Habitability of Exoplanets Around M – dwarf Stars

Introduction

For years, people have wondered: Are we alone in the vast universe? Over the past decade, the new field of exoplanets has exploded into one of the most popular topics in astronomy. In 2009, NASA launched the Kepler observatory into space, beginning a new era of space exploration: The search for Earth-like planets orbiting other stars. Kepler surveyed over 150,000 stars searching for these Earth-like planets. Kepler detects planets by looking for periodic dips in the brightness of stars. Some planets pass in front of their stars as seen from our point of view on Earth; when they do, they cause their stars to dim slightly. This is what is called the Transit Method. The Kepler satellite continuously surveyed a selected area of 10 degrees by 10 degrees in the Cygnus-Lyra region of the Galactic field to determine the proportion of stars, particularly Main Sequence type stars, showing the planetary transits using light curves (Rhodes and Budding, 2014). To get an idea of how powerful the detectors of the telescope are, that from up in space, it could detect someone in a small town turning off an outer light at night. Kepler has been placed in what's called an "Earth trailing" orbit around the sun. A little wider and slower than our own orbit, the spacecraft will take 371 days to complete one circuit. Each day Kepler falls farther and farther behind Earth—eventually the distance will open to tens of millions of miles. This uncommon orbit, used for the first time with the Spitzer infrared space telescope in 2003, has advantages for astronomical telescopes. One is that Earth doesn't obstruct their view of the sky. The spacecraft doesn't need to be boosted periodically to maintain its altitude above Earth. And best of all, it's a very fuel-efficient orbit, requiring less energy (smaller rocket, lower cost) to reach than the L2 Lagrange point which is where Kepler was originally planned to be Kepler’s target. Expect these Earth-trailing orbits to become a popular choice for future astronomy missions.

One year in to its three and one half year mission approximately 3000 planetary transits had been recorded and analyzed. Mostly these are attributed to planets larger than the Earth, although about 10% of candidates hitherto are of a size comparable to that of the Earth. The majority of known examples are smaller than Jupiter, although around 10 percent are of about the same size or larger. About 5% have been located in the ‘habitable zones’ of their parent stars. NASA announced the positive identification of Earth-sized planets towards the end of 2011. It should also be noted that a fair proportion of initially announced planet finds, perhaps more than ∼30% have since been marked as false positives (Rhodes and Budding, 2014).

Specifically, in this article, we will address the formation of exoplanets and what it has to do with stars. As a star begins to form, the protoplanetary disc around it has a collection of debris and other gases that did not fall into the protostar. The debris and gas begin to accrete and eventually will create either rocky planets or gas giants, much like Jupiter or Neptune. In the classical picture developed to explain the Solar System, the process starts with a disk of small solids having just enough mass to reproduce objects in the Solar System. Collisional processes merge small solids into km-sized or larger planetesimals, then Mars-mass protoplanets, and finally Earth mass planets (Kenyon et al., n.d.). These processes are violent and tear apart the protoplanets many times adding new material and also ejecting it. The ejected material is what later forms into the satellites of the planet by the same process on a smaller scale. Therefore, in these early stages the mass of the planets changes often and rapidly. When the star these protoplanets are orbiting finally begins hydrogen fusion, there is and initial "kick" which blows away most, if not all of the debris in the accretion disk revealing the star and its protoplanets. During this time, the protoplanets and their satellites are subject to heavy bombardment, which is one of the last steps in becoming a planet. After the bombardment period has ended, the final structure of the new solar system is exposed.

There are a lot of ways to detect if there is a planet orbiting a star, including transit events, radial velocities, microlensing, imaging, and pulsar timing. Today, the main method of detection is the first, transit events. This was the type of detection the Kepler observatory used. Light curves produced by these transits show dips in the star's brightness as the object transits in front of it. However we will briefly discuss the other types of exoplanet detections. Pulsar Timing is the method that was used in 1992 by Aleksander Wolszczan and Dale Frail to detect the first confirmed exoplanets. These exoplanets orbit a pulsar, which is a rapidly rotating neutron star. As they spin, pulsars emit intense electromagnetic radiation that is detected on Earth as regular and precisely timed pulses. By analyzing any irregularities in the timing, astronomers can determine if there is a planet orbiting it. Direct imaging of exoplanets is extremely challenging, and in most cases impossible. Being small and dim planets are easily lost in the brilliant glare of the giant stars they orbit. Nevertheless, even with existing telescope technology there are special circumstances in which a planet can be directly observed. Microlensing is the only known method capable of discovering planets at truly great distances from the Earth. Objects that are normally not visible or dim are magnified, leading to discoveries of planets orbiting them. The radial velocity method relies on the fact that a star does not remain completely stationary when it is orbited by a planet. It moves, ever so slightly, in a small circle or ellipse, responding to the gravitational tug of its smaller companion. When viewed from a distance, these slight movements affect the star's normal light spectrum.

There have been a lot of theories as to if there is life out there on these other planets, but we have to take into account the type of star that the planet would be orbiting. Giants and super giants have a relatively short life style. White dwarfs are too old because the event that made them into white dwarf, a supernova, would have likely destroyed any form of life on a planet orbiting. Therefore we are left with regular main sequence stars and to narrow it down to Sun-like stars. The Drake equation for calculating the number of intelligent, communicative civilizations is famously uncertain, with estimates of the civilization incidence per habitable planet ranging from 10^{-5} to arbitrarily small values. Combined with our estimates of the number of Earth-like planets and the fact of our existence, this would result in 1 to 10^{15} civilizations in the Universe and 1 to 10^{4} in the Milky Way at the present time. (Behroozi and Peeples, 2015). The more planets we observe with missions like Kepler, the better odds we have of finding another civilization out there in the unknown.

The trend in data so far shows a correlation between terrestrial planets within 1 AU and solar-type stars. Rocky planets within 1 AU appear to be fairly common companions to solar-type stars. Here, we focus on a comprehensive analysis of Kepler data which provides a detailed estimate for the occurrence rate of Earth-mass planets inside 1 AU (Kenyon et al., n.d.). Assuming the occurrence of Earth-like planets is this common we can reasonable assume that this would be a reasonable place to search for life on another planet. M-type stars have been found to have many exoplanets in recent studies. Tidally locked planets orbiting M-dwarfs face unique challenges to their atmospheric stability. The atmosphere may “collapse” if the volatile inventory freezes out and becomes trapped on the night side. The atmosphere is also subject to erosion by stellar winds, which are denser and faster for M-dwarfs than Sun-like stars. (Kreidberg and Loeb, 2016). The atmosphere must be able to withstand the harsh environments of space and hold in the elements necessary for life and the star must keep the planet at a suitable temperature.

Formation of Exoplanets

Protoplanetary Disks

The formation and early evolution of stars are intimately coupled to the properties of their accompanying circumstellar disks of gas and dust. These disks also provide the material reservoirs for the assembly of planetary systems. Angular momentum conservation dictates that a collapsing molecular cloud core with some initial rotation will result in both a central protostar and a flattened circumstellar disk (Andrews et al., 2005). The protoplanetary disk may also be thought of as an accretion disk for the star itself, because gasses and other material will be falling from the inner edge of the disk onto the surface of the star. But this process should not be confused with the accretion process which builds up the planets themselves.

Protostars mainly form from molecular clouds consisting primarily of molecular hydrogen. Conservation of angular momentum causes the rotation to increase as the nebula radius decreases. This rotation causes the cloud to flatten out—much like forming a flat pizza out of dough—and take the form of a disk. The initial collapse takes about 100,000 years. After that time the star reaches a surface temperature similar to that of a main sequence star of the same mass and becomes visible. Accretion of gas onto the star continues for another 10 million years, before the disk disappears, perhaps being blown away by the new star's solar wind, or possibly ceasing to emit radiation after accretion has ended. The oldest protoplanetary disk yet discovered is 25 million years old.

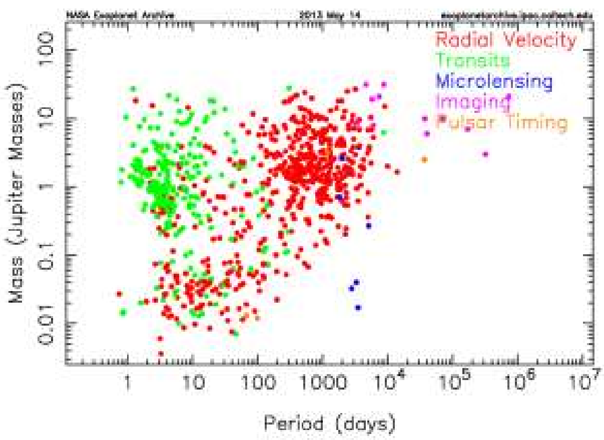
The mass of a typical proto-planetary disk is dominated by its gas, however, the presence of dust grains has a major role in its evolution. Dust grains shield the mid-plane of the disk from energetic radiation from outer space that creates a dead zone in which the MRI (magnetorotational instability) no longer operates.

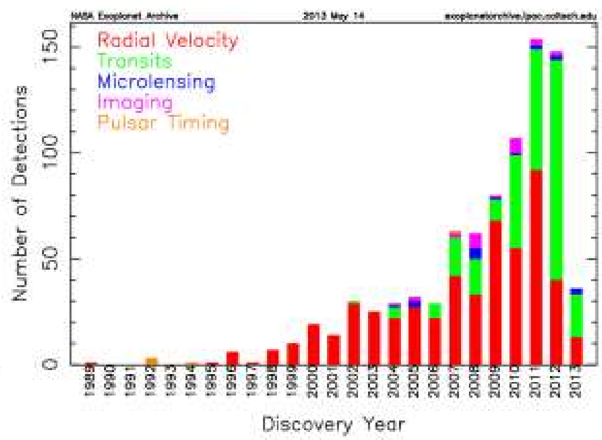
Accretion

Disks around pre–main-sequence stars are the likely sites of planet formation. As such, they have been targets of extensive research over the past two decades. Surveys of continuum emission at infrared and millimeter wavelengths have established that 50% of all classical T Tauri stars (CTTSs; ages less than 3 Myr) have disks with typical masses of 103 to 101 Msun, sufficient to form a planetary system like our own (Evans II et al., 2003). Electrostatic and gravitational interactions cause the dust and ice grains in the disk to accrete into planetesimals. This process acts against the stellar wind, which drives the gas out of the system, and gravity (accretion), which wants to pull material into the central star.

It is thought that moons of Jupiter, Saturn, and other planets formed as smaller, circumplanetary analogs of the protoplanetary disks. The formation of planets and moons in geometrically thin, gas-rich and dust-rich disks is the reason the planets are arranged in an ecliptic plane.

Detection Techniques





Radial Velocity

A star with a planet in its system will have its own small orbit in because of the planet's gravity. This causes variations in the speed with which the star moves toward or away from Earth, i.e. the variations are in the radial velocity of the star with respect to Earth. The radial velocity can be calculated from the displacement of the parent star's spectral lines due to the Doppler Effect. The radial-velocity method measures the variation of the star’s spectral lines in order to check for the presence of the planet.

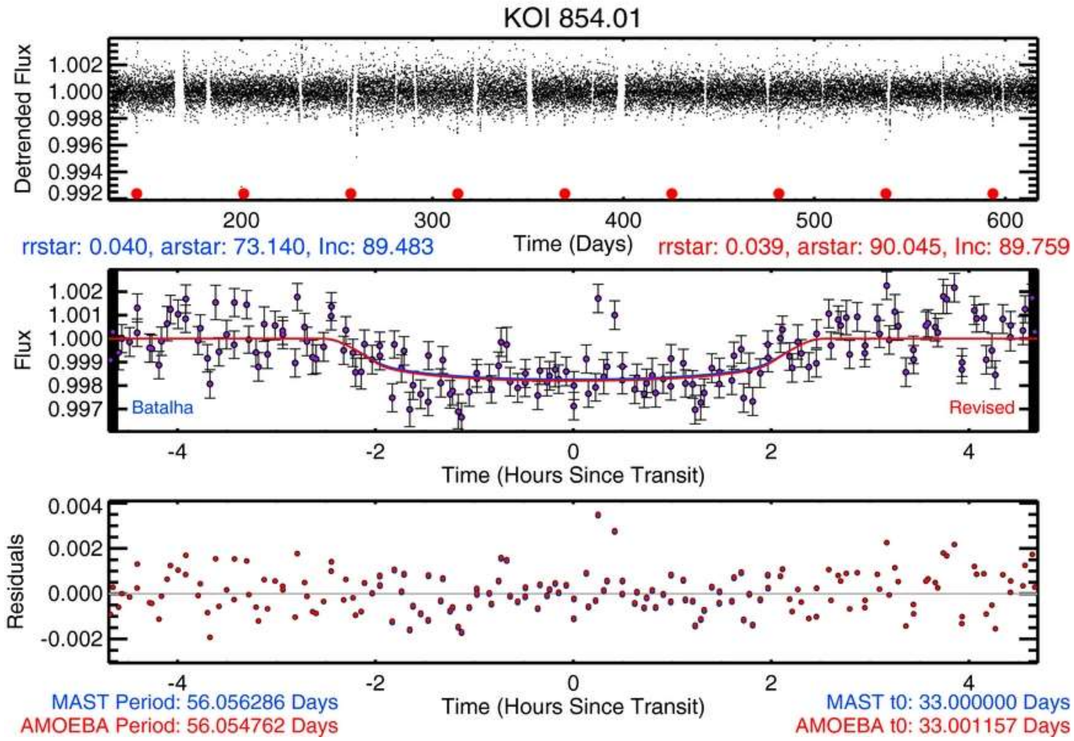
The radial-velocity method was the most wide used technique used by astronomers, until a It is also known as Doppler spectroscopy. The method is distance independent, but requires high signal-to-noise ratios to achieve high precision, and so is generally only used for relatively nearby stars to find lower-mass planets. It is also not possible to simultaneously observe many target stars at a time with a single telescope. Planets of Jovian mass can be detectable around stars up to a few thousand light years away. This method easily finds massive planets that are close to stars. Modern spectrographs can also easily detect Jupiter-mass planets orbiting 10 astronomical units away from the parent star, but detection of those planets requires many years of observing.

Planets around low mass stars are easier to detect, for two main reasons: For one, these stars are more affected by gravitational tug from planets and the other, is that low-mass main-sequence stars generally rotate fairly slow. Fast rotation makes spectral-line data unclear because half of the star quickly rotates away from observer's viewpoint while the other half approaches. Detecting planets around more massive stars is easier if the star has left the main sequence, because leaving the main sequence slows down the star's rotation.

Although radial velocity of the star only gives a planet's minimum possible mass, if the planet's spectral lines can be determined from the star's spectral lines then the planet’s radial velocity can be found. This allows for the measurement of the planet's actual mass. This also rules out the problem of false positives, and provides data on the planet that allows astronomers to determine its composition. The main issue is that such detection is only possible if the planet orbits around a relatively bright star and if the planet reflects or emits a lot of light.

Transit Events

While the radial velocity method gives data on a planet's mass, the transit method can determine the planet's radius. If a planet transits in front of its parent star, then the flux of the star drops by a small amount, shown in the figure below; depending on the relative sizes of the star and the planet.



This method has two main disadvantages. First, the planet's transits are only observable when the planet's orbit is aligned perfectly from the astronomer's view point. The probability of a planetary orbital plane being directly on the line-of-sight to a star is low even for planets with small orbits and this probability gets lower as the orbits get larger. The transit method cannot guarantee that any particular star is not a host to planets. But, by scanning large areas of the sky containing thousands or even hundreds of thousands of stars at once, transit surveys can find more extrasolar planets than the radial-velocity method.

The second disadvantage of this method is a high rate of false detections. Because of this, a star with a single transit detection needs to have more confirmation, generally from the radial-velocity method. Radial velocity method is especially necessary for larger planets as objects of that size encompass not only planets, but also brown dwarfs and even small stars. As false positive rate is very low in stars with two or more planet candidates, they often can be validated without extensive follow-up observations.

The most important advantage of the transit method is that the radius of the planet can be determined from the lightcurve. When combined with the radial-velocity method (which determines the planet's mass) astronomers can determine the density of the planet, and therefore learn something about the structure of the planet. Planets that have been studied by both methods are the best-categorized of all known exoplanets.

The transit method also makes it possible to study the atmosphere of the transiting planet. When the planet transits the star, light from the star passes through the uppermost parts of the atmosphere of the planet. By studying the stellar spectrum carefully, astronomers can detect elements present in the planet's atmosphere.

Microlensing

Gravitational microlensing occurs when the gravitational field of a star acts as a lens to magnify the light of a background star. This effect occurs only when the two stars are almost exactly aligned. Lensing events are brief, sometimes lasting for weeks or days, as the two stars and Earth are all moving relative to each other. More than a thousand such events have been observed over the past ten years.

If the foreground lensing star has a planet, then that planet's own gravitational field can make a detectable contribution to the lensing effect. Since that requires a highly improbable alignment, a very large number of distant stars must be continuously monitored in order to detect planetary microlensing contributions at a reasonable rate. This method is most fruitful for planets between Earth and the center of the galaxy, as the galactic center provides a large number of background stars.

A notable disadvantage of the method is that the lensing cannot be repeated, because the chance alignment never occurs again. Also, the detected planets will tend to be several kiloparsecs away, so follow-up observations with other methods are usually impossible. In addition, the only physical characteristic that can be determined by microlensing is the mass of the planet, within loose constraints.

The main advantages of the gravitational microlensing method are that it can detect planets with face-on orbits from Earth's viewpoint, and it can detect planets around very distant stars. When enough background stars can be observed with enough accuracy, then the method should eventually reveal how common Earth-like planets are in the galaxy.

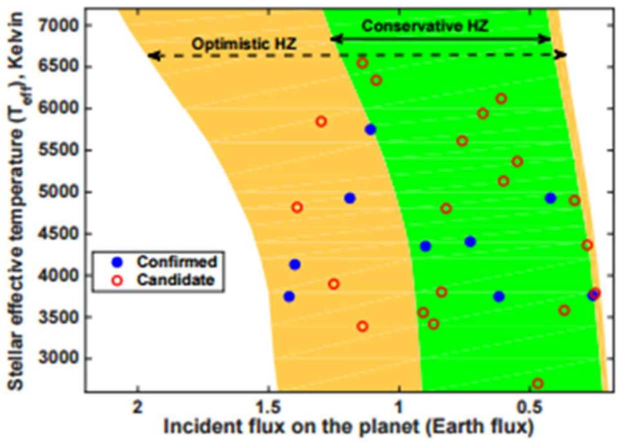
Probability of Life

Main Sequence

When astronomers think of planets as habitable they tend to look at the life and evolutionary stage of the star it is orbiting, because a lot can be deduce from this information.

Giant and subgiants would die too fast to be suitable hosts for life. White dwarfs are far too old to host life, especially since the supernova event that lead to the creation of the white dwarf itself. Thus astronomers settle to the middle group of these stars, known as the Main Sequence.

Main Sequence stars are ideal for life to form on planets because of their luminosities, and their lifespan. A typical main sequence star has an average lifetime of about 10 billion years



and its luminosity is comparable to our Sun. Therefore the luminosity is dominated by optical and UV wavelengths. The Kepler mission has a primary science goal of determining the frequency of terrestrial planets in the Habitable Zone: usually defined as the region around a star where water can exist in a liquid state on the surface of a planet with sufficient atmospheric pressure (Kane et al., 2016). This habitable zone definition get split into two categories: Optimistic Habitable Zone and Conservative Habitable Zone. thus, it makes sense to talk about a “conservative” Habitable Zone (0.99–1.7 AU) and an “optimistic” Habitable Zone (0.75–1.8 AU). These limits are shown in the figure above as a function of the flux from the star normalized to the flux at Earth’s orbit. The boundaries vary for different stellar types because of the different albedo of an Earth-like planet under different wavelengths of stellar irradiation. (Kane et al., 2016)

M-dwarfs and Earth-like Planets

Issues with M-dwarfs

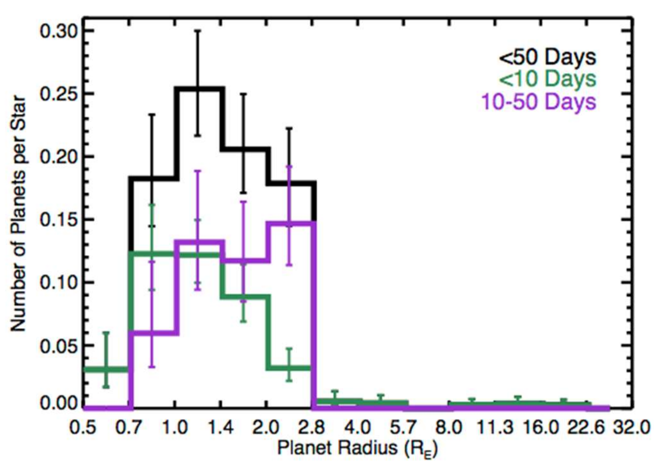
There have been many studies and papers about stars with habitable planets. However, some fairly recent research into the subject has led to the hypothesis that maybe M dwarfs would be good candidates for earth-like planets. Although early work suggested that a hypothetical planet in the habitable zone (the range of distances at which liquid water could exist on the surface of the planet) of an M dwarf would be inhospitable because the planet would be tidally locked and the atmosphere would freeze out on the dark side of the planet, more recent studies have been more optimistic. For example, it was shown that if there was enough carbon dioxide present that it could prevent the atmosphere from freezing. Additionally, a tidally locked planet could be in a partially habitable “Eyeball Earth” state in which the planet is mostly frozen but has a liquid water ocean at the substellar point. Moreover, planets orbiting M dwarfs might become trapped in spin–orbit resonances like Mercury instead of becoming spin-synchronized. (Dressing and Charbonneau, 2013)

A second concern for the habitability of planets orbiting M dwarfs is the possibility of strong flares and high UV emission in quiescence. Although a planet without a magnetic field could require years to rebuild its ozone layer after experiencing strong flare, the majority of the UV flux would never reach the surface of the planet. Accordingly, flares do not present a significant obstacle to the habitability of planets orbiting M dwarfs. Furthermore, the specific role of UV radiation in the evolution of life on Earth is uncertain. A baseline level of UV flux might be necessary to spur biogenesis, yet UV radiation is also capable of destroying biomolecules. (Dressing and Charbonneau, 2013)

Advantages

First, M dwarfs are small. This means that an Earth-sized planet crossing in front makes a deeper transit around an M dwarf than around a G dwarf like the Sun. Second, M dwarfs are much fainter (0.015 times the Sun's luminosity) which means that the habitable-zone orbits closer to the star. A smaller orbit means a lower period, which indicates that said planet will cross in front of the star much more frequently. The combination of a shorter orbital period, an increased transit probability, and a deeper transit depth greatly reduces the difficulty of detecting a habitable planet and has motivated numerous planet surveys to target M dwarfs. (Dressing and Charbonneau, 2013). Since Kepler finds small planets by phase-folding data (essentially adding the signal from all the observed transits together), observing ~5 times as many transits for each planet means that we have already found most of the Earth-sized "habitable zone" planets transiting M dwarfs in the Kepler sample already.

Second, studies of the solar neighborhood have revealed that M dwarfs are 12 times more abundant than G dwarfs. The abundance of M dwarfs, combined with growing evidence for an increase in the planet occurrence rate at decreasing stellar temperatures, implies that



the majority of small planets may be located around the coolest stars. (Dressing and Charbonneau, 2013). The occurrence rate of planets with radii between 0.5 and 4 Earth radii and periods shorter than 50 days is found to be 0.86 planets per M dwarf: a planet for almost every M dwarf in the galaxy. The figure to the left shows the planet occurrence rate around M dwarfs as a function of planet radius and orbital period. There’s a steep drop off at 2.8 radii, showing us that Neptune to Jupiter sized planets in less than 50 day periods around M dwarfs are very rare.