New Horizons in Time-Domain Astronomy
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Summary: A Very Timely Conference

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Invited Talk

1. Time Discovers Truth

The conference poster includes a very apt phrase that describes a primary motivation for this conference: Time discovers truth. This aphorism, attributed to Seneca, was certainly affirmed by the many exciting talks and discussions at this conference, in both formal and informal settings.

An incredible wealth of behaviour in astronomical objects of all scales and energies has been observed, manifesting a broad range of underlying physical processes. Phenomena that result in extremely small, time-dependent variations in optical photometry are now being revealed by dedicated surveys. For example, both external and internal processes can contribute to tiny variations in the light from stars: the detections of planetary transits of their host stars (transit depths of 0.01%) and stellar oscillations (the field of asteroseismology; ppm variations), are now routinely achievable for large samples of stars and stellar remnants, using both Earth- and space-based telescopes. Theories of planet formation and stellar structure and evolution are being tested as never before. Additionally, the public's imagination is being stimulated by the quest for Earth-like extra-solar planets.

Turning from these small masses to super-massive black holes, again precise measurements are giving credibility to estimates of mass. The differences in delay times, compared to the behaviour of the continuum light, for the variability of different spectral emission lines—probing different distances from the black hole—allows independent estimates to be made for the mass of the black hole, one for each emission line. Consistency of these estimates implies a robust result. Much recent effort in the development of theories of galaxy formation has been focussed on understanding the observed correlations between properties of the stellar content of a galaxy—such as the luminosity of the bulge component—and the mass of the super-massive black hole at its centre, and better quantification of these correlations will allow discrimination between theories.

In the radio regime, precision timing of pulsars is reaching even higher levels of sophistication, probing the pulsars themselves and the intervening interstellar medium—plus fundamental physics.

The physics of transient phenomena, as distinct from recurring variations, has also been under intense study. Prior to the advent of dedicated time-domain surveys, the distribution of optical luminous transients in the plane of characteristic time-scale of variability against peak luminosity was essentially bimodal, with low-luminosity novæ, varying on time-scales of around a day, well separated from the much more luminous supernovæ, which vary on tens of days. We have now identified populations that occupy loci between those two and even extend the occupied area to higher luminosities. Theories and theorists are validated and confounded. Radio transients have long been known to occupy many disparate regions of the time-luminosity plane but even here new types of variable objects are being discovered in hitherto empty loci (e.g., Rotating RAdio

Transients). Gamma-ray transients plausibly include emission (viewed at a favourable angle) after a star has been tidally disrupted upon getting too close to a super-massive black hole.

The truth revealed is that everything varies, in myriad ways. Even the gamma-ray emission from the Crab nebula, used to cross-calibrate telescopes, has now been detected to vary.

2. The Great Enemy of Truth is Very Often Myth

Several "unexpected" results, such as for the Crab nebula, reminded us to keep an open mind and to discard preconceived notions. As John F. Kennedy noted, "The great enemy of truth is very often myth, persistent, persuasive and unrealistic." Equally, "The unsought will go undetected" (Sophocles). Persistence and patience are required to reveal very long time-scale variability, while innovative application of (new) technology can enable the exploration of ever-faster variability. Time Allocation Committees should be adventurous (at least occasionally).

3. The Truth is Rarely Pure and Never Simple

What to make of this variability revealed by the time domain? Oscar Wilde's admonition that "The truth is rarely pure and never simple" is surely apt. As we were reminded by several speakers, simple detection of variability is not enough to claim a new discovery—understanding is required. For that, follow-up and/or simultaneous acquisition of data in other wavelength regions is critical. Indeed, many talks demonstrated the effectiveness of a multi-wavelength campaign, with added physical insight provided across the spectrum from gamma-ray to radio wavelengths. Surveys of the "static sky" are, in different ways, as important as surveys in the "time domain" for many fundamental questions. In that context, a medium-depth all-sky U-band imaging survey is badly needed—U-band data are crucial, for example, to enable reliable photometry-based estimates of the metallicity of stars like the Sun.

Imaging surveys with complementary capabilities should also be undertaken, such as a wide but shallow survey to augment the findings of a deep but narrow survey. A case study would be the issue raised at the conference as to the identification of possible hosts for the "orphan" supernovæ that have been detected in several wide-area imaging surveys on the lookout for transients. In order to rule out the existence of host low surface-brightness dwarf galaxies, deep-imaging follow-up with good sky-subtraction and flat-fielding would be needed. Different levels of follow-up are needed for objects of different perceived levels of scientific interest (which themselves change with time), and thus the design of the initial detection survey would ideally provide for automatic classification of newly identified variables, as input to their prioritisation for follow-up.

Indeed, ongoing and planned all-sky deep-imaging surveys need spectroscopic counterparts to aid much of the astrophysical interpretation. Photometric redshifts are not sufficient for much moderate- to high-redshift science. Spectra are required for the determination of line-of-sight motions of stars and nearby galaxies. Spectra with good enough signal-to-noise and resolution can be used to break degeneracies inherent in the analyses of solely photometric data, such as that between galactic star-formation rate and stellar mass function which is found when analysing the integrated light from galaxies. Spectral data allow AGN to be distinguished more readily from star-forming galaxies, and allow the progenitors and hosts of explosive events to be identified more robustly.

Spectroscopic surveys of stars provide estimates of important stellar parameters—metallicity, gravity and effective temperature—which in turn enable distances and ages to be estimated. By combining those with proper motions from time-domain imaging surveys, full 6-dimensional phase space can then be explored. The addition of chemical abundances provides yet more dimensions of space in which to look for structure that can be used to define stellar components of galaxies. "Near-field cosmology" exploits the conserved quantities in old, nearby stars to infer conditions long ago, when the stars formed. For example, the Initial Mass Function of long-dead massive stars can be constrained from the elemental abundances in the old, long-lived stars that they enriched. The ESA astrometric satellite Gaia will of course produce truly unprecedented data on positions and proper motions for stars throughout the Milky Way. Complementary spectroscopic data are already being acquired, as we heard.

The radio regime as yet lacks a comprehensive survey, but LOFAR, SKA and precursor surveys will provide that, and more, going a long way towards satisfying those who ask for "All the sky, all the time".

The high-energy regime is very active at the present. The unexpected detections enabled by dedicated all-sky surveys include M-dwarf stars emitting in the hard X-rays, relativistic outflows associated with a tidal disruption accretion event, and the highest redshift object (known at the present time)—a Gamma-ray Burster at a redshift of 9.3.

4. Survey Strategies

That surveys must maintain serendipity was a common refrain—the unknown and the unlikely happen. This is sometimes good! The Princes of Serendip succeeded through "accidents and sagacity" (according to Walpole), though it is hoped that astronomers depend more strongly on the latter while designing surveys and analysing data.

There was a general consensus that size alone is not sufficient as a measure of a survey's worth, no matter which algorithm is used to define "size". Clever ideas are also needed, in all aspects of survey design and execution. There must be careful selection of cadences and of the required precision of the data, in order to enable as much science as possible; maintaining flexibility is key to maximizing the discovery capabilities of a survey.

Saving the pre-pipeline data, or even raw data, if feasible, can also enable discoveries and analyses beyond the original science case for a survey or satellite mission (it is a truism that the actual scientific breakthroughs achieved by a given project are often far removed from the original science case). The tuning of a data reduction pipeline for the most efficient implementation of a particular science investigation can be viewed as indispensable, but can make other analyses effectively impossible.

The saving and archiving (after digitization) of "vintage" data can prove invaluable in identifying hosts/progenitors of transient events. Real-time stellar evolution can be observed using very long-term monitoring, but only provided that the older data are accessible. Significant efforts should be directed at data conservation.

There is undoubtedly a great challenge in the need to deal with the data deluge from large surveys, both coming and planned. Happily, astronomy is not alone in facing the deluge, and huge efforts are being made world-wide. Novel statistical techniques are being developed to aid such analyses. In this situation, as we heard, creative ideas beat data ownership.

5. Conclusions

There is clearly much that has been learned and understood from surveys of the variable sky, and much that remains to be learned and understood.

There were sentiments expressed that "the time domain" was such a large and growing field that this could well be the last all-encompassing conference on that topic. However, the lively discussions after the extremely stimulating talks argue strongly for the continuation of such a format. The more specialized workshops, held in the afternoons, provided a forum both for very rapid introductions to the most current topics in a given field and a means to discuss the most pressing issues. "Synergy" and "cross-fertilization" are much used and abused words, but were very apt when describing the outcome of the week's interactions.

However, "We are time's subjects, and time bids be gone" (Shakespeare)

I would like to thank the organisers, and especially Elizabeth Griffin and Bob Hanisch, for their vision, hard work and patience.