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Testimony to the Subcommittees on Space and Research of the
Committee on Science, Space, and Technology, of the U.S. House of
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Exoplanet Discoveries: Have We Found Other Earths?

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This testimony addresses the following topics: (1) presenter's work in exoplanet research; (2) resources, technologies, and methods used to do this work, including the Kepler telescope; and (3) future programs focused on exoplanet research.

The author's work in exoplanet research extends back 30 years, a decade before extrasolar planets were discovered. At that time there were apparently only three people in the world working on the transit method for extrasolar planet detection—the author, Jean Schneider in France, and William Borucki, the current Principal Investigator of the Kepler Mission. The transit method involves the detection of a planet as it moves across the disc of a star. In other words, one could say that it is the shadow of the planet that is detected. Today there are at least several thousand astronomers, astrophysicists, and their students throughout the world applying the transit method to detect and study extrasolar planets.

In the early years of this research, the author identified three new methods for the detection of extrasolar planets and, in the 1990s, did the first search for super-Earth-sized planets in the habitable zone of another star, directing a network of telescopes spaced around the Earth at different longitudes (Doyle et al. 2000, *The Astrophysical Journal* **535**, 338–349). As a Participating Scientist on the Kepler Science Team, the author was asked by the Principal Investigator to organize an eclipsing binary star working group. Eclipsing binary star systems are double stars that orbit in front of each other across our line of sight, so that they eclipse each other every orbital period. Background eclipsing binaries can look like foreground planetary transits, so it is important to know the eclipsing binaries in the Kepler telescope field of view so they will not be mistaken for new planets. Every one of the planets discovered by the Kepler mission had to pass such a test before it could be confirmed as a real planet. The author also participated in the compilation of two Kepler eclipsing binary catalogues that included the discovery of between two and three thousand new eclipsing double star systems.

Another task the author has been performing for the Kepler mission is assisting in the definition of habitable zones around stars with planets in or near the circumstellar

habitable zone—planets Kepler-62e and -62f being a recent example (Borucki et al. 2013, *Science* **387**, 587-590). The habitable zone around a star is the region where an Earth-sized planet may be able to maintain liquid water on its surface for an extended period of time. The assumption is, of course, that water is required for habitability, which is certainly the case for biology as we know it on Earth. At some point too close to a star, any oceans on a planet will evaporate. At another point too far from the star, the atmosphere will completely condense out as snow, and the planet will completely freeze over. In our own solar system, Venus and Mars, respectively, illustrate the basic concepts. The author has worked in this field since 1994, when he organized a conference on habitable zones (*Circumstellar Habitable Zones*, L.R. Doyle, ed., Travis House Publications, Menlo Park, CA), which was one of the precursors of the concept embodied in the current NASA Astrobiology Institute program which brings together multidisciplinary scientists such as biologists, astrophysicists, and planetary geologists to answer questions about life in the universe.

The author's main work with the Kepler Spacecraft has, however, concerned the detection of "circumbinary planets"—that is, planets that orbit around two stars at once; the planet circles around both stars as they orbit around each other. Before Kepler there were a handful of circumbinary planet candidates, but the planet formation community was split as to whether such double-star planets could really exist. With the discovery of the first transiting circumbinary planet, Kepler-16b, we were able to prove that such double-star planets do exist (Doyle et al. 2011, *Science* **333**, 1602–1606). Planetary transits across two moving stars are more complicated than transits across single stars, but since the discovery of Kepler-16b we have found about half a dozen additional such systems, several within the habitable zone of their (combined) stars. However, they are all large planets—closer in mass to, for example, Neptune. The scientific importance of these discoveries is that such double-star planetary systems are a fundamentally new kind of solar system. In science, the discovery of a new *kind* of phenomenon allows previous discoveries to be seen in context. The discovery of a new kind of biology on Mars would be an example; the origin of biology on Earth could be seen in the context of its origin elsewhere. In the case of Kepler-16b—and subsequent circumbinary planets—here was a fundamentally different kind of solar system where the planets form around and orbit two stars. Half the stars in our galaxy are double stars, so these discoveries bode well for life in the universe. Some of the excitement upon the announcement of the discovery of Kepler-16b also came from nicknaming this planet "Tatooine," after the home planet of *Star Wars* hero Luke Skywalker. Luke, in the film, spent some time watching a double sunset, a view that only became a reality with the discovery of Kepler-16b. George Lucas actually sent the Director of Industrial Light and Magic, John Knoll, to the Kepler-16 NASA press conference and the worldwide press picked up the discovery as a great example of science fiction becoming science fact. This discovery also reached a lot of students worldwide—from the correspondence received by the author—hopefully inspiring them, too, to make such real discoveries for themselves.

As mentioned, the transit method for detecting extrasolar planets detects the planet as it moves across—that is, "transits"—its parent star. While the Hubble Space telescope produces pictures, the Kepler Spacecraft produces what are called "light curves." A light curve is a measurement of the brightness of a star plotted over a given

time span. Some stars pulsate, some eclipse each other, and some are very steady in their brightness such as our Sun. A light-curve plot of brightness with time reveals how each of these types of stars behaves in varying its light output. And, if the light curve is accurate enough, it can reveal if there are any planets orbiting across our line of sight in front of the star, momentarily blocking out a little bit of the starlight. Not every star will have planets that happen to orbit edge-on, however, so one has to look at many stars to catch the small percentage with planets whose orbits are edge-on. Thus the Kepler telescope is an extremely wide-angle telescope that can view millions of stars continuously, with about 170,000 of the brightest stars being examined for planetary transits. The Kepler Spacecraft has been able to measure the brightness of stars about 100 times better than has ever before been achieved (on the ground or in space). As a consequence, it has revolutionized several astronomical fields such as eclipsing binary star systems, asteroseismology (the study of “starquakes” that tell about the interior of stars) as well as, of course, the field of extrasolar planets.

In the context of the search for life in the universe, the Kepler mission has made major contributions. This can be seen using the Drake Equation, which is a way of organizing the search for extraterrestrial intelligence, and the umbrella under which research is organized at the SETI (search for extraterrestrial intelligence) Institute, where the author works. (Incidentally, fifteen scientists from the SETI Institute currently work on the Kepler mission.) The Drake Equation is the product of the following terms: $N = R^* \times F_p \times N_e \times F_l \times F_i \times F_c \times L$. Each of these terms are actually fields of research in themselves. For example R^* refers to stars (created per year) that have stable habitable zones around them, that is stars that do not vary in brightness by too much. Consequently such “good” stars do not either burn and freeze their planets. F_p is the fraction of such “good” star that actually have planets. N_e is the number of planets that happen to orbit within the habitable zone of their stars. F_l is the fraction of potentially habitable planets that are, in fact, inhabited (by any biological forms). And the factors F_i , F_c , and L refer to the fraction of intelligent species of all species on an inhabited planet, the fraction of those intelligent species that develop technology capable of interstellar communication, and finally the lifetime of such advanced technological civilizations, respectively. Radio SETI—listening for signs of technology in space—is about 50 years old, and the term R^* has been known fairly well for this half century. The number of Sun like stars in our galaxy is about 30 billion with some cooler stars than the Sun also apparently having good habitable zones. The breakthrough that has been made with the work of the Kepler spacecraft over the past four years, is that a robust determination of F_p , the frequency of stars with planets, has now been definitively determined. Kepler has established the frequency of planets around the stars in only four years since its launch.

Finally, and most exciting to the SETI community, Kepler is discovering the value of N_e , the number of truly *Earthlike* planets within the habitable zones of their parent stars. To put Kepler’s discoveries in this context, of the seven factors in Drake’s Equation, one term, R^* , has been known for more than half a century, and in the past four years, the Kepler mission has determined the next term, F_p , and will soon add a determination of the third term, N_e , within the next few years. In the context of studies of life in the universe, this is a huge accomplishment, and radio astronomers at SETI

Institute are now targeting these Kepler planets known to orbit within the habitable zone. of their stars.

In the context of the Drake Equation, the next step in the discovery of life in the universe, illustrated by the term F_l , will be a next generation of telescopes that can discover biomarkers—evidence of life—in the atmospheres of Earthlike planets. An example of such a biomarker can be drawn from our own planet. The element oxygen is very reactive and so should, therefore, react with rocks or the ocean and consequently be removed rather rapidly as a constituent of our atmosphere. Yet oxygen is abundant in the Earth's atmosphere. This means that something must be producing it constantly in prodigious amounts. The large amount of free oxygen in the atmosphere of Earth, therefore, shows that we have huge photosynthetic systems operating here, including forests, seaweeds, and microflora. Taking remote spectra of the Earth, the detection of oxygen would be a major clue that the Earth does, indeed, harbor plant life and therefore possibly animal life, and perhaps even intelligent life. Thus with new missions to detect such biomarkers, it could be that forests may be the first extraterrestrial life that will be detected.

Finally, to answer the question that is the title of this session, *Exoplanet Discoveries: Have We Found Other Earths?* which is referring to the recent discovery of two planets within the habitable zone of the star Kepler-62. These planets—Kepler-62e, which is 1.6 times the radius of the Earth, and Kepler-62f, which is 1.4 times the radius of the Earth—are located within the habitable zones of their parent stars. Kepler-62f is actually more in the center of its habitable zone than the Earth is in our own Sun's habitable zone (we are closer to our inner boundary). So it is not the location of the planets that causes one to hesitate ... just a bit; it is their sizes. On Earth, the moving tectonic plates that make up continents are constantly being melted down as they dive under other continental plates. (The Pacific Plate and the North American Plate are well-known examples, meeting on the San Andreas Fault line.) This process of recycling continental rocks releases their gases back into the air. Plate tectonic activity stopped on Mars billions of years ago, so the atmosphere that did not leak into space was caught up in the rocks of Mars. Mars was too small, however to keep plate tectonics going. Some recent models have also found that if a planet is too large—near 1.4 Earth radii, for example,—a thick geological crust may possibly form that might also have the effect of stopping the plate tectonic recycling of the planet's atmosphere as well. Could this have happened to Kepler-62f? That will have to be further investigated. In the meanwhile, then, we will have to be just a bit cautious about claiming the habitability of Kepler-62f.

Fortunately, the discovery of even smaller planets than Kepler-62f within the habitable zone of their parent stars is still to come for the Kepler mission, and within the next few years Kepler will very likely find a true Earth-sized planet within its star's habitable zone. Writing 24 centuries ago in ancient Greece, Metrodorus of Chios said, "To consider the Earth as the only populated world in infinite space is as absurd as to assert that in an entire field sown with millet, only one grain will grow." Within the next few years we will have the privilege, through the Kepler Mission, to have the answer to this age-old question: "In the universe, is there another place like home?" I think we are on the verge of answering, "Yes!"