Advanced Compton Telescope Designs and SN Science

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Abstract

The Advanced Compton Telescope (ACT) has been suggested to be the optimal next-generation instrument to study nuclear gamma-ray lines. In this work, we investigate the potential of three hypothetical designs of the ACT to perform SN science. We provide estimates of 1) the SN detection rate, 2) the SN Ia discrimination rate, and 3) which gamma-ray lines would be detected from specific supernova remnants. We find that the prompt emission from a SN Ia is such that it is unlikely that one would be within the range that an INTERMEDIATE ACT would be able to distinguish between explosion scenarios, although such an instrument would detect a handful of SNRs. We further find that the SUPERIOR ACT design would be a truly breakthrough instrument for SN science. By supplying these estimates, we intend to assist the gamma-ray astrophysics community in deciding the course of the next decade of gamma-ray SN science.

Key words: gamma rays: observations -Galaxy: center -nucleosynthesis -ISM: general

1 Introduction

Detections of gamma-ray lines from supernovae are some of the most exciting aspects of “Astronomy with Radioactivites”. Radionuclei produced in both thermonuclear and core-collapse supernovae decay on various timescales leading to potentially detectable emission over a range of epochs. Initially, short-lived radionuclei produce intense gamma-ray lines that might be observed from supernovae in other galaxies. Detection of emission during the early epoch permits studies of the evolution of the opacity to the gamma-ray emission, and of the yields of short-lived isotopes\cite{5}. At later times, longer-lived radionuclei produce a less-intense emission that could be observed from multiple galactic supernova remnants (hereafter call SNR emission). Detection of emission during this intermediate epoch permits the study of the yields of
these isotopes as well as of the kinematics of the SN ejecta[6]. At even later
times, long-lived radionuclei produce a faint emission that is not attributable
to specific remnants, but rather is collectively observed as a diffuse emission.
Observations of this diffuse emission studies the million-year history of supernovae in the Galaxy, as a contributor to the total galactic line emission[25]. Although interesting, we do not discuss this diffuse emission.

We simulate the transport of gamma-ray line photons through the ejecta of
SN models. Combining these simulations with three sets of specifications of
Advanced Compton Telescopes (ACT), and inferred SN rates, we produce
estimates of the rate at which supernovae will be detectable as prompt gamma-
ray line sources. We also provide estimates of the various gamma-ray lines that
might be detectable from specific supernova remnants. The purpose of this
exercise is to quantify the expectations of an ACT in performing SN science,
and thus to assist the gamma-ray community in assessing what direction they
would like to pursue for the future of gamma-ray astronomy.

2 SN Types, Rates and Emission Profile

For this study we assume that 100 SNe Ia per year within 100 Mpc. Of these
100 SNe, 60 would be normally-luminous, 20 sub-luminous, and 20 super-
luminous. (The reader is referred to an earlier work (Milne et al. 2000a) for
a derivation of these rates, and the relevant references[2,8,18].) We further
assume that SNe Ia occur uniformly throughout space at this density, ignoring
the possibility of a nearby local void. The type II/Ib/Ic SN rate has always
been suggested to be higher than the SN Ia rate (we adopt a rate for the
Galaxy of 1.7 SNe II/Ib per century[3]). This is important for studies of SNR
and diffuse gamma-ray line emission. However, the distance to which a type
II/Ib SN will be detectable is much less than the distance to which a SN Ia will
be detectable. The much smaller volume that results negates the enhanced SN
rate. Thus, it is unlikely that a type II/Ib/Ic SN will be detected as a source
of prompt emission by an ACT.

Considerable variations exist within the collection of SN Ia models. These
variations are driven both by the uncertainty as to the correct explosion scen-
nario(s) and by the heterogeneity displayed in the spectra and light curves
of observed SNe Ia (for a general discussion, see Wheeler 1995). It is be-
yond the scope of this paper to define and compare SN explosion scenarios,
we will simply introduce the model types used in this study. We have in-
cluded four single-degenerate Chandrasekhar mass (SDCM) models in our
simulations (all with $M_{ej} \sim 1.4 M_{\odot}$); (1) the normally-luminous deflagration,
W7 ($0.58 M_{\odot}$ ($^{56}$Ni), Nomoto, Thielemann, & Yokoi 1984), (2) the normally-
luminous delayed detonation, DD23C ($0.60 M_{\odot}$ ($^{56}$Ni), Höflich et al. 1998), (3)
the sub-luminous pulsed-delayed detonation, PDD54 ($0.17 M_{\odot}$ ($^{56}$Ni), Höflich,
Khokhlov & Wheeler 1995), and (4) the super-luminous delayed detonation,
W7DT ($0.76 \, M_\odot^{(56}\text{Ni})$, Yamaoka et al. 1992). We have included three variants of the sub-Chandrasekhar mass (SC) scenario; (1) the normally-luminous SC model, HED8 ($0.96 \, M_\odot \, (M_{ej})$, $0.51 \, M_\odot^{(56}\text{Ni})$), (2) the sub-luminous SC model, HED6 ($0.77 \, M_\odot \, (M_{ej})$, $0.26 \, M_\odot^{(56}\text{Ni})$, Höflich & Khokhlov 1996), (3) the super-luminous SC model, HECD ($1.07 \, M_\odot \, (M_{ej})$, $0.72 \, M_\odot^{(56}\text{Ni})$ Kuma-gai & Nomoto 1997). A double degenerate scenario involving the merger of two CO white dwarfs has also been suggested to explain SNe Ia (MERG). We have included three variants of the MERG scenario; DET2, DET2ENV2, and DET2ENV6 (all with $0.62 \, M_\odot^{(56}\text{Ni})$, and $M_{ej} = 1.2, 1.4, 1.8 \, M_\odot$). Although the observations of SNe II/Ib also suggest considerable variations within this class, for this study we test only the model, W10HMM[23]. Simulations of gamma-ray and positron transport have been performed for all of these models. Explanations of the simulation algorithms are contained in previous works [1,24,19,20].

After the SN envelope is transparent to gamma-rays, line fluxes from SNRs reflect the decay rates, which gives the isotopic yield. In addition, the flux levels for Ti44 (1157 keV), Al26 (1809 keV), and Fe60 (1173 keV) remain roughly constant for many years, making young and old SNRs potentially detectable. However, the intensity of the flux is much lower than for prompt emission, so the majority of detectable SNRs will be in the Galaxy. The SN Ia yields used in this work are primarily from deflagration models (Iwamoto et al. 1999), and do not treat the variations within the type Ia class. The SN II/Ib yields are a compilation as summarized by Knodlseder (2000). The r-process isotopic yields ($^{126}\text{Sn}$) are based upon the assumption that the solar abundance of these isotopes has been entirely due to SNe II/Ib occurring at the rate of 1.7 SNe II/Ib per century in the Galaxy (see Ott, these proceedings).

In addition to these gamma-ray lines, we simulate the 511 keV line emission that would be expected from SNRs. For SNe Ia, we assume that 5% of the positrons created in 19% of $^{56}\text{Co}$ decays escape the ejecta ($8 \times 10^{52}$ positrons per SN Ia)[4,19]. For SNe II/Ib, we assume that 100% of $^{44}\text{Ti}$ and $^{26}\text{Al}$ decay positrons (scaled to 0.95 and 0.82 branching ratios, respectively) escape the ejecta. In both cases we make the ad-hoc assumptions that 1) the escaping positrons annihilate on a $10^5$ year timescale[7], and 2) the annihilation radiation matches that observed from the Galaxy-wide emission (i.e. with 0.58 511 keV photons produced per annihilation ($f_{\gamma s}=0.95$), and the 511 keV line having a 5 keV FWHM[9,14]). These assumptions lead to fluxes of $1.2 \times 10^{-4}$ phot cm$^{-2}$ s$^{-1}$ and $3.7 \times 10^{-6}$ phot cm$^{-2}$ s$^{-1}$, respectively, from 1 kpc distant SN Ia and SN II/Ib remnants.

*Prompt* SN emission has been treated as being emitted by a point source for the various instruments, but for SNR emission the angular sizes of the larger remnants are important. We performed our estimates assuming two extremes. The “extended source” extreme assumes that all of the emission is uniformly
distributed throughout the projected optical remnant. We then scaled the sensitivity such that the effective sensitivity scaled as, \( \text{Extended Sensitivity} = \text{Point Source Sensitivity} \times \left( \frac{\theta_{SNR}}{\theta_{Det}} \right)^{1/2} \), where \( \theta_{SNR} \) is the angular size of the optical remnant, and \( \theta_{Det} \) is the angular resolution of the detector. This is the lower limit for the detection of gamma-ray lines used in this work. The “single knot” extreme assumes that all of the emission emanates from a single knot that is smaller than the detector’s angular resolution. This is clearly an upper limit for the detection of gamma-ray lines.

### 3 Compton Telescope Options and Mission Scenarios

NASA’s Gamma-Ray Working Group (GRAPWG) identified the study of nuclear astrophysics and sites of gamma-ray line emission as its highest priority science topic (June 1999), and the development of an Advanced Compton Telescope (ACT) as its highest priority major mission. The GRAPWG has outlined a baseline ACT with a goal of achieving a point source localization accuracy of of \( \sim 5' \), an energy resolution of \( \leq 3 \text{ keV} @1 \text{ MeV} \), a FoV of \( 60^\circ \) and a broad-line sensitivity of \( 1 \times 10^{-6} \text{ phot cm}^{-2} \text{ s}^{-1} \) \((10^6 \text{s}, 3\sigma)\). The Naval Research Laboratory (NRL) is investigating both germanium and silicon Compton telescope designs, with the intention of exceeding the baseline specifications in both sensitivity and FoV (Kurfess et al. 1999). The advances that will make this improvement possible are: 1) large volume detector arrays which will increase the effective area, 2) excellent spatial and energy resolution from the use of position-sensitive solid-state detectors, and 3) in one mode of analysis, employing two Compton scatters and a third interaction to determine the incoming energy and angle rather than a single scatter and total energy absorption. The current NRL/ACT design will increase the FoV to \( 120^\circ \), and improve the broad-line sensitivity to \( 3 \times 10^{-7} \text{ phot cm}^{-2} \text{ s}^{-1} \) \((10^6 \text{s}, 3\sigma)\). The point source localization will be poorer than the baseline, increasing to \( 30' -60' \) for the weakest sources, but this improves for strong sources. The energy resolution is expected to be \( \sim 20 \text{ keV} \).

It is generally accepted that the timescale to construct an ACT capable of meeting either the GRAPWG specifications, or the NRL specifications, will be more than ten years. It has been argued that an “intermediate” instrument needs to be constructed, both to continue to develop the relevant technologies involved with the construction of an ACT, and to provide some data for scientists working in this field. During this meeting Bloser described one design of an intermediate ACT, the Medium Energy Gamma-ray Astronomy ACT. We have performed simulations loosely based upon the specifications described for MEGA. Shown in Table 1 are the sensitivities, FoVs, energy and angular resolutions that we assume for the “INTERMEDIATE”, “BASELINE” and “SUPERIOR” ACT concept designs. The accumulation efficiencies depend upon the observing mode. We have allowed for two observing modes for these designs, surveying or Target of Opportunity (ToO). The survey mode assumes
that the ACT has been placed in an equatorial orbit. The INTERMEDIATE and SUPERIOR instruments are nearly full-sky, and would be zenith-pointed in survey mode. The BASELINE instrument would alternate between $b=30^\circ$, and $b=+30^\circ$ pointings in survey mode. The accumulation efficiency for these instruments is then the combination of the fraction of the time the SN would be within the FoV and the estimate of roughly 10% dead-time for each instrument. The INTERMEDIATE instrument was alternatively operated in ToO mode, responding to the optical detection of a SN Ia one week pre-peak, or roughly 11 days after the explosion. The accumulation efficiency in ToO mode was adopted to be 65%, combining the influences of earth-occultation and dead-time.

The length of observation affects whether the SN or SNR will be detectable in a given gamma-ray line. For prompt emission, we assume that the observations continue until 300$^d$ after the SN explosion. The survey mode allows the observation of a SN from the time of explosion without requiring the optical detection of the SN! For SNR emission, we assume two year mission lifetimes for the survey mode. For ToO mode (better described as “pointed mode” when observing SNRs), we assume a two month observation. Also shown in Table 1 are the same specifications for the INTEGRAL instruments SPI and IBIS. These instruments would also operate in ToO mode for prompt emission and pointed mode for SNRs. The Vela and RXJ0852-4622 SNRs are scheduled to receive the equivalent of a one month observation in the first two years of the INTEGRAL Core Program.

4 SN Science Prospects for Different Instruments

Gamma-ray detection of SNe Ia will be the most basic level of SN science that will be performed with an ACT. Through SN detections we learn about the relative rates of SN Ia sub-classes, the SN Ia rate as a function of galaxy morphological class, and the radial distribution of SNe Ia. All of these studies assume that the gamma-ray observations are coordinated with optical observations. SN searches suffer from the Shaw effect as well as from extinction effects, as highly extincted SNe are less likely to be detected. Gamma-rays are not expected to suffer from these effects and will detect all SNe Ia in a galaxy.

Many SNe need to be detected for the estimated SN rates and distributions to be significant. Shown in the upper panel of Table 2 are the distances and rates at which given SN models could be detected (5$\sigma$) via the combined observation of the 812, 847, 1238 & 1562 keV lines. We assume all lines to be detected at the quoted broad-line sensitivity, and account for relative intensity. For each ACT the $^{56}$Ni-rich super-luminous SNe Ia will be detected to the largest distances, but the

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1 Current optical SN searches do not regularly achieve -7$^d$ detections. However, it is possible that searches will achieve such early detections by the time an INTERMEDIATE ACT would become operational.
Table 1
Specifications for three hypothetical ACTs.

| Spec                  | INT(Surv) | INT(ToO) | BASE. | SUP. | SPI   | IBIS   |
|-----------------------|-----------|----------|-------|------|-------|--------|
| Broad-line sensitivity | 1(-5)     | 1(-5)    | 1(-6) | 3(-7)| 2.5(-5)| 3.5(-4)|
| Narrow-line sensitivity | 1(-5)     | 1(-5)    | 2(-7) | 3(-7)| 1.3(-5)| 5.3(-4)|
| 511 keV sensitivity   | 3(-5)     | 3(-5)    | 4(-6) | 5(-7)| 4.2(-5)| 2.5(-4)|
| FoV                   | 120°      | —        | 60°   | 120°| —     | —      |
| Sky Coverage          | 87%       | —        | 51%   | 87% | —     | —      |
| Accum. eff.           | 30%       | 65%      | 15%   | 30% | 65%   | 65%    |
| Ang. Res.             | 2.4°      | 2.4°     | 5'(b) | 1°  | 2.5°  | 12’    |
| Energy Res.           | 30        | 30       | 2     | 30  | 2     | 60     |

a Sensitivities are in units of phot cm$^{-2}$ s$^{-1}$ (3σ, 10$^6$ s).
b We note that the angular resolution of ACT designs are limited by Doppler broadening, and it is not clear that 5’ angular resolution could be achieved.

A larger SN rate of normally-luminous SNe Ia make them the most frequently sampled sub-class. Sub-luminous SNe Ia will be infrequently detected due to both the under-production of $^{56}$Ni and the low SN rate. The INTERMEDIATE ACT would detect 1-2 SNe Ia per year, and would be slightly more efficient at detecting SNe if used as a ToO instrument (but only if the telescope can respond to 100% of nearby SNe Ia more than a week before the optical peak). Regardless of the mode of operation, a rate of a few SNe Ia per year is inadequate to contribute to the study of SN rates. The BASELINE design is more efficient at detecting SNe Ia, detecting roughly 10 per year. The SUPERIOR ACT would detect almost 160 SNe per year, detecting multiple members of each sub-class. We assert that a 5 year sampling of 800 SNe Ia will allow SN rate studies capable of quantifying the biases of optical searches.

For a subset of the detected SNe Ia, the line fluxes will be large enough to generate gamma-ray light curves. This will allow discrimination between the various models suggested to explain each sub-class. The estimated rate (per year) at which a given SN model could be distinguished from alternative models is shown in the lower panel of Table 2. The highest rate for discrimination between SN sub-classes with the INTERMEDIATE instrument (in either mode of operation) is less than one-SN per six years, thus those values are not shown. These discrimination rates assume that the explosion date is known to within ±1 days from optical spectra obtained as part of a coordinated study. It is unlikely that a SN will occur near enough for
Table 2
Maximum detectable distance and detection rates for various SN models, and rates at which SN Ia models would be distinguished (5σ).\textsuperscript{a}

| Sub-Class | Model | Normal | Super-lum | Sub-lum | Type II/Ib (Distances) |
|-----------|-------|--------|-----------|---------|------------------------|
| Normal    |       |        | W7        | HECD    | PDD54, HED6, DET2E6    |
|           |       | INTER(SURV) | Dist | Rate | INTER(ToO)\textsuperscript{b} | BASELINE | DIST | SUPERIOR |
| Normal    |       |          | 21 0.5 | 25 1.0 | 55 5.2 | 120 90 |
| Super-lum |       |          | 24 0.3 | 30 0.5 | 65 2.8 | 140 48 |
| Sub-lum   |       |          | 11 0.0 | 13 0.0 | 29 0.3 | 63 4.4 |
|           |       |          | 15 0.1 | 18 0.1 | 40 0.7 | 86 11 |
|           |       |          | 17 0.1 | 21 0.2 | 46 1.0 | 100 18 |
| Type II/Ib (Distances) |       |          | 265 kpc | 320 kpc | 750 kpc | 1.6 Mpc |

Discrimination Rates

| Normal | BASELINE | SUPERIOR |
|--------|----------|----------|
| HED8   | DD23C    | DET2E2   | HED8   | DD23C    | DET2E2   |
| W7     | 0.4      | 0.1      | 0.1    | W7      | 6        | 1.4(0.5) | 2.0(1.3) |
| HED8   | —        | 0.5      | 0.6    | HED8    | —        | 9        | 9.7     |
| DD23C  | —        | —        | 0.2(0.0) | DD23C   | —        | —        | 3.2(0.5) |

| Super-lum | HECED | DET2 | HECED | DET2 |
| W7DT      | 0.1   | 0.3  | W7DT  | 0.9(0.5) | 4.7(1.8) |
| HECED     | —     | 0.2  | HECED | —     | 3.6(2.3) |

| Sub-lum | HED6 | DET2E6 | HED6 | DET2E6 |
| PDD54   | 0.2(0.0) | 0.5(0.0) | PDD54 | 3.9(0.5) | 8.5(0.4) |
| HED6    | —     | 0.3   | HED6  | —     | 5.4(3.2) |

\textsuperscript{a} Rates are in units of [SNe/yr]. Detection and discrimination are at the 5σ level. Discrimination rates assume the distance to the SN is known and the explosion date is known to ± 1d. Discrimination rates in brackets () show cases where having the SN distance as an unknown appreciably lowers the discrimination rate.

\textsuperscript{b} Assumes that the detector slews to the SN 11 days after the explosion.
the INTERMEDIATE instrument to be able to discriminate between explosion scenarios. The BASELINE instrument would be more successful, but would require a multi-year mission to accumulate more than a couple of distinguishable SNe Ia. The SUPERIOR ACT would be capable of distinguishing between the SN models we simulated for about 10 SNe Ia per year. Over a 5 year mission, for perhaps 30 normal SNe Ia, the SDCM and SC explosion scenarios could be distinguished. In addition, multiple SNe from the super- and sub-luminous sub-classes would be distinguishable, especially if the distance to the host galaxy were known. It is clear from these estimates that improved sensitivity and a large FoV are more useful for studying prompt SN emission than are improved angular and energy resolution.

Using estimates of the distance, age, size and SN type of 19 SNRs previously compiled in Milne (2000b) combined with estimates of the isotopic yields and the instrument specifications, we predict which gamma-ray lines will be detected from these SNRs (Table 3). Lines denoted by capital letters would be detected during a 2 year mission, while lines denoted by lower-case letter would require a 5 year mission. Lines encased in parantheses would only be detected if the single-knot approximation is valid. The INTERMEDIATE ACT would primarily be capable of studying positron annihilation radiation from nearby and/or type Ia remnants and of studying 1157 keV emission from young SNRs. The BASELINE and SUPERIOR ACTs would be capable of detecting line emission from a large number of remnants. Note that the Fe60 line would be detectable from up to six remnants with the BASELINE ACT, and from seven remnants with the SUPERIOR ACT. The BASELINE ACT performance would be greatly improved for clumpy emission. The SUPERIOR ACT would even detect emission from SN 1987A.

5 Discussion

It should suprise no one that improved specifications from an INTERMEDIATE to a BASELINE to a SUPERIOR ACT lead to predictions of increased scientific capability. This exercise was performed not to demonstrate that the hypothetical SUPERIOR ACT is indeed a better ACT, but to quantify what can be anticipated from three different sets of specifications. The INTERMEDIATE ACT will not be an instrument ideally suited for studies of prompt emission from SNe Ia, but it will advance the understanding of galactic SNRs. It is up to the gamma-ray community to assess whether this level of gamma-ray SN science is important enough to include it as a selling point for an intermediate mission.

Between the BASELINE and the SUPERIOR ACT designs, we have shown that sensitivity and wide FoVs are crucial for high rates of SN detections and discrimination. The SUPERIOR ACT would be a truly breakthrough instrument for SN science, especially when consideration is given for the option of simultaneously using the SUPERIOR ACT in a second mode that accepts total deposition events (and thus improves the energy resolution and angular resolution for brighter objects). We argue that whether or not an intermediate ACT is constructed, the longer-term ACT is what is necessary for rich SN science. This ACT would be capable of studying SN rates, the explosion mechanism of type Ia SNe and the nucleosynthesis and ejecta kinematics in supernova remnants.
Table 3
Detectability of Gamma-Ray Lines ($5\sigma$)

| SNR          | SPI | IBIS | INTER | BASELINE | SUPERIOR |
|--------------|-----|------|-------|----------|----------|
| Cas A        | T   | T    | T     | T,e+     |          |
| Tycho        |     | T,e+ | T,e+  | T,e+     |          |
| SN 1006      | e+  | e+   | e+    | e+       |          |
| Vela         |     | e+   | a,e+,(F) | A,F,e+  |          |
| VelaJr. $^e$ | T,A,e+ | T,A,e+ | T,A,F,e+ | T,A,F,S,e+ |          |
| Kepler       |     | T    | T     | T,e+     |          |
| Cyg Lp       | e+  |     | (A,e+,f) | A,F,e+  |          |
| Monoc        | e+  |     | (A,e+,f) | A,F,e+  |          |
| LupusLp      | e+  | (e+) | e+    | e+,(F)   | F,e+     |
| G6.5-12      | e+  | (e+) | e+    | e+,(F)   | F,e+     |
| CTB 13       | e+  |     | (A,e+) | A,F,e+   |          |
| HB 21        | e+  |     | (A,e+) | A,e+,f   |          |
| IC443        |     |     | (e+ -5yr) | A,e+   |          |
| Crab         |     |     |       | T,A,e+   |          |
| Pup A        |     |     | (e+)  | A,e+     |          |
| W44 $^f$     |     |     |       | e+       |          |
| SN1987A      |     |     |       | T,C      |          |

$^a$ T=$^{44}$Ti (1157 keV), $A=^{26}$Al (1809 keV), e+ =511 keV, F=$^{60}$Fe (1173 keV),
C=$^{60}$Co (1173 keV), $N=^{22}$Na (1275 keV), S=$^{126}$Sn (666,695 keV)

$^b$The $^{44}$Ti, $^{22}$Na & $^{60}$Co lines were assumed to have 30 keV FWHM widths, the 511,
Al26, Sn126, & Fe60 lines were assumed to have 5 keV FWHM widths.

$^c$Lines in parentheses assume that all the emission emanates from a single compact knot.
Lines in lower-case require a 5 year mission.

$^d$ $^{22}$Na was not detected in any SN.

$^e$The remnant parameters for RXJ0852-4622 (Vela Jr). are currently debated.

$^f$The SNRs: RCW 103 & RCW 86 are similarly detectable.
References

[1] Burrows, A., The, L.-S., ApJ, 360, 626 (1990).
[2] Cappellaro, E. et al., A&A, 322, 431 (1997).
[3] Cappellaro, E., Turatto, M., astro-ph, 0012455 (2000).
[4] Chan, K.-W., Lingenfelter, R.E., ApJ, 405, 614 (1993).
[5] Clayton, D.D., Colgate, S.A., Fishman, G.J., ApJ, 155, 75 (1969).
[6] Diehl, R., Timmes, F.X., PASP, 110, 637 (1998).
[7] Guessoum, N., Ramaty, R., Lingenfelter, R.E., ApJ, 378, 170 (1991).
[8] Hamuy, M., Pinto, P.A., AJ, 117, 1185 (1999).
[9] Harris, M.J., et al., ApJ 501, L55 (1998).
[10] Höflich, P., Khokhlov, A., Wheeler, J.C., ApJ,
[11] Höflich, P., Khokhlov, A., ApJ, 457, 500 (1996).
[12] Höflich, P., Wheeler, J.C., Theilemann, F.-K., ApJ, 495, 617 (1998).
[13] Iwamoto, K., et al. ApJS 125, 439 (1999).
[14] Kinzer, R.L., et al., ApJ, 559, 705 (2001).
[15] Knodlseder, J., New Astronomy Rev., 44:4, 315 (2000).
[16] Kumagai, S., Nomoto, K., in Proc. of the NATO ASI on Therm. SNe (C486), ed. P. Ruix-Lapuente, R. Canal, J. Isern, (Dordrecht: Kluwer), p. 515 (1997).
[17] Kurfess, J.D., et al., in Proc. of 5th Compton Symposium, ed. M.L. McConnell, J.M. Ryan, New York: AIP, pp. 789-793 (1999).
[18] Li, W.D. et al., in Proc. of the 10th Maryland Astrophysics Conference, ed. S.S. Holt & W.H. Zhang, (New York:AIP), p.91 (1999).
[19] Milne, P.A., and The, L.-S., and Leising, M.D., ApJS, 124, 503 (1999).
[20] Milne, P.A., The, L.-S., Kroeger, R.L., in Proc. of 2nd Chicago Meeting on Thermonuclear Explosions, ed. J. Neimeyer, in press, astro-ph 0012073, (2000a).
[21] Milne, P.A., in Cosmic Explosions, ed. S.S. Holt, W.H. Zhang, (New York:AIP), p.85, (2000b).
[22] Nomoto, K., Theilemann, F.-K., Yokoi, K., ApJ, 286, 644 (1984).
[23] Pinto, P.A., Woosley, S.E. 1988, ApJ 329, 820 (1988).
[24] The, L.-S., Burrows, A., Bussard, R. W., ApJ,352, 731 (1990).
[25] Prantzos, N., Diehl, R., Phys. Rep., 267, 1 (1996).
[26] Wheeler, J.C., in Proc. of the NATO ASI on Evol. Proc. in Binary Stars (C477),ed. R.A.M.J. Wijers, M.B. Davies, C.A. Tout, (Dordrecht: Kluwer), p. 307 (1995).
[27] Yamaoka, H., et al., ApJ, 393, L55 (1992).