HAL
open science

Estimating the Explosion Time of Core-Collapse Supernovae from Their Optical Light Curves

D.F. Cowen, A. Franckowiak, M. Kowalski

To cite this version:

D.F. Cowen, A. Franckowiak, M. Kowalski. Estimating the Explosion Time of Core-Collapse Supernovae from Their Optical Light Curves. Astroparticle Physics, 2009, 33 (1), pp.19. 10.1016/j.astropartphys.2009.10.007 . hal-00521250

HAL Id: hal-00521250

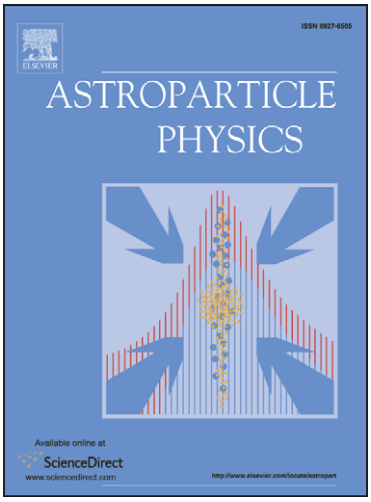
https://hal.science/hal-00521250v1

Submitted on 27 Sep 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript



Estimating the Explosion Time of Core-Collapse Supernovae from Their Optical Light Curves

D.F. Cowen, A. Franckowiak, M. Kowalski

PII: S0927-6505(09)00163-7
DOI: 10.1016/j.astropartphys.2009.10.007
Reference: ASTPHY 1444

To appear in: *Astroparticle Physics*

Received Date: 26 May 2009
Revised Date: 30 October 2009
Accepted Date: 31 October 2009

Please cite this article as: D.F. Cowen, A. Franckowiak, M. Kowalski, Estimating the Explosion Time of Core-Collapse Supernovae from Their Optical Light Curves, *Astroparticle Physics* (2009), doi: 10.1016/j.astropartphys.2009.10.007

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

Estimating the Explosion Time of Core-Collapse Supernovae from Their Optical Light Curves

D.F. Cowen [a,b] A. Franckowiak [a,c] M. Kowalski [a,c]

[a] *Institut für Physik, Humboldt-Universität zu Berlin, 12489 Berlin, Germany*

[b] *Departments of Physics and Astronomy and Astrophysics, Pennsylvania State University, State College, PA 16801 USA*

[c] *Physikalisches Institut, Universität Bonn, 53115 Bonn*

Abstract

Core-collapse supernovae are among the prime candidate sources of high energy neutrinos. Accordingly, the IceCube collaboration has started a program to search for such a signal. IceCube operates an online search for neutrino bursts, forwarding the directions of candidate events to a network of optical telescopes for immediate follow-up observations. If a supernova is identified from the optical observations, in addition to a directional coincidence a temporal γ-ν coincidence also needs to be established. To achieve this, we present a method for estimating the supernova explosion time from its light curve using a simple model. We test the model with supernova light curve data from SN1987A, SN2006aj and SN2008D and show that the explosion times can be determined with an accuracy of better than a few hours.

1 Introduction

Supernova explosions feature the interplay of all four known fundamental forces. A complete picture of supernova (SN) explosions will therefore require true multi-messenger observations, with data from traditional optical telescopes analyzed alongside coincident data from neutrino and gravitational wave detectors.

To provide such multi-messenger data as well as to increase the sensitivity to neutrinos from SNe, the IceCube Collaboration [1] together with the ROTSE Collaboration [2] have set up an optical follow-up program that triggers optical observations on multiplets of high-energy muon neutrinos [3] (a similar

ACCEPTED MANUSCRIPT

program has been inplemented by the ANTARES Collaboration [4,5]). A multiplet is defined as at least two muon neutrinos from the same direction that arrive within a short time window (e.g., $\sim$ 100 s). When this happens, an alert is issued to the four ROTSE-III telescopes, which immediately observe the corresponding region in the sky. Successful γ-ν coincident detection would allow one to infer the existence of jets in SNe and would probe the expected gamma-ray burst–supernova connection [6,7].

Absent any other corroborating astrophysical evidence, a standalone neutrino doublet is not a physically interesting occurrence because the background rate of such doublets from atmospheric muon neutrinos in IceCube is $O(10/\mathrm{yr})$. However, given the very small number of SN expected by random chance in the doublet's temporal and directional windows, the significance of a coincident optical observation of a SN rises dramatically: a neutrino doublet and an optical observation in a coincidence time window typically assumed to be $\Delta t \sim 1$ day (which we will show can be narrowed considerably) is of comparable significance to the detection of a standalone neutrino triplet [8]. (Neutrino triplets occur by chance only once every few millennia and therefore their detection would be intrinsically significant.) A gain in sensitivity is thus achieved by effectively lowering the neutrino multiplicity threshold (from $N = 3$ to $N = 2$) affording a factor of about two increase in the rate of detectable SNe [8]. In other words, the ability to narrow the coincidence time window provides a way to reduce the level of accidental coincidences between neutrino doublets and SNe. This useful reduction can be achieved by rejecting coincidences for which the neutrino doublet arrival time is statistically too far outside the narrower time window obtained from a fit to the SN explosion time.

This program thus relies on the ability to match the explosion time as determined from the neutrino multiplet arrival time to that determined from the optical data. Smaller explosion time uncertainties result in better rejection of accidental coincidences, lending more significance to a coincidence detection. Previous studies have assumed that the explosion time can be known with a precision of about one day without, however, supporting this assumption with observational data (see, e.g., [8,9]).

In this paper we present the first study of the determination of the explosion time, t_0, from the SN optical light curve. We have produced a generic model for the light curve that we test with light curve data from SNe with known explosion times. Such a study became attractive in the last few years due to the recent fortuitous discoveries of two nearby type Ib/c (stripped-core) SNe, SN2008D [10] and SN2006aj [11], each with an associated X-ray flash presumably from the shock breakout. The short X-ray flash provides a time stamp for the explosion that can be compared to the one obtained from fitting the optical light curve data. Furthermore, for obvious reasons the light curve

ACCEPTED MANUSCRIPT

data for these SNe begin very early after the X-ray flash, and as such are well-suited to the method described below, because as with an X-ray flash, a neutrino trigger will enable early optical observation of the target SN. The only other SN that has an explosion time known with even better precision is SN1987A. It is a low-luminosity type IIP SN with a light curve very different from that of SN2008D and SN2006aj. Nevertheless, the physics of the early part of the light curve is similar enough that we find we can successfully extend our analysis to SN1987A as well.

The explosion time of SN1987A is taken to be the time of the MeV neutrino burst. For SN2008D and SN2006aj, we take the X-ray flash as a rough proxy for the explosion time. The latter is justified by considering both radius and shock velocities for these SNe. The estimated radius at which SN2008D's progenitor system becomes optically transparent to X-rays, $r_* \lesssim 10^{12}$cm [10,12], is relatively small. For SN2006aj, a larger radius of $r_* \sim 5 \times 10^{12}$ cm is estimated [13,14], while for SN1987A a photospheric radius of $r_* \sim 2 \times 10^{12}$ cm is assumed [15]. The maximum shock velocity at the shock breakout has been computed as a function of radius, energy and mass in [16,17]. Inserting parameters for the SNe at hand we obtain ~ 0.5 c for SN2008D and ~ 0.1 c for SN1987A. The non-relativistic theory in [16,17] yields a maximum shock velocity for SN2006aj that exceeds the speed of light. The authors in [14] do a relativistic treatment and estimate 0.85 c. One obtains the minimum time scale $t_{\rm min} = r_*/v_s^{\rm max} = 70$ s for SN2008D, $t_{\rm min} = 200$ s for SN2006aj and $t_{\rm min} = 1300$ s SN1987A. While this crude calculation underestimates by a factor of five the 6×10^3 s delay time between explosion and shock breakout predicted by a detailed simulation of SN1987A [15], it indicates that for SN2008D and SN2006aj, the shock breakout is not expected to appear much later than $5 \times t_{\rm min} \sim 10^3$ s after the explosion. As will be shown in Sec. 3, this theoretical time scale for the shock propagation is much shorter then the resolution of the fit on the time of explosion t_0 that we obtain for SN2008D. For SN2006aj, it is comparable to the resolution of the light curve fits.

The remainder of this paper is organized as follows. In Sec. 2 we present the light curve data and the model that is used to analyze them. In Sec. 3 we present the results of the light curve fits for SN2008D, SN2006aj and SN1987A. In Sec. 4 we discuss the importance of early light curve data. We summarize the implications of our results in Sec. 5.

2 Light Curve Data and Model

The SN2006aj and SN2008D light curves contain data from times exceptionally soon after their putative explosions, making an accurate estimation of SN explosion times feasible. For SN2006aj we use the U, B and V band data from

ACCEPTED MANUSCRIPT

the SWIFT UVOT [13] and for SN2008D we use the B, V, R and I band data from FLWO [12]. Additional data from other telescopes is available, but in order to avoid calibration problems arising from different filter and instrument pass bands, we decided to work only with data from a single source[1]. For SN 1987A, we use the photometric B, V, R, and I band data compiled and analyzed consistently by Hamuy *et al.* [19]. The first data point is 1.14 days after the explosion. Again, to avoid calibration problems, we do not use the earlier discovery data points that exist for the V-band.

We estimate the explosion time by fitting light curves under the assumptions of an initial blackbody emission from the rapidly cooling shock breakout, followed by a phase dominated by the expansion of the luminous shell. For the latter we test two distinct models.

Shock Breakout Phase: To represent the shock breakout phase we use the formulation from Waxman et al. [14]. The flux during the shock breakout phase of the SN light curve is approximated by $\Phi_{BB} = IA$, where $A = 4\pi r^2$ is the area and I is the intensity. The intensity is taken as proportional to that produced by a blackbody at a fixed wavelength (we set $\lambda = 600$ nm, but this reference wavelength is not relevant for the results presented here since it appears as multiplicative factor to the fitted temperature). In addition to the explosion time t_0, the other free parameters of the model are the radius and temperature at a fixed reference time. Waxman et al. [14] give the SN radius $r \propto \delta_t^{0.8}$ and the shock breakout temperature $T \propto \delta_t^{-0.5}$, where $\delta_t = (t - t_0)$ is the elapsed time since the explosion. Inserting these relations in the flux equation yields:

$$\Phi_{BB} = \frac{a_1}{\exp(a_2 \delta_t^{0.5}) - 1} \delta_t^{1.6}, \tag{1}$$

with a_1, a_2 and t_0 free parameters.

Expansion Phase: For the expansion phase we use either a simple expanding photosphere model for the behavior of the light curve or the more complex description from Arnett [20] that uses a time-dependent diffusion equation.

In the first model, the flux in the pure expansion phase is approximated as

$$\Phi_{t^2} = a_3 \delta_t^2, \tag{2}$$

with δ_t defined above and a_3 and t_0 free parameters. This t^2 assumption treats the SN photosphere as represented by a blackbody of constant temperature, which expands with constant velocity v [21,22]. The area of the photosphere, which is directly proportional to the photon flux, then increases $\propto (v\delta_t)^2$. This *ansatz* works remarkably well for the rising part of type Ia SN light curves [23].

[1] Ref. [18] provides a V band data point 4 hours after t_0. While we have not included it in the fits shown in this paper, we note that it fits the model prediction well.

ACCEPTED MANUSCRIPT

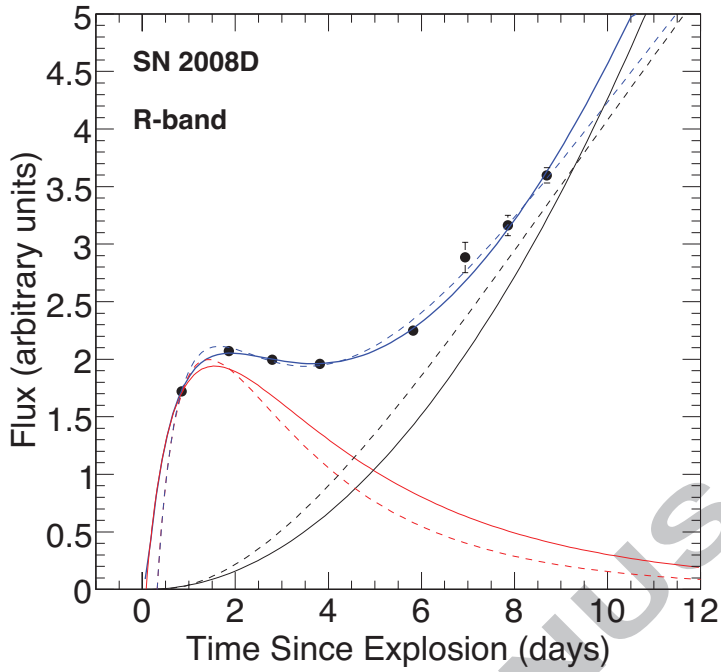


Fig. 1. The rising part of the R-band light curve data for SN2008D from [12] are shown along with the fit results. The fit model consists of a superposition of a blackbody spectrum (the initial "bump" of the curve) and a model for the later emission (the rising part of the curve). The solid lines represent the fit results using the t^2 dependence for the late time emission; the dashed lines the Arnett model (the t^2 formulation, which here gives $t_0 = 2 \pm 3$ hr, is preferred due to a better fit; see text in Sec. 3 for details).

The model has one free parameter and, when combined with the blackbody emission model, there are a total of four parameters in the fit to the light curve.

As an alternative to the expanding photosphere model, we use the light curve model of Arnett [20] (also used in [10]), that assumes homologous expansion, radiation pressure dominance, and ^{56}Ni present in ejected matter and distributed toward the center of the ejected mass. In this alternative model there are two free parameters for the rising part of the light curve model, so there are a total of five free parameters in the fit to the light curve.

As an example, Fig. 1 shows the results of the fits to R-band light curve data of SN2008D. The full set of light curves for SN2008D, SN2006aj and SN1987A are shown in Figs. 2 and 3. A systematic evaluation of fits to all available bands is the subject of the next section.

ACCEPTED MANUSCRIPT

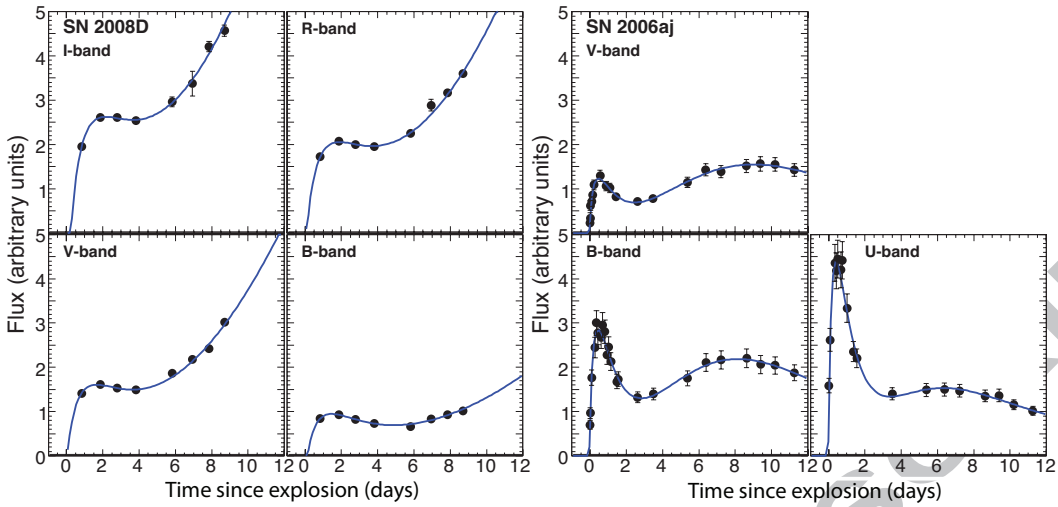


Fig. 2. Early light curve data for type Ib/c SN2008D (left) from [12] and for SN2006aj (right) from [13] are shown and the fit performed for several optical bands. For SN2008D the fit function is an initial blackbody spectrum followed by a t^2 dependence. The same fit function has also been used for SN2006aj in the t_0 analysis, but for illustrative purposes in this figure we show the fit using an initial blackbody spectrum followed by the Arnett formulation. The fit result is shown as a solid line.

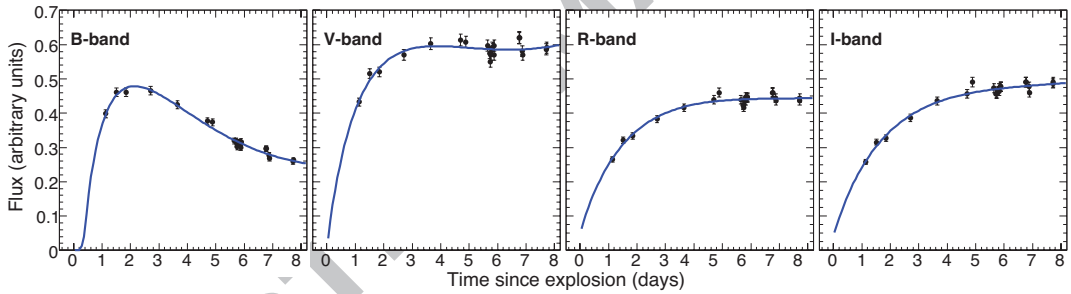


Fig. 3. Early light curve data for the type II SN1987A from [19] are shown. For the fit function we use the initial blackbody spectrum followed by a t^2 dependence.

3 Fit Results

We fit our two models to the light curve data in multiple bands for SN2006aj and SN2008D, as shown in Fig. 2. For each fit we extract the initial explosion time, t_0, the error on t_0, and the χ^2 of the fit.

For SN2006aj, we find only marginal difference in the accuracy of the fitted t_0 if we use the more complex Arnett formulation instead of the simpler t^2. (For the comparison, we restricted the fit to the first six days, since the light curve of SN2006aj evolves faster than other SNe, and for later times the t^2 approximation does not hold.) The agreement between both fit models is due to the fact that the earliest part of the light curve is entirely dominated by emission from the shock breakout and hence already strongly constrains t_0.

ACCEPTED MANUSCRIPT

We obtain an average t_0 that is shifted by -0.04 days relative to the X-ray flash, with a statistical error of about 0.005 days.

The light curve data of SN2008D can also be fit by both the t^2 and Arnett formulations. However, the early data shown in Figs. 1 and 2 is better represented by the t^2 model, as determined by the quality of the fit. We obtain from the fits a $\chi^2/\mathrm{NDF} = 15.9/16$ for the sum of all four bands. Fitting with the Arnett formulation instead of t^2 one obtains, with one additional fit parameter per band, a χ^2 that is significantly worse ($\chi^2/\mathrm{NDF} = 18.6/12$ for the sum of all data). We hence proceed with the t^2 fit model as our default fit method. The fit results for all bands using the t^2 formulation are shown in Fig. 4.

For SN2008D, whose light curves do not start so soon after the explosion time, we find the fitted t_0 is consistent with zero for three out of four bands (90% CL), with an average error of about 0.06 days. The largest outlier is the V-band, with $t_0 = 0.24 \pm 0.08$ days. If the Arnett formulation is used instead of the default t^2 formulation, the estimated t_0 would be shifted by almost 5 hours to late times (see also Fig. 1) .

In contrast to SN2006aj and SN2008D, SN1987A has its date of birth clearly marked by the observation of a short burst of neutrinos. Since its detection, SN1987A has been studied in great depth, both observationally and theoretically. We cannot expect to have such detailed information for future SNe unless they appear in our own galaxy and hence, for the sake of simplicity, we adopt the methodology already used above. We have fit the light curve data of SN1987A with the model composed of the shock breakout according to Eq. 1 and the t^2 dependence for the expansion phase. We fit the first eight days of data. Since the photometric data [19] does not come with estimated uncertainties, we have chosen them to be 0.03 mag to achieve $\chi^2/\mathrm{NDF} \approx 1$ in the fits. The size of this assumed uncertainty roughly matches the largest scatter of photometric data points observed during a single night. The fit results for four bands are shown in Fig. 4. In the figure, the larger error bar for the V, R and I-band fits with respect to the B-band fits reflects the fact that the shock breakout feature is not very evident for the redder bands, as can be seen in Fig. 3.

We have explored whether we can improve the fits by incorporating some key observations for SN1987A into the model, for example that an almost constant bolometric luminosity was observed after the first day after the explosion. In our simple picture, this is achieved by making the photosphere radius expand linearly with time, $r \propto \delta_t$, while keeping the photosphere temperature dependence as before: $T \propto \delta_t^{-0.5}$. Reinserting this into Eq. 1 provides a slightly modified model for the shock breakout phase. Fitting this shock breakout model results in a systematic shift of -0.3 days for all bands. While the B-band result is now consistent with the explosion time obtained from the neutrino

ACCEPTED MANUSCRIPT

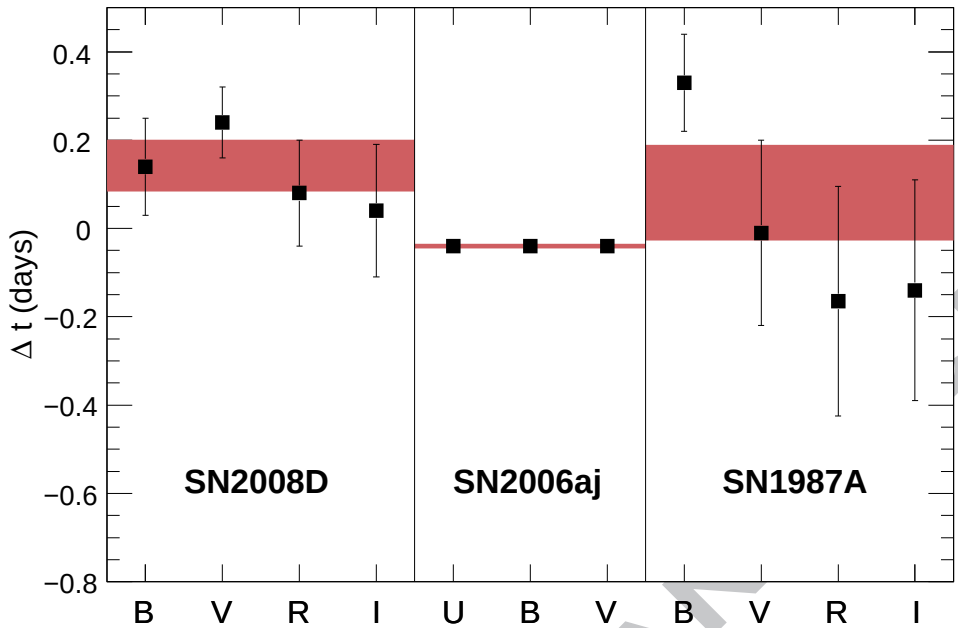


Fig. 4. Summary of the results of the fits to the light curves of SN2008D (left), SN2006aj (center) and SN1987A (right) in each optical band that was used. The horizontal shaded regions are centered vertically on the error-weighted mean of Δt (the difference between the fitted t_0 and the time of the X-ray flash or neutrino burst) and have a thickness corresponding to the error on the mean. The t^2 formulation is used throughout since it provides comparable or better quality fits relative to that of Arnett.

burst, the fits of the redder bands appear systematically shifted. Either way, we observe a deviation of the order of 0.3 days for one of the bands indicating the size of the systematic uncertainty involved in the extrapolation. (Using Arnett's formulation for the late times is not well justified for SN1987A. Nevertheless, we note that using it does not significantly worsen the fits or change the conclusions.)

Summarizing, for SN1987A the light curve data starting 1.14 days after the neutrino burst allows one to fit the explosion time with a fitting error of about 0.2 days and a systematic error of about 0.3 days. The systematic uncertainty reflects the crudeness of the light curve model employed. Nevertheless, relative to simply using $t_0 = 1.14$ days, the fitting technique yields a factor of ~ 3 improvement in the t_0 measurement.

The fitted t_0 values demonstrate that an estimate of the explosion time with an accuracy of much less than one day can be made using simple analytic light curve models. The estimates are robust on the scale of a few hours across several independent optical bands.

ACCEPTED MANUSCRIPT

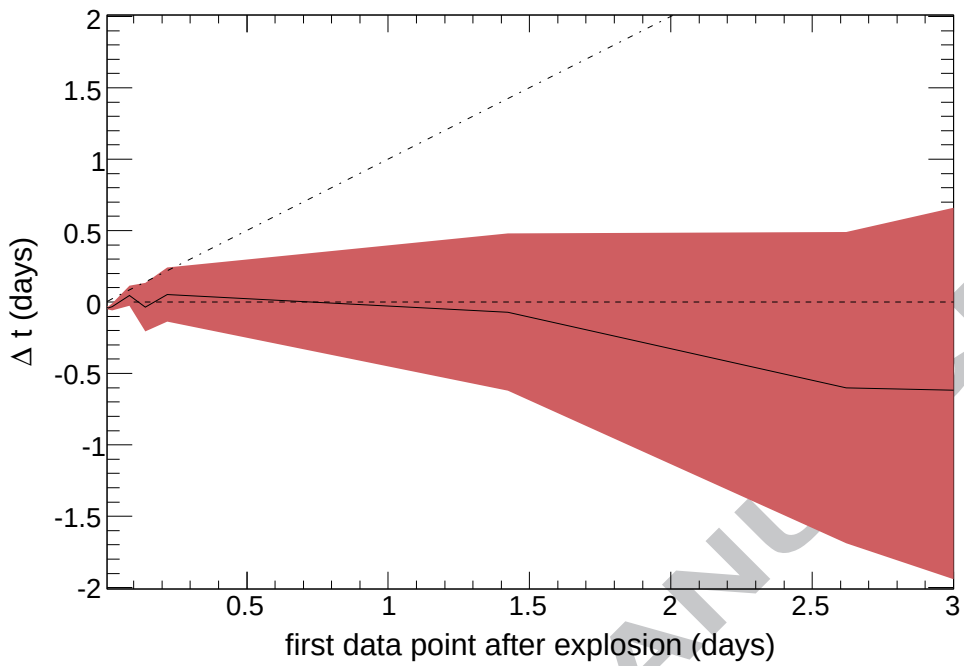


Fig. 5. To quantify the importance of acquiring data points early in the SN light curve, we manually remove the earliest V-band data points, one at a time, and refit the light curve for t_0 after each removal. The solid black line shows the resulting fitted t_0 values and the vertical height of the shaded region shows their 1-σ resolutions, as a function of the time of the earliest used data point in the fit. The dot-dash line shows the value obtained for t_0 simply using the earliest available data point. Comparing this curve to the black line from the fitted t_0 values, one sees that if there is a latency of roughly six or more hours after the putative explosion time before the first optical observation is made, the fitting technique provides the more accurate explosion time estimate.

4 Importance of Early Light Curve Data

Using the SN2006aj data, we demonstrate the importance of the early data points by manually removing the earliest data points, one at a time, and refitting the data each time. A summary of the result of this exercise is shown in Fig. 5. The figure makes evident the importance of the early data points, showing how the accuracy of the fitted t_0 depends strongly on these early data, although the accuracy drops most dramatically after about a day. This is consistent with the observation made for the other SNe: With a first data point at ~ 0.7 days for SN2008D, the explosion date can still be determined to within about 0.2 days, while for SN1987A, with a first data point at 1.1 days after the explosion, the uncertainty is around 0.3 days.

It is also informative to compare the accuracy of the t_0 from the fit with that

ACCEPTED MANUSCRIPT

obtained by simply using the first available point on the light curve. The dot-dash line in Fig. 5 plot shows this t_0 estimate, which is simply the difference in time between the X-ray flash and the earliest remaining data point on the light curve. The figure thus shows that if light curve data is acquired with about a six hour or greater delay from the explosion time, the fitting technique provides a more accurate and precise measure of the explosion time than simply using the earliest point on the light curve.

We have also studied the effectiveness of our method for estimating the t_0 when the acquired light curve follows a multi-day cadence, anticipating future survey telescopes such as LSST [24]. Since we need to have an estimator of the "true" t_0 to do this, we took the SN2006aj light curve and kept only a subset of its data, choosing those points separated by the LSST cadence of about three days. This was done for several distinct data subsets. In all cases, the fitted resolution on t_0 degraded substantially, to about 1.5 days, in agreement with the results shown in Fig. 5 with about 2.5 days of early data removed.

Our method thus relies explicitly on the early detection of the light curve. Barring future serendipitous discoveries akin to SN2006aj and SN2008D, we therefore rely on the neutrino-triggered optical follow-up technique (mentioned earlier) to provide us with a light curve that extends back suitably close in time to the actual t_0 of the explosion.

5 Conclusion

Both the IceCube and ANTARES Collaborations have started searching for high energy neutrinos from SNe by implementing a Target-of-Opportunity (ToO) program using robotic optical telescopes to identify an optical counterpart to the neutrino signal [3,5]. A crucial ingredient therein is the ability to determine the SN explosion time from the optically observed light curve which allows one to establish a temporal coincidence with the neutrino data. Using a model for the early part of the light curve, we show for the first time that one can estimate the explosion times with an accuracy much better than the one day generally assumed in the literature (see e.g. [8,9]).

We have fitted the light curves of three very different core-collapse SNe: SN2008D, SN2006aj and SN1987A. For the expansion phase of the SN we have tested two models, a simple t^2 model as well as a more detailed model by Arnett. We found that even with fewer parameters, the t^2 dependence generally provids a better fit to the data as well as a better match with the explosion time. We hence recommend that this be used for a future coincidence search.

As shown in Fig. 4, the estimated t_0 and its error, averaged over all avail-

ACCEPTED MANUSCRIPT

able bands, is about 0.14 ± 0.06 days for SN2008D, -0.04 ± 0.005 days for SN2006aj, and 0.08 ± 0.11 days for SN1987A. For SN2008D, the theoretical uncertainty associated with the use of the time of the X-ray flash as the reference t_0 is smaller than the resolutions on t_0 from our fits. The fits in all bands give explosion times that are slightly later than the time of the X-ray flash, indicative of limitations in the rather simple underlying physical model. For SN2006aj, the explosion date was determined from the fit to the light curve to be 3×10^3 s before the X-ray flash. As mentioned earlier, this is larger than the estimated time needed for the shock to propagate to the surface of the progenitor. Resolving this discrepancy would require more detailed modeling of the light curve and/or shock propagation. In any case, the discrepancy for both type Ib/c SNe investigated is < 4 hrs, which can be considered the characteristic size of the systematic uncertainties in t_0. Note that the resolutions on t_0 for both SNe are longer than what is expected for the onset of gravitational wave or high energy neutrino emission [25].

The model does not take into account possible effects due to circumstellar interactions, asymmetries in the ejecta or the differences in the density profiles of the progenitors. These effects might explain the observed deviations that are difficult to explain with statistical errors alone. Nevertheless, the fitted SN explosion time t_0 represents a successful extrapolation of the data to earlier times, and the magnitude of the extrapolation is large compared to the quoted error. This suggests that the model captures dominant physical properties of the SN during the period shortly after its explosion.

For the ongoing programs [3,5], one can not expect to have similarly detailed multiband, high signal-to-noise observations as we had available for this study, hence we have focused only on one band at a time. If multiband light curves are available, one could do a combined fit and further improve the constraints. In any case, a future optical observation of a SN triggered by a neutrino detector like IceCube or ANTARES should start early enough to capture the initial shock breakout. If the initial shock breakout is not observed, and the first observed point on the light curve is more than 1-2 days after the actual explosion, the fits give large uncertainties in the explosion time. This illustrates the cardinal importance of having fast follow-up capabilities in place to perform ToO observations.

This work shows that the optical data can be fit accurately using the formulation developed above, and that by doing so the statistical significance of the coincidence can not only be quantified but also significantly improved.

ACCEPTED MANUSCRIPT

6 Acknowledgements

The authors would like to thank L. S. Finn, M. D. Kistler, P. Mészáros and especially J. F. Beacom for helpful and informative discussions. DFC thanks the Deutscher Akademischer Austausch Dienst (DAAD) Visiting Researcher Program and the Fulbright Scholar Program, and acknowledges the support of the National Science Foundation (NSF). AF and MK acknowledge the support of the Deutsche Forschungsgemeinschaft (DFG).

References

[1] Achterberg, A. et al. 2006, Astropart. Phys., 26, 155

[2] Akerlof, C. et al. 2003, PASP, 115, 132

[3] Franckowiak, A. et al. 2009, in Proceedings of the 31th International Cosmic Ray Conference.

[4] Aguilar, J. et al. 2006, Astropart. Phys., 26, 314

[5] Dornic, D. et al. 2008, in SF2A-2008, ed. C. Charbonnel, F. Combes, & R. Samadi, 199–202

[6] Razzaque, S., Mészáros, P., & Waxman, E. 2004, Phys. Rev. Lett., 93, 181101

[7] Ando, S. & Beacom, J. F. 2005, Phys. Rev. Lett., 95, 061103

[8] Kowalski, M. & Mohr, A. 2007, Astropart. Phys., 27, 533

[9] Ando, S., Beacom, J. F., & Yuksel, H. 2005, Phys. Rev. Lett., 95, 171101

[10] Soderberg, A. M. et al. 2008, Nature, 453 (7194), 469

[11] Pian, E. et al. 2006, Nature, 442, 1011

[12] Modjaz, M. et al. 2008, ArXiv e-print 0805.2201v2, submitted to Ap.J. Only data from after the putative explosion time are used.

[13] Campana, S. et al. 2006, Nature, 442, 1008, light curve data at http://www.brera.inaf.it/utenti/campana/060218/060218.html (S. Campana, private communication)

[14] Waxman, E., Mészáros, P., & Campana, S. 2007, Astrophys. J., 667, 351

[15] Ensman, Lisa and Burrows, Adam, 1992, Astrophys. J., 393, 742

[16] Matzner, C. D., & McKee, C. F. 1999, Astrophys. J., 510, 379

[17] Chevalier, R. & Fransson, C. 2008, Astrophys. J., 683, 135

ACCEPTED MANUSCRIPT

[18] Mazzali, P. A. et al. 2008, Science, 321, 1185

[19] Hamuy, M., Suntzeff, N. B., Gonzalez, R., and Martin, G. 1988, Astron. J., 95, 63

[20] Arnett, W. 1982, Astrophys. J., 253, 785

[21] Goldhaber, G. et al. 1998, Bulletin of the American Astronomical Society, 30, 1325

[22] Riess, A. et al., 1999, Astron. J., 118, 2675

[23] Conley, A. et al. 2006, Astron. J., 132, 1707

[24] Ivezic, Z. et al. 2008, ArXiv e-print 0805.2366

[25] Fryer, C. L. & Mészáros, P. 2003, Astrophys. J., 588, L25

ACCEPTED MANUSCRIPT