ANTARES: An Overview

1 Introduction

The changing night sky has been an important element of astronomy and astrophysics since the ancients first looked up and used the stars to tell the stories of their lives. This history reverberates even in the modern era as we continue to call the ‘wandering stars’ planets and explosive disruptions of stars are still named *nova stella* as Tycho Brahe did in 1572. The changing nature of the night sky has revealed secrets from the atomic scale to the cosmological, so it has remained at the forefront of astronomical research. There were attempts to develop systematic studies of time-domain astronomy starting in the early 20th century, but success has only come more recently. As with most fields of astronomy, the growth came not just from the desire of the astronomer to collect more and better data, but also from dramatic improvements in technology.

Sources in the sky that vary often reveal more about their physical nature than their static counterparts. Since the laws of physics govern the variable behavior, studies of varying phenomena illuminate the physical nature and context of the sources. Historically, the study of variable phenomena has revealed quite fundamental things, from the masses (and life-cycles) of stars to distances on all scales that form the bed-rock of our cosmography. Most recently, the detection of gravitational waves from the merger of black holes stars has provided proof of a predicted but until now unproven phenomenon. These examples underscore the importance of discovering and following up on investigations of hitherto unknown variable phenomena for the window they will undoubtedly provide for our understanding of the Universe.

We now stand on the cusp of a new era of time-domain astronomy where the scale of transient events and data volume will be unprecedented. Given the high demand for the limited number of available astronomical observing resources, the ability to derive the maximum scientific benefit from this vast time-domain data influx will require software infrastructure to prioritize the high-value discoveries. During operations, the Large Synoptic Survey Telescope (LSST, Ivezić et al., 2008; Kantor, 2014; Kahn, 2016) will detect ∼10,000,000 transient and variable events each night for ten years. Hidden among these events will be rare and unusual objects, some never seen before and some with short lifetimes. Without an efficient software infrastructure to filter these alerts, they will remain undiscovered. This is why we began the development of the Arizona-NOAO Temporal Analysis and Response to Events System: ANTARES. The ultimate goal of the ANTARES project is to filter the LSST alert stream and enable full scientific exploitation of the time-domain data LSST will provide.

2 A Brief History of Time-Domain Astronomy[1]

Astronomers originally recorded what they had observed by hand, drawing a representation of what they had seen. Though subjective, this was the standard from naked-eye observations through the development of telescopes. The use of photographic plates with telescopes to record astronomical images began in the latter half of the 19th century. Despite their low efficiency in recording photons (with a quantum efficiency generally less than 10%) and their non-linear response, the permanency of photographic places and their objective record of the sky opened a new phase in quantitative astronomy. The ability to record spectra essentially created the field of astrophysics. Photographic plates were also an important part of the development of time-domain astronomy. With accurate representations of the sky observed at different times, changes in brightness or position can be discovered. Often, just placing one plate over another was enough to distinguish changing objects. In 1904, the blink comparator was invented at Carl Zeiss. This device allowed an astronomer to quickly change view from one plate to another, effectively blinking the two. This was how Clyde Tombaugh found Pluto after looking at plates containing twenty million other objects (Tombaugh, 1946).

These advances enabled the first systematic time-domain programs. One such program was Fritz Zwicky's search for novae and supernovae using facilities at Mt. Palomar (Zwicky, 1938; Herzog & Zwicky, 1951; Zwicky et al., 1963). Surveys for asteroids often used blink comparators to find small Solar System bodies (e.g., Kuiper et al., 1958; van Houten et al., 1970). Although these surveys could attempt a systematic approach, they were hampered by the relative inefficiency of photographic plates as photon detectors. This made it difficult to cover a large amount of sky, even with telescopes that could afford a wide field of view. Finding uncommon objects is harder when the area to search is limited by resources. This meant, though, that the rate of alerts was low, with a volume that could easily be evaluated by humans alone.

The next technological leap that transformed much of astronomy was the introduction of electronic detectors to replace the photographic plates. The most successful of these continues to be charge-coupled devices (CCDs), first used in astronomy in the 1970s. These devices provide a quantum efficiency that is often greater than 90%. Moreover, they have a linear response over a wide dynamic range allowing for much more precise measurement and calibration of astronomical sources. In addition, with digital images, observations at different epochs could be matched and subtracted electronically, revealing all the changes of the astronomical objects between the two epochs of observation (e.g., Alard & Lupton, 1998). This was a significant improvement over the blink comparator. Nonetheless, when they first came into use, CCDs were both expensive and relatively small, so, even on telescopes that

[1] For a more complete history, see, e.g., Djorgovski et al. (2013).

could provide a large field of view, only small areas of sky could be sampled at once. This meant that time-domain surveys with CCDs were not initially competitive with photographic plates. A clear example of this is the highly productive photographic Calán/Tololo Supernova search (Hamuy et al., 1993).

The next step was CCDs that could accommodate a larger field of view. One of the first astronomical cameras to do this was the Large-Format Prime-Focus CCD (LF-PFCCD) camera used at the Blanco 4-m telescope at the Cerro Tololo Interamerican Observatory (CTIO). It used a 2048×2048 CCD with a 15 arcminute field. The next generation camera after that at CTIO was the Big Throughput Camera (BTC) built at Bell labs. It used four CCDs in a mosaic to cover an even larger field of view. For a more complete discussion, see Walker (2015). Once large CCDs could be mosaicked, ever larger cameras could take advantage of very wide fields of view, subject mainly to the constraint of cost. Examples include the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS) 1.4 gigapixel camera using 60 4k×4k CCDs (Onaka et al., 2008), the forthcoming Zwicky Transient Facility (ZTF) 576 megapixel camera that will use 16 6k×6k CCDs imaging 47 square degrees (Bellm, 2014), and, the biggest camera in development, the LSST camera itself with 3.2 gigapixels over 189 4k×4k CCDs for a 10 square degree field of view. See Bellm (2016) for a more detailed discussion of the growth and capacity of time-domain astronomy.

In parallel with the growth of CCD cameras for astronomy, time-domain surveys expanded to take advantage of the new capabilities. The two cameras at CTIO mentioned above (LF-PFCCD and BTC) were used in supernova searches that lead to the discovery of dark energy (Riess et al., 1998; Perlmutter et al., 1999). Other examples include the Lick Observatory Supernova Search (Li et al., 2000), the time-domain component of the Pan-STARRS medium deep survey (Kaiser et al., 2002), the Catalina Sky Survey (CSS, Larson et al., 1998) and the associated Catalina Real-Time Transient Survey (CRTS, Djorgovski et al., 2011), the Palomar Transient Factory (PTF, now the intermediate PTF or iPTF and soon to be ZTF, Law et al., 2009; Rau et al., 2009), the La Silla-Quest Variability Survey (LSQ, Hadjiyska et al., 2012), SkyMapper (Keller et al., 2007), Evryscope (Law et al., 2015), and the All-Sky Automated Survey for Supernovae (ASASSN, Shappee et al., 2012). The LSST project dwarfs all these in scale.

LSST is a joint project between the National Science Foundation and the Department of Energy to build a large imaging telescope on Cerro Pachón in Chile. It will have a 8.4m diameter mirror, although the design of the telescope yields an effective collecting aperture of a 6.7m diameter mirror. This is large enough to capture the light from even faint objects in short (∼30 second) exposures. As described above, the LSST camera covers a large field of view 10 square degrees. It will image the southern sky every night for ten years with a cadence that is still under consideration, but will typically return to a field after a few days. In addition, for moving-object identification, each field is imaged twice in a given night within ~ 90 minutes. The camera uses six filters to isolate the optical/infra-red light from the sources into six bands. The ten-year survey will cover $\sim 18,000$ square degrees (roughly half the sky). Each field will be observed ~ 800 times in that ten years, with those visits distributed over the six filters. Every visit will be compared with a reference image and objects that have changed in brightness or position with a 5σ confidence will generate an alert. The large collecting area allows the survey to detect fainter objects (go deeper, in astronomical jargon) faster, while the large field of view enables wide coverage. The general description of the main survey is wide, fast, and deep. The ability to go deep enormously expands the potential discovery space available to LSST, as fainter objects are generally further away, and the volume increases as the cube of the distance. In addition, the ten-year baseline affords time-domain coverage at an unprecedented scale. Given the anticipated depth of the images, the expectation is that each will yield as much as $\sim 10,000$ alerts. This is $\sim 10,000,000$ per night, each night for ten years. It is likely that a significant fraction of these alerts ($\gtrsim 90\%$, Ridgway et al., 2014) will be repetitions of known variables stars and moving objects. Those still need to be identified in the alert stream and even then it will leave a large number of new alerts.

While the main wide survey of the Southern sky takes up most of the time, $\sim$10% of the survey will be devoted to 'deep-drilling' fields. These are specified fields on the sky, typically chosen for their astronomical interest or past history of coverage by other surveys. These regions will be imaged on a much higher cadence and with filter changes. This increases the amount of information available in the alerts, but also requires that systems to process alerts can respond to the difference in the style of alerts.

For all the past and currently active surveys, even those that employed some automated techniques to categorize variable detections (e.g., Bloom et al., 2012), there was and continues to be a significant human involvement in evaluating the nature of the alerts. Both iPTF and CSS, despite numbers of alerts climbing close to a million per night, still rely on humans to sort the alerts (E. Bellm, E. Christensen, priv. comm.). The capacity to build bigger CCD cameras will outstrip the ability of human evaluators to keep up. Human involvement will not scale to the alert rate and volume that LSST will produce. In addition, many of these surveys had specific science goals, so objects unrelated to that goal were typically ignored. A truly public time-domain survey cannot ignore large portions of the time-domain community. The time-scale for follow-up continues to decrease as ever more short-lived objects become interesting and accessible to astronomers. The Use Cases document describes some examples that require rapid response. All this points to the need for a software infrastructure designed to filter alerts at the rate and volume LSST will produce.

3 What is a Broker?

The software infrastructure necessary to filter alerts acts as an intermediary between the source of alerts and the consumer, adding value through annotation from other sources of information and past history, characterizing the alerts, applying a ranking of interest to the consumer, and distributing the alerts to the consumer. Such an intermediary in the commercial world has come to be known as a broker, with a stock broker being perhaps the closest analogy. This term has been adopted by the astronomical community (e.g., Borne, 2008).

There are many examples of software systems that have performed at least some of the functionality envisioned for the ANTARES project. For PTF, an automated system sorted alerts into three categories (variable stars, transient, rock, Bloom et al., 2012) before they were passed along for human inspection (the PTF Marshal is designed more for human interaction via a web interface). The Las Cumbres Observatory, a leader in the development of software tools for time-domain astronomy, hosts the Supernova Exchange (SNEx[2]) and the Near-Earth Object (NEO) Exchange (Lister et al., 2016). Other examples include the NEOCP[3] run by the Minor Planet Center under the auspices of the International Astronomical Union and the ExoFOP[4], for coordinating studies of exoplanets, run by NASA's Infrared Processing and Analysis Center. For a broader discussion of the current time-domain infrastructure landscape see chapter 9 of Najita et al. (2016).

The system with the functionality that represents the most general case for a broker is SkyAlert (Williams et al., 2009). It would accept alerts from time-domain astronomy surveys, apply user-defined filters based on features from the alerts and aggregated information, and distribute these to the users. SkyAlert is currently not operational, but may be resurrected at NOAO in the near future. The SkyAlert design, however, will not scale to LSST rate and volume.

LSST itself will also operate an internal broker. This will only operate on data available from the survey itself without any external annotations. It is expected that ∼500 users could select ∼20 alerts per visit (out of ∼10,000). This will enable many science use cases, but will not have the capacity to address the full range of scientific questions that LSST will be able to answer.

The vision for the ANTARES project, as laid out in the Architecture document, is to fulfill this need of a software infrastructure that can act as an intermediary for the LSST alert stream. The long-term goal is to serve the needs of the community as broadly as possible. The near-term goal is to complete a functional prototype that can perform the core tasks

[2] http://supernova.exchange

[3] http://www.minorplanetcenter.net/iau/NEO/toconfirm_tabular.html

[4] https://exofop.ipac.caltech.edu/

necessary for the broker, but also have the flexibility to accommodate the functionality that the community will want at the scale LSST will provide. This prototype is the object of our NSF INSPIRE grant (CISE AST-1344204, PI:Snodgrass) and the focus of the review.

4 Community Demand for an LSST Broker

It has long been recognized that the scale and rate of LSST alerts will require an automated system to prioritize the alerts for follow-up observations (e.g., Borne, 2008). There have been many broad-based, community-led reports that have strongly recommended support for a broker to process LSST alerts.

In 2013, the "Spectroscopy in the Era of LSST" workshop synthesized a set of recommendations covering a wide range of science topics and the broker was a top priority (Matheson et al., 2013):

> Although time domain science is the primary beneficiary of a broker to sort through the alerts generated by changes in brightness (or position), the cosmological use of SNe Ia, the study of AGNs, and the study of brown dwarf weather all will rely on the ability to recognize interesting events when they happen. For each case, the signal hidden in the noise of one million alerts per night will be different, but they will all require a system to winnow alerts done to the ones they will find of interest. Hidden among those million alerts will be rare and interesting objects, and these will be lost without a working broker.

In 2015, the National Academy of Sciences issued a report from the Committee on a Strategy to Optimize the U.S. Optical and Infrared System in the Era of the Large Synoptic Survey Telescope (the 'Elmegreen' report) and, again, the necessity of a broker was recognized as a high priority via this recommendation (National Research Council, 2015):

> RECOMMENDATION 4a. The National Science Foundation should help to support the development of event brokers, which should use standard formats and protocols, to maximize Large Synoptic Survey Telescope transient survey follow-up work.

In 2016, instigated by the Elmegreen report, the Kavli foundation funded a study titled "Maximizing Science in the Era of LSST: A Community-Based Study of Needed US OIR Capabilities." This study covered a wide range of scientific topics and provided realistic estimates of resources needed to accomplish specific goals (Najita et al., 2016). The synthesis across all the topics included an event broker as one of the critical resources needed. From the list of recommendations:

Ensure the development and early deployment of an alert broker, scalable to LSST. Public broker(s), and supporting community data and filtering resources, are essential to select priority targets for follow-up. The development of an alert broker that can process the LSST alert stream has challenges beyond the field of astronomy alone. These challenges can be effectively tackled by computer scientists working with astronomers on this multi-disciplinary problem, and support is needed to enable effective collaboration across the relevant fields.

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