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Synergies in Variability Studies of Stars, Supernovae, and Active Galactic Nuclei

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Abstract. We introduce some basic concepts concerning multiband investigations of variable sources such as stars, supernovae, and active galactic nuclei. These topics have been widely discussed during the international workshop *Variability with Wide Field Imagers*. We summarize the main conclusions of this Workshop and briefly outline possible avenues for future broad collaborations.

Key words. Variability - Supernovae - Active Galactic Nuclei

1. Introduction

The organization of this workshop was motivated by the circumstantial evidence that present day telescopes equipped with CCD mosaics allow the observation of a large number of objects in wide ($\sim 1deg^2$) fields down to very faint limiting magnitudes. Repeated observations of the same field also allow the determination of light curves of statistical sample of variable sources. The main goal of this Workshop was to bring together scientists from different astronomical and astrophysical communities whose common interest was the study of variable phenomena with time scales ranging from seconds to years, and were potential users of wide field capabilities of state-of-the-art technologies.
The astrophysical research we are interested in presents two key features. First, the very nature of the time dependent phenomena require that observations be distributed over long time interval. This causes difficulties both in obtaining such a substantial amount of observational time and in scheduling the observations according to the required strategy. Second, all these projects end up with a huge amount of data. These databases require unprecedented capabilities in data handling, reduction, and analysis. However, quite often the gathered observations for a specific project may be useful for other projects in different scientific areas. The recent literature demonstrates that survey data are a longstanding gold mine, and therefore they should be archived and made available to the community. The main aim of this workshop was to discuss whether it is possible, and/or in which cases it makes sense

to plan survey projects that may satisfy the needs of more than one community. Moreover, what are the main requirements for producing data that, even if not optimal, present the great advantage to have a large number of end users and, finally, what are the advantages in terms of the cost/benefit ratio?
Thus the purpose of the discussion was to share competencies and to identify a few possible "common projects" that could then be studied in detail and possibly lead to joint projects. The starting point was to define the different needs concerning spectroscopy, photometry, astrometry, integration time, repetition rate, field width, speed of data analysis. Also different strategies, like continuous monitoring of specific regions versus scanning large portions of the sky, or number of detections versus magnitude depth, or detailed investigations versus "quick look" approaches have also been addressed.
In the following we introduce some concepts concerning variability studies in the fields of Variable Stars (VS), Supernovae (SN), and Active Galactic Nuclei (AGN). In the last section we briefly outline some ideas which emerged during the meeting.

2. Variable Stars

During the last few years variable stars have been the crossroad of several empirical and theoretical investigations. The reasons are manifolds. Radial variables and in particular classical Cepheids are the first ladder in the cosmic distance scale. The HST key project succeeded in the identification of these objects in the Virgo and in the Fornax cluster and provided the unique opportunity to calibrate secondary distance indicators such as the Supernovae Type Ia and the Tully-Fisher relation (Freedman et al. 2001; Saha et al. 2001), and in turn the evaluation of the Hubble constant (Bono 2003a).
At the same time, the microlensing experiments (EROS, OGLE, MACHO, PLANET), aimed at the detection of baryonic dark matter in the halo and in the bulge of the Galaxy, provided an unprecedented amount of photometric data. These experiments have been run for several years with small telescopes (1-1.5 m) and mosaic CCD cameras with field of views of the order of 0.15-0.25 deg^2. Thanks to these experiments the number of variables for which accurate pulsation parameters (periods, mean magnitudes, colors, amplitudes) are available has been substantially increased often by one order of magnitude. To increase the probability to detect microlensing events, these experiments required background fields characterized by high stellar density, namely the Galactic bulge and the central regions of the Magellanic Clouds. On the other hand, experiments aimed at detecting low and high redshift SNe (Perlmutter et al. 1997; Schmidt et al. 1998, 2003; Cappellaro et al. 2003) as well as the Sloan Digital Sky Survey (Fan et al. 2001; Ivezic 2003) were mainly interested in high Galactic latitude fields to avoid both the crowding and the reddening problem. The time sampling of these survey is limited and they do not cover a long time interval. However, they are relatively deep and typically they collected *at least* three photometric bands. On the basis of these data, Yanny et al. (2000) and Ivezic et al. (2000) identified an overdensity of A-type giants and RR Lyrae in the halo located at ≈ 50 Kpc from the Galactic center. Subsequent independent observational investigations (Ibata et al. 2001; Vivas et al. 2001; Vivas 2003) brought forward the evidence that such a clump is the northern tidal stream of the Sagittarius dSph. Note that according to current empirical evidence the stellar content of Sagittarius in a few Gyr will merge with the Milky Way due to the strong gravitational interaction between these systems (Ibata et al. 1994). The key role that RR Lyrae stars can play as tracers of the old stellar component has been further strengthened by the results obtained by Schwarzenberg-Czerny (2003). They detected a sizable sample of RR Lyrae stars

and on the basis of their radial distribution found that the halo might extend up to 100 kpc from the Galactic center. Note that globular clusters can hardly be adopted to trace the shape and the extent of the halo, since only a dozen of globular clusters are located at distances of the order of 100 kpc.

These results disclose two interesting new paths in the field of the Galactic structure: *i)* the radial distribution of field stars in the halo is clumpy and these structures might supply fundamental hints on the dynamical interaction between the Galaxy and Local Group galaxies (Lynden-Bell 1999). *ii)* The radial distribution of RR Lyrae, once confirmed by independent investigations, seems to suggest that several LG dwarf galaxies up to the Carina dSph are inside the Galactic halo.

The empirical scenario has been jazzed up by new ongoing projects aimed at monitoring the entire sky for variability, such as ROTSE, ASAS, and TASS. These experiments use instruments with apertures of the order of a few inches but they cover the entire sky twice per night. They have already discovered thousands of new variables and according to very preliminary estimates they should be able to discover more than one million variables in a few years (Paczynski 2000). The ROTSE experiment has been constructed to search for gamma-ray burst optical afterglows soon after the trigger and it was successful (Kehoe et al. 1999). Even though the limiting magnitude of this experiment is of the order of $m_v \approx 15$, in a small subsample of data covering 2000 deg^2 ($\approx 5\%$ of the entire dataset) have been identified more than 1700 variables and more than 90% of them are newly identified variables (Akerlof et al. 2000). They extracted a sample of $\approx$ 190 RR Lyrae stars and on the basis of their radial distribution provided an independent estimate of the tick disc scale height (Amrose & Mckay 2001).

Although the above experiments were designed for specific targets their impact on variable stars and stellar populations was striking. The key reason for this circumstantial evidence is that the time scale of variable stars cover a broad period range: a few minutes for white dwarfs; hours for δ Scuti, Oscillating Blue Stragglers, RR Lyrae, and β Cephei (Bono 2003b); days for BL Herculis; tens-hundreds of days for classical Cepheids, type II Cepheids (Bono et al. 2002); and years for Mira. Moreover and even more importantly, they are ubiquitous in the Galaxy. This means that wide and/or deep surveys for the detection of variable stars are marginally affected by pointing issues.

Radial variables are generally characterized by luminosity amplitude larger than one magnitude in the B-band. However, some groups of variable stars such as the δ Scuti and binary stars may present luminosity amplitudes of the order of a few tenths of magnitude or even smaller. Moreover, large amplitude variables present along the light curve secondary features such as bumps and/or dips with amplitudes ranging from a few hundredths to a few tenths that are crucial to properly investigate the dynamical motion in the outermost layers (Bono et al. 2000). This means that photometric accuracy (S/N$>$ 50) is a major issue in the observation of variable stars. The same outcome applies to both absolute and relative zero-point calibrations (Dall'Ora et al. 2003; Monelli et al. 2003; Bono et al. 2003c).

The reduction technique adopted to perform the photometry and to identify variable sources is also crucial. Obviously this problem becomes of paramount relevance in crowded regions such as the bulge or the innermost regions of globular clusters. To overcome these problems it bas been recently developed by Alard (1999, 2000) a new method of image subtraction (ISIS) that when compared with the canonical profile fitting methods supplies a substantial increase in the number of variable stars detected as well as an improvement in the photometric accuracy of light curves (Olech et al. 1999). According to recent evidence it is not clear whether this method might be affected by calibration problems (Corwin et al. 2003). A different approach to analyse large datasets of multiband time-series data collected with different telescopes has been adopted by Stetson et al. (2003), who adopted DAOPHOT/ALLFRAME (Stetson 1994). This method is computer demanding, since the profile fitting is simultaneously performed over the entire sample of CCD frames, but the absolute calibration is trivial.

A further substantial requirement to fully exploit the use of variable stars not only as standard candles but also as stellar tracers is to collect data in at least two and possibly in three different bands. The color information is crucial to properly estimate the reddening, and in turn to soundly locate the variable in the Color-Magnitude diagram. Finally, we mention that for photometric data sets that include more than 20-30 phase points in at least one band, the time sampling might not be a thorny problem, if the data are homogeneous and cover a large time interval.

3. Supernovae

In the local Universe Supernovae are discovered by means of dedicated surveys on large samples of individual, nearby galaxies carried out by professional and amateur astronomers. At larger distances the SNe become fainter but the volume inspected by a single frame increases to include thousands of galaxies. The introduction of mosaics of CCDs has improved this favorable condition so that there is a significant chance to image a new SN in each deep, mosaic frame at high galactic latitude. This means that the searches at high and intermediate redshifts can discovered SNe "on demand".

The scientific interest for distant SNe is manyfold. Type Ia SNe are probably the best probes of the cosmological models; their systematic discovery and photometric calibration at high redshift, carried out independently by the Supernova Cosmology Project and the High–Redshift Supernova Search (Perlmutter et al. 1997; Schmidt et al. 1998), has excluded the existence of a deceleration as expected from an Einstein–de Sitter Universe and has provided evidence for a cosmic acceleration in a low mass–density Universe consistent with a non–zero vacuum energy density (Riess et al. 1998; Perlmutter et al. 1999). Although the importance of such finding cannot be underevaluated it is clear that these results need excellent supporting evidence during the next few years in order to test the homogeneity, the environmental effects and evolutionary trends of SNIa. Clearly the new wide field imagers entering into operation at major observatories will play a major role.

Cosmological SN searches will provide the natural database for the determination of the frequency of SNe. So far the computation of the rate of SNIa at redshift z $\simeq$0.55 has been performed on the SPC material (Pain et al. 2002). On the other hand the determination of the rate of core–collapse SNe (SNII and Ib/c) is particularly suited for the study of the instantaneous star formation rate at different redshifts because of the short life time of their progenitors. A SN search devoted to the determination of the rate of SNe of different types (including those from core–collapse) at intermediate redshift is providing the first results (Altavilla 2003).

Both the study of the cosmological parameters and the determination of the history of the SF need large statistics in order to get significant improvements with respect to current results. This translates in enormous amounts of observing time and archiving plus data reduction resources. It becomes therefore natural to look for synergies with other wide field surveys and to compare the requirements of various science projects.

Because of the isotropy of the Universe at large scale and the format of the new CCD mosaics (up to 1 sq. deg), *all fields at high galactic latitude are in principle suitable* for the search of high–redshift SNe. This is important issue in favor of possible collaborations.

On the other hand SNe require a *specific observing strategy*. Indeed SNe are discovered by comparison of the frames with reference images obtained before the SN explosion. Since the rise to maximum luminosity is fast and the the light peak deserves most of the interest both for the photometric calibration and for getting the spectroscopy, the new and the reference images have to be taken at short distance. The high–z SNe have usually chosen a spacing of 2 weeks between the reference and the discovery images.
The typing of the SNe is usually performed with spectroscopy and in the case of high–z SNe very long exposure times at the largest telescopes are requested. Going to handle very large samples of candidates, one has to find other ways of classification. A possible alternative is to make use of photometric classification (light and color curves, e.g. (Poznanski et al. 2002). In other words it is possible to envisage *multiband SN surveys* which are self-contained, i.e. do not need follow up programs for spectroscopy and photometry. Such surveys offer the advantage to allow the determination of the photometric redshifts of the galaxies under investigation and naturally provide the ideal database for several other variability subjects.
Finally, a major issue is the *data handling* of the variable objects detected during each night of wide field imaging. As an example, a specific MySQL tool for SNe has been developed for the ESO search at intermediate redshifts (Riello 2003). Thanks to their flexibility such tools can be improved to include features useful to any other variable source.

4. Active Galactic Nuclei

Wide field variability studies allow to carry out different, and partly related, projects.

i) Detection of new Active Galactic Nuclei candidates

The study of the cosmological evolution of the luminosity function (LF) of quasars (QSOs) and Active Galactic Nuclei plays a crucial role in understanding the AGN phenomenon and its relation to the formation and evolution of structures in the Universe. According to recent studies, after $z \sim 3$ the change in cosmic time of the LF depends on galaxy encounters and the associated change of feeding rate of the central black hole (Cavaliere & Vittorini 2000). To understand these phenomena, statistical samples of QSOs/AGNs with known and quantifiable biases are needed. Color selection, i.e. non stellar color, is the most common technique adopted to identify QSO/AGN candidates, but it is restricted to objects of point like appearance, namely to objects whose nuclear component swamps the emission from the host galaxy. The evolution of the bright end of QSO LF is relatively well known, thanks also to the huge amount of new data provided by recent surveys as the 2dF (Boyle et al. 2000) and the Sloan Digital Sky Survey (SDSS)(Fan et al. 2001). However at low luminosities the information on LF evolution is poor. Not only for the apparent faintness of high redshift, intrinsically faint objects, but also for the impossibility of applying the color technique to objects dominated by the host galaxy (stellar) light (Trevese et al. 1989; Sarajedini et al. 2000, 2003). Selecting QSOs/AGNs through their variability (Hawkins 1983) allows the evaluation of the incompleteness of color selected samples and selection of nuclei with intrinsic luminosity comparable or lower than the host galaxy (Bershady, Trevese, & Kron 1997). Representing the "structure function" of variability as $S(t) = A[1-e^{(-t/T)}]$, where t is the time lag between observations and A the r.m.s. variability at "large" t, typical values are $A \approx 0.4$ mag and $T \approx 6$ months (Trevese et al. 1994). A minimum of 3 observations with a time interval of a few months is required for candidate identification. The minimum time interval, however, depends on photometric accuracy, since small variation can be detected with time intervals < 1 month (Ivezic 2003). Notice also that proper motion information allows discriminating between variable stars and (point-like) QSOs/AGNs.

ii) Variability of the continuum spectral energy distribution

Despite the role of variability in constraining the size of active regions, its very origin is substantially unknown. In fact the most diverse mechanisms have been proposed, as supernovae explosions (Aretxaga et al. 1997), gravitational lensing (Hawkins 1993) and instabilities of the accretion disk (Kawaguchi et al. 1998). Most of the information available so far is based on single band variability studies of statistical QSO samples. These studies have demonstrated a dependence of variability amplitude on intrinsic luminosity and redshift (Giallongo, Trevese, & Vagnetti 1991), the latter being due to the increase of variability with emission frequency, coupled with the increase of the rest-frame frequency with redshift, for a fixed observing band (di Clemente et al. 1996). This dependence has been confirmed by Trevese, Kron, & Bunone (2001) for a relatively small complete sample of objects observed in four bands at two different epochs. More recently the increase of variability with frequency has been quantitatively confirmed in a large sample of objects, on the basis multi band data of the SDSS (Ivezic 2003), which however provide only a sparse time sampling, at least so far. To date, the only existing statistical AGN sample monitored in two bands, with adequate time sampling and duration, has been provided by the Wise Observatory group (Giveon et al. 1999). This is a subsample of nearby ($z< 0.4$) and bright ($B< 16$) PG quasars, monitored in B and R bands for about 7 years with a typical sampling of about one month. On the basis of these data (Trevese & Vagnetti 2002) have shown that, a statistical analysis of spectral slope changes allow to set constraints which exclude some possible mechanism for the origin of variability see also Vagnetti & Trevese (2003). Monitoring of a wide field to faint magnitudes can provide light curves for a large statistical sample of objects (e.g. several hundreds). Taking into account the increase of variability for decreasing intrinsic AGN luminosity, and the fact that high redshift objects are observed at higher rest-frame frequencies, where they are more variable, a survey of this type is ideal to detect intrinsically faint AGNs at intermediate redshift. For the sole purpose of detection, the number of observations would be minimized by the use of a single band, and a samplig interval of ≈ 6 months, however, multiband photometry with a sampling of ≈ 10 days would provide unprecedented statistical information to constrain the physical nature of variability allowing at the same time the detection of new AGNs. Moreover, as in the case of Supernovae, *all fields at high galactic latitude are in principle suitable* for this kind of studies.

5. Final remarks

We have discussed the impact that multiband time-series data might have in different fields of current astrophysical research. The main conclusions can be summarized as follows:

i) Several new variability surveys are being planned for specific goals. However, sometimes the optimization of the observing strategy, i.e. time sampling, photometric system, area covered, hampers the use of the same database for different scientific projects. In some cases even minor modifications to the strategy, non altering the focus of the survey on the main scientific driver, may considerably increase the impact of the same data for parallel projects. In this sense the involvement of scientist interested in different projects may contribute to increase significantly the scientific throughput and hence the success of the survey.

ii) The new observing facilities that are or will become soon available to the astronomical community (SuprimeCam@Subaru, LBC@LBT, VISTA, OmegaCAM@VST) allow to develop deep compact surveys that cover limited sky regions (≈ 100 deg^2) down to very faint limiting magnitudes $m_V \approx 26$. Detailed plans concerning the time sampling, the photometric bands, signal to noise ratio of individual measurements, and the target selection (high vs low Galactic latitude) can allow us to accomplish outstanding scientific goals in different astrophysical and cosmological fields. The main advantage in these projects is that quite often contamination problems (background, foreground stars and galaxies) might be a gold mine of information for other communities.

iii) Finally we also like to mention that such large amount of data will require the development of new algorithms not only to perform the photometry and the astrometry but also to detect variability in a broad range of astronomical sources that might be periodic or aperiodic on time scales that range from minutes to years (Schwarzenberg-Czerny 2003). These future scientific challenges can be hardly accomplished by small groups, large international collaborations seem to be mandatory.

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