Assassinating ASASSN:
Supernovae Identification Using ATLAS Data

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Using current data collection and reduction techniques, we plan to identify supernovae (SNe) faster and fainter than the All-Sky Automated Survey for Supernovae (ASASSN) team. We expect to identify all SNe down to magnitudes of 17.5, with declinations (Dec) above $-30°$, before ASASSN. Over the course of four nights, ATLAS images each spot on the sky a minimum of five times. With a minimum of five observations per night of each object, it is possible to achieve magnitudes as low as 18.5. In the ATLAS pipeline, images are collected, reduced, and differenced. To generate difference images, a composite image (wallpaper) is subtracted from the reduced images. Stationary transients stand out in difference images, increasing their probability of detection. Once images are differenced, certain restrictions are needed to distinguish between SNe and other real objects. To differentiate between SNe and asteroids, multiple observations must be taken at the same position. To eliminate variable stars, light curves must be constructed and analyzed. Unlike variable stars, the light curve of SNe will not be periodic; it will contain only one node.

1. INTRODUCTION

Observation of supernovae (SNe) is important in determining the distances of remote galaxies. Type Ib and Ic supernovae have been shown to vary greatly in peak brightness, but type Ia supernova (SNIa) share the same magnitude (m) at the time of peak brightness. For this reason SNIa are commonly referred to as "standard candles." This is an important feature, allowing for the calculation of distances to remote galaxies. Observing the violent outburst of a supernova (SN) gives us insight into our universe, as it was when the explosion occurred. Many cosmological questions are answered by SNe observations. Based on the current data, we know the universe is expanding at an accelerated rate. Another vital function of SN explosions is the dispersion of heavy elements throughout the universe. Using Asteroid Terrestrial-impact Last Alert System (ATLAS) data, we plan to identify SNe, with a focus on SNIa, faster and fainter than All-Sky Automated Survey for Supernovae (ASASSN).

2. COLLECTED DATA

2.1. ASASSN Data

The All-Sky Automated Survey for Supernovae (ASASSN) group collects data using eight 14 cm telescopes. Each night, these telescopes are able to cover roughly 20,000 deg^2, reaching down to ∼17th magnitude. These eight telescopes are split evenly between two sites. The first telescope array is located on Haleakala and began collecting data in Dec 2013. In Jul 2015, the second array became operational at the LCOGT Cerro Tololo station. This allows ASASSN to detect SNe in both hemispheres.[1]

Using 400 mm f/2.8G Nikon lenses allows for a large field of view, while ProLine PL230 CCD cameras are used as detectors. Detection of transients is made possible using image subtraction. With images having 7.8″ pixels, ASASSN relies on volunteers collecting confirmation images with larger telescopes.[2]

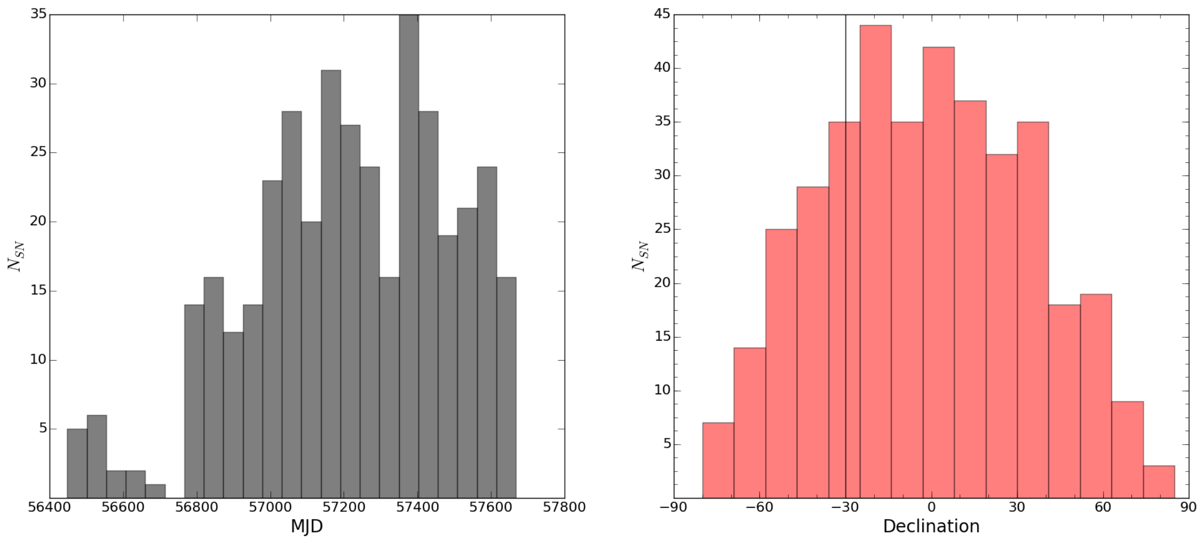
2.2. ATLAS

ATLAS is a project funded by NASA to find dangerous asteroids. The motivation and science justification was described by Tonry (2011).[3] To compare ASASSN to ATLAS, ATLAS used an f/2, 0.5 m Schmidt telescope on Haleakala and a 110 Mpixel detector to collect 30 deg^2 with each exposure. This telescope was installed in Jun 2015, and achieved more or less continuous operation around Sep 2015.

ATLAS will shortly install a second telescope on Mauna Loa, and a proposal to NASA is being evaluated to build two more units for the southern hemisphere.

The pixel size is 1.86″ and the field of view is 5.4×5.4 deg. The PSF is currently no better than 6.5″ which degrades the limiting sensitivity by one magnitude. The faulty Schmidt corrector will be replaced in Mar 2017. ATLAS uses two filters "*o*" (essentially $r+i$) and "*c*" (essentially $g+r$), changing according to the phase of the moon.

With the basic observation consisting of a 30 sec exposure and about 13 sec of overhead, about 900 observations are collected per night. The observation strategy has varied since the telescope was installed, but currently observes one of four declination (Dec) bands between −30 and +60 Dec, imaging each spot 5 times on a ∼15 min cadence. The overlap between observations is about 0.4 deg, and



(a) (b)

Figure 1: *SN discovered by the ASASSN project. Panel '(a)' shows ASASSN SN peak brightness dates. Panel '(b)' is ASASSN data, binned by Dec. The vertical line at $-30°$ indicates the lower limit on ATLAS observations.*

they are dithered by a random amount for a given night, so each object is seen 5 or more times, depending on whether it falls in an overlap. Prior to Apr 2016, ATLAS collected 4 or more observations of each object per night. Increasing the number of observations per night from 4 to 5, while maintaining the same 4 day cadence, required an upper limit to be placed at a +60 Dec. This is shown by the dark gray region in the upper right hand corner of Figure 6.

The observations are processed by the ATLAS pipeline which consists of image flattening, star finding, star identification, high precision fits to astrometry (typically RMS of $0.3''$ per star and more than 10,000 stars) and photometry (typically 0.1 mag RMS, limited by the current reference catalog), image differencing against a static sky image, and detection of objects that have moved or changed. Difference imaging and the detection of changing objects are discussed in § 2.2.1.

2.2.1. Difference Imaging

Difference images are generated by subtracting the wallpaper from reduced images. This is done to isolate objects that are changing, as shown in Figure 2. Figures 2a and 2b are reduced and difference images, respectively, of the SN "ASASSN-16ke." Subtraction of a properly calibrated wallpaper will produced a difference image containing only objects that are changing in the reduced images. After subtraction of the wallpaper, the SN is much more easily detected.

The "wallpaper" (static sky image) is the weighted sum of many observations at each point in the sky. ATLAS currently uses the Alard algorithm[4] for differencing, and the differences are dominated by photon noise and by systematics from saturated stars or flare artifacts from the Schmidt corrector.

The ATLAS mission is to find moving objects, but the processing automatically finds all stationary transients and variable stars as well. Once the image is differenced, the program tphot detects all sources at 3-sigma, and cut that back to 5-sigma once each source has been fitted and the detection significance is known. This is augmented by calculated RA, Dec, magnitudes, and other relevant quantities into a "ddt" (difference detection table) file.

The most useful classification variable is "starrat" (star ratio), which is defined to be the ratio of flux on the original, un–subtracted image to flux on the difference image. Both fluxes are measured using a circular aperture of 2.0 pixel radius. The star ratio is used in determining if an object is real or just a residuals from subtracted stars. For these, the star ratio will be large (usually greater than 5) because the star was much brighter before it was subtracted. For asteroids and supernovae, we expect the star ratio to be near 1.0. Since they are not usually in their recorded locations, such objects should not

(a) (b)

Figure 2: *Comparison between reduced and differenced images. Panel '(a)' shows a reduced image containing the SN "ASASSN-16ke." Panel '(b)' shows the same SN, but in a difference image. The SN is located at the center of each image and an unidentified stationary transient is in the upper–left corner.*

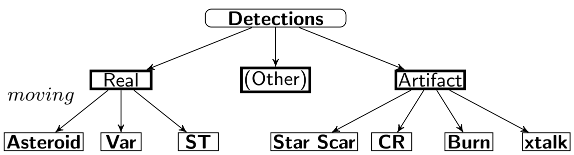


Figure 3: *Object classification probability flowchart. Asteroids are real objects that are moving, ST stands for stationary transient, Var is variable star. Artifacts arise during image processing and are not real objects.*

show up in the wallpaper. Any object that isn't in the wallpaper is left unchanged by difference imaging. This means the recorded flux to be the same both before and after image subtraction, resulting in starrat=1.0. Figure 4 shows the distribution of starrat values for all objects observed on the night of 57680. SNe are located in the tight cluster around starrat=1.0. Isolation of good stationary transient detections was achieved by applying classification restrictions.

Difficulties include cases where a real transient can produce a high starrat, and cases where a false detection from a star residual can produce a low starrat. The former arise from the fact that supernovae happen in galaxies, which do get subtracted and can raise starrat substantially above 1.0 if they are bright. The latter can occur when we have a star residual detection substantially off-center from the star, so the flux on the un–subtracted image is not as bright as we might expect, and starrat can be lowered to the 2-5 range, or in some odd cases can be negative. So starrat is not foolproof. Nevertheless, a starrat value near 1.0, especially if accompanied by other indications such as consistent astrometry, is a useful piece of evidence pointing toward a real SN, asteroid, or other interesting transient.

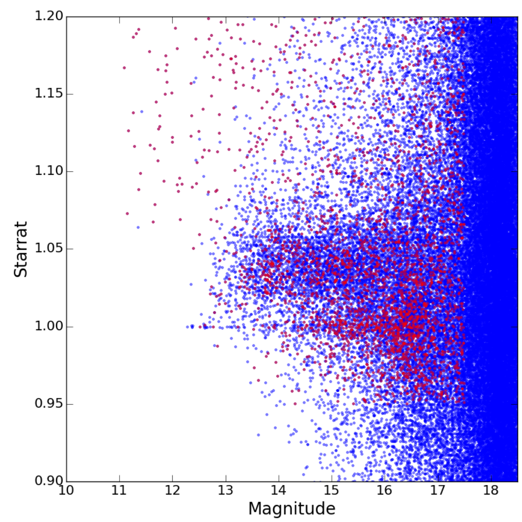


Figure 4: *57680 is used as an example to show the distribution of starrat as a function of magnitude. Starrat values for all objects detected that night are shown in blue. Shown in red are the starrat values of good stationary transient detections made that night.*

3. PROCEDURE

In order to assassinate ASASSN, it was necessary to show that ATLAS had the potential to find all of ASASSN discovered SNe. To do this, a list of all ASASSN discovered SNe was obtained.[1] By Oct 11, 2016 ASASSN has reported discovering 385 SNe. Many of these objects were reported before ATLAS was operation. Object cuts are discussed in § 4. Once the data were properly culled, the remaining SNe were found in observations made by ATLAS. The values of classification variables associated with

ASASSN SNe will be used to restrict the number of potential ATLAS SNe that need to be inspected. One classification variable is starrat. All ASASSN SNe have starrat values between 0.9 and 1.2. Such a wide starrat range will ensure no SN goes undetected, but it also drastically increases the false alarm rate.

4. EXPECTED OBSERVATIONS

With a Dec limit of approximately $-30°$, 100 SNe were not expected to be present in the ATLAS data. ASASSN reported the discovery of another 165 SNe before ATLAS began collecting data. These two sets do not exist independent of one another. After applying Dec and MJD based restrictions and accounting for overlaps between these groups, 161 SNe remained from the initial 385 reported by ASASSN. Another 65 SNe peaked before ATLAS was truly operational, leaving 96 as potential candidates. All 96 of these objects were found in the ATLAS data, resulting in a 100% completion rate.

The 65 SNe that peaked before ATLAS was truly operational can be further broken down as follows. Reported peak brightnesses occurring on or before 57364 accounts for 14 SNe. During this time the ATLAS reduction process was still being refined, making any reduced data unreliable. Another 50 SNe fell in regions that had no overlap with ATLAS observations due to the pattern in which data were collected. The final case was a Type II supernova (SNII). SNII are notoriously short lived, making it likely that ATLAS observed this region of the sky in the time surrounding the explosion, but not during the event.

5. FAILED MATCHES

We expect to see 96 of the ASASSN SNe in ATLAS observations. This presents us with 850 overlap opportunities, using a ± 10 day window. Of these, 694 observations were recorded and properly reduced. Figure 5 shows these 694 observations as a function of their pixel coordinates. The four reasons these matches failed, as discussed in § 5.1–§ 5.4, are: no match, no difference (diff) image, no ddt file, or no match within an existing ddt file.

5.1. No Match

A total of 25 expected observations lack any matches with ATLAS data. These 25 observations correspond to 25 distinct SNe. Since these SNe appear in other observations made by ATLAS, we maintain 100% completeness. Of these 25 SNe, 23 were found in ATLAS observations outside the ± 10 day window used. The remaining two objects were identified in reduced images. These two SN explosions ended before observations were made by ATLAS and were not expected to show up in the difference images.

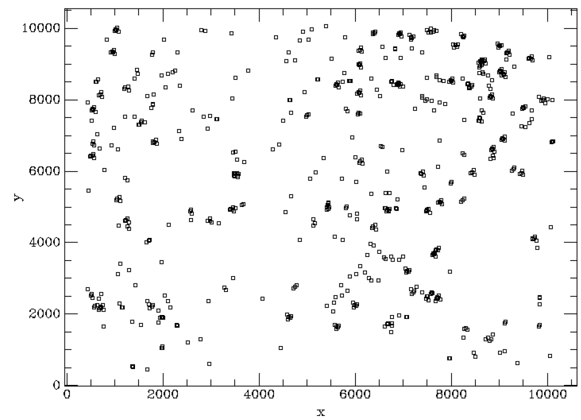


Figure 5: *Of the 850 expected observations, 694 were reduced properly. Each observation's x,y–position on the detector is represented by a black square.*

5.2. No diff File

Missing difference images account for 49 of the expected 850 observations. Matches that were missing difference images can be attributed to an error in the ATLAS pipeline. An error during differencing caused a break in the pipeline and no further images were generated for that night. Such an error will be corrected once the data is re–reduced.

5.3. No ddt File

For matches that were completely missing a ddt file, ddt files were missing for the entire night. This accounts for 15 failed matches and will be corrected by the next round of differencing.

5.4. No ddt Match

Of the total 850 expected matches, 67 do not show up in existing ddt files. Nature constantly plays a role in collecting astronomical data. When observations are made at the beginning or end of a night, ambient light levels rise and sky background fluctuations. 3 of the 67 missing ddt lines can be attributed to poor observation conditions, brought on by clouds and increased levels of sky background.

Errors during the image differencing process led to the loss of 8 expected overlaps. Older differencing techniques caused entire portions of images to be lost, accounting for 3 failed matches.

There were 6 cases where bright host galaxies caused the SNe to become extremely faint in the difference image. Outdated differencing procedures lead to less uniform backgrounds, making it harder to identify faint objects. During photometric calculations, the ATLAS pipeline failed to trigger on these 6 faint objects.

There are various reason why the PSF across an image may vary. Here, the major contributors are high levels of sky background and optical issues inherent to the ATLAS system. If not properly corrected, such issues cause observed objects to become distorted. Distortion can cause sharp edges to become fuzzy, resulting in the ATLAS pipeline failing to trigger on such objects. This accounts for 3 of the missing matches. Objects that were only in reduced images, but not in differenced images, account for 26 of the matches missing from the ddt files. Such instances arise when the object is fully subtracted during differencing, due to it existing in the wallpaper. As the wallpaper is an ongoing project, corrected future versions will not cause this issue.

There were 17 cases in which the SNe was not detecting in either the reduced or differenced image, indicating poor astrometry. Another possible explanation is bad photometry. If photometry is the issue, the SN explosions must have occurred outside the nominal ± 10 day window.

No two detectors are identical, since each one is handcrafted. As excess silicon is removed from the edges of a detector, minor defects are introduced. Many of these defects are removed during image processing. Corrections cannot be made for data that fall on the edges of a detector, where the silicon has been trimmed away. To account for this, ATLAS observation patterns are dithered. This dither allows for objects that fall on the edges of the detector to be observed more than 5 times a night. The final group of matches that are missing from the ddt files are of objects that fall on the edges of an observation. Such objects only exist in one of the two overlapping observations.

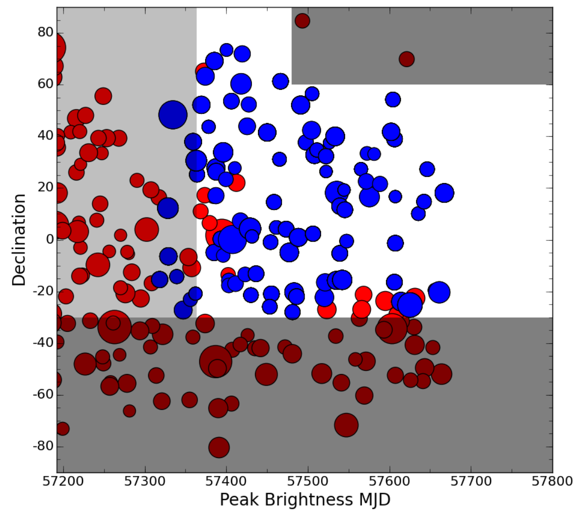


Figure 6: *ASASSN SNe that do not have matches in ATLAS data are shown in red. SNe that were found in ATLAS observations are shown in blue. Regions that have a lower chance of containing SNe have been covered in gray. The lower dark gray region eliminates objects below the ATLAS observation limit of $-30°$. A dark gray region starting at 57480 has been added to show when ATLAS went from 4 to 5 observations a night, giving an effective limit of Dec=$+60°$. This figure has been restricted to only includes SNe discovered by ASASSN during the time ATLAS was collecting data. The light gray region extends from ATLAS first night of collecting data up until 57364, when the reduction method was refined enough to produce usable data.*

6. CONCLUSIONS AND FUTURE OPPORTUNITIES

Of the 385 SNe ASASSN discovered by Oct 2016, only 96 overlapped with ATLAS in sky and time. In § 4 and § 5 we discussed the 850 ATLAS observations associated with the 96 SNe expected to be present in ATLAS data. It has been shown that all 96 ASASSN discovered SNe overlapping ATLAS observations in sky and time are detectable in ATLAS data.

SNe discovered by ASASSN were used in refining ATLAS classification variables, such as starrat. Variables like starrat reduce the false alarm rate by eliminating artifacts produced during image subtraction, as shown in Figure 4. We verified all ASASSN SNe to have a starrat values between 0.9 and 1.2. Although using such a large starrat range would allow all SNe to be detected, it would also drastically increase the false alarm rate. Further tests need to be conducted in order to find the optimal range for starrat; one that maximizes the number of SNe detected while minimizing the number of objects that need to be examined. Restricting classification variables drastically reduces the false alarm rate and leads to fewer objects needing visual inspection. This shows the ability for ATLAS to identify all SNe faster and fainter than ASASSN is able to.

The detection of all SNIa between -30 and $+60$ Dec with magnitudes down to 17.5, is possible using ATLAS data. All SNe discovered by ASASSN, after

ATLAS became truly operational, were able to be identified with ATLAS data alone. This is shown in Figure 6, with missed SNe falling on the edges of ATLAS observational limits.

With a relatively short average lifespan, detection of a SNIa requires frequent coverage of the entire sky. Using current observation patterns, ATLAS surveys the entire sky, between -30 and $+60$ Dec, in just 4 nights. Five observations of the entire sky are recorded by ATLAS every four nights, making it possible to detect SNIa down to magnitudes of 18.5. During our analysis we ran successful tests down to $m = 18$.

To differentiate between real objects and artifacts, we require objects to show up on more than one image collected during the night it was observed. This requirement drastically reduces the false alarm rate by eliminating artifacts such as star scars, as they are not consistently present. An object is determined to be real if it appears in all good observations overlapping that region of the sky. If an object appears in one of the images, it is expected to appear in the other overlapping images collected that night. Any object that appears in only one observation is deemed to be an artifact. This simple criteria allows us to easily distinguish between artifacts and real objects.

The final distinction that must be made is between the different types of real objects. All real objects have defining characteristics. Asteroids and other non–stationary objects are not expected to be observed in the same position more than once. Unlike moving objects, SNe are stationary transients; their positions do not change as a function of time. To remove the possibility of an object being an asteroid, we require multiple detections to be made at the same position. In order to distinguish between SNe and other stationary transients, light curves must be constructed. The light curve of a variable star will appear periodic, while that of a SNe will increase suddenly, then rapidly fall off.

The order of a polynomial that best fits each light curve will distinguish between different stationary transients. SN light curves are best fit by second degree polynomials. Higher order polynomials and sinusoidal fits are indicative or periodic objects, such as variable stars. A similar but less robust technique would be the fitting of a Gaussian. A Gaussian fit that converges exactly one time represents a single peak in the brightness. SNe are not the only type of transients that peak only once, so using a Gaussian fit will increase the false alarm rate. The benefits of a Gaussian fit are being able to use width, height, and other parameters to distinguish between different stationary transients and even determine the type of identified SNe.

7. ACKNOWLEDGMENTS

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