The Discovery of Extrasolar Planets by Backyard Astronomers

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Abstract: The discovery since 1995 of more than 80 planets around nearby solar-like stars and the photometric measurement of a transit of the jovian mass planet orbiting the solar-like star HD 209458 (producing a more than 1% drop in brightness that lasts 3 hours) has heralded a new era in astronomy. It has now been demonstrated that small telescopes equipped with sensitive and stable electronic detectors can produce fundamental scientific discoveries regarding the frequency and nature of planets outside the solar system. The modest equipment requirements for the *discovery* of extrasolar planetary transits of jovian mass planets in short period orbits around solar-like stars are fulfilled by commercial small aperture telescopes and CCD (charge coupled device) imagers common among amateur astronomers. With equipment already in hand and armed with target lists, observing techniques and software procedures developed by scientists at NASA's Ames Research Center and the University of California at Santa Cruz, non-professional astronomers can contribute significantly to the discovery and study of planets around others stars. In this way, we may resume (after a two century interruption!) the tradition of planet discoveries by amateur astronomers begun with William Herschel's 1787 discovery of the "solar" planet Uranus.

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1. Introduction and Background

Extrasolar giant planets that "transit" their host stars are rare and valuable. Recent observations of the atmosphere of the one known transiting extrasolar planet HD 209458-b via Hubble Space Telescope spectroscopy [1] demonstrates that detailed study of the physical nature of transiting planets is greatly enhanced compared to non-transiting planets. During a transit, a small fraction of the parent star's light passes through the planet's atmosphere and imprints characteristic absorption lines upon the stellar spectrum. This information taken together with the planet's size and density (obtained by careful analysis of the transit light curve shape) allows detailed study of the planet's physical makeup beyond the minimum mass, orbital eccentricity and period obtained from radial velocity measurements alone.

More than eighty extrasolar planets have been discovered around nearby stars by measuring the velocity wobbles of their parent stars [2]. Twenty percent of these planets reside in short period orbits where the probability of viewing a transit is about 10% [3]. In late 1999, two radial velocity teams discovered a planet orbiting the star HD 209458 [4,5,6]. Photometric observations detected a 1.7 % dimming of this star's light consistent with a planetary transit. The repeated transit signal allowed determination of the planet's mass (by knowing the inclination) and radius (from the depth of the transit), giving a mass of 0.63 Jupiter masses and a radius of 1.4 Jupiter radii [6]. The inflated physical size of the planet is consistent with models for hot extrasolar planets [7,8]. This photometric measurement of the transit of the planet orbiting HD 209458 and the subsequent detection of atmospheric sodium [1] by the Hubble Space Telescope (HST) has heralded a new era in astronomy where the fundamental properties of transiting planets around other stars can be studied. Obviously, in order to study these planets in detail, they must first be discovered. For the first time it is now possible for small telescopes equipped with sensitive and stable electronic detectors to make these discoveries. In fact, an amateur group in Finland observed the transit of HD 209458-b during September 2000 (Sky and Telescope, January 2001) and amateur Ron Bissinger observed the transit on the night of October 12, 2001 in Pleasanton, California using equipment similar to what we consider a typical system. The modest equipment requirements for the measurement of extrasolar planetary transits of hot Jupiters are achieved by commercial small aperture telescopes and CCD (charge coupled device) imagers common among amateur astronomers and educational institutions.

2. Approach

Although extrasolar planets are lost in the glare of their parent star and are not resolved by even the largest telescopes, the planet's presence can nevertheless be revealed by the periodic dimming of the star if the planet crosses the stellar disk as viewed from Earth. For the near-jovian mass planet found around the solar-like star HD 209458 (the only known transiting extrasolar planet), the planet produces a dimming of the star of 1.7 % that lasts for about 3 hours. Although this effect is far too small for the unaided eye to discern, a typical off-the-shelf amateur CCD detector has sufficient sensitivity and stability to measure relative changes in brightness much smaller than this given proper observing procedure and data reduction techniques [9]. Equipped with CCDs, small telescopes (Figure 1) CAN detect planets around other stars (as illustrated in Figure 2)! NASA Ames and UCSC scientists have identified several hundred stars more likely than average to possess short period planets. These planet candidates come from three search projects being conducted by our team as described in the following section "Target Stars".

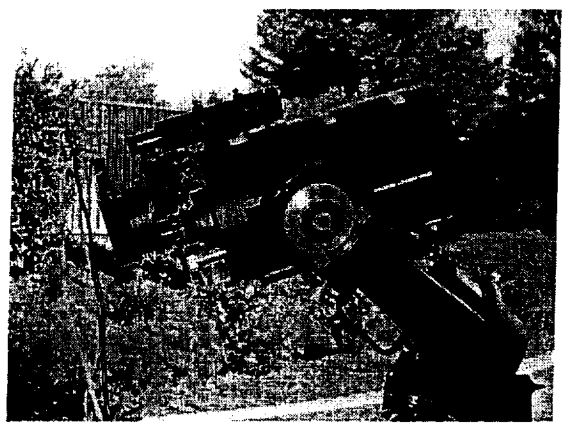

Figure 1. Our prototype Santa Barbara Instruments Group (SBIG) ST-7E CCD and Meade LX-200 8 inch aperture telescope system

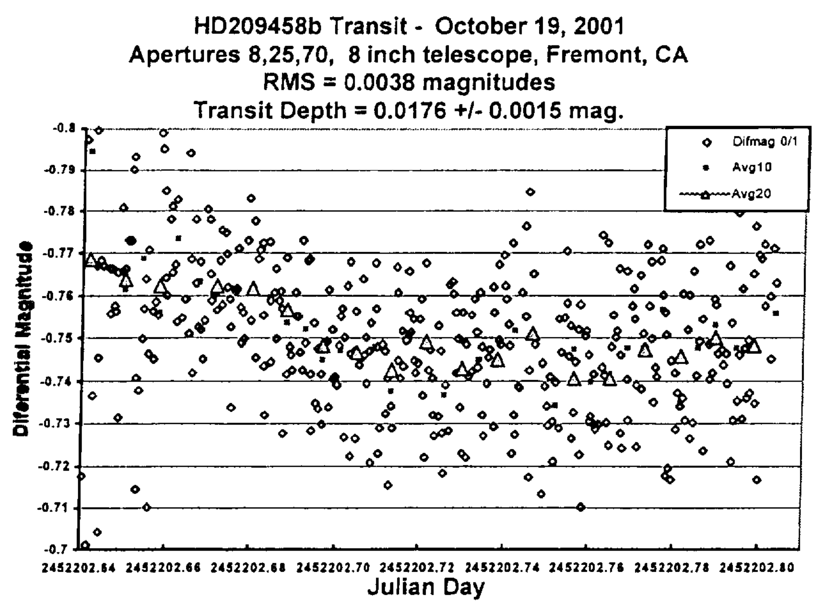

Figure 2. The transit of HD 209458-b observed in a typical backyard with the prototype telescope/CCD system. Images were reduced and the results plotted using commercially available software. The light colored dots are individual measurements and the dark triangles are the average of 20 measurements. The precision of the average of 20 measurements is about 0.4 % with a time sampling of about 10 minutes. The transit begins at JD 2452202.67. The end of the transit was not observed this night.

3. Target Stars

Hipparcos Satellite Photometry Identified Candidates A search of the 12,690 main sequence stars of spectral types F, G, K and M in the *Hipparcos* Satellite photometry catalog conducted by one of us revealed several dozen with photometric features consistent with a planetary transit [10,11,12]. Although some of these are likely due to previously unknown stellar companions, stellar variability or noise, a few may be newly discovered extrasolar planets that transit. See Table 1 for a representative sample labeled "Hipparcos Selected".

Metal Rich Stars Statistical analyses of the population of parent stars of the known extrasolar planets indicate that approximately one in ten metal-rich stars should harbor a short-period planet. Given the ten percent chance that a given short-period planet displays transits, we therefore expect that approximately 1% of the most metal rich stars will have a planetary companion detectable by this project. A catalog of 206 highly metal rich stars has been compiled [13]. See Table 1 for a representative sample labeled "Metallicity Selected".

51 Pegasi Planets Stars found by radial velocity techniques to harbor massive planets in short period orbits will be potential candidates for transit measurements because on average 10% of these "hot Jupiters" are expected to transit based on random orbital inclinations. Several of these "hot Jupiters" are discovered by radial velocity techniques each year (http://exoplanets.org/).

Preliminary Target List February 2002

HIP Catalog Number	HD Number	R.A. (hr.)	Dec. (deg.)	Spectral type	V (mag)	Fe/H (dex)	Distance (parsecs)
Hipparcos Selected							
17972	GJ3251	3	63	M1.5	11.5	NA	34.66
56299	....	11	57	K2V	9.3	NA	38.52
62523	111395	12	24	G7V	6.3	NA	17.17
108859	209458	22	18	G0V	7.9	NA	47.08
111942	GJ 870	22	43	K8V	10	NA	42.94
Metallicity Selected							
94615	230999	19	19	G5	9.76	0.410	99.30
46639	233641	9	52	G0	9.28	0.335	96.62
66621	118914	13	31	G0	8.90	0.304	73.75
58318	103829	12	53	F8	9.29	0.274	89.21
49060	86680	10	28	G0V	8.05	0.262	99.70
New *Hipparcos* Variables?	HD Number	R.A. (hr.)	Dec. (deg.)	Spectral type	V (mag)	χ^2	Period (days)/delta
13313	17791	2	2	K5V	7.0	16.859	4.73954 / 0.1
111278	213617 (39 Peg)	22	20	F1V	6.5	5.071	1.79625 / 0.06
60074	107146	12	16	G2V	7.2	4.811	7.13116 / 0.06
77408	141272	16	1	G8V	7.6	3.712	4.15717 / 0.06
4956	SAO11548	1	61	K5V	9.0	2.853	3.01776 / 0.1
100346	193706	20	21	F9Vw	8.0	2.436	20.7231 / 0.08
18719	SAO 76384	4	20	G4V	8.8	2.406	5.88196 / 0.08
Well Known Eclipsing Binaries	Variable Name	R.A. (hr.)	Dec. (deg.)	Spectral type	V (mag)	Epoch	Period (days)/delta Prim, Sec
8115 (x2?)	V773Cas (Algol)	01	57	A3V	6.2	2448500.931000	2.93660 / 0.07, 0.03?
24836 (x2?)	DV Cam (Algol)	5	58	B5V	6.1	2448501.086000	1.529500 / 0.12, 0.12?
47279	VVU Ma (Algol)	9	56	A2V	10.3	2448500.2300	0.687377 / 0.8, 0.1
97263	HZ Dra (Algol)	19	69	A0	8.1	2448500.7650	0.772943 / 0.08, 0.02
114484	RT And (DW)	23	53	F8V	9.0	2448500.3671	0.628939 / 0.7, 0.2

Table 1.–Representative target stars selected based on *Hipparcos* photometry or high metallicity as well as possible new variable stars and some well known short period eclipsing binaries.

4. The Amateur's Role

We have acquired a telescope/CCD/software system representative of what a dedicated amateur might own late in the "transit season " for HD 209458 (illustrated in Figure 1) and have begun experiments whose goal is to achieve the required photometric precision. A first attempt at observing the transit of HD 209458 was shown in Figure 2. These procedures will be further refined and communicated to the amateur community along with candidate lists, finding charts and sample images. Of the thousands of amateurs who own the necessary telescope/CCD systems, it is hoped that a few percent will take up the challenge and make the necessary observations consistently. A night's worth of data from each amateur will consist of several dozens images of the specified field of stars. To reduce the data each observer will download the images to a personal computer and use commercially available software to calibrate the images and extract the photometric brightness of each star in each frame via aperture photometry. These tables of individual brightness measurements along with their time tags and estimated errors can then be imported into a spreadsheet program resulting in differential photometry and a graph of the results (more about how to do this in Section 6). It is these tables of differential stellar brightness and times of observation that will be transmitted to the *transitsearch.org* data center in electronic form, where they will be further analyzed, their quality checked, and then placed in an online database along with the contributor's identity. Candidate stars that show transit-like events that persist for several orbital periods, are seen by more than one observer and pass a test for stellar companions, will be added to radial velocity target lists for swift and unambiguous confirmation.

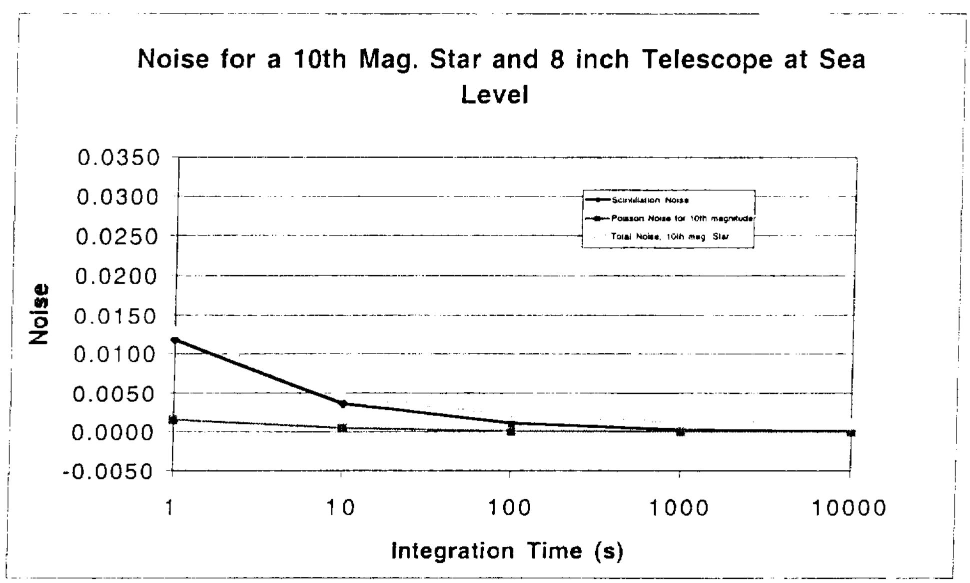

Figure 3. The calculated noise in magnitudes expected from atmospheric scintillation (twinkling) and shot noise for our prototype system (an 8 inch Schmidt-Cassegrain located at seal level).

5. The Technical Challenge

Achieving photometric precision of better than 1% for the bright stars found to have short period planets does not require a gigantic telescope or a remote mountain-top observatory, but it does require careful attention to some avoidable and some unavoidable sources of noise. These are primarily atmospheric scintillation (twinkling), random noise [14]. and CCD noise sources such as dark current and read noise. For a counting process, such as the detection of photons, the random noise is proportional to the square root of the number of photons received. Typically, scintillation rather than shot noise sets the precision limit for the bright stars found to have planets. Instrumental (CCD) noise sources such as read noise (15 electrons RMS typical for our ST-7E CCD) and dark current (less than 1 electron per second) can't be ignored. Figure 3 shows that for integration times approaching 100 seconds, scintillation and random noise added together results in total noise less than 0.5%.

6. How to Achieve Precise Photometry with an Off-the-Shelf CCD

The objective of our observing program is to measure the relative change in brightness of a star that (potentially) has a transiting planet as compared to another star in the same relatively small CCD field of view. By measuring the brightness of two stars simultaneously in the same CCD images, changes in the transparency of the atmosphere (clouds) or the response of the CCD with time become less important. By measuring the relative brightness of two (or more) stars, corrections due to first order extinction (extinction makes stars appear dimmer the further they are from the zenith) and color dependent extinction (bluer stars suffer from greater extinction) become very small or zero. In this way the difference in brightness of two stars can be compared over the entire night even though sometimes the stars are near the zenith and at other times the stars may be near the horizon. Experience with this technique (called differential photometry), reveals that changes as small as 0.2 % in brightness can be measured in less than perfect observing conditions if great care is taken [9].

Transits of Jupiter sized planets in 3 or 4 day period orbits (the so-called 51 Pegasi-b type planets or "hot jupiters") in front of solar-sized stars last about 3 hours and produce a 1 to 2 percent dimming of the star's light. To detect these transits we need to be able to:

a) Image the star with the suspected planet and a suitable (equally bright and the same color ideally) comparison star and keep both well located on our CCD for at least a transit duration (3 hours) and hopefully all night long. Typically in order to have reasonable chance of finding a suitable comparison star, a field of view that is about 1/2 degree on a side is necessary. For an ST-7E and an 8 inch F/10 telescope a focal reducer is required (Figure 4).

b) Take multiple (many!) CCD images of our field of interest at intervals much less than a transit duration (every few minutes is very good) with the precision of each measurement being less than 1/3 the transit depth expected. Since each image can be close to 1 megabyte, plenty of hard disk space is required and a way to permanently archive raw, calibrated and calibration images (CD-ROM) is recommended.

   Precision – we will define it as the standard deviation of the measurements of a constant brightness star (think of precision as the repeatability of a measurement). Note we are not very concerned with *accuracy* (that is, being able to compare the magnitude of a target star to that obtained by someone else or in a catalog).

c) We need to minimize systematic effects produced by poor tracking, focus changes or telescope light throughput changes (dew on the corrector plate for example). <u>Good autoguiding to keep the stars on the same places on the CCD chip seems to be especially important</u>.

d) Allow long enough exposures so that the brightness variations due to the atmosphere (scintillation) is not the dominant source of error in each measurement. For HD 209458 and an 8 inch telescope, a focal reducer and no filter it is easy to saturate the CCD in just a second or two. For the data from the night of October 19, 2001 we were forced to take many short exposures and average them. This is not the best approach because a) each time the CCD is read out noise is introduced b) it takes 13 seconds or more to read the CCD. During this time the shutter is closed, no light is being collected and autoguiding is interrupted (for our 2–chip SBIG ST-7E CCD camera). Taking 100 images per hour makes the data reduction tedious and computer memory intensive. If exposure times could be as long as (for example) 6 minutes the scintillation noise will have very small values (more on this in paragraph h).

e) We need to be able to repeat results for the same star field on many nights in a row. To date we have not determined how best to do this.

f) Take very high precision calibration frames that do not introduce errors into our results. This requires taking many bias, dark and flat-field frames and averaging them to produce master bias, master dark and master flat-fields that are then used to reduce your science frames. Flat-field frames need to have at least 100,000 counts per pixel (for example 5000 counts per pixel for each flat and 20 flats averaged together to make a master flat) to not introduce significant errors.

g) CCD limitations need to be understood and worked around. It would be great if we had the same CCDs that professional observatories have (very low noise, very uniform and very stable because of liquid nitrogen cooling) but we don't. Effects such as non-linearity must be considered. The CCD can saturate (the silicon wells cannot hold any more charge) or the analog to digital converter (A/D) can saturate first. Know what happens to your CCD as more light falls on it! The counts (analog to digital units or ADUs) displayed by your software reflects what the A/D measures, but the silicon collects a factor of the gain more electrons. So for example, our anti-blooming CCD becomes non-linear above about half-well capacity (20,000 electrons) so we have to limit the ADUs to about 8000 or so per pixel.

h) Carefully account for and minimize noise sources. We desire to have as many photons as possible to minimize the random noise inherent in any counting process. To get precision better than 0.3%, 100,000 electrons must be collected (see Table 2)! Note that in Table 2 below, 44,000 and 440,000 ADUs exceed the maximum A/D counts specified for the SBIG ST-7E [15] pixel's full well capacity. Do not be disturbed by this! The light we collect will be spread over many pixels, what we must pay attention to is the peak ADUs in any single pixel. For example, for the data we took on the night of October 19, 2001 we achieved about 4000 ADU maximum in one pixel for HD209458 which for a full width half maximum (FWHM) of about 5 pixels resulted in 50,000 total electrons (summed over an aperture of 8 pixels radius) and a best theoretical precision possible of about 0.5% per image. In practice, each measurement was limited by atmospheric scintillation to about 1.5% precision (theoretical for a 2 second exposure and about 1.5% actually measured). If the exposure could have been about 20 seconds long, we could have had two 0.5% precision measurements per minute rather than one 0.5 % precision measurement every 13 minutes! Fewer higher precision measurements are better than more lower precision measurements averaged together, because the former method keeps the CCD shutter open more of the time and results in fewer images to reduce.

ADUs (for a gain of 2.3)	Electrons	Random Noise	Signal/Noise	Precision
44	100	10	10	10%
440	1000	31.6	31.6	3.2%
4400	10000	100	100	1%
44000	100000	316	316	0.3%
440000	1,000,000	1000	1000	0.1%

Table 2. This is the best precision we could ever expect with zero atmospheric noise, zero detector noise and no systematic errors.

i) The data must be reduced (calibrated with flat fields, bias and darks) and the photometry performed without introducing additional errors. The selection of aperture sizes seems to be particularly important. This may require some trial and error for your observing setup and local conditions, so a facility for quickly evaluating the precision of your results for different aperture sizes is very helpful. For us MIRA AP 6.0 and a spreadsheet program worked well. Expect to spend at least a few hours reducing the data from each night. We found that star apertures on the small side worked best provided that tracking and image quality did not vary too much during the night.

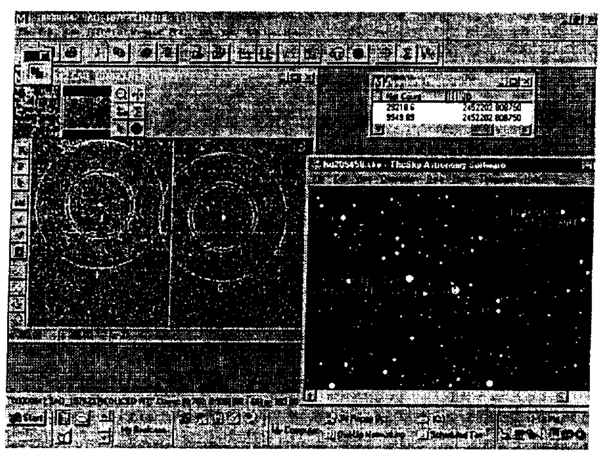

Figure 4. A sample computer screen showing HD 209458 (HIP 108859) and the comparison star HIP 108793 (left window) from MIRA AP 6.0. To achieve a field of view this large, a focal reducer was required. The large photometry apertures shown here would not be advised because it allows the read noise from too many pixels to contribute to the noise budget. The upper right window shows a portion for the photometry report generated by MIRA AP 6.0 for the image shown, The net count is the total number of electrons gathered within the apertures after the background is subtracted. Note that for this image, the dimmer of the two stars (the comparison star) has a net count of about 20,000 which we know is good for no better than 0.6% photometry by Table 2. Since this was in fact a 2 second exposure we were limited to 1.5 % precision by scintillation. TheSky Level IV 5.0's representation of the field of view of our LX-200 telescope and ST-7E CCD is shown in the right window, this allows the observer to confirm that the correct star field is being imaged.

6. Conclusion

Only one transiting Jupiter mass short period extrasolar planet has been found to date. Precision differential photometry (< 1 %) can be obtained with small telescopes and amateur grade CCDs with careful observing and data reduction. The large number of such systems owned by amateur astronomers makes it possible for additional transiting extrasolar giant planets to be discovered by a network of dedicated, careful, and patient observers. The potential scientific reward from such a discovery easily justifies the effort required. We hope you will join us!