White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
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ANTARES: A gateway to ZTF and LSST alerts

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Abstract. Studies of white dwarfs have greatly benefited from time-domain surveys and subsequent follow-up observations. However, with the avalanche of alerts delivered by ZTF and LSST and the limited resources for follow-up, we will need brokers to select intriguing alerts that warrant follow-up in a timely manner. At the University of Arizona and NSF's OIR Lab, we are developing the Arizona-NOAO Temporal Analysis and Response to Events System, to hunt for the rarest of the rare events in the time-domain. In this work, we provide an overview of the ANTARES system, how we use ZTF as a training set, and the way forwards to LSST.

Keywords. Surveys, astrostatistics techniques, transient sources, variable stars, small solar system bodies.

1. Introduction

The advent of wide-field camera, large-area, and high-cadence surveys have revolutionized time-domain astronomy that relates to many aspects of white dwarf studies. For example, the explosion of supernova type Ia (SN Ia) was conventionally pictured as the end product of a white dwarf accreting materials from a non-degenerate companion. However, there is mounting evidence that some SNe Ia are products of two merging white dwarfs: the Kepler satellite has delivered exquisitely cadenced light curves at the rise of several SNe Ia with no sign of ejecta interaction with a stellar companion, thus suggesting double-degenerate progenitors (Olling *et al.* 2015). There are also heavily polluted white dwarfs, likely the product of accreting planetary debris as there are infrared signatures indicating existence of debris discs around those white dwarfs (see, e.g., Jura 2003). In this regard, time-domain surveys have revealed circumstellar discs transiting two white dwarfs, WD1154+017 (Vanderburg *et al.* 2015) and ZTF J0139+5245 (Vanderbosch *et al.* 2019), providing crucial evidence about the circumstellar material around polluted white dwarfs. To test the theories of white dwarf formation and evolution, we also need better estimates of their physical parameters (i.e., mass and radius). In this regard, the Catalina Sky Surveys have also revealed a handful of ultra short period eclipsing binaries (Drake *et al.* 2014), where one of the stars is likely to be a white dwarf, hence providing a unique opportunity to probe the fundamental physical parameters that are otherwise hard to determine. There are also eclipsing binaries with double white dwarfs (Burdge *et al.* 2019) that are not only valuable for studies of white dwarf properties, but can serve as potential gravitational wave sources for LISA as well.

While time-domain surveys have identified numerous promising candidate white dwarfs, it requires dedicated follow-up observations, especially spectroscopically, to reveal their true nature. With the Zwicky Tranisent Facility underway and the Large Synoptic Survey Telescope on the horizon, there are already millions of alerts per night and will be ten millions of alerts per night in the future that require follow up. This is beyond the capability of any single astronomer, and we will need to rely on community brokers to digest and select the most intriguing events worthy of follow-up.

2. ANTARES

In order to cope with the flood of millions of alerts from ZTF and LSST, we will need a software infrastructure to sift through the alerts. At the University of Arizona and NSF's National Optical Infrared Astronomy Research Laboratory (NSF's OIR Lab), we are developing the Arizona-NOAO Temporal Analysis and Response to Events System (ANTARES Saha *et al.* 2014, 2016; Narayan *et al.* 2018). After several years of planning and prototype testing, ANTARES beta† was launched in December 2018 to digest alerts from the Zwicky Transient Facility and disseminate value-added information from multi-wavelength catalogs in real time. ANTARES aggregates alerts at the same location of the sky (dubbed "locus") to form light curves. Each locus is also cross-matched with external catalogues, including, but not limited to, Gaia, 2MASS, WISE, SDSS, GALEX, NED, RC3, Veron Catalog of Quasars & AGN, NYU Value-Added Galaxy Catalog, Catalina Sky Survey Variables, ASAS-SN variable catalog, etc., to provide contextual information. With these pieces of information in hand, users can design and submit their own filters to select targets of interests in real time. Users can interact with ANTARES via different interfaces. We have a web portal that allows users to browse and search alerts (see Fig. 1) and submit user-defined filters (including sophisticated machine learning models). We also have a custom API that allows users to download alerts in batch mode, and can query our alert database in a programmatic manner. Finally, we also have a Slack channel that can notify users right away when an alert of interest is flagged by the user-defined filters.

In addition to user-defined filters, ANTARES is now actively broadcasting alerts in streams with pre-defined filters that are of potential interest and warrant spectroscopic observations. There is a filter flagging alerts associated with external galaxies ("extra-galactic stream") that can be supernovae. We also monitor alerts within $2{\times}2$ square degrees centered on M31 that may contain extragalactic novae and output to the "in_m31 stream". There is also a filter that flags alerts with high signal-to-noise ratio detection ("high_snr stream"), which are mostly bright transients in the Milky Way (e.g., novae, dwarf novae) that even small telescopes can provide decent spectra for classifications. As a demonstration, the ANTARES team has been conducting spectroscopic observations and classifications of alerts flagged by our customized filters. We have issued 19 Astronomer's Telegrams so far, and many of those classifications are related to white dwarfs, ranging from SNe Ia, to fast novae in M31, and highly extinguished Galactic novae and dwarf novae. A summary of the Astronomer's Telegrams issued by the ANTARES team and collaborations can be found in Table 1.

3. Prospect

The community alert broker will play a pivotal role in the future time-domain ecosystem, especially enabling rapid responses to the rarest of the rare events. Our broker, ANTARES, has been ingesting and disseminating alerts from ZTF as a step forwards for LSST. On top of that, ANTARES is also well-connected to a suite of tools that are currently under development at NSF's OIR Lab and by the community. ANTARES can

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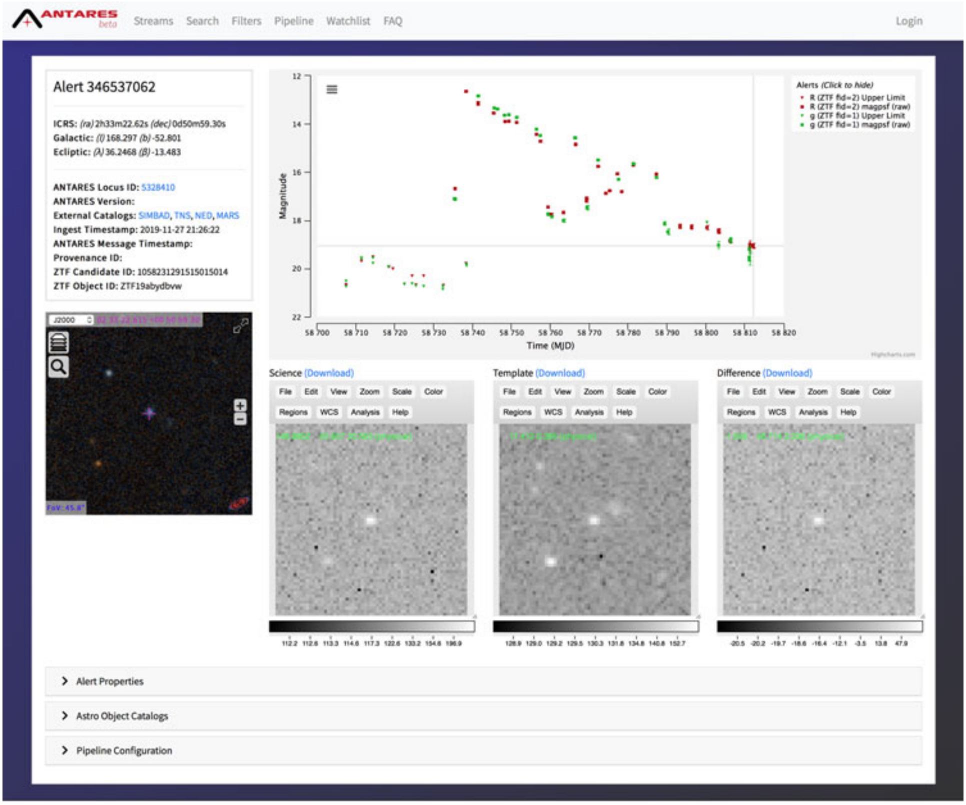

Figure 1. ANTARES alert information page. We aggregated alerts on the same position of the sky and formed light curves. The ANTARES web portal also displays the science, reference, and difference image from ZTF. We also provide contextual information by cross-matching multi-wavelength catalogues. All of the information (including light curves) are downloadable from the web portal. The example shown here is a Galactic dwarf nova HP Cet during superoutburst. Follow-up spectroscopic observations by the ANTARES team and collaborations can be found in Table 1 and in Soraisam *et al.* (2019).

connect to the Las Cumbre Observatory Target and Observation Manager† (TOM) that can handle target information, observation scheduling, and data visualization. ANTARES not only provides a searchable database for TOM to query targets, but also enables TOMs to subscribe to pre-defined or user-specified filters and streams. The ANTARES team also obtained classification spectra from telescopes that are part of the Astronomical Event Observatory Network‡ (AEON), in particular the Las Cumbres Observatory and the Gemini telescope. In the future, we can use TOMs to cross-talk with ANTARES and the facilities in the AEON, and stream-line an end-to-end follow-up infrastructure with minimum human interactions to maximize the science outcome from time-domain surveys.

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† https://lco.global/tomtoolkit/
‡ http://ast.noao.edu/data/aeon

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Table 1. Summary of ATels by ANTARES team and collaborations

ATel#	Name	Classification	Report date	Facilities
12935	ZTF19aazcxwk	SN Ia	7/12/2019	LCO 2m telescope
12943	ZTF19abfqlzi	M31 recurrent nova	7/15/2019	Gemini telescope
12946	ZTF19abdooly	dwarf nova	7/18/2019	LCO 2m telescope
12980	ZTF19abgsssu	dwarf nova	8/2/2019	Shane 3m Telescope, Lick Observatory
13053	ZTF19abpmetl	SN Ia	8/30/2019	Shane 3m Telescope, Lick Observatory
13055	ZTF19abraqpf	dwarf nova	8/30/2019	Shane 3m Telescope, Lick Observatory
	ZTF19abqstxq	dwarf nova	8/30/2019	Shane 3m Telescope, Lick Observatory
13115	ZTF19abtuflm	SN II	9/18/2019	Shane 3m Telescope, Lick Observatory
13119	ZTF19abpvysx	SN Ia	9/21/2019	Shane 3m Telescope, Lick Observatory
	ZTF19abrelog	SN Ia-91T	9/21/2019	Shane 3m Telescope, Lick Observatory
	ZTF19abulrfa	SN IIP	9/21/2019	Shane 3m Telescope, Lick Observatory
13141	M31N2019-09b	M31 nova	9/28/2019	Gemini telescope
13149	ZTF19abyukuy	Galactic nova	10/1/2019	Shane 3m Telescope, Lick Observatory
13153	ZTF19abxnerq	M31 nova	10/1/2019	Gemini telescope
13178	ZTF19abzpkss	dwarf nova	10/9/2019	Shane 3m Telescope, Lick Observatory
13183	ZTF19abydbvw	dwarf nova	10/11/2019	Shane 3m Telescope, Lick Observatory
13200	ZTF19acbwmqd	SN IIP	10/18/2019	Shane 3m Telescope, Lick Observatory
13210	ZTF19acbzgog	M31 nova	10/21/2019	Gemini telescope
13231	ZTF19acfsteg	M31 nova	10/28/2019	Gemini telescope
13261	AT2019tsc	M31 nova	11/4/2019	Gemini telescope
13286	ZTF19acmdpyr	SN Ia	11/12/2019	Shane 3m telescope, Lick Observatory
	ZTF19acklbjr	SN Ia	11/12/2019	Shane 3m telescope, Lick Observatory
13317	ZTF19acnfsij	M31 nova	11/29/2019	Shane 3m telescope, Lick Observatory

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