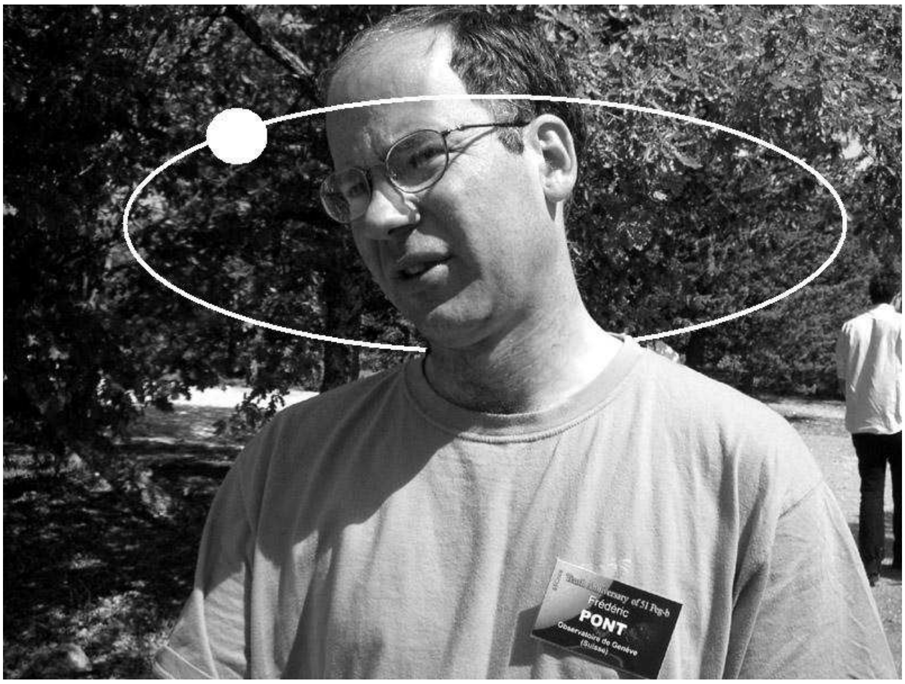
## Session 3: Ground-based transit searches



*Tenth anniversary of 51 Peg-b : Status of and prospects for hot Jupiter studies*
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# Photometric searches for transiting planets: results and challenges

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**Abstract.** Ground-based photometric surveys have led to the discovery of six transiting exoplanets, five of which were detected by the OGLE surveys. The FLAMES multi-object spectrograph on the VLT has permitted a very efficient follow-up of the OGLE transit candidates, characterising not only the 5 planets but also more than 50 systems producing similar photometric signatures – mainly eclipsing binaries. The presence of these ubiquitous "impostors" is a challenge for transit surveys. Another difficulty is the presence of red noise in the photometry, which implies a much lower sensitivity to transiting planets than usually assumed. We outline a method to estimate how the red noise will affect the expected yield of photometric transit searches.

## 1. Introduction

During the first 8 years after the discovery of 51 Pegb, only one transiting exoplanets was found. But now, as we mark the 10th anniversary, nine are known (Fig. 1). Three of them were discovered by radial velocity planet searches, and six by ground-based photometric transit surveys.

The statistics of gas giant exoplanets inferred from radial velocity surveys indicate that about one star in a thousand should be transited by a hot Jupiter. Assuming a solar-size star and a Jupiter-size planets, such transits produce periodic 1% dips in the light curve of the star lasting 2-4 hours. Hence the idea of detecting transiting gas giants by monitoring in photometry a few thousand stars with an accuracy of better than 1%. Since the confirmation of the first transiting exoplanet by Charbonneau et al. (2000), several dozen photometric transit surveys were started, from the ground with small telescopes (10-20cm) on wide fields and relatively bright stars (10-14 mag), with larger telescopes (1-

2m) on smaller fields and fainter stars (14-20 mag), and from space with the HST. On paper, these surveys could be expected to detect dozens or even hundreds of hot Jupiters (e.g. Horne 2001). Even the most modest of the surveys were expected to find one or two transiting hot Jupiters each season.

The results up to now, however, have been meager in comparison with initial expectations. Most surveys have failed to confirm any transiting exoplanet candidate. Indeed only two surveys, the TrES network (Alonso et al. 2004) and the OGLE survey (Konacki et al. 2003, Bouchy et al. 2004, Pont et al. 2004, Konacki et al. 2005) have yielded any detection at all. The OGLE survey alone can be credited with 5 of the 6 transiting planets found by ground-based transit surveys. In this review, I will concentrate on the OGLE survey, considering how the conclusions from the analysis and follow-up of the OGLE data are also relevant to other surveys generally, in particular to the issue of why the yield of most surveys has been modest.

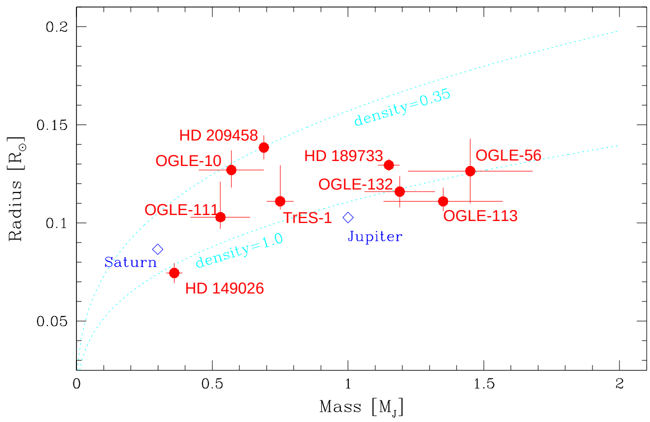


Figure 1. *Mass-radius relation for the known transiting exoplanets.*

## 2. The OGLE planetary transit candidates

Using the 1.3-m Warsaw University Telescope at Las Campanas Observatory (Chile) with an 8k×8k CCD mosaic covering a 0.34 deg$^2$ field-of-view, the OGLE-III survey (Udalski et al. 2002a-c, 2004) has realised an extensive photometric search for planetary and low-luminosity object transits. In four observing seasons, about 3 square degrees near the Galactic plane were monitored for periodic eclipse signals with depth from a few per cent down to slightly below one per cent. Altogether

177 shallow periodic transit signals were detected and announced . The radii of the transiting low-luminosity objects, estimated from the shape of the transit signal, range from 0.5 Jupiter radius to 0.5 solar radius, and their orbital periods from 0.8 to 8 days. The smallest objects could be suspected to be extrasolar giant planets, but the radius estimated from the photometric signal is not sufficient to conclude on the planetary nature of the objects. They could as well be brown dwarfs or low-mass stars, since in the low mass regime ($M < 0.1$ $M_\odot$) the radius becomes practically independent of the mass. Some configurations of grazing binary eclipses and of eclipsing binaries in multiple systems can also mimic a planetary transit signal.

Some indications on the nature of the OGLE transiting companion can be gathered from the light curve (e.g. Sirko & Paczyincki 2003) and with low-resolution spectroscopy (e.g. Dreizler et al. 2003, Gallardo et al. 2005). However, high-accuracy radial velocity follow-up is the only way to confirm the exact nature of the systems by measuring the true mass of the companions. The spectroscopy of the central star, which is a by-product of the radial velocity measurement, allows to constrain the radius of the star and hence the real size of the transiting companion. The measurement of the true mass of the companion by the radial velocity orbit, coupled with the measurement of its radius, also leads to a direct measurement of its mean density.

The difficulty of Doppler follow-up of OGLE candidates comes from the faintness of the stars (with V magnitudes in the range 15-18) located in very crowded fields. To characterize a hot Jupiter, one needs radial velocity precision better than 100 $\mathrm{m\,s^{-1}}$ and the capability to distinguish whether the system is blended by a third star. Radial velocity of such accuracy had never been measured before for such faint stars.

## 3. Follow-up of OGLE candidates with VLT/FLAMES

Sixty of the most promising OGLE candidates from the first two seasons (OGLE-TR-1 to TR-137) were observed with the FLAMES facility on the VLT (Bouchy et al. 2005, Pont et al. 2005a). FLAMES is a multi-fiber link which feeds the UVES echelle spectrograph with up to 7 targets in a field-of-view of 25 arcmin diameter, in addition to a simultaneous Thorium calibration. The fiber link allows a stable illumination at the entrance of the spectrograph, and the simultaneous Thorium calibration is used to track instrumental drift. As a result the systematics in the radial velocity measurements are reduced to less than 35 $\mathrm{m\,s^{-1}}$. A 45-minute exposure on a $V = 17$ magnitude target gives in a photon-noise limit of 30 $\mathrm{m\,s^{-1}}$ on the radial velocity for late-type, slow-rotating targets. Combining photon noise and systematics, typical precisions of 40-60 $\mathrm{m\,s^{-1}}$ are reached on each individual Doppler measurements for the OGLE planet-host targets.

Radial velocity orbits of planetary amplitudes were detected with FLAMES for five of the targets (see Table 1), one of them (OGLE-TR-56) already known from similar measurements by Konacki et al. (2003).

| | Period [days] | Transit Depth [%] | Planet mass [$R_J$] | Planet radius [$M_J$] |
|---|---|---|---|---|
| OGLE-TR-10 | 3.10 | 1.9 | 0.57 | 1.24 |
| OGLE-TR-56 | 1.21 | 1.3 | 1.45 | 1.23 |
| OGLE-TR-111 | 4.01 | 1.9 | 0.53 | 1.00 |
| OGLE-TR-113 | 1.43 | 3.0 | 1.35 | 1.08 |
| OGLE-TR-132 | 1.69 | 1.1 | 1.19 | 1.13 |

Table 1. *Data for the OGLE transiting planets. The uncertainties are ~10% on the masses and ~5% on the radii.*

The characteristics of the five OGLE transiting planets have already lead to a series of interesting conclusions on hot Jupiters, the most prominent being the existence of the so-called "very hot Jupiters" (Bouchy et al. 2004), gas giants on very short orbits (shorter than 2 days) and heavier on average (Mazeh et al. 2004) than the more common $P > 3$-days hot Jupiters.

## 4. Sorting out planetary transits from impostors

Along with the five transiting hot Jupiters, the spectroscopic follow-up programmes has led to the characterisation of more than 50 cases of "planetary transit impostors", i.e. configurations that could mimic the photometric signal of a planetary transit within the level of photometric noise of a ground-based transit survey. These systems fall into four categories. Let us review these four types of impostors in terms of implications for the follow-up of transit surveys:

**(1) Grazing eclipsing binaries**
Two large stars, when eclipsing at an inclined angle, can produce shallow transit-like dips in the light curve. These cases produce, on average, rather deep signals in the light curve and are the easiest to discriminate. Several hints are usually present in the light curve itself, such as a V-shaped transit curve, ellipsoidal modulations due to tidal effects, or a mismatch between the transit duration and the transit depth assuming a planet-sized transiting body. Nevertheless, at low signal-to-noise such systems can also be mistaken for planetary transits. They are easy to

resolve with spectroscopic observations, thanks to the presence of two sets of lines in the spectra with large velocity variations.

**(2) M-dwarf transiting companions**
A small M-dwarf transiting a larger star can produce a photometric signal closely similar to a planetary transit. If the companion is not larger than a hot Jupiter, and the orbital distance is too large for tidal and reflection effects to be detectable in the light curve, then the photometric signal is strictly identical to that of a planetary transit. In both cases, an opaque, Jupiter-size object transits the target star. These cases can only be resolved by Doppler observations, the amplitude of the reflex motion of the star revealing the mass of the transiting companion. Two nice examples of planet-size transiting stellar companions were found in our FLAMES follow-up among the OGLE candidates, OGLE-TR-122 (Pont et al. 2005b) and OGLE-TR-123 (Pont et al. 2005c). In particular, OGLE-TR-122, with a period of 7.2 days and a companion size smaller than that of HD209458b, produces a light curve that is strictly identical to that of a planetary transit down to a very high level of detail.

**(3) Multiple systems**
An eclipsing binary can produce shallow transit-like signals if the eclipse is diluted by the light of a third star. There are many possible configurations for such systems, and as a result they can be very difficult to disentangle, even with Doppler information. In most cases, multiple systems are readily discriminated with high-resolution spectroscopy from the presence of several systems of lines in the spectra (see Figure 2, lower left panel). However, in some cases, the parameters can conspire not only to mimic the light curve of a planetary transit, but also to induce planet-like variations of the inferred radial velocity, produced by the blending of several sets of lines in the spectra. OGLE-TR-33 (Torres et al. 2004) is such a case. Another similar case was found in the TrES survey (Mandushev et al. 2005).

**(4) False positives**
Stellar variability and systematic trends in the photometry can produce fluctuations in the light curve interpreted as a possible transit signal, especially as one tries to detect shallower signals near the detection threshold. OGLE-TR-58, for instance, was found to exhibit an intrinsic level of variability that could explain the transit-like signal detected by OGLE without invoking a transiting companion (Bouchy et al. 2005). Further photometric observations at the epoch of the detected signal are needed in these cases to distinguish bona fide transits from false positives.

The FLAMES/VLT Doppler follow-up, by illustrating the ubiquity of the "impostors" and the ability of certain configurations to mimic sev-

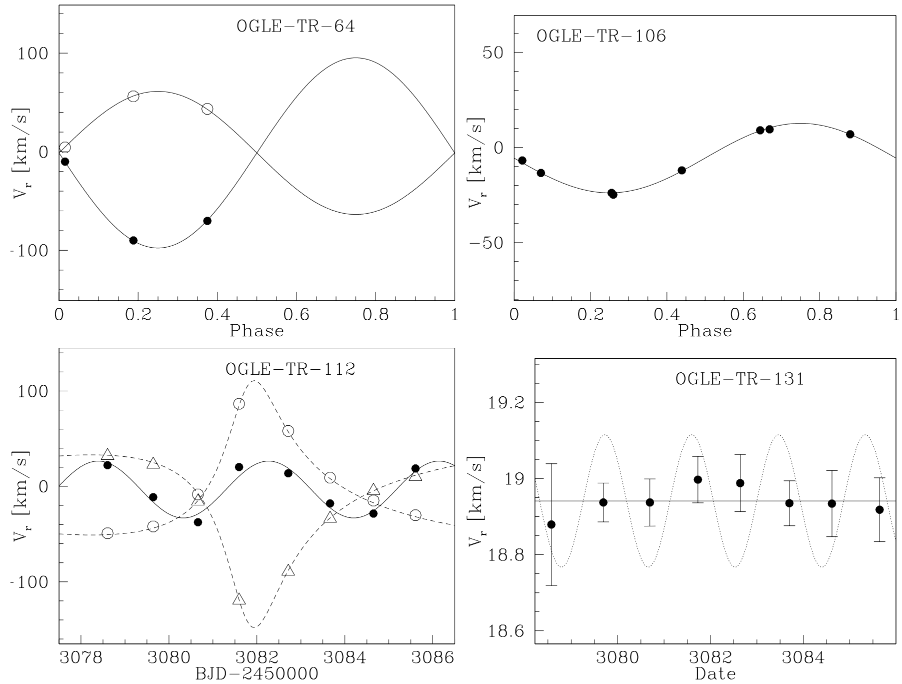


Figure 2. *Example of radial velocity data for the four types of planetary transit "impostors": grazing binary (top left), low-mass companion (top right), multiple system (bottom left) and false positive (bottom right, the dotted line indicates a Jupiter-mass orbit). Figure from Pont et al. (2005a).*

eral aspects of the signal of bona fide transiting planets, showed that the detection of a planetary radial velocity orbit was mandatory to establish the planetary nature of a transit candidate. Moreover, the spectroscopic data must be of high-enough resolution and signal-to-noise to be able to study the evolution of the line shape (bisector analysis) over the course of the transit phase, to eliminate scenarios of multiple systems. The present practical limit for such observations is around $V = 17$ mag with FLAMES on the VLT. This has an important implication for transit surveys: deep transit surveys using large telescopes and the HST will produce candidates that are to faint to be confirmed spectroscopically with present-day telescopes ($V > 17$), and therefore will not lead to any confirmed transiting planet detection! This is in contrast to their very good detection rates "on paper" and represents a large drawback for such programmes.

## 5. Detection threshold and expected yield of transit surveys

Three transiting exoplanets have been found by radial velocity searches, out of a few thousand target stars. This is roughly in line with prior expectations: the rate of occurrence of hot Jupiter transits is about one in a thousand. On the other hand, photometric transit surveys have found 1 transiting planet around a relatively bright star (TrES-1), and 5 around fainter stars (OGLE). This is much lower than initial expectations, with hundreds of thousands of field stars having been sampled by several dozen surveys (STARE/WASP/VULCAN/EXPLORE/RAPTOR/PSST/SLEUTH/PISCES/OGLEIII/STEPS/BEST/UNSW etc...).

The case of the most successful transit search so far, the OGLE survey, gives some precious hint as to the basic reason behind this meager results. Table 1 gives the period and transit depth of the five planets detected by the OGLE survey. A remarkable conclusion stems from this table: the detected planets all have exceptionally favourable parameters for transit detection. A typical hot Jupiter hosted by a typical field star will have a period above 3 days and a transit depth of the order of 1%. By contrast, each of the detected planets has a combination of at least two of these three factors favouring detection:

- A very short period ($P < 2$ days) – thus providing many more transit signals in a given survey duration;
- A period resonant with the 1-day peak of the observation window function, like OGLE-TR-111 at almost exactly 4 days or OGLE-TR-132 near 5/3 days – which allows the transit signal to be oversampled;
- A host star much smaller than the average in the field – which causes a large transit depth.

The implication of this is that no "normal" transiting hot Jupiter was detected by the OGLE survey. Thus the OGLE survey – again, the most successful ground-based survey to date – had to rely on the very large number of targets observed to pick up a few exceptional transiting hot Jupiters. Its detection threshold was actually too high to detect normal hot Jupiters! TrES-1 also produces an exceptionally deep transit, and it is likely that our considerations apply to other ground-based transit survey as well.

In theory, estimating the detection threshold and expected yield of a given transit survey is rather straightforward. The transit detection procedure is akin to finding a periodic square-shaped decrease in the flux from the target. The signal-to-noise ratio of the detection is the significance of the difference between the signal during the putative transit and the signal outside the transit. If most data points are outside the transit, the uncertainty on the continuum level is negligible, and the detection signal-to-noise is simply the transit depth divided by its uncertainty:

$$SNR = \frac{depth}{\sigma/\sqrt{n}} \tag{1}$$

where $\sigma$ is the photometric uncertainty on individual points and $n$ is the number of data points during the transit.

To compute the expected yield of a given survey, one can simulate the population of target stars, assume a frequency of planet, then compute the expected number of detections given two conditions: (1) that at least 2 or 3 transits are observed (to establish the periodicity of the signal); (2) that the detection SNR is above some threshold, $\mathrm{SNR}_{min}$. The $\mathrm{SNR}_{min}$ threshold is usually assumed between 7 and 10 according to the number of false detections deemed acceptable.

Such simulations have been done for many existing and planned surveys. If the survey duration is sufficient for at least 3 transits to be observed for most hot Jupiters, then these simulations invariably predict good SNR detectability for normal hot Jupiters, at least for the brightest targets, hence resulting in significant predicted yields.

However, there is an important hidden assumption in Eq. 1 above: it is based on the assumption of white, independent noise. If the noise is not independent and has some covariance structure, then the equivalent formula is

$$SNR = \frac{depth}{\sqrt{\sigma^2/n + 1/n^2 \sum_{i \neq j} cov[i;j]}} \tag{2}$$

where the $cov[i;j]$ are the elements of the covariance matrix. Therefore, the estimated yields based on the assumption of white noise are correct only if $\sigma^2/n >> 1/n^2 \sum_{i \neq j} cov[i;j]$. However, in real ground-based data in the relevant regime for hot Jupiters, the opposite is true! Plugging representative numbers shows that generally $1/n^2 \sum_{i \neq j} cov[i;j] > \sigma^2/n$. For instance in the OGLE survey, $\sigma = 3-10$ mmag, $n = 20-50$, so that $\sigma^2/n \simeq 0.2-5$ mmag$^2$, whereas the covariance of the residuals sampled on constant lightcurves gives a covariance term $1/n^2 \sum_{i \neq j} cov[i;j] \simeq 9-11$ mmag$^2$.

In the jargon of signal analysis, the noise in photometric data has a *white* component (mainly photon noise) and a *red* component. The noise on ground-based millimagnitude photometry is *"pink"*. The red component comes from the systematics caused by the variations in atmospheric conditions, telescope tracking and detector characteristics. Figure 3 (left panel) displays an example of these three kinds of noise, white, red and pink. Ground-based photometric data at the millimagnitude level look like the bottom curve, with some white noise superimposed on some systematics trends on longer timescale.

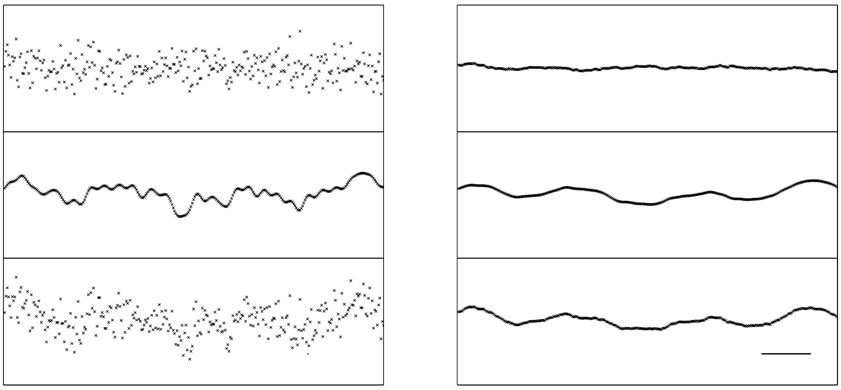

Figure 3. **Left:** *A photometric time series with white, red or pink noise. The global dispersion is the same for the three curves.* **Right:** *the same series averaged over a transit duration (the transit duration is shown by the bar at the bottom right).*

It is clear that the systematic trends will limit the detectability of transit signals, especially the trends operating on hour timescale – the timescale of transits. What Eq. 2 expresses is that the detection threshold of transit surveys will depend on the average of the photon noise over a transit-length duration and the average of the covariance over this duration. The right panel of Fig. 3 shows the average of the curves in the left panel over a transit duration. It shows graphically what was found algebraically from Eq. 2: for transit detections, the effect of the red components dominates over that of the white component (because the white component averages out to very small values over the duration of transits, whereas the red component does not).

## 6. Revised yield estimates for ground-based surveys

The implications of the presence of red noise ("systematics") in the photometric data on the expected yields of transit surveys are fundamental. In fact, in many cases a good approximation is to ignore the white noise entirely, and to base the detection threshold on the red noise only.

This profoundly modifies the predictions for the sensitivity of ground-based transit surveys. Not only the resulting detection threshold is higher than with the white-noise assumption, it also has a different dependence on period and magnitude. For instance, the presence of red noise favours the detection of very short-period transiting planets ("very hot Jupiters") compared to longer periods.

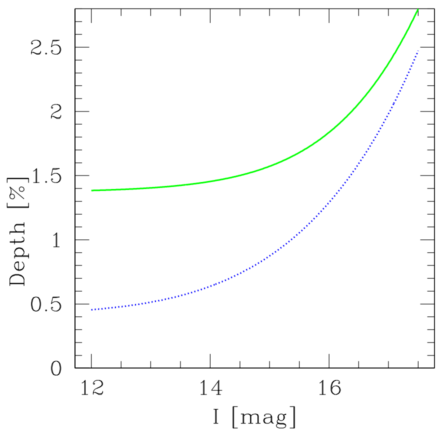


Figure 4. *Detection threshold in transit depth vs. magnitude, for a 3.5-day period planet in the OGLE survey. Dotted line: with the assumption of white noise, solid line: taking the red component of the noise into account.*

Figure 4 gives, for the OGLE survey, the detection threshold of transit signals as a function of magnitude, assuming white noise only (dotted curve) and assuming pink noise (solid curve), for planets at $P = 3.5$ days. The difference between the two thresholds has a large effect on the expected rate of detection of hot Jupiter transits, since those are expected to produce typical transit near 1%, exactly in the region where the prediction of white noise and pink noise diverge.

White-noise calculations predict the detectability of transit signals around the brightest stars in the survey down to very small transit depths – thanks to the averaging of the independent noise. But taking into account the red noise leads to a much higher effective threshold, and to a floor value that is higher than the typical depth of hot Jupiter transits. The bottom line is that the presence of systematics in the photometry drastically reduces the detectability of planetary transits in ground-based surveys.

We have devised a simplified model of the covariance matrix to be able to estimate the yields of transit surveys in the presence of red noise (Pont & Zucker 2006, in prep.). This model uses a simplified description of the matrix based on a single parameter, called $\sigma_r$, describing the amplitude of the red noise in the relevant regime. This model was applied to some ongoing transit surveys[1] estimating $\sigma_r$ from published data, to predict the yield of these surveys per season in terms of transiting hot Jupiter detections (we did not include "very hot Jupiters"). Table 2 shows the results compared to the predictions assuming white noise only.

| | STARE | OGLE | HAT-5 | Vulcan | UNSW |
|---|---|---|---|---|---|
| HJ/season (pink noise) | 0.9 | 1.1 | 0.2 | 0.6 | 0.01 |
| HJ/season (white noise) | 7 | 14 | 18 | 16 | 2 |

Table 2. *Expected number of detections of transiting hot Jupiters per season for some ground-based surveys, assuming pink (correlated) noise, or white (independent) noise.*

Generally, taking the red component of the noise into account results in a drastic downward revision of the expected yields, more in line with the actual rates of detection.

Our revised estimates tend to indicate that major surveys, such as TrES or OGLE, have the potential to detect a number of transiting hot Jupiters of the order of unity per season, while more modest surveys or surveys affected by a higher level of covariance are reduced to rather negligible values. A possible implication of our studies is that, contrary to the indications of initial estimates based on white noise, transit surveys of limited scope and duration are unlikely to make a contribution to the field. Only long-term, ambitious searches with great care invested in the correction of the systematics will detect transiting hot Jupiters in significant numbers – numbers that are going to be roughly one order of magnitude lower than white-noise estimates.

Some authors have predicted that with large telescope, transiting planets of much smaller size than hot Jupiters ("hot Neptunes") will become detectable from the ground (Gillon et al. 2005, Hartman et al. 2005). However, the reasoning used to reach these conclusions are based on the same white-noise assumptions as those leading to the predictions of very high rates of hot Jupiter detections by the on-going surveys. When the red component of the noise is taken into account, we find that hot Neptunes are not likely to be detected in significant numbers from the ground, and that space missions like Corot and Kepler will be needed to avoid the type of hour-timescale red noise that the Earth's atmosphere is causing in light curves.

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[1]STARE (Brown & Charbonneau 2000), OGLE (Udalski et al. 2002a), HAT (Bakos et al. 2004), Vulcan (Borucki et al. 2001), UNSW (Hidas et al. 2005)

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# Sys-Rem – A new algorithm to remove systematic effects in large photometric datasets: application to OGLE and SuperWASP lightcurves

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**Abstract.** We constructed a new algorithm, Sys-Rem, to remove systematic effects in a large set of lightcurves obtained by a photometric survey. The algorithm can remove any systematic effect, like the one associated with atmospheric extinction, detector efficiency, or PSF changes over the detector. Sys-Rem works without any prior knowledge of the effect, as long as it linearly appears in many stars of the sample. The algorithm, which was originally developed to remove atmospheric extinction effects, is based on a lower rank approximation of matrices, and reduces to the Principal Components Analysis (PCA) algorithm for equal uncertainties. Sys-Rem is therefore specially useful in cases where the uncertainties of the measurements are unequal. Application of Sys-Rem to the OGLE and the SuperWASP dataset demonstrates the power of the algorithm.

## 1. Introduction

We report here on the performance of Sys-Rem, an algorithm to remove some of the systematic effects in a large set of lightcurves. The algorithm works without any *a priori* knowledge of the different observational features that might affect the measurements (Tamuz, Mazeh, & Zucker 2005). It finds the systematics and their manifestation in the individual stars, as long as these effects appear in many lightcurves.

We started the development of our algorithm in an attempt to correct for the atmospheric extinction, with an approach similar to that of Kruszewski & Semeniuk (2003). We derived the best-fitting airmasses of the different images and the extinction coefficients of the different stars, without having any prior information on the stellar colours. However, the result is a general algorithm that deals with linear systematic effects. In some restricted cases, when one can ignore the different uncertainties of the data points, this algorithm reduces to the well-known Principal Component Analysis (Murtagh & Heck 1987, Ch. 2). However, when the uncertainties of the measurements vary substantially, as is the case in many photometric surveys, PCA performs poorly relative to Sys-Rem.

Section 2 presents the principles of Sys-Rem and Section 3 discusses the application of the algorithm to the OGLE and SuperWASP surveys. We conclude with some remarks.

## 2. The principle of Sys-Rem

Colour-dependent atmospheric extinction is an obvious observational effect that contaminates ground-based photometric measurements. This effect depends on stellar colours, which are not always known. To correct for the atmospheric extinction one can find the effective colour of each star, which characterizes its variation as a function of the airmass of the measurements.

Specifically, consider a set of $N$ lightcurves, each of which is derived from $M$ images. Define the residual of each observation, $r_{ij}$, to be the average-subtracted stellar magnitude of the $i$-th star derived from the $j$-th image, taken at the $a_j$-th airmass. We can then define the effective extinction coefficient $c_i$ of star $i$ to be the slope of the best linear fit for the residuals of this star as a function of the corresponding airmasses, aiming to remove the product $c_i a_j$ from each $r_{ij}$. In fact, we search for the best $c_i$ that minimizes the expression

$$S_i^2 = \sum_j \frac{\left(r_{ij} - c_i a_j\right)^2}{\sigma_{ij}^2} \quad , \tag{1}$$

where $\sigma_{ij}$ is the uncertainty of $r_{ij}$. Note that the derivation of each $c_i$ is independent of all the other $c_i$'s, but does depend on all the $\{a_j\}$.

The problem can now be turned around. Since atmospheric extinction might depend not only on the airmass but also on weather conditions, we can ask ourselves what is the most suitable "airmass" of each image, given the known effective colour of each star. Thus, we can look for the $a_j$ that minimizes

$$S_j^2 = \sum_i \frac{\left(r_{ij} - c_i a_j\right)^2}{\sigma_{ij}^2} \quad , \qquad (2)$$

given the previously calculated set of $\{c_i\}$. We can now recalculate new best-fitting coefficients, $c_i$, for every star, based on the new $\{a_j\}$, and continue iteratively. We thus have an iterative process which in essence searches for the two sets – $\{\bar{c}_i\}$ and $\{\bar{a}_j\}$, that best account for the atmospheric extinction.

Many simulations have shown that this iterative process converged to the same $\{\bar{a}_j\}$ and $\{\bar{c}_i\}$, no matter what initial values were used. Therefore, we suggest that the proposed algorithm can find the most suitable effective airmass of each image and the extinction coefficient of each star.

What we got is, in fact, an algorithm to find the best two sets of $\{c_i \; ; i = 1, N\}$ and $\{a_j \; ; j = 1, M\}$ that minimize the *global* expression

$$S^2 = \sum_{ij} \frac{\left(r_{ij} - c_i a_j\right)^2}{\sigma_{ij}^2} \quad . \qquad (3)$$

Therefore, although the alternating 'criss-cross' iteration process (Gabriel & Zamir 1979) started with the actual airmasses of the different images, the values of the final set of parameters $\{\bar{a}_j\}$ and $\{\bar{c}_i\}$ are not necessarily related to the true airmass and extinction coefficient. They are merely the variables by which the global sum of residuals, $S^2$, varies linearly most significantly. They could represent any strong systematic effect that might be associated, for example, with time, temperature or position on the CCD. This algorithm finds the systematic effect as long as the global minimum of $S^2$ is achieved.

Now, suppose the data includes a few different systematic effects, with different $\{c_i\}$ and $\{a_j\}$. Sys-Rem can be applied repeatedly, until it finds no *significant* linear effects in the residuals.

## 3. Application to OGLE and SuperWASP

### 3.1 OGLE

We applied Sys-Rem to the photometric data collected by the OGLE survey in three Carina fields: CAR100, CAR104 and CAR105 (Udalski *et al.*2002). This dataset includes 1200 measurements of about one million stars. In each field, we applied Sys-Rem separately to each of the 8 CCD chips.

To present the effectiveness of Sys-Rem's application to the OGLE data we present in Figs. 1 and 2 some results from the data of chip 8 in field CAR105. We selected 200 bright stars from the chip, calculated AoV periodograms (Schwarzenberg-Czerny 1989) for each, and then averaged the periodograms to produce the upper panel of Fig. 1. The averaged periodogram shows clearly a periodicity of 1 day and its harmonics, and some low-frequency power.

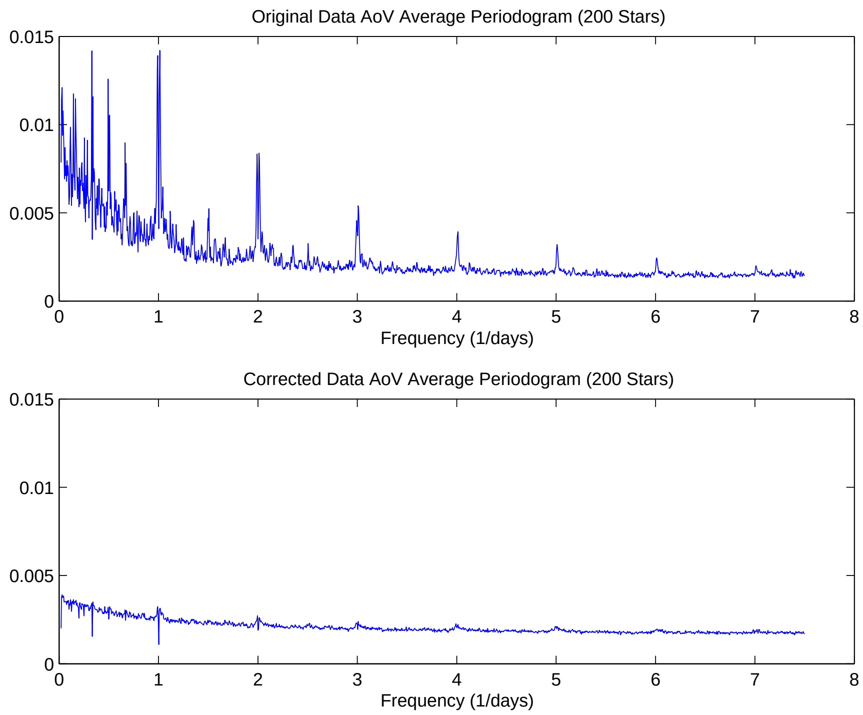


Figure 1. *Averaged AoV periodograms of 200 OGLE stars before (upper panel) and after (bottom panel) applying Sys-Rem*

We generated similar averaged periodogram after we applied Sys-Rem, to produce the bottom panel. As is evident, Sys-Rem removes not only periodic variability with frequencies with integer number of cycles per day, but also most of the low-frequency variability. Note, however, that some troughs appear in one day harmonics, which indicate that Sys-Rem may have removed some true signal along with the systematics, impairing detection of transits in these frequencies. Kruszewski & Semeniuk (2003) got similar results when they searched for systematics with periodicity of one day and its harmonics.

Fig. 2 shows, for the same chip, the *fractional* change in the RMS scatter obtained by Sys-Rem (in percentage of the initial scatter), as a function of the magnitude and the original scatter. The top panel of the figure shows that Sys-Rem is most effective in reducing the scatter of the brighter stars, where the systematic noise is more dominant. For those stars the improvement can get up to 30% of the original scatter. Note that a small but substantial improvement can be seen for all stars. The increase of Sys-Rem improvement for the faint stars is probably due to removal of systematics associated with background subtraction.

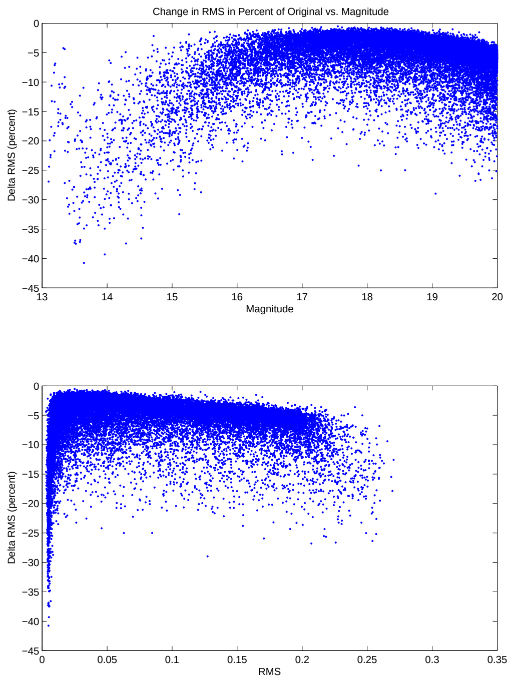


Figure 2. *The reduction in the RMS scatter of the OGLE lightcurves as a function of the magnitude (upper panel) and the initial scatter*

### 3.2 SuperWASP

The SuperWASP camera array on La Palma operated from 2004 May to September with a mosaic of 5 wide-field imaging systems, each covering an area of sky nearly 8 degrees square. The photometry is corrected for primary and secondary extinction, and a zero-point calibration is performed. The magnitudes of non-variable stars are generally found to exhibit RMS scatter of order 4 or 5 millimagnitudes in the brightest unsaturated stars on timescales of many nights.

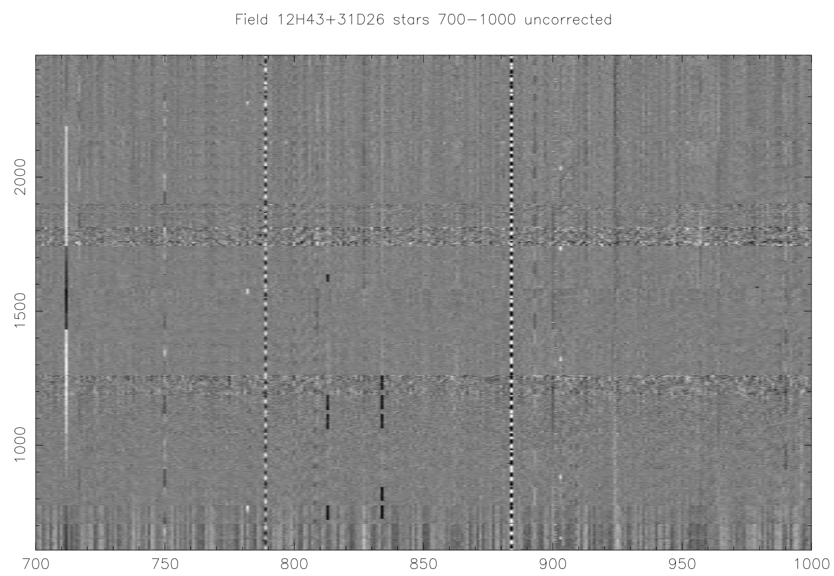


Figure 3. *The WASP light-curves of a set 300 stars in a single camera field, from 2004 May to September. Columns represent light-curves of individual stars, while each row represents a single CCD image. The greyscale runs from white at 0.1 mag fainter than average, to black at 0.1 mag brighter than the average magnitude of each star. The vertical striated patterns show correlated systematic errors.*

Some systematic errors, however, remain, as shown in Fig. 3. We used Sys-Rem to remove the remaining low-level systematic errors before carrying out a preliminary transit search. As other groups have found, the strongest Sys-Rem component tracked the nightly airmass variation, suggesting that it mainly arises from secondary extinction in stars with poorly-determined colours. The second component is a linear trend through each night, possibly arising from temperature-dependent focus degradation. The third component is a quasi-sinusoidal variation of unknown origin within each night, while the fourth described an unexplained but strong differential trend appearing in just one night of observation.

The resulting improvements in light-curve scatter are illustrated in Fig. 4. One can see that the "after" plot looks much cleaner than the original one.

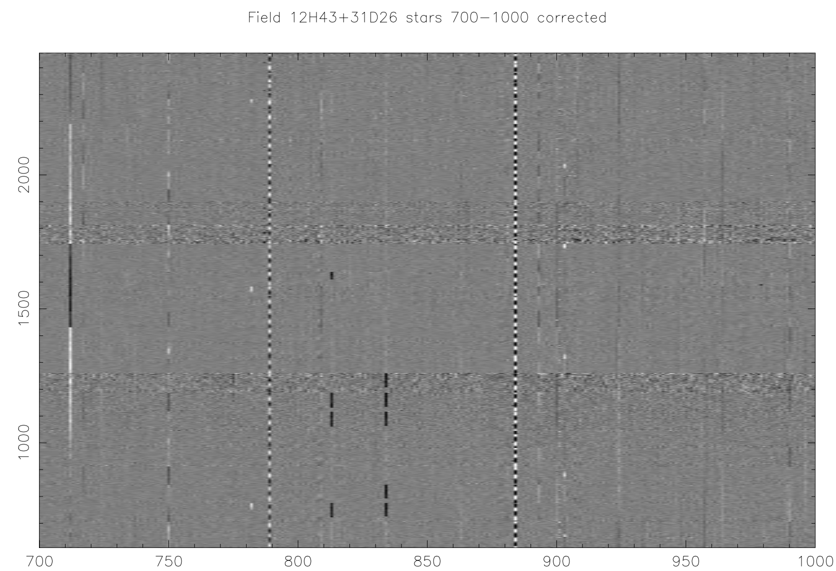


Figure 4. *As for Fig. 3, but after the removal of four correlated systematic error components using the Sys-Rem algorithm.*

## 4. Conclusion

We have presented the first application of Sys-Rem to real datasets from the photometric surveys of OGLE and SuperWASP. We demonstrated that the algorithm can eliminate a significant part of the systematic noise hidden in the light curves of those surveys. The mainly affected stars are the brighter ones, where the photon noise is less significant and the systematics grow in importance.

The growing number of photometric projects that search for transiting planets might turn Sys-Rem most useful. We offer the community an 'overnight cleaning service' that applies our Sys-Rem code to their photometric data and return the data clean of systematics, ready for search for minute periodic variability.

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*Edited by L. Arnold, F. Bouchy, and C. Moutou*

# Three interesting transits: OGLE-TR-109, OGLE-TR-111, and OGLE-TR-113

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**Abstract.** We started a program to monitor photometrically the OGLE transiting extrasolar planet candidates. VLT images in the $V$-band are used to make light curves of transits of confirmed OGLE planets. The data for some of the targets are complemented with NTT $K$-band images. Using difference image photometry, we are able to achieve milli-mag errors in the individual data points. Here we discuss three examples: OGLE-TR-109, OGLE-TR-111 and OGLE-TR-113. The main transits of these hot Jupiters are well defined. The analysis of the light curves allows to measure improved transit amplitudes and ephemerides.

## 1. Introduction

We started a program to monitor photometrically the confirmed OGLE transiting planets. The main aim of this program is to improve upon the planetary parameters: the planetary radii are measured to about

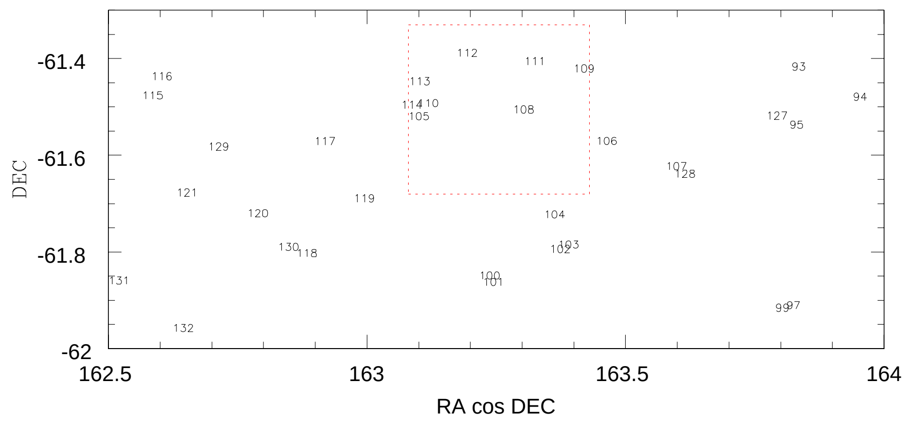


Figure 1. *Location of the OGLE transit candidates.*

10% by OGLE. With millimagnitude photometry during transits we expect to halve this uncertainty as done by Moutou et al. (2005).

Additional but not less interesting goals are to search for long time trends in the mean transit times in order to constrain the presence of other planets in these systems (Holman & Murray 2005, Agol et al. 2005), and to search for planetary satellites (Sartoretti & Schneider 2000), and star spots (Silva 2003).

In this paper we report the progress made, presenting some of the results obtained for OGLE-TR-109, TR-111 and TR-113.

## 2. Data and analysis

This program was allocated 4 nights with VIMOS at the Unit Telescope 4 (UT4) of the European Southern Observatory Very Large Telescope (ESO VLT) at Paranal Observatory during the nights of April 9 to 12, 2005. All four nights were clear throughout, with sub-arcsecond seeing during most of the time.

VIMOS is an imager and multi-object spectrograph. Its field of view consists of four 7×8 armin fields covered by the four CCDs arranged in a square pattern with a separation gap of 2 arcmin. In preparation for the run a selection of fields was made based mostly on maximizing the number of interesting transiting candidates to be monitored, and we made maps of the positions of the transit candidates (Figure 1), and computed the expected transit ephemerides during the 4 nights

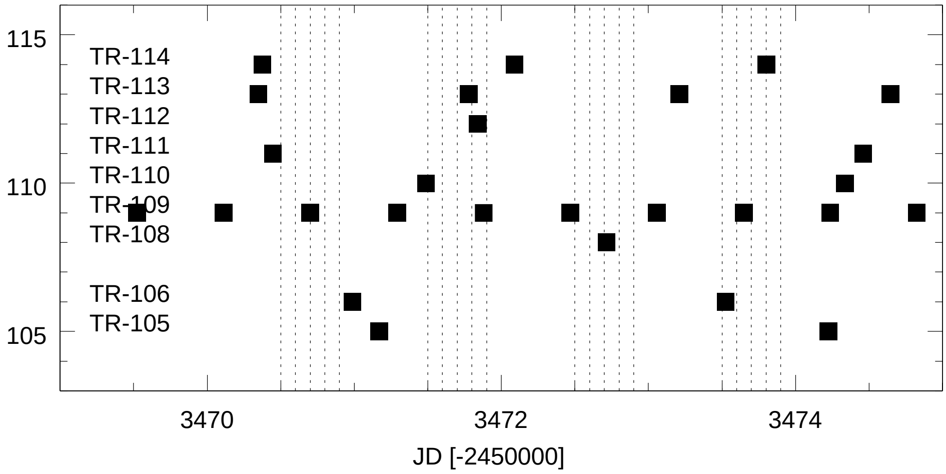


Figure 2. *Computed transit times of the OGLE candidates during the 4 nights of the VIMOS observing run in April 2005.*

of observations for the targets within the field of view (Figure 2). Because of the large effective field of view of 14×16 arcmin, that allows to monitor several transit candidates simultaneously, VIMOS is one of the most efficient instruments in the world for our project.

We monitored 4 fields in total, but here we discuss the best field, that contains the stars OGLE-TR-109, TR-111 and TR-113. The VIMOS pixel scale of 0.205 arcsec/pixel in combination with the good seeing also allow us to discard possible contaminants. Figure 3 shows the high quality of the images of the target stars, confirming that none of them is significantly blended by a nearby star.

The filter used was the $V_{bess}$, with $\lambda_0 = 5460\,\text{Å}$, $FWHM = 890\,\text{Å}$. We choose the $V$-band because the sampling rate did not allow us to have two filters, and because the OGLE light curves are made with the $I$-band filter. One of the main objectives of this work was to discard blends and binary stars present among the transit candidates. For this, light curves measured in the $V$-band can be compared with the OGLE light curves, and non-planetary eclipses can be discarded when very different amplitudes are measured, for example. We note that the $V$-band shows better the effects of limb darkening during the transit, and is adequate for the modeling of the transit parameters in combination with the OGLE $I$-band photometry.

The bulk of the data acquired with VIMOS amounts to 82 Gb. In order to reduce the analysis time, here we decided to process images around the transit candidates rather than the whole images. The

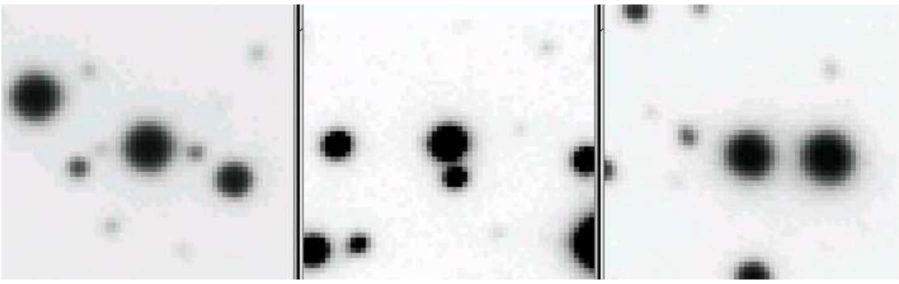

Figure 3. *Reduced VIMOS images centered on OGLE-TR-109 ($V$ = 15.8), OGLE-TR-111 ($V$ = 16.9), OGLE-TR-113 ($V$ = 16.5), Each image covers* $10 \times 10$ *arcsec, and represents the best FWHM obtained* ($0.5''$)*. The faintest stars detected in our images have* $V \sim 24$.

processing of the whole images is nevertheless a gold mine to identify additional hot Jupiters around stars with $16 < V < 20$, and even hot Neptunes around stars with $16 < V < 18$, complementing the OGLE search. We estimate that the whole dataset contains $> 10000$ stars for which light curves can be obtained with individual errors of $< 0.01$ mag.

The difference image photometry was performed using as reference a master image made of the 7 best seeing images taken at low airmass following Alard (2000), Alard & Lupton (1998), Udalski et al. (2002). Extensive tests with the difference image photometry were performed, varying various photometric parameters and choosing different sets of reference stars.

## 3. The transits of OGLE-TR-109, TR-111, and TR-113

These three stars had scheduled transits during our observations.

Radial velocity measurements of OGLE-TR-109-b were discussed by Pont et al. (2005), and our follow-up photometry is analyzed in detail by Fernandez et al. (2005). Because of the short period ($P = 0.589$ *days*), we could observe during one full transit, two partial transits, and also during the expected time for one secondary transit. When a secondary eclipse is detected, the candidates are binary stars and can be ruled out as planetary transits. The secondary transit was not detected to $< 0.001$ *mag*. Figure 4 shows the full transit monitored during the 3rd night of the run.

OGLE-TR-111-b was discovered by Pont et al. (2004) based on accurate radial velocities, and our photometry is analyzed in detail by Minniti et al. (2006, in preparation). We monitored one full transit in

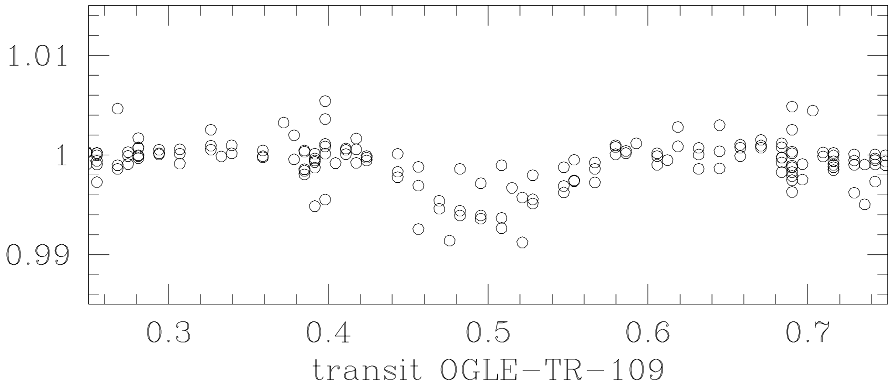


Figure 4. *Light curve for one transit of OGLE-TR-109.*

night 1, shown in Figure 5, and also during the expected time for one secondary transit, which was not observed.

OGLE-TR-113-b was confirmed as a planet by Bouchy et al. (2004) based on accurate radial velocities, OGLE-TR-113, for which photometry with $rms = 0.001$ mag was obtained, is analyzed in detail by Fernandez et al. (2006, in preparation). There was a transit scheduled for night 2, and a partial secondary transit at the beginning of night 3, which was not present. Additional data in the $K$-band was acquired with SOFI+NTT for a single transit in May 2005. The amplitude measured in the near-infrared is very useful to test the significance of the planetary transits and to discard potential impostors such as binary stars, even though measuring $A_K$ with millimagnitude precision is a challenge. Figure 6 shows the OGLE-TR-113 transits in the 3 different bands: $V$, $I$, $K$. The durations and amplitudes of the transits shown in Figure 5 are consistent with a planet.

Because we normally observe only a single transit (Figure 6 top and bottom), it is necessary to find a quantitative way to evaluate the significance of the individual transit observed. For OGLE, several transits are monitored with few points per transit, but with many points in the phased light curve (Figure 6 middle). Then, the significance of the transits is –in part– judged by the number of transits detected. In the case of the present study, we compute the signal-to-noise of the single, well sampled transit. For a given photometric precision of a single measurement of $\sigma_p$ and a transit depth $A$, this signal-to-noise transit is $S/N = N_t^{1/2} A/\sigma_p$ (Gaudi 2005). For the monitored transits we find the range of S/N to be $S/N = 30 - 60$ using typically $\sigma_p = 0.002 - 0.003$.

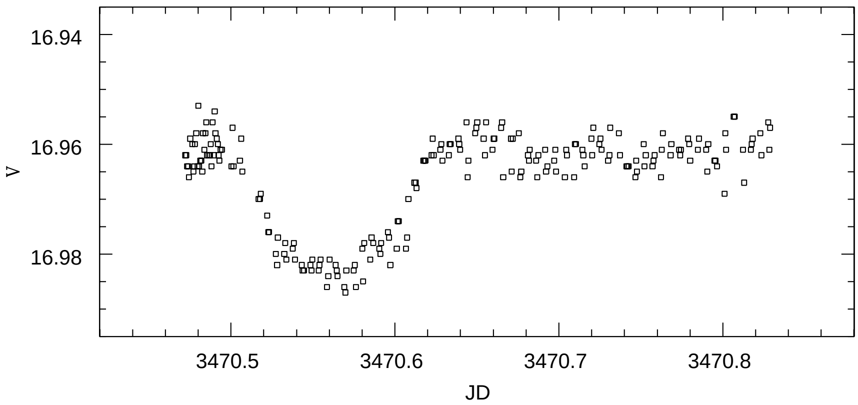


Figure 5. *Light curve for one transit of OGLE-TR-111.*

These transits are well sampled, there are usually $N_t = 30 - 50$ points in our single transits, allowing us to measure amplitudes accurate to $< 0.001$ mag. The accurate photometry also allow us to examine the possible light curve modulations due to ellipsoidal variability of some of the sources (Drake 2004, Sirko & Pacszynski 2004).

When a full transit is observed, accurate transit ephemerides can also be computed. It is important to compute mean times of transit as well as to evaluate the transit timing errors, for future studies of multiplicity in these systems (Murray & Holman 2005, Agol et al. 2005). The precision with which the mean transit time can be determined can be estimated as: $\delta_t = \sigma t_T/(2A\sqrt{N})$, where $\sigma = 0.002 - 0.003$ is the individual error of the relative photometric points, $t_T = 3\ h$ is the transit duration, $N$ is the number of measurements within transit, and $A = 0.01 - 0.03\ mag$ is the transit amplitude (Doyle & Deeg 2003). Using this approximation, we find typically $\delta_t = 60 - 180\ sec$.

In summary, the optical photometry allows us to accurately measure the transit amplitudes, the transit durations, the mean times of transit, and the presence or absence of ellipsoidal modulations, from which important parameters for extrasolar planets would be derived. In the nearby future the CoRoT and the Kepler missions from space (Bordé et al. 2003, Borucki et al. 2003) would yield hundreds of transiting hot Jupiters and Neptunes, and the present work also shows that accurate photometry from the ground would be possible for long term follow-up of these objects.

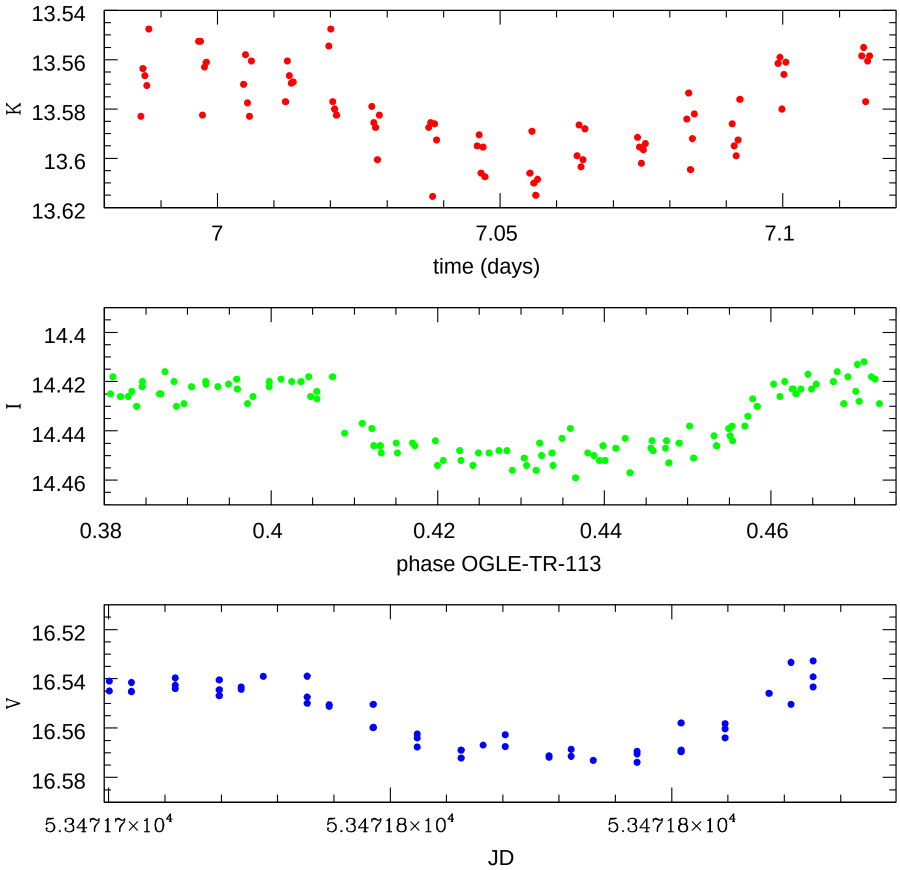


Figure 6. *Comparison of an individual transit for OGLE-TR-113 in the K-band (top), the phased OGLE I-band light curve for several transits (middle), and another individual transit it the V-band (bottom).*

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# Transiting planets and brown dwarfs in star forming regions and young open clusters.

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**Abstract.** The *Monitor* project[2] is a large scale photometric monitoring survey of a dozen star forming regions and open clusters aged between 1 and 200 Myr using wide-field optical cameras on 2 to 4 m telescopes worldwide. The primary goal of the project is to search for close-in planets and brown dwarfs (BDs) at young ages through the detection of transit events. Such detections would provide unprecedented constraints on planet formation and migration time-scales, as well as on evolutionary models of planets and brown dwarfs in an age range where such constraints are very scarce. Additional science goals include rotation period measurements and the analysis of flares and accretion-related variability.

## 1. Motivation

Though well over 100 extrasolar planets are known today, the vast majority orbit field stars with poorly determined ages. This is true of all 8 known transiting exoplanets, which are the only cases for which radii are known. The detection of a transiting exoplanet orbiting a

[2]`www.ast.cam.ac.uk/~suz/monitor/monitor.php`

star of known age would thus constitute the first firm anchoring point for evolutionary models of extrasolar planets. Over the last few years, several transit surveys (e.g. Explore OC, von Braun et al. 2004) have been targeting 'middle aged' ($\geq 1$ Gyr) open clusters, but no confirmed discoveries have been reported to date. We are targeting nearby star forming regions and open clusters in the so far uncharted 1 to 200 Myr age range. In our youngest targets ($< 10$ Myr), a detection would take added significance, as it would have implications for the disk evolution, planetesimal formation and migration timescales. We are also interested in searching for very low mass short-period eclipsing binaries, with at least one BD or very low mass star (VLMS) component. Evolutionary models in this age and mass range are notoriously uncertain – as highlighted by recent detections of ultra-low mass visual binaries in young associations (Close et al. 2005). The *Monitor* project's high precision, high cadence (in some cases multi-band) photometry of 10000's of low-mass cluster PMS stars will also allow an unprecedented study of angular momentum evolution, flares and accretion-related variability.

## 2. The Survey

About 10 target clusters were selected on the basis of youth, richness, proximity and compactness, as well as the existence of a known low-mass PMS population. We have observed or are scheduled to observe 8 of those by the end of 2005B (see the *Monitor* webpage for a list), and will apply to survey the remainder over the next few semesters. Sampling times are 3.5–15 min to ensure appropriate sampling of eclipse ingress/egress. 300–1000 frames in $i'$ or (for the ONC and M34) $V$ & $i'$ are obtained for each cluster, with exposure times ensuring SNRs $> 30$ down to the BD. Standard data reduction steps are done automatically using our in-house pipeline (Irwin & Lewis 2001). We then perform list driven aperture photometry and remove temporal and spatial systematics by fitting and subtracting a 2–D polynomial surface to light curve residuals in each frame. Typical relative precisions reach 2–3 mmag at the bright end, and remain $< 1\,\%$ over $\sim 4$ magnitudes. We have adapted the calculations of Gaudi et al. 2005 to estimate the expected number of detections from *Monitor*, using assumptions specific to our young cluster targets. Taking into account cluster (age, distance, size, richness) and obervational (magnitude range, precision, sampling) characteristics and using suitable assumptions for companion incidence and theoretical mass-radius-luminosity relations, we calculate that *Monitor* as a whole should detect several planets and several tens of VLMSs / BDs that transit their primaries (see the *Monitor* webpage for more details).

## 3. Preliminary results and prospects

13 eclipse candidates with colours consistent with cluster membership have been identified in the 4 clusters observed so far (see Figure 1 for examples), using the algorithm of Aigrain & Irwin (2004) plus visual light curve examination. Several have likely primary masses below the BD limit, and half could be planets (no secondary eclipses). We have started follow-up with medium-resolution spectrographs on 4 m telescopes.

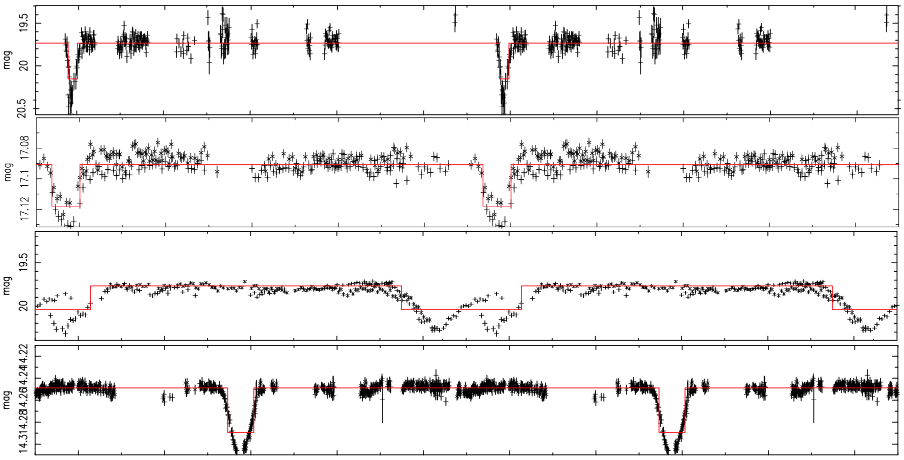

Figure 1. *Phase-folded light-curves of 4 of our eclipse candidates (M34, M50, NGC 2362 and ONC from top to bottom). Cluster ages are 180, 130, 7 and 1 Myr respectively, periods range from 0.5 to 2 d and likely system masses from 0.1 to* $0.8\,M_{\odot}$.

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# Extrasolar planet search with the HAT network

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**Abstract.** We summarize the current status of the HAT Network project. Started up in 2003 with a single telescope, HATNet has grown to an array of six almost identical, fully automated, wide-field telescopes spread in geographical longitude, plus a higher resolution photometry follow-up instrument called TopHAT. The instruments are maintained and controlled from the Center for Astrophysics, and are fully dedicated to planetary transit and variability search. Photometric precision reaches 3mmag for stars at $I \approx 8$, and data from separate stations can be readily combined. TopHAT is able to achieve millimag follow-up photometry. As of June 2005, 100000 stars have been thoroughly analyzed (30000 with photometry better than 1%); numerous transit candidates have been found and followed up by spectroscopy or photometry. Most of these turned out to be false positives, with a few cases still pending.

## 1. Hardware and Network Description

HAT is small, fully robotic "observatory" that consists of an equatorial horseshoe telescope mount, clam-shell enclosure, wide-format, front-illuminated $2K \times 2K$ Apogee CCD, 110mm diam. Canon f/1.8 telephoto lens, high-precision filter-exchanger, and control electronics. All components are driven by a single PC running RealTime Linux. The setup yields an $8 \times 8$deg field-of-view with $14''$ pixel size, and 1.5 pixel PSF width (Bakos et al. 2002, 2004).

The HAT Network consists of six, nearly identical HAT units. Four telescopes are installed at the Fred Lawrence Whipple Observatory (FLWO), Arizona, and two instruments are atop Mauna Kea (MK), Hawaii, on the roof of the SMA building. We can achieve networked operation, whereby instruments at FLWO and MK share the fields, and effective observing time is extended by some 4 hrs (longitude difference).

## 2. Observations and Data Reduction

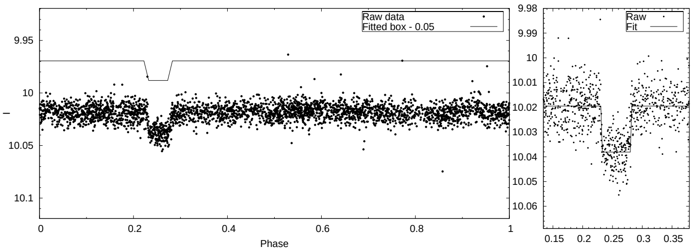
The observing technique is such that one to three fields are assigned to a telescope, with several fields shared between FLWO and MK. A field is continuously observed with 5min exposures through Cousins I-band filter as long as it is visible, or until another, higher priority field rises. To achieve optimum photometric precision we use a PSF broadening technique (Bakos et al. 2004). As of August 2005, about 200,000 science frames have been taken by HATNet.

We use aperture photometry, and reach 3mmag precision at $I \approx 8$ mag, which drops to 1% at $I \approx 11$; thus we get 1% photometry for approx 5000 stars per field (depending on galactic latitude). The data originating from the individual instruments can be readily merged. Systematic variations in the light-curves are corrected by using the TFA algorithm developed by Kovács et al. (2004).

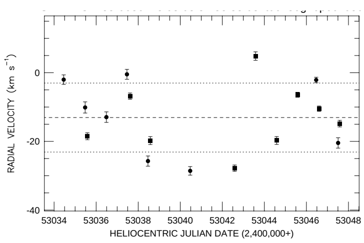
## 3. Search for Transits and Follow-up Observations

We search for shallow transit events by running BLS (Kovács, Mazeh & Zucker 2002) together with TFA. Using the combination of an automated selection procedure based on the BLS output parameters, followed by a careful manual inspection (color-index, shape, depth, out-of-transit variations, appearance of star on POSS, proper motion, etc.), we find about half a dozen of candidates per field.

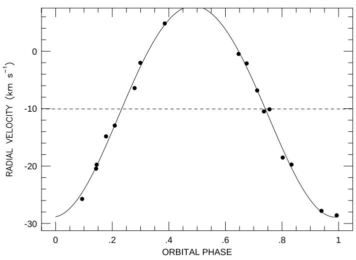
Altogether ~100 sources have been followed up by spectroscopy by D. Latham using the CfA Digital Speedometers (Latham 1985) at the FLWO and Oak Ridge Observatories. The precision of the speedometer radial velocity measurements is about 1km/s, corresponding to the semi-amplitude of a G0 dwarf when orbited by a $5M_J$ source with 1day period. Thus, the speedometers are useful for rejecting most of the false positives, but not confirming the planetary nature of an object. Most of the candidates turned out to be false positives, belonging to the following groups in roughly equal ratio: i) ~ F + M dwarf eclipsing binaries (Fig. 1), ii) grazing eclipsing binaries (EBs) with low S/N, iii) diluted EBs (optical or hierarchical triples). A few cases, including new targets, are still pending.




(a) Phase light-curve of HTR205-013, an F+M dwarf eclipsing system.




(b) Radial velocity vs. Julian Date.




(c) Radial velocity phased with the spectroscopic period.

Figure 1. *The 2% transit of HTR205-013 is due to an F+M dwarf EB.*

*Acknowledgements.* Development of HAT was initiated by Bohdan Paczyński. We acknowledge the help from the ROTSE-I project, the NASA Origins NAG5-10854 and SAO internal funds in the development of HATNet, and the support from FLWO and SMA in the installations. Operation and development of HATNet is currently supported by NASA-TPF grant NNG04GN74G. G. Bakos wishes to acknowledge support from the Hubble Fellowship grant HST-HF-01170.01-A.

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# PASS prototype observations in 2005

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**Abstract.** The Permanent All Sky Survey (PASS) will consist of arrays of wide angle CCD cameras, that will permanently survey the entire visible sky from several observing sites. Its major objectives are the detection of *all* giant-planet transits across bright stars and the detection and continuous tracking of any variable or transient phenomena in the full sky. A prototype with one CCD camera has been set up at Teide Observatory, Tenerife, and has been in regular operation since April 2005. Here is given an overview over the ongoing observations and the quality control that has been implemented.

## 1. Introduction

PASS will consist of several arrays of wide angle CCD cameras, each with short-focal optics (f≈50mm), that would cover completely the entire visible sky at a given observing site. Its major objectives are the detection of *all* giant-planet transits across bright stars and the detection and continuous tracking of any variable or transient phenomena in the full sky. The cameras would be placed on a common fixed mount, which has the advantage of mechanical simplicity and avoids any guiding errors. With images taken at exactly the same sequence of sidereal times every night, stars will move over exactly the same pixels every night, which allows a very precise calibration of pixel, and inter-pixel response functions. The instrument and its objectives are described in more detail in Deeg et al. (2004a).

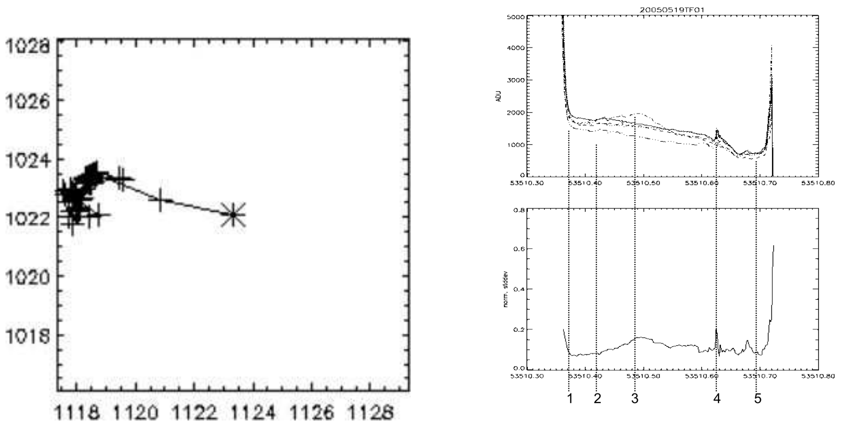


Figure 1. *Left: Position of a star in pixel coordinates during 61 nights at the same sidereal time. After a settling during the first 2 to 3 nights, it remains stable with an rms of 0.4 pixels. Right: Sky-brightness in 5 regions of an image during one night (top), and a normalized standard-deviation among them (bottom). The numbers indicate: 1: initial twilight, 2: photometric conditions with moon, 3: a reflex from the moon, 4: an individual cloud, and 5: dark sky after moon-set.*

## 2. PASS prototype observations and quality control

A prototype of the PASS instrument has been mounted at Teide Observatory, Tenerife, with the aim to: show that the required photometric precision can be achieved; acquire real observational data that serve for the development of a data analysis pipeline; optimize the instrumental set-up and the observational procedures (Deeg et al. 2004b for more details). The prototype operates with one Apogee 2k x 2k CCD camera and a Nikon f=50mm lens, set to an aperture of f/2.0. The camera is controlled by a script which synchronizes exposures with the sidereal time, and two exposures of 20 seconds are taken every minute. The instrument has been in operation since 2004, but only with the addition of a solid enclosure in March 2005 regular stable observations could be performed. The current pointing towards +29°declination, in effect since June 2005, was chosen to include the transiting system HD209458. Since stars will cross the field of view (30°x 30°) in somewhat over 2 hours, no complete coverage of a transit is achievable yet, but several partial transit events during summer and fall of 2005 are being recorded.

Images taken by the prototype currently undergo the following procedure: adding of astrometric information, archiving, and quality control. A photometric analysis based on image-subtraction techniques is currently under development in the frame of a PhD thesis project and will be presented elsewhere. One first concern with the PASS instrument has been pointing stability. The instrument is mounted fixed and stars will move across the field. However, for precise photometry, stars should appear at exactly the same spot every night in images taken at the same sidereal time. While early tests showed large motions, a much improved pointing stability with an rms of 0.4 pixels has been achieved since April 2005 (Figure 1, left). Remaining residuals may arise from flexions of the mount or optics (possibly from temperature changes), or from errors in the timing (which we are confident to be minor). Nightly observing runs result in approximately 1000 images, requiring 8 Gbyte of storage space. For an efficient data analysis, the rejection of poor data and the classification of usable ones is therefore needed. Evaluation of the individual nights is based on a measurement of the sky brightness in the four image corners and in the center (Figure 1, right). Based on comparisons with low-resolution movies from nightly data, it has been found that these brightness levels, and the standard deviation among them, provide a reliable indicator of a nights meteorological quality. An automatic quality classification based on such graphs is currently under development.

## 3. Future development of PASS

The principal goal of the current prototype is the undertaking of a feasibility study. A thorough analysis of these data will show, if modifications to the instrument design or to the observing procedure will be required. A complementary system of two further cameras with more efficient CCD detectors is scheduled to start operation in late 2005 as part of the WASP planet detection project in La Palma. When instrument design, observing routines and data analysis have matured, the adding of further cameras or instrument locations would lead to a start of the Permanent All Sky Survey.

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# RATS: the photometric data reduction automatic pipeline

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**Abstract.** The automatic photometric pipeline provides a real time images reduction and directly the light curves of object in the field within the RATS project (RAdial Velocities Transit Search). The light curves themselves will be analyzed in order to catch light dimming due to a transit. For this purpose, the algorithm needs as input files a list of fits images taken at Schmidt Telescope of Asiago (INAF, Italy), a reference master list of stars and three files with the optional parameters for the DAOPHOT photometry package (Stetson 1987). The master list is previously obtained from a photometric characterization of the field (for more details: www.rats.it and see R. Claudi's paper for the proceedings).

## 1. Introduction

RATS (Radial velocities and Transit Search) is an Italian collaboration between several INAF Observatories (Padova, Catania, Napoli, Palermo), the Astronomy and Physics Departments of Padova University and ESA. The project is devoted to search for extrasolar planets using the transit photometric technique together with a spectroscopic follow up strategy for reconnaissance of false alarms. The main aim of the RATS project is twofold. We are planning to observe simultaneously thousands of stars (magnitude range between 9th to 14th) in selected star fields for five years. In this manner we are confident to find 10 new transiting planets. The second aim of the project is to use its observing strategy and the scientific data management as a bench work for future planetary transits search mission. In order to achieve the RATS project goals we use two different telescope for both the photometry search and the spectroscopic follow up. The photometric transit search will be conducted with the 67/92 Schmidt telescope of Cima Ekar equipped with one of the frame transfer CCDs forecast for the ESA EDDINGTON space mission. The spectroscopic follow up will be conducted with the "Copernico" Telescope equipped with the echelle spectrograph. Candidate identification requires a preparatory work starting from stellar field selection with higher probability to find a transit event. An automatic photometric pipeline with a real time images reduction, will directly provide light curves of object in the field. The light curves themselves will be analyzed in order to catch light dimming due to a transit. Once a transit alarm is found, it is observed with the spectroscopic telescope to rule out astrophysical false alarm like eclipse binary blended with giant stars.

## 2. The RATS automatic pipeline

Every night of observation the system will acquire 7 images for the same field of 1 square degree each. The time exposure is 10 sec. RATS will supervise continuously the same stellar field visible in that season, taking one image every 15 sec.

Iteratively, for each frame we find the center of each defocused star in every image and we match with DAOMATCH and DAOMASTER (Stetson 1992a; Stetson 1992b) each image with the first one, initially chosen as a reference frame. Then we transform the coordinate of each stars in the matched frames in the spatial reference system of the master list and we re-run DAOPHOT to obtain the new photometry with the transformed coordinates. In the next step we store the output files with the light curves, one for each star in all the images. Finally, we calculate iteratively the mean magnitude with which we correct the magnitude of the stars.

The pipeline is divided into four parts:
(*i*) a shell script (DAOPHOT photometry package - Stetson 1987) produce ASCII files with the coordinates of the centroids which identify a star;
(*ii*) some FORTRAN programs re-adjust the center of the centroids in the reference system of the first image. It is necessary because the telescope is bad-guided;
(*iii*) the pipeline re-run the DAOPHOT package to obtain the ASCII files with the new coordinates of each stars from a matching with the master list;

(*iv*) the FORTRAN programs calculate the mean magnitude for each star and write ASCII files with the light curves.

We applied the procedure to a one night observations finding two variable stars RATS V1 and RATS V2

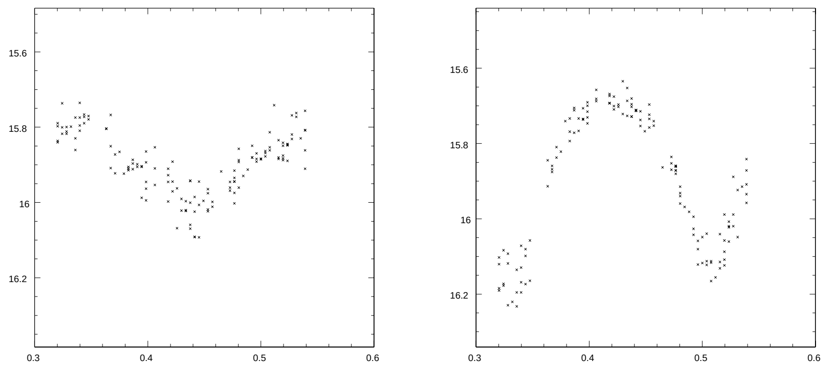


Figure 1. *RATS V1 and RATS V2 light curves, respectively.*

## 3. Conclusions

RATS will contribute to disentangle the planetary formation mechanism, to identify the environmental condition where these objects form or not and to have more hints about their physics. The transit's observations, together with the spectroscopic observations of the radial velocity fluctuation, allow an estimate of the projected area of the planet and hence of its radius. Thus, if the planetary mass is known, e.g. by radial velocity observations (edge – on orbits allow reduction of the planetary mass uncertainty), it is possible to determine the density of the planet, its surface gravity and have hints about the atmospheric gas composition (escape velocity) and lay down limits on structural model of extra solar planets. The case of the six up to day detected transiting planets has shown that this is possible in practice.

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# Search for transiting planets in the Hipparcos database

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**Abstract.** We investigated the possibility to find transiting planets around relatively bright stars in the *Hipparcos* Catalog. We systematically searched in the *Hipparcos* photometry data for periods compatible with planetary transits, and constructed a ranked list of candidates for follow-up measurements. Radial velocities of 194 of the candidates were measured using HARPS, but these observations did not lead to identification of new transiting hot Jupiters. Our procedure seems to preferentially select active stars. Beginning in 2012, the *Gaia* survey should allow numerous transiting hot Jupiters to be detected, since the corresponding photometric errors should be significantly smaller than those of *Hipparcos*.

## 1. Presentation

The *Hipparcos* Epoch Photometry Annex contains between 40 and 300 measurements performed during the 1226-day duration of the mission for each of the 118 204 stars of the catalog. We investigated the possibility to find transiting planets around bright stars in this all-sky survey. Indeed, with about 0.06% chance that a given star harbors a transiting extrasolar planet, the *Hipparcos* catalog must contain photometric measurements for tens of transiting hot Jupiters. This belief is reinforced by the case of HD 209458b, which was *a posteriori* re-discovered in *Hipparcos* data by Robichon & Arenou (2000), Castellano et al. (2000), and Söderhjelm (1999). Thanks to the long time baseline, these data allow the orbital period to be measured with a 1 second accuracy. However, with photometric variations of about 1% or less, such transits are difficult to identify with *Hipparcos*. The 0.003 mag deep transits of HD 149026b (Sato et al. 2005) were not detected with *Hipparcos*. Jenkins et al. (2002) concluded that because of its poor photometric quality, the *Hipparcos* catalog does not represent a likely place to detect planets in the absence of other informations. Laughlin (2000) has searched in the *Hipparcos* epoch photometry for transiting planets within 206 metal-rich stars. None have been confirmed thereafter.

Here we present a systematic search in the *Hipparcos* catalog for periods compatible with planetary transits, in order to construct a ranked list of candidates for follow-up radial velocity (RV) measurements.

## 2. Selection of the targets

First, we selected 23 304 F2 or later types stars in the *Hipparcos* catalog with radii below $2\,R_\odot$. We kept targets with at most one epoch brighter than $3\,\sigma$ from the average magnitude and at least 40 available epochs. We performed the periods' research on the 17 800 remaining stars.

For each target, we took the two faintest epochs and we scan all the possible periods with those two points in a transit. We adopted the period producing the lowest flux in the drop. We also computed the $\chi^2$ for the fit with a transit curve for a planet with a radius $R_p = (0.11 \pm 0.04)\,R_\odot$. The selection of candidates is based on those parameters.

We performed simulations in order to tune the thresholds. It allowed us to estimate to 2% the detection rate. With 0.06% chance that a given star harbors a transiting extrasolar planet, the 17800 targets of our latest sample should include $\sim$ 11 transiting planets. The expected transiting planet detection number with our method should thus be slightly less than unity. The probability to have at least one or two transiting planet(s) are respectively 19% or 1.9%.

## 3. Observations

We performed follow-up observations of 194 targets. These observations were performed in 2004/2005 using HARPS. The magnitudes of the observed stars range from 4.9 to 11.5. 70 to 90 targets were observed each night; errors on the measured RV are typically of the order of 2 m/s.

RV dispersions larger than 20 m/s were measured for 37 stars. Several are still monitored with HARPS but up to now, none of these targets have shown a RV oscillation in agreement with a reflex motion due to a hot Jupiter. Instead, most of the RV variations seem to be caused by stellar activity. Some cases revealed a clear correlation between RV and line-bisector orientation. Such correlations might be understood if there are dark spots on the stellar photospheres (Queloz et al. 2001).

Most of the targets with large RV variations show emissions in the Ca II lines, which suggests chromospheric activity. Thus, our procedure seems to preferentially select active stars. This should be contrasted with transiting candidates obtained from the OGLE survey, which are mainly eclipsing binaries or transiting planets (Pont et al. 2005).

## 4. Gaia prospects

Whereas the *Hipparcos* catalog does not seem to be a promising source for the detection of transiting planets, the situation should be different with *Gaia*. With a launch planned in late 2011, the 5-year survey performed by this space observatory will provide astrometric, photometric, and spectroscopic data for about one billion objects, up to $V = 20$. In the same spirit that for *Hipparcos*, *Gaia* will produce photometric measurements for about 200 different epochs. The photometric accuracy should be significantly improved by comparison with *Hipparcos*. Robichon (2002) shown that thousand to tens of thousands of transiting planets should be detected with *Gaia*. Depending its the actual photometry accuracy, *Gaia* might provide a detection rate for transiting hot Jupiters about twenty times larger than this reported in § 2.

Shortly after the Colloquium, Bouchy et al. (2005) announced the detection from ground-based observations of a new transiting planet, HD 189733 b. They also reported its detection within *Hipparcos* data. Detection of HD 189733 b transits within *Hipparcos* data are discussed in details by Hébrard & Lecavelier des Étangs (2005).

*Acknowledgements.* This work is based on observations collected at the European Southern Observatory, La Silla, Chile. We thank F. Arenou, X. Bonfils, C. Lovis, C. Moutou, D. Naef, D. Sosnowska, and A. Vidal-Madjar for help.

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# The WHAT project

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**Abstract.** We describe WHAT, a small-aperture short focal length automated telescope with an $8.2° \times 8.2°$ field of view, located at the Wise Observatory. The system is aimed at searching for transiting extrasolar planets and variable stars. Preliminary results of 3892 exposures of a single field are presented, where the telescope achieved already a precision of a few mmag for the brightest objects. Additional information can be found at: `http://wise-obs.tau.ac.il/~what`.

**WHAT** is a **W**ise observatory **H**ungarian-made **A**utomated **T**elescope located at the Wise Observatory in Mizpe Ramon, Israel. It is a collaboration between the Wise Observatory of the Tel Aviv University and Konkoly Observatory of the Hungarian Academy of Sciences. Like all other HAT telescopes (Bakos et al. 2004, and references therein), WHAT is a combination of a fully automated telescope mount, a clamshell dome, 2K × 2K CCD, 200 mm $f/1.8$ telephoto lens, Real-Time Linux PC and a software environment, "ProMount".

WHAT operation is fully automated. The only manual interaction is that of establishing weather conditions and enabling the telescope on each evening. This nightly operation is done through a web interface, by a teamwork from Wise and Konkoly observatories.

The WHAT wide field of view, $8.2° \times 8.2°$, allows it to simultaneously observe tens of thousands of stars. Observations are carried out in a Point Spread Function (PSF) broadening mode, whereby the telescope is stepped on a prescribed pattern, thus achieving a better sampled PSF (Bakos et al. 2004). Most of WHAT observations are conducted through a standard Cousins $I$-band filter. For future calibration, a Johnson $V$-band filter is also used occasionally. Each exposure is 300 s long, therefore, approximately 100 object images are accumulated nightly.

WHAT primary objective is to search for transiting extrasolar planets by monitoring pre-selected fields. As a by-product, a large variable star inventory is also produced.

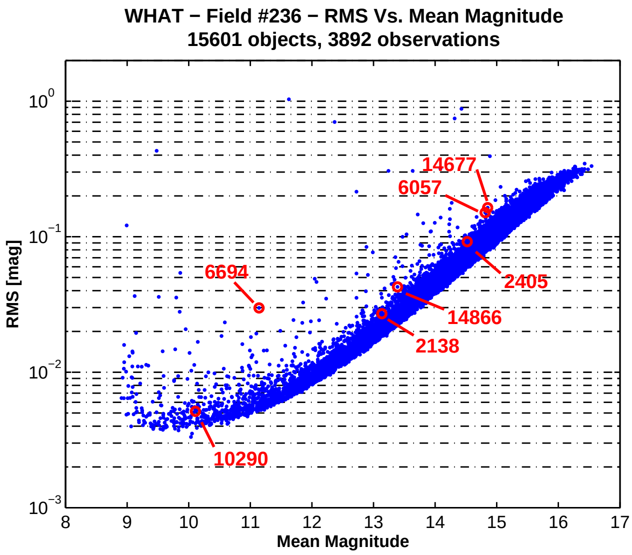


Figure 1. *Photometric results for WHAT field #236. RMS is presented against instrumental I magnitude, which is close to standard V. Objects presented in Figures 2 and 3 are encircled here in grey, along with their ID numbers.*

Over 65,000 images have been accumulated since WHAT became operational on Jan. 2004. Preliminary results for one of the observed fields, #236, are presented here. Located at R.A. 15:28 and Dec. +30:00, it was observed 3892 times on 162 nights between 2004 Feb 20 and 2004 Aug 1. Light curves of 15601 field objects were extracted using aperture photometry. RMS versus mean magnitude for all objects are presented in Figure 1. The systematic scatter reaches 4.5 mmag.

To demonstrate the capability of WHAT in detecting small-amplitude periodic variables, we present in Figure 2 one such case. Detection is highly significant, even though the signal's amplitude is only 4.2 mmag. In Figure 3 six eclipsing binaries of different types, detected in the same field, are presented.

We are currently engaged with finalizing our photometric pipeline and observing additional fields.

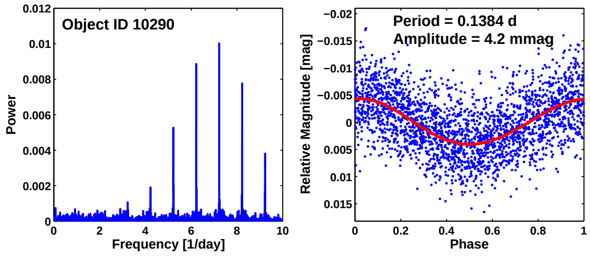


Figure 2. Left: *Power spectrum of object 10290.* Right: *Folded, mean subtracted, light curve, overplotted in grey by the corresponding Fourier fit, with an amplitude of 4.2 mmag.*

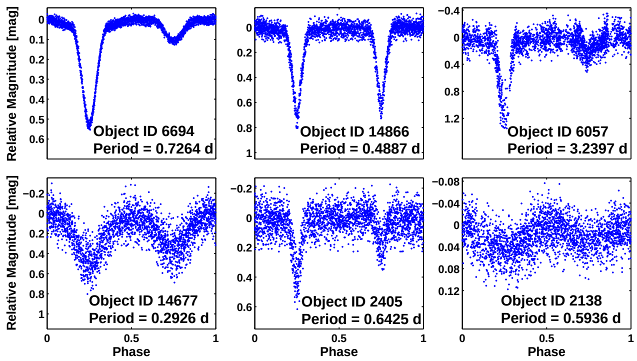


Figure 3. *Examples of eclipsing binaries detected by WHAT.*

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# Revised parameters for OGLE-TR-10 from UVES spectra: updated planetary physical properties

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**Abstract.** We have obtained high-resolution UVES spectra with S/N>100 to accurately characterize the stellar parameters for the transiting planet-hosting star OGLE-TR-10. The obtained values were used to rederive the planetary radius and mean density.

## 1. Introduction

Using radial-velocities obtained with the FLAMES/UVES spectrograph at the VLT telescope, Bouchy et al. (2005) found strong evidence that the observed photometric transit of OGLE-TR-10 (Udalski 2002) was due to the presence of a short period planetary companion. This conclusion was confirmed by Konacki et al. (2005). One disagreement persisted, however, between the studies by Bouchy et al. (2005) and Konacki et al. (2005): the stellar parameters of OGLE-TR-10. The former authors used FLAMES/UVES spectra with S/N$\sim$50 to derive ($T_{\mathrm{eff}}$,$\log g$,[Fe/H])=(6220 k, 4.70 dex, 0.39 dex), in contradiction with the values obtained by Konacki et al. (5750 k,4.4 dex,0.0 dex). This led to the derivation of different physical parameters for OGLE-TR-10, and consequently different parameters for the transiting planet.

## 2. UVES spectroscopy of OGLE-TR-10

In order to clarify this situation we have gathered R=50 000, S/N=100 spectra of OGLE-TR-10 with the UVES spectrograph at the VLT Kueyen telescope. The final spectrum was used to derive stellar parameters for OGLE-TR-10 using a set of 33 FeI and 11 FeII lines, and making use of iron excitation and ionization balance (e.g. Santos et al. 2004). The analysis was done in LTE using the radiative transfer code MOOG2002 (Sneden 1973) and a grid of ATLAS9 atmospheres (Kurucz 1993). The results provided accurate values for $T_{\rm eff}$, $\log g$, [Fe/H] and the microturbulence parameter (see Table below). The derived values are typical of a metal-rich solar-type dwarf. These values are compatible, within the errors, with the ones presented in Bouchy et al. (2005) using the lower S/N FLAMES/UVES spectrum.

| $T_{\rm eff}$ [K] | $\log g$ [dex (cgs)] | $\xi_t$ [km/s] | [Fe/H] [dex] |
|---|---|---|---|
| 6075±86 | 4.54±0.15 | 1.45±0.14 | 0.28±0.10 |

As a test for the derived stellar parameters we have also done a fit to the observed $H_\alpha$ line using Kurucz Balmer profiles for temperatures of 5750, 6000, and 6250 K, a metallicity of 0.30 dex, and a surface gravity of 4.50 dex. We have chosen the profiles taken from R. Kurucz's WWW page http://kurucz.harvard.edu/grids.html. The results show that the $H_\alpha$ profile that best fits the data has a temperature of 6000 K, similar to the one derived from the Fe-line analysis. The fits exclude a temperature of 5750 K for OGLE-TR-10 as derived by Konacki et al. (2005).

## 3. Revised parameters for OGLE-TR-10b

Using the recipe described in Bouchy et al. (2005) we have derived revised parameters for the planet transiting OGLE-TR-10. As input, we took the stellar parameters described in the previous sections, a planet-stellar radius ratio $r_p/R_\star$= 0.129±0.007 (derived from the original OGLE photometry – see also Bouchy et al. 2005), a transit duration d = 2.75±0.06 hours and an impact parameter in the range 0.12-0.33 (derived from Holman et al. 2005). When iterating to derive our solution of stellar and planetary parameters we also used the stellar evolutionary models of Girardi et al. (2000). We have further done the same analysis considering a $r_p/R_\star$ = 0.102±0.003, derived from the recent photometry presented in Holman et al. (2005). The results of this analysis are presented in the table below, and in the Mass-Radius plot of Figure 1.

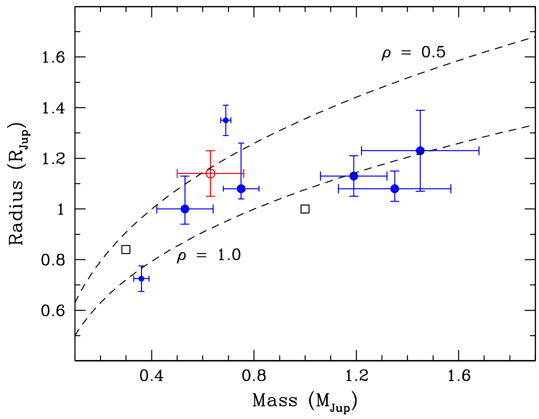


Figure 1. *Mass-Radius diagram for the know transiting exoplanets (dots), Jupiter and Saturn (open squares). OGLE-TR-10b (open circle) is considered with the radius derived taking into account the $r_p/R_\star$ ratio derived by Holman et al. (2005) and the stellar parameters presented in this poster. Iso-density curves are presented for $\rho$=0.5 and 1.0 g cm$^{-3}$.*

| Used $r_p/R_\star$ | $M_\star$ [$M_\odot$] | $R_\star$ [$R_\odot$] | $m_p$ [$M_{Jup}$] | $r_p$ [$R_\odot$] | $\chi^2$ |
|---|---|---|---|---|---|
| 0.129±0.007 | 1.17±0.04 | 1.14±0.05 | 0.63±0.13 | 0.147±0.010 | 1.2 |
| 0.102±0.003 | 1.17±0.04 | 1.14±0.05 | 0.63±0.13 | 0.117±0.009 | 0.1 |

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