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 magnitude. 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 lightcurve. Our study shows that GAIA will report data on ~ 21 400 SNe during the five-year mission lifetime, of which ~ 14 300 are SNe Ia, ~ 1400 are SNe Ib/c and ~ 5700 are SNe II. Using the simulations, we estimate that the numbers caught before maximum are ~ 6300 SNe Ia, ~ 500 SNe Ib/c and ~ 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 ~ 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: supernovae: general – neutrinos – gamma rays: theory – gravitational waves – gravitational lensing

1 INTRODUCTION

GAIA is the super-Hipparcos satellite that is planned for launch in 2010 (see “http://astro.estec.esa.nl/gaia” or Perryman et al. 2001). It is the successor to the pioneering Hipparcos satellite which revolutionised our knowledge of the solar neighborhood. GAIA gathers 4 colour broad band and 11 colour narrow band photometry on all objects brighter than 20th magnitude and it performs spectroscopy in the range 850-875 nm on all objects brighter than 18th magnitude. 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 lightcurve 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 lightcurves 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 ~ 2000 SNe available in the standard catalogues (see Tsvetkov et al. 1998 or
time. This breaks down into data on at least 21 400 SNe during the five-year mission life-

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will discover. Here, we carry out detailed simulations using provided rough estimates of the numbers of SNe Ia that GAIA Makarov 1999; Tammann & Reindl 2002) have already pro-

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will be good numbers of rarer phenomena, such as sublumi-

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to compute the numbers of SNe detected as a function of Galactic extinction model and the satellite scanning law.

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GAIA In other words, \[ \sim \] will provide a huge dataset of high quality local SNe Ia in which any deviations from “standard candles” can be analysed. As the dataset is so large, there will be good numbers of rarer phenomena, such as subluminous SNe and SNe Ib/c. Earlier papers (Hog, 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 lightcurve. We show that GAIA will record data on at least 21 400 SNe during the five-year mission lifetime. This breaks down into \[ \sim 14 300 \] SNe Ia, \[ \sim 1400 \] SNe Ib/c and \[ \sim 5700 \] SNe II. These SNe span a redshift range up to \[ z \sim 0.14 \]. GAIA will probably alert on all SNe detected before maximum. These numbers are \[ \sim 6300 \] SNe Ia, \[ \sim 500 \] SNe Ib/c and \[ \sim 1700 \] SNe II during the whole mission. In other words, GAIA will issue \[ \sim 1700 \] SNe alerts a year or \[ \sim 5 \] alerts a day. Roughly 75% 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 \[ \sim 2 \] 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 \[ 65 \text{ km} \text{s}^{-1} \text{Mpc}^{-1} \], which we use henceforth. As GAIA’s limiting magnitude is \[ G \sim 20 \], this means that the most distant SNe Ia accessible to GAIA are \[ \sim 630 \] 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 \[ \sim 355 \] Mpc away. SNe II are subdivided further according to lightcurve 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 \[ \sim 335 \] Mpc and \[ \sim 195 \] Mpc respectively. Such distances emphasise 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 \[ 10^{10} L_\odot \]. 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 \[ \sim 0.18 \] per century per \[ 10^{10} L_\odot \] for redshifts \[ z \geq 0.02 \] to 0.2. Second, Pain et al. (1996) found a SNe Ia rate of \[ \sim 0.36 \] per century per \[ 10^{10} L_\odot \] at the somewhat higher redshift of \[ z \sim 0.4 \]. Third, 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 two.

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 \[ \sim 20 000 \] galaxies. On plotting numbers of galaxies versus distance, the graph peaks at \[ \sim 75 \] Mpc and thence shows a steady decline. This suggests that the catalogue can be used out to at most \[ \sim 75 \] 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 \[ M \sim -20 \] to 0.2. In all, there are at least \[ \sim 48 000 \] SNe Ia and \[ \sim 7000 \] SNe Ib/c. The numbers for SNe II depend on the relative

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Table 1. SNe explosion rates (in units of SNe per $10^{10} L_\odot$ 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).

| Type     | E-S0 | S0/a, Sa | Sab, Sb | Sbc-Sd | Sdm-Im |
|----------|------|----------|---------|--------|--------|
| Type Ia  | 0.42 | 0.21     | 0.21    | 0.21   | 0.21   |
| Type Ib/c| -    | 0.01     | 0.11    | 0.33   | 0.38   |
| Type II  | -    | 0.07     | 0.57    | 1.66   | 1.78   |

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 year 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 $-14$.

| Type     | E-S0 | S0/a, Sa | Sab, Sb | Sbc-Sd | Sdm-Im |
|----------|------|----------|---------|--------|--------|
| N (galaxies) | 1200 (4850) | 679 (3024) | 867 (3694) | 1993 (6957) | 1798 (3701) |
| Type Ia  | 29 (80) | 7 (11)   | 11 (31)  | 19 (52) | 16 (16) |
| Type Ib/c| 0 (0)   | 1 (1)    | 6 (16)   | 30 (80) | 29 (29) |
| Type II  | 0 (0)   | 2 (4)    | 31 (85)  | 152 (412) | 135 (135) |

Figure 2. This shows the number of transits made by the ASTRO-1 and ASTRO-2 telescopes as a function of ecliptic latitude. The figure is drawn by choosing 5000 random directions on the sky, and computing the ecliptic latitude and number of transits using software supplied by L. Lindegren. The transits are strongly clustered into groups of between two and five.

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 $D^3$ 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 lightcurve can now be generated using the templates illustrated in Figure 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 with a peculiar spectrum (Saha et al. 2001). However, our algorithm chooses the magnitude at maximum from a Gaussian distribution and so only the shape of the template is important. Therefore, although SN 1991T is overluminous, this does not cause exaggeration of our results. We reconstruct the rising part of the lightcurve of SNe Ia using the fact that luminosity is proportional to the square of the time since explosion (e.g., Riess et al. 1999). For SNe Ib/c, we use the photometry on SN 1994I from Richmond et al. (1996). This is a SN Ic, but we use it as a template for all SN Ib/c, taking the view that there is little point in trying to distinguish between SN Ibs and SN Ics in our simulations. It is not even clear that they are intrinsically very different, other than in the location of the ionizing source for helium. There is considerable diversity in SNe II lightcurves, as illustrated in Patat et al. (1994). We use the photometry of Cappellaro et al. (1995) on SN 1990K as the basis of our standard template for SNe II-L. However, this is missing the rising part, which is reconstructed using the mean lightcurve data in Doggett & Branch (1985). We use the photometry of Hamuy et al. (2001) on SN 1999em as a template for SN II-P.

Lastly, the lightcurves are sampled according to GAIA's scanning law using software kindly supplied by L. Lindegren. GAIA has three telescopes on board. ASTRO-1 and ASTRO-2 perform astrometry and broad-band photometry on all objects brighter than $G \sim 20$. SPECTRO performs spectroscopy and medium-band photometry. The spacecraft is assumed to rotate about its spin axis once every $\sim 3$
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}.

| SN Type | M_G   | σ_G |
|---------|-------|-----|
| Type Ia | -18.99 | 0.76 |
| Type Ib/c | -17.75 | 1.29 |
| Type II-L | -17.63 | 0.88 |
| Type II-P | -16.44 | 1.23 |

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\% of all SNe Ia. Within 355 Mpc, GAIA detects \sim 20\% of all SNe Ib/c. For SNe II-L, GAIA detects \sim 31\% within 335 Mpc. Finally, for SNe II-P, GAIA detects \sim 48\% within 195 Mpc. Note that by detection, we mean that GAIA records at least one datapoint on the standard SNe templates shown in Figure 1.

3 RESULTS

3.1 Numbers Detected

Figure 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\% of all the SNe Ia within 630 Mpc, which marks the limit of the most distant SNe Ia accessible. The 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\% of all SNe Ib/c, \sim 31\% of all SNe II-L and \sim 48\% SNe II-P within these distances. This means that GAIA will provide some (perhaps rather limited) information on 14 300 SNe Ia and 14 000 SNe Ib/c during its five-year mission. For SNe II, the number depends on the relative frequency f_{II} and is \sim 8700 f_{II} + 2700 (1 - f_{II}). If SNe II-L and SNe II-P occur equally frequently (f_{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, Hog 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 datasets gathered by other planned space missions. Almost all the SNe that GAIA misses explode in the 20 days 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). It may be wondered 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'' at FWHM). 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\% of SNe Ia.

Figure 4 shows the fraction of the detected SNe as a function of phase of the lightcurve. Some 44\% of the detected SNe Ia are caught before maximum, 37\% of the detected SNe Ib/c, 37\% of the detected SNe II-L and 9\% 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_{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 brightening object is not just a common variable star. We use the General Catalogue of Variable Stars (Kholopov et al. 1999) to build a subsample of variables with periods in excess of 10 days. Some 34\% of this subsample have periods less than 6 months and 86\% have
Figure 4. This shows histograms of the numbers of detected SNe against phase of the lightcurve. The shaded area corresponds to the fraction of SNe caught before the maximum of the lightcurve.

periods less than 1 year. In practice, ~12 months baseline photometry may be needed to discriminate against common forms of stellar variability. One way round this problem 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). Høg (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 nova per year in the GAIA datastream. 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% from a single spectrum and photometric epoch. For a 20th magnitude SN, the most suitable combination is a 2m telescope for imaging and a 4m for spectroscopy. On a 2m telescope, it is feasible to carry out high signal-to-noise UBVRI photometry on a 20th magnitude SN in \(<1\) hr. The typical signal-to-noise needed for identifying type from spectroscopy is \(\sim 30\). This needs \(\sim 2\) hrs on a \(V \sim 20\) 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 2m and one 4m) 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 lightcurves), 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 emphasised 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.
The maximal amplitude of gravitational waves for a SNe at 50 Mpc is in the range $10^{-21}$ to $10^{-25}$ (e.g., Mönchmeyer 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 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 rôle 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 $\sim 10$ 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, about 10$^6$ detected events are expected from a core collapse SN at an assumed distance of 10 kpc (Beacom, private communication). This is larger than the SN 1987A yield in Kamiokande II by roughly the factors 25 (5 times closer), 16 (32 kton detector rather than 2 kton), and 2 (optimisa-
tion). In addition, some other reaction channels are expected to become important once the yield is so high.

Scaling this result, the typical number of MeV neutrinos expected from a SN Ib/c or II in a host galaxy at a distance \( D \) with a 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 \( \sim 5 \) Mpc may be detectable. This is the hardest challenge of all! Only a very few 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 dataset 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 minimised 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 datasets (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 center of the galaxy – seriously afflict all current datasets. 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’s – 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 \( \sim 200 \) Mpc, the projected position can be determined to \( \sim 1 \) 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) emphasise 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 Figure 4 of Balberg & Shapiro (2001), we see that the fraction of suitable SNe comprise roughly 10% of all core collapse SNe within 50 Mpc. From Table 5, it follows that there will be \( \sim 10 \) SNe Ib/c 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 onto the emerging black hole.

Another application of GAIA’s SNe Ia dataset is to measurements of the local velocity field (e.g., Heg 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 \( V \) which minimises

\[
\chi^2 = \sum_i \left( \frac{v_i - \hat{V}_i}{\sigma_i} \right)^2,
\]

where \( v_i \) is the observed peculiar velocity for the ith galaxy, whose direction vector 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 \( \sim 5\% \). 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
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GAIA has exactly the required capabilities. GAIA is the European Space Agency satellite that is the successor to Hipparcos. Over GAIA’s five 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 21 400 SNe during the mission, of which \( \sim 14,300 \) 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 lightcurves are sampled according the scanning law of the satellite. 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 “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 dataset 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 database of nearby SNe which are particularly interesting for studies of the explosions themselves. Many statistics – SNe rates, frequency of different lightcurve morphologies, location in the host galaxy – are poorly known. GAIA will provide the definitive dataset. 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 database. Despite the enormous efforts of the last decade, there are still very few subluminous SNe, over-luminous 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 SNe 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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