, crucial extra information for characterizing an exoplanet. If the mean density is less than water, it is good evidence that the eclipsing object is a rocky, terrestrial planet.

The most compelling evidence of an exoplanet is an image showing separated from its star, with its orbit traced by multiple observations. This was very difficult to obtain because the reflected light from a giant planet is swamped by hundreds of millions of times brighter starlight. As with the radial velocity method, technical innovation opened the door for progress. Adaptive optics systems on large telescopes started to be able to correct for the distorting effects of the atmosphere on the incoming light wave front from a star. This allows a telescope to approach its diffraction limit, which is a linear function of diameter, and resolve or separate the dim light of the exoplanet from much brighter star. Imaging is most sensitive to large separations like 10 or 100 AU so is complementary to selection by the Doppler effect or by transits. It's also best done in the infrared when the contrast between the exoplanet and its star is time times better than at optical wavelengths. Exoplanets were first imaged a decade after they were first discovered (Chauvin et al. 2004), and the number successfully imaged is still only a few dozen. Rapid advances in achieving better contrast through adaptive optics led to the first image of multiple planets just a few years later (Marois et al. 2008).

The last and perhaps cleverest method for detecting exoplanets employs microlensing. When a star passes directly in front of another star, general relativity predicts a brightening of the background star by about 30 % as its light is magnified by the intervening star. No image splitting is seen because the gravity deflection angle is very small. If the foreground star has an orbiting exoplanet, it can cause a secondary brightening. Microlensing succeeded around the same time as imaging (Bond et al. 2004) and it has the potential to detect Earth-like planets (Gaudi et al. 2008). Unfortunately, the incidence rate of microlensing events is only one in a million and the events are not repeatable, limiting the amount that can be learned about these systems.

10.7 The Exoplanet Zoo

After the initial surprise of the hot Jupiters, planet hunters settled down for the long haul, lowering their detection thresholds and accumulating statistics. After nearly 20 years it's still too early to measure the abundance of normal gas giants on orbits like those in the Solar System, although some proxies have finally been detected. Observational biases still strongly favor the more massive and rapidly-orbiting exoplanets, but we're gradually getting a better sense of the exoplanet "zoo." The range of physical properties makes is challenging to decide what is normal or typical in the underlying population. Pulsar planets were an early oddity, but the following sampling may give a sense of the bestiary.

The Methuselah planet, or PSR B1620-26b, is 12,400 light years away and is the oldest known exoplanet, with an age of 12.7 billion years. It orbits a pulsar and a white dwarf. It most likely formed around a Sun-like star but when they entered the dense environment of the M4 globular cluster, the planet was captured by a neutron star and its companion while its original host was ejected from the system. The Jupiter-sized planet settled into a distant orbit with a good view of a binary where material from a red giant turned a neutron star into a pulsar spinning 100 times a second. Some exoplanets have extreme eccentricities. HD 80606b goes from distance like the Earth's from its star to a distance less than Mercury's, getting blasted by a blowtorch every 4 months. Other exoplanets are scorched all the time. Corot-7b is five times Earth's mass and is in a tight orbit with its star-facing side at 2,330 °C (4,220 °F) and its outward-facing side at −220 °C (−370 °F). With an atmosphere of sodium and oxygen, the hot side probably has molten pebbles raining down from the sky. SWEEPS-10 is even closer to its parent star, which is a red dwarf. It whips around in 10 h, 200 times faster than Mercury. The "Tatooine" planet, or Kepler 16b, orbits twin red dwarfs and is near the edge of the habitable zone. From Tatooine, double sunsets would be visible as from the fictional planet in the Star Wars movies. In addition to these extremes there are dozens of hot and icy giants, water worlds, rocky super-Earths, and even free-floating planets. The Sun-like star HD 10180 has at least seven and possibly as many as nine planets, rivaling the Solar System in richness.

10.8 The Hunt for Earths

The bulk of the heavy lifting in extrasolar planet research has used, and continues to use, the indirect Doppler method. In the past decades, eclipses have given the extra information on size, and so a constraint on mean density, while direct imaging has become effective with space-based observations and nulling interferometry on the ground. About 10 % of Sun-like stars have planets, with indications that the true fraction might be much higher and that rocky terrestrial planets may outnumber gas giants (Marcy et al. 2005). Over a hundred multiple planet systems are known. Simulations do what NASA does by "following the water" as a nebula forms and planets grow by accretion, and they suggest that the Earth has a typical inventory of water so terrestrial planets with all the ingredients needed for life should not be rare (Raymond et al. 2004). Even giant planet migration does not preclude habitable planets because it happens so rapidly that rocky planets can grow after the gas giant has moved in and parked. The Doppler method has detected several dozen super-Earths, rocky planets with three to ten Earth's mass, however, a true Earth clone is just beyond reach (Mayor et al. 2013).

The transit method requires a precision that depends on exoplanet size: 1 % for a Jupiter and 0.01 % for an Earth. Atmospheric turbulence and transmission variations make it impossible to measure variations much less than 0.1 % from the ground, putting Earth's beyond reach. But within the last few years, the European CoRoT satellite and NASA's Kepler satellite have been launched and the stability of the space environment gives much better photometric precision. Very few exoplanet systems will happen to be aligned suitably for a transit, so the strategy is to "stare" at a large patch of sky containing a large number of stars. Kepler uses a one-meter mirror to measure the brightness of 170,000 stars in the direction of the Cygnus constellation every 7 min; after a recent mission extension it will do this for a total of 7 years. Three transits have to be observed to confirm a planet. Once the size is measures by a transit, the Doppler method can be used to measure mass and characterize the exoplanet.

NASA's Kepler mission has blown the lid off the search for low mass planets. The team announced over 1,200 candidates in early 2011, over fifty of which were in their habitable zones, among which five are probably less than twice the Earth's size (Borucki et al. 2011). By early 2012, the number of candidates had grown to over 2,300, nearly 250 of which are less than 1.25 times Earth's size (Batalha et al. 2013). It's just a matter of time before Earth-like planets are found in Earth-like orbits. Mission leader Bill Borucki and his team pitched the project to NASA Headquarters in 1992, but it was rejected as being technically too difficult. In 1994 they tried again, but this time it was rejected as being too expensive. In 1996, and then again in 1998, the proposal was rejected on technical grounds, even though lab work had proved the concept and exoplanets had recently been discovered. By the time the project was finally given the go ahead as a NASA Discovery class mission in 2001, the first transits had been detected from the ground. Kepler launched in 2009 and it promises to rewrite the book on exoplanets. Persistence paid off.

10.9 Habitable Real Estate

Astronomers adhere to a conventional and conservative definition of habitability: the zone around a star within which water can be in stable liquid form on the surface of a rocky planet. This calculation is strongly affected by atmospheric thickness and composition; Venus and the Earth are similar in mass and size and would be equally detectable by the Doppler or transits methods, yet Venus is almost certainly uninhabitable due to a strong Greenhouse effect. Another complication is the fact that habitable zones evolve as stars age and the amount of radiation they deliver changes, and planetary atmospheres also evolve due to geological activity (and of course, life). The definition is conservative because it supposes that stellar radiation is the only energy source that can power biology. On Earth, life can exist above the boiling point of water and below its freezing point, and in total darkness on the sea floor or deep inside rock. In the Solar System, there may be a dozen habitable "spots," many of which are in a cryogenic habitable zone where icy and rocky surfaces conceal water kept liquid by pressure, geological heating and, in the case of moons around giant planets, tidal heating. Enceladus provides the perfect example of a Solar System body that may harbor microbial life and yet is completely unnoticeable in a distant solar system.

Planet hunters have concentrated on Sun-like stars for obvious reasons, but simple arguments suggest that the habitable "real estate" around dwarf stars far exceeds that around Sun-like stars, motivating new wide-field surveys for transits associated with stars much nearer and brighter than Kepler's faint targets. Observational selection effects favor the detection of Earths around M stars rather than G stars in almost every way. In fact the two worlds closest to habitability discovered so far are Gliese 581 c and d, in orbit around an M dwarf (Mayor et al. 2009). Exoplanet research is a burgeoning but still young field, with many observational and theoretical puzzles to solve before we can confidently project a number of habitable worlds (Baraffe et al. 2010). However, rough estimates based on the relatively unbiased method of microlensing suggest at least one planet per star in the Milky Way, or a total of 100 billion (Cassan et al. 2012). That conservatively (but uncertainly) projects to 100 million terrestrial planets around Sun-like stars in the Milky Way, several million of which are probably both Earth-like and habitable.

10.10 Biomarkers and Life

Biomarkers are required to take the huge step forward from demonstrating habitability to the first detection of life beyond Earth. That detection—keenly anticipated by all astrobiologists and by members of the general public with an interest in science—might come in the form of a shadow biosphere on our planet, from trace fossils in a Mars rock, from future exploration of targets in the outer Solar System, from a spectral signature in the atmosphere of an extrasolar planet, or even from success in the campaign to detect signals from remote civilizations. Each possibility implies a different type of evidence, which must be matched against very uncertain criteria for the definition of success.

Mars gives an indication of the challenges in life detection. It is in our cosmic back yard and we have landed over a dozen probes on it and mapped the entire surface with a resolution of a couple of meters. Geochemical traces in the Martian meteorite ALH 84001 and the more recent remote sensing of methane seemed to implicate biological activity, but in both cases we're left with the Scottish verdict "not proven" (McKay et al. 1996; Mumma 2009). If there is extant life on Mars, it is likely to be in a subsurface aquifer that is beyond the reach of any lander that has yet been contemplated. Titan presents a different conundrum. We simply do not have a basis in lab experiments or in a general theory of biochemistry to predict what to look for (e.g. Bains 2004). All astrobiology is based on life as we know it rather than life as it could be.

Extraolar planets simplify the problem because the bar is set at the global alteration of atmospheric composition by metabolic processes. An important observational advance in the early 2000s was taking spectra of stars during exoplanet transits; the exoplanet atmosphere is backlit by the star, which imprints extra absorption due to constituents in the atmosphere of the exoplanet (Charbonneau et al. 2002). Alternatively, the star can be used as a natural coronagraph to enable an emission or a reflection spectrum to be taken of the exoplanet at different phases (e.g. Charbonneau et al. 2005; Knutson et al. 2007). These difficult observations require the stability of the Hubble and Spitzer Space Telescopes and they have been done for less than a dozen objects, all gas giants. But new information can be derived with transit spectroscopy, including albedo, “weather,” and hints of atmospheric composition (Seager and Deming 2010). At infrared wavelengths, H_2O, CO, CO_2 and CH_4 have been detected (Tinetti et al. 2010).

This work is “proof of concept” for spectroscopy of rocky exoplanets that will require upcoming facilities like the James Webb Space Telescope and as-yet-unfunded NASA and ESA missions. Oxygen, and its photolytic product, ozone, are the “gold standards” of biomarkers because their reactivity means they are rapidly depleted on any Earth-like planet without continual replenishment by biogenic photosynthesis. Methane and nitrous oxide are also good biomarkers. Even with the 6.5 m JWST, these observations are extremely challenging. The stars that Kepler is studying in one small patch of sky are thousands of times fainter than the bright stars that will yield the most sensitive Doppler measurements, so wide but shallow surveys are needed to identify the closest Earth-like planets as biomarker targets. In practice, a suite of biomarkers will be needed to confidently assert microbial life on another planet, bolstered by simulations and lab experiments (Kaltenegger et al. 2010). Yet this may be the approach that yields the first detection of life beyond Earth.

10.11 Conclusion

The Copernican Principle has been robust enough to bear our weight at every turn in the long history of astronomy. Our situation on a rocky planet that orbits a middle-weight star on the outskirts of an unexceptional spiral galaxy appears not be unusual or unique. In just two decades astronomers have come close to measuring two terms in the Drake equation: the fraction of stars in the Milky Way that have planets, and the number of planets per system that can potentially support life. A conservative estimate might be a billion habitable “spots”—terrestrial planets in conventionally defined habitable zones, plus moons of giant planet harboring liquid water—in the Milky Way alone (Impey 2011). That number must be multiplied by 10^{11} for the number of "Petri dishes" in the observable cosmos. Do we imagine that they are all stillborn and inert? Or do we think a significant fraction of them host biological experiments, either like or unlike the experiment that took place on Earth? That is the central question of astrobiology, and it feels like we're finally getting much closer to the answer.

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