New Opportunities in the Search for Life Among the Lowest-Mass Stars

Statement of

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On

Advances in the Search for Life

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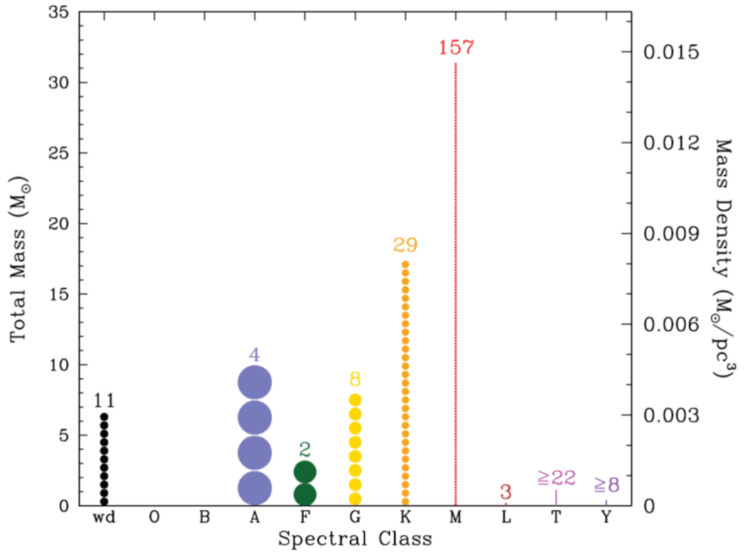
Chairman Smith, Ranking Member Johnson, and esteemed Members of the Committee, it is an honor and privilege to discuss with you recent discoveries and future opportunities in the search for potentially habitable worlds and life among the smallest stars. I am particularly honored to speak today as a representative of the team that discovered the seven-planet system around the star TRAPPIST-1, a system that harbors as many as three potentially habitable Earth-sized worlds. This and other recent discoveries represent a beginning of an era of exoplanet exploration that in the next 5-10 years will enable measurements that identify habitable worlds and possibly life beyond Earth. In the next 15-25 years, we will have the capability to directly image other Earths. These transformative discoveries, which address one of humanity's most persistent questions, "Are We Alone?", are fully achievable through a diverse portfolio of research programs led by US scientists and supported by federal funding to NASA and NSF.

My own research interests center on cool, low-mass stars like TRAPPIST-1, which are the most common stars in the Milky Way Galaxy, and yet in many ways the most difficult to study. My path to this work began as a child in the late 1970s and 1980s in post-industrial Buffalo, NY, at a time when Dr. Carl Sagan appeared on PBS to talk about the beauty of the billions of galaxies, stars and worlds in the cosmos; and when the Voyager 2 spacecraft sent back the first close-up views of Uranus and Neptune. My love of math fed an interest in physics and a deep curiosity about the Universe, encouraged by many teachers and mentors. As an undergraduate and Physics major at UC San Diego, I had the privilege to work with Dr. Sally Ride on a project, which enabled high school students around the country to take pictures of their own planet. As a PhD student at Caltech, I used data from the 2 Micron All Sky Survey (2MASS), a sky



(Figure 1) The distribution of stars within 25 light-years of the Sun, ordered by spectral type. Massive hot stars are to the left, low-mass cool stars are to the right. The Sun is one of 8 G-type stars in the local volume. The vast majority of stars are dim, low-mass M dwarfs. (From Kirkpatrick et al. 2012, *Astrophysical Journal* **753**, 156)

survey using newly developed infrared array technology, to discover an entire class of invisible, low-mass stars. These data were available to myself and many other early career scientists exploring new areas of astronomical research thanks to federal funding provided by NASA and NSF. Today, I am able to weave these life-long scientific interests into the search for potentially habitable worlds around the lowest mass stars, a search that has recently born fruit and is transforming the way we see the Universe and our place within it.

Overview

When we look up into a clear, dark night sky, most of the stars we see are hot, luminous, massive and distant. This "visible" sample is not representative of our Milky Way’s overall stellar population, which is dominated by cool, low mass and dim stars, barely perceptible even with a sizeable telescope. Astronomers designate these stars as cool or ultracool dwarfs. Compared to our Sun they are less than half as warm, have less than half the mass, and radiate less than 1% of the light energy. Most of this light is emitted at far-red visible and infrared wavelengths, beyond our visual range. They are literally invisible stars, only recently discovered in large numbers thanks to infrared detector technology development (a collaboration of military, university and private research) and the use of these detectors in federally supported surveys of the sky. Despite their recent detection, these lowest-mass stars are proving to be extremely important in the search for life in our Universe.

Cool dwarf stars have a number of unique properties that are important in the search for life beyond our Solar System. First, they are common. Over 75% of stars in the immediate vicinity of the Sun are cool or ultracool dwarfs (Figure 1), and the lowest-mass stars (≤10% the mass of the Sun) are more than five times more abundant that Sun-like stars. This fact means that low-mass stars are typically the closest stars to the Sun, including the closest star, Proxima Centauri (12% of the Sun’s mass), 4.2 light-years away. The 5th, 6th and 7th nearest stars to the Sun, and a star that passed within 1 light-year of the Sun roughly 70,000 years ago, are examples of very low-mass stars found only the past 4 years. These stars have extremely long lifetimes, measured as the time over which they extract energy from the fusion of hydrogen into helium in their hot cores. The Sun is about halfway through its lifetime and will deplete its core hydrogen supply in the next 4-5 billion years (in the process, engulfing or rendering uninhabitable the inner terrestrial planets). The lowest-mass stars will continue to fuse hydrogen for *trillions* of years, one hundred times longer than the current age of the Universe. This means that nearly every low-mass star ever formed is still around today and will persist well past the demise of the Sun, making them very long-term sanctuaries for life if they possess habitable worlds. Finally, we now know that the lowest-mass stars are capable of forming planets - and specifically Earth-sized planets – thanks to recent discoveries summarized in this testimony.

Why search for habitable worlds around the lowest-mass stars?

The low-mass star population provides an exciting opportunity for the search of potentially habitable worlds. Here, I will follow scientific convention to define "potentially habitable world" as one in which there is the possibility of persistent liquid water on its surface. While worlds with interior oceans (such as the icy moons Europa and Enceladus) or other surface liquids (such as the hydrocarbon lakes on the Saturnian moon Titan) may support the development of novel life forms, life as we know it – Earth-based life – requires liquid water at or near the planet's surface to thrive. Liquid water can exist only on planetary surfaces with an atmosphere and within a specific range of temperatures, 0ºC to 100ºC at standard atmospheric pressure. The surface temperature of a planet is determined primarily by the amount of radiation it receives from its star, which in turn depends on the star's surface temperature, size, and distance from the planet, as well the fraction of starlight absorbed by the planet surface, and the fraction of thermal radiation emitted out into space. Other heat sources, such as geothermal activity and tidal forces, can also play a role. The primary factors define a star’s "habitable zone", the region in which planets could maintain surface liquid water. Not surprisingly, Earth resides in the Sun's habitable zone, but so does the Moon and Mars, illustrating the importance of atmospheres (for the Moon) and the transience of habitability (Mars likely lost its surface water to by exposure to the Solar wind and the atmospheric escape of hydrogen).

The lowest-mass stars have several properties that make them ideal targets in the search for potentially habitable worlds. First, both theoretical calculations and observational studies show that the kinds of planets with surfaces – rocky or icy "terrestrial" worlds – are more likely to form and be found around the lowest-mass stars. Analysis of data from the *Kepler* spacecraft and ground-based

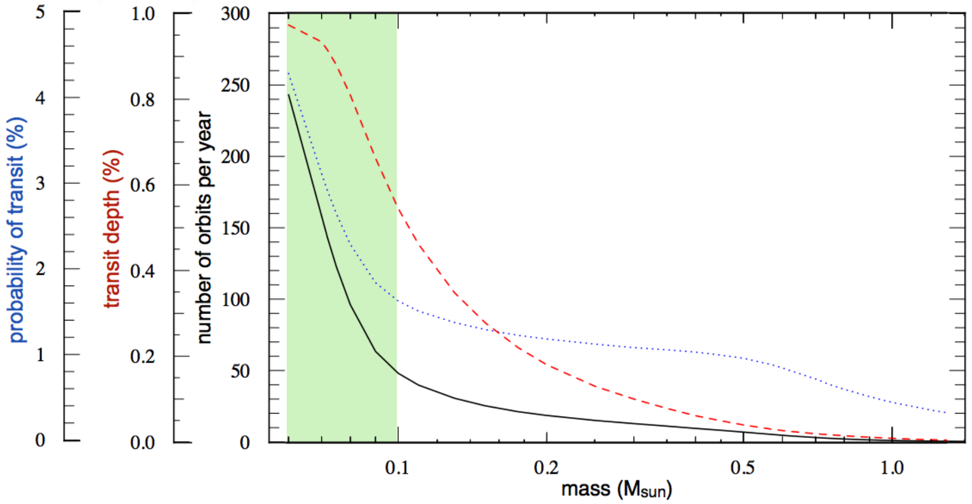


Figure 2: Measures of detectability for transiting Earth-sized planets in the habitable zones of 1 billion-year-old stars of different stellar mass. Curves show the geometric probability of transit (blue dotted line), transit depth (red dashed line) and number of orbits in a year (black solid line). All of these metrics strongly favor searches for planets among the lowest-mass stars (green region). From Triaud et al. 2013, https://arxiv.org/abs/1304.7248.

microlensing surveys find that there are on average 2 Earth-sized planets per low-mass star. Compared to Sun-like stars, low-mass stars have 3.5 times more Earth-sized planets and 50% more terrestrial planetary mass overall. With infrared-sensitive detectors, planets in the habitable zones of low-mass stars are also easier to detect. Because these stars are both cooler and smaller than the Sun, their habitable zones are closer in, so habitable-zone planets have shorter orbital periods. This facilitates their discovery by the radial velocity technique, in which the presence of a planet is inferred by its back-and-forth gravitational pull on the star. The closer the planet, the stronger the pull, and a lower mass star will also exhibit a greater reflex motion. Habitable zone planets are also easier to detect through the transit method, applicable for a small fraction of systems (about 1-4%) in which a planet passes between us and its star, briefly blocking a small fraction of the star's light. The amount of light blocked – the transit signal – is larger for smaller stars, while the probability of transit is greater for closely orbiting planets. For both radial velocity and transit methods, the short orbit periods of close-in habitable zone planets produce more frequent periodic signals, improving the likelihood of their detection.

Low-mass stars may also have pitfalls when it comes to planet habitability, although here there is more uncertainty given our very recent discovery of these systems. Planets orbiting close to their stars are subject to tidal locking, in which the star’s gravitational forces cause the planet to rotate so that it always faces one side toward the star (tidal locking is why we see only one side of the Moon from Earth). While initial research suggested that tidal locking would be catastrophic for planet habitability, causing atmospheres to evaporate on the day side and freeze out on the night side, more recent work has shown that heat can be redistributed around a tidally-locked planet even with a relatively thin

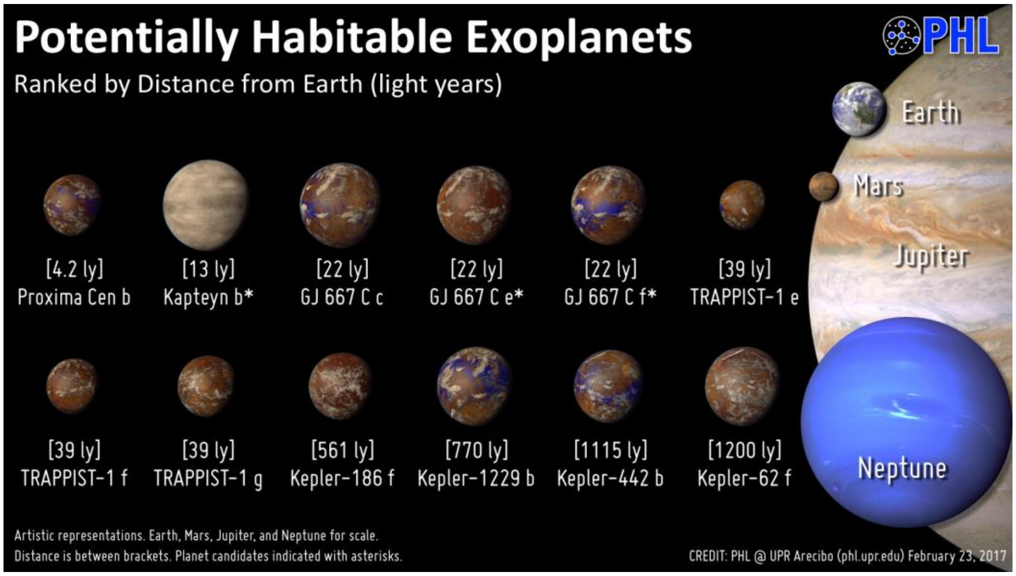


Figure 3: Graphical summary of 12 potentially habitable exoplanets as compiled by the Planet Habitability Laboratory at the University of Puerto Rico at Arecibo. These are the most “conservative” systems, with the highest probability of having surface liquid water. The images of the exoplanets are artistic representations scaled in size relative to the Solar System planets shown at right. The distances and names of the exoplanets are listed, and those marked with an asterisk (*) are still considered candidates. From the PHL website, http://phl.upr.edu/projects/habitable-exoplanets-catalog.

atmosphere. Cloud formation on the dayside can also play a role in stabilizing the environment. Indeed, tidal locking could reduce variations in planetary tilt, resulting in global climates that are *more stable* than Earth, and thus well suited for the development of life. The forces that cause tidal locking can also heat the interior of the planet, potentially driving excessive geothermal activity similar to that seen on Jupiter's volcanic moon Io. Again, while extensive volcanism could be problematic for the development of life, tectonic activity drives many of the chemical cycles (such as the silicate-carbon cycle) that are essential for life on Earth. Low-mass stars are also known to be highly magnetically active, producing high-energy flares and coronal mass ejections with often greater intensity that the Sun. The X-ray and ultraviolet radiation, and high energy particles, emitted by this magnetic activity can damage biological organisms, evaporate the oceans, and strip away the atmospheres of closely-orbiting planets. On the other hand, if the planets themselves had strong enough magnetic fields and ozone in their atmospheres (possibly produced from the oxygen released by evaporating oceans), their surfaces would be shielded from these effects, just as the Earth’s magnetic field shields us from the Sun's magnetic storms.

The habitability and evolution of terrestrial planets around the lowest mass stars are among the most uncertain and exciting aspects of this developing area of research, allowing us to explore the origins of life in novel systems. Fortunately, we are entering an era in which both targets (planets) and the tools (technology) will be available to find and characterize these worlds.

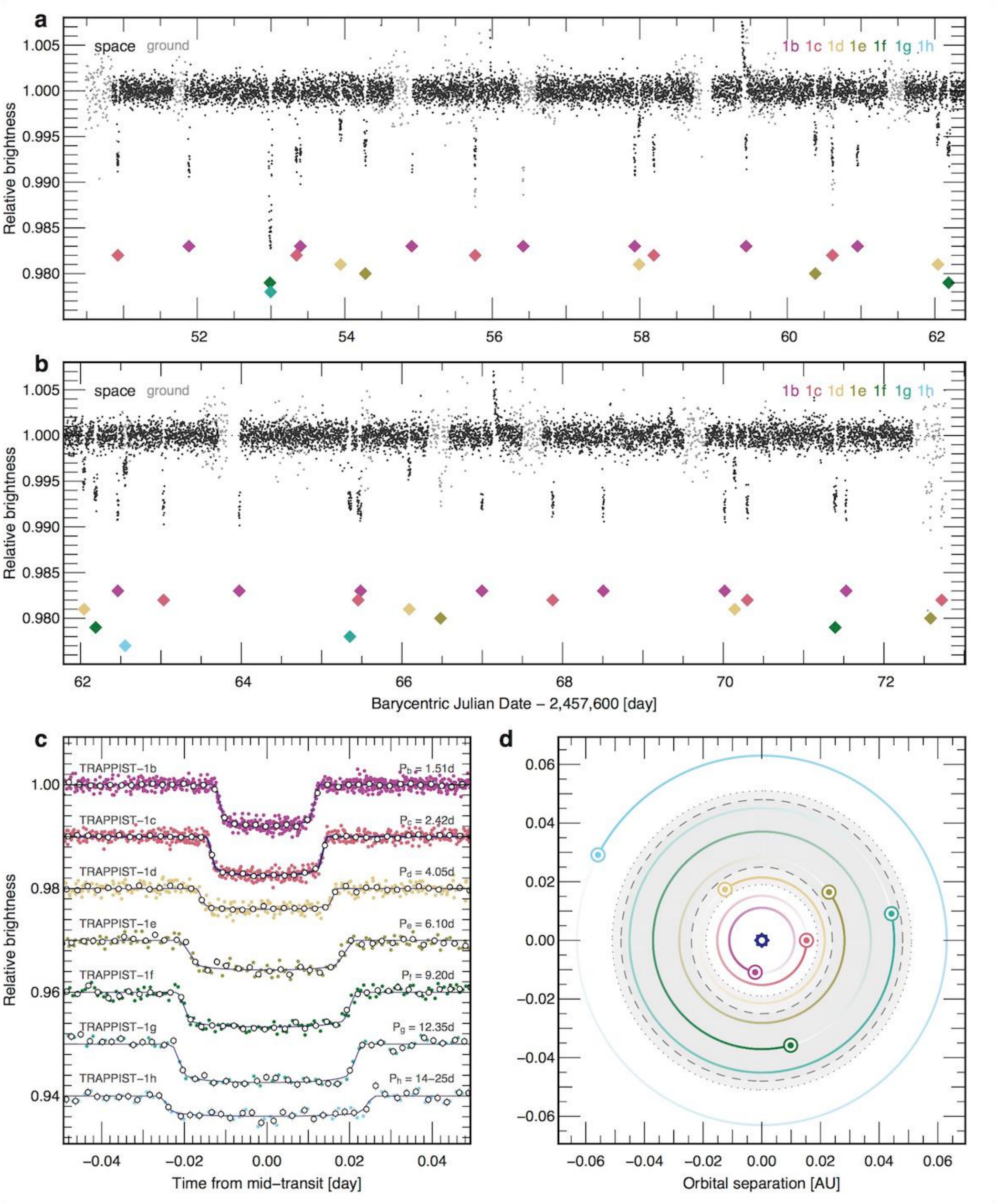


Figure 4: Data leading to the discovery of the TRAPPIST-1 seven-planet system. Panels (a) and (b) show the 22-day light curve obtained in September 2016 with space-based *Spitzer* observations (dark points) and ground-based measurements (grey points). Colored symbols denote the transit times for each of the seven planets. Panel (c) shows the individual transits for each of the planets. The transit depth measures the size of the planet relative to the star, while the transit duration measures the speed of the planet and thus its orbit distance. Panel (d) is a visualization of the planet orbits, with the grey region mapping the TRAPPIST-1's habitable zone. Three planets – e, f and g – orbit within this zone. The axes are measured in Astronomical Units (AU), the distance between the Earth and the Sun. For comparison, Mercury orbits between 0.31 and 0.39 AU from the Sun, about 10 times the distance of TRAPPIST-1f and g. From Gillon et al. 2017, *Nature* **542**, 456.

Discovering potentially habitable terrestrial exoplanets

Given that conditions favor their detection around the lowest-mass stars, it is no surprise that the first discoveries of potentially habitable Earth-sized worlds were made around stars less massive than the Sun. *Kepler*-62f and *Kepler*-186f, each the fifth planet around their respective host stars, were the first potentially habitable planet discoveries, both identified through the transit method with the *Kepler* spacecraft. Similar planets have been found around low-mass stars by the radial velocity method, most notably Proxima Centauri b, a greater-than Earth mass planet orbiting in the habitable zone of the nearest star to the Sun. The University of Puerto Rico Planet Habitability Laboratory maintains an up-to-date list of potentially habitable planets, and categorize 12 planets as "conservatively" likely to have surface liquid water (Figure 3) All of these were discovered in the past 5 years, and all orbit stars less massive than the Sun, most less than one-third the Sun's mass. Eight of the twelve planets are within 40 light-years, considered "very nearby" on a cosmic scale. While there are many selection effects that enter into these statistics, these discoveries nevertheless confirm that potentially habitable worlds are present and detectable around the lowest mass stars.

Earlier this year, three of these planets were discovered by our team as part of a system of seven Earth-sized planets orbiting a very low-mass star 39 light-years from Earth (Figure 4). This star, called TRAPPIST-1, is an ultracool dwarf first discovered with 2MASS data in 2000, and has a mass 8% that of the Sun and a diameter equivalent to the planet Jupiter. All seven planets were detected by the transit method, combining data from ground-based and space-based facilities. Three of the planets – e, f and g – orbit within the star’s habitable zone. Because TRAPPIST-1 is dim (emitting less than 0.1% of the Sun’s total radiation), these potentially habitable planets orbit close to their star, less than 5% of the distance between the Earth and the Sun. The entire system fits easily within the orbit of Mercury. The seven planets have orbit periods between 1.5 and 18.8 days and are organized in “resonance chains” that cause them to gravitationally pull on each other in their orbits, a phenomenon we can discern by variations in their transit times of up to 40 minutes. Overall, this small, compact system looks more like the Galilean moon system around Jupiter than the Sun’s planetary system, a potential clue to its origin.

Our discovery was possible thanks to an international collaboration of scientists from two dozen institutions in ten countries on four continents, including US researchers based in the states of California, Maryland, Massachusetts, Texas, and Washington. In 2015, our team reported the detection of three transiting planets orbiting TRAPPIST-1 based on observations obtained with the TRAnsiting Planets and PlanetesImals Small Telescope South (TRAPPIST-South), a 60-cm robotic telescope located in Chile. A second telescope, TRAPPIST-North, is in operation at Oukaïmden Observatory in Morocco (Figure 5). Both facilities are operated by the University of Liege, Belgium, and led Dr. Michael Gillon with support by European research funds. We found two close-in

Figure 5: The TRAPPIST facilities at the ESO La Silla Observatory in Chile (left) and the Oukaïmden Observatory in Morocco (right). Both are 60 cm robotic telescopes optimized for the detection and characterization of exoplanets and small bodies in our solar system. (Photo credit: Emmanuel Jehin)

planets too hot to sustain life; and a third candidate habitable zone planet with only two transit detections and a highly uncertain orbit period. Uncertainties in planet detections are common for ground-based transit programs, as data can only be acquired at night, in good weather, and when the star is well above the horizon, resulting in significant sampling bias. As we continued to monitor this star using facilities in Chile, South Africa, the United Kingdom, Spain, Morocco and the US, we began to see evidence that there were more planets in the system. We turned to the *Spitzer* Space Telescope, a NASA-funded infrared space facility launched in 2003 onto an Earth-trailing orbit around the Sun. As a stable, space-based platform, *Spitzer* provides exceptional brightness measurements with no day/night or weather interruptions. Monitoring TRAPPIST-1 with *Spitzer* for 21 days along with concurrent ground-based observations revealed 92 transits that could be assigned to seven distinct planets. These results were subsequently verified in a 74-day monitoring campaign conducted by the NASA-funded *Kepler* space telescope, with data released to scientists and the public last month.

Beyond revealing the presence of a planet, the transit method yields measurements of its size relative to its star. Our observations and analysis of the TRAPPIST-1 star show that the planets are between 0.7 to 1.1 times the size of the Earth. In addition, the transit timing variations observed for these planets have yielded the first estimates of the masses of the planets (0.09 to 1.6 times the mass of Earth) and their average densities (0.2 to 1.4 times the density of Earth). These measurements currently have large uncertainties but will improve with time. Importantly, the indicate that the planet’s interiors are dominated by rock and volatiles, the latter including liquid and solid water, carbon dioxide and ammonia. These worlds may be the first ocean worlds to be discovered in the habitable zone of a star, which would have profound implications on the search for life beyond the Solar System.

The TRAPPIST-1 system establishes several exoplanet firsts, including the lowest-mass star known to host planets and the largest number of Earth-sized worlds found around any star (including the Sun). It is arguably the most promising system to date in the search for life beyond our Solar System, with at

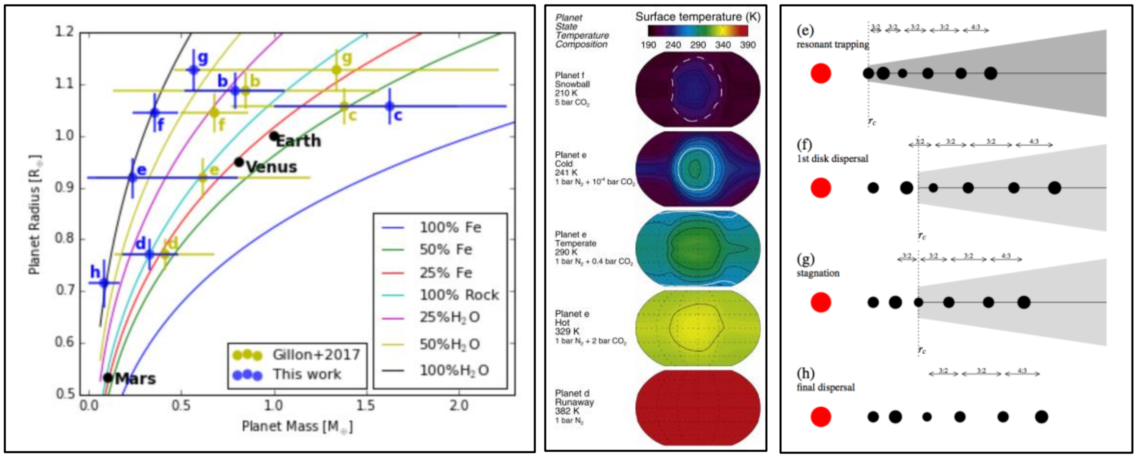


Figure 6: Characterization of the TRAPPIST-1 system. (Left) Planet radii and masses measured from transits and transit timing variations compared to models of interior composition. This study predicts that the habitable zone planets – e, f and g – may have interiors of up to 50-100% water. (Middle) Surface temperature maps of planets d, e and f based on climate modeling. (Right) One possible scenario for the formation of the TRAPPIST-1 system based on migration and circumstellar disk interaction. (Figures from Wang et al. 2017, submitted to Astrophysical Journal, https://arxiv.org/abs/1704.04290; Wolf 2017, Astrophysical Journal Letters 839, L1; and Ormel et al. 2017, submitted to Astronomy & Astrophysics, https://arxiv.org/abs/1703.06924).

least three chances at a habitable world. The system has energized the scientific community, with over a twenty follow-up studies published since the full system was announced in February 2017. These studies are exploring the origin, orbits, composition, and climates of the planets, as well as the space environment around by the star (Figure 6).

Yet TRAPPIST-1 is only one of many systems with habitable zone Earth-sized worlds around low-mass stars that we expect to find over the next several years. Just last week, the NSF-funded MEarth project, which has deployed a network of 40-cm telescopes in Chile and Arizona for its own search for planets around low-mass stars, reported the discovery of a super-Earth (6.6 times the mass of Earth) in the habitable zone of a star that has 15% the mass of the Sun and is also 39 light-years away. As the TRAPPIST and MEarth programs continue, our team will also be expanding our ground-based transit search through the Search for habitable Planets EClipsing ULtra-cOOl Stars (SPECULOOS) project, with four 1-meter robotic telescopes optimized for the lowest-mass stars currently under construction in Chile. These ground-based programs will soon be joined by the NASA-funded Transiting Exoplanet Survey Satellite (TESS), scheduled for launch in March 2018, which is expected to discover hundreds of planets around the nearest and brightest low mass stars. Other program, funded by NASA, NSF, and international funding agencies, are also gearing up to identify planets around low-mass stars through the radial velocity and microlensing techniques, using new instrumentation and multi-telescope systems sensitive to dim red stars.

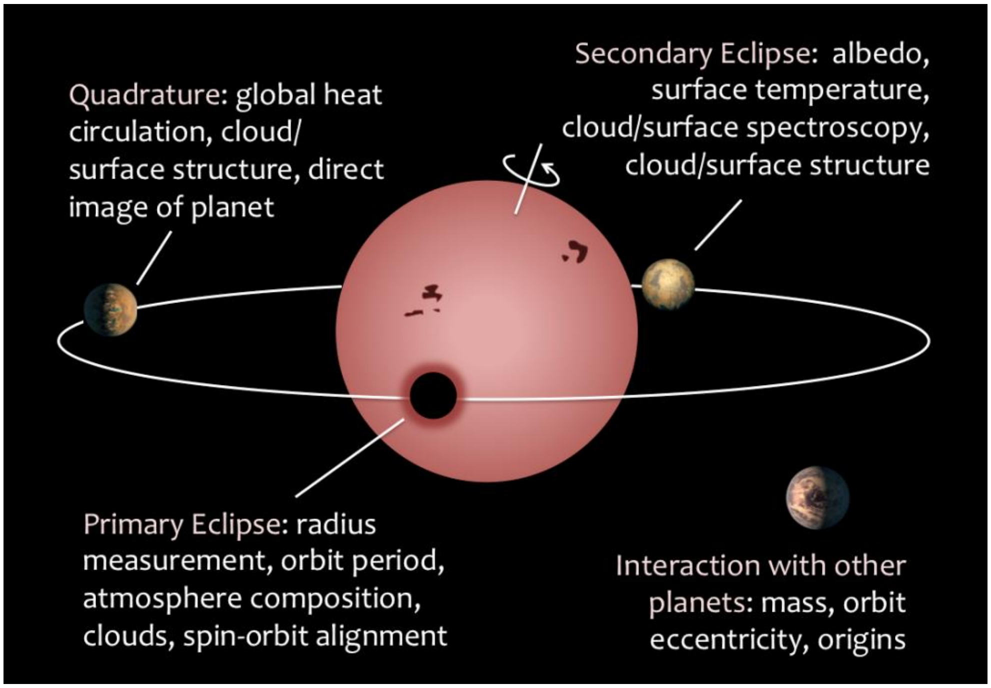


Figure 7: Methods for characterizing planets transiting a low-mass star.

The number of potentially habitable worlds around the lowest mass stars is expected to increase dramatically over the next several years, and with that comes an opportunity to directly search for evidence of life on other worlds.

From discovery to planet characterization to the search for life

Determining whether a potentially habitable planet is in fact habitable requires observations of its atmosphere and surface. Astronomers have developed a number of techniques to do these challenging measurements (Figure 7). During transit, spectroscopic observations can be used to measure the gas composition of the atmosphere and infer the presence of high-altitude hazes and clouds. These measurements may provide evidence for atmospheric water vapor, which would link directly to the presence of surface liquid water; they can also probe geothermal processes (volcanism) and life (biogenic gases). Transit observations can also assess the stability of an atmosphere through the search of trailing absorption features, signatures of atmospheric gases escaping from the planet. Additional dips in starlight following a planet’s transit could signal the presence of a large moon. When the planet passes behind the star, a phase known as secondary eclipse, starlight reflected by the planet’s clouds or surface can be used to infer their composition and structure. Infrared observations at this phase can measure the temperature of the planet, and with spectroscopy the dayside surface or atmospheric composition. As the planet orbits between these two phases, variations in the combined light of star and planet can constrain both heat circulation and cloud/surface structure around the planet. For planets on wider orbits, quadrature is the optimal phase to obtain a direct image or spectrum

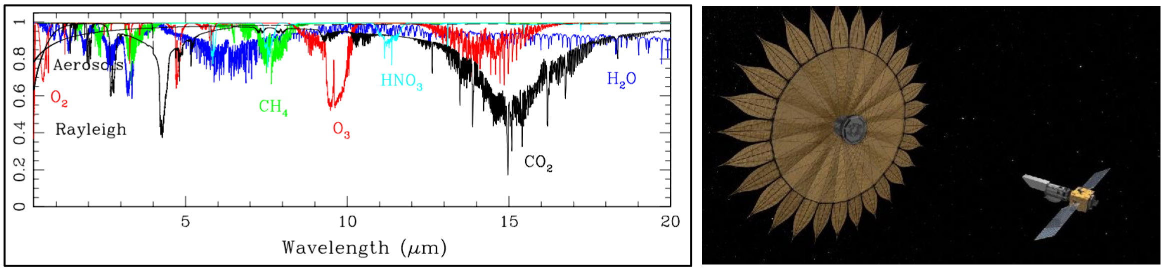


Figure 8: (Left) Model transit spectrum of an Earth-like world, showing the locations of water vapor and potential biogenic gases. JWST will be sensitive across the entire wavelength range shown. (Right): Visualization of the Starshade concept by NASA for direct exoplanet imaging. An external occulting array is placed up to 50,000 kilometers in front of a space telescope like WFIRST to suppress the planet's host starlight. (From Kaltenegger & Traub 2009, *Astrophysical Journal* **698**, 519; and NASA/JPL)

of the planet. Some of these measurements can be achieved for non-transiting planets as well, although the separation of star and planet light becomes more challenging.

Each of these measurements has been achieved for the largest transiting exoplanets (Jupiter- and Neptune-like gas giants) and attempted for Earth-sized planets around low-mass stars (including TRAPPIST-1), using large ground-based telescopes and the *Hubble Space Telescope* (HST). Unfortunately, these facilities do not have the sensitivity to detect the spectroscopic signatures of an Earth-like atmosphere (e.g., CO_2 or O_2-rich) or reflectance signal from a terrestrial world. Extending these techniques to potentially habitable worlds will require the next generation of ground-based and space-based facilities. Very large telescopes in the 25-35 meter diameter range, including the Thirty Meter Telescope (TMT), the Giant Magellan Telescope (GMT) and the European Extremely Large Telescope (E-ELT), coupled with advanced instrumentation, should have the resolution and sensitivity to detect Earth-sized planets around low-mass stars with the radial velocity technique, as well as measure the atmospheres of transiting and non-transiting super-Earth planets around these stars. These facilities are expected to come online in the next decade. The *James Webb Space Telescope* (JWST), HST's successor with a planned launch in late 2018, will extend atmospheric characterization to Earth-sized worlds in the habitable zones of the lowest-mass stars, particularly at mid-infrared wavelengths where several important biomarkers (e.g., oxygen, ozone, methane and nitrogen-oxide compounds; Figure 8) have strong absorption features. JWST will also have the sensitivity to measure the thermal emission from these worlds during secondary eclipse, allowing us to map out heat circulation to assess the overall environments of these planets. Again, such measurements favor systems around the lowest-mass stars, and could reveal evidence of liquid water or life on any of these worlds.

Full characterization of potentially habitable worlds will ultimately require direct detection of their surfaces and atmospheres, a task made challenging by the overwhelming glare of the star the planet orbits. NASA's Exoplanet Exploration program will be a critical asset in this endeavor, as only space-based facilities will have the stability, sensitivity and capability of imaging a potentially habitable world around another star. Following JWST, the Wide Field Infrared Space Telescope (WFIRST), the top priority among large space missions from the 2010 National Academy of Sciences Astronomy Decadal Review, will greatly increase the number of known exoplanets, particularly through the microlensing technique. For direct detection, NASA scientists and engineers are now exploring the feasibility of matching WFIRST to an external occulter to suppress starlight – the Starshade concept – a facility that could directly image an Earth-like world around a Sun-like star by 2030, if implemented. This facility won't be able to resolve planets in the close-in habitable zones of the lowest-mass stars, but the technology does pave the path for future direct imaging missions of these systems, possibly through concept missions Habitable Exoplanet Imaging Mission and the Large UV/Optical/Infrared Surveyor. Meanwhile, the Origins Space Telescope would provide detailed chemistry of the atmospheres of these planets in the far infrared. If selected, these facilities would conduct observations in the 2030s and 2040s.

While the potential for an image of an Earth-like world in the next 15-25 years is exciting in its own right, it is worth noting other ambitious programs aimed at exploring these worlds in different ways. These include the Breakthrough Initiative Starshot project that aims to propel ultralight satellites at high speeds to the nearest stars through laser propulsion; and the search for signals from advanced life forms across the electromagnetic spectrum through the Search for Extraterrestrial Intelligence (SETI) project. These public-private partnerships will have plenty of potentially habitable worlds to target among the many low-mass stars in the immediate vicinity of the Sun.

Concluding Remarks

Our recent advances in the search for habitable worlds and life beyond our Solar system has captured the imagination of people around the world, including US citizens of all backgrounds. After the announcement of TRAPPIST-1 was made in February 2017, I and my colleagues have had hundreds of conversations with children and parents, students and teachers, scientists and artists, Uber drivers and airline pilots, janitors and Senators, friends, family and complete strangers, people from all walks of life who are curious about these worlds and what they mean for life on and beyond Earth. I have personally received emails, texts, tweets and good old-fashioned letters suggesting names for the planets, presenting personal artwork (Figure 9), and sharing stories both fiction and non-fiction inspired by this discovery. These messages reflect a diversity of engagement with science, technology, engineering and math that extend beyond the classroom. Research leading to the discovery of new worlds is also broadly accessible to young scientists and the public alike, thanks to the open data policy of federally-funded programs. In my own lab, I have had high school students and teachers from local underserved school districts, undergraduates from minority-serving institutions, and graduate students from around the world

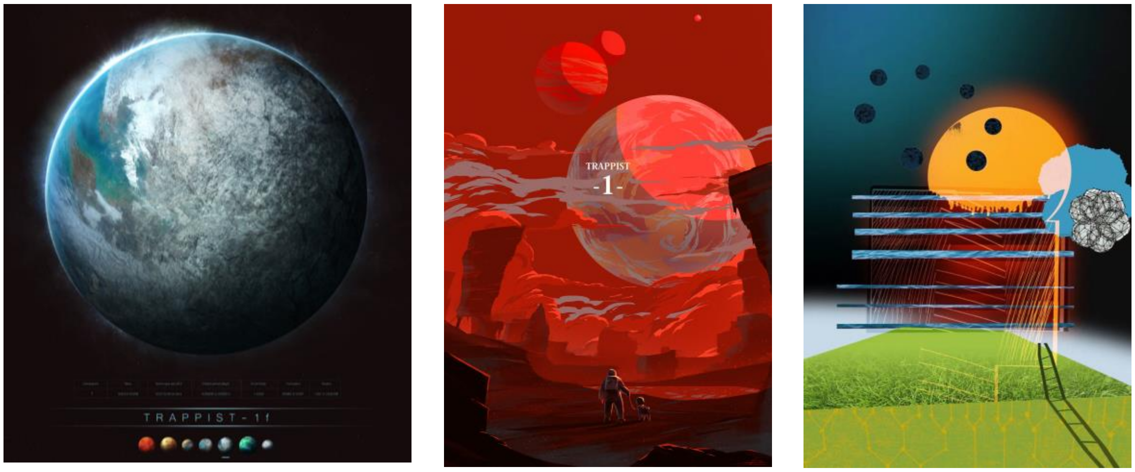


Figure 9: Examples of creative work by artists inspired by the TRAPPIST-1 discovery. From left to right: Guillem Pongiluppi (https://www.artstation.com/artwork/nLnEO), Kontorn Boonyanate (https://www.artstation.com/artwork/LBYov), and Amanda J. Smith (http://www.trappist.one/#posters).

working on these data to better understand the stars and planets we have found. And many people are excited to learn that they can be directly involved in the search for habitable worlds through citizen science programs such as Planet Hunters, Exoplanet Explorers, Backyard Worlds, SETI@home, and Project Panoptes, to name a few. There is undeniably a broad interest among our fellow citizens to be part of the search for life beyond Earth.

Continued federal funding of a diverse portfolio of research programs is critically essential to this work. None of this is possible without public support. Federal funding is also critical for maintaining US leadership not just in astrobiology and space science, but in science and technology in general. The search for life beyond Earth requires advanced observational facilities and instrumentation on Earth and in space, computational facilities and data science programs to process the petabytes of data from current and future missions, theoretical work to understand the origins and evolution of other worlds, and laboratory experiments to explore the diverse biochemistry of life in environments that may exist on these worlds, among other areas. As in all basic research programs, public investment and public-private partnerships in this area will have broad impacts on society through technology development, new materials, biomedical applications and computational advancements. Perhaps most important are the educational and public outreach initiatives that not only share these exciting discoveries with the nation, but train the next generation of scientists to tackle a broad range of challenges and opportunities we have now and in the future.

This generation is the first in human history to know that there are other worlds beyond our Solar System. Will the next generation know that life exists on those worlds? We have both the opportunity and the responsibility to continue our nation’s legacy of exploration and discovery so that our children and grandchildren will know more about life in the Universe than we can even hope to imagine.