Core-collapse and Type Ia supernova studies with the SKA

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Abstract

We discuss in this chapter some of the possibilities opened by the future availability of the SKA in the study of both core-collapse and thermonuclear runaway supernovae. **Core-collapse SNe (CCSNe):** Optical searches of CCSNe miss a significant fraction of them due to dust obscuration; CCSN radio searches are thus more promising for yielding the complete, unobscured star-formation rates in the local universe. The SKA yields the possibility to piggyback for free in this area of research by carrying out commensal, wide-field, blind transient survey observations. SKA1 should be able to (blindly) discover several hundreds of CCSNe in just one year. SKA, with an expected sensitivity ten times that of SKA1, is expected to detect CCSNe in the local Universe by the thousands. Therefore, commensal SKA observations could easily result in an essentially complete census of all CCSNe in the local universe, thus yielding an accurate determination of the volumetric CCSN rate. **Type Ia SNe:** We encourage the use of the SKA as the most sensitive trigger machine to unveil the putative prompt (\(\lesssim\) first few days after the explosion) radio emission of any nearby type Ia SN, via target-of-opportunity observations. The huge improvement in sensitivity of the SKA with respect to its predecessors will permit to unambiguously discern which progenitor scenario (single-degenerate vs. double-degenerate) applies to them.

1 CCSN searches with the SKA

The limited sensitivity of pre-eMERLIN/VLA interferometric arrays has biased past radio observations of CCSNe towards the study and monitoring of only the brightest events, thus
preventing systematic radio follow-ups of CCSNe. This makes the currently existing radio observations of CCSNe of rather limited use.

In this section, we discuss the benefits that can be obtained from simply making use of commensal, wide-field, transient surveys with the SKA. In particular, such surveys could potentially allow us to obtain a complete census of CCSNe in the local universe, and therefore permit us to determine the true CCSN rate and the star-formation rate of the population of massive stars in the local universe. They could also yield important information on the Initial Mass Function (IMF) of the host galaxies. In addition, some specific, relevant questions that will be tackled by those observations include the following:

- **Unveiling the hidden CCSN population and the true volumetric CCSN rate in the local universe.** Ref. [10] found out an apparent mismatch between the measured CCSN rate (mostly from optical observations) and the cosmic massive star formation rate, which was twice as large as the measured one. However, [13] and [17] have shown that a significant fraction of the exploding CCSNe in the local universe are hidden behind dust, and that this fraction seems to increase significantly as one goes back in the history of the universe (see Fig. 1, left panel), i.e., there seems to be no mismatch when the hidden CCSNe are taken into account. Radio observations have the advantage over both optical and near-IR that the emission from CCSNe is not hampered by dust, and thus offers an excellent opportunity to determine the true core-collapse supernova rate in the local universe. Wide-field SKA observations covering a significant area of the sky will discover many CCSNe in the nearby universe, and therefore will allow us to accurately determine this relevant parameter.

- **Probing the SN-CSM interaction for all CCSN types**, from the relatively faint Type IIP to the extremely radio bright Type IIn SNe, thanks to the superb sensitivity of SKA. Probing the SN-CSM interaction for all CCSN types will allow us to obtain basic, crucial information to characterize their progenitors, including mass-loss rates and, for synchrotron-self-absorbed SNe, the shock radius and the magnetic field—directly from the light curves (see, e.g., [3]).

- **Bridging the gap between Type Ibc SNe and (long) γ-ray bursts.** Type Ibc are arguably the CCSNe that show the highest blastwave speeds, yet most of them are energetically much less powerful than GRBs. Recently, however, cases like SN 2009bb, with $\beta \sim 0.9$ and energy $\sim 10^{49}$ erg seem to be intermediate cases. These “engine-driven” CCSNe could be detected with the high-sensitivity offered by the SKA, thus filling this gap in the energy-blastwave velocity parameter space of SNe-GRBs ([8] and references therein).

- **Typing CCSNe from their radio behaviour.** A systematic monitoring could permit us to type CCSNe from their radio light curves. This is crucial for the study of the hidden SN population in (Ultra)Luminous Infra-Red Galaxies, where a spectroscopical classification, or even an optical discovery, is essentially impossible (see [17] and Fig. 1).

- **Correlating optical and radio properties.** The combined use of optical information for both SN and host galaxy in dust-free environments, together with the obtained peak
Figure 1: Left: Fraction of CCSNe missed by rest-frame optical searches as a function of redshift. The solid red line shows the best estimate, with the upper and lower bounds of the missing fraction shown as dashed lines. The solid grey line corresponds to the missing fraction from [13]. (Figure from [17].) Right: Core-Collapse Supernova rate as a function of redshift. (Figure from [31].) The use of the SKA as a CCSN discovery machine will reduce the relatively large uncertainty in the missing fraction of CCSNe in the local universe ($z \leq 0.3$), as well as in the volumetric CCSN rate (right figure). (radio) luminosities will allow us to check whether there is a correlation between the optical and radio properties of CCSNe, as well as with their host galaxies. This will be possible by, e.g., making a combined, commensal use of wide-field surveys programmed at radio wavelengths with SKA, and at optical wavelengths with, e.g., the LSST or similar telescopes. Obviously, the most interesting cases will likely be subject of targeted, monitoring observations with these and other facilities. For example, [8] clearly showed the impact of carrying radio and optical follow-up observations of all possible radio transients discovered in surveys covering a significant fraction of the sky area, in terms of GRBs and SNe studies.

2 CCSN searches with the SKA

Several wide-field sky surveys will be carried out with the SKA pathfinders MeerKAT and ASKAP, as well as with the upgraded Very Large Array. Those surveys can be used commensally for transient studies, by profiting from programmed wide-field observations. For example, the planned Very Large Array Sky Survey (VLASS) is contemplating the possibility of observing wide field areas (a few hundreds to about one thousand of square degrees) with nominal sensitivities of $1\sigma \simeq 70\mu Jy/beam$ per epoch, aiming at reaching r.m.s. values of $\simeq 30\mu Jy/beam$ after stacking multi-epoch observations. However, those sensitivities are just too shallow to be of any real use for CCSN studies. Indeed, a $5\sigma$ figure of merit corresponds
to 500 µJy/beam per epoch, so that the maximum distance to detect a type IIP event would be \( \sim 9 \) Mpc (Table 1). Unless sky areas close to the full celestial sphere are surveyed—which is very unlikely—VLASS will only pick up a handful of CCSNe after one year of observations (Table 1). Those few CCSNe will be discovered first by optical searches, and some of them will be subject of targeted radio observations anyway, given their vicinity. Thus, deeper sensitivities are needed to make a substantial contribution to the field.

### 2.1 SKA survey strategy for commensal CCSN searches

The best strategy for transient studies with the SKA is one that combines good angular resolution (\( \lesssim 1.5 \) arc sec) and a large field of view (FoV) at frequencies around and above \( \sim 1.7 \) GHz. Those parameters warrant essentially unambiguous source identification and large numbers of potential SNe in the field of view. After the SKA rebaselining in March 2015, SKA1 will consist of two instruments, SKA1-LOW and SKA1-MID.

SKA1-LOW is not suitable for searching young CCSNe. First, disentangling the radio emission of a CCSN from that of the host galaxy will be essentially impossible with the angular resolution provided by SKA1-LOW. Second, at the low frequencies of SKA1-LOW (\( \lesssim 350 \) MHz), there will be significant absorption due to H II regions, which would prevent the discovery of many CCSNe. Finally, the radio light curve evolution at low frequencies is very slow, which severely impacts on the cadence time needed to ascertain the variability of a CCSN candidate. In fact, given the radio spectral evolution of supernovae, the cadence time should be roughly inversely proportional to the observing frequency. Therefore, visiting the same field at 110 MHz implies a cadence time about 16 times larger than at 1.7 GHz. Since at the latter frequency the cadence time is \( \sim 90 \) days (thus taking about one year to complete five visits of the same field), this would take almost 16 yr at 110 MHz, which is unrealistic for any sensible blind search of CCSNe.

The other instrument approved after the rebaselining, SKA1-MID, will observe at frequencies above 350 MHz, in principle up to 14 GHz, and will have a maximum baseline of 150 km. At the nominal frequency of 1.7 GHz, SKA1-MID will thus yield an angular resolution of \( \sim 0.25 \) arcsec. It will have a nominal continuum sensitivity of 1.14 µJy/b after one hour, for an assumed effective area of 33000 m\(^2\) and a bandwidth of 770 MHz. Since SKA1-MID will be made of \( \sim 15 \) m dishes, the FoV will be of \( \sim 0.50 \) deg\(^2\) at its nominal frequency of 1.7 GHz.

We assume here that SKA1-MID will observe the sky for \( \gtrsim 2000 \) hr in its first year of operations. For the sake of simplicity, we also assume that the observing band will be centered at 1.7 GHz, and that one hour of on-source time is devoted to each field, which means that the area will be of \( \sim 1000 \) deg\(^2\) after one year, with a typical r.m.s. of 1.14 µJy/b per pointing. To be of use for CCSNe searches, each field of view should be visited five times (each time for an on-source time of 12 minutes), at a cadence of one visit every \( \leq 90 \) d. This scheme is also handy to obtain an homogeneous r.m.s. across the whole FoV, since each pointing can be done at slightly different positions. Since we aim at a final, stacked r.m.s. of \( \sim 1.14 \) µJy/beam, the r.m.s. attained in each individual visit will be \( \sim 1.14 \times \sqrt{5} = 2.55 \) µJy/beam.
Table 1: Expectations for CCSN detections from commensal radio surveys for the VLASS, SKA1-MID, and SKA. $D_{\text{max}}$, in Mpc; $L_{\nu,26} = L_{\nu,\text{peak}}/10^{26}$ erg/s/Hz; $\nu_5^{-1} = \nu/5$ GHz.

<table>
<thead>
<tr>
<th>SN Type</th>
<th>$\Delta t_{\text{peak}}\nu_5^{-1}$ [days]</th>
<th>$L_{\nu,26}$</th>
<th>VLASS</th>
<th>SKA1-MID</th>
<th>SKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ib/c</td>
<td>30</td>
<td>20</td>
<td>69</td>
<td>8</td>
<td>362</td>
</tr>
<tr>
<td>IIb, IIL</td>
<td>~150</td>
<td>10</td>
<td>49</td>
<td>1</td>
<td>256</td>
</tr>
<tr>
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<td>40</td>
<td>0.5</td>
<td>11</td>
<td>0</td>
<td>57</td>
</tr>
<tr>
<td>IIn</td>
<td>1000</td>
<td>100</td>
<td>154</td>
<td>11</td>
<td>810</td>
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<tr>
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</tr>
<tr>
<td>Total</td>
<td></td>
<td>~20</td>
<td>~310</td>
<td>~9790</td>
<td></td>
</tr>
</tbody>
</table>

### 2.2 Expectations for CCSN discoveries with wide surveys

Table 1 summarizes the expectations for detecting CCSNe using the VLASS, SKA1-MID, and SKA. We show the expected number of detected CCSNe, $N_{\text{det}}$, up to the maximum distance, $D_{\text{max}}$ to which CCSNe of a given type are expected to be detected above 5$\sigma$, for the nominal r.m.s. values of VLASS ($\sim 70\mu$Jy/b/pointing) and SKA1-MID ($\sim 2.55\mu$Jy/b/visit), as well as for SKA (ten times more sensitive than SKA1). We assumed that each survey observes at a nominal frequency of 1.7 GHz. We also assumed that the area covered by the observations after one year is of 1,000 deg$^2$ (SKA1-MID and SKA) and ten times larger (10,000 deg$^2$) for the VLASS.

We refer the interested reader to [22] for details on how the numbers in Table 1 are obtained, and highlight here that the expected number of detected CCSNe from commensal surveys will be much larger than expected from currently envisioned surveys with state-of-the-art arrays.

The main limitation is due to the relatively small value of the maximum distance that will allow a detection of a type IIP SN, which is why so few detections of them are expected. The relatively high luminosity of spirals at those frequencies ($\sim 7 \times 10^{37}$ erg s$^{-1}$ Hz$^{-1}$) may also prevent the unambiguous detection of even Type IIn at those distances with SKA1, as the synthesized beam of 1.0$''$ corresponds to 2.1 kpc, which could pick up a significant amount of the background galaxy luminosity, thus the need for high angular resolution. This limitation will be overcome once SKA is completed, as is foreseen to have a twentyfold better angular resolution. In addition, one has to take into account that around 10% of the massive star-formation already at $z \sim 0.1$ will come from Luminous Infrared Galaxies [12]. While those galaxies are prolific CCSN factories, their detection with SKA1, or even with SKA, will not be possible in general, as the compact starburst (size $\lesssim 500$ pc) will have a typical 1.4 GHz brightness well in excess of our 5-$\sigma$ sensitivity limit. For particular targets of interest, SKA-VLBI (VLBI observations incorporating the phased-array of the inner core of SKA; see chapter by Ros et al. in this book) will be able to detect individual radio supernovae and supernova remnants in the circumnuclear starbursts.
3 Type Ia supernovae with the SKA

Type Ia SNe are the end-products of white dwarfs (WDs) with a mass approaching, or equal to, the Chandrasekhar limit, which results in a thermonuclear explosion of the star. While it is well acknowledged that the exploding WD dies in close binary systems, it is still unclear whether the progenitor system is composed of a C+O white dwarf and a non-degenerate star (single-degenerate scenario), or both stars are WDs (double-degenerate scenario). In the single-degenerate scenario, a WD accretes mass from a hydrogen-rich companion star before reaching a mass close to the Chandrasekhar mass and going off as supernova, while in the double-degenerate scenario, two WDs merge, with the more-massive WD being thought to tidally disrupt and accrete the lower-mass WD [14]. This lack of knowledge makes difficult to gain a physical understanding of the explosions, and to model their evolution, thus also compromising their use as distance indicators.

Radio and X-ray observations can potentially discriminate between the progenitor models of SNe Ia. For example, in all scenarios with mass transfer from a companion, a significant amount of circumstellar gas is expected [1], and therefore a shock is bound to form when the supernova ejecta are expelled. The situation would then be very similar to circumstellar interaction in core-collapse SNe (see above), where the interaction of the blast wave from the supernova with its circumstellar medium results in strong radio and X-ray emission [2]. On the other hand, the double-degenerate scenario will not give rise to any circumstellar medium close to the progenitor system, and hence essentially no prompt radio emission is expected. Nonetheless, we note that the radio emission increases with time in the double-degenerate scenario, contrary to the single-degenerate scenario. This also opens the possibility for confirming the double-degenerate channel in Type Ia SNe via sensitive SKA observations of decades-old Type Ia SNe.

Radio [18, 9] and X-ray [11, 23] observations of SNe Ia resulted in upper limits on the wind density around SN Ia progenitors of the order of $\dot{M} = 1.2 \times 10^{-7} \, M_{\odot} \, yr^{-1}$, assuming a wind velocity of 10 km s$^{-1}$. At the moment, the deepest radio limits on circumstellar gas come from SNe 2011fe and 2014J. The limits on mass-loss rate from the progenitor system of SN 2011fe are $\dot{M} = 6 \times 10^{-10} \, M_{\odot} \, yr^{-1}$ and $\dot{M} = 2 \times 10^{-9} \, M_{\odot} \, yr^{-1}$ from radio [4] and X-rays [15], respectively, assuming a wind velocity of 100 km s$^{-1}$. Similarly, the mass-loss rate limits for the progenitor system of SN 2014J are $\dot{M} = 7 \times 10^{-10} \, M_{\odot} \, yr^{-1}$ and $\dot{M} = 1.2 \times 10^{-9} \, M_{\odot} \, yr^{-1}$ from radio [21] and X-rays [16], respectively, for a wind velocity of 100 km s$^{-1}$. The above limits permit to rule out all symbiotic systems and the majority of the parameter space associated with stable nuclear burning WDs, as viable progenitor systems for either SN 2011fe or SN 2014J. Recurrent novae with main sequence or subgiant donors cannot be ruled out completely, yet most of their parameter space is also excluded by those radio observations (see Fig. 2).

3.1 Unveiling the progenitor scenarios of type Ia SNe with the SKA

With the advent of the SKA, we will be able to obtain significantly deeper radio limits: for a SNe Ia exploding at the distance of M 82, we should eventually detect it; for more
Figure 2: Constraints on the parameter space (wind speed vs. mass-loss rate) for single degenerate scenarios for SN 2014J. Progenitor scenarios are plotted as schematic zones, following [4]. We indicate our 3σ limits on $\dot{M}/v_w$, assuming $\epsilon_B = 0.1$ (solid line) and the conservative case of $\epsilon_B = 0.01$ (dashed line). Mass loss scenarios falling into the gray-shaded areas should have been detected by the deep radio observations, and therefore are ruled out for SN 2014J. For a comparison, we have included also the limit on SN 2011fe (dash-dotted line) for the same choice of parameters as the solid line for SN 2014J, which essentially leaves only room for quiescent nova emission as a viable alternative among the single-degenerate scenarios for SN 2011fe (see [21] for details).

For distant supernovae, we will be able to obtain similar or even more constraining limits to those obtained for SNe 2011fe and 2014J, which will allow us to build a global picture thanks to the availability of a larger statistical sample of observed SNe Ia.

SKA1-MID promises to yield 1σ sensitivities of $\sim 0.7\mu$Jy/beam in one hour at a fiducial frequency of 1.7 GHz. This figure is five times better than currently provided by the most...
Figure 3: Constraints on the parameter space (wind speed vs. mass-loss rate) for the same single-degenerate scenarios as in Fig. 2, as expected with SKA1 (dashed lines) and the full SKA (solid line). SKA1 will be able to unambiguously probe all single degenerate scenarios for SNe Ia exploding at distances similar to that of M 82 (3.5 Mpc), and will be more sensitive than current state of the art, deep radio observations of SN 2014J in M 82, up to a distance of 25 Mpc, or even larger. When SKA is completed, we will be able to unambiguously probe the prompt radio emission within the single degenerate scenario up to distances of ≥ 25 Mpc. All lines correspond to 3-σ. (Figure taken from [22].)
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every ∼15 yr within a distance of ∼8 Mpc (more than twice the distance to M 82), which is a value too small to allow for any statistical improvement in a reasonable amount of time. [24] found 26 Type Ia SNe out of 132 SNe from a 10.5 year-long survey within 28 Mpc. This figure corresponds to about 1 SN Ia every 13 yr within a distance of 8 Mpc, in agreement with the value found by [6].

To obtain a statistically significant sample of SNe Ia observed in radio and with similar upper limits to those obtained for SNe 2011fe and 2014J, we need to sample significantly larger volumes and need much more sensitive radio observations. For example, by sampling out to a distance of 25 Mpc, we can expect ∼2 SNe Ia per year within this sampled volume, which in 10 years would result in a total of ∼20 SNe Ia, enough to extract statistical results. At this maximum distance, we need a sensitivity ∼50 times better than obtained by the deep radio observations discussed in [4] and [21], i.e., 80 nJy/beam (1-σ), to be as constraining. The fiducial 1-σ sensitivity of SKA should be 10 times better than that of SKA1-MID, or about ∼70 nJy/beam in one hour, which will allow to obtain deep radio limits (or eventually the detection) of type Ia SNe in a short amount of time and out to 25 Mpc, or even further. To get a more clear idea of what can be reached with SKA1 and SKA, we plot in Fig. 3 the constraints on the mass-loss rate parameter for an upper limit of 3-σ (3×0.7 µJy/beam for SKA1, or 3×70 nJy/beam for SKA) for a Type Ia SN exploding at the distance of M 82 and at 25 Mpc. It is evident that, at this level of sensitivity, a non-detection would be essentially as meaningful as a detection, since the former would imply that only the double-degenerate scenario is viable, while the latter would tell us which of the single-degenerate channels results in Type Ia SNe. The overall time needed to carry out such a target-of-opportunity programme will require no more than about 12−24 hr/year, overheads included, for an average of two targets/year within a radius of 25 Mpc. Such modest time requests can be easily accommodated within a sensible period of time.

4 Summary

We have presented the prospects for advancing our understanding of the physics of supernovae via their study at radio wavelengths with the SKA. Our suggested approach for core-collapse supernovae is a commensal one, taking advantage of the deep, sensitive surveys that are planned with SKA. We have discussed the expectations for CCSN studies under the specific case of SKA1-MID (∼2000 hr in one year, covering an area of ∼1000 deg² in one year, rms=1.14 µJy/beam in 1-hr, bandwidth=770 MHz, central observing frequency = 1.7 GHz). The expected number of new CCSNe discovered after one year would be ∼310. For SKA, the expected number of expected CCSN discoveries is close to 10,000 in one year. Therefore, the number of detections is expected to approach the number of explosions of all CCSNe in the local universe, thus allowing us to obtain a dust-free, complete census of CCSNe. The only request from such a programme is a multi-epoch approach, observing a cadence-time of ∼90ν⁻¹ days, where ν=ν/1.7 GHz.

We have also discussed the prospects for probing Type Ia SNe progenitor scenarios with the SKA via ToO observations. The SKA can be used at very low time-cost for searching the putative prompt radio emission arising, in the single-degenerate scenario, from the circum-
stellar medium around Type Ia SN progenitors in the nearby universe. Complementarily, in
the double-degenerate scenario, the radio emission of Type Ia SNe is expected to increase
with time and, therefore, the SKA should observe decades-old, nearby Type Ia SNe. In con-
cclusion, the huge improvement in sensitivity of the SKA with respect to their predecessors
should allow us to unambiguously discern which progenitor scenario (single-degenerate vs.
double-degenerate) applies to them, thus solving this long-standing issue.

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