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First Results of the SkyMapper Transient Survey

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Abstract. The SkyMapper Transient survey (SMT) is exploring variability in the southern sky by performing (a) a rolling search to discover and study supernovæ, and (b) a Target of Opportunity programme that uses the robotic SkyMapper Telescope at Siding Spring Observatory. The supernova survey is obtaining a non-targeted sample of Type Ia supernovæ (SNe Ia) at low redshifts, $z < 0.1$, and studying other interesting transients found with the search strategy. We have a Target of Opportunity programme with an automatic response mechanism to search for optical counterparts to gravitational-wave and fast radio-burst events; it benefits from SkyMapper's large field of view of 5.7 sq. deg. and a rapid data reduction pipeline.

We present first results of the SMT survey. The SMT pipeline can process and obtain potential candidates within 12 hours of observation. It disentangles real transients from processing artefacts using a machine-learning algorithm. To date, SMT has discovered over 60 spectroscopically confirmed supernovæ, several peculiar objects, and over 40 SNe Ia including one (SNIa 2016hhd) which was found within the first few days of explosion. We have also participated in searches for optical counterparts of gravitational waves, fast radio bursts and other transients, and have published observations of the optical counterpart of the gravitational-wave event GW170817. We also participate in coordinated observations with the *Deeper Wider Faster* programme, and the Kepler *K2* cosmology project.

Keywords. Supernovæ: general, surveys, gravitational waves, cosmology: observations

1. Introduction

The SkyMapper 1.3-m instrument at Siding Spring Observatory is a robotic telescope with a wide field of view of 5.7 sq. deg. (Keller *et al.* 2007). The *SkyMapper Southern Sky Survey*, SMSS (http://skymapper.anu.edu.au), a comprehensive digital survey of the entire southern sky, was begun in March 2014. Details about the SkyMapper instrument and its eponymous survey can be found in Wolf *et al.* (2018), which also describes the first SMSS data release.

Alongside the Southern Survey, SkyMapper is carrying out the *SkyMapper Transient Survey* (SMT), which is a search for supernovæ and other transients. The search strategy is optimised for discovery and follow-up of low-redshift Type Ia supernovæ, by searching uniformly a region of ∼2000 sq. deg. with a cadence of $\leqslant 5$ days (Scalzo *et al.* 2017). By selecting those search parameters, and working in multiple well-determined bandpasses (Bessell *et al.* 2011), SkyMapper aims to address the limitations of the current sample of nearby SNe Ia. The resultant low-redshift SN Ia sample ($z < 0.1$) will be magnitude limited, with a selection function more similar to that for the high-z sample. More information about the infrastructure and operations of the SMT, and first results including the performance during an early Science Verification period, can be found in Scalzo *et al.* (2017).

2. Transient Survey Strategy

Although SMT and SMSS both use the SkyMapper telescope, SMT has its own data reduction pipeline infrastructure, which is maintained and run separately from that for the SMSS. The goal of our pipeline is to have rapid turnround of < 12 hours for the discovery of new transient candidates. Our pipeline performs image subtraction to detect transients, and provides additional data, such as historical light-curves, to support situational awareness of active transient candidates.

We describe the transient detection procedure in the following simplified steps; more details are given by Scalzo *et al.* (2017).

• Image subtraction: This requires a pre-existing template image of the sky ('REF') to remove host galaxy light and non-variable sources from each new exposure ('NEW'). The REF is convolved with a suitable kernel to match its point-spread function to that of the NEW. References must be taken at least two weeks prior to the NEW image because the rise time of a typical SN Ia to maximum light is about 17 days.

• Source detection: This is carried out in the subtracted image ('SUB') using Source Extractor (Bertin *et al.* 2002).

• Classification: All detections on the SUB are run through an automated classification routine to determine the likelihood that they are real astrophysical sources rather than artefacts from an imperfect subtraction process. This classification is performed using machine learning with a Random Forest algorithm implemented in Pedregosa *et al.* (2011).

• Candidate detection: All high-quality detections in the SUB image are matched astrometrically to previous detections. For sources passing a threshold number of high-quality detections in one or more subtractions, a historical light-curve is compiled using all detections of the transient at that position.

• Transient selection: selected candidates are then inspected visually to discard possible bogus detections. Bogus detections are mostly caused by processing artefacts in SUB images. Before May 2017 the inspection was done by members of the SMT team, but currently they are carried out by citizen scientists. In May 2017, in partnership with the Zooniverse, we launched a citizen science project called *Supernova Sighting*[1], in which volunteers inspect the NEW, REF, SUB images of possible candidates and select those which appear to be promising ones. Through an API we both upload images and also download classifications[2]. The selection of promising candidates is then passed to our SMT team.

• Public transients: candidates whose properties are consistent with astrophysical sources are communicated publicly using the Transient Name Server, TNS[3].

• Spectroscopic follow-up: supernova candidates are sent to the Public ESO Spectroscopic Survey for Transient Objects (PESSTO) and to our Target of Opportunity

[1] https://www.zooniverse.org/projects/skymap/supernova-sighting
[2] implemented by P. Armstrong
[3] https://wis-tns.weizmann.ac.il

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(ToO) programme at the 2.3-m ANU telescope in order to derive a spectroscopic classification and a redshift. Since candidates are in the public domain, other spectroscopic surveys are also able to classify our targets.

The reduction pipeline is the same for the ToO programmes, including Gravitational Waves, searches for electromagnetic counterparts to Fast Radio Bursts, and simultaneous observations with *Deeper Wider Faster* and the Kepler *K2* cosmology project, until the point of 'Transient Selection', when notifications of events go to the SMT team and collaborators.

This SkyMapper pipeline and early survey data have been used to develop the pipeline for the MeerLICHT and BlackGEM projects.

3. First Results

3.1. *Supernovæ*

Since December 2016, when automation of the TNS reporting was implemented, we have reported over 70 transients. To date, SMT has discovered more than 60 spectroscopically confirmed supernovæ. In that sample over 40 non-targeted SNe Ia have been discovered within the redshift range $0.02 < z < 0.16$. In addition SN Ia 2016hhd, a Type Ia supernova discovered by our team, was found within the first few days of its explosion and may present evidence of shock interaction with a SN Ia companion.

Within the first 24 hours of our launching *Supernova Sighting* in May 2017, in collaboration with the Zooniverse project, over 18,000 volunteers had classified 30,000 transient candidates into 'real' or 'bogus'. Soon after that, the first spectroscopically confirmed Type Ia supernova to be found by volunteers was announced (Tucker *et al.* 2017). Overall, volunteers have discovered 45 astrophysical transients; they include supernovæ, flares, AGNs and unclassified ones. Their contributions can be found on the SMT webpage[4].

Although the SMT search cadence is optimised for normal SNe Ia, we devote a small fraction (5%–10%) of our follow-up resources to individual objects of interest that are likely to generate high-impact single-object papers. Exotic transients discovered so far include SN 2016doj, an object similar to the one in the so-called superluminous gap reported by Arcavi *et al.* (2016).

Our survey may be sensitive to other non-supernova transients. By using realistic simulations based on the light-curve of the GW170817 electromagnetic counterpart (Scolnic *et al.* 2017), we have concluded that our past survey data are not expected to contain any kilonovæ.

3.2. *Target-of-Opportunity and Collaborations*

Since 2015 the ToO programme has observed nine triggers: four Fast Radio Bursts, four Gravitational Waves (GWs), and one high-energy neutrino event. These programmes search for an optical counterpart by imaging the localisation footprint and searching for transients within the footprint of the source localisation. Recently we observed the footprint of the FRB170827 detection by the UTMOST project (Farah *et al.* 2018).

We participated in the follow-up of the recent gravitational-wave event GW170817, observing the first electromagnetic counterpart to a GW event (Andreoni *et al.* 2017; LIGO-Virgo collaborations 2017). We searched in the SMT supernova survey for possible transients at the location of GW170817 before the GW trigger, but found none (Möller *et al.* 2017).

[4] https://www.mso.anu.edu.au/skymapper/smt/supernovasighting

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We also participate actively in coordinated observations with the *Deeper Wider Faster* programme and the Kepler *K2* cosmology project. Those programmes are based on scheduled observations to provide multi-colour light-curves of interesting events. The *Kepler Extra-Galactic Survey* (KEGS) is using the Kepler *K2* mission to monitor supernova fields at the very high cadence of 30 minutes. K2 fields 1, 3, 4, 5, 6, 8, 10, 12, 14, 16 and 17 have been KEGS-focused fields, discovering to date 23 supernovæ of all Types, several of which been observed by SkyMapper (Rest *et al.* 2018). The *Deeper Wider Faster* collaboration coordinates simultaneous observations from over 40 observatories at all wavelengths (radio to gamma-ray) and multi-messenger detectors. Events currently being analysed include SNe Ia DWF17a5068 and DWF17a23 with SkyMapper data.

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