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Symposium 339: Summary

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Abstract. Time-domain astronomy is a key theme on research roadmaps worldwide, as was amply demonstrated by the energy which the participants (coming from 33 different countries) brought to this Symposium, as they shared their experience and expertise through various time-domain projects and discussed the challenges and strategies for the road ahead. This short summary is simply a personal view of the many key topics that were discussed.

1. Symposium Rationale and Format

Time-domain astronomy captures the formation, evolution, interaction and end states of cosmic sources. It can reveal physical structure and geometry (e.g. through astroseismology or eclipse modelling), lead to the discovery of new objects (such as transients or variable stars), and give insight into the physical processes driving the observed variability. It naturally covers the full electromagnetic spectrum and a broad range of time-scales, and hence – in a meeting like this – a very broad range of scientific topics.

The introduction of parallel Workshops each afternoon allowed for plenty of fruitful discussions on critical topics like the planning of follow-up strategies, data pipeline demonstrations and question-and-answer sessions, and encouraged the formation of new collaborations. The goal (which it certainly seemed to meet) was to explore synergies between different areas of research and to share skills, insights and excitement for future projects.

This summary is simply a personal view of the highlights and key themes discussed during the week, most of which are summarized in the reports included in this volume.

2. New Developments and Broad Collaborations

In the six years since the first IAU Symposium on time-domain astronomy (IAU S285, held in Oxford, UK, in 2011) several new surveys and satellite telescopes have come online to explore the time domain in various ways. SkyMapper is a multi-epoch, multi-colour southern-sky survey in *ubvriz* (Möller, p. 3); the Next Generation Transit Survey (NGTS) surveys its 96 square degree field-of-view with high cadence (12 s), high-precision photometry (Burleigh, p. 22); Gaia Alerts is an all-sky transient survey based on the Gaia data, which includes a low-resolution spectrum for each observation (Breedt, p. 12). Perhaps the most exciting result in the months immediately before this meeting was the optical detection of the LIGO/Virgo gravitational-wave event, GW170817. This was the first ever optical detection of a gravitational-wave event, confirming the association of kilonovæ with merging neutron stars and also confirming neutron-star mergers as the production sites of heavy elements. In the week that followed the gravitational-wave detection, follow-up observations were carried out across the electromagnetic spectrum, resulting in 84 papers on arXiv on the day of the announcement! We heard an excellent summary of the science highlights from those papers, and several other talks described their specific findings from the follow-up data.

The scale of the GW170817 collaboration was unprecedented; it will not be possible to follow up every event to that level of detail. As we were reminded in a number of talks, a detection alone is hardly ever enough – follow-up and/or auxiliary data are needed to understand the nature of an object. As our surveys grow ever larger, it is necessary to think about how to manage and organize future data exchanges and follow-up programmes. We have seen at this meeting a variety of strategies, including the "Deeper, Wider, Faster" programme (Andreoni, p. 135) which is coordinating more than 20 multi-wavelength observatories worldwide in searches of fast burst events. There is also still great value in targeted follow-ups of current photometric surveys, to test different target selection strategies and data pipelines, to define the parameter space for follow-ups, and to learn how to recognize the most interesting events among the millions expected from future surveys (Buckley, p. 176; Charles, p. 127).

As our surveys and data volumes get ever larger, citizen scientists are increasingly called upon to help. This is not just for the purposes of education and outreach; the contribution of these large groups of people is becoming essential for basic classification and characterization of survey data. Examples include the now-famous Galaxy Zoo project and its various spin-off surveys, and the SkyMapper Supernova search (Möller, p. 3). There are also highly skilled citizen astronomers (amateur observers) who collect data on specific objects, such as microlensing events and cataclysmic variable outbursts. Weather-permitting, they can get on target at short notice, and in many cases the science would not have been possible without their contributions. Stella Kafka gave a public talk highlighting some of their projects, and also led a lively Workshop discussion about our requirements in terms of data quality and calibration, and how to sustain public interest in helping us in this way.

3. Long Baseline and High-Cadence Photometry

Another theme that stood out is the transformations that long-term photometry from space and from the ground, such as the Kepler satellite, the Optical Gravitational Lensing Experiment (OGLE) and the Catalina Real-time Transient Survey (CRTS), have had on stellar astrophysics and exoplanetary science. From asteroseismology and stellar interiors to dust formation in Asymptotic Giant Branch stars, understanding large flares on A stars, mapping the Galaxy with Cepheid and RR Lyr pulsators, Luminous Blue Variables and population synthesis of supernova progenitors, long-baseline and high-precision photometry are bringing data and theory together as never before.

A key to many of these projects and science results has been the availability of the long, continuous light-curves in open archives that can be used beyond the original survey programmes. In the near future NGTS, TESS (the Transiting Exoplanet Survey Satellite) and Gaia will continue that trend. In the next few months we will also have the first parallax measurements from the Gaia mission, which will be particularly beneficial for both stellar and Galactic science.

To create long-baseline comparisons it can also be beneficial to look to the past. A Workshop (Workshop 12, p. 269) was therefore dedicated to accessing and using data from digitized plates, and an impressive talk was given on the Chinese plate-digitization project (Tang, p. 69). We were also reminded of the critical importance of describing our calibration procedures in detail, to ensure that datasets from different surveys or telescopes can be standardized and combined properly (Sterken, p. 139).

4. Radio and X-Rays

GW170817 may have opened up a new era of multi-messenger astronomy, but it is by no means the only new discovery space. The improved sensitivity of radio telescopes means that specific searches for short-duration events in radio data are now revealing a growing population of Fast Radio Bursts (Stappers, p. 27). These radio-bright millisecond-timescale events have extragalactic origins, but there is no consensus yet on what causes them. The MeerKAT/MeerLICHT radio–optical partnership is also expected to detect new classes of radio transients, along with the expected signals from cataclysmic variables (Coppejans, p. 43), X-ray binaries (Charles, p. 127) and Tidal Disruption Events and supernovæ (Matilla, p. 65). This community is looking ahead to the Square Kilometer Array, and is already discussing various observing strategies and requirements for doing transient science with it.

X-ray astronomy has seen some exciting developments in the past few years with the launch of telescopes such as MAXI (Kawai, p. 144), AstroSAT (Hutchings, p. 117) and NICER. Future X-ray missions include ATHENA, STROBE-X, HEX-P and XARM (Haggard, p. 143). 2018 will also see the launch of eROSITA – a 4-year all-sky X-ray survey with high sensitivity at both soft and hard X-ray energies (Rau, p. 145). The high-energy sky is highly variable, so this field has always been a strong driver for time-domain astronomy. Some events, like the thermonuclear X-ray bursts on the surfaces of neutron stars, last only $\sim 10 - 20$ seconds, but display great diversity in terms of emitted energy, duration and recurrence time (Galloway, p. 121). Events like those require continuous high time-resolution observations, as the bursts can reveal properties of the accreting neutron star as well as the accretion processes that led to the bursts.

5. Looking Ahead: Challenges and Future Developments

It is largely the improvements in detector technology and computing over the past few decades that has made time-domain astronomy possible to its present degree. Whether in the form of surveys covering large areas of sky multiple times, or high-cadence observations of individual objects, our datasets are increasing exponentially in size and also in complexity (Djorgovski, p. 23). The Zwicky Transient Facility (ZTF), which saw First Light during this meeting (Bellm, p. 160), is a good example. With its 47° square field of view, ZTF will survey the sky ten times faster than its predecessor, the Palomar Transient Factory (PTF), and is expected to produce 10^6 transient alerts per night. In turn, the ZTF data rate is only one-tenth of that expected from the Large Synoptic Survey Telescope (LSST; Graham, p. 189), which is expected to produce 10^7 alerts per night when it starts operations in 2023 (Matheson, p. 155).

Human interaction is unsustainable and unproductive when dealing with data on this scale. The challenge is to identify and extract meaningful information as well as "interesting unknowns" from these large volumes of data in an automated way (Saha, p. 151). Classifications of these alerts need to be carried out rapidly to enable timely triggering of follow-up observations of the most interesting events. At present, in existing surveys only a small fraction of targets can be followed up spectroscopically, a situation that will only become a bigger problem in the future. Automated classification remains a hard problem to solve, as there is normally very little information available about the source at the point of detection. Contextual information (e.g. a nearby galaxy, detections at other wavelengths, colours, etc.) are crucial ingredients for any classifier.

Machine learning is an increasingly popular way of exploring the vast parameter space covered by these multi-dimensional datasets (Bassett, p. 202), so an afternoon workshop was dedicated to this topic (Workshop 13, p. 274). The application of machine learning and deep learning techniques to survey data from CRTS, for example, has tripled the number of known changing-look quasars and has been used to classify 50,000 variable star light-curves from the survey (Mahabal, p. 165). One drawback of these methods is that error propagation is not straightforward, or even possible in some cases. Furthermore, different types of events have different distinguishing features, and no single machine-learning algorithm can capture them all. Domain knowledge (i.e., understanding the data) remains very important, and as with any statistical analysis, samples and training sets have to be well understood and representative in order to yield reliable results.

6. Final Remarks, and Thanks

How do we overcome these challenges? Openness and collaboration seem to be key. Collaborations can take on many forms, and the methods discussed included data sharing (accessible archives), joint software development (e.g. the ZTF–LSST partnership), simultaneous and commensal surveys (e.g. the MeerKAT–MeerLICHT partnership), software sharing (e.g. publishing code to the Astrophysics Source Code Library ASCL.net, sharing Jupyter notebooks and developing and sharing reliable priors for machine learning), having dedicated telescopes and instruments for follow-up (e.g. OCTOCAM: Thöne, p. 181, SOXS: Ivanov, p. 172, ULTRASPEC: Irawati, p. 185), supporting guest-observer programmes and targets of opportunity in space missions, and getting involved in the next generation of time-domain surveys (e.g. SDSS-V; Kollmeier et al. 2017, arXiv1711.03234).

Meetings like this provide excellent opportunities to share skills and ideas. It has been a very productive week in that sense, and I hope that our new collaborations will continue to grow over the next few years. If we have another symposium on Time-Domain Astronomy in six years' time, LSST will already be operational and taking data, so the time to act is now!

Many thanks to the organizers – Patrick Woudt, Elizabeth Griffin, Mark Sullivan and Rob Seaman – for an enjoyable and productive conference. Thank you also to the Local Organizing Committee, and to the staff of the Wallenberg Centre for their hard work and hospitality. You have been wonderful hosts.