Amateur and Professional Astronomer Collaboration Exoplanet Research Programs and Techniques

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Abstract

In 1995 the breakthrough announcement was made that a planet had been discovered orbiting a star in the constellation Pegasus. Prior to that time, for decades astronomers had searched in vain to confirm that planets existed around any other star besides our own Sun. Yet it was a mere five years after the first exoplanet discovery that the first amateur astronomers observed a transit of an exoplanet using a 16-inch (40 cm) telescope in Finland. The realization that amateur astronomers could in fact detect exoplanets lead to the formation of transitsearch.org, the first amateur/professional collaboration to discover exoplanets. In the ensuing years numerous other such collaborations have been formed and dozens of amateur astronomers around the world now regularly observe stars identified by professional astronomers as possibly harboring exoplanets. This paper summarizes the more notable amateur and professional collaborations now ongoing to discover and characterize exoplanets. Tools and techniques used by amateur astronomers in such research are reviewed with an eye towards how amateur astronomers may soon help discover the first earth-sized exoplanet capable of supporting life as we know it.

1. Introduction

1. 1. Background

As humanity seeks to determine if intelligent life exists elsewhere in the universe, current efforts are focused on finding planets similar to our own Earth. While evidence was found in 1994 of planets orbiting a pulsar, it was in 1995 that the first exoplanet was found orbiting a sun-like star in Pegasus (Mayor & Queloz, 1995). Until 2000 exoplanets were found using Doppler shifts in stellar spectra as the orbiting exoplanets pulled on the parent star. One such exoplanet, HD 209458b, also in Pegasus, was determined to cross in front of, or transit, its parent star as seen from Earth (Charbonneau et al 2000).

Detection of exoplanets using spectroscopy requires large, professional observatories and expensive equipment beyond the reach of amateur astronomers. But the dip in the light of a star caused by the transit of an exoplanet is within reach of the amateur. So it was on September 16, 2000 that a group of amateur astronomers using a 16-inch (40 cm) telescope at the Nyrola Observatory in Finland observed a 1.7% decrease in the light of the parent star caused by a transit of HD 209458b. Inspired by the success of the Finnish amateurs, Transitsearch.org was formed in 2001 as the first collaboration between professional and amateur astronomers to find new transiting exoplanets. Since then, dozens of amateur astronomers worldwide have captured the signature dips in lightcurves caused by transiting exoplanets.

Professional astronomers have used two broad approaches to selecting and observing transiting exoplanet candidates. The first is a wide field search using wide angle optics and large CCDs to survey large swaths of the sky. The second is a targeted search where telescopes are used to monitor star clusters or specific stars. The wide field searches generally identify transit candidates with $m_v < 12$ but are generally not suited for finding transits in dimmer stars.

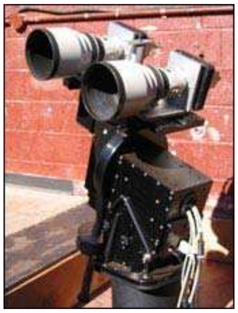

Figure 1. XO Project Wide Field System

Figure 1 shows an example of the instruments employed in wide field searches, in this case the system used by the XO Project on the 3054 meter summit of Haleakala on Maui, Hawaii. This automated system uses two commercial 200mm f/1.8 Canon EF200 lenses coupled to two Apogee Ap8p CCD camera. Each lens covers 7.2 degrees of the sky.

1. 2. An Increasing Focus on Red Dwarfs

Most of the exoplanets discovered to date are much larger than Earth with orbits closer to their stars than Mercury is to our own Sun. Since their stars are as hot as or hotter than our own Sun, we know that these exoplanets are far too hot to harbor life similar to that on Earth.

In recent years researchers have proposed that exoplanets orbiting class M stars, particularly red dwarfs, may be capable of supporting life. Red dwarfs have surface temperatures of 3,000 deg K or even lower compared to over 6,000 deg K for our own Sun. Even if orbiting close to their stars, exoplanets of red dwarfs could have zones in their atmospheres where liquid water could persist, allowing life to flourish.

Confirmation of this possibility came in May 2007 with the announcement that an exoplanet only 1.5 times the size of Earth was found to orbit the red dwarf Gliese 581 which lies 20.5 light years from Earth. The exoplanet has an orbital period of 13 days and is at a sufficient distance from its relatively cool parent star that liquid water could persist.

As red dwarfs become subject to more scrutiny, amateur astronomers have the opportunity to participate and contribute to the newest frontier of exoplanet research.

2. Habitable Transiting Exoplanets Detectible by Amateur Astronomers

2. 1. Minimum Detectable Transit Depth by Amateur Astronomers

The measurement of changes in stellar light flux, called photometry, is limited from ground-based observatories largely by atmospheric scintillation as well as the intensity of the stellar flux relative to that of the background sky. Increasing the aperture of the telescope and increasing the time of exposure can improve the overall precision of the photometry but realistically only to certain levels.

Amateur astronomers commonly use telescopes with apertures ranging from 10 to 14 inches (25 to 35 cm) although some have access to instruments with apertures greater than 20 inches (0.5 m). For ground-based instruments with apertures of 14 inches (35 cm) or greater, it has been shown that exoplanet transits with depths of 0.2% to 0.3% (2 to 3 mmag) can be detected using multiple observations assuming stellar magnitudes $m_v < 12$ (Bissinger 2005). In practice, a 14-inch (35 cm) telescope was used by the author to detect the 0.3% depth transit of HD149026b as shown in Figure 2.

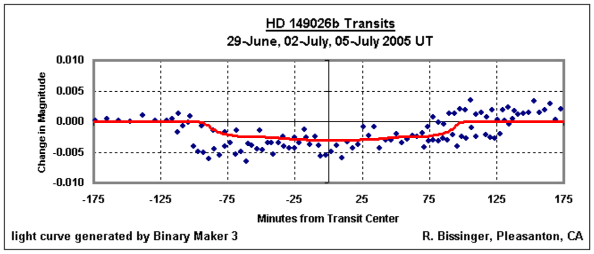

Figure 2. Exoplanet transit with 0.3% depth

2. 2. Sizes of Detectable Exoplanets

Given the typical equipment used by amateur astronomers, the possibility of whether they could detect an Earth-sized planet can be determined as well as the conditions under which it would be possible to do so.

Assuming a telescope aperture of 14 inches (35 cm) and a minimum detectable transit depth of 0.2% the relationship between exoplanet and parent star sizes can be approximated simply by using the ratio of the squares of their radii as shown in Figure 3.

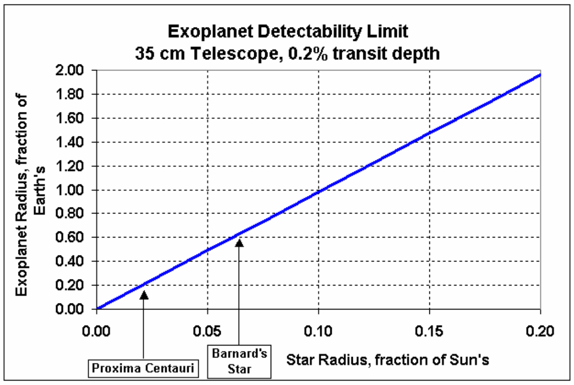

Figure 3. Minimum Detectable Exoplanet Size

Figure 3 plots the parent star radius as a fraction of that of our own Sun against the radius of the transiting exoplanet expressed as a fraction of the radius of Earth. We see that it is then possible for an amateur astronomer using a 14 inch (35 cm) telescope to detect transits of an exoplanet the size of Earth if it is orbiting a star with a radius 0.10 that of our Sun.

There are, however, certain conditions that need to be satisfied for Figure 3 to apply. The first would be that the star's magnitude would need to be $m_v < 12$. Obtaining 0.2% (2 mmag) photometric precision on fainter stars with a 14-inch (35 cm) telescope would be difficult if not impossible. The second would be that a single observation of a transit event by itself may not be evident, nor would it be convincing. So multiple observations of a transit need to be obtained, either by multiple observers detecting the same transit or by a single observer detecting multiple transits of the same star. Two to four such multiple observations would be required to indicate a significant probability that such a transit is indeed occurring (Bissinger 2005).

2. 3. Target Stars for Earth-sized Exoplanet Searches

Figure 3 shows that in order for amateur astronomers using typical equipment to detect transiting exoplanets approximately the same size as Earth they must observe stars that have radii less than 20% that of our own Sun.

Fortunately, our sky is filled with such targets, but they are not the stars we can see with our naked eyes. They are a class of stars called red dwarfs which are estimated to account for as many as 75% of the stars in our galaxy..

For example, Figure 3 also shows that two well known red dwarfs, Proxima Centauri and Barnard's Star, could provide transit signatures sufficient to be detected by amateur astronomers if they harbored transiting Earth-sized exoplanets.

An excellent discussion of the probability of terrestrial-sized planets forming in red dwarf systems and why such exoplanets might be capable of supporting life as we know it has been provided previously (Wolf, Laughlin 2006). In recent years a number of papers have presented strong arguments as to why such exoplanets make compelling targets for indicators of life (Tarter et al, 2007; Segura et al, 2005).

While several space-based instruments are or will be searching for exoplanets using the transit method (the European Space Agency's COROT, NASA's Kepler, and the Canadian Space Agency's MOST, for example) amateur astronomers have the equipment and time to monitor many single red dwarf targets for transiting exoplanets.

But unlike previous efforts where amateurs observed fairly bright stars with $m_v<9$, red dwarfs are considerably fainter with $m_v>11$. In order to yield usable signal to noise ratios, the red dwarfs that lend themselves to amateur observing must be relatively close to Earth. So it is indeed fortunate for the interested amateur astronomer that professional astronomers have prepared several lists of potential close-in red dwarf targets as part of their preparations for the space missions mentioned previously as well as future missions such as NASA's Terrestrial Planet Finder and Space Interferometry missions.

An ongoing project, the Research Consortium on Nearby Stars (RECONS), is in the process of identifying our closest neighbors. A list of the closest 100 stars, including many red dwarf stars brighter than m_v =12, is maintained and updated by the group at:

http://www.chara.gsu.edu/RECONS/

Another target list developed for NASA's upcoming Space Interferometry Mission (SIM) includes many red dwarfs and is maintained at:

http://tauceti.sfsu.edu/~chris/SIM/t1.html

Figure 4 shows some of our nearest neighbors in space, many of which are red dwarfs not visible to the naked eye.

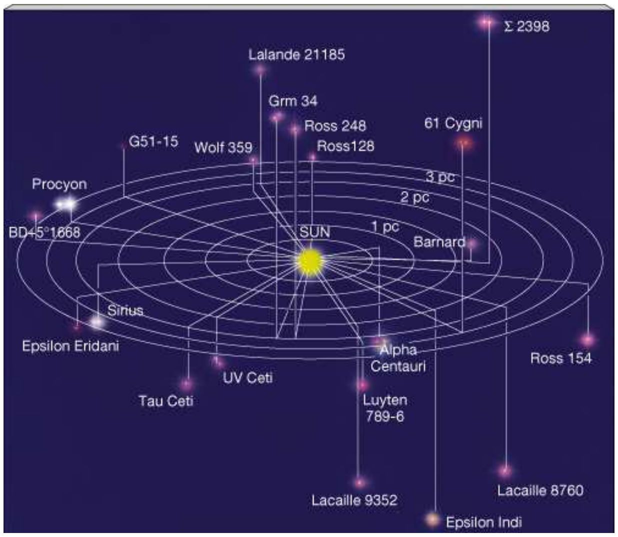

Figure 4. Our Nearest Neighbors (from Astronomy Today, Chaisson and McMillan, 2002)

As is apparent from inspecting the RECONS and other lists, however, the number of red dwarfs observable by typical amateur astronomers is quite large.

One approach for selecting a suitable target to monitor would be to pick one that is observable in the eastern sky shortly after nightfall and then make repeated observations over a month or two. Unfortunately, visual inspection alone might not be sufficient to pick out a small transit in such a large set of data.

There are some commercially available software packages that have the capability to isolate a transit signal buried within a large set of data taken over multiple observing sessions. One such package is

PERANSO, available at http://www.peranso.com. Another product that could be used is MPO, available at http://www.minorplanetobserver.com.

3. Pro-Am Exoplanet Search Collaborations

3. 1. History of Pro-Am Collaborations

Most amateur astronomers, however, will quickly find it quite daunting and challenging to sift through the gigabytes of data an individual might generate from such an observing endeavor. A better approach for the individual observer might be to participate in a professional-amateur (Pro-Am) collaboration to monitor red dwarf candidates.

The advantages of such participation are many. First, the amateur will be able to observe a list of target stars that are prioritized based on the professional astronomers' latest understandings of planetary formation. Second, the amateur will be able to pool their observations with those of others so as to maximize the coverage of a target star, increasing the likelihood that they will observe and detect a transit if one occurs.

One of the first, if not the first, such Pro-Am collaborations was Transitsearch.org which was launched in 2002 to find new transiting exoplanets. Other Pro-Am collaborations followed, including the XO Project which has yielded the discovery of the transiting exoplanet XO-1b and offers the promise of uncovering more exoplanets in the future (see http://www-int.stsci.edu/~pmcc/xo/science/).

3. 2. Systemic – A Web-based Collaboration

It was in 2006 that an innovative program called Systemic was launched that allows interested amateurs and the public to participate in a wide-scale simulation to quantify the likelihood of planetary formation. No equipment is necessary. The project is web-based, and uses a catalog of 100,000 stars to allow users to discover exoplanets using model radial velocity curves for the catalog stars. The properties of the theoretically-discovered exoplanets are then compared with those of real ones.

Systemic has the potential to provide additional guidance for follow-up radial velocity or transit observations of promising candidate stars.

3. 3. A Red Dwarf Exoplanet Pro-Am Collaboration

Interest in red dwarf systems as potential harbors of life has spurred increasing professional observations as well as a new Pro-Am collaboration. GEMSS, an acronym for Global Exoplanet M-dwarf Search Survey, is designed to provide focus for professional and amateur efforts to observe red dwarfs (http://gemss.wordpress.com). The project is in its early stages but will be reaching out to interested amateurs, the AAVSO and Transitsearch.org for additional participation.

4. Exoplanet Transit Detection Tips and Techniques

The literature and online forums are full of procedures and techniques for performing photometry. As instruments used by amateurs have increased in capability over the years, so has the number of people performing precision photometry. Five years ago amateurs aspired to achieve differential photometric precisions of 1%, or 0.01 mag. Recently, in part driven by the need for high precision photometric time series of exoplanet transit candidates, differential photometric precisions of 0.2%, or 0.003 mag, are becoming commonplace.

Much has been said and written about the quality of flat fields, dark subtraction, and signal to noise ratios, all of which is valuable to learn and to put into practice. But beyond these frequent topics, it is from the author's experience observing exoplanet transit targets for several years that two techniques stand out that have consistently helped achieve high levels of differential photometric precision.

4. 1. Sticky Pixels

It is commonly accepted that flat fielding is necessary when performing CCD photometry, and very often it is. It is also recognized that unless carefully prepared, flat fields themselves can introduce errors and artifacts into the science images.

The combination of precision telescope mounts and CCD guiders that can track to sub-pixel accuracy allows observers to keep a star image on a very small spot of their CCD chips. Doing so minimizes errors introduced by small difference in sensitivities of individual pixels and other variations on the chip itself. A slight amount of defocusing can spread the star image over a small number of pixels and the precise tracking will keep the image on the same spot throughout the observing session. The author has found this technique very useful.

Another advantage of this technique is that only carefully prepared flat fields will improve the accuracy of the photometry. For example, in the situation where a near-full moon can cause uneven illumination of the sky depending on telescope position, flat fielding will not correct all the images uniformly and can actually degrade photometric precision when applied to a series of images taken over an entire night, especially when differential photometric precisions of ~0.5% (5 mmag) or less are required. In such cases it has been seen that raw images reduced with only darks and bias frames can provide better results, again assuming precise tracking of the star on a small area of the chip.

4. 2. Systemic De-trending

Amateur and professional photometrists will often use color transformations to account for differential atmospheric extinction of stars of different colors. By doing so they are eliminating a quantifiable factor in their data that would provide an inaccurate result.

For years professional astronomers have used a similar philosophy when working with time series differential photometry. They have recognized that there are predictable and quantifiable trends in their photometry that have been introduced because of variations in tracking, individual pixel sensitivity, artifacts on their CCD chips and other factors. They have characterized these trends as systemic errors (not to be confused with the Systemic exoplanet project mentioned previously!) and have developed methodologies for their removal from their data. Several variations of de-trending algorithms can be found in the literature (Manfroid et al, 2001; Mazeh et at, 2006).

While the application of complex de-trending algorithms can be done by amateurs, differential photometric precisions can often be improved in time series by some simple mathematics.

Amateur differential photometry time series often exhibit cyclic trends readily discernable to the eye. These cycles will often have periods considerably longer than that of an exoplanet transit. It then becomes possible to use a simple sine function to remove the long period trends from the data without compromising short term variations.

Figure 5 shows an example of differential photometry obtained with a 14-inch (35cm) telescope. The standard deviation of the raw data shown is 0.14% (1.4 mmag). The figure also shows a cyclic trend in the data which was modeled using a sine function and least squares fit to the data. The sine function was then simply subtracted from the raw data yielding a smoother time series having a standard deviation of 0.12% (1.2 mmag), a 14% reduction in scatter.

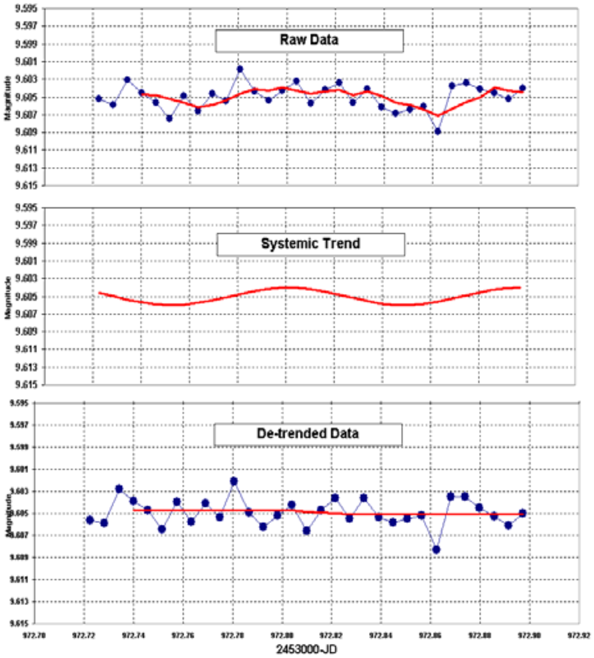

Figure 5. Simple De-trending Algorithm Effect

While 14% reduction may not appear to be that much, when several nights worth of such time series observations are combined, the de-trending algorithm makes discerning a small transit significantly easier.

As more amateurs seek smaller exoplanet transits it is likely that more de-trending approaches will be used in the data analysis.

5. Conclusions

The monitoring of red dwarfs for transiting exoplanets is a new opportunity for amateur and professional astronomer collaboration. Amateur astronomers have ready access to the equipment, tools and time with which to make a significant contribution to exoplanet research and the ultimate search for life in the universe.

6. Acknowledgements

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