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Using Supernova Observations in the Electromagnetic Spectrum to Guide LIGO Searches for Gravitational Waves
LIGO Summer Undergraduate Research Report

K. Kaufman, UCLA and CaRT
kfarore@ucla.edu

Abstract

Core-collapse supernovae are predicted to be significant sources of gravitational waves; however, their signals are also predicted to lie close to the noise threshold of LIGO even for a galactic event. In order to make a search for true signals from any of these events practical, the time of core collapse must be constrained to a reasonable window within the data. In this project, we have compiled a catalogue of over 100 supernovae of types Ib, Ic, and II within 50 Megaparsecs that occurred after November 2005. The first light visible from a supernova, the shock breakout, is almost never observed directly, so methods must be developed to trace back to that time from observations made days or weeks afterward. We have been able to constrain the shock breakout times to within a few days or less for 8 supernovae based on non-detections made just before discovery. We have begun to use the Expanding Photosphere Method to determine the shock breakout times for type II supernovae once photometry and spectra for each become available, and we are investigating a similar method for the remaining types Ib/c.

WWW: http://www.ligo.org/ and http://www.virgo.infn.it

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Contents

1 Introduction

At the end of their lives, massive stars form an electron-degenerate iron core and nuclear fusion stops. When the iron core can no longer maintain hydrostatic equilibrium, the core collapses until its inner regions reach nuclear densities. Here, the nuclear equation of state stiffens, leading to a rebound (”bounce”) of the core and creating a shock wave that travels through the stellar envelope. However, the shock wave created by this core bounce alone remains hydrodynamic only for milliseconds, quickly turning into an accretion disk. It must be instead revived by some mechanism in order to create the supernova[1]. Although this mechanism is yet to be determined, the three major candidate processes are all predicted to be generators of gravitational waves, each with a distinct signature[2]. Detecting gravitational waves from these sources can help constrain the supernova mechanism, an important goal for astrophysics.

However, the predicted gravitational-wave strains from these waves are rather weak, even for nearby ($\lesssim$10 Megaparsecs) events, making only extreme models easily constrainable with initial LIGO[2]. In addition, nearby events are much rarer, only a few per year, lessening the chances even more that an energetic/extreme supernova will be detected by LIGO. Nevertheless, we intend to perform a gravitational-wave search targeted at nearby core-collapse supernovae that exploded during the S5 and S6 LIGO data-taking operations. In order to do this, we will employ electromagnetic observations of supernovae as triggers to constrain on-source regions to reduce the false alarm rate.

In order to pick out time frames to mine in LIGO data, we decided to compile a list of candidate supernovae that fit certain criteria and try to constrain their times of explosion. The most direct way of finding a given CCSN’s explosion time would be neutrino detections, as these particles are created coincident with gravitational wave emission. However, neutrino detection is also extremely difficult, and current detectors have a limited range of a few hundred kiloparsecs for neutrinos from CCSNe. Supernovae are most commonly studied through their electromagnetic (EM) radiation, usually beginning after the shock wave has broken through the outer layers of the star, allowing light in the ultraviolet, visible and infrared regimes to be observed. Using EM data such as light curves and spectra, our initial goal is to try to find the time of shock breakout for as many supernovae as possible, and trace back to the time of core collapse to within ± 1 day.

Section 2 describes the criteria used to create the supernova catalogue, and the resources used to compile it. It also describes methods we use to find the time of shock breakout, namely the Expanding Photosphere Method for type IIP SNe. Section 3 describes the progress and results we have made this summer, including a discussion of the supernovae we have been able to constrain shock breakout times for. Lastly, Section 4 summarizes our findings and plans for future work.

2 Methods

Our criteria for candidate supernovae are as follows: The supernova must be a core-collapse type, which includes the types Ib/c and type II. We also included supernovae whose types are so far unknown, in the event that subsequent information shows them to be a core-collapse type. The supernova must have occurred in a galaxy whose distance is known, so we can make a priori estimates on whether its gravitational waves would be measurable by us and make a posteriori upper limit statements. The distance cutoff for this list is set to 50 Mpc. The supernova must also have occurred after November 2005, when LIGO started taking data in S5 at design specifications. For this project, supernovae occurring up until the LIGO upgrade shutdown begins on October 20, 2010 will be considered.

Supernovae were chosen from the archives of the Harvard CfA[3] and Rochester Astronomy catalogues[4]. These lists compile messages from the Central Bureau for Astronomical Telegrams known as Electronic Telegrams (abbreviated CBET) about new supernovae , which report discovery and other information on new astronomical events. They also specify whether the event occurred in a known galaxy, and provide links to the galaxy's entry in the NASA/IPAC Extragalactic Database, which contains distance information[5].

2.1 General Method: Non-Detection

The simplest, most universal method of determining the shock breakout time of a supernova would be an observation of the supernova preceded by an observation of the host galaxy where the supernova is not visible. If such measurements are made on subsequent nights, the shock breakout time is known to within a day. As CBETs often contain information on when the last non-detection was made, this will be our first method to try.

However, this information may not be known for all supernovae, or the time between non-detection and discovery may be far too large to be of use. In these cases, other methods must be developed for the specific type of supernova at hand.

2.2 Type IIP: Expanding Photosphere Method

Type IIP supernovae are characterized by a long period of near-constant luminosity known as the 'plateau' right after shock breakout. Figure 1 from Eastman et al. (1994)[6] shows a theoretical lightcurve of a type IIP in various photometric bands; the plateau region is apparant. This nearly constant luminosity feature is due to a front of recombination traveling through an initially ionized hydrogen envelope in the outermost layers of the supernova. Once the front has moved through the entire shell, the luminosity is due to radioactive decay in the core, and declines steadily[6]. The Expanding Photosphere Method is a technique originally intended to for the determination of the distance to supernovae by treating the photosphere during the plateau phase as a blackbody expanding spherically symmetrically[7, 8]. However, it can also be used to determine the time of shock breakout. A step-by-step derivation of the simplified technique we used is detailed below, the bulk of which is adapted from Schmidt, Kirshner & Eastman (1992)[7] and Dessart & Hillier (2005)[8].

The method in this summary assumes 4 things are known: distance to the supernova (host galaxy), photometry in any visible band (photometry in multiple bands helps with accuracy, but is not necessary for the most basic treatment), $B - V$ color, and expansion velocity of the shell material, which is determined by the blueshift of spectral lines. The latter three must be from the same date or at least very close together.

The EPM assumes that the photosphere of the supernova is expanding spherically symmetrically and radiating like a blackbody. The specific luminosity of the photosphere can be described in two equivalent ways: one as a function of observed flux, and the other as a function of intensity.

$$4\pi R^2 \pi B_\lambda(T) = 4\pi D^2 f_\lambda \tag{1}$$

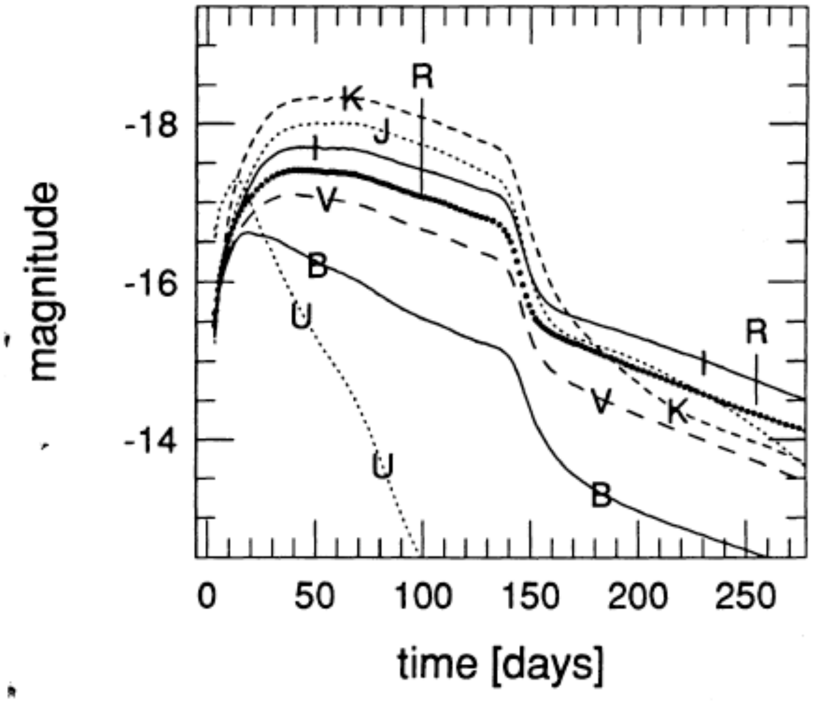

FIG. 13.—Computed *U*, *B*, *V*, *R* (Cousins), *I* (Cousins), *J*, and *K* broadband light curves for s15s7b (unmixed).

Figure 1: A type IIP theoretical light curve from Eastman, et al. (1994)[6].

It can then be seen that the angular size of the supernova in the sky can be defined by radius and distance,

$$\theta = \frac{R}{D} = \sqrt{\frac{f_\lambda}{\zeta^2 \pi B_\lambda(T)}} \tag{2}$$

where ζ is called the flux dilution correction factor. This factor, less than or equal to 1, needs to be applied since the SN does not produce flux like a perfect blackbody. The factor corrects the flux to make it closer to a blackbody's. However, determining this factor is one of the most complicated and subtle parts of EPM, which our collaborator Luc Dessart (Marseille) in particular has spent much time working on. In our approximation, we take ζ to be 1 (no dilution). With the assumption of spherically symmetric expansion, the radius of the photosphere can be written as a linear function of time since shock breakout based on its initial radius and expansion velocity:

$$\theta D = v\Delta t + R_0 \tag{3}$$

In addition, we assume the radius of the progenitor to be much smaller than the radius after the explosion. Thus, we can solve for the time since shock breakout simply by using

$$\Delta t = D\frac{\theta}{v} \tag{4}$$

Since D and v are already known, all that remains is to calculate θ (Equation 2). The specific flux can be found using the magnitude in a suitable band and a zero-point flux in the same band as a reference point.

The zero-point flux refers to the observed flux in a certain band corresponding to a magnitude of 0. For example, the zero-point flux of the B-band is 0.064 $[J/s \cdot m^3]$[9].

$$-m_\lambda = -2.5 \log \left(\frac{f_0}{f_\lambda} \right) \tag{5}$$

The specific intensity of a blackbody is easy to calculate, using the familiar Planck Equation.

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}(e^{\frac{hc}{\lambda kT}} - 1)^{-1} \tag{6}$$

It is important to note that the wavelength used here must correspond to the photometry band that was used to calculate the specific flux, i.e. the effective wavelength of the band. The last thing needed to calculate the specific intensity is the effective temperature of the photosphere. If a spectrum is available for the needed date, the temperature can be calculated by fitting a blackbody curve to it. As that may be more difficult to obtain, the color temperature derived from $B - V$ can also be used,

$$\frac{10^4}{T_c} = 1.605(B - V) + 0.67[7]. \tag{7}$$

This treatment does not take into account a number of corrections which improve the accuracy, including flux dilution or even extinction. Leaving out flux dilution will underestimate the shock breakout time, and ignoring extinction may both overestimate or underestimate it [**?**].

This method is not suited equally well to all times of the plateau period. At later times, spectra are noisy, and the photosphere cannot be approximated to have a well-defined radius, so emphasis should be placed on using early data[8].

2.3 Other Types: So Far Unknown

There remain the other major supernova types: Ib/c, IIb, IIL, and IIn. Unfortunately there is much less literature on these types than on type IIPs.

Type Ib and Ic do not have a hydrogen envelope; they have a Helium shell and no Helium, respectively. While these two are the second most common types of CCSNe, there is surprisingly little on their nature from which to derive a method. However, Cowen, Franckowiak and Kowalski (2010) have published a paper wherein they use a method similar to EPM involving light curve fitting to determine the explosion time of certain CCSNe, including two type Ib/c's[10]. As we have focused mostly on EPM this summer, we have not yet had a chance to follow up on this method for viability though it is our best candidate for these types.

Type IIb supernovae are those that show hydrogen spectral features like a type II in the beginning of the explosion, but lose them during the process and end up looking like a Ib. Because of these features, they may start out with a small hydrogen envelope, and a small plateau period may be present. However, these types are complex and also not very well understood, making a method for these types even more difficult to establish.

The rarest types are IIL and IIn, both having Hydrogen present, but the first having a linearly declining luminosity, and the second having very narrow spectral lines. Types IIL appear to be between type IIP's and IIb's in the amount of hydrogen present, and type IIn's are characterized by the interactions their shock front makes with circumstellar material [11]. These types are not as well-studied as the former ones, and in particular the nature of type IIn's makes their evolution complex. However, as they are the rarest types, they will likely not be too populous in our catalogue.

3 Results

A catalogue of 129 candidate supernovae has been completed, which currently contains all candidate supernovae up to SN2010ir, discovered October 09, 2010. This encompasses all known supernovae that fit our criteria for our chosen time period. If more are discovered with possible explosion dates before October 20, they will be added to the catalogue. The catalogue includes information for each one such as type, distances to host galaxy, date of discovery and inferences about the time of explosion, all with references. The catalogue is stored in the Extensible Markup Language (XML) format so it can be easily transformed and read by different programs using the Extensible Stylesheet Language Transform (XSLT). The full catalogue can be found at
https://trac.ligo.caltech.edu/snsearch/wiki/SupernovaList.

Of the 129 supernovae, 55% were of type II/IIP, 23% were of type Ib/c, and 22% were of the rarer types or had unknown types. Figure 2 shows the distribution of the nearest measured distances of each supernova's host galaxy. The number of supernovae jumps significantly at around 10 Mpc, although there are still a few closer than that. The supernovae in the catalogue can also be roughly grouped based on how long after explosion the discovery was made. When the type of the supernovae is determined by taking a spectrum, often times the spectrum is compared to other, well-studied supernovae, and can be placed on an approximate evolutionary timeline. From this we determined that 27% were discovered over a month after explosion, making these events the most difficult to constrain. Sixty percent were discovered between one week and one month after explosion, which may be constrainable depending on the type (particularly type IIP) and how much information about the event is available. Ten percent were discovered within a week of explosion, making this group the first set to try to constrain. The remaining 3% had unknown explosion time estimates.

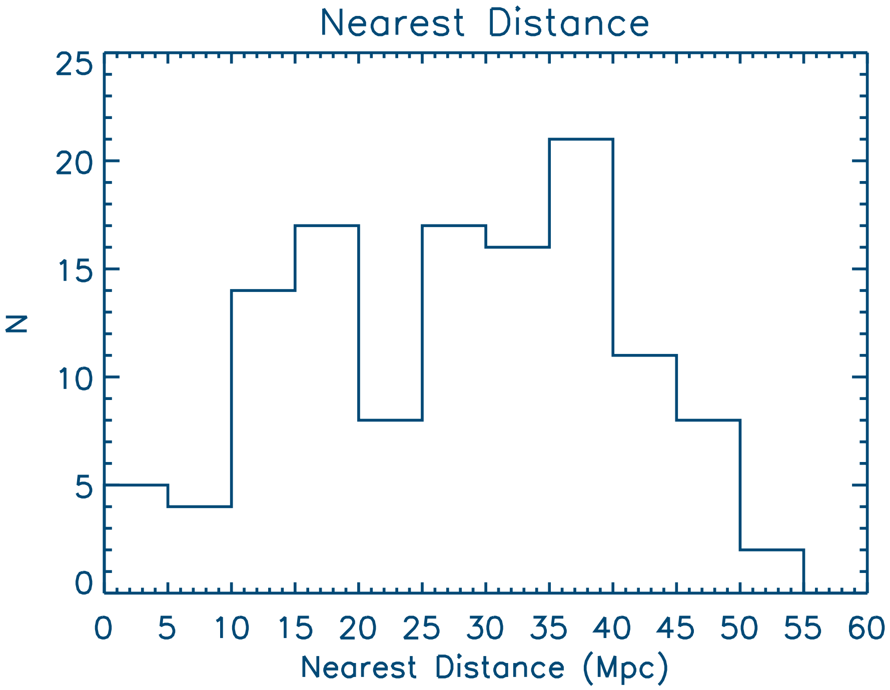

Figure 2: Distribution of nearest distances.

3.1 Constrained Supernovae

So far the shock breakout times of 8 supernovae have been constrained to a period of a few days, sometimes much less. Table 1 describes the basic properties of these supernovae such as type, distance, shock breakout time, and which LIGO segment the explosion occurred in. Each one is discussed in more detail below.

3.1.1 SN 2006bp

A type II around 18 Mpc away. Quimby et al. (2007)[12] estimate the date of shock breakout from spectral features and photometry, and Dessart et al. (2008)[13] use EPM to arrive at a shock breakout time of 2006 04 07.9 ± 0.4 days. Occurred during S5.

3.1.2 SN 2007gr

A type Ib/c constrained by non-detection. Discovered 20070815, not visible 20070810[14], giving a shock breakout time of 2007 08 12.5 ± 2.5 days. Spectrum taken on 20070816 appears soon after explosion[15]. Occurred during S5.

3.1.3 SN 2008D

A type Ib/c constrained by X-ray flash observed while observing another SN in the same galaxy. Shock breakout time constrained within a few seconds by Modjaz et al. (2009)[16], but we are currently unsure of appropriate error bars. Estimated time between observation and core collapse is less than an hour by Cowen, Frankowiack, & Kowalski (2010)[10]. Occurred between S5 and A5, so LIGO detectors were not on during the explosion, but GEO was taking data at a 75% duty cycle.

3.1.4 SN 2008ax

A type IIb with its last non-detection 6 hours before discovery[17], giving a shock breakout time of 2008 03 03 ± 0.15 days. Crockett et al. (2008)[18], Roming et al. (2009)[19], and Chevalier & Soderberg (2010)[20] suggest a compact Wolf-Rayet progenitor. Occurred during A5.

3.1.5 SN 2008ij

A type IIP constrained by non-detection. Discovered 20081219, not visible 20081216[21], giving a shock breakout time of 2008 12 17.5 ± 1.5 days. Spectrum taken on 20081221 appears young[22]. Occurred during A5.

3.1.6 SN 2009K

A type IIb constrained by non-detection. Discovered 20090114, not visible 20090111[23], giving a shock breakout time of 2009 01 12.5 ± 1.5 days. Spectrum taken on 20090117 appears soon after explosion[24]. Occurred during A5.

3.1.7 SN 2009bb

A type Ic constrained by non-detection. Discovered 20090321, not visible 20090319[25], giving a shock breakout time of 2009 03 20 ± 1 day. Spectrum taken on 20090328 appears young[26]. Occurred during A5.

Name	Type	Distance (Mpc)	t_{SBO}	LIGO Operation
2006bp	II	∼18	2006 04 07.9 ± 0.4 days	S5
2007gr	Ib/c	∼8	2007 08 12.5 ± 2.5 days	S5
2008D	Ib/c	∼30	2008 01 09 ± 6 seconds	Between S5 & A5
2008ax	IIb	∼8	2008 03 03 ± 0.15 days	A5
2008ij	IIp	∼20	2008 12 17.5 ± 1.5 days	A5
2009K	II/IIb	∼40	2009 01 12.5 ± 1.5 days	A5
2009bb	Ic	∼40	2009 03 20 ± 1 day	A5
2009dq	IIb	∼18	2009 04 14 ± 4 days	A5

Table 1: Well-constrained supernovae and their properties.

3.1.8 SN 2009dq

A type IIb constrained by non-detection. Discovered 20090419, not visible 20090411[27], giving a shock breakout time of 2009 04 14 ± 4 days. Occurred during A5.

3.1.9 From Shock Breakout Time to Time of Core Collapse

The shock breakout time is the closest we can come to finding the core-collapse time using EM signals alone. We still have to trace back to core collapse using other knowledge. If the radius of the progenitor star is known (R_0), then one can use the speed of sound in the star to find how long it took the shock to travel from the core to the breakout point. Otherwise, it is a good enough assumption to say that it usually takes around 1 day for the shock wave to break out for a type IIP; it will be faster for types Ib/c[28]. And since our uncertainty goal is ±1 day, that estimate is sufficient for the majority of these cases.

3.2 EPM Results

So far we have only been able to test EPM on one supernova, 2008bk, which was only ∼4 Mpc away, and appears to have occurred at the beginning of A5. We have good photometry from Giuliano Pignata (CHASE), and an expansion velocity from one CBET[29]. Figure 3 shows the light curve of this supernova in four different bands, uncorrected for extinction. It appears to have been caught early, and its similarity to the theoretical light curve is apparent. Table 3.2 shows the results for finding the shock breakout time. The only velocity data point is from 2008 04 12, and we have photometry data points from the end of 04 10 and 04 13. The velocity was used for both dates. The mean distance was determined from NED distances.

Date	B ±0.016	V ±0.016	D ±0.9 (Mpc)	v (km/s)	Δt (days)	t_{SBO}
2008 04 10	13.459	12.934	4	4100	14 ± 3	2008 03 27 ± 3
2008 04 13	13.418	12.955	4	4100	12 ± 3	2008 04 01 ± 3

Table 2: SN 2008bk

The errors were derived from errors in photometry and the distance used. No error for velocity was found, and the velocity datum is not from the exact dates tested, so the errors are thus far underestimated. SN 2008bk was discovered on 2008 03 25, making the first date's result barely plausible, and the last one's not possible. However, none of this photometry has been corrected for extinction, nor for flux dilution. The

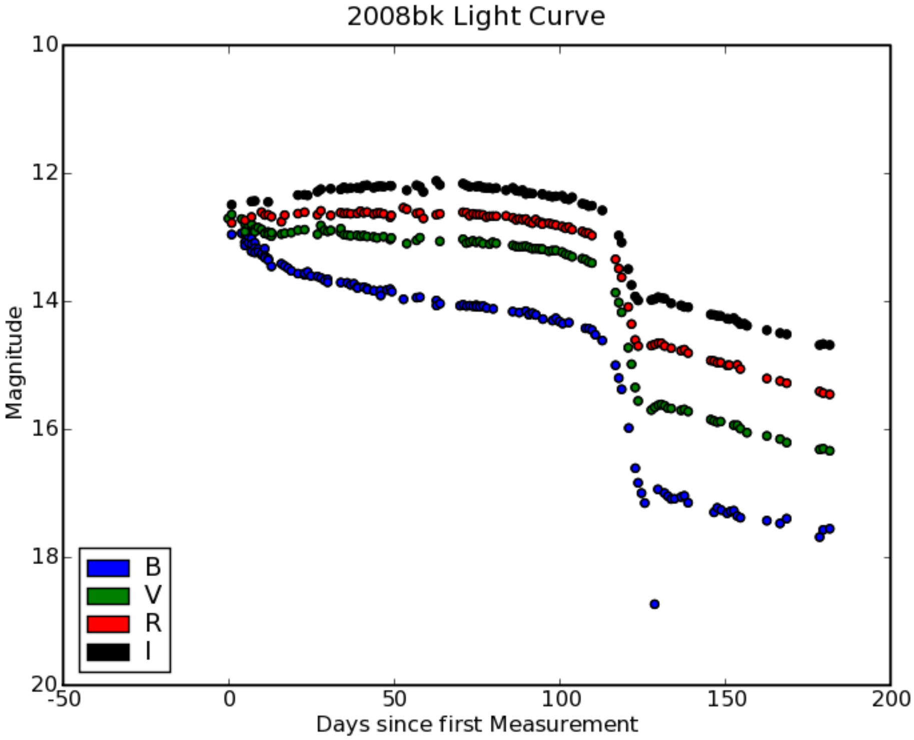

Figure 3: Light curve of SN 2008bk in four bands, provided by Giuliano Pignata.

omission of both of these may lead to an underestimate of the shock breakout time. However, if the same precision can be preserved, then the shock breakout time can be constrained to less than a week.

Luc Dessart is currently working on more accurately modeling this supernova with EPM and has agreed to share his results with us, which would be most beneficial for this nearby event.

We currently have some spectra and photometry for a few other type IIP supernovae from Alexei Filippenko (Berkeley), but not concurrent measurements that would enable us to use EPM. We are seeking more data from other astronomers on these and other type IIPs in order to make more use of this method.

4 Conclusions & Future Work

This summer we have created the infrastructure to build an external trigger events list for the first dedicated core-collapse supernova gravitational wave search, which will remain intact for the addition of future events as LIGO ends the enhanced stage and enters the advanced stage. The 8 supernovae for which shock breakout times have been well-constrained will make up the first set of events to search for in LIGO data. While some are better-constrained than others, the nearest-by supernovae provide the best chance for an astrophysical analysis because of LIGO's increased sensitivity for nearer sources. In addition, we will continue working with Luc Dessart on developing EPM for our uses, and continue searching out data on other type IIP supernovae. Methods for reliably constraining the explosion times of types other than IIP have largely yet to be developed or tested.

We have learned over the course of this project that constraining the shock breakout times of supernovae is not nearly as straightforward as we expected. Most of the supernovae we have been able to constrain were due to lucky observations and non-detections. In addition, the amount of information and general data availability vary incredibly from event to event, making the process of obtaining what we need much more difficult. Moreso, early follow-up data on supernovae is rare, which reduces the accuracy of non-detection and EPM. In the future, automatic supernova searches may help this problem significantly. Many of the ones in place, such as the Palomar Transient Factory and Catalina Real-Time Transient Survey, do not regularly identify host galaxies, which is useless to us. Potential future searches scanning a number of known galaxies every other night or so to provide quick follow-up would help our efforts greatly.

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