

Synergies between exoplanet surveys and variable star research

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Abstract. With the discovery of the first transiting extrasolar planetary system back in 1999, a great number of projects started to hunt for other similar systems. Because the incidence rate of such systems was unknown and the length of the shallow transit events is only a few percent of the orbital period, the goal was to monitor continuously as many stars as possible for at least a period of a few months. Small aperture, large field of view automated telescope systems have been installed with a parallel development of new data reduction and analysis methods, leading to better than 1% per data point precision for thousands of stars. With the successful launch of the photometric satellites CoRoT and *Kepler*, the precision increased further by one-two orders of magnitude. Millions of stars have been analyzed and searched for transits. In the history of variable star astronomy this is the biggest undertaking so far, resulting in photometric time series inventories immensely valuable for the whole field. In this review we briefly discuss the methods of data analysis that were inspired by the main science driver of these surveys and highlight some of the most interesting variable star results that impact the field of variable star astronomy.

1 Introduction – some historical background

Up until 1999, telephoto lenses were not acknowledged as a source of major astronomical discoveries. This has changed dramatically when, after the discovery of the first extrasolar planet 51 Peg ([61, 62]), many research teams started concentrated efforts to observe the photometric transit signals of the already discovered planets, and find new ones. Because some of the systems discovered by radial velocity methods had short periods of a few days and the estimated masses were in the range of Jupiter masses, these extrasolar planets (dubbed as Hot Jupiters, or HJs for short) with their 5 – 20% transit probabilities and ~ 1% transit depths were excellent targets for photometric detection, even for telescopes with apertures of ~ 5 – 10 cm. Indeed, five years after the discovery of 51 Peg, the photometric monitoring of HD 209458 resulted in the multiple observations of the transit events of the companion ([23, 42]). This important discovery immediately fixed the ambiguity of the planet mass due to orbital inclination, proved that the source of radial velocity variation is an orbiting companion and not a stellar surface phenomenon, and allowed for the first time to derive the two basic parameters (mass and radius) of an extrasolar planet.

After this ground-breaking discovery, over twenty different projects started to monitor large (~ 100 square degrees) chunks of the sky and look for the same kind of events in millions of stars,

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without a priori radial velocity monitoring. Interestingly, the first photometric discovery came not from these small-telescope projects but from the OGLE project, operating a 1.3 m telescope and originally devoted to microlensing surveys. Unlike HD 209458, OGLE-TR-56 ([92]) is a faint, $V = 16.6$ mag star. This posed rather strong constraints on the possible spectrographs used for the validation of the system. Nevertheless, in spite of its faintness, the system was successfully verified (see [49]). It was soon realized that small telescopes are vital for the more massive discovery of additional systems that are considerably brighter.

In 2004, the first transiting extrasolar planet (TEP) was discovered by using small aperture wide-field automated telescopes, namely TrES-1 ([5]). The Trans-Atlantic Exoplanet Survey (TrES) network hosted the STARE telescope, the one that was instrumental in the discovery of the first transiting exoplanet, HD 209458. Although the discovery of TrES-1 was a good sign that small telescope projects are, indeed, capable of making significant discoveries, it was not until the fall of 2006 when these projects started to yield the rate of discovery hoped for. The relatively long delay between conceiving the idea and the first science output is attributed to several factors. This includes the time needed for the technical implementation (please note that these telescopes are autonomous with sophisticated software making decisions on telescope operation, data acquisition and basic image reduction); development of new methods for massive signal search and, especially, to solve the problem of filtering out colored noise; and accessibility of proper instrumentation for precise follow-up observations with the proper amount of telescope time to get accurate light curve and radial velocity solutions. Last, but not least, these objects are rather rare, with a $\sim 0.4\%$ (or lower) true occurrence rate (see, e.g., [37]) and an even lower (by a factor of 10 – 30) observability rate.

With the discovery of HAT-P-1 and WASP-1 ([10, 25]), the speed of the discoveries substantially increased, yielding by now over 200 well-characterized HJ systems, covering a wide variety of stellar and planet parameters. Meanwhile, the long-planned space mission CoRoT was launched in 2006 and started to deliver high-quality, uninterrupted photometric time series on thousands of stars, leading to the discovery of the first super-Earth object, CoRoT-7b. Three years later, after many years of planning, the *Kepler* satellite was launched and a new era began with startling discoveries, such as Kepler-9, the first system with multiple transiting planets ([45]), or Kepler-186f, the first of the several systems hosting planets in the habitable zone ([74]), some of which might even be similar to Earth, such as Kepler-22b ([17]). The *Kepler* mission still continues, from 2014 under the name K2, showing the ingenuity of engineering and community support for the brilliant solution for the loss of the two reaction wheels by the time the main mission was completed. The K2 mission has proven to be quite successful. By visiting ecliptic fields, a broad spectrum of astrophysically interesting objects are visited, driven by researchers across the various disciplines of astronomy.

The main science (discover and characterize planets outside the solar system) that drives the above ground- and space-based projects resulted in an increase in the quality and amount of photometric data never seen before. It is obvious that this fundamental change has a serious impact also on variable star research. In this review we focus on the ground-based wide-field surveys as the results of the variable star works on the space mission data are more widely known due to the large number of researchers working on these data. On the other hand, works on the variable star aspects of the ground-based surveys are less organized and sporadic. Nevertheless, as we will see, these surveys are both complementary and in many respects competitive to the space surveys. Therefore, it is very important to be aware of the results obtained so far and also of what these data could be used for in future works.

2 Wide-field photometric surveys – the overall importance

Unlike variable searches, targeting specific stars in earlier surveys (e.g., globular cluster studies, works on RR Lyrae stars in microlensing survey data [3]), current photometric projects, while looking for periodic transit signals, scan through the whole list of objects passing some minimum precision condition. Photometric surveys targeting extrasolar planets have to satisfy high standards in data quality (continuity and precision) and in volume (due to the rare occurrence and short duration of the event, even though it is periodic). This results in time series that surpass the quality of most of the photometric data gathered earlier and yields valuable sources for a large diversity of studies, not directly related to extrasolar planetary science. These science “by-products” may often be as important as those targeted by the original idea that has led to the initialization of the project.

Many projects started after the first discovery of the transit of HD 209458 in 2000. Some of them were not realized (e.g., Permanent All Sky Survey, or PASS¹, [28]), some of them were abandoned (e.g., Wise observatory Hungarian-made Automated Telescope, or WHAT²), and some of them survived, expanded and became important/major contributors to the exoplanet inventory (e.g., Wide Angle Search for Planets, or WASP, [73]).

In the design of the instrumentation of these surveys, one might consider the optimization of the system (including hardware and observational strategy) for the most effective survey of large numbers of stars. One of the issues is the size of the optics used. In an interesting paper by [71], the authors come up with a solution that employing a 2 inch telescope, with a 4K × 4K CCD camera, would be optimum. Indeed, this setting is very close to the ones used by most of the “classical” surveys that range from 4 cm (KELT) to ~ 20 cm (e.g., HATSouth), with 10 cm as the most often used, and also a combination of these under the same closure (Qatar Exoplanet Survey, or QES³, [6]).



Figure 1. The KELT-North building at the Winer Observatory (Arizona, USA), and the instrument hosted. The instrument is equipped with a 42 mm diameter Mamiya f/1.9 telephoto lens, a 4 K × 4 K Apogee AP16E CCD camera put on a Paramount mount. The observations are fully robotic without the need for onsite supervision. The data are periodically transferred to the Ohio State University.

For illustration, the somewhat unique setting for KELT-North is shown in Figure 1. The instrument has a field of view of 26×26 square degrees, almost seven times as large as that of the instrument aboard the *Kepler* satellite. The southern station is hosted by the South African Astronomical Observatory and consists also of a single instrument, a replica of the one at the northern station. Both instruments are fully robotic. They covered so far ~ 70% of the sky, and supplied 4.5×10^6 light curves. As of today, they discovered 15 TEPs⁴ and made possible visits to several important “side topics” (see Sect. 3).

¹<http://www.iac.es/proyecto/pass/>

²<http://wise-obs.tau.ac.il/~what/index.html>

³<http://www.qatarexoplanet.org/>

⁴<http://exoplanet.eu>

Figure 2 summarizes the major photometric surveys that have contributed (or will contribute) to the discovery of TEPs. For a broader view, we included also related space missions⁵. It is impossible to give even a brief description of all these projects. Therefore, we focus on HAT-N/S and WASP, the two main surveys contributing most of the TEPs discovered from the ground, and describe some of the main parameters of these projects. However, it is important to note that several other projects also made very significant contributions. For example, MEarth⁶ (M dwarf stars in search of new Earth-like exoplanets, see [47]) has provided an important contribution to the variability survey of M dwarfs ([67]), and made the first discoveries of a transiting Super-Earth/Mini-Neptune ([24]) and an Earth-sized planet from the ground ([15]). Yet another, highly significant discovery comes from the TRAPPIST⁷ (TRANSiting Planets and Planetesimals Small Telescope) project. The system consists of two 60 cm robotic telescopes that are located at La Silla Observatory (Chile) and at the Oukaïmeden Observatory (Morocco). In 2016 TRAPPIST made the first ground-based discovery ([34]) of a multi-planetary system (consisting of three Earth-sized planets) around a nearby M8 dwarf. The proximity of the system makes it a prime candidate for a deep study of the long-chased class of multiplanetary transiting planets around M dwarfs. And indeed, just before completing this review, four additional planets were announced for this system, discovered by the *Spitzer* Space Telescope ([35]).

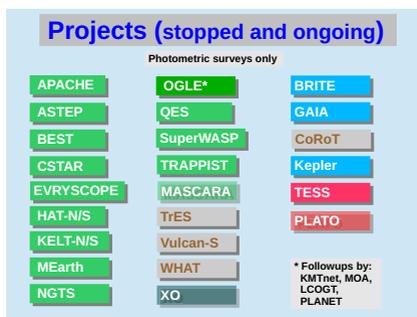


Figure 2. Summary of the photometric survey programs with past/current/future contributions to exoplanet science. Different coloring/shading refer to the current status of these projects. The first two columns are for the ground-based projects, whereas the third column is for the space missions. Green and blue are for ongoing, gray for past/no longer running, red/orange for immediate/near future projects. The MASCARA project is at an early stage of operation ([88]). The XO project has recently been revitalized ([27]). The microlensing planet search conducted by the OGLE project tightly relies on the follow-up collaborative efforts with the participating projects/instruments shown in the lower right.

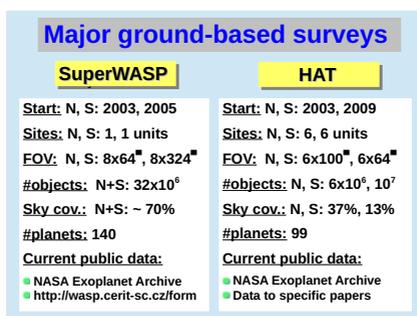


Figure 3. Brief list of the main characteristics of the two major ground-based transiting extrasolar planet surveys. SuperWASP has recently switched to smaller diameter lenses at the southern site. Earlier field of view was the same as that at the northern site. Current sky coverages are based on private communications (SuperWASP) and on recently published papers (HAT-N/S, [16, 48]). Planet statistics are based on <http://exoplanet.eu> and contain a few commonly discovered systems.

Some of the basic characteristics of the two major survey programs are listed in Figure 3. SuperWASP⁸ consists of two observing units. One (SuperWASP-North) is in La Palma (Spain), while

⁵Gaia is not specified for planetary system search but will obviously yield a great contribution to it – mostly via the precise position measurements, but even through its low cadence photometry, once it is combined with dedicated ground-based follow-up observations (see [32]).

⁶<https://www.cfa.harvard.edu/MEarth/Welcome.html>

⁷http://www.ati.ulg.ac.be/TRAPPIST/Trappist_main/Home.html

⁸<http://www.superwasp.org>

the other (SuperWASP-South) is at the South African Astronomical Observatory. Each unit consists 8 telephoto lenses (of 11 cm and 7 cm diameter) attached to $2K \times 2K$ CCD cameras enabling to take images on a very large chunk of the sky. The more detailed description of SuperWASP can be found in [73] and an update in [84].

The HAT project went through two major steps in the development. The survey on the northern hemisphere, HATNet⁹, started in 2004, and consists of two sites (one at Mauna Kea Observatory/Hawaii and the other at the Fred Lawrence Whipple Observatory/AZ) with altogether 6 observing units, each equipped with a 11 cm diameter telephoto optics and a $4K \times 4K$ format CCD camera. The southern counterpart (HATSouth¹⁰) is a bigger undertaking, with observing units different in design from those of HATNet. Established in 2009, HATSouth consists of three sites: Las Campanas Observatory (Chile), High Energy Stereoscopic System (HESS, Namibia) and Siding Spring Observatory (Australia). At each site there are two units with four $4K \times 4K$ CCD cameras attached to 18 cm diameter astrographs. The detailed description of HATNet and HATSouth can be found in [9] and [12], respectively.

Both projects made (and are making) important discoveries in the field of extrasolar planets. With the spread in longitude, careful data acquisition, in-depth treatment of the data and longevity of the projects, these surveys are capable of detecting short period Hot Neptunes (e.g., HAT-P-11b [11] and HAT-P-26b [39]), Warm Jupiters with periods longer than 10 days (e.g., HAT-P-15 [52], WASP-130 [41], HATS-17 [20]) and HJs with shallow transits around evolved stars (e.g., WASP-73 [31], HAT-P-50 [40]). Both projects make the data used in their published papers available for the public. In addition, SuperWASP deposited all light curves gathered between 2004 and 2008 in a searchable format at the NASA/IPAC exoplanet site¹¹.

3 Impact on data analysis – curing the red noise syndrome

As emphasized in Sect. 2, wide-field surveys have to satisfy certain conditions in order to meet the original science goal. Because in the transit surveys all “photometrically sound” objects are searched for signals, any minuscule detail counts. Therefore, it is not surprising that a considerable effort has been made to achieve the highest data quality possible for a given instrumentation. In this section we briefly summarize the various methods that are intended to reach this goal.

As follows from their very names, wide-field surveys cover a large part of the sky even if we consider only the single exposure images. Therefore, already the basic method of reduction (ensemble photometry, e.g., [46]) should be modified ([9]), considering vignetting, differential reddening and refraction, change in the size and shape of the point spread function (PSF). Furthermore, even after taking all these into account, most of the stars will still contain some residual scatter due to uncured (or improperly considered) observational and environmental effects. Although a considerable filtering of these effects is possible with the aid of Differential Image Analysis (DIA, [4], or OIS, [2]), even this, more in-depth treatment cannot cure all remaining systematics ([29]). Therefore, *post-processing* is an inevitable step in modern photometric surveys.

Differing in the details in the implementation, all these methods are based on the general idea that systematics are characterized by some combination of: a) the common perturbations in many objects in a given field, b) perturbations depending on external parameters, associated with each star, allowing peculiar (non-common) types of variability. Examples of type a) systematics are the nightly variation of the transparency, the trace of the improperly corrected track of an airplane or that of a cosmic ray.

⁹<http://hatnet.org/>

¹⁰<http://hatsouth.org/>

¹¹Similar (albeit less extensive) depository exists for the KELT project and fractional data releases for TrES and XO – see <http://exoplanetarchive.ipac.caltech.edu>.

Table 1. Major red noise filtering methods developed during the past 12 years.

Acronym	Expanded name	Brief description*	Ref.
TFA	Trend Filtering Algorithm	Cotrending by the stars in the field using simple least squares	[53]
SysRem	Systematics Removal	Iterative step-by-step cotrending by the stars in the field, using PCA-related method	[89]
SARS	Simultaneous Additive and Relative System	SysRem extended to additive and multiplicative red noise	[68]
EPD	External Parameter Decorrelation	Using parameters (e.g., object pixel coordinates) external to the light curve	[11]
PDC	Presearch Data Conditioning	Cotrending by using Bayesian approach with PCA-selected template light curves	[87] [85]
MarPLE	Marginalized Probability of a Lone Eclipse	Using Bayesian method to find single transit events and the period to combine them	[14]
TERRA	Transiting Exoearth Robust Reduction Algorithm	Cotrending by employing least squares fit, PCA and template outlier selection	[72]
ARC	Astrophysically Robust Correction	Cotrending by using Bayesian approach with entropy criterion and PCA to select the essential contribution from the templates	[75]
SFF	Self Flat Fielding	Systematics, due to the roll correction of the <i>Kepler</i> (K2) spacecraft, are filtered out by using pixel positions as external parameters	[93]
CPM	Casual Pixel Model	Using pixel-level autoregressive model to predict systematics during transit	[95]
GPM	Gaussian Process Model**	Signal search by using Gaussian models for a simultaneous fit of the systematics and the underlying signal	[1]
FFF	Full-Fledged-Fit**	Periodic transit search by simultaneous fit for systematics and the signal	[33]
SIP	Systematics Insensitive Periodogram	FFF extended to sinusoidal signals	[7]
DOHA	capital of Qatar	Cotrending by best-correlating templates on full and nightly time bases	[64]

* The description given may not fully reflect the full depth of the method.

** Our acronym attached to the method.

Type b) systematics include flux variability due to changes in the size and shape of the PSF, or to the spatial-dependent pixel sensitivity. The idea of systematics correction can be represented perhaps in the simplest way within the framework of TFA/EPD (see Table 1). We approximate the observed flux variation $F(t)$ of our target of interest by the following expression:

$$\hat{F}(t) = F_0(t) + N(t) + \sum_{j=1}^M a_j X_j(t) + \sum_{i=1}^K b_i E_i(t) , \quad (1)$$

where $F_0(t)$ is the “true” signal (free from systematics and random – uncorrelated – noise); $N(t)$ is the instrumental/environmental white noise component; and $\{X_j(t) : j = 1, 2, \dots, M\}$, $\{E_i(t) : i = 1, 2, \dots, K\}$ are, respectively, the M template/cotrending time series of a representative group of objects in the field and the K external parameters. The regression coefficients $\{a_j\}$ and $\{b_i\}$ are determined by some multiple regression method, in the simplest case by standard least squares. Since $F_0(t)$ is not known a priori, the standard approach in the case of signal search is to assume that systematics dominate the observed signal and set $F_0(t)$ equal to zero. The period search is performed on the time series obtained after the subtraction of the so-determined contribution of systematics. Once the period is found, the signal reconstruction phase follows, in which the complete signal model, represented by Eq. (1), is solved. For transit signals this step is iterative, whereas for multiperiodic signals, representable by Fourier series, the solution can be obtained in a single step ([51]).

Please note that the philosophy of all systematics filtering methods is fundamentally different from the standard ensemble approach. In the latter we *do not fit* the target time series but simply use the time-dependent total (ensemble) flux to correct for the effects of atmospheric variations by dividing the instantaneous target fluxes by the corresponding ensemble fluxes. Under ideal circumstances, this method filters out only the atmospheric component of the variation, but leaves the intrinsic variation of the object intact. On the other hand, all systematics correction methods listed in Table 1 *distort* the signal to some degree, and the main purpose of many methods is to minimize this effect without jeopardizing the filter efficiency too much. This can be attempted by using only the “essential” cotrending time series (estimated by Principal Component Analysis, e.g., TERRA) and formulate the problem in the Bayesian framework to allow proper weightings of the different contributions to the systematics (e.g., PDC, ARC). One may also try to employ the full model (see eq. 1) already in the period search phase, by assuming a certain type of signal with limited number of parameters. Surprisingly, this highly time consuming method can be implemented by a proper grid-search algorithm that runs with an acceptable speed ([7, 33]). Yet another way of running “full-fledged” period searches is to employ a Gaussian Process model that allows to weigh the different contributions to the signal by using properly chosen correlation kernels ([1]). MarPLE, the method developed for transit search on the sparse data of MEarth ([14]), is aimed also at conserving the signal shape, by using single nights to find single transits and combine these results within the Bayesian framework on the full dataset to find the period.

Unfortunately, these works lack a thorough comparison with the more traditional approach, in which the data are filtered first for systematics, and then, the signal search is performed on these filtered data (containing considerably less systematics and the signal – albeit the latter with various degrees of distortion). In a subsequent study by [54] this comparison was performed on the subsets of the HATNet and K2 databases. They found that full-fledged methods may have limited applicability due to problems related to the proper disentangling of the signal and systematics in the observed signal. It seems that the traditional approach (filter first, then analyze) works better.

4 Selected highlights – the variable star aspects

In addition to the highly competitive nature of the field of extrasolar planets, ground-based wide-field surveys have been making a significant impact also on various fields of variable star research. So far, altogether over a hundred papers have been published by these projects on objects (directly) unrelated to exoplanets. Several of them have received a considerable attention from the particular field (e.g., stellar rotations among Galactic field K–M stars [38] and in the open clusters Comae Berenices [26] and in the Hyades and Praesepe [30]). The fields covered by these “side” studies range from rotating asteroids ([70]) through classical pulsating stars ([81]) to supernovae ([80]). It is impossible to summarize all these topics in the depth they deserve. Therefore, here we go through the main fields

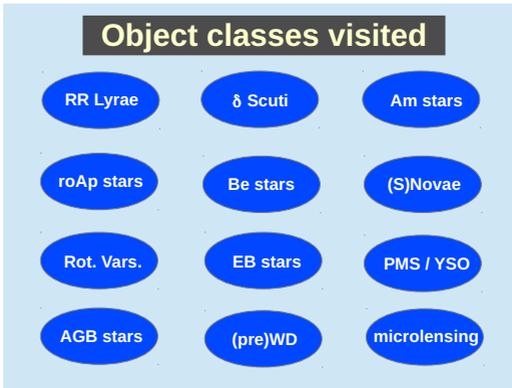


Figure 4. Classes of variable stars studied in various works using the data acquired by ground-based wide-field surveys.

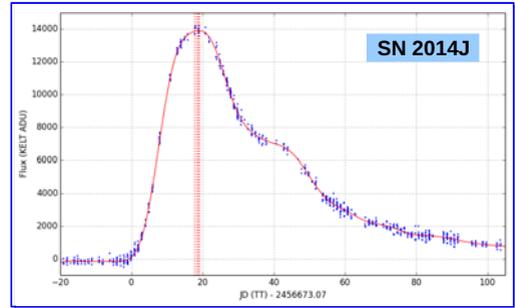


Figure 5. Detection of the pre- and post-outburst states of SN 2014J by using the survey data of the KELT project ([80]). (Reproduced with the authors' permission from [https://arxiv.org/.](https://arxiv.org/))

of study only briefly. Nevertheless, a few topics (reflecting mainly the prejudice of the author of this review) will be discussed somewhat deeper.

Except for some special topics (e.g., Solar System bodies [70]), the main types of objects visited by the survey-related investigations are shown in Figure 4. For curiosity, we also list “microlensing”, albeit this topic is limited to a single project only (for testing the ability of HATNet to detect microlensing events toward the Galactic Bulge [66]).

- *SN 2014J and eruptive stars:* By the very nature of the supernova explosions, they are usually discovered in the brightest phase, although some of them are caught already during rising light (e.g., [79]). On the other hand, the observation of the *pre-supernova* phase of SN 2014J in M82 ([80]) was absolutely unique until three similar events, back to 2011 and 2012, were disclosed in [69], by using the archive of the *Kepler* satellite. The full light curve, as observed by the KELT project, is shown in Figure 5. Analysis of the pre-burst state is very important for making a distinction between the various progenitor scenarios leading to type Ia supernovae explosions. In the particular case of SN 2014J, other (e.g., HST, X-ray and radio) observations exclude the single degenerate+large companion model, but white dwarf mergers are allowed both by the above data and by the pre-burst light curve ([36]).

Similarly exciting are the discovery of the precursor of Nova Sco 2008 ([91]) and the quite recent announcement of the nova candidate KIC 9832227 for an outburst in 2022 ([65]). In both cases the precursors are W UMa binaries, and the prediction in the latter case relies on the observation of a similar steep decrease in the orbital period as for V1309 Sco, the binary progenitor of Nova Sco 2008. Both works utilize survey data, including those coming from wide-field projects (NSVS, ASAS, SuperWASP).

For other eruptive phenomena, we draw attention to several studies performed by utilizing the SuperWASP survey. A handful of novae (recurrent and transient) were investigated by [63]. Other works on eruptive variables can be found in [22] and [90].

- *Pulsating subdwarf B (sdB) stars:* SuperWASP pioneered the extension of variability search in the frequency regime close to or above the sampling rate used in the standard exoplanet survey mode.

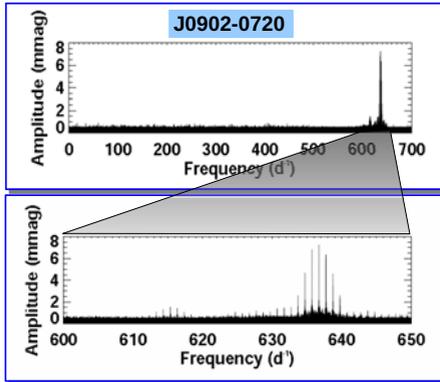


Figure 6. Frequency spectrum of the sdB variable J0902 discovered by [44] using the survey data of the SuperWASP project. *Upper panel:* full spectrum. *Lower panel:* spectrum zoomed in around the high-power regime. Please note the absence of low-frequency alias due to the lack of strong periodicity in the data sampling. (Adapted with the authors' permission from [https://arxiv.org/.](https://arxiv.org/))

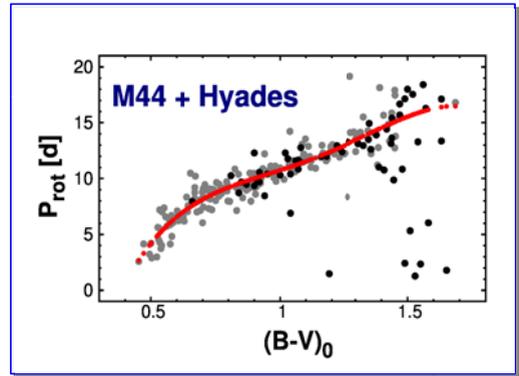


Figure 7. Color-period diagram for the rotational variables of the open clusters Praesepe and Hyades ([50]). Red dots show the fourth-order polynomial fit to the combined data of Praesepe (gray points, HATNet) and the Hyades (black points, SuperWASP [30]). The two clusters have similar ages, leading to similar ridges for the rotationally settled stars. (© ESO; reproduced with permission.)

This has led to various exciting discoveries, including rapidly oscillating Ap stars (see later) and pulsating sdB stars (see Fig. 6).

- *Rotating stars in open clusters:* Stellar rotation can be exhibited through the photometric variation induced by the varying spot coverage of the visible hemisphere of the star. Prior to the wide-field surveys, specific targets in the field and open clusters were the subjects of individual projects, often facing with the difficulties detecting low-amplitude non-stationary signals on the time scale of few days to months. On the other hand, this kind of variability is in the comfort zone of the wide-field surveys. As already noted at the beginning of this section, several pioneering works have been made on open clusters and on the field by SuperWASP, KELT and HATNet.

Figure 7 shows the combined diagnostic diagram of stellar rotation for two famous clusters of the same age. The method of gyrochronological age determination of field stars is based on these kinds of diagrams ([13]; see, however, the current controversy on the applicability of this method to field stars: [21, 50, 94].)

- *δ Scuti stars and variability of A-type stars:* Stars on and close to the main sequence with spectral types A to F are known to exhibit low-amplitude, short period pulsations, often identified as p- or g-mode pulsations or some mixture of these. One of the unanswered questions concerning these variables is the dependence of the occurrence of the pulsations on the physical parameters. In spite of the theoretical expectations, only a fraction of the stars pulsate in the instability strip. Low sensitivity of the variability surveys is no longer an issue. Indeed, even with the exquisite accuracy of the *Kepler* space telescope, we find that only 12% of the stars in the instability strip are δ Scuti or γ Dor (or mixed) variables (44% are spotted or eclipsing variables, and the remaining 44% are constant [19] – see also [18] for a more extended survey). Most of the variables have amplitudes above 1 mmag, i.e., within the reach of ground-based wide-field surveys. Indeed, many papers have been published on these stars, most of them utilizing the SuperWASP data.

One of the most exciting findings was the discovery of the large occurrence of pulsators among Am stars (although rare occurrence of Am star pulsations was known from sparse earlier works – e.g., [56]). From the examination of 1600 Am stars, [82] found 200 variables exhibiting pulsations similar to those of “normal” δ Scuti or γ Dor stars. The excitation mechanism of these stars could result from some delicate mixture of gravitational depletion of metals, rotation and turbulence (see the spectroscopic survey of Am stars by [83]). Further examination of 1.5 million stars in the F–B spectral range also in the SuperWASP database by [43] has led to the discovery of additional Am stars and 10 rapidly oscillating Ap stars (a class of chemically peculiar stars, discovered unexpectedly by [55] in 1982).

- *Other diversities:* Unfortunately, we have space only to name a few of the many exciting results: dimming episodes in young stellar objects ([76, 77]); active main sequence B stars ([57]); RR Lyrae stars with Blazhko effects ([81, 86]); AGB stars ([8]); eclipsing variables: quadruple (quintuple?) system ([59]), the longest eclipse ever measured ([78]; see also [58]), eclipsing variable close to the short period limit ([60]), etc.

5 Conclusions

We cannot conclude without emphasizing the great importance of the Northern Sky Variability Survey, NSVS (based on the observations of the Robotic Optical Transient Search Experiment, ROTSE-I, PI: *Carl Akerlof*) and the All Sky Automated Survey, ASAS (PI: *Grzegorz Pojmanski*) that proved the concept, the significance and the competitive scientific role of small, fully robotic instruments. We should also recall the indefeasible role of *Bohdan Paczynski*, who was a very strong supporter of small telescope variability surveys.

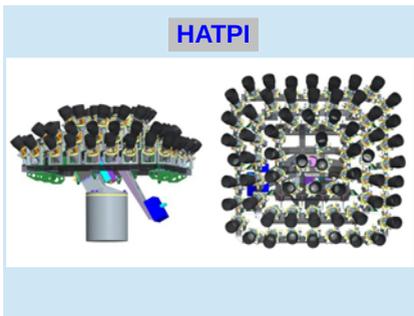


Figure 8. Computer drawing of the HATPI platform, hosting 63 instrument-holder units (with optics, CCD and fine-pointer mechanics). The cameras will take images in every 30 seconds virtually on the full visible sky at the Las Campanas Observatory. The project is in the active phase of development. When operational, it will be the biggest undertaking relative to other similar projects, such as EVRYSCOPE (<http://evryscope.astro.unc.edu/>), FLY’S EYE (<https://flyseye.net/>) and MASCARA (<http://mascara1.strw.leidenuniv.nl/>).

Today’s wide field surveys grew up from the exciting and highly challenging idea of discovering extrasolar planetary systems by using the rare events of tiny dimmings of light when the planet moves across the line of sight between the star and the observer. These projects have reached the level of efficiency when the discovery of this kind of events became standard. New methods of time series analysis have been developed, fertilizing other fields of research and helping in the development of the proper filtering of the data acquired by the various space missions. The data gathered by these projects are immense in size and we are only at the beginning of utilizing the millions of light curves observed over the past 15 years. The examples shown in this summary suggest the wide range of applicability of these databases.

Continuing and further developing ground-based wide field surveys will remain a significant goal in observational astronomy, in spite of highly competitive ground- and space-based projects (e.g., LSST, TESS). Full utilization of these data (including merging the different databases and their combination with other data from the ground and space) is still ahead. New projects are in progress (e.g.,

see Fig. 8), aiming at more continuous sky monitoring with the goal of covering a great variety of astrophysical phenomena from transiting planets to supernovae. We are sure that these assets will constitute an integral part of future variable star studies.

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