PASS - A PERMANENT ALL SKY SURVEY FOR THE DETECTION OF TRANSITS

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Abstract

A project to survey the entire visible sky for the presence of transits by extrasolar planets is presented. The experiment would consist of one or two fixed arrays of wide-angle cameras, that would permanently take images of the entire visible sky more then 30 deg above horizon. A preliminary design consists of 15 cameras in each array, with optics based on SLR camera lenses, with f=50mm and aperture f/1.4. With images being taken every few minutes, the brightness limit for transit detections will be about 10th magnitude. One such instrument located around 30 deg N should allow the surveying of about 150 000 stars, with a southern declination limit of 18 deg. With the addition of a similar instrument in the opposite hemisphere, a coverage of the entire sky can be obtained (250 000 stars), and coverage is relatively uniform over all declinations. The result would be a complete catalog of all transiting giant planets around bright stars, with an estimated 120 planet detections. The sample stars' high brightness would make transits detected with this system the best suited ones for follow-up studies from ground and space mission.

Key words: Planets: exoplanets – transits – instrumentation

1. Introduction

The discovery of the first transiting planet, HD209458 (Charbonneau et al. 2000, Henry et al. 2000) made a new range of planetary parameters accessible to observations, such as precise planet size, density, and orbital inclination measurements. It also spun a range of follow-up observations, intended to detect planetary atmospheric features by spectroscopic transit observations (currently attempted by several groups) or by multi-color transit observations (Jha et al. 2000, Deeg et al. 2001). For the detection of spectral features, the major limitation is the achievable S/N in observed spectra. Current studies are at the limit of the capabilities of the largest telescopes, with more detailed studies having to be left for the next generation of extremely large telescopes. This makes it clear, that the detection of further transiting planets is of high interest, and several projects are under way to detect transits in small areas in the sky such around moderately bright stars, such as Vulcan (Borucki et al., 2001) or STARE (Brown 2001). However, the acquisition of the sample of transiting planets around around the *bright stars*, as proposed here, would be the most useful one. Only these systems will allow the deepest and widest range of follow-up observations.

Here, an experiment is outlined, that would perform a survey of *all* bright stars ($V \leq 10$) for transiting giant planets. Hence, a complete catalog of those transiting planets that are most suited for follow up studies would be obtained. The instrument would be in the form of a fixed array of wide angle CCD cameras, that will permanently survey the entire visible sky from one location in each hemisphere. The experiment should lead to the detection of about 120 Hot Giant Planets, and - depending on the duration during which it is being employed - to the detection of a considerable number of longer-periodic giant planets.

The experiment would also detect any other temporal astronomical phenomena, and could be of interest to a wide range of fields:

- variable stars of any kind
  - detection and follow-up of stellar variabilities with low amplitudes (up to 0.1%, depending on stellar brightness and frequency)
  - flares
  - detection of supernovae
- detection of meteorites (their frequency, brightness and direction)
- detection of optical counterparts to gamma ray bursts and 'optical flashes of unknown origin
- discovery and follow-up of asteroids and comets
- sky quality and meteorological statistics:
  - recording of sky brightness in all directions
  - percentage of clear sky, clouds
  - detection and recording of direction of satellites and airplanes (intrusions into protected sky area over observatory)

2. The instrument

The instrument would consist of an array of wide angle CCD cameras, with commonly available optics ($F \approx$ 50mm) for photographic cameras, and CCD cameras of

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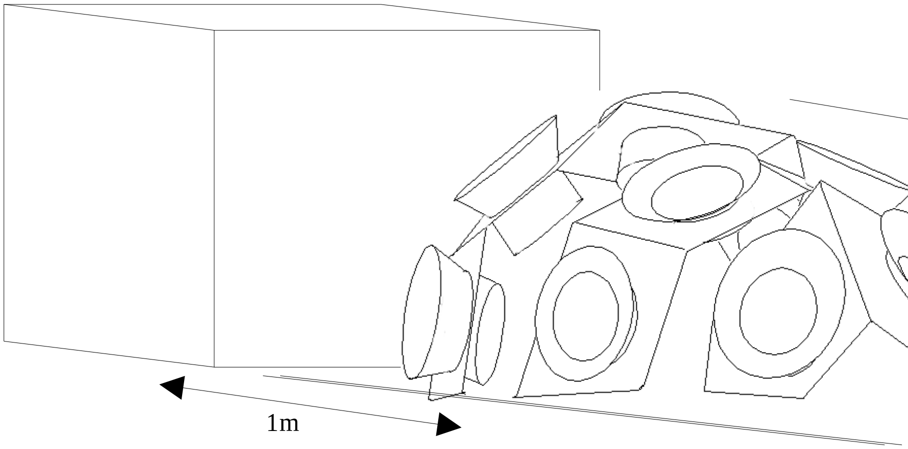

Figure 1. Schematic view of the PASS experiment, here drawn with 10 cameras. The box in the background is the removable enclosure. An approximate size-scale is indicated.

the kind available for advanced amateurs, that would cover the entire visible sky (Fig. 1). It should be noted, that a space mission with some similar design elements, - 'Treasure' - was proposed by Schneider et al. (2000) for the ESA call for F2/f3 missions.

The cameras would be placed on a common fixed mount, which has the advantages of mechanical simplicity and avoidance of any guiding errors, as stars will move over exactly the same pixels every night. This allows a very precise calibration of intra- and inter-pixel response functions. Only the point spread function (psf) of the stellar images would vary, but from observations of many nights the response of the CCD below the stellar track can be characterized for all commonly appearing psf-widths. The common mount should be adjustable in a small range around the precession axis, to keep stars moving over exactly the same pixels during the course of the survey. The array should be within an enclosure that is completely removable.

A current design study is based on f=50mm/f1.4 lenses for common high quality 36mm reflex cameras (Canon or Nikon for example). Detector would be a Kodak KAF-1001E CCD of 24.6 x 24.6 mm size and 1024^2 pixels or similar (available with cooling and electronics from several vendors) which gives a field of view (fov) of 28.5deg, and pixels with a linear size of about 100 arcsec. Fig. 2 shows that 15 cameras of that type give gap-less coverage of the sky above ≈ 30deg altitude, except in the southernmost direction, were no efficient coverage is possible (see next section). The experiment would need to be mounted on a sturdy platform, such as the roof of an existing building, and be covered with a completely removable enclosure with a size of about 2 x 1.5 x 1.5m. The entire array needs to be turnable around the precession axis with a fine adjustment, and be able to cover a precession angle large enough for the life-time of the experiment. With a precession rate of 50 arcsec per year, adjustments may have to be made every 2-3 months to avoid significant deviations of

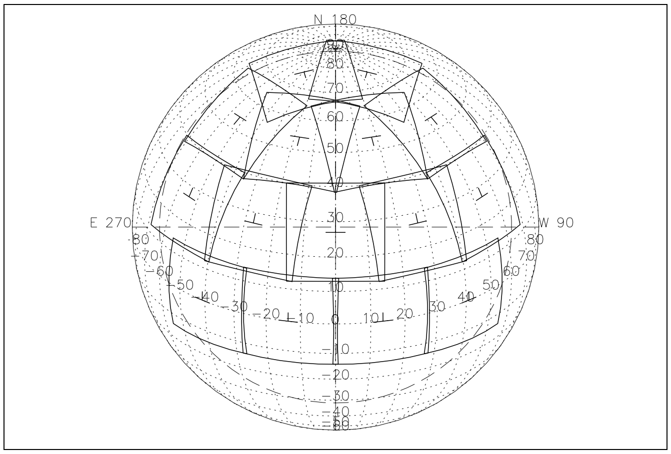

Figure 2. Local all-sky view from a location at 28.5 deg N, showing camera positions for a system of 15 units (each with a field of view of 28deg x 28deg), in orthogonal projection. Coordinate lines are declination and hour angle; also indicated is an altitude of 30deg (long dashes). In this configuration, the sky is completely covered for altitudes ≥ 34deg, with an average limit around 30deg, except for declinations below -17.5 deg, where no efficient coverage is possible (see Fig. 3). Other camera positionings have been evaluated, – for a viewing angle of 28deg this appears to be the most efficient one.

stellar paths. Images with exposure times of about 50 seconds will be co-added and saved to disk every 500 seconds. The experiment will thus generate about 7-800 images every night, each with a size of 2 Mbyte. The nightly total of 1.5 - 2 Gbyte of data can be saved on a single DVD disk.

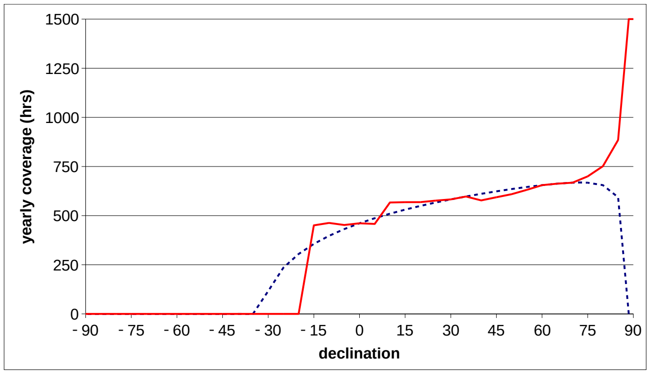

Figure 3. Temporal coverage in dependence of declination, assuming a yearly total of 1500 hours of clear observing conditions (200 nights of 7.5 hours) for a site at 28.5deg N. The coverage shown here is the average for stars at any right ascension (There is only small coverage variation with right ascension, due to variations in nights lengths and weather conditions throughout a year). Solid (red) line: coverage from a uniform minimum altitude of 30deg above horizon. The North Pole, at an elevation of 28.5deg, is not covered. Dashed (blue) line: coverage by the 15 camera system shown in Fig. 2. A small region around the celestial North Pole is now circumpolar by lowering the altitude limit to 27deg at very high northern declinations. All declinations up to the southern limit at 17.5 deg S are covered for at least 450 hr/yr.

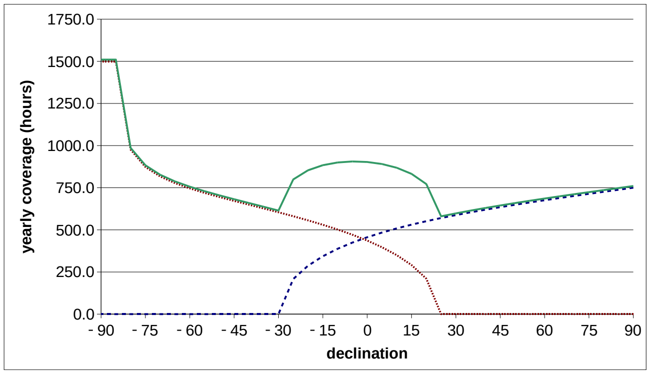

Figure 4. As Fig. 3, showing temporal coverage from a northern (30deg N - dashed blue line) and southern(35deg S - dotted brown line) site, both with 30deg altitude limits. If night time does not overlap among the sites, coverage near the celestial equator will be the sum from both sites (solid green line), and a relatively uniform coverage is achieved over the entire sky, of at least 600 hr/yr at any declination.

3. Sky Coverage

The sky above 30deg altitude has a spatial angle of $\omega_{>30} = 1\pi$ rad^2. Thus, anytime a quarter of the entire sky (4π rad^2) will be observed. The amount of time that a star can be observed during the course of a year depends primarily on its declination and on the observatorys geographical latitude (Fig. 3). For an instrument located at mid-northern latitudes (25-40 deg N), coverage at high northern declinations depends critically on the altitude limit; stars at the stellar equator are visible about a third of the yearly night-time, and coverage declines rapidly towards southern declinations.

Coverage of southern declinations would be achieved from a similar observatory located at 30-40 deg S, that ideally should be located at a far-away *longitude*. This would avoid any overlap of observations with the northern instrument, and coverage for stars near the celestial equator would then be doubled (Fig. 4).

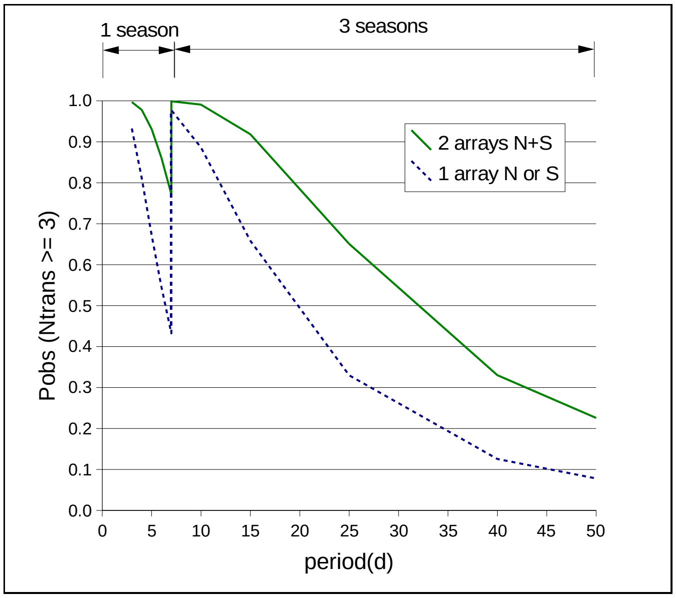

Figure 5. Probability that transiting planets will be detected by observing at least 3 transits. The upper (solid) line shows this probability for a configuration of two arrays, based on 650 hours of coverage per year (compare to Fig. 4). The lower line is for a single array, based on 400 hours per year. The left side, for periods up to 7 days, is based on observations from a single season, whereas for periods of 7-50 days, observations spanning 3 years were assumed.

4. Expected planet detections

Within the bright stars ($V < 12$), about half are Main Sequence stars. From a *single northern location*, about 65% of the entire sky (with a declination limit of -17.5 deg) would be observable with efficient coverage, of better then

400hrs/yr (Fig. 3). With a limiting magnitude of $V \approx 10$, given by achievable photometric precision, there would be about 150 000 stars to magnitudes that could be surveyed with sufficient precision for the detection of giant planet transits (photometry of better then 0.7%). Assuming that 1% of all main-sequence stars have hot giant planets, and that their probability for transits is 10%, about 70 such planets should exist. When adding a similar array in the southern hemisphere, a true all-sky survey of about 250 000 stars is obtained, and there should be *about 120 detectable transiting planets.*

The probability that these systems are going to be detected is given in Fig. 5, in dependence on orbital period. This detection probability is based on the probability, that observations of a given length and duty-cycle 'catch' at least three transits from an arbitrary transiting system of period P. The calculation of this probability is shown in the Appendix.

Observations lasting only one season give already better then 90% detection probabilities on very short periodic transiting planets (P < 3 days for one array or P < 5 days for two arrays), and all of them should be detected in observations spanning 3 years. A 3 year run would also achieve 90% detection probability on transiting systems with P < 10 days for one array or P < 15 days for the two-array system. With the two-array system, a very *complete sample of all transiting Hot Giant planets around bright stars* could therefore be achieved.

For the two-array system, longer-periodic giant planets would also be detectable with considerable probabilities - in 3 years about a third of all transiting planets with 40 day periods should be found. Of course, this number can be improved with longer observing time-spans - about 10 years would be needed to detect 40 day periodic planets with 90% probability. Estimations on the abundances of longer-periodic planets are very uncertain - assuming a 1% abundance, and with a transit probability of 3% for a P=30 day planet, *tens of planets with few-week long orbits may be found.*

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Appendix A: Probability to observe a minimum number of transi

The following calculation gives an answer to the question: What is the probability that at least N_{rmtr} transits of a transiting system are being observed, in observations spanning a time $T_{\rm obs}$, during which an temporal coverage of a fraction $f_{\rm cov}$ is achieved.

For a transiting planet with period P, the probability $p_{\rm tr}$ to observe a transit with observations lasting for one period ($T_{\rm obs} = P$) is given by

$$p_{tr} = \frac{(\text{time observed within } P)}{P} = f_{\rm cov}$$

The probability to miss the transit is $p_{\rm notr} = 1 - f_{\rm cov}$. For multiple transits, the probability to observe exactly k transits within a time $T_{\rm obs} = n \cdot P$ is then given by:

$$\begin{aligned} p_{k \text{ transits in } n\cdot P \text{ time}} &= \binom{n}{k} p_{\rm tr}^{k} p_{\rm notr}^{n-k} \\ &= \binom{n}{k} f_{\rm cov}^{k} (1 - f_{\rm cov})^{n-k} \end{aligned}$$

where $\binom{n}{k}$ is the number of combinations of k in n without repetition. The probability to observe *at least* $N_{\rm min}$ transits during $n \cdot P$ time is then given by the summation:

$$p_{N_{\rm tr} \geq N_{\rm min}} = \sum_{k=N_{\rm min}}^{n} \binom{n}{k} f_{\rm cov}^{k} (1 - f_{\rm cov})^{n-k},$$

representing the Binomial function. It should be noted that probabilities to detect some number of transits are independent from the concentration of observations at certain times (such as within a yearly season) as shown in the following example:

One instrument observes for 3 years a transiting system with a 20 day period. Each year, this system will be observed for 400 hours = 16.7 days, which are concentrated into seasons lasting 120 days.

The probability to observe at least 3 transits can then be calculated in two ways:

- We consider the observing time span to consist only of the 3 seasons, and therefore lasting 360 days during which a coverage of $f_{\rm cov} = (3 \cdot 16.7d)/360d = 0.138$ is achieved. The number of periods within the observing time span is $n = T_{\rm obs}/P = 18$, and above equation gives $p_{N{\rm tr} \geq 3} = 0.461$

- Alternatively, one may consider the observing time-span to be 3 years = 1095 days, with an average coverage of: $f_{\rm cov} = (3 \cdot 16.7d)/1095d = 0.046$. The number of periods is now $n = 1095d/20d \approx 55$, and we get $p_{N{\rm tr} \geq 3} = 0.462$