Proceedings for the 25th Annual Conference of the Society for Astronomical Sciences

Society for Astronomical Sciences

Symposium on Telescope Science

Editors:
Brian D. Warner
Jerry Foote
David A. Kenyon
Dale Mais

May 23-25, 2006
Northwoods Resort, Big Bear Lake, CA

Reprints of Papers

Distribution of reprints of papers by any author of a given paper, either before or after the publication of the proceedings is allowed under the following guidelines.

1. Papers published in these proceedings are the property of SAS, which becomes the exclusive copyright holder upon acceptance of the paper for publication.
2. Any reprint must clearly carry the copyright notice and publication information for the proceedings.
3. The reprint must appear in full. It may not be distributed in part.
4. The distribution to a third party is for the sole private use of that person.
5. Under NO circumstances may any part or the whole of the reprint be published or redistributed without express written permission of the Society for Astronomical Sciences. This includes, but is not limited to, posting on the web or inclusion in an article, promotional material, or commercial advertisement distributed by any means.
6. Limited excerpts may be used in a review of the reprint as long as the inclusion of the excerpts is NOT used to make or imply an endorsement of any product or service.
7. Under no circumstances may anyone other than the author of a paper distribute a reprint without the express written permission of all authors of the paper and the Society for Astronomical Sciences.

Photocopying

Single photocopies of single articles may be made for personal use as allowed under national copyright laws. Permission of SAS and payment of a fee are required for all other photocopying.

Disclaimer

The acceptance of a paper for the SAS proceedings can not be used to imply or infer an endorsement by the Society for Astronomical Sciences of any product or method mentioned in the paper.

Published by the Society for Astronomical Sciences, Inc.

First printed: May 2006

ISBN: 0-9714693-5-0

Extrasolar Planets and the Race to Uncover the First Habitable Terrestrial Planet

Aaron Wolf
kheldar@ucolick.org

Gregory Laughlin
uco/lick observatory
1156 high street
santa cruz, ca 95064-1077
laughlin@ucolick. org

Abstract

Over the last decade, advances in technology and scientific technique have allowed scientists to discover more than 150 planets outside of our solar system. By using a number of different techniques, including radial velocity measurement, transit observation, astrometry, and spectroscopic observation, we have pushed the limits of our understanding of planets and how they form throughout our galaxy. With each year, we edge ever closer to the ultimate goal of discovering a terrestrial planet in the habitable zone, and perhaps even an undeniable detection of life outside of our solar system. This paper focuses on the possibility of locating the first terrestrial habitable planet by searching for transits around the lowest mass M stars. While these small and photometrically active objects provide many challenges for photometric study, they are perfectly well suited to the capabilities of the amateur community. The goal is now to find the first habitable terrestrial from the ground.

1. Introduction

In 1916, in circular #30 of South Africa's Union Observatory , Robert T. A. Innes reported the discovery of a faint red star in Centaurus. This otherwise unremarkable star, more than 100 times too faint to be seen with the naked eye, attracted his attention because it was rapidly moving with respect to other stars in the same part of the sky. This large proper motion indicated that the star was almost certainly a close neighbor of the Sun, and in 1917, this suggestion was verified. The distance to the star was measured to be only 4.22 light years, closer to the Sun than any other known star. Its extremely faint appearance, in spite of its close proximity, made it the intrinsically least luminous star known to astronomy at that time. Proxima Centauri, as the star was later named, is now known to be merely the nearest, and most famous, of the roughly 50 billion red dwarfs, or M stars, which inhabit our galaxy.

While M stars are the most abundant stellar type, their low intrinsic luminosities place serious constraints on our ability to study them. Even so, there exist about one hundred M stars that lie close enough to the earth such that their apparent luminosities are brighter than sixteenth magnitude, the current practical limit for transit observations with a high-end amateur telescope. The question then remains, is it possible that these small faint stars could harbor planets? The remainder of this paper provides relevant background information on M stars and discusses the possibility of finding terrestrial habitable planets around M stars. We argue that not only do we expect that terrestrial planets are common companions to red dwarfs, but also the transit signals of these objects are perfectly suited to the talents of the ground-based amateur astronomy community. We are leading this observational effort, along with other transit and radial velocity related projects, from our extrasolar planets website www.oklo.org. Our investigation shows that the first habitable terrestrial extrasolar planet can be found around an M star, it can be detected from the ground, and it can be done with equipment and techniques accesible to amateurs.

2. Lifespan and Evolution of M stars (Red Dwarfs)

Red dwarfs, or M stars, are by far the most common type of star, and they differ fundamentally from the Sun in several ways. Proxima, for example, has about 11 percent of the Sun's mass, and an average density several times that of lead (11.4 gm/cc). The Sun's average density, on the other hand, is only 1.4 times that of water (1 gm/cc). Proxima's total luminosity is about a thousand times less than the Sun, yet even this rather modest energy output has a difficult time escaping from Proxima's interior. The center of Proxima is so opaque that radiation cannot efficiently transport all of the energy produced by fusion in the interior to the surface. Proxima must therefore resort to convection, a process in which the turbulent motion of stellar gas physically carries energy away from the center.

The basic process of convection can be observed in a pot of water heated on a stove. Prior to the start of actual boiling, hot water wells up near the center of the pot, divests some of its heat at the surface, and then dives back down. Convection also carries the energy through the outer two percent of the Sun's mass, and the uppemost layer of convective cells are visible as granulation on the solar surface.

An important implication of this is that M stars are highly photometrically active, with their total luminosity fluctuating on a time-scale of, at worst, only a few nights. We will see later that this fact poses an important challenge to photometric monitoring of these objects.

Proxima's whole interior is convective, and hence all the stellar material is continuously and thoroughly mixed. A helium nucleus forged in Proxima's nuclear-burning core can expect to visit the surface regions within a relatively short time. This freedom of movement is in direct contrast to the interior of the Sun, where the core is radiative rather than convective. Helium that forms in the center of the Sun never strays far from its place of origin. The Sun's core thus becomes slowly enriched in helium, while the original composition of the outer regions remains unaffected.

The Sun can't access its entire store of hydrogen, and this will profoundly shorten its productive, hydrogen-burning lifetime. A completely convective low-mass star like Proxima, on the other hand, maintains access to its entire initial reserve of hydrogen fuel. Complete convection, coupled with an underwhelming power output, allows red dwarfs to survive almost unaltered, long after the higher mass stars have turned into white dwarfs, or self destructed in supernova explosions. Two trillion years from now, Proxima Centauri will still be shining, much as it shines today.

The ultimate fate of red dwarfs such as Proxima, was explored using a stellar evolution code in Laughlin, Bodenheimer, and Adams (1997). Figure 1 is adapted from that paper. It indicates that a 0.1 solar mass star will live for about 6 trillion years before exhausting its hydrogen. Instead of becoming red giants, the lowest mass stars actually become dramatically brighter and bluer before ending their lives as helium white dwarfs.

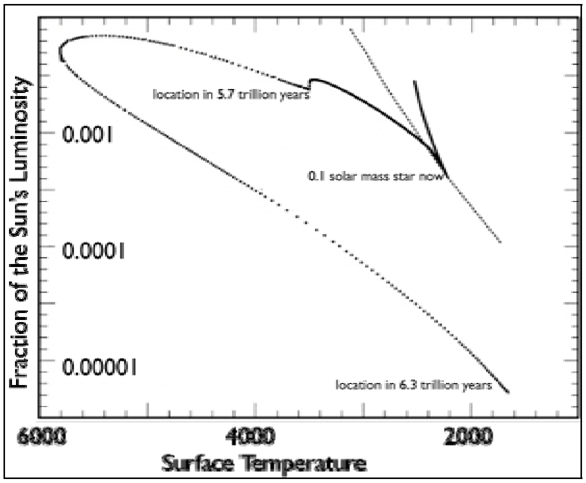


Fig. 1. Evolution of a 0.1 solar mass star in the Hertzsprung Russell Diagram

3. Radial Velocity Observations of M stars

About 130 red dwarfs, nearly all of which are more massive than Proxima, are close enough to the Sun such that their apparent luminosity is bright enough (V<11) to allow radial velocity observations. These red dwarfs have been part of the California-Carnegie Planet Search list for about 8 years. To date, only one M-dwarf system (GJ 876) has been found to harbor Jupiter-mass planets. The occurrence rate of Jupiter-mass planets, therefore, seems to be roughly a factor of ten less for red dwarfs than for stars that are similar in mass to the Sun.

Should we interpret this as a clue that M stars do not tend to form planetary companions? On the contrary, the fact that Jupiter-mass planets seem to be rare in orbit around red dwarf stars seems to be a natural consequence of the core accretion theory of planet formation. In the core-accretion theory, the formation of a giant planet occurs when a large core of solid material (with a mass of roughly ten times the Earth's mass) rapidly accretes gas from the surrounding protostellar disk. The smaller the parent star, the longer it takes for the core to form.

In a protoplanetary disk surrounding a newborn red dwarf star, by the time the cores form, the gas has generally been lost. We predict, then, that Neptune-mass and smaller mass planets will be very common around red dwarfs, whereas Jupiter-mass planets will be quite rare.

It is also interesting to note that the apparent lack of Jupiter-mass planets around M stars seems to support the hypothesis that core accretion is the dominant mechanism for planet formation. Alan Boss, of the Carnegie Institute of Washington, has recently published a preprint that shows that if the alternate gravitational instability mechanism is the dominant mode of giant planet formation, then Jupiter-mass planets should be just as common around red dwarfs as they are around solar-type stars.

There are now observational indications that suggest that low-mass planets may indeed be common around red dwarfs. The radial velocity surveys have recently reported the detection Neptune-mass companions in short-period orbits around the red dwarfs GL 581 and GL 436. Additionally, a team of observers using the microlensing method, have detected the signature what appears to be a planet with 5.5 Earth Masses orbiting a distant red dwarf.

4. Habitable Planets Around Red Dwarfs

The possibility of discovering the first habitable extrasolar planet is quite exciting, so before discussing whether we expect these objects to exist around M dwarfs, we will provide ample motivation by exploring the properties that they would posses. Thus, let us imagine an Earth-sized world orbiting a star with a tenth of a solar mass. A metal-rich 1/10th solar mass red dwarf has a radius about 1/10th of the Sun's radius, and a surface temperature of about 2750 Kelvin (compared to 5800 Kelvin for the Sun). This radius and temperature gives the red dwarf about 1/2000th of the Sun's energy output.

Therefore, in order for our putative habitable world to receive the same amount of energy that Earth gets from the Sun, it needs to orbit at a distance of 0.022 AU. From Kepler's third law, we see that this corresponds to an orbital period of 3.85 days. An Earth-like planet with a period of 3.85 days will be tidally locked to the red dwarf.

In the absence of any significant perturbing bodies, its orbit will be almost perfectly circular, and its spin period will be the same as the orbital period. Like the Moon with respect to the Earth, the planet will always show one face to the red dwarf: one hemisphere will have an eternal day, the other hemisphere eternal night.

Naively, one might think that such a situation would be disastrous for planetary habitability. The lit side of the planet will bake, and the night side will be inhospitably cold. Worse yet, if the night side grows cold enough for the atmospheric gases to condense, then the resulting cold trap will rapidly render the planet airless and uninhabitable. Interestingly, however, simulations show that this situation will not occur. A 1997 study by Joshi et al. used a global climate model to investigate how the Earth's climate would respond if the Earth were tidally locked to the Sun. The results were encouraging: the substellar point on the surface was warmer than the Saharan Summer, and the antisolar point on the dark side was colder than the Antarctic Winter, but the atmosphere did not collapse. The oceans and atmosphere effectively transported heat from the dayside to the night, and the tidally locked Earth remained habitable.

5. The Formation of M Dwarf Terrestrial Companions:

The all-important question still remains: Do we expect habitable terrestrial planets to form around 0.1 solar mass stars? A planet with a 3.85 day period orbiting a 0.1 solar mass red dwarf is about 20 times closer to its parent star than Mercury is to the Sun. Is it reasonable to expect to find a planet orbiting this close? As a first piece of evidence, we know for sure that the nearby 0.32 solar mass red dwarf GJ 876 is accompanied by a 7.5 earth mass planet with an orbit of only 1.9379 days (Rivera et al. 2005).

Most important, recent simulations performed by University of California, Santa Cruz graduate student Ryan Montgomery are supporting the existence of habitable terrestrial planets around M dwarfs. Montgomery has performed an extensive set of computer calculations that simulate the last evolutionary stages of planet formation from an initial swarm of planetesimals that make up the protoplanetary disk of a young low-mass red dwarf star. This simulation employs the Wetherill-Chambers method, which has had good success in explaining the latter stages of formation of the terrestrial planets in our own Solar System.

The simulation's underlying physical picture has a star and a disk that are of order one million years old, having already completed the initial stages of planet formation. Grains of solid material have stuck together to build larger and larger objects in the disk. Most of the gas that was originally in the disk has either accreted onto the star, or has been photoevaporated by high-energy photons originating from both the parent star as well as neighboring stars.

Currently, three sets of calculations have been completed, while a large number of additional runs are still computing. In the first set, containing sixty individual simulations, we assume that two Neptune-like giant planet cores have already managed to form beyond the protostellar ice-line.

The ice-line begins where the temperature is lower than 150K, the freezing point of water at zero pressure, and thus planets can grow more quickly due to the increased availability of solid material. We also assume that the innermost Neptune-mass core has undergone planetary migration, placing it at a distance of ~0.2 AU from the central star.

This situation was chosen so as to be in analogy with the known Neptune-mass planets orbiting the red dwarfs GL 436 and GL 581. In a second set of sixty simulations, no giant planet cores were included. In our simulations, the Neptune-mass cores assume a role similar to that which Jupiter and Saturn are believed to have had during the formation phases of the terrestrial planets in our own solar system.

In each of the 120 simulations that comprise the first two sets, we distribute 1000 planetesimals in initially circular orbits in the region between 0.04 AU and 0.12 AU surrounding the eventual stellar habitable zone for the 0.12 solar mass star. Each planetesimal contains 0.003 Earth masses (about a quarter of a lunar mass). The swarm of planetesimals is then allowed to evolve under its own self-gravity, the gravity of the star, and the gravity of the ice-giant cores, if present. Planetesimals that collide with each other are assumed to conserve total angular momentum in their collision, while merging to form larger composite objects. Some planetesimals collide with the ice giants or with the star, or are thrown out of the system.

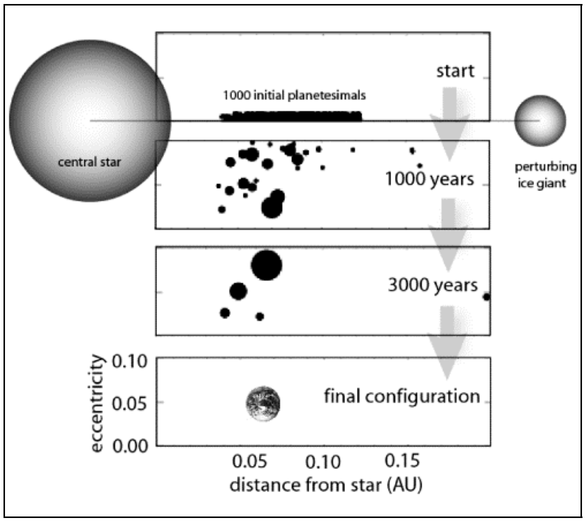


Fig. 2. Schematic diagram showing evolution of swarm of planetesimals to form terrestrial mass planets

In a typical simulation, depicted in Figure 2, the swarm rapidly works itself down over a period of a few thousand years into a system of several terrestrial mass planets. Earth-mass planets in the habitable zone of the star are a very common outcome of both sets of simulations, though they form more readily in the systems with ice-giant cores.

In a third set of thirty simulations, we lowered the masses of the planetesimals to 0.0003 Earth-masses, decreasing total disk mass by a factor of ten. The results of these simulations were the formation of Mars-sized or smaller bodies in the stellar habitable zone. These results have a simple interpretation.

The final stages of terrestrial planet formation in the protoplanetary disks of red dwarf stars appears to be an efficient process. If one starts with an adequately high effective surface density of solid material in the disk, then one frequently gets Earth-mass planets in the habitable zone. If one starts with a lower surface density, then one gets final sets of terrestrial planets that, on average, have proportionally lower masses.

6. A Case for High Surface Densities

Having demonstrated the importance of initial surface density to the final outcome of the simulations, we expended great effort in determining the appropriate surface density. If one makes reasonable extrapolations from the minimum-mass solar nebula that formed our own solar system, or if one extrapolates from the dust disks which are observed around young stars in the solar neighborhood, then one should adopt a low surface density.

This was the approach taken by Sean Raymond, presented at AbSciCon, 2006. Raymond's results agreed quite well with our low-surface density simulations, namely, Mars-sized or smaller planets in the habitable zones of red dwarfs. Sub-millimeter observations of dust masses in young stellar systems also seem to agree with the low surface densities employed in the "less-succesful" simulations.

These observations, however, only measure the amount of mass in dust, and are not directly sensitive to the amount of mass in large, planetesimal-sized bodies. Furthermore, such measurements give the dust mass at large distances, greater than one astronomical unit from the star, and hence do not give information about the mass of solids present in the innermost region of the disk.

According to these arguments, we choose to favor the high surface density scenario based on the “Minimum Mass Nebulae” for the inner regions of GJ 876 (0.32 solar mass) and Jupiter (0.001 solar mass). These are the two objects closest in mass to our hypothetical 0.12 solar mass star whose “terrestrial planet” systems we can measure.

In the case of the Jupiter satellite system, the moon Io has a mass of 8.93e+25 grams, an orbital radius of 0.0028 AU, and an orbital period of 1.8 days. This implies a minimum solid surface density of approximately 12,000 grams per square centimeter at the 1.8 day orbital radius in the proto-Jovian nebula necessary to form Io. In the case of GJ 876, planet “d” has a mass of 4.5e+28 grams (7.5 Earth masses), an orbital radius of 0.02 AU, and an orbital period of 1.94 days.

If we make the reasonable assumption that GJ 876 d fed off material reaching out to a radius of 0.075 AU, then this implies a minimum solid surface density of 11,000 grams per square centimeter at the 2.0 day orbital radius in GJ 876’s protoplanetary nebula. The effective surface densities of solid material implied by these two systems are thus remarkably similar, each valued at about 10,000 grams per square centimeter at a 2-day orbital period.

Accordingly, we allow these two real-world bounding cases to guide our choice of appropriate initial surface density, adopting a solid surface density of 11,000 grams per square centimeter at the 2-day orbital radius for our 0.12 solar mass star (0.015 AU).

We apply this constraint using a reasonable $r^{-3/2}$ falloff in surface density as we move away from the star, suggesting a fiducial density of 2000 grams per square centimeter at a habitable-zone radius of 0.045 AU. It is this final value for the surface density that was employed in our first two sets of preferred simulations.

7. Possibilities for Ground-Based Detection

If habitable planets do commonly form in orbit around low mass red dwarfs, as Montgomery's simulations indicate, our analysis shows that our chances of detecting and characterizing them are surprisingly good. The radius of a 0.1 solar mass star is roughly 10 times smaller than the Sun, and 10 times larger than the Earth. This means that the transit of an Earth-sized planet will block about 1% of the red dwarf’s light.

For the example case of our planet on a 3.85 day orbit, the transit will be relatively brief, lasting about 40 minutes. In principle, a 1% photometric dip is readily detectable, and in fact, amateur astronomers who participate in the transitsearch.org collaboration, which is one of our projects organized from www.oklo.org, routinely achieve detection thresholds of considerably better than 1%.

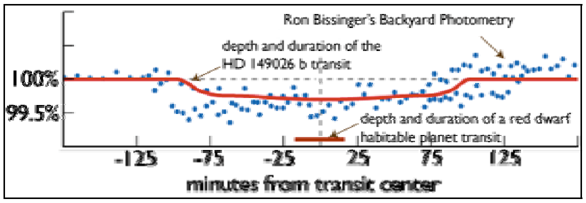


Fig. 3. Comparison of skilled amateur photometry of HD 149026 transit with potential habitable terrestrial planet transiting parent M star.

Figure 3 shows Ron Bissinger’s observation of the transit of HD 149026 b, which has a transit depth of 0.3%, compared to the depth and duration of the transit of an Earth-sized planet. Skilled amateurs such as Bissinger or Tony Vanmunster have backyard techniques that are good enough to detect the passage of even a Mars-sized body in front of an 11th magnitude 0.1 solar mass red dwarf.

Montgomery's simulations were also used to help determine the feasibility of ground-based detection by skilled amateurs. Once a particular simulation run is completed, we choose a random angle from which the system is to be viewed. We then generate photometry that is typical of what high-end amateur observers such as Ron Bissinger or Tonny Vanmunster are capable of regularly achieving (see Figure 3).

Next we “observe” the system by creating a simulated photometric time series over a period of several hours, during the intervals in which a transit might possibly occur. Figure 4 displays just one example of a simulated successful transit detection.

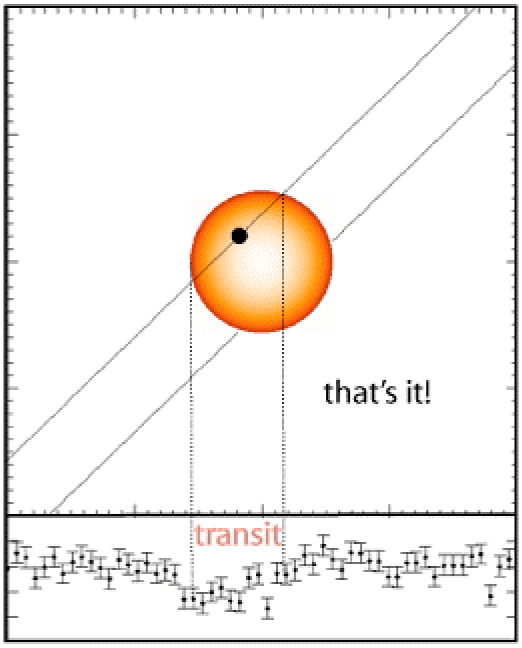


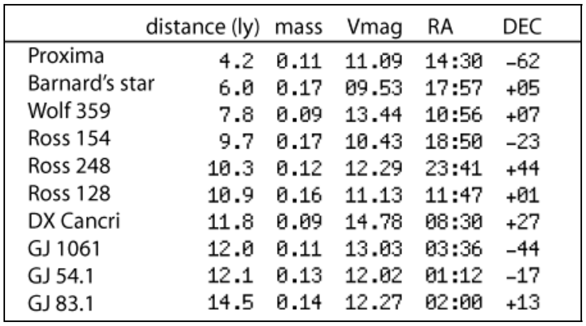
Fig. 4: Synthetic detection of a habitable terrestrial planet transiting an M dwarf with high-end amateur equipment.

It is important to note that the useful technique of "folding" photometric data in order to find periodic intensity dips will likely be of little use in locating the transit of a red dwarf companion. This is because these low mass stars are highly photometrically active, and thus tend not to have night-to-night photometric stability.

It is thus absolutely important that photometric observations are made simultaneously by multiple observers in order to ensure confidence in a potential detection. Even with these constraints, it is encouraging to note that in total, our simulations imply about a 1.0% a-priori probability that a 0.12 solar mass red dwarf has a detectable, habitable planet.

8. Conclusion

The final question that remains, then, is how many suitable red dwarfs are available on the sky? Even though the lowest-mass M stars are the most common type of star, they are also exceedingly dim. A 3m-class telescope, such as the Shane Reflector on Mt. Hamilton would be required to properly search the magnitude range V=16-18 where the lowest-mass red dwarfs begin to be plentiful (and indeed, many 0.1 solar mass stars within 10 parsecs still remain to be discovered). In the meantime, however, we recommend that observers join our efforts, which are being coordinated from www.oklo.org, and immediately consider obtaining high-cadence photometry of the nearby stars presented in Figure 5. Each candidate star has a one percent chance of harboring a detectable transiting, potentially habitable planet. It is now our responsibility to find that lucky system.



	distance (ly)	mass	Vmag	RA	DEC
Proxima	4.2	0.11	11.09	14:30	-62
Barnard's star	6.0	0.17	09.53	17:57	+05
Wolf 359	7.8	0.09	13.44	10:56	+07
Ross 154	9.7	0.17	10.43	18:50	-23
Ross 248	10.3	0.12	12.29	23:41	+44
Ross 128	10.9	0.16	11.13	11:47	+01
DX Cancri	11.8	0.09	14.78	08:30	+27
GJ 1061	12.0	0.11	13.03	03:36	-44
GJ 54.1	12.1	0.13	12.02	01:12	-17
GJ 83.1	14.5	0.14	12.27	02:00	+13

Fig. 5: Selection of nearby M dwarf stars from the RECONS catalog of the 100 nearest stellar systems maintained by Todd Henry and his collaborators at Georgia State University