1. Introduction

Astronomy has always progressed by taking advantage of the latest observing techniques and combining information from across the electromagnetic spectrum. This approach has led to the modern subject of astrophysics in which sophisticated models have been constructed to explain everything from planets to the origin of the Universe. These models are largely based on either a static or slowly evolving set of data.

Time-domain astronomy has come of age with astronomers now able to monitor the sky at high cadence, both across the electromagnetic spectrum and using neutrinos and gravitational waves. The advent of new observing facilities permits new science, but the ever-increasing throughput of facilities demands efficient communication of coincident detections and better subsequent coordination among the scientific community so as to turn detections into scientific discoveries. To discuss the revolution occurring in our ability to monitor the Universe and the challenges it brings, on 25–26 April 2012, a group of scientists from observational and theoretical teams studying transients met with representatives of the major international transient observing facilities at the Kavli Royal Society International Centre, UK. This immediately followed the Royal Society Discussion Meeting ‘New windows on transients across the Universe’ held in London. Here, we present a summary of the Kavli meeting at which the participants discussed the science goals common to the transient astronomy community and analysed how to better meet the challenges ahead as ever more powerful observational facilities come on stream.
A revolution is now beginning in terms of our ability to monitor the Universe using both existing and new observing facilities, such as the Low-frequency Array for Radio Astronomy (LOFAR) radio telescope, the IceCube neutrino observatory and a range of optical telescopes with of order 10 square degree imaging capabilities (Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), Palomar Transient Factory (PTF), La Silla-QUEST, SkyMapper, Catalina real-time survey). The data from these ground-based facilities, when combined with those from orbiting high-energy observatories, such as Swift, Fermi and Monitor of All-sky X-ray Image (MAXI), allow us to say that multi-messenger astronomy has now come of age. Gravitational wave experiments (Laser Interferometer Gravitational Wave Observatory (LIGO, VIRGO) have been running now for some years. While detection still awaits, the upgrade path to advanced LIGO promises exciting opportunities in opening a new window in astrophysics. In this new paradigm, astronomers are aiming to capture the behaviour of the temporal sky with high cadence across the electromagnetic spectrum and through neutrino and gravitational wave physics.

Using the temporal domain enables a census of the transient sky and permits a detailed study of individual objects that test our understanding of the laws of physics under the most extreme conditions. The best-known examples of luminous extragalactic transients involve the death of massive stars or the merger of compact objects that produce phenomena such as supernovae and gamma-ray bursts (GRBs) [1–3]. Numerous types of less luminous but astronomically important transients involving stellar flaring or accretion processes are also seen in our Galaxy. Overall, the importance of the temporal domain in terms of understanding the evolution of stars and galaxies and how they interrelate has been recognized in many recent reports, such as those by the European Union ASTRONET group and the USA National Research Council Decadal Survey.

The increasing rate of transient detection and observation cadence provides an opportunity to accurately track transient evolution and can bring relatively rare events into view that can greatly increase our understanding. But with the opportunity also comes a threat that our previous ways of working and communicating may be inadequate to cope with the data deluge. On 25–26 April 2012, a group of about 50 astronomers working in the area of transient astronomy met under the auspices of the Royal Society to discuss their common science goals and ways to enhance the use of multi-messenger facilities. This gathering followed immediately after the Royal Society Discussion Meeting in London on ‘New windows on transients across the Universe’, the papers of which are presented in this issue.2 The participants were divided into three groups (led by Lars Bildsten, Neil Gehrels and Brian Schmidt), each charged with the same tasks to see whether any consensus could be achieved and to inject a note of competition. This paper summarizes the outcome on the following topics. (i) What are the key science questions? (ii) How do we better coordinate the use of facilities? (iii) What future facilities are envisaged?

2. Science drivers

Traditionally, wide-field sky monitoring has been confined either to observing high energies from space (e.g. the detection of GRBs) or to the optical regime (e.g. the detection of novae and supernovae). While existing gamma-ray detectors can survey large sky areas (thousands of square degrees) simultaneously on millisecond time scales, optical surveys have tended to monitor small sky areas (few to a few tens of square degrees) with a cadence from several hours to days or weeks [4]. This observation strategy has differentiated the science discoveries at the shortest time scales, but there is considerable overlap in the source types monitored on longer time scales. Some of the transient source types monitored in optical and X-ray astronomy are shown in figure 1.


2Talk slides are available at http://www.star.le.ac.uk/~pto/RS2012/.
Figure 1. (a) Typical observed X-ray flux plotted against variability time scale for a variety of source types (colour-shaded regions) and for the prompt and afterglow fluxes for GRBs detected by the Swift mission (individual points). Black points are swift Burst Alert Telescope (BAT) GRBs (with the $T_{90} < 1$ s in red), green points are Swift X-ray Telescope GRB afterglow fluxes. AGN, active galactic nucleus; SFXT, supergiant fast X-ray transients. (b) Taken from Kulkarni [5] and shows the optical phase space of cosmic explosive events and their characteristic time scales. Image credits: (a) Julian Osborne and (b) Shri Kulkarni. (Online version in colour.)
The late time 0.3–10 keV X-ray light curve of Swift J164449.3+573451, a relativistic tidal disruption event at z = 0.3543 [6–8]. The data were taken from the UK Swift data centre site http://www.swift.ac.uk/xrt_curves/00450158/ [9]. Even allowing for modest beaming, this event has a luminosity after a year that is comparable to that of a bright AGN.

The more recently commissioned monitoring facilities are starting to fill in sections of the phase space shown in figure 1. For example, PTF, Panoramic Survey Telescope and Rapid Response System 1 (PS1) and La Silla-Quest have detected several luminous supernovae, whereas the Swift satellite and the PS1+Galaxy Evolution Explorer combination have detected several long-lived transients that appear to be tidal disruption events (TDEs; figure 2). Once detected, these sources have to be classified by bringing together information from multiple follow-up facilities.

The three breakout groups all came up with broadly similar views of the high-priority outstanding science questions to address in the broad field of astrophysical transients.

(1) Extreme physics: the study of black holes, neutron stars, compact binary evolution, supernovae, GRBs and TDEs.

— What are the explosion mechanisms for massive stars and how many progenitor types are there that produce the observed diversity?
— What exactly are the progenitors of thermonuclear supernovae and how many channels can produce explosions?
— Can we confirm that compact binary mergers are the origins of short GRBs—can coincident photonic and gravitational wave detection be realized for these objects?
— What is the relative importance of accretion and jet power in the active galactic nucleus (AGN), GRBs and TDEs, and what makes the greater than $10^{18}$ eV cosmic rays?
— Can we determine the equation of state of neutron stars using gravitational waves, neutrinos and electromagnetic timing data?
— Are there ultimate physical limits in energy and time to explosive events?
Gravity beyond Einstein: testing our understanding of relativity and determine the properties of dark matter and dark energy.

- Test the propagation and polarization of gravitational waves.
- Test Lorentz invariance using light from radio to gamma-ray energies.

Transients as probes: use transients as a means to constrain cosmology and illuminate the early Universe.

- Determine the nature of dark energy using cosmic probes, primarily via supernovae, but possibly also gravitational wave sirens.
- Use GRBs as bright beacons to locate the first stars and galaxies.

The meeting attempted to distil the overarching science questions into ideas for future coordination, building of facilities and future missions, and working coherently together. While this diverse group obviously had many opinions on the exciting science areas that could be opened up in this regime, two particular areas stood out that could provide potentially ground-breaking results, if facilities can either work together or new, affordable, missions are built. These were the first gravitational wave sources, which are most likely to be neutron star–neutron star (NS–NS) or neutron star–black hole (NS–BH) mergers, and ensuring that GRBs can be used to probe the high redshift Universe and the first stars. In §3, we describe what the meeting participants thought about current facilities and how they could work together more coherently. In §4, we discuss the facilities required to target these areas, and how the science goals could be realized.

3. Opportunities and threats

The exciting science opportunities from the combinations of multi-wavelength and non-photonic experiments are potentially threatened by how well we do (or do not) design communication channels. The synergy and direct link between experiments is effectively another requirement that we should build into the design of the facilities.

An alert—a message announcing a new transient event—can, in principle, be issued for many types of transient and electromagnetic/non-photonic signals. For example, gamma-/X-ray (AGN, GRBs, TDEs), UV/optical (supernova, TDEs, novae), radio (supernovae, GRBs, TDEs), neutrino (supernovae, AGN, GRBs) and gravitational waves (GRBs, AGN). The meaning of an alert varies somewhat among the transient monitoring facilities, but as a minimum usually involves the release of a time stamp and a sky position for the transient, which can be accompanied by a flux/magnitude and a source-type classification. There is a tension between providing rapid alerts with this basic information and waiting to provide enough information such that the basic alert is usable to a scientist. For example, one does not want to be overwhelmed with variable stars when searching for supernovae in difference images of optical fields. While that particular problem has been solved for PTF and PS1 (by simple catalogue cross-matching where reliable star–galaxy separation exists), a more subtle problem is finding rare high-redshift transients beyond the foreground fog of the ubiquitous type Ia supernovae (SNe). One might be able to declare that a transient is an extragalactic supernova (SN) of some sort, even with only two reliable detections, but beyond that, it is difficult to further classify without a spectrum or a full light curve. If one waits for the latter, the interesting early explosion phase is an opportunity missed. The capability of getting multi-wavelength data at these physically interesting early stages can be lost if one waits to confidently classify a particular transient. This tension will almost certainly increase in future as the rate of transient detections increases e.g. multi-wavelength triggers from LOFAR, GAIA, the High-Altitude Water Cherenkov Observatory, the Asteroid Terrestrial-impact Last Alert System Project (ATLAS) and finally the Large Synoptic Survey Telescope (LSST) [4,10,11]. The challenge will often be classifying the physically different and interesting events early enough that observations which probe the very earliest stages are ensured without wasting resources. The latter issue is not just one of wasting telescope time, humans will often tire of chasing transient events that have a low probability of being new and interesting.
Transient monitoring facilities are, in general, operated by dedicated science consortia. The bulk data are not usually made public rapidly, and sometimes not made public at all, but alerts usually are on a variety of time scales. Examples include PTF, Pan-STARRS-1 Skymapper, La Silla-Quest, IceCube, Astronomy with a Neutrino Telescope and Abyss Environmental Research (ANTARES), LOFAR, MAXI, advanced LIGO, etc. There are a few facilities (e.g. Swift) where the data become public after either no delay or a short delay. The most rapidly released truly public information (i.e. that which anyone can access) tend to come from GRB facilities, as for GRBs, rapid follow-up is absolutely essential given their fast decay rates. Even when data and alerts are made public rapidly, there are many issues limiting science opportunities such as how to best disseminate the information, how to ensure good coordination of subsequent observations and how to provide adequate scientific reward to those providing the original triggers so as to maintain motivation and funding. We give some examples of strengths and weaknesses for some representative transient facilities in table 1. There is a common thread to the weaknesses among many facilities and can be approximated under the headings of communication and coordination.

(a) Communication

The different communities in transient research tend to use different means to communicate, related to the traditions of that field.

(1) The gamma-ray coordinates network (GCN) system run from Goddard Flight Space Center was originally developed for the Compton Gamma-Ray Observatory Burst and Transient Source Experiment era to provide alerts for GRB detection and follow-up observations. GCNs are used by a large number of facilities and can be delivered via email, text messaging, web pages, etc. They come in three different flavours. ‘Notices’ are usually automatically generated, provide source locations but can also have appended small amounts of data such as a light curve. ‘Circulars’ are often handwritten and provide a description of data analysis results, updates on follow-up observations (e.g. a redshift) and can announce intentions to do something in order to encourage collaboration. ‘Reports’ are handwritten and summarize what has happened (currently only issued by the Swift project).

(2) VOEvent: an international system to define the content and meaning of standard packets of information about a celestial event. The system is targeted at automated systems that can generate and translate VOEvent packets and use them to trigger telescopes, build web pages, etc. (GCN notices have similar functionality.) VOEvent is used by some facilities (e.g. Swift) often in parallel with GCNs. Some future facilities, particularly LSST, plan to use VOEvent for all reporting.

(3) The Astronomers Telegram uses HTML-formatted, handwritten text to report and comment on observations of transients. They are submitted via a web interface and are mostly used for ‘slower’ transients, such as supernovae, but have a wider audience in terms of research fields than GCNs.

(4) International Astronomical Union (IAU) circulars: the oldest and most widely recognized means of communication is run from Harvard and today is mostly used for distribution of alerts for reporting on novae, supernovae and comets (with an analogous system for reporting on minor planets). These circulars are distributed via a subscription service, although some circulars are freely available. There is a general feeling that this process is no longer fit for purpose. For example, PTF have discovered and classified approximately 1700 SNe to date, Pan-STARRS1 has discovered approximately 3000 SNe candidates and spectroscopically confirmed approximately 300. However, neither project has systematically pursued IAU circulars or IAU names for the transients. The professional discovery industry has now moved beyond the use of circulars, although they do still serve an important purpose for amateur astronomers to gain recognition for their discoveries and, as such, it is an essential public outreach tool.
The variety of communication systems used by different parts of the community discussed earlier illustrates the disparity between automated and human-driven alerts and how well-intentioned standards may not be accepted by the community. Disparities lead to delays and errors. VOEvent was conceived as a means to solve some of those issues, and it is relatively well defined under international agreements. But, it is managed in a way that is slow to respond to community requests for changes (e.g. the current lack of time stamps). The management of the GCN system in contrast is quick to respond to facility/user requests, but it is debatable whether it is best suited for the multi-messenger era if transient detection rates increase by many orders of magnitude, as they will with LSST, for example. ATELS and IAU circulars would certainly be hard to use were transients to be discovered at large rates. It is fair to say that there has, as yet, been no community buy in to a standard way of communicating across wavelength regimes, and each community has tended to develop what works for them.

These have tended to be relatively successful solutions. But the vision from this Kavli meeting was that a uniform and standard reporting method that would facilitate communication on all time scales and information is both desirable and achievable. The majority view was to adopt VOEvent as the standard, but with the requirement of changes in defining and adapting the standards more rapidly to better respond to the user community.

(b) Coordination

The variety of transient types and follow-up requirements make the issue of coordination perhaps the greatest challenge in future for transient research, particularly if transient detection rates dramatically increase. Increased detection rates not only make communication harder, but also drive us to use automated, scientifically well-defined classification schemes. Initial classification most likely requires some degree of follow-up of a detection (the PTF-integrated approach of discovery and rapid follow-up with coordinated resources is a recent example), although multi-wavelength detection coupled with matching of source properties across online, large-area databases can permit some types of source class classification automatically.

Following initial classification (it is a GRB, a supernova, etc.), the next requirement is to maximize efficient further follow-up. Today, there are numerous examples where coordination is barely acceptable. These include: (i) heterogeneous target of opportunity (TOO) procedures among observing facilities, even within the same waveband, (ii) no centralized information available on who has triggered what facility (wasting human and observing time on multiple requests), and (iii) lack of rapid response speed from some facilities due either to inherent capability (e.g. Hubble Space Telescope, Chandra) or lack of a clear TOO procedure.

The majority view from the Kavli meeting discussion was that coordination needs to improve. Especially in the era of multi-messenger signals, for example, from high-energy transient emission [12] and future radio surveys [13]. One option would be to have a central clearing house approach to TOOs. Requests could be submitted to multiple telescopes and the one best-placed, with clear skies, carries out the observation. Demanding that all future publicly funded facilities are designed for rapid response to TOOs would also help, as would allowing space mission teams to request coordinated ground-based follow-up as part of the mission proposal. Such changes would come at the cost of large consortia, perhaps discouraging younger scientists, but changes to proprietary periods and data rights could be put in place so as to enhance competition in science.

4. Future facilities and instrumentation

As discussed earlier, there were two science priorities that were consistently thought to be of such promise that they could potentially lead to ground-breaking new results and potentially impact on fundamental physics and cosmology.

The first of these was the detection of gravitational waves from compact binary mergers and short GRB detections [1,14]. Advanced LIGO’s most promising first sources are likely to be short GRBs from NS–NS or BH–NS mergers [14]. This discovery requires cooperation between
Table 1. Example transient facilities and their strengths and weaknesses in the area of communicating and coordinating follow-up.

<table>
<thead>
<tr>
<th>strengths</th>
<th>weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Swift</strong></td>
<td></td>
</tr>
<tr>
<td>rapid trigger release</td>
<td>insufficient optical/IR follow-up spectroscopic facilities</td>
</tr>
<tr>
<td>GCN network for alert and prompt data dissemination</td>
<td>lack of buy in to VOEvent</td>
</tr>
<tr>
<td>motivated follow-up community</td>
<td>difficult to coordinate multiple follow-up groups</td>
</tr>
<tr>
<td><strong>Palomar transient factory and Pan-STARRS-1</strong></td>
<td></td>
</tr>
<tr>
<td>rapid discovery and initial classification</td>
<td>discoveries mostly private, most interesting not released</td>
</tr>
<tr>
<td>good light curve coverage and spectral follow-up</td>
<td>neither are all sky, still area limited</td>
</tr>
<tr>
<td>(different strategies, but both work)</td>
<td></td>
</tr>
<tr>
<td>large number of interesting sources</td>
<td>fast prioritization and multi-wavelength links could be automated better</td>
</tr>
<tr>
<td><strong>advanced LIGO and advanced VIRGO</strong></td>
<td></td>
</tr>
<tr>
<td>new discovery space</td>
<td>large position errors in early years</td>
</tr>
<tr>
<td>willing to work with external teams and release alerts</td>
<td>need dedicated wide-field follow-up facilities</td>
</tr>
<tr>
<td>motivated expert team</td>
<td>tension between rewarding instrument versus follow-up team</td>
</tr>
<tr>
<td><strong>LOFAR</strong></td>
<td></td>
</tr>
<tr>
<td>real-time alerts planned</td>
<td>delay in implementation of alert system</td>
</tr>
<tr>
<td>large simultaneous sky coverage</td>
<td>small temporal buffer (≤ 1 min)</td>
</tr>
<tr>
<td>large discovery space</td>
<td>unknown rapid transient radio sky</td>
</tr>
</tbody>
</table>

advanced LIGO, gamma-ray satellites (of which Swift, Fermi and the Space-based Multi-band Astronomical Variable Objects Monitor (SVOM) are the most likely), but also a very wide-field optical monitor that can scan the whole sky every night and efficiently observe large error regions. The ATLAS project [4] is a pair of 0.5 m telescopes with a 40 square degree camera that can scan the available sky twice per night to approximately 20\(^{\text{th}}\). It has been given funding from the National Aeronautics and Space Administration to enter the construction phase. The next-generation PTF is a project to fill the Palomar Schmidt focal plane with charge-coupled devices to create a 30–40 square degree field of view (FoV). Pan-STARRS-2 has entered construction, which will give a pair of sensitive 7 square degree FoV cameras on 1.8 m telescopes. These three projects have the potential to provide the optical follow-up to gravitational wave and gamma-ray sources, giving a powerful combination that could detect gravitational waves and quantify their sources. This has potential implications far beyond astronomy, and will test fundamental physics if these sources can be found and measured.

The second priority was the discovery and characterization of high-redshift GRBs. The immense luminosity of GRBs has allowed their detection at \(z \sim 9\), but this requires rapid near-infrared follow-up to Swift triggers and further rapid response from the largest telescopes. The fact that they can be used as beacons to probe the intervening intergalactic medium and also locate the first galaxies means that this type of transient science has exciting potential for early Universe studies. This meeting highlighted the importance to have combined facilities of a gamma-ray burst monitor (Swift and SVOM are the only two missions currently working or funded), a suite
of 4 m near-infrared telescopes for rapid response (and filtering the J+H band drop out afterglows) and access to 20–40 m telescopes (European Extremely Large Telescope, Thirty Meter Telescope, Giant Magellan Telescope) at the same time. While all of these facilities either exist, or are likely to exist at some time in the future, this group foresees challenges in them existing at the same time and working coherently together with large collaborations.

Discussions among the teams and in the plenary session also led to a conclusion that a wide-field X-ray facility would facilitate both of these science areas. A coded-mask instrument operating in the 1–100 keV range with around 5000 square degrees FoV, combined with a focusing telescope for softer X-rays (900 square degrees FoV over 0.1–10 keV) would target enable rapid and precise localization of X-ray sources (targeting soft GRB afterglows) of advanced LIGO/advanced VIRGO gravitational wave sources and potential neutrino transients. This instrument would also be capable of identifying high-luminosity high-redshift GRBs and provide X-ray detections of transients located by the new generation of optical wide-field facilities. The latter include supernova shock breakouts, black hole tidal disruptions, magnetar flares and daily X-ray monitoring of large areas of sky. Such a mission has already been proposed as an S-class mission to the European Space Agency (All-Sky Transient Astrophysics Reporter) and its science goals were focused by the expert gathering at the Kavli Royal Society International Centre.

We are grateful for the generous funding provided by the Royal Society to enable many participants to attend the meeting and for the hospitality of their staff at the Kavli Royal Society International Centre. We thank all of the participants for their enthusiastic participation and in particular Lars Bildsten, Neil Gehrels and Brian Schmidt for acting as group leaders. We thank Julian Osborne for providing figure 1a and Shri Kulkarni for providing figure 1b.

References