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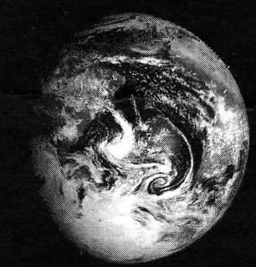
Detecting Habitable Planets: The Next Decade

by Andrew J. LePage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How many habitable planets similar to the Earth exist? While we search for an answer, a number of proposed projects might yield data we can use.

THE DRAKE EQUATION

$$N = R\, f_p\, n_e\, f_l\, f_i\, f_c \cdot L$$

where:

- N = Number of detectable civilizations in space
- R = Rate of star formation (in units of stars per year)
- f_p = Fraction of those stars that form planetary systems
- n_e = Number of planets hospitable to life
- f_l = Fraction of suitable planets on which life actually emerges
- f_i = Fraction of life-bearing planets where life evolves into intelligent beings
- f_c = Fraction of planets with intelligent creatures capable of interstellar communication
- L = Length of time that such a civilization remains detectable

The Drake Equation gives us the means of estimating the number of extraterrestrial civilizations that exist in the galaxy. Unfortunately many of the important terms in this equation are not known with any degree of certainty. One of the more important terms in this equation is the fraction of stars that possess planets. In the past estimates ranged from an optimistic "almost 100 percent" to a more pessimistic "much less than 1 percent." While a definitive number has not yet been found, we are getting closer since the discovery two and a half years ago of the first extrasolar planet orbiting a Sun-like star.

Since that time, almost a dozen extrasolar giant planets (EGPs) of Jovian to super-Jovian proportions have been discovered (see "The Discovery of Extrasolar Planets" in *SETIQuest* Vol. 2, No. 2, pp. 3-10 and "Extrasolar Planet Update" in *SETIQuest* Vol. 2, No. 4, pp. 6-11). These discoveries have confirmed the popular view that other planetary systems exist and imply that the fraction of stars with planets must be at least several percent. But at the same time, these new systems possess a broad range of EGP placements that have confounded the prevailing theories of planet formation. This has left astronomers thoroughly puzzled over the next term in the Drake Equation: The average number of potentially habitable planets in other solar systems.

As a result of their success, many of the radial velocity and astrometric surveys responsible for this initial spurt of discoveries have been greatly expanded. Within the next decade and a half we will have surveyed, via indirect means, almost all of the hundreds of Sun-like stars within 200 light years for the presence of Jupiter-like giant planets within a few astronomical units (AU) of their primaries (1). Follow-up programs to directly image these worlds with new ground- and space-based telescopes should not only confirm these discoveries but promise to shed much light on the nature of these worlds.

Questions Abound

While these surveys will reveal much about the arrangement and distribution of EGPs in other solar systems, they will not be able to detect Earth-sized planets in and around the habitable zones of other solar systems. The minute size of the reflex motion these small planets induce in their suns would be hopelessly swamped by sources of natural noise (e.g., surface convection and the passage of star spots) making their detection by the indirect means of radial velocity measurement or astrometry almost impossible (2).

The surveys to date indicate that about five percent of Sun-like stars possess a giant planet and another one percent have brown dwarfs orbiting within a few AU. It is possible that a small fraction of these substellar companions lie within their sun's habitable zone and have moons large enough to be habitable (see "Habitable Moons: A New Frontier for Exobiology" in *SETIQuest* Vol. 3, No. 1, pp. 8-16). While promising EGPs and brown dwarf candidates will be identified in the coming years, the detection of the potentially habitable moons themselves is not yet possible.

The origins of these EGPs is also a matter of much debate but all the proposals to date result in the destruction, or at the very least complicate the formation, of any terrestrial planets in the habitable zone. How frequently this happens in forming solar systems is not known. As a result, predictions of the ubiquity of habitable bodies based on these latest theories of planet formation are no help. The only consensus in the astronomical community from

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all the chaos produced by the discovery of close-orbiting EGPs is that more observations of extrasolar systems are needed to sort everything out.

A number of proposals exist for space-based imaging interferometers that, in theory, could obtain images and spectra of not only EGPs but smaller Earth-sized planets around Sun-like stars within a few tens of light years of us. One example is NASA's proposed Terrestrial Planet Finder (TPF) shown in Figure 1.

Unfortunately the TPF and similar instruments are still in their earliest stages of development and require the mastery of many unproven technologies. Consequently these novel telescopes will not be operational until well into the next century and it will be years more before a statistically meaningful number of stars are sampled. For those impatient individuals interested in determining the number of habitable Earth-like planets, the big question remains: Is there a method to detect terrestrial, and potentially habitable, planets around Sun-like stars using current technology?

The Answer: Photometry

Under special conditions, high-precision photometry (i.e., the accurate measurement of a star's apparent brightness) can be used to determine the presence of planets. One way that a planet can affect a star's brightness is through gravitational microlensing. The gravitational field of any massive body will bend and focus light similarly to a glass lens. If a massive body passes through the line of sight between Earth and a very distant star at the proper distance, the brightness of that star will temporarily increase just as a glass lens will brighten the image of distant object. The degree of this brightening and its duration can then be used to estimate the mass of the intervening body. Since this effect is only noticeable in a very narrow range of alignments between the observer, microlensing body, and background star, such microlensing events are quite rare.

A number of programs are currently under way, such as MACHO, OGLE, and EROS, that are using this effect to search for the missing mass in the halo of our galaxy in the form of MACHOs (Massive Compact Halo Objects). They are doing so by photometrically observing millions of stars either in the direction of the Large Magellanic Cloud or our galaxy's central bulge. These programs are most sensitive to microlensing bodies that are tens of thousands of light years away. The gravitational fields of bodies that are significantly more or less distant cannot properly focus the light of the distant background stars and do not noticeably affect their brightness. While these programs have failed to identify the presence of any of the more exotic proposed forms of the missing mass, they have occasionally detected the passage of dim, ordinary stars in our galaxy.

Calculations have shown that any planets orbiting these microlensing stars could cause additional, shorter term brightenings if these planets are properly placed in relation to their primary. Conceivably high time-resolution ground-based photometry could detect planets as small as the Earth (3). By observing hundreds if not thousands of these events, statistical models for the size and arrangement of planets in microlensing star systems could be produced. At this time there are a number of programs, such as PLANETS, that are currently searching for the signature of planets in microlensing events (4).

Unfortunately this method of detection is most efficient at spotting planets two or more AU from their primary. While the detection of Earth-sized planets at closer distances, such as in the habitable zone, is statistically possible, the chances that any such planet has the required apparent position relative to its sun during the primary microlensing event is vanishingly small (3). Even much more massive EGPs near the habitable zone are unlikely to be detected using this method. In addition, gravitational microlensing does not offer the opportunity for follow-up observations.

As mentioned above, the typical distance to microlensing stars is measured in tens of thousands of light years. Any planets that are detected around these distant stars would be too far away to be observed using any other technology that will be available in the foreseeable future. Additional microlensing events that could confirm and add to the initial observation would require a wait of decades or centuries.

Planetary Transits

The second way in which a planet can affect the brightness of a star is to transit the disk of the star it orbits. Otto Struve was the first astronomer to mention this mode of detection in 1952 (5). The concept was examined in more detail in the 1970s by F. Rosenblatt (6) and later in the 1980s by William Borucki and Audrey Summers (7) as well as others. They found that depending on the orientation of the planet's orbit, its orbital velocity, and the size of the star, such transits are expected to last from a few hours to the better part of a day. The drop in the star's brightness also provides an estimate of the transiting planet's size since the drop is proportional to the ratio of the projected areas of the star and the planet.

The transit of a Jupiter-sized EGP across a Sun-sized star, for example, would cause an easily observable 1.0 percent or 0.01 magnitude decrease in brightness. A smaller Earth-sized terrestrial planet would cause only a 0.008 percent or 0.0001 magnitude decrease in brightness in a Sun-like star. This level of photometric precision is not achievable using ground-based measurements due to the deleterious effects of our atmosphere.

On the other hand, transits of Earth-sized planets across the face of a much smaller M-type dwarf star would cause a larger drop in brightness than could be detected from the ground using large telescopes and sophisticated data-analysis techniques. Space-based photometric measurements, which would not be limited by the effects of our atmosphere, would have a much better chance of detecting the transit of a terrestrial planet.

Unlike the case with gravitational microlensing, planetary transits will repeat with the time between successive transits being equal to the orbital period of the planet. These regularly spaced transit events would be definitive evidence for a planet. Combined with a knowledge of the primary's mass and absolute brightness, it can be immediately determined if the detected planet lies within the system's habitable zone. Information on the length of the transits, in conjunction with the size of the star and the planet's mean orbital parameters, can be used to determine the inclination of a circular orbit to our line of sight or can place stringent limits on the eccentricity and orientation of an eccentric planetary orbit.

Since any planet detected by this method will be relatively close to us, follow-up observations using other planet detection methods are possible. In the case of the detection of an EGP orbiting a fairly bright star, radial velocity measurements will yield a definitive mass for the body when combined with the orbit inclination derived from the transit observations. Such observations will allow theoreticians to verify their calculation of how EGP radius varies with mass. When telescopes of the appropriate design become available, direct imaging of these large planets can be performed.

The only problem with planetary transits is that the orbit of the planet has to be almost perfectly aligned with the observer's line of sight so that it appears to cross the disk of its sun as viewed from the Earth. The geometric probability that a randomly oriented orbit is aligned to allow transits is simply the ratio between the star's radius and the radius of the planet's orbit. In the case of the Earth orbiting the Sun, the probability of a transit is 0.47 percent (8). For planets in smaller orbits, the chances are proportionally larger while for planets in larger orbits the opposite is true.

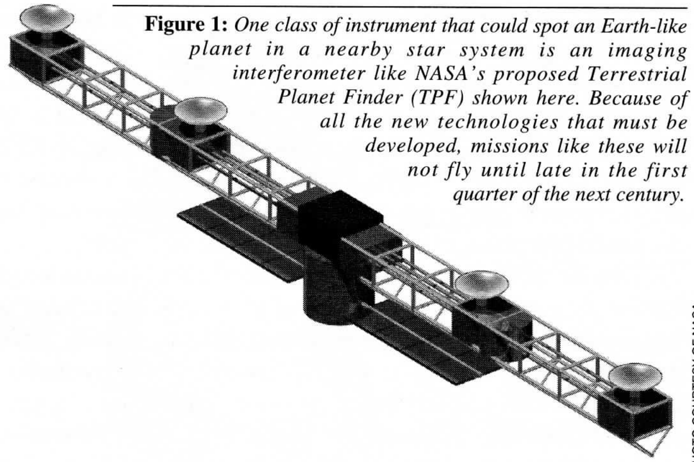


Figure 1: *One class of instrument that could spot an Earth-like planet in a nearby star system is an imaging interferometer like NASA's proposed Terrestrial Planet Finder (TPF) shown here. Because of all the new technologies that must be developed, missions like these will not fly until late in the first quarter of the next century.*

PHOTO COURTESY OF NASA

The probabilities of detection are also dependent on the total time in which observations are made. For example, the chances of a one-year observing program detecting a single transit of a twin of Jupiter in another solar system is the geometric probability of transit (i.e., about 0.09 percent) times the ratio of the length of the observing run to the orbital period of the planet (i.e., about 1:12). As a result, the probability of detecting a Jupiter-twin is about 1 in 130.

Even when a single planet is detected, there is no guarantee that other planets in the system will be detected—assuming, of course, they exist. This is because the orbits of the planets are expected to be slightly inclined to each other as is the case in our Solar System. Simulations have been performed to determine the likelihood of detecting additional planets in a system using our Solar System as a model (8).

The chance that either Venus or the Earth would be detected is about 1.2 percent. There is a 0.07 to 0.14 percent chance that more than one planet eventually will be detected around any given Sun-like star. Of the systems showing the transit of a large terrestrial planet, 7 to 10 percent will also experience a transit of a gas giant (although it may take decades of observing to see it). While a statistical model for the size, distribution, and number of planets per system can be compiled based on the analysis of a large number of stars experiencing transits, the problem is where to look.

The TEP Network

One place to search for the transits of extrasolar planets is in short-period eclipsing binary systems. Eclipsing binary systems consist of a pair of stars locked in an orbit that appears to be nearly edge-on as viewed from the Earth. This viewing geometry permits periodic mutual eclipses of the two stars to be seen. Since it is generally believed that the orbits of any planets in closely spaced multiple star systems will lie about in the same plane as the orbit of the binary, there is a much higher than average chance of observing planetary transits among the mutual eclipses of the binary.

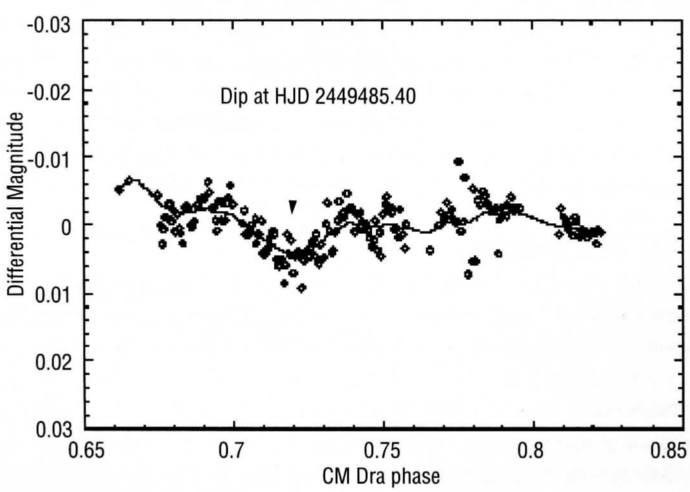
This is the line of thinking by the participants of the Transits of Extrasolar Planets (TEP) network. The network, which started making observations in 1994, consists of a collection of as many as seven one-meter class telescopes scattered across the globe (9). The target of their search is the eclipsing binary called CM Draconis located about 50 light years away. This system is composed of red dwarf stars (an M3V and an M4V) locked in an orbit with a period of 1.26 days with an inclination of 89.8 degrees to our line of sight. Each component has a diameter about a quarter that of our Sun, making the brightness drop by the transit of a planet of a given size even more noticeable.

Given the fact that the stars in this system are moving back and forth as they orbit about their center of gravity, the stars "scan" a larger volume of space in the system than a lone star could. Since the stars orbit each other so quickly, multiple planetary transits are possible. This property further increases the chances of a transit being observed. Originally the members of the collaboration estimated that they could detect the transit of a 2.6 $R_\oplus$ (33,000 kilometer in diameter) planet (9). A new cross-correlation analysis technique that they developed now allows them to detect the transits of planets about as small as the Earth (10).

CM Draconis first caught the attention of astronomers in June of 1996. On June 1, astronomers from Villanova University (who are working independently of the TEP network) detected a decrease in the brightness of CM Draconis using the Four College Consortium 0.8-meter APT on Mount Hopkins. Their results were consistent with the transit of a 0.85 $R_{♃}$ planet (11). Days after this announcement, the TEP team reported that they observed a similar event on May 27, 1994, hinting that there was an EGP orbiting CM Draconis in a 735-day (or 1.2 AU) orbit (12).

Since then the members of the TEP team retracted their claim when they discovered that the "event" they observed was in fact caused by an image-processing problem (12). To date, TEP has failed to detect the transit of any EGP. In fact, based on their 600 hours of observations between 1994 and 1996, the TEP network has 80 percent confidence that no planets larger than 2.5 $R_\oplus$ orbit CM Draconis with a period less than 60 days (which corresponds to a maximum orbital radius of about 0.23 AU) (13,14).

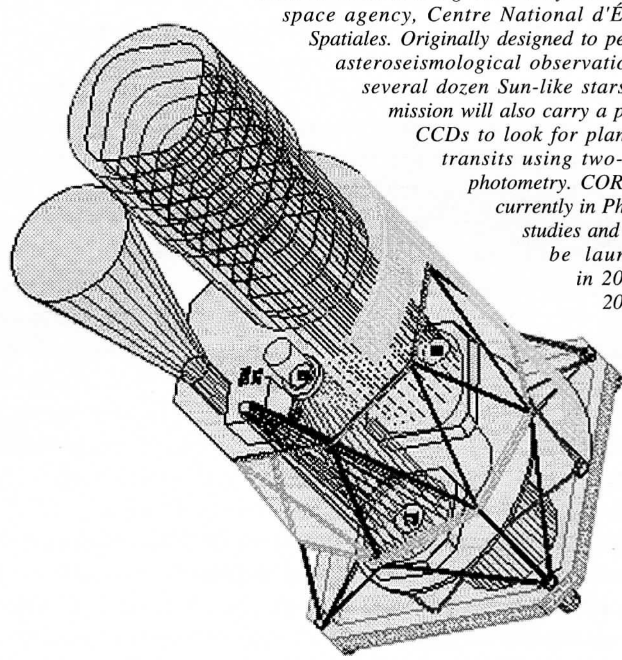
The TEP network, for all its effort, has not come up totally empty-handed however. The analysis of its data from 1994 to 1996 has uncovered five "events" that could be consistent with the transit of a planet or planets in the 1.5 to 2.5 $R_\oplus$ (19,000 to 32,000 kilometer) size range (14). An example of one of these "events" is shown in Figure 2. If these bodies actually exist and prove to be similar to the Earth in composition, they would have masses between 3 to 15 $M_\oplus$. The TEP group states that more observations will be required to determine the true nature of these "events" and whether or not planetary transits are responsible.



GRAPH COURTESY OF H. DEEG AND THE TEP PROJECT

Figure 2: *The Transits of Extrasolar Planets (TEP) network has been monitoring the eclipsing binary system of CM Draconis since 1994 in hopes of spotting a planetary transit. Shown here is a photometric "event" recorded on Heliocentric Julian Day 2449485.40 by the 1.2-meter telescope at the Observatoire Haute Provence in France during the 1994 observing season. This and five other events recorded between 1994 and 1996 could be consistent with the transit of a 1.5 to 2.5 $R_\oplus$ planet.*

Figure 3: *The optical system shown here is for the COROT mission being studied by the French space agency, Centre National d'Études Spatiales. Originally designed to perform asteroseismological observations of several dozen Sun-like stars, this mission will also carry a pair of CCDs to look for planetary transits using two-color photometry. COROT is currently in Phase A studies and could be launched in 2001 or 2002.*



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If these and future events are caused by a planet or collection of planets, their properties will prove to be of great interest since they fall in a previously unobserved portion of the planetary radius spectrum: Larger than the largest known terrestrial planet, Earth, with a radius of 1 $R_\oplus$, yet smaller than the smallest known gas giants, Uranus and Neptune, which have radii approximately 3.6 $R_\oplus$.

Observing More Transits

One way to spot more stars experiencing planetary transits is to observe a large number of stars for long periods of time at high photometric accuracy. If enough stars are observed, a number of transits would be expected to be seen so long as extrasolar planets are common. One proposed mission to do just that is COROT (COnvection & ROTation) shown in Figure 3.

Instead of searching for planets, however, the primary mission of COROT is to perform asteroseismology (15,16). Like helioseismology of the Sun, asteroseismology is the study of surface oscillations caused by sound waves traveling through a star. One way these oscillations manifest themselves is through tiny changes in a star's overall brightness with periods on the order of a few minutes (or conversely with frequencies on the order of millihertz). The only place to make months of continuous photometric observations with the parts-per-million accuracy required for this endeavor is from space. Asteroseismological observations of many Sun-like stars should provide much information on the interior structure and motions of these stars, making possible detailed comparisons with theoretical models and our Sun's structure.

COROT, named after the French Impressionist painter Jean-Baptiste Corot, is a small mission that has been selected by the French space agency, CNES (Centre National d'Études Spatiales), for Phase A study. COROT will be carried by a PROTEUS space platform that is to be placed into a quasi-polar orbit in the years 2001 or 2002 (15). The spacecraft will use a three-element 0.25-meter off-axis mirror telescope with a one-meter focal length and a 5-degree field of view to observe six different areas of the celestial sphere during a nominal 2.5-year-long mission. It will use three CCD arrays, each with a 1.5-degree field of view, to monitor the brightness of four or five Sun-like stars in each field continuously at the parts-per-million level of accuracy for 150 days (16). Such observations should allow the identification of low degree modes of surface oscillation to microhertz resolution.

Due to the 150-day observation time for each star field, such a mission is not ideal for spotting Earth-like planets with year-long orbital periods in the habitable zone of a star. Combined with the geometric probability of detection, there is only about a 0.2 percent chance that the transit of a twin of the Earth would be observed for any given Sun-like star. Still, it does offer the opportunity to systematically search for the transits of planets in smaller orbits, especially epistellar EGPs like 51 Pegasi B.

To this end, another instrument will share COROT's telescope that is specifically designed to detect planetary transits not only in the stars being observed by the asteroseismology instrument, but in the more numerous dim stars in the telescope's field of view as well (17). This instrument will use a beam splitter to separate the incoming light from the stars in a target field into two colors whose intensity will be precisely measured by a pair of CCD arrays. The use of a two-color measurement scheme will allow a transit event to be differentiated from something else like the passage of a large star spot. The scientists who are developing COROT estimate that several tens of epistellar EGPs should be detected along with the transits of about 30 longer period planets during the mission (15,17).

While not ideal for planet hunting, COROT should offer us our first glimpse at the arrangement of smaller planets in the inner portions of other solar systems.

The Ideal Transit Hunter

The ideal means of detecting the transits of Earth-sized planets would be to observe thousands of stars continuously for years at high photometric precision. The best place to do that is from a spacecraft in solar orbit well away from the interference of the Earth. By observing thousands of stars, the transits of hundreds of planets could be detected. Observing for long periods of time allows the detection of repeat transits, thus allowing the determination of the orbital period as well as the detection of smaller planets. Long observation runs also increase the chances of spotting the transits of planets in long period orbits. Combined with the size of the planets derived from the depth of the transit event, an excellent statistical model of the number, size distribution, and placement of planets in other solar systems could be determined. This data would finally allow us to derive a realistic estimate for the prevalence of habitable bodies in our galaxy.

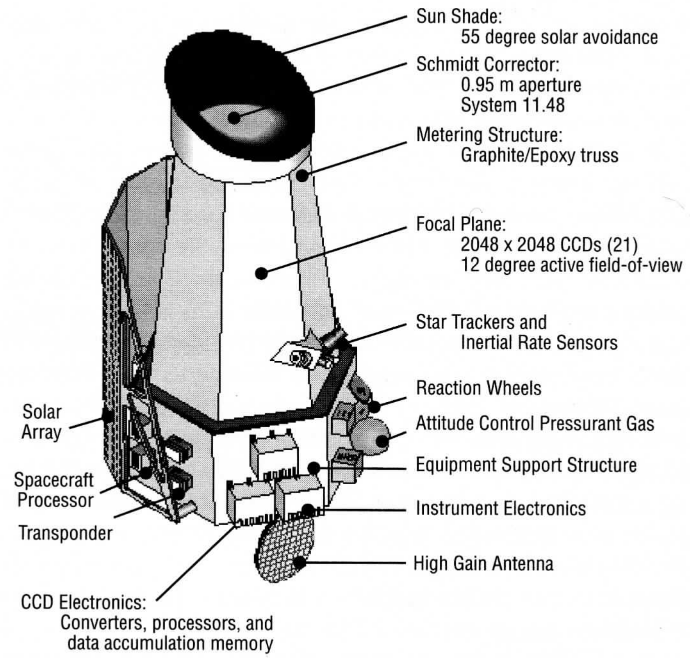

Figure 4: *The major components of the Kepler spacecraft are shown. Kepler is proposed as a Discovery-class mission by a joint NASA Ames Research Center–Lockheed Martin team. It will continuously make photometric measurements of 80,000 main sequence stars for four years searching for planetary transits. If terrestrial planets are common, Kepler could spot as many as 480 planets in or near the habitable zones of their solar systems.*

The one proposed spacecraft capable of performing this mission is called Kepler and is shown in Figure 4. This mission, which grew out of Borucki's earlier FRESIP (FRequency of Earth-Sized Inner Planets) concept (18), is the brainchild of a group of scientists and engineers at the NASA Ames Research Center's Space Science Division and Ball Aerospace. Named after the sixteenth century Dutch astronomer Johannes Kepler, this proposal is a low-cost Discovery-class mission that will place a one-meter clear-aperture Schmidt telescope into a 372.5-day heliocentric orbit using a Delta II 7425 launch vehicle (19). The instrument will use 21 2048 x 2048 pixel CCD arrays to continuously monitor the brightness of all the stars with a V magnitude greater than 14 in its 12-degree field of view for a nominal mission length of four years.

The CCD arrays would be read every three seconds and the results processed to produce the brightness of all the stars in the field of view every 15 minutes. By transmitting only the brightness values instead of an entire image, the data rate demands are greatly lessened (19). The baseline goal is for Kepler to be capable of detecting the 0.008 percent brightness drop caused by the transit of an Earth-sized planet in front of a Sun-like star with an apparent V magnitude of 12. Assuming this Earth-sized planet has an orbital period of one year, a four-year mission is the exact length needed to ensure the detection of two transits plus permit the prediction and observation of a third transit as confirmation.

A series of tests have shown that Kepler's goals are realizable with the proposed design. In order to observe the largest number of stars possible with the limited field of view as well as avoid the blinding glare of the Sun, Kepler will be aimed at a densely populated region of the sky at right ascension 19 hours 45 minutes and declination +35 degrees in the northern constellation of Cygnus (19). This area of the sky presents 160,000 stars brighter than V magnitude 12 to Kepler's field of view. Half of these stars would be on the main sequence. The members of the Kepler mission group estimate that as many as 480 habitable planets as large and larger than the Earth could be detected, including 60 cases of more than one planet observed in a system (19).

In reality if our Solar System is typical (which the Kepler mission hopes to determine), only about 80 transits of Earth- and Venus-twins will actually be detected and both planets would only be detected in five to nine of the stars observed. This is because only one-eighth of the sample of main sequence stars in Kepler's field of view will have radii small enough—and an apparent magnitude high enough—for the transits of Earth-sized planets to be detected. In addition to inner-orbit terrestrial planets, as many as 24 one-time transits of EGPs in distant orbits are also expected. The relatively large brightness changes caused by the transits of these EGPs will allow follow-up transit observations using Earth-based telescopes. Kepler could also detect the transits of eccentric planets such as 70 Virginis or 16 Cygni B and determine the occurrence of these and other classes of EGPs that might exist in or near the habitable zones of other solar systems.

With minor modifications, Kepler could also determine the level of stellar activity and the rotation rates of many stars in its sample. Follow-up observations of any of the discoveries using radial velocity measurements, astrometry, spectroscopy, or imaging are all possible and will shed more light on the properties of these stars and their planets.

Kepler should also be able to help settle the controversy behind epistellar EGPs like 51 Pegasi. Some doubt has recently been cast on the existence of these planets with the commentary that the radial velocity surveys that discovered these planets could be detecting some new form of non-radial stellar oscillation instead (20). If the EGP interpretation of present radial velocity surveys is accurate, Kepler should detect the transits of about 160 epistellar EGPs (19). Follow-up radial velocity measurements from the ground, when combined with the orbit inclination derived from the transits, are expected to yield accurate masses for about seven of these planets. Coupled with the transit-derived planet radius, the density of these seven EGPs can be calculated thus allowing astronomers to zero in on viable models for their structure.

Follow-up spectrographic observations made during future transits may even be able to detect the constituents of any extended atmospheres these EGPs might have (21,22). In addition to detecting the transits of epistellar EGPs, Kepler will be sensitive enough to measure the phase-induced brightness modulation caused by the light reflecting off 1400 EGPs with orbital periods up to a week. When the decrease in illumination at greater orbital radii is taken into account, this signature is lost in the star's natural background "noise" for orbital periods longer than this (19). By using both brightness modulation and transit depth data, it will be possible to determine the albedos of 160 epistellar EGPs.

With such a large sample, a definitive statement of the occurrence and properties of epistellar planets could finally be made.

The Future

Kepler, along with 33 other mission proposals, was submitted for consideration in NASA's Discovery program in 1996. On April 23, 1997, NASA announced the results of this competition and Kepler unfortunately did not make the cut. The reviewers stated that the proposal would have ranked in Category One were it not for some relatively minor and, in the opinion of the proposers, ill-founded weaknesses (23). These "weaknesses" are being ironed out and Kepler will be proposed again at the next Discovery opportunity around April of 1998.

While it is impossible to forecast when (or even if) Kepler will finally fly, it is possible that it could start gathering data in the opening years of the next century. A decade from now, with luck, the information from Kepler combined with that gleaned from other surveys, will allow astronomers to determine whether or not our Solar System is typical as well as estimate the number of potentially habitable worlds.

With that knowledge in place, two more variables in the Drake Equation will be known and we will be that much closer to determining if we are unique.

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