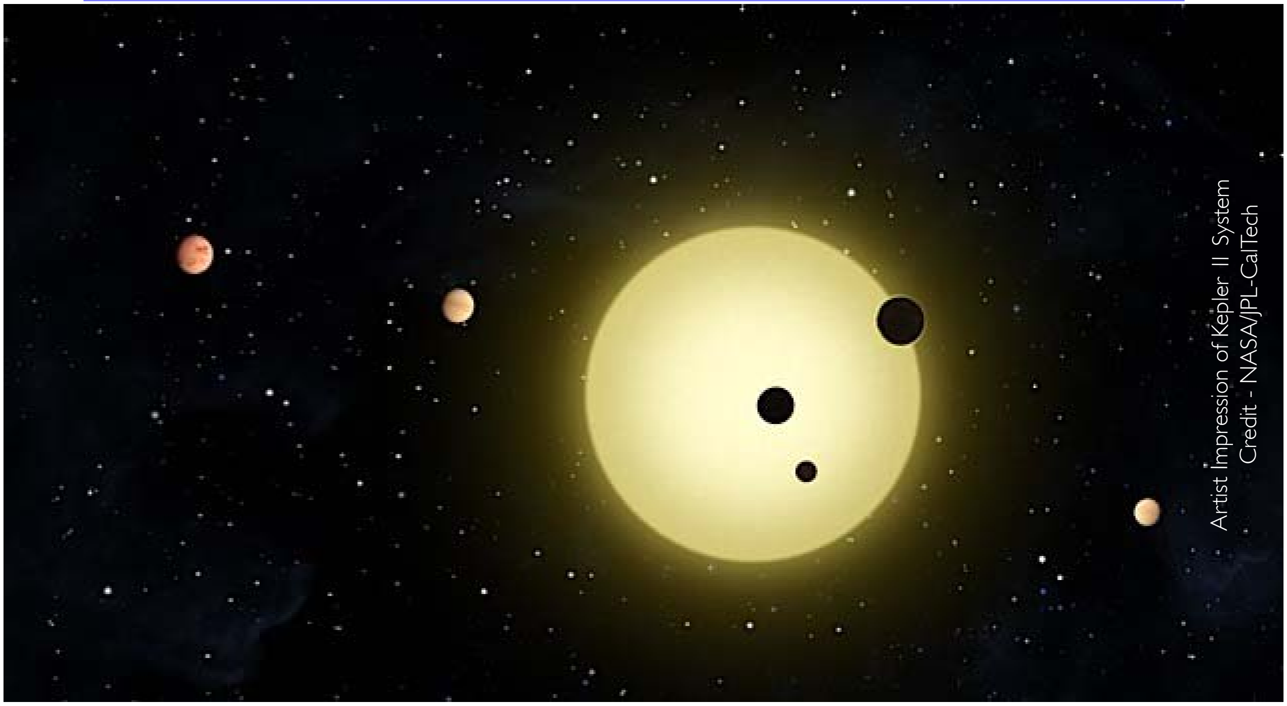

Artist Impression of Kepler 11 System
Credit - NASA/JPL-CalTech

What Color Is Your Planet?

The Great Age of Exoplanet Exploration Begins

BY THOMAS M. CIESLA

There are worlds black as coal that reflect no light, red worlds covered with molten rock, worlds of solid diamond, and worlds with double suns. Extra-solar planet (exoplanet) research over the past two decades has vastly improved our understanding of stellar and planetary evolution. Yet, as we peer into the Cosmos we face an existential uncertainty: Does life exist elsewhere in the universe? Despite the hubris of our anthropocentric viewpoint, we humans, isolated on a small ball of rock in orbit around an unremarkable star, still cannot answer that question. As our search for other planets within our galaxy identifies increasingly exotic worlds, perhaps we will eventually discover that life – at various levels of complexity – is as ubiquitous 'out there' as it is down here on Earth.

Five hundred years ago the standard view of the Cosmos was that Earth was at the center, with all the other celestial bodies (including the Sun), moving around it. In the 1530's, Copernicus challenged the Plato-Aristotelian geocentric view (also called the **Ptolemaic system)** by proposing his heliocentric theory which had the Earth and other planets in our solar system orbiting the Sun. Known as the beginning of the Copernican Revolution, it took 200 years for the heliocentric system to replace the Ptolemaic system.

Mankind's direct exploration of our Solar System (and increasing evidence for the heliocentric model) began in the early 1600's when Galileo started using his newly invented telescope to observe that changing phases of Venus and the moons of Jupiter. [1] This was followed by increasing discoveries: Uranus (1781), Neptune (1846), and Pluto (1930). Robotic explorers ventured for close-up inspections of these planets in the late 20th century, explorations that continue into the 21st century. Thanks to the vast amounts of data returned by these spacecraft we've discovered the diversity and complexity of the planets in our Solar System: the vast (and complex) satellite systems surrounding the gas giants; the fact that not only Saturn has a ring system, and the close up inspection of the nature and structure of comets, to name just a few discoveries.

Earth-based tools have discovered objects the size of Pluto (and somewhat smaller) in the far out reaches of the Kuiper Belt, a vast reservoir of debris and bodies large enough to be classified as minor planets – Pluto now being one of these Kuiper Belt Objects (KBO's).[2] The farther out we look, the more planetary-type objects we find, and many scientists speculate that beyond the Kuiper Belt is a region called the Oort Cloud – a shell of debris and cometary bodies surrounding the Solar System out to a distance of at least one light year, and possible out to our nearest stellar neighbor Proxima Centauri, which is roughly four light years away.

[1] What for centuries had been mere points of light in the night sky, could suddenly be seen as orbs with changing features, and even moons orbiting these 'planets'.

[2] Caltech Professor of Astronomy, Mike Brown's discovery of the KBO "Eris", was responsible for Pluto's reclassification as a minor planet. Several more KBO's have since been discovered.

Is there more out there beyond the Oort Cloud? Mankind has long wondered if planets exists around other stars, if there are other solar systems, and if life is Earth-centric or ubiquitous in the Universe. In the 1897 book, *Eclectic Physical Geography*, [3] author Russell Hinman speculates, *"It is possible that each one of the other fixed stars is really a sun, and the center of a separate system of planets, but so far from us that the planets are invisible."* Yet the speculation about planets around other stars goes back as far as the ancient Greeks. The philosophical concept of Cosmic Pluralism (belief in numerous other worlds with extraterrestrial life) was argued by Leucippus, Democritus and Epicurus – the early proponents of 'atomism'.[4] As mentioned, the notion of other planetary systems was put on scientific footing by the Copernican Revolution, but it took someone like Giordano Bruno to take Copernican theory to the next level when he wrote:

"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system.....the countless worlds in the universe are no worse and no less inhabited than our Earth" [5]

Unfortunately, the Dominican monk was burned at the stake in the year 1600 for his enlightened writings.

[31] '***Eclectic Physical Geography'***, Russell Hinman, American Book Company, New York, NY 1897; page 36.

[4] Atomists believed that the natural world consisted of two fundamental parts: indivisible atoms and voids.

[5] Giordano Bruno, ***'On The Cause, Principle, and Unity***; 5th Dialogue

Artist impression of a 'super-earth'. Credit NASA/JPL-Caltech

Image of exoplanet 1rxs1609b;
Credit: Gemini Observatory,
D. Lafreniere, R. Jayawardhana,
M. van Kerkwijk (Toronto)

Today we know that beyond our Solar System, the Milky Way Galaxy is teeming with planets.[6] The first solid evidence for an exoplanet came in 1992 when scientists calculated that 2 bodies must be orbiting the pulsar PSR1257. The first exoplanet orbiting a main sequence star was discovered in 1995 around the Sun-like star 51 Pegasi. The planet, designated *51 Pegasi b*, is classified as a ‘hot Jupiter’, about the size of our Jupiter, but orbiting its star at one-eighth of the distance that Mercury orbits the Sun. It must have a surface temperature above 1,000^{0}C, but calculations show that it is massive enough to prevent its atmosphere from being boiled away.

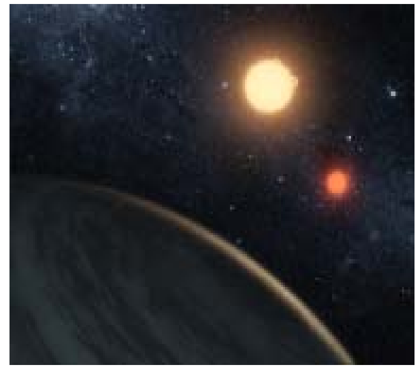
As of November 14, 2011 there are 699 confirmed exoplanets and over 1,200 other candidates awaiting confirmation. This is beyond a doubt only the beginning of the golden age of exoplanet exploration, which appears to answer the question, “Are We Alone?,” with a resounding, “NO,” at least at the planetary and solar systems level. As the list for exoplanets grows we find that these planets can be stranger than the planets in our own Solar System, and even stranger than we could ever imagine, requiring modifications to our planet formation theories. In fact, these discussions began early on with the discovery of *51 Pegasi b*; our current theories couldn’t account for the planet’s close proximity to its host star.[7]

How strange? Take for example *Kepler-16 b*, a planet that circles a binary star system much like Luke Skywaker’s planet Tatooine in the Star Wars series, showing a dramatic sunset with two suns. Though double-sun solar systems had been predicted by theoretical models, some felt that the twisting gravitational fields of the two stars whizzing around each other would disrupt the orbit of any planet circling them. Yet, the *Kepler 16* solar system appears to be stable. Or consider exoplanet *TrES-2b*, which is the darkest planet ever found – it reflects almost no light. Another mysterious exoplanet lies 4,000 light years from Earth, and based on density measurements, it must be made entirely of diamond. Orbiting the pulsar *J1719-1438*, the planet completes one revolution around its host star every two hours, in an orbit so close to the star, that if were placed within our solar system, its orbit would lie within the sphere of our Sun.

[6]The Kepler Observatory scientists estimate that there are over 50 billion planets in our galaxy.

[7] This tidally locked planet is sometimes referred to as Bellerophon, the Greek hero who tamed Pegasus.

Some planets are almost twice the age of the Earth, while some like *LkCa 15*[8] are so young that it is still clearing a gap in the protoplanetary disk. Planetary diversity also extends to the solar systems they form in: we've discovered two-planet, three-planet, five-planet, and even six-planet solar systems.[9] The *Kepler 11* system has six planets that are so tightly packed, that if placed within our solar system, only one planet would orbit beyond the orbit of Mercury. We also know that not just binary-sun systems can have exoplanets; *HD-18753-Ab* is a triple star system with a possible distant planet, as are the systems *HD132563* and *Gliese 667 C*.



Artist impression of Kepler-16b; A planet orbiting a binary star system. Credit NASA/JPL-Caltech

Super-Earths are exoplanets that range from three–to–ten times the mass of the Earth. *HD 85512 b* is only 3.6 times more massive than the Earth and is at the edge of the habitable zone of the star, where liquid water could exist. Planets lying within the habitable zone of a host star are at just the right distance from the host star so as be large enough to retain an atmosphere, but not so large as to become a gas giant like Jupiter. Scientists[10] believe some super-earths with a mass under 10 Earth masses could be a mixture of 50% water and 50% rock, a composition that under the right conditions could create worlds entirely covered by water, or possess a deep ocean covered by an icy shell.

Rogue Planets. Some of the oddest exoplanets discovered by the Kepler Observatory technically do not fit the definition of a planet. One condition for an object to be called a planet is that it must orbit a star. Studies by different teams of scientists have discovered a number of Jupiter-sized planets that appear to be drifting around the galactic core, not around stars. These rogue planets had been theoretically predicted earlier, but the formation process may vary from planet to planet. Some could be formed in nebulas that break down into smaller clouds before a star captures all of the material in the original cloud.[11] Others could have been formed along the traditional solar system formation method, only to be ejected from the solar system by some gravitational perturbation.[12] If the latter be the case, these ejected

[8] ***'LKCA 15: A Young ExoplanetCaught At Formation?'*** ; Adam L. Kraus, Michael J. Ireland; http://aps.arxiv.org/PS_cache/arxiv/pdf/1110/1110.3808v1.pdf

[9] ***A Survey of Multiple Planet Ssystems*** **;** Jason T. Wright; http://arxiv.org/PS_cache/arxiv/pdf/0909/0909.0957v1.pdf

[10] ***'Could we identify hot Ocean-Planets with CoRoT, Kepler and Doppler velocimetry?'*** F. Selsis, B. Chazelas et.al., http://arxiv.org/ftp/astro-ph/papers/0701/0701608.pdf

[11] ***'The Origin Of Exoplanets,'*** HELMUT A. ABT; http://aps.arxiv.org/ftp/arxiv/papers/1008/1008.4637.pdf

[12] It is conceivable that something similar occurred in our own Solar System when Jupiter and Saturn migrated to their current orbits.

Exoplanet HD149026b. A planet blacker than coal, reflecting almost no light but glowing in the infrared. Credit - NASA/JPL-Caltech/ Tim Pyle SSC

planets could have dragged along companion satellites containing copious amounts of water as possessed by some of the Jovian satellites.

The High Accuracy Radial Velocity Planet Searcher (HARPS) surveyed 376 stars. Of those 40% have at least one planet less massive than Saturn, and Neptune mass planets are common in multiple planet systems. Sixteen of fifty smaller planets are super-Earths, with masses a few times that of our planet. Two of these, *Gliese 851d* and *HD 85512 b* lie within the habitability zone of their respective stars. An exoplanet designated *Kepler-10b*, also known as the 'iron ball' planet, is the first confirmed rocky planet that is roughly eight times the mass of Earth. It takes just .84 Earth-days to complete an orbit. This close proximity to the host star means it is tidally locked and the side facing the star is probably covered in molten rock.

Why is it that we haven't found any Earth-sized exoplanets? Is our Solar System unique to have so many terrestrial type planets? It's important to remember that finding a Jupiter or Neptune size planet has become relatively easy with enhanced observation techniques and theoretical models. Large mass planets exert forces on the companion stars that are easier to detect. Finding an exoplanet as small as the Earth (in both diameter and mass) is a more daunting task with the current level of technology. However, of the few hundred solar systems discovered to date, many may already contain Earth-sized terrestrial planets – we just can't detect them at this point. NASA Post Doctoral Fellow Sean N. Raymond[13] has performed simulations using data collected from exo-solar systems, and has concluded that up to one third of the known systems with extra-solar (giant) planets could allow a terrestrial planet to form. It's important to note that direct imaging of Earth-size or even Jupiter-size exoplanets is an enormous observational challenge, since the planet is millions of times fainter than the star. Many of these planets orbit so close to their host stars that they are buried within the stellar glare.

[13] ***'Terrestrial Planet Formation in Extra-Solar Planetary Systems'*** Sean N. Raymond; http://aps.arxiv.org/PS_cache/arxiv/pdf/0801/0801.2560v1.pdf

Exo-Moons; Exo-Rings

What of exo-moons or exo-rings? We know from our own solar system that satellites and rings are common. Minor planets and asteroids have been found to include one or more satellites: Pluto has four satellites and Kuiper Belt Object Haumea has one satellite. Many asteroids have one or more satellites, such as 243 Ida in the asteroid belt and 617 Patroclus, a Trojan binary system orbiting with Jupiter. The Earth has only one Moon, right? Not quite; we know of two co-orbital satellites that share Earth's orbit: Asteroid 2003 YN107 and 2004 GUG. The former was drawn into a horseshoe orbit in 1999, the latter is estimated to have shared our orbit for the past 500 years and will continue to do so for another 500 years. Scientists believe that there are many more co-orbital Earth objects out there; our technology is only now capable of finding them.

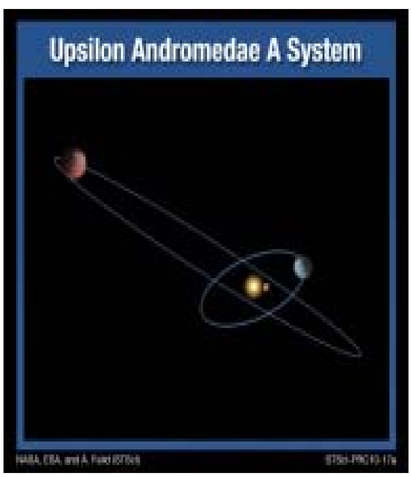
The asteroid 243 Ida and it's moon Dactyl

For many years, we thought Saturn was the only planet with a ring system, until missions to the outer planets discovered rings around Jupiter, Uranus and Neptune. At present, Pluto – often classified as a 'binary planet system' because of the comparable size of Pluto and it's moon Charon, is not known to have a ring system. Some scientists believe that a ring may be found around Pluto upon arrival of the New Horizons

Artist concept of an exomoon orbiting a ringed exoplanet.
Credit - Andy McLatchie

spacecraft in 2015. Satellites and ring systems seem to go together, with minor satellites often functioning as 'Shepherd moon's' defining rings in multiple ring systems. There are three possible ways for a ring system to form: from material of the protoplanetary disk that was within the Roche limit [14] of the planet and thus could not coalesce to form moons; from the debris of a moon that was disrupted by a large impact; or from the debris of a moon that was disrupted by tidal stresses when it passed within the planet's Roche limit.

The development of satellites and ring systems appears to be a normal part of the planet building process, and therefore it's likely that this same process has been active in other solar systems. Unfortunately, our technology, as it stands, is incapable of resolving this level of detail in other solar systems, but the presence of exomoons could be profound. Saturn's moon Titan seems to be a perfect picture of the Earth when it first formed – albeit much colder. Instead of water, Liquid methane rain falls from the sky forming lakes and rivers that sculpt the surface of that moon. Other moons such as Ganymede and Enceladus are thought to have icy shells covering vast oceans of water capable of supporting biotic life due to heat generated by gravitational stress. Many of the exoplanets we have discovered are gas-giants, unlikely to be able to support life. Perhaps these planets possess moons that are more Earth-like and exhibit the right conditions to support life. Planetary research within and beyond our Solar System may prove to be synergistic for astrobiologists.

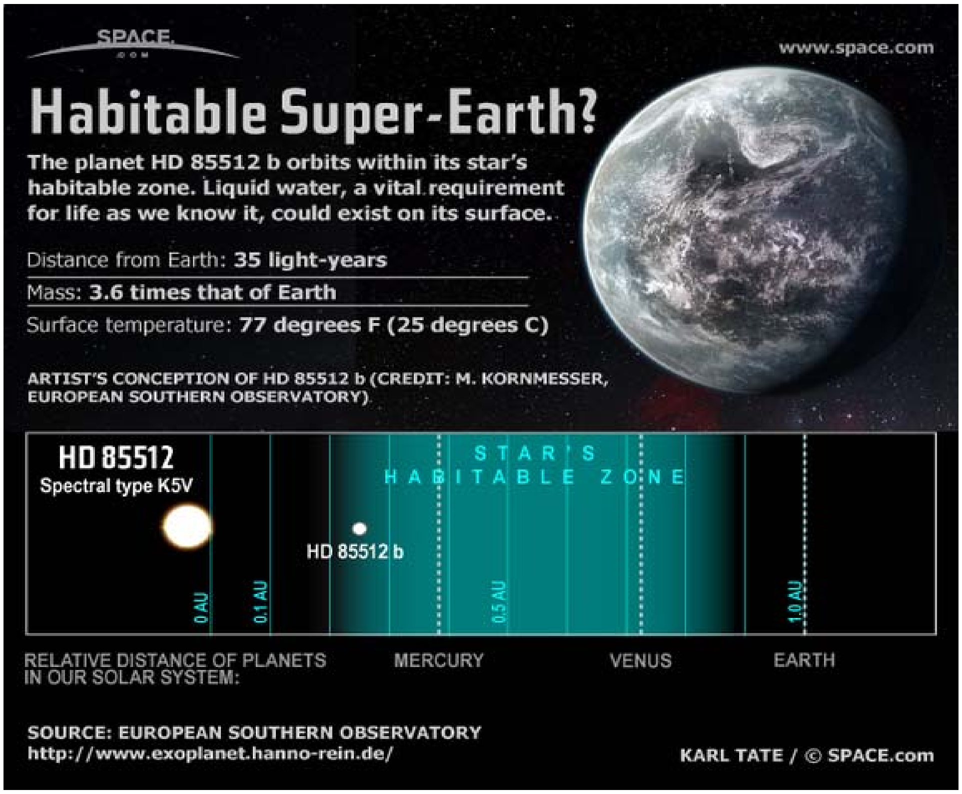


Some exoplanets orbit their star at wild angles such as the one shown above. Upsilon Andromedae A is part of a binary star system. Scientists believe that encounters with the other star at its closest approach has disturbed the planetary orbits. Credit - NASA, ESA and A. Feild (STScl) and B. McArthur UT @ Austin McDonald Observatory

Exo-Solar Systems and the Search for Habitability

Though the search for exoplanets is in its infancy, we have learned a great deal about stellar disk formation, solar system architecture and planetary formation. Planet building appears to be part of the natural process of stellar formation and is by all indicators, ubiquitous in the galaxy. Yet, as we have seen, the size, shape and assemblage of exoplanets is bizarrely varied from solar system to solar system. Studying other solar systems helps us to better understand the formation and structure of our own. For example, the observation of 'hot-Jupiters' orbiting extremely close to the host star has led to a revision of our theories regarding planetary migration.

[14] The **Roche limit** is the distance within which a celestial body, held together only by its own gravity, will disintegrate due to a second celestial body's tidal forces exceeding the first body's gravitational self-attraction.

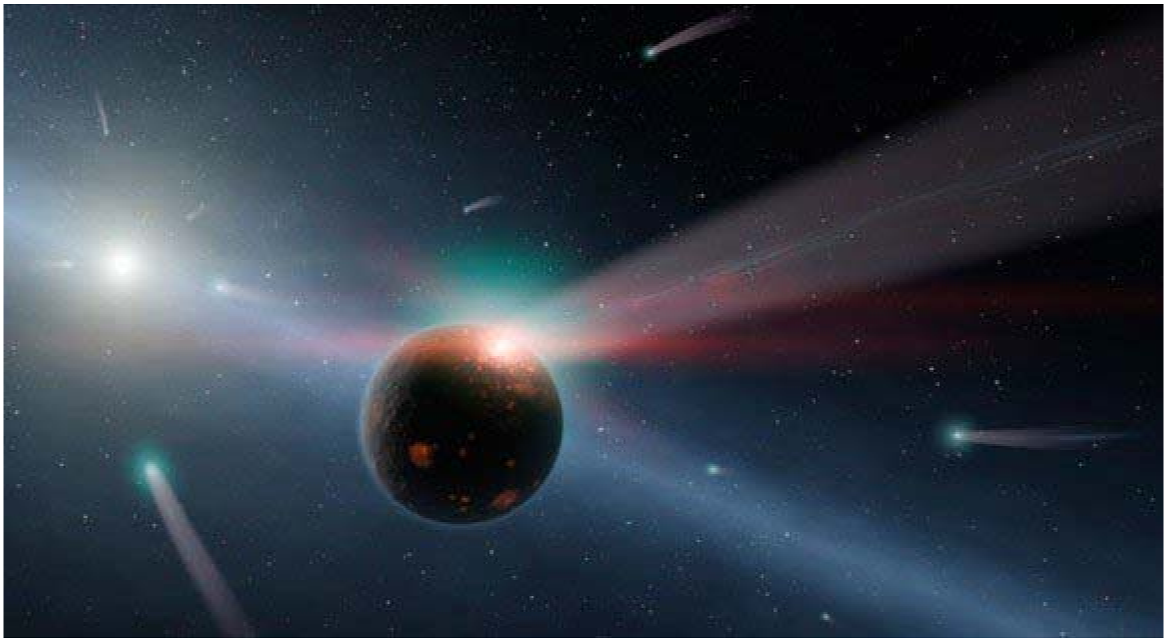


Gas giants like Jupiter or Saturn can only form in the outer regions of a protoplanetary disk, where the radiation from the new star is weaker and the necessary building materials are in abundance. Scientists believe that our own Jovian planets went through such a migration that in turn, caused adjustments to the orbits of Uranus and Neptune. The movement of these two ice giants to their present locations disrupted the planetesimals and cometary bodies in the Kuiper Belt, creating the Late Heavy Bombardment (LHB) of the inner Solar System.

This year, scientists believe they found evidence of this same type of late heavy bombardment around the star Eta Corvi. In a paper by C.M. Lisse, et.al [15] the authors conclude, "The spectra show clear evidence for warm, water- and carbon-rich dust at ~3 AU from the central star, in the system's Terrestrial Habitability Zone. Spectral features due to ultra-primitive cometary material were found, in addition to features due to impact produced silica and high temperature carbonaceous phases." They believe this dust ring is the result of large comets impacting planets in the system, much like what happened in our solar system. And, at approximately one billion years old, this would match the timing of our

[15] '***Spitzer Evidence for a Late Heavy Bombardment and the Formation of Urelites in ç Corvi at ~1 Gyr';*** http://www.ast.cam.ac.uk/~wyatt/lwcm11.pdf

LHB. Finding dust rings may be yet another way of searching for exoplanets. As the authors note in their paper, “*It is important to remember that the detection of collisional products implies not only an impactor, but also an impactee, and are thus an indirect method of planet detection.*”



Artist concept of the LHB in the Eta Corvi system. Credit -NASA/JPL-Caltech

Finding the instance of another LHB in our galaxy might indicate that this is a common part of solar system formation for some percentage of stars. This is a remarkable conclusion; scientists believe that beyond the destruction the LHB inflicted on the inner solar system, it is also likely responsible for delivering the water in our oceans, as well as organic and carbon rich compounds necessary for life. An LHB could be the genesis event needed to kick-start the creation of life on a planet.

Finding habitable exoplanets won’t be easy with present technology; it takes more than just a rocky planet roughly the size of Earth to be able to support life. The most obvious factor, and one that we CAN ascertain, is the orbit of the planet compared to the habitability zone (HZ) of the star. For our Sun, only Earth lies within the HZ. Venus falls short of the inner edge of the HZ, while Mars lies just outside of the outer edge of our HZ. This makes Earth not too hot and not too cold, but just right for liquid water – that is to say – in the ‘Goldilocks Zone’.

Other factors include stability of the planets axial tilt, presence of a magnetosphere to shield against radiation, presence of liquid water, the proper atmospheric mix[16] , sufficient cloud cover, and of course, a star that is stable over a long period of time. There are other factors to consider, but even in this limited group, determining some of these remains elusive.

The Big Picture

Today, as far as we know, Earth is the only celestial body that harbors life. That is not to say that life doesn't exist somewhere in our own solar system or exo- solar systems. It simply means we have yet to find life beyond the Earth. The Milky Way contains some 400 billion stars of all types. Conservative estimates indicate that there are hundreds of thousands of millions of galaxies in the Universe. Over the past two decades of searching for exoplanets, our ground and space-based observatories have examined less than 200,000 stars. Our most ambitious mission, the Kepler Observatory, simultaneously monitors about 150,000 stars for changes in brightness, which may indicate a planet passing in front of a star. But this represents a small segment within one arm of the galaxy. Despite all of our recent exoplanet discoveries, we've only scratched the surface of a vast collection of stellar systems.

"We think there are actually more planets out there than stars."

David Benett, Astrophysicist at the University of Notre Dame

The discovery of planets beyond our solar system puts mankind on the threshold of answering one of the oldest questions: are there other worlds capable of supporting life? It may take a decade or more before our technology reaches the level of sophistication to detect signs of life (past or present) either on Mars, one of the Jovian moons, or on an Earth-like planet circling a star 50 light years away. What sort of life will be found is anyone's guess. Presently, we focus our search for types of life that requires carbon, oxygen, phosphorus and water. We know that works here on Earth, but need it be so for 'life' elsewhere? By looking for life-as-we-know-it, we could be missing the chance to find life-as-we-don't-know-it. Political, social, and financial realities dictate that we have to start somewhere, so focusing on a functioning model makes the most sense. Serendipitously, our discoveries with extremophiles has expanded our understanding of how versatile life can be, surviving in environments toxic to most complex life forms on Earth's surface. Armed with this knowledge, we can 'tweak' experiments to expand the range of 'life' in our search.

[16] This is a bit tricky. Earth's early atmosphere was quite different than today's. Early Earth's atmosphere was a reducing one, full of methane, ammonia, hydrogen and water vapor — deadly to us — yet life began in that toxic mix..