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THE ALL-SKY AUTOMATED SURVEY FOR SUPERNOVAE

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RESUMEN

Presentamos un resumen del Cartografiado de Todo el Cielo para la búsqueda de supernovas (ASAS-SN). Mostramos brevemente el hardware y las capacidades para el cartografiado, y también describimos los resultados científicos más recientes, en particular los fenómenos debidos a rupturas de estrellas por fuerzas de marea y también las supernovas, incluyendo la SN más brillante encontrada hasta la fecha.

ABSTRACT

This is an overview of the All-Sky Automated Survey for SuperNovae – ASAS-SN. We briefly present the hardware and capabilities of the survey and describe the most recent science results, in particular tidal disruption events and supernovae, including the brightest SN ever found.

Key Words: methods: observational — supernovae: general — surveys — techniques: image processing

1. INTRODUCTION

Astronomers want to observe fainter and fainter objects to peer deeper and deeper into the Universe. The bright sky still has a lot to tell us and this is what the *All-Sky Automated Survey for Supernovae*, ASAS-SN, will attempt to do. This survey is based on the successful All-Sky Automated Survey (ASAS, see e.g. Pojmanski 1997, 2004). It was a low cost project to monitor the whole sky down in the magnitude range $7 \leq m_I \leq 13$. Nearly 4×10^7 stars have been observed and over 50,000 new variables were discovered. On that basis, the ASAS-SN project goes deeper, has a faster cadence and processes data in real-time. Reaching a limiting magnitude of $m_V \simeq 17$ allows us to explore the bright *extragalactic* variable sky. The focus of the project is on supernovae (SNe) in the nearby Universe, hence its name.

Surprisingly, the bright sky is still relatively unexplored. Here is what we expect to see: (1) 5×10^7 stars in our galaxy, $\sim 1\%$ are variable; (2) 250,000 stars in Large Magellanic Cloud, 50,000 stars in Small Magellanic Cloud; (3) 50 SNe II, 200 SNe Ia, 10 super-luminous SNe (SLSNe) *per year* to distances of $\sim$50, 150 and 400 Mpc; (4) thousands of active galactic nuclei, all variable; (5) thousands of asteroids.

2. SURVEY DESCRIPTION

The equipment used is mostly off-the-shelf. This not only keeps cost reasonably low but it also allows to deploy new telescopes rapidly when new funding is secured.

A full *unit* comprises four individual telescopes but a unit can be operated with less telescopes. Each of these is a Nikon 14 cm diameter lens, to which is attached a Fairchild Imaging CCD camera with 2k×2k pixels. The telescopes are on mount made by Las Cumbres Observatory (LCOGT). With a pixel scale of $7.8''$ per pixel, the field of view of each telescope is $4.47° \times 4.47°$. A V filter is used and the limiting magnitude is $V_{\rm lim} \sim 17$. The four telescopes in a given unit point in slightly different directions so that there is a little overlap between the fields of each telescope. As a result, we can cover about 10^4 square degree per night with a given unit. Currently there are two units, both hosted by Las Cumbres Observatory Global Network (LCOGT). One unit, named Brutus, is in Haleakala (Hawaii, USA) and the other, named Cassius, is at the Cerro Tololo Observatory (Chile), thereby giving access to the whole sky. Both units now have four telescopes (see Figure 1 for the Brutus unit in Hawaii).

The telescope motion is controlled by LCOGT software. Our own software determines what fields will be observed for each night, taking into account in particular the time of the last visit and the probability that a SN is above the detection limit if it exploded since the last visit. Two images are taken at each pointing and we are now experimenting with three images, as a way of reducing the number of "fake" transients, i.e. false positives. After a field is observed, all images are compressed and immediately transferred to Columbus, Ohio, where they are reduced. To search for transients, we use a modi-

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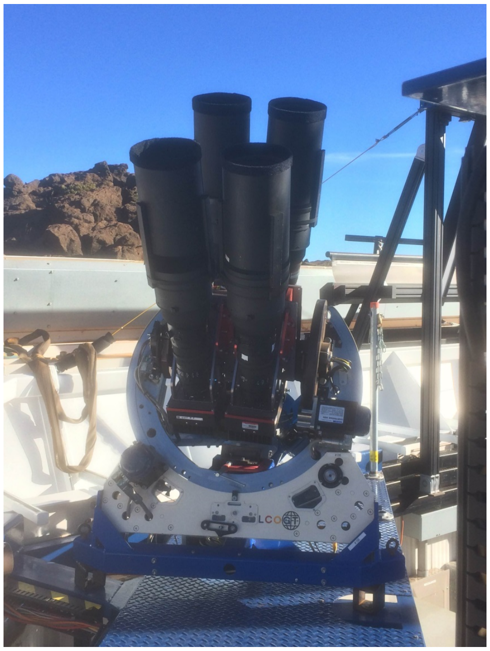

Fig. 1. The Brutus four-telescope unit in Haleakala.

fied version of the ISIS image subtraction program (Alard & Lupton 1998; Alard 2000). Subtracted images are available to team members on a web interface in order to scan for legitimate transients.

Most supernovae (SNe) are close enough to the detection limit that the validity of the transient needs checking. We obtain confirmation images from a network of amateur astronomers located around the planet (Australia, Japan, USA, South Africa, France, Italy, New Zealand) who make their images immediately available. If a transient is confirmed, we then announce it via an Astronomer's Telegram (ATel). A number of transients, particularly cataclysmic variables (CVs), are bright enough in ASAS-SN data that they do not need confirmation and are announced immediately.

2.1. *Followup facilities*

Compared to transients found by most other surveys, ASAS-SN transients are bright enough that they can be followed on relatively small facilities. We use a number of telescopes to follow selected transients, mostly extragalactic objects. Facilities include LCOGT 1 m telescopes at various sites, the MDM 2.4 m telescope (Kitt Peak), the robotic 2 m Liverpool Telescope (La Palma), the Apache Point Observatory 3.5 m, as, well as facilities in Chile. We also have access to the Large Binocular Telescope 2×8.4 m for late-time observations when transients have faded significantly. Furthermore, we have been successful in obtaining time on the *Swift* satellite for followup in the UV/X rays.

3. RESULTS

Since operations started in 2013, we have found numerous transients leading to over 300 announcements in ATels. Many transients are flares from late-type dwarf stars in our Galaxy (e.g. Schmidt et al. (2014)) or CVs. The advantage of looking at the whole sky often is that we can find rare events. For instance, we found an EXor accretion event on a young stellar object, ASASSN-13db (Holoien et al. 2013). There are numerous variable Active Galactic Nuclei and one notable example is the "changing-look" AGN in NGC 2617 (Shappee et al. 2014), changing from a Seyfert 1.8 to a Seyfert 1. ASAS-SN has found over 500 *new* CVs, and has excellent light curves for many known ones. There are already twelve papers published and several more are in preparation.

3.1. *Tidal disruption events*

The disruption of a star by a super-massive black hole (SMBH) can give rise to a flare, a sudden transient. Such tidal disruption events (TDE) have been found at X-ray energies (e.g. Komossa & Bade 1999) initially but we are now beginning to discover them at lower frequencies, in the UV and in the optical (e.g. Gezari et al. 2008; van Velzen et al. 2011, among several others). With several surveys scanning a large portion of the sky on a regular basis (e.g. Pan-STARRS, PTF, ASAS-SN), one can expect this field to blossom. Indeed, ASAS-SN discovered three TDE. Here we describe results for two of them.

ASASSN-14ae ASASSN-14ae was discovered on Jan 25 2014. At a redshift of z=0.0436 (corresponding to $D = 193$ Mpc), it was the closest TDE candidate found at optical wavelengths. The position of the transient was compatible with being at the center of its host galaxy. We initiated a followup campaign using ground-based telescopes as well as UV and X-ray monitoring with *Swift*.

The light curve looks unlike that of any known type of SN (see Fig. 3). Similarly, the colors remained very blue, unlike what most SNe do. The analysis showed that the temperature remained high at $T_{eff} \approx 20,000$ K, hence explaining the blue colors, even though the luminosity dropped significantly. The spectra showed broad Balmer lines in emission as well as He II lines. We might have missed the peak brightness of the event but even then, the maximum luminosity we measured was bright at $L \simeq 8 \times 10^{43}$ erg/s. Our interpretation is that this

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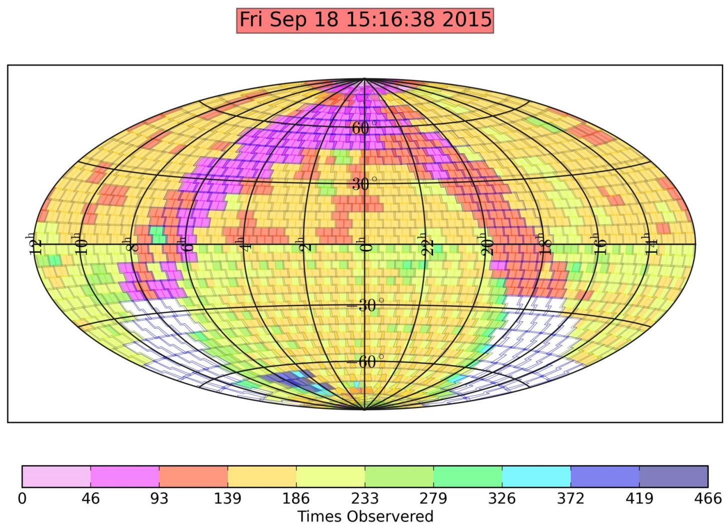

Fig. 2. This shows the number of observations per field over a whole year. There are more observations in the northern hemisphere than in the southern one because we only had two cameras in Chile until about the middle of the year 2015.

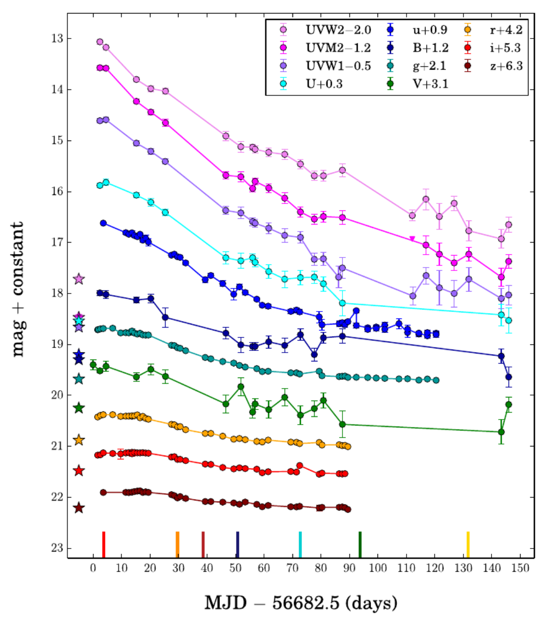

Fig. 3. The light curve of the tidal disruption events ASASSN-14ae (Holoien et al. 2014).

was a TDE, whereby only a small fraction of a star was actually accreted (the energy needed to power the event is $M_{\rm acc}c^2 \sim 10^{-3} M_\odot c^2$) onto a black hole with a mass $M_{\rm SMBH} \sim 10^{6.5} M_\odot$. Details of the analysis are in Holoien et al. (2014).

ASASSN-14li The transient was discovered on 2014 November 22. The story is largely the same as for ASASSN-14ae, in terms of what was observed and what was inferred from the data. At $z = 0.0206$ ($D = 90.3$ Mpc), ASASSN-14li is even closer than ASASSN-14ae. The UV+optical emission was well fitted by a blackbody with a temperature remaining roughly constant at $T \sim 35,000$ K. The luminosity evolution was consistent with an exponential decline. The peak luminosity was $L \simeq 10^{44}$ erg/s. The decline in the X-ray was fairly shallow, to the extent that the late-time luminosity was dominated by X-ray emission. The spectra showed a strong blue continuum with broad Balmer and Helium emission lines (see Holoien et al. 2015 for full details).

Counting another candidate, ASASSN-15oi, ASAS-SN has now found three TDEs. One consequence is that TDEs can be found at optical wavelengths (see also, e.g., van Velzen et al. (2011)) about as efficiently as at high energies. The TDEs found in various wavelengths ranges may be different classes of events, those with γ-rays may well have a jet (e.g. Bloom et al. (2011); Cenko et al. (2012a)), although the presence of a jet has been inferred for ASASSN-14li as well (van Velzen et al. 2015).

Unless we have been exceptionally lucky in finding these TDEs, our discoveries open the possibility that there are many more relatively nearby TDEs to be discovered and that our completeness for such events is higher than for other surveys. We calculated a TDE rate of 4.1×10^{-5} yr^{-1} galaxy^{-1}.

3.2. *Supernovae*

The main focus of the survey is on supernovae. The majority of them are near the detection limit of the survey and often require a confirmation image from an amateur astronomer or from one of our

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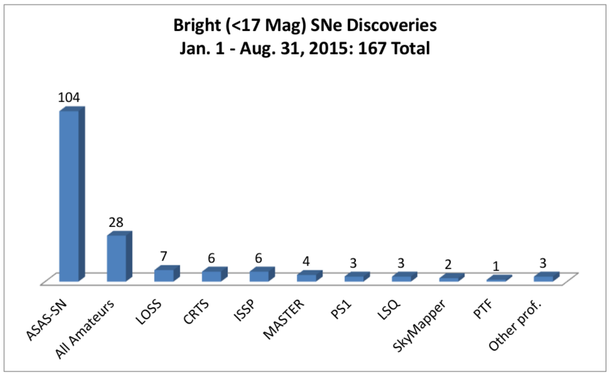

Fig. 4. Supernova discoveries by various surveys, all SNe classified (i.e. with a spectrum) and $m_V < 17$.

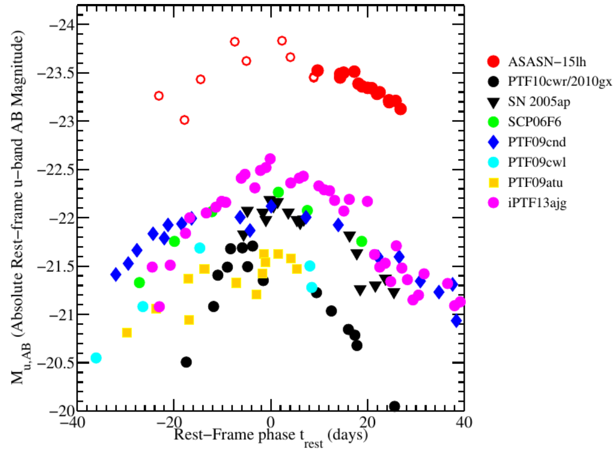

Fig. 5. The light curve of ASASSN-15lh (red dots) compared to other super-luminous SNe. It is brighter by at least one magnitude compared to the second brightest SN.

follow-up facilities. This is usually done within hours and most discoveries are announced promptly via an Astronomer's Telegram.

To date, we have found over 240 SNe of nearly all known types, in particular this includes over 160 SNe Ia. Figure 4 shows the statistics of bright SN discoveries for the first eight months of 2015. This is for SNe brighter than $m_V = 17$ for which there is a spectroscopic classification.

Of course, several other surveys find many more SNe than ASAS-SN, some of them substantially fainter but they are much harder to classify and follow up. The point of this histogram is to show that the bright sky is actually under-observed. Before ASAS-SN, a lot of the bright transients remained undiscovered, hence not followed. In a sense this justifies even more a survey like ASAS-SN since there is so much to observe.

ASASSN-15ed (Pastorello et al. 2015) is a transition object. It was a bright SN, reaching peak magnitude $M_r \approx -20.04$, initially classified as a SN Ibn on the basis of the blue early spectra with narrow P-Cygni profiles of He I. In later spectra, broad P-Cygni profiles of He I became prominent. This is the first object to be caught transitioning from Ibn to Ib.

Shappee et al. (2015) described a thorough study of a SN Ia discovered very early after explosion. This was the second brightest SN in the year 2014 (after SN 2014J) and it was found very early after explosion. Its brightness provided us with the opportunity for a long and sustained followup campaign, resulting in superb photometric and spectroscopic coverage.

3.2.1. *ASASSN-15lh*

This source was discovered on 2015 Jun 14. Upon inspection of images taken prior to discovery, it turns out that the object could be detected in stacks of several epochs, starting from May 8. The first spectrum was very blue and almost featureless, with only a broad absorption trough near 5100 Å. This spectrum resembles that for a type I superluminous SN, PTF10cwr (≡ SN 2010gx) that has a strong absorption at 4200 Å. Assuming that these absorption features in these two SNe are the same, that places ASASSN-15lh at $z \sim 0.23$. Several optical spectra revealed absorption lines that unambiguously place the SN at $z = 0.2326$. All spectra show a blue continuum with a broad ($\sim 10^4$ km/s) O II absorption. Furthermore there is no sign of hydrogen nor helium in the spectra.

Fitting a blackbody to the energy distribution at several epochs shows that the temperature declines slowly and that the emission radius, $\sim 5 \times 10^{13}$ m ($\sim 7 \times 10^4\ R_\odot$), is comparable to other SLSNe-I.

At $z = 0.2326$ (corresponding to $D = 1171$ Mpc), it has an absolute magnitude $M_u(AB) < -23.5$ (in the rest frame u-band). This makes it the most luminous supernova ever discovered (Dong et al. 2015). An estimate of the bolometric luminosity yields $L_{\rm bol} > 2.2 \times 10^{45}$ erg/s, unprecedented for a supernova of any kind. Integrating the bolometric luminosity over a period of 50 days, the total energy radiated is 7.5×10^{51} erg. When compared to other SLSNe, ASASSN-15lh clearly stands out (see Fig. 5). It is substantially more luminous than any other SLSN.

The light curve, spectra and brightness of this event seriously stretches the imagination. It is not clear how one can make such a bright stellar explosion. Some SLSNe may be powered by interaction between the SN ejecta and hydrogen-rich circumstel-

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lar material. This seems unlikely given that we see no evidence of H nor He in the spectra. Most type I SNe are powered by the decay of radioactive ^{56}Ni but in this case, one would need $\sim 30\ M_\odot$ of ^{56}Ni to explain the brightness at peak, nearly two orders of magnitude more than most SNe. Another possibility for the source of power is a magnetar, a fast-spinning neutron star with a high magnetic field.

It is possible that the late-time light curve will allow us to determine the mechanism powering this SN. If the SN is powered by ^{56}Ni decay, the light curve must be exponential whereas it should follow t^{-2} in the case of a magnetar.

To put things in perspective, 7.5×10^{51} erg is a fairly high explosion energy for a normal SN. Either ASASSN-14lh has a much larger explosion energy or the physical mechanism powering the SN needs a nearly 100% efficiency in transforming the energy of the explosion into electromagnetic radiation.

4. NUCLEAR TRANSIENTS

In the past, a number of SN surveys have been targeting bright and massive galaxies. The reason was to maximise the number of SNe discovered. Some surveys explicitly stayed away from low-luminosity (i.e. dwarf) galaxies. When finding more and more SNe by various means, astronomers eventually realised that "not all galaxies are equal" when it comes to hosting SNe. Some sub-types of SNe seem to occur preferentially in specific types of host galaxies. This led to new surveys, "blind" or "untargeted", that just look at the sky without any reference to specific galaxies. In other words, they are looking at random parts of the sky, and discover SNe that happen in any kind of host.

Another shortcoming of past surveys is that they were avoiding the brightest regions of galaxies. This introduced a bias in the sense that SNe occurring in the central regions of their hosts were not found. It has been realised that the environments of SNe contain clues as to the nature and physics of these explosions, in other words SNe do not happen just anywhere. The image subtraction technique now commonly used by modern surveys allows to find SNe — and any other type of transient – even at the very center of galaxies. Figure 6 shows the offsets between SNe positions with respect to the center of their host galaxies. ASAS-SN can find SNe in the very cores of galaxies, in spite of a seemingly adverse pixel scale. This shows that large pixels do not affect our ability to detect transients, even in crowded or challenging environments.

Another proof of the efficiency of modern surveys to find nuclear transients is in the fact that tidal disruption events have been discovered. By definition, these transients occur at the very center of their host galaxy which is most often the brightest part of a galaxy. Several modern surveys have found TDEs, not only ASAS-SN (see above) but also by, e.g. Pan-STARRS (e.g. Gezari et al. 2012; Chornock et al. 2014) and PTF (e.g. Cenko et al. 2012b; Arcavi et al. 2014).

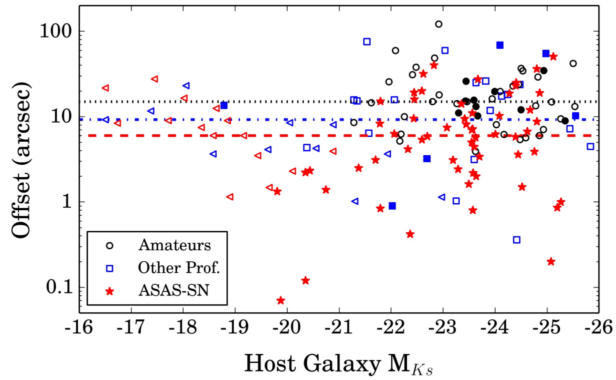

Fig. 6. Offsets between SNe and the center of their host galaxies, for various surveys, plotted as a function of host absolute magnitude in the K band. SNe discovered by amateur astronomers tend to be "avoid" central regions (i.e. small offsets) as the SNe are largely discovered by visual inspection of the images. Surveys done by professional astronomers — ASAS-SN in particular — now do find SNe in the central regions of galaxies.

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