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New Instrumentation for Transient Follow-Up

Workshop 10

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Abstract. Wide-angle surveys at different wavelengths are already providing triggers for very different kinds of transients. The most interesting science is produced when new sources are followed-up and characterised by using the right instrumentation, telescopes and observing strategies. In the coming years, with new large-scale surveys such as ZTF and LSST, the amount of triggers is expected to scale up massively. Furthermore, new observational windows, such as gravitational waves or neutrinos, are now opening and adding complexity to the picture. The instrumentation and strategies that we have been using over recent years may just not be appropriate for those new situations. In this Workshop we discussed the present and projected future of transient discovery, the instrumentation that will be needed for the follow-up of those targets, and the observing strategies, data analysis and community efforts that will be required to tackle the challenges that lie ahead of us.

Keywords. Instrumentation: miscellaneous, techniques: miscellaneous, methods: miscellaneous

1. Introduction

Transient astronomy is entering a golden era as new large surveys such as ZTF and LSST promise to multiply the rate and amount of transient sources that are discovered. The numbers of sources will be too great to apply past follow-up strategies, and we must rethink pre-selection and follow-up strategies in order to characterise the sources adequately. What the actual survey telescopes do in that regard is only very rudimentary.

With the detection of the first counterpart of a gravitational-wave (GW) source, we have also entered into the multi-messenger era that is joining the electromagnetic (EM) and GW fields. This first example has probably been the most intensely observed object in the history of astronomy, but such an effort will not be possible for future events. Another connection that is still missing is the detection of EM counterparts to neutrino events. Both regimes, GWs and neutrinos, are very complementary to EM emission from luminous explosions since (for instance) they are the only ones able to probe the processes going on inside the exploding star.

In this Workshop we discussed current transient sources and the follow-up challenges which they have presented to us to date. We then discussed the needs of future instrumentation for both the follow-up and the machine-learning techniques that would be required to filter out the most interesting events in order to follow them up more closely. The discussion was lively, and although it did not reach a final conclusion, the participants were made aware of the manifold issues which will have to be addressed in carrying out transient follow-ups in the era of large-scale surveys.

2. Transient Surveys and Alert Observatories (led by D.A. Kann)

2.1. *Overview*

Transients include any kind of variable sources. Here we concentrated on explosive transients. The most luminous are gamma-ray bursts (GRBs) and supernovæ (SNe); classical novæ are at the lower end of the luminosity scale. New objects or types have been found, such as tidal disruption events (TDEs, e.g. Levan *et al.* 2011), kilonovæ (associated with short GRBs, see e.g., Tanvir *et al.* 2013) and luminous red novæ. Another curious transient class are so-called 'fast radio bursts', whose nature is still unclear (Katz 2016).

Following the nature and evolution of different transients involves different reaction times. GRBs fade very quickly, but fortunately rapid localisations are available these days. *Swift* (Gehrels *et al.* 2004) is providing arcsecond positional accuracy within minutes, though other detectors such as Fermi/GBM are more challenging as their error boxes are of the order of square degrees. The interplanetary network (IPN) of gamma-ray detectors in Earth orbits was once a valuable source of GRB triggers, but after several missions dropped out the error boxes became large and alert distributions very slow. For alerts with large error boxes, there are two approaches for searching for the afterglow: a 'brute-force' method that simply makes tiling observations of the entire error box, or a more sophisticated method which targets specific galaxies that could have hosted the event. This was highly successful in the case of the GW/EM event GW170817, where we were given additional information of the distance. In fact, its EM counterpart was discovered by the Swope SN survey (Coulter *et al.* 2017) and the DLT40 survey (Valenti *et al.* 2017) that targeted all non-star forming galaxies at distances <40 Mpc.

Supernovæ are usually discovered by wide-field transient surveys with possible back-tracking, and evolve slowly for weeks to months. Alerts are distributed in a semi-fast way, of the order of hours to days. However, recent research has shown that faster reaction time for so-called 'flash-spectroscopy' (Gal-Yam *et al.* 2014) in order to catch the shock breakout provides crucial insight into the explosion mechanism. Kilonovæ, on the other hand, evolve relatively quickly, particularly at optical wavelengths, but more slowly in the NIR; NIR observations have therefore proven important for those transients.

Future challenges for these explosive transients are many. For GRBs, we are still highly dependent on the accurate localisations provided by *Swift*. A few relevant missions are being planned, e.g., THESEUS (Amati *et al.* 2017) and ATHENA (Nandra *et al.* 2013), but only the French-Chinese SVOM mission (Godet *et al.* 2012) is scheduled to launch in the near future. We expect to discover SNe in large numbers once all-sky surveys go on-line. The current classification of SNe is mostly complete, but will not be sustainable as numbers increase, and statistical studies will be affected. The EM detection of a GW was probably a fortunate coincidence; better collaborative efforts are probably needed to catch more of those events. EM counterparts to neutrinos are the next challenge, but their positional error boxes are also many square degrees, making localisations difficult.

2.2. *Discussion*

The first large-scale survey scheduled to come on-line is ZTF (Smith *et al.* 2014); see Bellm (p. 160). ZTF saw first light in 2017 November, and will distribute the first alerts in 2018 April. It is expected to detect 10^6 alerts per night per year. For the two public surveys (40% of the total survey), alerts will be public in real time, providing ∼600,000 alerts per night; a 30-day history with forced photometry will also be provided.

Alerts will have a delay of at least 30s; more realistic values are 2–5min. Transients can be detected at a Dec. > –30 deg and a limiting magnitude of ∼20.5. Radio transients will also be detected by MeerKAT, and will be fully public. The additional information

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Table 1. Examples of transients and typical follow-up strategies

Object	Type	Detection	Follow-up	Primary observations
Novae	Recursive	Optical	Optical/NIR	Broad wavelength, high spectral-resolution
Supernovae	Destructive	Optical	Radio to X-ray	Broad wavelength
GRB	Destructive	Gamma-rays	Radio to X-ray	Fast response, broad wavelength
SGR	Recursive	Gamma-rays	Radio to X-ray	Fast response, high time-resolution
TDE	Destructive	Gamma-rays,optical	Radio to X-ray	Broad wavelength
XRB	Recursive	X-rays, optical	Radio to X-ray	High time-resolution

will enhance and improve the alerts for FRBs so we hope that finally we can determine their nature.

As the community agrees, there is a need for a sociological change to how we cope with huge numbers of alerts. Collaborative efforts are needed, instead of repeating observations between competing groups; otherwise, most transients will be 'lost'. For example, *Kepler* discovered thousands of planets, but only about 5 were followed up thoroughly.

Furthermore, we need to find a way to share data better, even if there is no immediate plan to publish them; they might not be numerous enough for an article, but could be very interesting for other groups or statistical samples. A good example in that respect was the recent GW/KN event GW170817: studying the object in only one wavelength region would have been of little value. Finally, large samples of transients will enable us to carry out improved statistical studies on even the most rare transients.

3. Follow-up Instrumentation (led by A. de Ugarte Postigo)

3.1. *Overview*

The varied families of transient sources are detected by different types of surveys and alert telescopes. Gamma-ray bursts and magnetars are usually detected by high-energy satellites; novæ and supernovæ are discovered by optical surveys, and fast radio bursts have been discovered exclusively by radio telescopes. Furthermore, owing to the ranges in brightness and variability time-scales, these different types of transients may also require tailored follow-up instrumentation and observing strategies. The respective 'response times' similarly vary; sources such as GRBs require very fast reaction times of a few minutes (or even seconds!), whereas for novæ or supernovæ reaction times of days are adequate for most science cases. As to wavelength coverage, in most cases follow-ups will be desirable in as many wavelength regions as possible, from radio to X-rays or even gamma-rays, although interest may be focused on a specific range. As an example, we have compiled in Table 1 the information relative to some typical transient events.

No single instrument exists that can cover the needs for the follow-up of all types of transients. There are two principal characteristics that render an instrument very valuable for observing transient sources: (a) broad wavelength coverage, and (b) simultaneity. The following discusses three types of instrument: imagers, spectrographs and polarimeters.

Imagers: Imagers can be used to localise targets when the trigger coordinates are not precise enough. For that purpose, a field of view is needed that is at least as large as the error box, and preferably operating robotically, to respond quickly to those alerts (e.g., MASTER, Lipunov *et al.* 2016). Imagers can be also used to study the spectral energy distribution by providing photometry of the object in different bands. To that end, an imager with several simultaneous bands observed, for example, with the use of dichroics, is ideal (e.g., GROND, Greiner *et al.* 2008, LSST, LSST Science Collaboration *et al.* 2009, and RATIR, Butler *et al.* 2012). For transients with rapid temporal variations such as pulsars or magnetars, we would be looking also for high time-resolution; ULTRACAM and HiPERCAM are good examples there: e.g., Dhillon *et al.* 2016).

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Spectroscopy: Spectrographs used for transient studies will need to offer a range of spectral resolutions. Classifying objects like supernovæ, for instance, usually only requires low resolution; on the other hand, many novæ are bright and detailed analyses benefit from high spectral resolution. Somewhere in between lie GRBs, which need only low resolution for redshift determinations but high resolution can be put to good use for studying the dynamics of their host galaxies if absorption features can be resolved. In all cases, a desirable characteristic is broad spectral coverage. The X-shooter spectrograph (Vernet *et al.* 2011), at ESO's VLT, is a good example of an intermediate-resolution spectrograph having broad wavelength coverage, and is optimal for transient study. Other examples of instruments that share the characteristics of X-shooter are NTE at the 2.5-m NOT, SOXS at the 3.5-m NTT (Schipani *et al.* 2016), and OCTOCAM at the 8.1-m Gemini-South (de Ugarte Postigo *et al.* 2016).

Polarimeters: Polarimeters provide information about the geometry and magnetic fields of a transient. They can be constructed as imaging polarimeters, using observing bands similar to those used by normal imagers, or spectropolarimeters which combine polarimetry and spectroscopy to obtain a very detailed view of a source. Those instruments usually require very high signal-to-noise ratios, so their use is limited to bright sources. They usually require multiple exposures to obtain a measurement (e.g., FORS Appenzeller & Rupprecht 1992), but can be built so as to work with single exposures and are thus more suited for rapidly evolving transients; examples are RINGO (Steele *et al.* 2006) and WeDoWo (Oliva 1997).

One will often need to combine some of those technologies to obtain a complete analysis of a transient source. Suggestions are currently being mooted to combine all the characteristics into a single instrument. A good example is OCTOCAM (de Ugarte Postigo *et al.* 2016); it has broad wavelength coverage, multi-band imaging, intermediate resolution spectroscopy, high time-resolution capabilities, and the potential to incorporate a spectropolarimeter. When considering instrumentation for transients, it is important to include reliable pipelines for reducing and analysing data rapidly, to incorporate efficient operations for optimising the observing times, and to rely, as much as possible, on automatic procedures, for example for target acquisition.

Efficient follow-up of transients often implies involving multiple observatories. That has already been tried by projects like the Palomar Transient Factory (PTF, iPTF, ZTF, Smith *et al.* 2014) and Las Cumbres Observatory (Brown *et al.* 2013), which combine different instrumentation operating over a similar range of observations. A good example of coordinated observations employing different spectral ranges is MeerKAT+MeerLICHT (Bloemen *et al.* 2016), which will combine radio and optical observations.

3.2. *Discussion*

Current observatories and instruments can play a very important role in transient studies if they are suitably optimised. Optimisation can include implementing procedures such as rapid response modes (RRM, Vreeswijk *et al.* 2007), adding operations that do not require human intervention, and coordinating observations made by different telescopes.

The selection of targets to be observed is also important. Instruments such as 4MOST (de Jong *et al.* 2012), which has 2400 fibres, can be optimised through the use of dynamic target selection connected with target brokers linked to big surveys, thereby providing many transient detections. Having efficient transient classifications and studies implies a good target selection to optimise observations and efficient target classification, using as few observational data as possible. We expand on this aspect below.

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4. Follow-up Strategies (led by A. Mahabal)

4.1. *Overview*

The crucial stage of the next generation of surveys will be the selection of the most interesting targets from hundreds of thousands of potential alerts. An early probabilistic classification of targets is needed in order to decide whether a detection warrants a follow-up. Machine learning, aided perhaps by citizen science to generate early training data sets, will be indispensable. We will also have to determine how best to distribute the alerts among available facilities in order to optimise the scientific returns.

Many of these issues have been discussed in the past at great length. The solutions have invariably been focused on the survey at hand, and invoke some use cases, generally at the expense of additional potential science. The sociology of follow-up is often interesting; for example, CRTS releases transient alerts in real-time and does not have follow-up resources for a vast majority of sources. Yet many sources that are potentially interesting go unresearched because the community is split through various alliances. Something like the TNS service may be a good start, but it needs go further and to become more encompassing and universal.

Triggers detected by surveys can be private or public. While most are in the public domain, the extent of accompanying information varies greatly, and at times the attendant additional data are not available until an annual release. Because large teams built LIGO, initial access has only existed by way of MOUs. LVC explored selective distribution of error-areas, and parsed the follow-up space by a meaningful division of labour, but quickly discovered the difficulties. As the follow-up of GW events were to show, sharing data and collaborating is going to be increasingly important as we concentrate on similarly rare and interesting objects.

Facilities such as SED machines can provide additional information more rapidly for larger numbers of targets. Fibre spectrographs are another possibility for fields with large numbers of targets of interest. Equally important will be software-based solutions that can parallelise the workflows and take advantage of GPUs to obtain early probabilistic classifications. Speaking a common processing language by sharing a modular set of libraries is required. Fortunately, astronomers are starting to move in the right direction with the incorporation of libraries like astropy via APIs and githubbed jupyter notebooks.

4.2. *Questions and Discussion*

A significant part of extracting science from these observations will depend on finding how to identify scientifically interesting objects among the whole pool of transients. Naturally we want to research unusual transients, but it might be difficult to determine early on which ones those might be. It is important, therefore, to bring on board colleagues with expertise in a variety of different areas. Significant science can also be carried out by delving into archives, as they have now grown larger, richer and more diverse.

Some points that we discussed included:

- How to sub-select follow-up targets from larger numbers
- Filtering and distributing triggers to different communities
- How to encourage surveys to release triggers and data earlier
- Optimizing data sharing through standardised data formats, reduction pipelines, and access interfaces
- How to simulate triggers to ensure a proper response chain. Some examples exist
- How to distribute alerts in a modern way, i.e., moving away from the GCN/ATel era to more machine-friendly formats. A scalable version of something like a VO event will be an option. ZTF and LSST are experimenting with Kafka, for instance.

5. Conclusions

We summarise below what the community felt are the main challenges for, and aspects of, follow-ups and instrumentation which need to be addressed:

• Transient alerts need to be made public in order to deal with the huge numbers anticipated. This is already the case for LSST and MeerKAT, where all alerts will immediately become public (although not all the scientific information will be provided to non-LSST community members). For ZTF, only part will be made public.

• The ideal follow-up instrument will be wide ranged and versatile, such as OCTOCAM (de Ugarte Postigo *et al.* 2016; Thöne *et al.*, see p. 181). Characterising transients requires spectroscopic capabilities, especially long-slit designs, which have high efficiency. Telescopes need to be capable of rapid response modes (RRM) for reacting quickly to triggers. (This is already installed at VLT, SALT and Gemini).

• New reporting schemes are needed. ATEL and GCN formats are not suitable for distributing information about many thousands of transients per night. VO events might be an option.

• It is highly important to be able to identify unusual transients. However, it might be challenging to filter them out from the vast sea of alerts that is anticipated.

• Coordinated multi-wavelength follow-ups are crucial. The value has already been proven for many transients and even across fields for GWs and neutrino alerts.

• We need to share codes and tools for analysing and coordinating observations.

• Access to archived data will be important if a source has previously shown activity.

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