Supernovae with ‘super-Hipparcos’

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ABSTRACT

GAIA is the ‘super-Hipparcos’ satellite scheduled for launch in 2010 by the European Space Agency. It is a scanning satellite that carries out multi-colour, multi-epoch photometry on all objects brighter than 20th mag. We conduct detailed simulations of supernovae (SNe) detection by GAIA. Supernovae of each type are chosen according to the observed distributions of absolute magnitudes, and located in nearby galaxies according to the local large-scale structure. Using an extinction model of the Galaxy and the scanning law of the GAIA satellite, we calculate how many SNe are detectable as a function of the phase of the light curve. Our study shows that GAIA will report data on \( \sim 21400 \) SNe during the five-year mission lifetime, of which \( \sim 14300 \) are SNe Ia, \( \sim 1400 \) are SNe Ib/c and \( \sim 5700 \) are SNe II. Using the simulations, we estimate that the numbers caught before maximum are \( \sim 6300 \) SNe Ia, \( \sim 500 \) SNe Ib/c and \( \sim 1700 \) SNe II. During the mission lifetime, GAIA will issue about 5 SNe alerts a day.

The most distant SNe accessible to GAIA are at a redshift \( z \sim 0.14 \) and so GAIA will provide a huge sample of local SNe. There will be many examples of the rarer subluminous events, over-luminous events, SNe Ib/c and SNe II-L. SNe rates will be found as a function of galaxy type, as well as extinction and position in the host galaxy. Amongst other applications, there may be about 26 SNe each year for which detection of gravitational waves is possible and about 180 SNe each year for which detection of gamma-rays is possible. GAIA’s astrometry will provide the SN position to better than milliarcseconds, offering opportunities for the identification of progenitors in nearby galaxies and for studying the spatial distribution of SNe of different types in galaxies.

Key words: gravitational lensing – gravitational waves – neutrinos – supernovae: general – gamma-rays: theory.

1 INTRODUCTION

GAIA is the super-Hipparcos satellite that is planned for launch in about 2010 (see http://astro.estec.esa.nl/gaia or Perryman et al. 2001). It is the successor to the pioneering Hipparcos satellite, which revolutionized our knowledge of the solar neighbourhood. GAIA gathers 4 colour broad-band and 11 colour narrow-band photometry on all objects brighter than 20th mag and it performs spectroscopy in the range 850–875 nm on all objects brighter than 18th mag. Here, we discuss the capabilities of this remarkable satellite for supernovae (SNe) detection.

SNe are divided into type I and II primarily on the basis of their spectra, with light-curve shape as a secondary diagnostic. SNe Ia are thermonuclear explosions in white dwarf stars which have accreted too much matter from a companion. It is unclear whether the companion is also a white dwarf or is a main sequence/red giant star. In fact, whether the progenitors of SNe Ia are doubly degenerate or singly degenerate binaries is one of the major unsolved problems in the subject. SNe Ib/c and II originate in the core collapse of massive stars. SNe Ia have found ready application in cosmology. Their intrinsic brightness means that they can be detected to enormous distances. Although their peak luminosities vary by a factor of 10, Phillips (1993) found a correlation between the peak absolute magnitude and the rate of decline, which enables SNe Ia to be calibrated and used as ‘standard candles’. Claims for an accelerating universe (e.g. Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999) partly rest on their use as distance estimators, yet there are obvious concerns regarding systematic errors (e.g. Leibundgut 2000, 2001). So, a major thrust of modern SNe studies is to understand and quantify the differences in the morphology of SNe Ia light curves and the scatter in the Phillips relation.

SNe surveys go back at least as far as Zwicky (1938). Amongst the most influential are the Asiago SNe survey (Ciatti & Rosino 1978) and the Calán/Tololo SNe survey (Hamuy et al. 1993). At the moment, there is some, albeit limited, information on \( \sim 2000 \)
SNe available in the standard catalogues (see Tsvetkov, Pavlyuk & Bartunov 1998 or http://www.sai.msu.su/sn/sncat/ and Barbon et al. 1999 or http://web.pd.astro.it/supern/). Perhaps only as many as ~300 SNe have reasonably detailed light curves (e.g. Leibundgut et al. 1991; Hamuy et al. 1996; Leibundgut 2000). Even with the limited data set available, there is a considerable spread in the intrinsic properties and uncertainty as to the rate, type and location of SNe as a function of host galaxy.

**GAIA** is an ideal tool to study nearby SNe (within a few hundred Mpc). **GAIA** will provide a huge data set of high-quality local SNe Ia in which any deviations from ‘standard candles’ can be analysed. As the data set is so large, there will be good numbers of rarer phenomena, such as subluminous SNe and SNe Ib/c. Earlier papers (Hsieh, Fabricius & Makarov 1999; Tammann & Reindl 2002) have already provided rough estimates of the numbers of SNe Ia that **GAIA** will discover. Here, we carry out detailed simulations using a Galactic extinction model and the satellite scanning law to compute the numbers of SNe detected as a function of the phase of the light curve. We show that **GAIA** will record data on at least 21 400 SNe during the five-year mission lifetime. This breaks down into ~14 300 SNe Ia, ~1400 SNe Ib/c and ~5700 SNe II. These SNe span a redshift range up to ~0.14. **GAIA** will probably alert on all SNe detected before maximum. These numbers are ~6300 SNe Ia, ~500 SNe Ib/c and ~1700 SNe II during the whole mission. In other words, **GAIA** will issue ~1700 SNe alerts a year or ~5 alerts a day. Roughly 75 per cent of all alerts will be SNe Ia, the remainder will be SNe Ib/c and II. All these numbers are lower limits and may be increased by a factor of ~2 depending on the SNe contribution from low-luminosity galaxies.

### 2 Monte Carlo Simulations

**GAIA**'s G band is very close to the conventional V band for a wide colour range (ESA 2000). Richardson et al. (2002) use the Asiago Supernova Catalogue to study the V band absolute magnitude distributions according to type. They find that the mean absolute magnitude of SNe Ia at maximum is ~18.99. This figure includes the contribution from the internal absorption of the host galaxy, as well as a correction to our preferred value of the Hubble constant of 65 km s⁻¹ Mpc⁻¹, which we use henceforth. As **GAIA**’s limiting magnitude is G ~ 20, this means that the most distant SNe Ia accessible to **GAIA** are ~630 Mpc away. Similarly, the mean absolute magnitude of SNe Ib/c at maximum is ~17.75, so that the most distant SNe Ib/c detectable by **GAIA** are ~355 Mpc away. SNe II are subdivided further according to light curve into linear (L) and plateau (P) types. The mean absolute magnitude of II-L type is ~17.63 and of II-P type is ~16.44 (Richardson et al. 2002). These correspond to distances of ~335 Mpc and ~195 Mpc respectively. Such distances emphasize that **GAIA** is the ideal tool to discover relatively nearby SNe, but will not make any contribution to the searches for high redshift SNe.

The rates with which SNe occur in different galaxies at low redshift are given in Table 1, inferred from van den Bergh & Tammann (1991). This gives the number of SNe per century per 10¹⁰ L⊙. Although the data come with substantial uncertainties, there are three recent studies that provide some supporting evidence. First, the EROS collaboration (Hardin et al. 2000) found a SNe Ia rate of ~0.18 per century per 10¹⁰ L⊙ for redshifts z in the range 0.02 to 0.2. Secondly, Pain et al. (1996) found a SNe Ia rate of ~0.36 per century per 10¹⁰ L⊙ at the somewhat higher redshift of z ~0.4. Thirdly, the rates in Cappellaro et al. (1997) are of the same order as van den Bergh & Tammann (1991), although typically lower by a factor of 2.

The host galaxies follow the local large-scale structure. We use the latest version of the CfA redshift catalogue (Huchra et al. 1992, see http://cfa-www.harvard.edu/huchra/zcat/). This contains the sky positions and heliocentric velocities of ~20 000 galaxies. On plotting numbers of galaxies versus distance, the graph peaks at ~75 Mpc and thence shows a steady decline. This suggests that the catalogue can be used out to at most ~75 Mpc. The number of galaxies of each Hubble type in the CfA catalogue within 75 Mpc is listed in Table 2. These numbers must be regarded as lower limits to the true numbers within 75 Mpc, as the luminosity functions (LFs) derived from the CfA catalogue are incomplete at faint magnitudes. To take this into account, we assume that after reaching maximum the galaxy LF remains flat down to an absolute magnitude of ~14. Given in parentheses in Table 2 are the number of galaxies and SNe within 75 Mpc assuming such a flat LF. These numbers can be regarded as upper limits. Beyond 75 Mpc, we assume that the distribution of galaxies is homogeneous and that the number scales like D³ where D is the heliocentric distance. Given the numbers of galaxies and the observed rates, we can then straightforwardly compute the total number of SNe that explode during the five-year **GAIA** mission lifetime and are brighter than the limiting magnitude. In all, there are at least ~48 000 SNe Ia and ~7000 SNe Ib/c. The numbers for SNe II depend on the relative frequency of II-L with respect to II-P, which is not very well-known. Henceforth, we denote the fraction of all SNe II that are L-type by f_L. Then, the numbers of SNe II that explode are ~28 500 f_H + 5600 (1 − f_L). These numbers are lower limits for two reasons – first because no contribution from faint galaxies is included and second because **GAIA**’s limiting magnitude may be deeper than 20th in practice. Allowing for faint galaxies with the flat LF gives results a factor ~2 times larger.

To assess the efficiency of SN detection, we perform Monte Carlo simulations (e.g. Li, Filippenko & Rieß 2001). First, the distance to the host galaxy is picked from the D³ distribution. If D < 75 Mpc, then the galaxy is chosen from the CfA catalogue. If D > 75 Mpc, then the galaxy positions are distributed uniformly over the sky. Next, we choose the SN absolute magnitudes from Gaussian distributions with means and dispersions given in Table 3. These numbers already includes the effects of absorption in the host galaxy. The contribution to dimming of the SN from Galactic absorption is calculated using software kindly supplied by R. Drimmel, which is based on the extinction model of Drimmel & Spergel (2001).

The light curve can now be generated using the templates illustrated in Fig. 1. For SNe Ia, we use the data of Lira et al. (1998) on SN 1991T as a standard template. This is an unusually bright SN Ia illustrated in Fig. 1. For SNe Ia, we use the data of Lira et al. (1998) on SN 1991T as a standard template. This is an unusually bright SN Ia

### Table 1. SNe explosion rates (in units of SNe per 10¹⁰ L⊙ per century) according to Hubble type, adapted from the van den Bergh & Tammann (1991) values using a Hubble constant of 65 km s⁻¹ Mpc⁻¹. The galaxy types follow the classification scheme of de Vaucouleurs (1959; see also van den Bergh 1998).

<table>
<thead>
<tr>
<th>Type</th>
<th>E-80</th>
<th>S0/a, Sa</th>
<th>Sab, Sb</th>
<th>Sbc-Sd</th>
<th>Sdm-Lm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>0.42</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Ib/c</td>
<td>-</td>
<td>0.01</td>
<td>0.11</td>
<td>0.33</td>
<td>0.38</td>
</tr>
<tr>
<td>Type II</td>
<td>-</td>
<td>0.07</td>
<td>0.57</td>
<td>1.66</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Table 2. Number of galaxies of each Hubble type within 75 Mpc in the CfA catalogue. Also shown is the number of SNe within 75 Mpc during the 5-yr mission lifetime. For comparison, the figures in parentheses are based on an extrapolation of the galaxy LF that is flat down to an absolute magnitude of −14.

<table>
<thead>
<tr>
<th>Type</th>
<th>E-S0</th>
<th>S0/a, Sa</th>
<th>Sab, Sb</th>
<th>Sbc-Sd</th>
<th>Sdm-Im</th>
</tr>
</thead>
<tbody>
<tr>
<td>(galaxies)</td>
<td>1200</td>
<td>679</td>
<td>867</td>
<td>1993</td>
<td>1798</td>
</tr>
<tr>
<td>Type Ia</td>
<td>29</td>
<td>7</td>
<td>11</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Type Ib/c</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>Type II</td>
<td>0</td>
<td>2</td>
<td>31</td>
<td>152</td>
<td>135</td>
</tr>
</tbody>
</table>

Table 3. The means and dispersions in SNe absolute magnitude at maximum adopted for the Monte Carlo simulations. The numbers are derived from the uncorrected distributions in Richardson et al. (2002), but are adjusted to our preferred Hubble constant of 65 km s⁻¹ Mpc⁻¹.

<table>
<thead>
<tr>
<th>SN type</th>
<th>M₀</th>
<th>σ₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Ia</td>
<td>−18.99</td>
<td>0.76</td>
</tr>
<tr>
<td>Type Ib/c</td>
<td>−17.75</td>
<td>1.29</td>
</tr>
<tr>
<td>Type II-L</td>
<td>−17.63</td>
<td>0.88</td>
</tr>
<tr>
<td>Type II-P</td>
<td>−16.44</td>
<td>1.23</td>
</tr>
</tbody>
</table>

3 RESULTS

3.1 Numbers detected

Fig. 3 shows the fraction of SNe within a distance D which enter the field of view of GAIA’s telescopes ASTRO-1 and ASTRO-2. GAIA records data on 30 per cent of all the SNe Ia within 630 Mpc, which marks the limit of the most distant SNe Ia accessible. The
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Figure 3. This shows the total number of SNe detected within distance $D$ as a fraction of the total number exploded. Within 630 Mpc, GAIA detects $\sim$30 per cent of all SNe Ia. Within 355 Mpc, GAIA detects $\sim$20 per cent of all SNe Ib/c. For SNe II-L, GAIA detects $\sim$31 per cent within 335 Mpc. Finally, for SNe II-P, GAIA detects $\sim$48 per cent within 195 Mpc. Note that by detection, we mean that GAIA records at least one data point on the standard SNe templates shown in Fig. 1. Distance cut-offs for the intrinsically less bright SNe Ib/c, II-L and II-P are 355 Mpc, 335 Mpc and 195 Mpc respectively. GAIA records data on $\sim$20 per cent of all SNe Ib/c, $\sim$31 per cent of all SNe II-L and $\sim$48 per cent SNe II-P within these distances. This means that GAIA will provide some (perhaps rather limited) information on 14 300 SNe Ia and 1400 SNe Ib/c during its five-year mission. For SNe II, the number depends on the relative frequency $f_{\text{II}}$ and is $\sim$8700 $f_{\text{II}} + 2700 (1 - f_{\text{II}})$ if SNe II-L and SNe II-P occur equally frequently ($f_{\text{II}} = 0.5$), then the total number of SNe II is $\sim$5700. In other words, GAIA will provide some information on $\sim$21 400 SNe in total. For comparison, Høg et al. (1999) used simple scaling arguments to estimate that the total number of SNe in the GAIA observations would be $\sim$100 000.

These are huge numbers, both compared to the sizes of existing catalogues and to the likely data sets gathered by other planned space missions. Almost all the SNe that GAIA misses explode in the 20 d just after GAIA samples that location in the sky. Before the next transit of ASTRO-1 or ASTRO-2, the SN reaches maximum and then fades to below GAIA’s limiting magnitude ($G \sim 20$). One may wonder whether some SNe are missed because light from the background galaxy can overwhelm the SN. This is clearly a problem for distant galaxies, which are wholly contained within GAIA’s PSF ($\sim$35 arcmin full width at half-maximum). However, rough calculations show that this is not a problem for SNe Ib/c and II, as they occur relatively close by; we estimate that it may affect $\lesssim$10 per cent of SNe Ia.

Fig. 4 shows the fraction of the detected SNe as a function of phase of the light curve. Some 44 per cent of the detected SNe Ia are caught before maximum, 37 per cent of the detected SNe Ib/c, 37 per cent of the detected SNe II-L and 9 per cent of the detected SNe II-P. The low fraction for SNe II-P is largely a consequence of the fact that they are intrinsically the faintest. The numbers of each type of SNe caught before maximum by GAIA are recorded in Table 4. The total number of all SNe found before maximum during the 5-year mission lifetime is $\sim$8500. This number can be broken down into $\sim$6300 SNe Ia, $\sim$500 SNe Ib/c and 1700 SNe II (assuming $f_{\text{II}} = 0.5$). If data on a SN is taken before maximum, then GAIA has an excellent chance of identifying the rapidly brightening object as a SN.

3.2 Identification strategy

Every new object in a field of view is potentially a SN. Before GAIA can identify a SN, it must have visited that location on the sky at least once before. To provide SN alerts, we must ensure that the Table 4. The numbers of SNe of different types detected before maximum during the 5-yr GAIA mission lifetime. The last row assumes that the fraction of SNe II-L compared with all SNe II is $f_{\text{II}} = 0.5$.

<table>
<thead>
<tr>
<th>SNe</th>
<th>Total number detected</th>
<th>Fraction detected before maximum</th>
<th>Number detected before maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Ia</td>
<td>14 308</td>
<td>44 per cent</td>
<td>6317</td>
</tr>
<tr>
<td>Type Ib/c</td>
<td>1370</td>
<td>37 per cent</td>
<td>501</td>
</tr>
<tr>
<td>Type II-L</td>
<td>8735 $f_{\text{II}}$</td>
<td>37 per cent</td>
<td>3205 $f_{\text{II}}$</td>
</tr>
<tr>
<td>Type II-P</td>
<td>2683 $(1 - f_{\text{II}})$</td>
<td>9 per cent</td>
<td>236 $(1 - f_{\text{II}})$</td>
</tr>
<tr>
<td>Total</td>
<td>21387</td>
<td>40 per cent</td>
<td>8538</td>
</tr>
</tbody>
</table>


Figure 4. This shows histograms of the numbers of detected SNe against phase of the light curve. The shaded area corresponds to the fraction of SNe caught before the maximum of the light curve.
brightening object is not just a common variable star. We use the General Catalogue of Variable Stars (Kholopov 1999) to build a subsample of variables with periods in excess of 10 d. Some 34 per cent of this subsample have periods less than 6 months and 86 per cent have periods less than 1 yr. In practice, ∼12 months baseline photometry may be needed to discriminate against common forms of stellar variability. One way round this problems is to restrict SN alerts to high galactic latitudes (|b| > 30°), where the problem of variable star contamination is mitigated.

The objects that can cause most confusion are fast-moving solar system asteroids and novae. Main Belt asteroids move at ∼10 mas s⁻¹ and Near-Earth objects at ∼40 mas s⁻¹ (e.g. Mignard 2002). Hog (2002) has shown that fast moving objects can be detected by a single field of view crossing. This offers quick discrimination between solar system asteroids and SNe. More problematical are novae. Shafter (1997) gives the Galactic nova rate as 35 ± 11 yr⁻¹.

We assume that this is typical of large galaxies. We take the absolute magnitude of novae to be in the range −6 < M < −9 (Sterken & Jaschek 1996). Given GAIA’s limiting magnitude, there are between 20 and 150 galaxies in CfA catalogue for which novae are detectable. This means that there are ∼1000 novae per year in the GAIA data stream. These can possibly be distinguished from SNe on the basis of colour information and spectroscopy. However, contamination by novae from external galaxies – which is the bulk of the numbers – is restricted to a number of small and pre-determined areas of the sky. These can, if necessary, be excised from the SNe survey.

Therefore, a reasonable expectation is that GAIA will alert on all SNe caught before maximum, that is ∼1700 SNe a year. Riess et al. (1998) show how the distance to a SNe Ia can be estimated to within 10 per cent from a single spectrum and photometric epoch. For a 20th mag SN, the most suitable combination is a 2-m telescope for imaging and a 4-m for spectroscopy. On a 2-m telescope, it is feasible to carry out high signal-to-noise ratio UBVI photometry on a 20th mag SN in ≤1 hr. The typical signal-to-noise ratio needed for identifying type from spectroscopy is ∼30. This needs ∼2 h on a V ∼ 20 point source in dark sky at low spectral resolution. However, roughly half the SNe will not be suitable for follow-up from the ground as they will be daytime objects. Assuming we wish to follow up the sample of (nighttime) SNe alerted before maximum, then roughly two dedicated telescopes (say one 2-m and one 4-m) are required to get distance and phase estimates. This will confirm detection and type. Based on the information from the one night snapshot, selected SNe can be chosen for more detailed monitoring. Candidates for intensive monitoring might include all the SNe Ib/c and II-L (as there is little information on their light curves), subluminous and over-luminous events, all SNe Ia caught well before maximum and any SN for which the snapshot gives an unusual luminosity or spectral composition. Tammann & Reindl (2002) have also recently emphasized the value for the extragalactic distance scale of such a follow-up program of GAIA SNe Ia alerts.

4 SCIENTIFIC RETURNS

4.1 Follow-ups, neutrinos and gravitational waves

Of course, it is important to follow up the alerted SN in bandwidths other than the optical, including infrared, X-rays and gamma-rays. This is needed – amongst other things – for the calculation of the bolometric luminosity, which sums together all the flux associated with the energy of the explosion and which provides tests and constraints on the progenitor and detonation models (e.g. Mazzali et al. 2001). More exotically, the SN can also be sought with neutrino and gravitational wave detectors, though these signals reach us before the optical detection.

Infrared and optical photometry of a SN can be used to construct a curve of colour versus time. By matching this to a template with zero reddening, the extinction in the host galaxy can be measured (e.g. Krisciunas et al. 2001) and hence the absolute magnitude and distance of the SN found. There are additional benefits to infrared follow-ups. One of the causes of uncertainty in SNe rates is extinction. For SNe Ib/c and II, which originate in the core collapse of massive stars, the observed rates are likely to be a severe underestimate of the true rate as extinction is usually high – as much as 10–20 mag – in some starburst regions (Grossan et al. 1999). Of course, the true SNe rate is important for understanding chemical enrichment and evolution of galaxies and the interstellar medium (ISM). Infrared photometry, together with GAIA data, will allow the rates to be computed as a function of infrared (rather than blue) luminosity.

The X-ray and gamma-rays are associated with the radioactive decay of nuclides produced in the SN explosion or Compton scattering associated with high energy radiation. Only the explosions of SN 1987A and SN 1993J were detected in X-rays, whereas SN 1987A remains the only one thus far detected in gamma-rays. The present generation of satellites, such as the International Gamma-Ray Astrophysical Laboratory (INTEGRAL) can detect the gamma-ray signal of SNe out to ∼10 Mpc. However, as Höflich, Wheeler & Khoklov (1998) point out, next generation Laue telescopes will allow gamma-rays from SNe within ∼100 Mpc to be detected. The numbers of SNe alerted by GAIA within 100 Mpc are listed in Table 5. Some of these SNe (typically those brighter than 15th mag) are likely to have been found by other means beforehand. So, we conclude that GAIA will alert on ∼920 SNe in total for which the X-ray and gamma-ray signal will be detectable. Of these, ∼760 SNe will not have been discovered by others beforehand.

Gravitational waves may also be sought from nearby SNe. For SNe Ib/c and II, the asymmetry of the core collapse generates

Table 5. The numbers of SNe detected within 50 and 100 Mpc over 5 yr. The upper table refers to all SNe brighter than 20th mag. However, SNe brighter than 15th mag will probably be found beforehand by other means. The lower table gives the numbers of all SNe between 15th and 20th mag at maximum light. This gives an idea of the numbers of nearby SNe that only GAIA will find. The last column assumes that the fraction of SNe II-L compared with all SNe II is f II-L = 0.5.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Magnitude</th>
<th>SNe Ia</th>
<th>SNe Ib/c</th>
<th>SNe II-L</th>
<th>SNe II-P</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50 Mpc</td>
<td>G &lt; 20</td>
<td>23</td>
<td>16</td>
<td>90 f II</td>
<td>92 (1 − f II)</td>
<td>∼130</td>
</tr>
<tr>
<td>&lt;100 Mpc</td>
<td>G &lt; 20</td>
<td>179</td>
<td>107</td>
<td>649 f II</td>
<td>616 (1 − f II)</td>
<td>∼918</td>
</tr>
<tr>
<td>&lt;50 Mpc</td>
<td>G &gt; 15</td>
<td>8</td>
<td>10</td>
<td>65 f II</td>
<td>75 (1 − f II)</td>
<td>∼88</td>
</tr>
<tr>
<td>&lt;100 Mpc</td>
<td>G &gt; 15</td>
<td>115</td>
<td>79</td>
<td>554 f II</td>
<td>574 (1 − f II)</td>
<td>∼758</td>
</tr>
</tbody>
</table>

gravitational waves which have a typical frequency $\sim 1 \text{ kHz}$ (e.g. Möenchenmeyer et al. 1991). For SNe Ia, if the progenitor is a singly degenerate binary (white dwarf and main sequence or red giant star), then no detectable gravitational waves are expected. However, if the progenitor is a double degenerate binary, then the collapse will look like a SN II probably with a similar output of gravitational waves. The maximal amplitude of gravitational waves for a SNe at $30 \text{ Mpc}$ is in the range $10^{-21}$ to $10^{-25}$ (e.g. Möenchenmeyer et al. 1991; Bonnell & Pringle 1995; Yamada & Sato 1995). The Laser Interferometer Gravitational Wave Observatory (LIGO, see http://www.ligo.caltech.edu/) is scheduled to begin taking data in 2003. The advanced LIGO will be operational after 2006 and can measure gravitational waves with an amplitude down to $10^{-21}$. This raises the possibility that gravitational waves from SNe within $10$–$50 \text{ Mpc}$ may be detected. From Table 5, there may be $\sim 130$ SNe alerted by GAIA over 5 years for which detection of the gravitational wave signal is feasible. Note that gravitational waves arrive before any photons. However, the directional sensitivity of gravitational wave detectors is very poor, so GAIA may play an important rôles in identifying the relevant SN.

Lastly, little is known about the neutrino emission from SNe Ia. For SNe associated with core collapse, there are detailed theoretical predictions. However, the only SN for which neutrinos have been detected remains SN 1987A. Neutrinos were registered by the Kamiokande II, the Irvine-Michigan-Brookhaven and the Baksan neutrino detectors. From the three detectors, a combined total of $\sim 25$ neutrinos with energies in the range 10-50 MeV are reckoned to originate from SN 1987A (e.g. Burrows 1989). These are believed to be anti-electron neutrinos, for which the detection cross-section is largest. They were emitted in a burst of $\sim 10^3$ s associated with the birth of the neutron star. However, both global fits to the SN parameters as well as theory suggest that the Kamiokande II yield was smaller than expected, probably due to statistical fluctuations and the fact that the detector was not optimized at low energies. By comparison, in the 32 kton Super-Kamiokande water-Cerenkov detector of volume $V$ is

$$N \sim 30 \left( \frac{\text{Mpc}}{D} \right)^2 \left( \frac{V}{\text{Mton}} \right).$$

By GAIA’s launch date of 2010, it is reasonable to expect 1-Mton Hyper-Kamiokande detectors and so neutrinos from SNe at distances up to $\sim 5 \text{ Mpc}$ may be detectable. This is the hardest challenge of all! Only a very few such nearby SNe are expected over the 5-year GAIA mission lifetime, and they may perhaps have been found by other means before GAIA alerts on them. However, even today, very nearby SNe are still missed, particularly those that are intrinsically faint or those occurring in obscured parts of the sky.

### 4.2 Applications

Cosmological problems regarding the dark energy will not be addressed directly by GAIA. Even the most distant SNe that GAIA detects have $z \sim 0.14$. By contrast, GAIA will provide a large data set of nearby SNe. These are more interesting from the point of view of understanding the properties and the underlying physics of the explosions themselves.

The advantage of SNe surveys with GAIA is that selection effects are either minimized or easy to model, and that there will be many examples of comparatively scarce phenomena (e.g. subluminous SNe, SNe II-L, SNe Ib/c). At present, SNe rates come from relatively small data sets (e.g. Hardin et al. 2000) and are subject to substantial uncertainties. Selection effects – depending on the type of host galaxy, the extinction and the distance from the centre of the galaxy – seriously afflict all current data sets. Given the large numbers of alerted SNe, GAIA will provide accurate rates as a function of position, extinction and type of host galaxy. These give valuable, if indirect, information on both the star formation rate and the high mass end of the mass function. There have also been suggestions that populations of subluminous SNe may have been systematically missed in existing catalogues (e.g. Richardson et al. 2002). If so, then GAIA is the ideal instrument with which to find them. The value of GAIA in richly populating the Hubble diagram has also been pointed out recently by Tammann & Reindl (2002).

The nature of the progenitor populations of the different types of SNe – and especially SNe Ia – will probably remain unsolved over the next decade. GAIA can help as it provides milliarcsecond astrometry or better with a single transit. For a SN at a typical distance of $\sim 200 \text{ Mpc}$, the projected position can be determined to $\sim 1 \text{ pc}$ (assuming the main error contribution comes from angle measurements). There are only two detections of a SN progenitor before explosion (namely SN 1987A and SN 1993J). Attempts have been made to locate the progenitors of nearby SNe using astrometry with an accuracy of $0.17''$, though without success so far (Smartt et al. 2002). GAIA will provide milliarcsecond error boxes and therefore it may be easier to locate the progenitor for nearby SNe using HST or other deep search archives. Even if no star is visible, then constraints can still be placed on the progenitor mass, as Smartt et al. (2002) demonstrate. Accurate positional information on the location of SNe within galaxies is important because it sheds light on the spatial distribution (and hence nature) of the progenitor population.

Zampieri et al. (1998) and Balberg & Shapiro (2001) emphasize that the formation of the black hole may also be detectable in nearby SNe as luminosity generated by late-time accretion. This is only possible in the case of subluminous SNe, as otherwise it is masked by radiative heating. Using fig. 4 of Balberg & Shapiro (2001), we see that the fraction of suitable SNe comprise roughly 10 per cent of all core collapse SNe within $50 \text{ Mpc}$. From Table 5, it follows that there will be $\sim 10$ SNe Ibc and II with the required properties alerted by GAIA during the whole mission. If subluminous SNe have been systematically missed in current catalogues, then this number will be still higher. For these SNe, follow-ups may be able to detect the faint luminosity indicative of black hole accretion. This requires scheduling observations with instruments like the Hubble Space Telescope or the Next Generation Space Telescope of the declining light curve with the hope of observing accretion on to the emerging black hole.

Another application of GAIA’s SNe Ia data set is to measurements of the local velocity field (e.g. Høg et al. 1999; Tammann & Reindl 2002). Nowadays, the bulk flow and the bias parameter are often calculated using distance estimators of galaxies such as the Tully–Fisher relationship or the fundamental plane, combined with radial velocity measurements (e.g. Hudson et al. 1999). Typically, this proceeds by finding the best-fitting bulk flow $V$ that minimizes

$$\chi^2 = \sum_i \frac{(v_i - V \cdot \hat{r}_i)^2}{\sigma_i^2},$$

where \(\nu_i\) is the observed peculiar velocity for the \(i\)th galaxy, the direction vector of which is \(\hat{r}_i\), and \(\sigma_i\) is an estimate of the error. As pointed out by Riess et al. (1997), SNe Ia offer a more accurate distance estimator than galaxies, as the typical uncertainty is reduced to \(\sim 5\) per cent. In other words, every SNe Ia identified by \(GAIA\) can give the distance of its host galaxy with unprecedented accuracy. When combined with ground-based spectroscopy, \(GAIA\) will provide \(\sim 6300\) positions and peculiar velocities of galaxies in the nearby Universe. These can be used to study the deviations from the Hubble flow and compared with the velocities predicted by gravity fields of full-sky galaxy catalogues. With such data, not merely the local bulk flow but also the shear field will be measurable.

5 CONCLUSIONS

The theory of SNe explosions is well-developed but somewhat poorly calibrated against data. Nearby SNe are ideal for carrying out such detailed comparisons. Provided we can alert on a large enough sample of SNe, then there are good prospects for the identification of the progenitor population and the detection of the ongoing explosion in all wavebands. All these provide tests and checks on the theory of stellar evolution and SNe detonation. The identification of the gamma-ray and gravitational wave signals may also be possible for close SNe (within 50 Mpc).

We have demonstrated that the astrometric scanning satellite \(GAIA\) has exactly the required capabilities. \(GAIA\) is the European Space Agency satellite that is the successor to \(Hipparcos\). Over \(GAIA\)’s 5-year mission lifetime, we estimate that the numbers caught before maximum are \(\sim 6300\) SNe Ia, \(\sim 500\) SNe Ib/c and \(\sim 1700\) SNe II. After launch in about 2010, \(GAIA\) will issue \(\sim 5\) SN alerts a day. In total, \(GAIA\) will report data on at least \(21400\) SNe during the mission, of which \(\sim 14300\) are SNe Ia, \(\sim 1400\) are SNe Ib/c and \(\sim 5700\) are SNe II. These numbers come from detailed simulations in which SNe explode in galaxies tracing the local large-scale structure. The effects of the dimming of SNe because of absorption in the host galaxy and in the Milky Way are included. The SNe light curves are sampled according to the scanning law and the Galactic extinction law. We note that, though huge, these numbers are lower limits. They do not take into account the contribution of SNe in low-luminosity galaxies, which may result in a further doubling of the numbers. They do not take into account the fact that \(GAIA\)’s limiting magnitude is likely to be somewhat deeper than 20th in practice.

\(GAIA\) is complementary to the \(SNAP\) satellite (see \url{http://snap.lbl.gov}), which will probe much deeper out to a redshift of \(\sim 1.7\) to obtain \(\sim 2000\) SNe Ia a year. By contrast, \(GAIA\) will obtain data on \(\sim 4280\) SNe a year but probe at most out to a redshift of \(\sim 0.14\). \(GAIA\) will play its role in cosmology by providing a huge data set of high-quality local SNe Ia in which any scatter in the Phillips relation with colour can be quantified and analysed (Tammann & Reindl 2002).

\(GAIA\) will provide an important data base of nearby SNe which are particularly interesting for studies of the explosions themselves. Many statistics – SNe rates, frequency of different light-curve morphologies, location in the host galaxy – are poorly known. \(GAIA\) will provide the definitive data set. In particular, SNe rates can be corrected for known biases, such as extinction and position in the host galaxy, and so will be measured with unprecedented accuracy. The huge numbers mean that even examples of comparatively rare phenomena will be present in the data base. Despite the enormous efforts of the last decade, there are still very few subluminous SNe, overluminous SNe, SNe II-L and SNe Ib/c in the standard catalogues. \(GAIA\) will present us with good chances of finding examples of nearby subluminous SN Ib/c and II, which needed to detect the emergence of the black hole. Every SNe Ia identified by \(GAIA\) can give the distance of its host galaxy with better accuracy than any other method. Thus, the density and velocity field within a few hundred Mpc will be delineated with unprecedented precision.

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