Ecospheres Project

Report

Number 1. January 2012

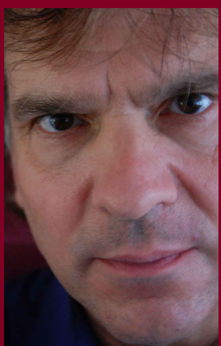
Mission accomplished!

NASA press conference breaks the news – quest to confirm planet circling two suns ends with a spectacular discovery - and the new world might possess habitable moons.

Artwork: NASA/ Tim Pyle, JPL

The Ecospheres Project is a collaboration pursuing front-line science, campaigning for the Earth sciences and promoting environmental initiatives. This newsletter is launched as a vehicle through which we can share the excitement of our research and campaigning interests. We welcome a broad readership, including co-workers across a range of fields, the public and potential sponsors.

Hunting for special worlds: protecting our own special world.

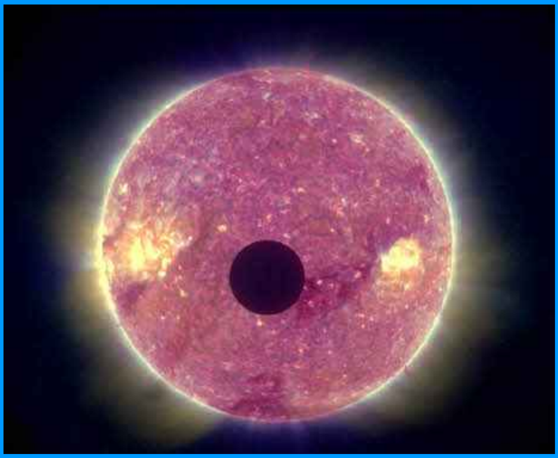


Dr. Martin Heath, co-ordinator of the Ecospheres Project: 2011 was a rewarding year which saw an element of drama. My principle research collaborator, Dr. Laurance R. Doyle of the SETI Institute, a participating scientist with NASA's Kepler mission, led the team which found Kepler 16b, the first Kepler-named object (confirmed by the transit method) to be orbiting two suns - and his September 15, 2011 press conference brought a long personal quest to a successful conclusion. Shortly, Laurance and I had the pleasure of pegging up this new planet as the first confirmed Kepler object to be of potential interest to astrobiologists.

The Ecospheres Project, centred on our research symbiosis, embraces two goals. Our first and most urgent priority is the planet on our doorstep, a planet subject to telling blows from human activity on a broad front. At the same time, as the search for other habitable worlds moves, for the first time in history, from the realm of educated guesswork and science fiction into that of reality, Laurance and I are exploring what it takes for a basically Earth-like planet to host complex life. He brings perspectives from astrophysics and I from biology and geology. Kepler 16b is not an Earth-like planet; if it hosts complex organisms, they would have to be distinctly different from those known on Earth. Given its hardiness, however, bacterial-grade life, at least, might, if there are moons, be able to exploit their sub-surface environments.

Kepler 16b – a planet for life? ➔

The transit method for planet-hunting.



The passage of a planetary body across the face of its star is termed a transit. From the Earth, we can occasionally see the planets Mercury and Venus, whose orbits lie within that of the Earth, cross the disk of the Sun as small dots. Venus transits have been important historically, because they have been exploited in attempts to determine the Earth-Sun distance. A pair of Venus transits famously took place in 1874 and 1882, to be followed by a pair in 2004 and 2012. An observer on the Martian surface could enjoy not only occasional transits of Mercury and Venus, but also of the Earth and its Moon. No one, of course, has yet enjoyed such a sight directly, but the STEREO (Solar TErrestrial RElations Observatory) B probe, placed into an orbit outside that of the Earth, returned images (above right) of the passage of the Moon across the Sun from such a distance (around 1.6 x 10^6 km – over four times farther than the Moon seen from Earth) that our natural satellite no longer obliterated the solar disk, as in the eclipses that we see from Earth, but actually transited (Feb. 25, 2007: NASA image). The transit method for detecting planets of other stars, exploits the fact that if a planet's orbit is correctly aligned as seen from Earth, that the planet will cross the disk of its parent star, causing a very small drop in brightness - the Earth would dim the Sun by just 84 parts per million, for a period of hours (a central transit of the Earth could last for about 13 hours).

Laurance Doyle was associated closely with developing and applying the transit method for detecting planets of other stars. For an external observer in another planetary system and placed randomly with regard to the Solar System, the probability of the Earth and Sun lining up for a transit would be just 0.465%. However, Doyle focussed on very close binaries in which the two stars eclipse each other as seen from the Earth. It was thought (astronomers are no longer so sure) that in such a system, planets orbiting around the outside of the binary, but sufficiently close to lie in the classic Habitable Zone (HZ) could have stable orbits only if these orbits are at least of the binary. Find an eclipsing binary, went the argument, and you would have a very much better chance of catching a planetary transit than with a star selected at random.

The first transit search.

In 1994, Doyle and co-workers launched the first observational programme to use the transit method for planet-hunting. They studied the eclipsing red dwarf binary CM Draconis. Doyle used the Lick Observatory's Crossley reflector on Ptolemy Ridge in California's Coast Ranges (Left: Image M. J. Heath).

Pioneering studies, imagination and guesswork.

Doyle became co-director of the TEP (Transit of Extrasolar Planets) observing network, and together with astronomers Hans Deeg (Instituto de Astrofisica de Canarias and Principal Investigator for the IAC Permanent All-Sky Survey project for detecting extrasolar planets) and Jon Jenkins (SETI), designed the Transit Detection Algorithm (TDA), which was adopted for NASA's *Kepler* mission. With Deeg, he developed a planet detection method for use in eclipsing binary systems, and with Jenkins, a method based upon the reflected light phase of a planet. It was on the basis of this work that he was appointed in 2007 as a Participating Scientist on the Kepler mission.

Observations of CM Draconis began shortly after Doyle staged the First International Conference on Circumstellar Habitable Zones in 1994. At that time, the only convincing claim for planets beyond the Solar System was from Wolszcan & Frail (1992) namely objects of comparable masses to the Sun's terrestrial planets orbiting in the inhospitable environment close to the pulsar PSR B1257+12, a neutron star remnant of a supernova. It would be late 1995 before Mayor and Queloz (1995) reported the discovery of the first “hot Jupiter,” as they came to be known, a giant planet orbiting very close to its star, in this case, the 51 Pegasi, a solar-type star that has evolved further than our Sun, and become a sub-giant. Planetary scientists believe that giant planets form in the colder parts of the disks of gas and dust surrounding young stars, and then migrate inwards in response to tidal interactions with the disk. Continuing studies of CM Draconis did not provide unequivocal evidence of a planet (Deeg *et al.*, 2000; Doyle *et al.*, 2000), but they did successfully eliminate the possibility of objects of more than about 2.3 Earth radii in the HZ - valuable information about the environment of this double star 47 light years away.

This early transit work could not have revealed an object as small the Earth. We fell back upon imagination and guesswork when, from 2003, the Ecospheres Project worked as a consultancy to *Big Wave*, an award-winning TV company, which used CGI to portray two hypothetical Earth-sized bodies. One, a planet in synchronous rotation around a single red dwarf, was based on a paper (Heath *et al.*, 1999) on which Doyle had worked with me as second author, and I devised the other, an Earth-sized moon of a gas giant that orbited in the HZ, with feedback from Doyle and producer Nick Stringer. It incorporated Doyle's interest in the possibility of circum-binary planets, having two solar-type yellow dwarf (class G) stars at the heart of the system, and I had the satisfaction of seeing my scruffy sketch of the system converted by special effects experts into a believable scene complete with simulated lens flares (above). Imagination and guesswork, however, are no substitutes for reality. Doyle's goal would not be achieved until NASA launched its Kepler mission.

The Kepler mission gets underway.

It was quite unintentional, but appropriate, that the Kepler space craft should have been launched during the year that saw the bicentenary of the birth of Charles Robert Darwin (1809-1882), who pioneered the concept of evolution through natural selection. It is no exaggeration to hail the Kepler mission as one of the most important and exciting scientific adventures ever undertaken by *Homo sapiens*. It carries forwards the investigation of the environmental context of life to which Darwin's 1831-1846 voyage on HMS *Beagle* and the later Malaysian explorations of Alfred Russell Wallace (1823-1913) gave such impetus, and it promises to transform the way in which we understand our place in the universe. It is easy to underestimate the potential impact of Kepler because we are over-familiar with the imaginary universe of scientific conjecture and science fiction. Shortly, however, for the first time in history, we could be armed with genuine *knowledge*, rather than guesswork, about the existence of planets the size of our own around other stars, about how common they are and what kinds of orbits they pursue.

Lift-off of the Delta Two rocket carrying Kepler was at 03:49:57 UTC on March 7, 2009 (22:49:57 EST), from Cape Canaveral Air Force Base, Florida. As part of the Kepler team, Doyle was present as an official observer, whilst I caught the lift-off live on the BBC. We had not forgotten what had happened to NASA's Carbon Observer, and that added an element of inevitable tension to the proceedings. Launched on a Taurus XL rocket from Vandenberg Air Force Base in California, on February 24, 2009, it had failed to enter orbit and had plunged back to Earth in the Southern Ocean. However, Kepler was placed successfully into its heliocentric orbit following the Earth, and after a number of hiccups which did not kill the mission, it was able to begin its task of surveying a section of the sky free from the interference of Earth, Moon, Sun or other Solar System planets. Kepler's 95 cm aperture photometer has been observing some 155,000 stars simultaneously, so even though the probability that planets in any particular system will have orbits aligned in such a way as to allow transits is very low, the data analysts were shortly able to publish a provisional list with 1,235 candidate planets (Borucki *et al.*, 2011)

The Kepler Field of View (FOV) is a small patch of sky comprising just 105 square degrees, but it is by no means obscure. It intrudes into the Summer Triangle," defined by the bright stars Deneb in Cygnus, Vega in Lyra and Altair in Aquila, straddling the jagged boundary drawn up by astronomers to divide Cygnus and Lyra, and it intrudes a little way into the less resplendent constellation of Draco (the Dragon). There is no arcane insight required to locate the general area of the FOV, because a line drawn between Deneb and Vega passes through its more southerly reaches.

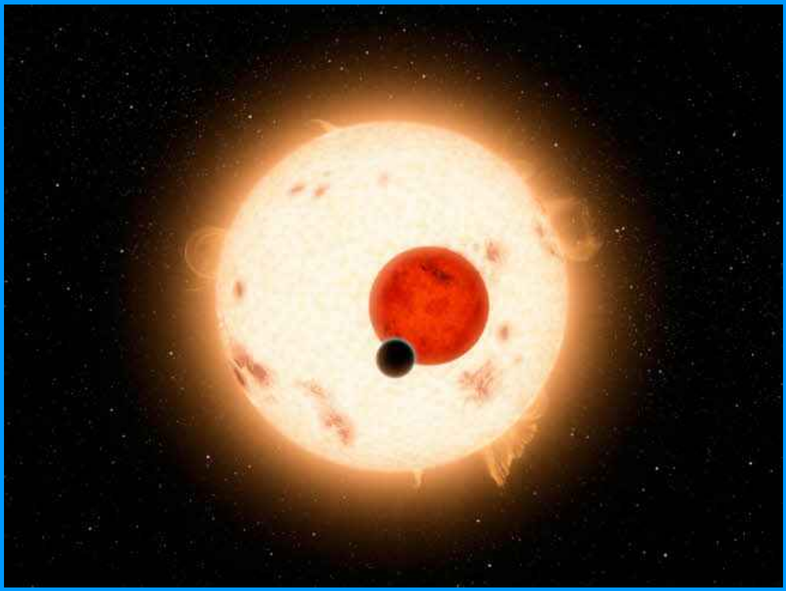
NASA graphic.

It is thought-provoking, on clear nights, to look up at the Kepler FOV and to know that at the same time, way out in space, Kepler's electronic eye is also scanning it. It is there that the adventure of discovering other Earth-sized planets begins. For those of us who have devoted much of our academic lives to considering what would make another planet truly habitable, the last two and three quarter years have been a heady time, because our field has appeared, at long last, to be on the very brink of becoming an observational science.

Tantalisingly, however, just as the discovery of other Earths appears to lie within our grasp, there has emerged a threat to the Kepler mission, which could mean that it will fail to achieve its major objective. It had been anticipated that an Earth-sized body could be confirmed after it had made three observed transits across the face of its star. Kepler scientists discovered that stars generally have more surface activity (spots and bright areas) than anticipated (Gilliland *et al.*, 2011; see also review by Cowan, 2011), so the mission will have to be extended to around 8 years, over twice its proposed lifetime of 3½ years, if genuine transits are to be identified unequivocally. Otherwise, the Kepler legacy may take us no further than a list of unconfirmed candidates for Earth-sized planets.

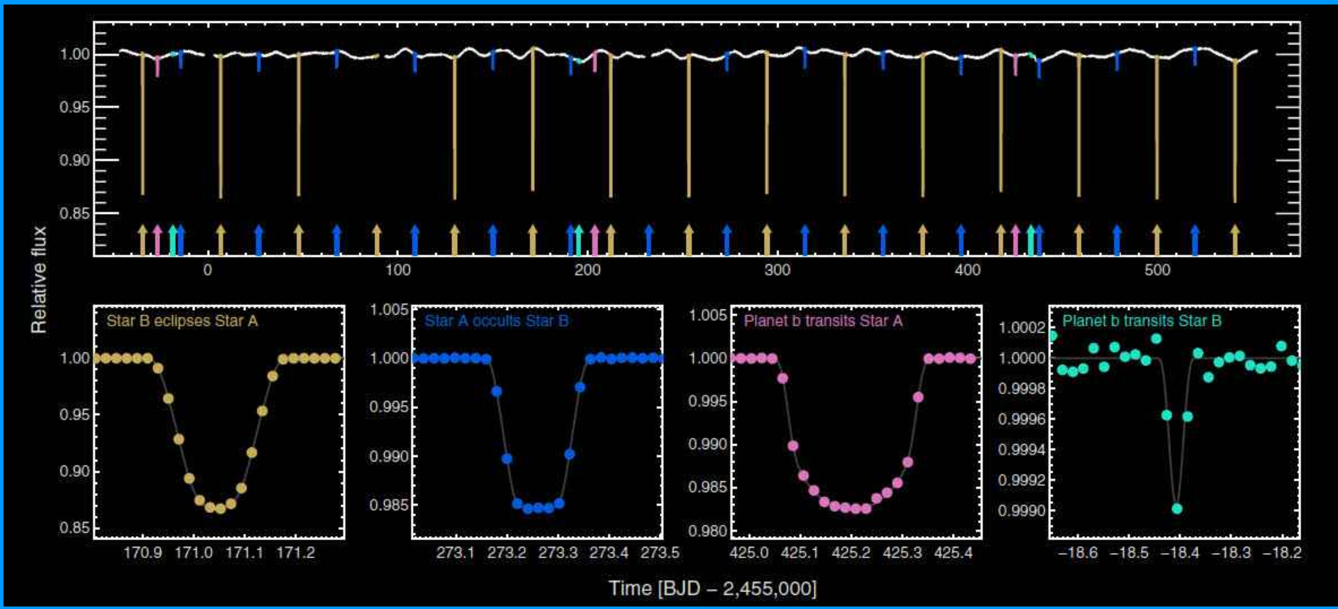
This threat has thrown into sharp relief the significance of the search being conducted by Doyle and others on circum-binary planets. The advantage of their methodology is that planetary transits will involve two stars rather than one, and that makes it easier and faster to confirm the existence of a planet. Likewise, it enables astronomers to derive planetary characteristics with much more accuracy. Should the Kepler mission not to be extended (and there are strong rivals for funding), data from eclipsing binaries might be our best hope for extracting high quality data from the tragedy of a lost opportunity.

A strange new world.



Kepler 16b was announced by Doyle *et al.* (2011) in *Science*. Its system is remarkable and will require astronomers to re-think the possible dynamics of planetary systems. Two stars lie at its heart. The larger has been classed as a K2 (orange) dwarf, with a mass 0.6897 that of the Sun. Its companion is a faint red dwarf star whose mass is 0.2026 that of the Sun. The stars circle each other in a period derived precisely as 41.07922 days, at a mean distance of 0.2243 AU (the Astronomical Unit is the mean Earth-Sun distance). Their orbit is notably eccentric (15.94 %), yet that of the planet (a giant close in at 0.7048 AU), surprised theorists by being nearly circular (eccentricity just 0.69 %). A stable planetary orbit should have a period at least 5.5 times that of the central stars. Kepler 16b just qualifies with a ratio of 5.569.

Artwork: NASA/Robert Hurt.

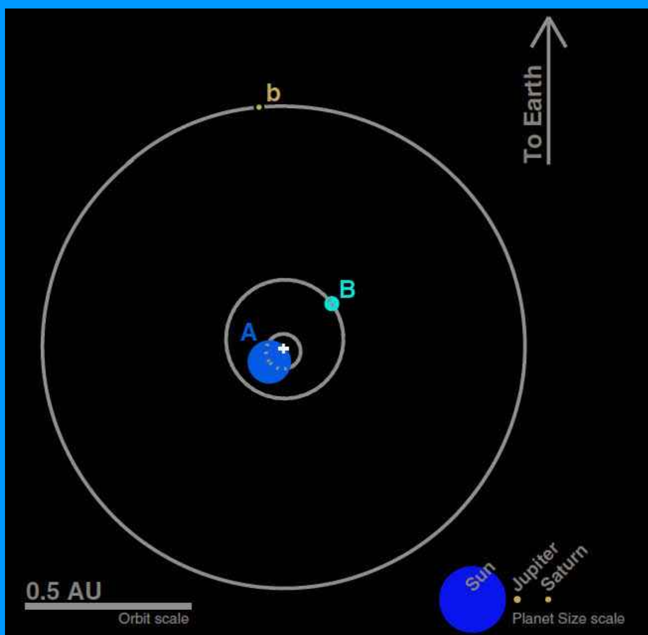


Above: Light curves observed for eclipses and transits in the Kepler 16 system (after Doyle *et al.*, 2011).

The road to discovery began when the star 12644769 from the Kepler Input Catalogue was identified as an eclipsing binary. During primary eclipses, when the smaller star passes in front of the larger, the binary's brightness falls by 13%. During secondary eclipses, the larger star passes in front of the smaller and brightness falls by just 1.6%, because the red dwarf is so cool and faint. Subtle tertiary (1.7%) and quaternary (0.1%) falls in brightness implied a third body transiting the brighter and duller star respectively – but were astronomers seeing a planet in transit, or grazing eclipses by a third star? The answer was provided by variations in the timing of eclipses, which revealed how the three bodies interacted gravitationally, and so vital information about their masses. The third body was established firmly as a planet. The fact that its orbit aligns with that of binary to within 0.4°, is consistent with the planet having formed within a disk around the binary.

The planet's mass is 105.8 Earths and its radius 8.2 Earths. For comparison, Saturn, the Sun's second largest planet has a mass of 95.2 Earths and a mean radius of 9.0 Earths. The planet's density of 0.964 g cm^{-3}, is greater than that of Saturn (0.687 g cm^{-3}), implying a higher proportion of heavy elements (up to half the mass, with other half consisting of H and He). The Sun's gas giants have been generally dismissed as offering homes for life, although there have been bold (and highly controversial) suggestions that life might thrive in their atmospheres at levels between the intense heat of their deep interiors and the chill of space.

Artwork: Josh Carter.



The Kepler 16 system: (orbits not to scale with star and planet sizes. After Doyle *et al.* (2011).

The Habitable Zone.

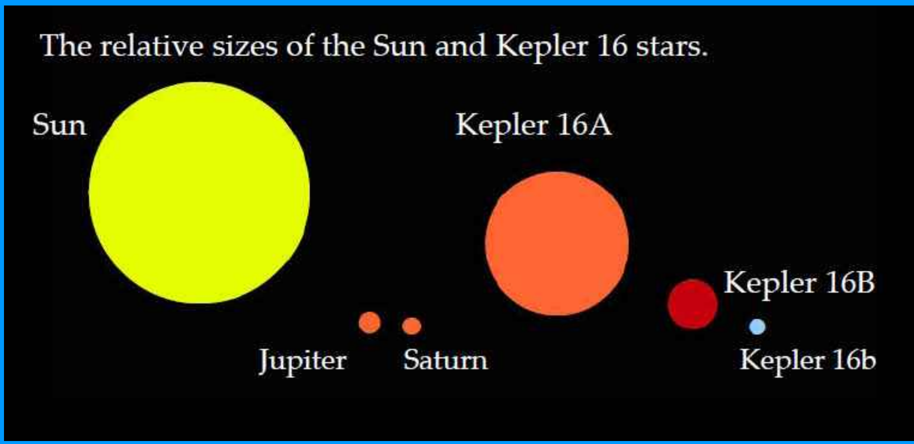
The Holy Grail of the quest to discover planets around other stars is an Earth-like body orbiting within the HZ. It might be a planet in its own right, or it might be a large moon.

Our current understanding of the HZ derives from the work of James G. Walker *et al.*, 1981, who drew attention to the carbonate-silicate cycle. Put simply, volcanoes (such as Etna in Sicily, below) emit CO_2. It dissolves in rain water to form a weak solution of carbonic acid. This weathers rocks and rivers carry weathering products to the sea. The fate of CO_2 is to be locked up in limestones. Later geological activity, involving volcanism or convergence of the Earth's moving geological plates can release CO_2 from limestones, and also juvenile CO_2 from the Earth's mantle. Weathering acts to adjust the quantity of the greenhouse gas CO_2 in the atmosphere, so that if the Earth received more energy from the Sun (insolation) the quantity of CO_2 would fall, reducing greenhouse warming. If the Earth received less, the quantity of CO_2 would rise, increasing greenhouse warming.

The essential requirements of the carbonate-silicate cycle are seen in this NASA image. Active volcanism is evident brown plume). Clouds of water droplets and water ice crystals float in a substantial atmosphere. Rocks are available for weathering on land and river systems drain to the sea. Mountains attest to plate convergence.

James F. Kasting *et al.* (1993) combined the carbonate-silicate cycle with climate models and estimated the width of the HZ around stars of differing temperatures, defining the HZ as the zone within which a suitable planet could retain bodies of liquid water (essential for life as-we-know-it) on its surface. For the Sun, they placed the inner edge of the HZ at 0.95 AU (Astronomical Unit = mean Earth-Sun distance), where the Earth would receive 1.1 its present insolation and lose its water. The outer margin might be taken as 1.37 AU, where crystals of reflective CO_2 ice begin to form in a planet's atmosphere, or more optimistically, 1.67 AU, with 0.36 $I_\oplus$ ($I_\oplus$ = Earth level insolation), where the amount of CO_2 in the atmosphere would be about 8 bars, and the atmosphere itself would be so highly effective at back scattering incoming solar radiation to space that any further increases in CO_2 would be counter-productive. Later, two other workers in the field, François Forget and Raymond Pierrehumbert (1997), argued that CO_2 ice crystals in the atmosphere would be sufficiently efficient at down-scattering the infra-red component of insolation to a planet's surface, that the HZ outer margin might be extended to 2.4 AU.

The hope of discovering an Earth-sized body within the HZ is what makes it so exciting to watch the roll-call of confirmed Kepler bodies as it grows.



Kepler 16b and the classic HZ.

Immediately after the Kepler 16b press conference, Doyle and I conferred by telephone. On television and the internet, various experts contacted for opinions were delivering off-the-cuff pronouncements that the giant planet was very unlikely to host life. I pointed out that every other Kepler object confirmed to date had been simply too hot for life-as-we-know-it. This object was different. It was going to receive less energy than the Earth, but at the same time, far more energy than the moons of Jupiter. That opened up exciting possibilities. After a frustrating delay resulting from a submission technicality, we posted a notice (Heath & Doyle, 2011) on the astro-ph website operated by Cornell University. We discovered later, from email exchanges, that there had been some discussion amongst researchers about the location of the planet Kepler 16b in relation to the HZ, and Eric Ford had produced a graph showing how insolation would vary on the planet, although we did not have the advantage of his work until we had already submitted.

Bill Borucki, Prinicpal Investigator for the NASA Kepler mission, had always emphasised the importance of the HZ. Borucki *et al.* (2011, p. 21): "*The habitable zone (HZ) is often defined to be that region around a star where a rocky planet with an Earth-like atmosphere could have a surface temperature between the freezing point and boiling point of water, or analogously the region receiving roughly the same insolation as the Earth from the Sun (Rampino and Caldeira 1994, Kasting 1997, Heath et al. 1999, Joshi 2003, Tarter et al. 2007). The temperature range for actual habitable zones is likely to include equilibrium temperatures well below 273 K because of warming by any atmosphere that might be present. For example, the greenhouse effect raises the Earth's temperature by 33 K and that of Venus by approximately 500 K.*"

For progressively cooler (redder) stars, Kasting and co-workers predicted that the outer margin of the HZ would lie out at progressively lower insolation values, as their output became more red biased. This is because the longer (redder) the wavelength of light, the greater is its ability to penetrate planetary atmospheres and warm the surface, without being back-scattered to space. The temperature of the larger star, Kepler 16A was estimated by Doyle *et al.* (2011) as 4,450 ± 150 K (significantly cooler than our Sun whose effective temperature is around 5770 K). Even without taking this into account, Kepler 16b would lie within the HZ, if Forget and Pierrehumbert are correct about its outer edge.

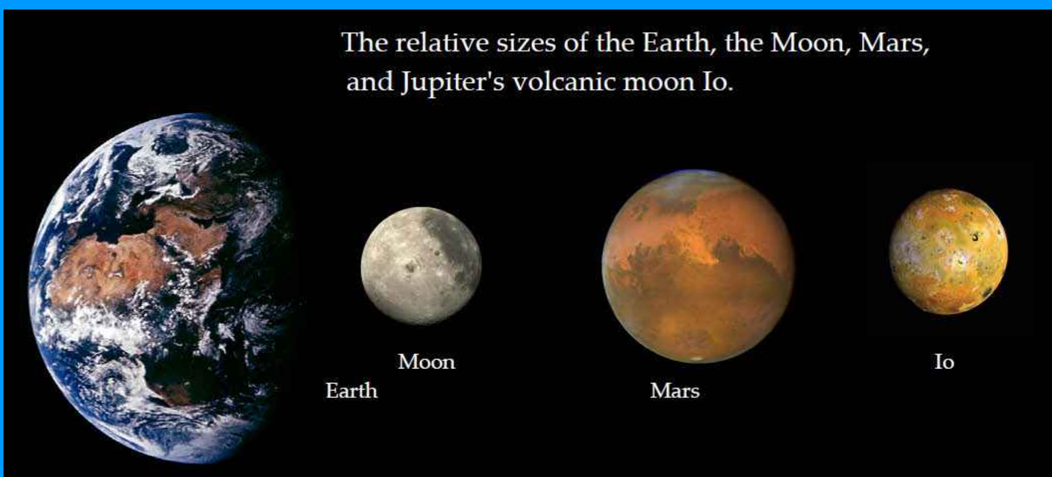
Moons and the classic HZ.

Close as Kepler 16b might lie to the outer edge of the HZ – or even if it lies within it, the planet itself is clearly not Earth-like. It would, moreover, be special pleading to assume that this body possesses a moon large enough to function like the Earth and to retain sufficient internal heat over thousands of millions of years to sustain geological activity at a level compatible with running the natural thermostat of the carbonate-silicate cycle. Something like our fictional Blue Moon may well exist somewhere in our Galaxy of hundreds of thousands of millions of stars, but it would be unlikely to turn up so conveniently in the early Kepler mission data.

An object does not, of course, have to be Earth-sized to be geologically active. Jupiter's moon Io has just 1.5% the mass of the Earth, and 28% of its radius, but thanks to tidal interactions with neighbouring large moons Europa and Ganymede, it has the greatest flux of internal heat and the most dramatic volcanism of any Solar System body. We know nothing, of course, about whether Kepler 16b has moons, let alone whether their mutual interactions would enable tidal heating, but the possibility is worth bearing in mind.

Aside from tidal heating, Williams *et al.* (1997) estimated that a moon with 23% the mass of the Earth (and possessing a magnetic field to protect its atmosphere from being swept away by the wind of particles emitted by its star) could retain seas and atmosphere and remain geologically active for significant periods of time. Calculations of planet radii versus mass by Seager *et al.* (2007) indicate that of body of basically Earth-like composition having a mass of 23% Earth mass would have a diameter approaching 70% that of the Earth. The Earth is much more massive, but not vastly larger, because as bodies of given composition become more massive, their interiors suffer gravitational compression and their densities rise exponentially. For comparison, Mars has a mass of 11% Earth and a radius of 53% Earth. One might have expected an object that big to have betrayed itself already; it would have noticeably modified the Kepler 16b transits. There are also reasons (although little is certain here) to question whether a moon that large is likely for a planet of comparable mass to Saturn. Solar System satellite systems have maximum masses $< 2.5 \times 10^{-4}$ of their primary planets and this has been explained (Canup & Ward, 2006) in terms of the limited amount of material available in embryonic planetary systems to form moons.

NASA Images.



Will ice-rich moons offer habitats?

We emphasised the potential of icy moons to support life. Those of the Solar System giant planets all lie outside the HZ, but several may host internal bodies of water and, in principle, life. Jupiter's moon Europa (below right; NASA image) and Saturn's moon Enceladus have received particular attention from astrobiologists. Reynolds *et al.* (1983), Greenberg *et al.* (2000), Marion *et al.* (2003), McKay *et al.* (2008), Parkinson *et al.* (2008) and Rampellotto (2010) are among authors who have discussed the feasibility of life beneath the frozen surfaces of these bodies – and bacterial grade life might survive given liquid water, mineral nutrients and an energy source. Caleb Scharf (2006) examined the prospects for life on moons of planets around other stars and argued (p. 1,196): *Moons of giant planets may represent an alternative to the classical picture of habitable worlds. They may exist within the circumstellar habitable zone of a parent star, and through tidal energy dissipation they may also offer alternative habitable zones, where stellar insolation plays a secondary, or complementary, role.*" Tidally-heated moons enclosed in icy outer layers might support sub-surface life without having to be large enough to retain atmospheres.

Astronomers have sought to account for the presence of gas giant planets close to their stars in terms of inward migration from a zone of formation in the cold outer parts of the planet-forming disk-shaped nebulae which surround young stars. Their place of formation is out beyond the "*snowline*," where ice would be stable, and tidal interactions with the disk send them spiralling inwards (see, for example, review by Papaloizou & Terquem, 2005). It is not unreasonable to expect such planets to have formed ice-rich moons, which will travel with them as they travel inwards.

A major difference between Kepler 16b and the giant planets of the Solar System is that the former will receive substantially greater insolation. We estimated insolation using a derived luminosity for the orange dwarf of 0.149 solar luminosity (the red dwarf has about 1.55% the larger star's luminosity, so we ignored it). Later, astronomer Willie Torres emailed Doyle with a lower estimate of the K star's brightness, namely 0.133 solar. This reduced the energy reaching Kepler 16b, but the quantities are still encouraging. The planet, whose mean distance from the system's centre of mass has been determined with precision as 0.7048 ± 0.0011 AU, will receive, on the average, 0.266 $I_{\oplus}$. In comparison, Jupiter is the closest of the Solar System's giant planets to our Sun, and depending on Jupiter's distance from the Sun at any time, its moons receive only between about 0.03 and 0.04 $I_{\oplus}$. Kepler 16b follows a near circular orbit, but the eccentric motion of the two suns around their centre of mass (barycentre) will impose a non-trivial seasonality even were moons of Kepler 16b to possess 0^{o} axial tilt with regard to the orbit of Kepler 16b around the binary. The planet orbits once every 228.8 days, so that the synodic period of the binary and the planet, after which basic configurations will be repeated, will be 50.07 days.

At mean separation, the spectral class K star will lie 0.050 AU and the red dwarf (spectral class M 4.5), considered here to provide negligible insolation, around 0.17 AU from the barycentre. The displacement of the K star will decrease to 0.042 AU when the two stars are closest (periastron) and increase to 0.058 AU when they are furthest apart (apoastron). Minimum insolation will be received when the K star lies at apoastron and on the opposite side of the barycentre to the planet. At such times it will lie 0.763 AU away and the planet will receive 0.228 $I_\oplus$ - which is still over six times the greatest insolation at Europa. Maximum insolation will be received at those times when the K star lies farthest from the system barycentre and when, simultaneously, the K star – planet distance is smallest. At such times the K star will lie 0.058 AU outwards from the barycentre and the centre of the K star will lie at 0.646 AU from the planet, which will receive > 0.318 $I_\oplus$. This is comparable with the 0.36 $I_\oplus$ received by Mars when it lies furthest from the Sun. At those times when the planet's orbital eccentricity is highest, Kepler 16b can approach the K star as closely as 0.583 AU and it will receive a maximum of 0.391 $I_\oplus$ (compared to 0.52 $I_\oplus$ for Mars at its closest to the Sun, and very respectably Martian).

On the Earth, the difference in the apparent size of the Sun over an orbital cycle is very subtle (negligible for most purposes) and it is the axial tilt of the planet which creates the seasons. On any moons of Kepler 16b, however, the apparent size of the major sun will change dramatically. For the planet's present near-circular orbit, the size of the K star in the sky will vary from 85% the diameter of our Sun to 100%. The M star at its closest will grow to 45% the apparent size of our Sun, and it will provide spectacular eclipses as it sweeps across the face of its bigger companion, something quite unknown in the Solar System.

At times of maximum eccentricity of the planet's orbit, the K star at its closest will actually appear 11% wider than our Sun, although each unit area of its surface will be radiating much less energy, and it would be a deathly chilly substitute as far as human life was concerned. In terms of astrobiology, on the other hand, which considers the physiological tolerances of the most hardy known organisms, the figures for insolation are not un-encouraging. What we must consider also, however, is the fate of icy moons at the kinds of insolation level experienced at Kepler 16b.

Below: Surface of Europa. NASA.

The fates of icy moons and the implications for astrobiology.

What happens to icy moons carried inwards with migrating giant planets is an question of prime interest to astrobiologists. In the case of any particular object it will depend upon many factors in addition to rising insolation levels. These will include the moon's mass, composition, structure, charged particle environment, impact history, and the history of its geodynamic regimes. Depending upon how intense insolation becomes, the destinies of moons migrating inwards with giant planets may include retaining substantial shrouds of frozen volatiles, including high-pressure ices, possessing subsurface oceans, evolving into substantial silicate-dominated objects, or (particularly for the smallest icy moons) *de facto* comets which disintegrate leaving only dusty rings around their planets.

The snowline is taken as 170 K, because this is the temperature at which H_2O ice will sublime to vapour in a vacuum. Scharf (2006) considered the fates of icy moons carried with migrating planets into higher insolation regimes. He considered that for moons of less than 10% Earth mass (the minimum size for long-term retention of an atmosphere after Williams *et al.*, 1997) and lacking magnetic fields to protect them from atmospheric loss by sputtering with charged particles from stellar winds, that it was reasonable to speculate that (1,201): "*icy moons that spend significant time within the sublimation line are likely to lose sublimated material and eventually all surface volatiles over relatively short timescales. The major caveat to this statement is that if a small moon with a host planet in such an orbital configuration has a strong magnetic field, it might retain a cold atmosphere of volatiles and their dissociated atomic species over longer timescales.*"

On the other hand, I suggest that even if very substantial loss of volatiles has taken place, the silicate cores of icy moons, overlain by layers of dust liberated from sublimated ice, and rubble from impacts, could still be of astrobiological significance if they had relatively wet interiors. It seems not unlikely that water percolating at depth through a deep rubble layer might deposit mineral cements, which could suppress migration of volatiles towards the surface and so protect the interior from further sublimation losses.

It should be pointed out also that residual localised volcanic activity on small bodies in the absence of tidal heating could provide limited environments in which bacterial grade organisms might flourish. Schultz *et al.* (2006) presented evidence that even our own Moon (1.2 % Earth mass) might today, at Solar System age 4.6 thousand million years, sustain local volcanism, at scattered sites, which include the small Ina Formation. This is despite the fact that widespread volcanism died out on the Moon by 3.2 thousand million years ago, that is at Solar System age 1.4 thousand million years (Schultz & Spudis, 2006).

For now, this is just hypothetical. However, the possibility of identifying moons of Kepler 16b has been put on the agenda. One of the Kepler team, Daniel C. Fabrycky, of the University of California at Santa Cruz, has been long working towards finding moons of confirmed Kepler mission planets. Only time will tell what waits to be discovered and what it will mean for our search for potential homes for biology.

The impact of Kepler 16b.

Kepler 16b did not, of course, initiate the discussion of whether extrasolar giant planets could possess habitable moons. Of 1,235 planet candidates which they then had identified in data from the Kepler mission, Borucki *et al.* (2011) noted 54 (this figure has been debated) which might be deemed to lie in the HZ. Most were significantly larger than the Earth. Kasting (2011) discussed these candidates from a level-headed perspective. He also noted (pp. 363-364) that "*dozens of gas giant planets within stellar habitable zones were already known from prior RV surveys. Life could still exist within these systems if these planets have large moons (Williams et al., 1997); however, the prospects for detecting life on such moons are extremely slim*." [RV stands for "Radial Velocity." The method exploits the fact that as a planet orbits a star, the star will experience a gravitation acceleration, and that at different times, the star will experience a component of velocity towards or away from Earth along the line of sight.]

Such caution is appropriate, and the points made by Kasting (2011) should serve to curtail uncritical enthusiasm. Without greeting Kepler 16b with a naive fanfare, the fact remains that the system does pose challenges for astrobiologists, and its discovery may help to catalyse pursuit of appropriate models and rewarding thought experiments.

Moreover, the hypothesis that icy-rich bodies may harbour sub-surface life, whilst difficult to pursue in the case of Kepler 16b (which lies about 200 light years away), is open to being tested directly in the course of missions within the Solar System, in the asteroid belt, around giant planets, or in the Kuiper Belt.

Beyond expressions of scientific caution, there can be no doubt that the discovery of Kepler 16b has made a major contribution to promoting a positive public perception of the Kepler mission. *Time* magazine placed the discovery at number 3 on their top ten space events of 2011.

The description of a planet that would enjoy double sunrises and sunsets caught the imagination of the global media and journalists besieged Laurance Doyle by phone and email. The clamour, of course, owed much to the memorable scene in George Lucas' *Star Wars* which finds Luke Skywalker gazing wistfully at two suns sinking behind the horizon on his home world of Tatooine. Reviewing our paper for the Cornell University "*Astrobites*" website (November 3, 2011), graduate student Lauren Weiss described the discovery of Kepler 16b as "*one of Kepler's most exciting results thus far*". Commenting on the questions which we raised about habitable moons, she pointed out, correctly, that "*The seasons on such a moon would be more complicated than those implied by the calculations outlined above, since the moon would also be orbiting the planet. However, detecting (and characterizing) such a moon is a challenge yet to be overcome.*"

Kepler 16b has provided one of the most intriguing and stimulating episodes of the Ecospheres Project collaboration, and it may yet have surprises to spring on us.

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