*Supernova 1987A:30 years later - Cosmic Rays and*
*Nuclei from Supernovae and their aftermaths*
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# Synergy SKA - CTA: Supernova remnants as cosmic accelerators

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**Abstract.** Supernova remnants (SNRs) are one of the most important sites where particles are accelerated with high efficiency and in a wide range of energies, becoming an important component of cosmic rays. A good test for this hypothesis will be possible using the data collected by next-generation radio and gamma-ray observatories, like the Square Kilometre Array (SKA) and the Cherenkov Telescope Array (CTA). Radio emission is fundamental to explore the SNR environment and to shed light on the physical processes involved in particle acceleration, providing direct links to high-energy physics. Two cases of SNRs recently studied in radio are presented, showing the importance of high-resolution radio images. An overview of SKA and its precursors is given with our ongoing preparation work. In particular, we present the EMU survey and the pathfinder project SCORPIO. Finally a direct view of the tight connection between SKA and CTA future studies of SNRs is provided.

**Keywords.** acceleration of particles, masers, instrumentation: interferometers, supernova remnants

## 1. Introduction

Radio is probably the best suited band at which searching for Galactic SNRs. About 95% of all of the known Galactic SNRs are detected in radio (Dubner & Giacani 2015) and many of them are detected only in this band. The radio emission originates from synchrotron processes involving electrons accelerated up to relativistic energies. Radio is therefore a unique tool to locate the potential particle acceleration sites and probe the local plasma conditions. Radio spectral index maps, for example, allow us to reveal the interaction of the remnant with molecular clouds (Giacani *et al.* 2011) or the presence of a pulsar wind nebula (PWN; Gaensler & Slane 2006). In these cases a significant spatial variation of the spectral index is expected. Furthermore, radio polarimetric study can give us hints on the intensity and direction of the magnetic field disclosing the observation of turbulence in plasma (DeLaney *et al.* 2002). Finally the observation of the OH maser transition at 1720 MHz is an extremely powerful tracer of shocked medium, since this line is inverted only collisionally (Frail, Goss & Slysh 1994). These phenomena (interaction with molecular clouds, presence of a PWN, turbulence and shocks) are directly associated with sites where particle acceleration can take place. These sites are therefore usually characterized also by $\gamma$-ray emission, from GeV to PeV. In this sense radio observations are a valuable probe of those environments where high-energy emission originates.

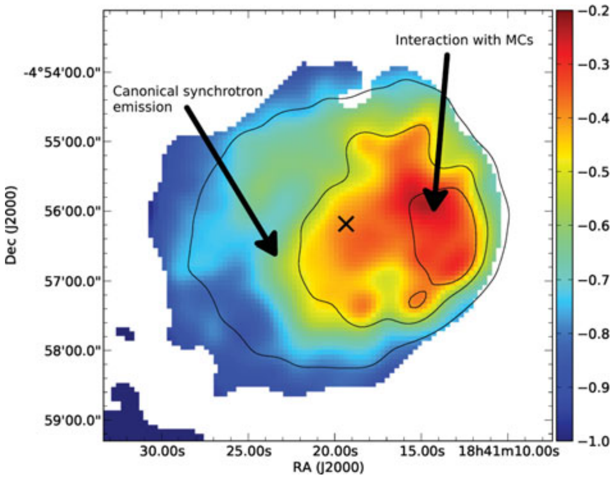

**Figure 1.** Spectral index map of SNR G027.4+00.0 (adapted from Ingallinera *et al.* 2014).

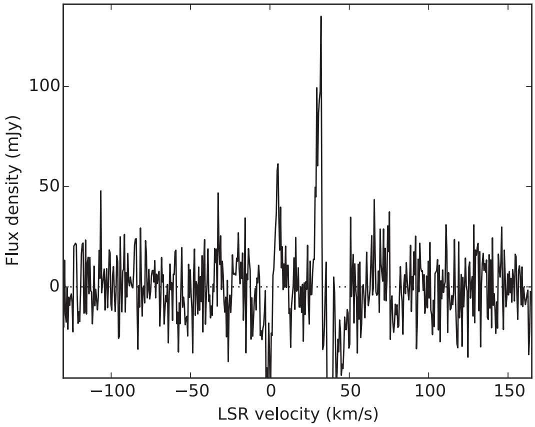

**Figure 2.** OH maser line at 1720 MHz detected toward SNR G011.2-00.3.

## 2. Case studies: SNR G027.4+00.0 and SNR G011.2-00.3

In this Section we provide two examples of SNRs recently studied by our group (Ingallinera *et al.* 2014), using the Very Large Array (VLA) and the Green Bank Telescope (GBT). The data from the interferometer and from the single-dish telescope were combined in the *uv*-plane ("feathering" process) to achieve both a very high resolution and the full sensitivity to large spatial scales. The images of the two SNRs produced in this way do not suffer from those flux-loss issues typical of interferometers, and accurate flux density measurements can be obtained. The first remnant is SNR G027.4+00.0, observed at two different frequencies, 1.4 and 5 GHz, in order to derive spectral information. In Figure 1 we show the spectral index map of SNR G027.4+00.0, which clearly shows a flatter spectral index toward the west region, interpreted as the sign of an interaction with molecular clouds.

The second remnant is SNR G011.2-00.3, observed in continuum at 5 GHz and in spectral line at 1.7 GHz. For this remnant we were able to detect the OH maser line at 1720 MHz (Figure 2), signature of an ongoing shock.

The two SNRs presented in this Section have a radius of about 2 arcmin. SNRs with such an angular extension are too small to be investigated only with single-dish radio

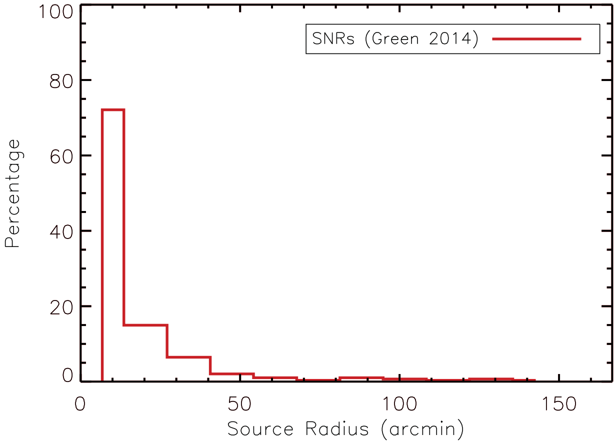

**Figure 3.** Distribution of Galactic SNRs in Green (2014) according to their radius.

telescopes and interferometric data are absolutely necessary. On the other hand, remnants with small angular extension are very common. In Figure 3 we show a histogram plotting the percentage of the Galactic SNRs included in the catalogue by Green (2014) against their radius. It is possible to notice that the majority of known Galactic SNRs have radii of order of 5 arcmin or less. Furthermore, it is likely that many missing SNRs could be even smaller. So, in order to increase the sample of Galactic SNRs that can be studied in detail, achieving a good angular resolution in radio data will be mandatory.

## 3. Science with SKA and its precursors

In the next future radio astronomers will be provided with have access to the most advanced astronomical facility ever designed, SKA. SKA will consist of two different arrays, LOW and MID, located in Australia and South Africa, respectively, and will cover a frequency range between 50 MHz and 14 GHz. Its construction is divided in two phases. SKA-1 phase (10% of the array) will start in 2018 and its early-science is expected around 2022. SKA-2, that is the full array as originally designed, will start to be built just after SKA-1 and its completion is scheduled in 2030. SKA-1 angular resolution will span from about 20 arcsec down to tens of milliarcseconds, and a two-order of magnitude improvement is expected at the fully completion of the array (SKA-2). Since SKA is a revolutionary telescope, before its construction several minor observatories have been built as precursors and are now operational, among which MWA, MeerKAT and ASKAP. The task of SKA precursors is not only to address scientific and technological challenges of the SKA but also to test innovative elements (for example the Phased Array Feeds) and huge data sets processing.

ASKAP (Australian SKA Pathfinder) is testing the Phased Array Feeds technology, by which large-area very-sensitive surveys will be feasible in reasonable amounts of time. The Evolutionary Map of the Universe (EMU) is one of the large programs already approved for ASKAP (Norris *et al.* 2011). It is a wide-field survey that will observe the entire southern sky up to $\delta = +30°$, with a resolution of about 10 arcsec. About 75% of the Galactic plane will be imaged. EMU will cover approximately the same sky extension as NVSS, the current reference all-sky survey, but it will be 100 times more sensitive (down to 0.01 mJy/beam at $1\sigma$ level). The impact of EMU on Galactic science and in particular on Galactic SNRs will be extraordinary. It will allow a detailed study of the entire evolution of massive stars, from their formation to their last phases (e.g.

LBV and WR stars) and eventually their death as SN. But it will also provide a direct contribution to SNRs, for example with the detection of missing SNRs, in particular the young SNRs, or with the possibility of high-resolution polarimetric study of their filamentary structures.

ASKAP, and the other SKA precursors, will bring several innovations, so a long verification phase has been undertaken where extensive tests and pathfinders have been employed. In this context, between 2011 and 2016 we carried out a blind survey, named SCORPIO, conducted in a $2 \times 2$ deg$^2$ patch of the sky, mainly using the Australia Telescope Compact Array, the Parkes Telescope and the first data from ASKAP commissioning (Umana *et al.* 2015). SCORPIO has a resolution similar to that expected in EMU, and a sensitivity down to 0.03 mJy/beam. SCORPIO is designed to identify in advance what kind of problems we will face with EMU, regarding data reduction and analysis in the Galactic plane. But it also proved to be a scientific golden mine. A catalogue of point and extended sources are in preparation (Trigilio *et al. in prep.*; Ingallinera *et al. in prep.*), a method for extended source extraction has already been published (Riggi *et al.* 2016) and work on the spectral index analysis is submitted (Cavallaro *et al. submitted*). The SCORPIO field harbours a SNR (G344.7-0.1) and two SNR candidates. Studies are ongoing to characterize and classify these three sources.

## 4. Connection between SKA and CTA

Radio observations of SNRs with next-generation instruments will have a tight link to those high-energy phenomena that will be probed by future $\gamma$-ray instruments like CTA. CTA is a high-energy observatory that will be fully operational in 2024. It will cover an energy range from 20 GeV to 300 TeV, a window suitable to directly observe many energetic phenomena taking place in SNRs. Radio data with SKA, thanks to its sensitivity, can help addressing and refining CTA observations, providing the possibility to study the counterparts of $\gamma$-ray sources in a completely different region of the electromagnetic spectrum.

In this scenario, SNRs are the most interesting Galactic sources that can be studied simultaneously with the SKA and the CTA. In fact, though the hypothesis that SNRs are by far the main contributor of Galactic cosmic rays has gained an enormous consensus among the scientific community (e.g. Bell 2013), a conclusive evidence still lacks (Cristofari *et al.* 2013). In particular it must be proven that SNR shocks are able to accelerate particle with an energy spectrum compatible to what we observe for cosmic rays. The most direct way to link the SNRs to the cosmic rays is $\gamma$-ray observations. In fact, the charged particle constituting the cosmic rays are deflected by magnetic fields and their origin cannot be inferred by their detection. But $\gamma$-rays associated with sites where charged particle are accelerated travel in straight lines and their origin can be reconstructed. However, SNRs are predicted to emit $\gamma$-rays also via inverse Compton scattering of cosmic microwave background photons by relativistic electrons (e.g. Aharonian *et al.* 2008). These two $\gamma$-ray emission mechanisms, referred to as 'hadronic' and 'leptonic' respectively, are concurrent and, so far, it has been difficult to asses which one dominates over the other. SNRs can be the main (or only) source of Galactic cosmic rays only if their $\gamma$-ray emission is dominated by the hadronic process. Otherwise SNRs cannot take into account the measured cosmic ray fluxes and other sources must be searched. It is then fundamental to have a more accurate picture of the acceleration sites and more reliable and extended spectral energy distributions (SEDs) of as many SNRs as possible, and SKA and CTA are the ideal facilities to achieve these goals. The two observatories will provide complementary information on the local conditions and phenomena characterizing each remnants. But they will also be able to observe different aspects of the same feature, concurring to give us the most detailed picture ever on the physics of these celestial objects, especially thanks to their unprecedented resolution and sensitivity.

The best candidate regions for particle acceleration are the filaments, where magnetic field amplification takes place at scales $< 0.1$ pc. SKA-MID will be able to observe in great detail the filamentary structures of the SNRs, achieving a very high resolution and, simultaneously, a very high sensitivity. But it will be also sensitive to large scale structures (up to several arcminutes), providing an extremely accurate picture of these regions of SNRs. Its high resolution will significantly reduce depolarization phenomena occurring when different polarization angles are averaged together because of poor resolution. This prevents the reconstruction of the magnetic field, both in direction and in intensity, heavily affecting studies on the local dynamics of plasma. The other main depolarization agent is the Faraday rotation. Different rotations are produced by different plasma depths, so it is very difficult to estimate its contribution to total depolarization. However, provided enough resolution and a wide observing band, in principle the Faraday rotation can be determined by studying the position angles of polarization vectors at different frequencies (e.g. DeLaney *et al.* 2002). Once these issues will be overcome, radio observations will disclose us the finest details of the plasma interacting with magnetic fields, allowing us to make accurate predictions on particle acceleration location and efficiency.

At lower frequencies, SKA-LOW will observe radio emission from low-energy electrons, those with energies of order of GeV, resulting a mirror of the $\gamma$-ray emission at this energy band. Deviations from the canonical spectral behaviour of synchrotron emission are expected at this very low frequency when the hadronic process dominates over the leptonic one as the origin of $\gamma$-ray emission. In fact in this case radio emission is mainly due to secondary electrons generated in *pp* collisions (Wang *et al.* 2015). An analogue difference in the spectral energy distribution is expected to be observed with the CTA, resulting in an independent test of the same phenomenon.

Therefore the results of the two facilities will have a great impact in answering the open questions on the cosmic ray origins. In order two achieve these goals observations are already planned and included in key science projects of both instruments. For CTA the main possibility for SNR observations will be supplied by the Galactic Plane Survey. Designed to achieve a sensitivity of at least 4.2 mCrab, the survey will observe the entire Galactic plane, using both northern and southern arrays, in about 1600 hours. One of its scientific goal is to provide a census of Galactic SNRs and pulsar wind nebulae. On the other hand, one possibility for the study of SNRs with SKA, already in phase 1, are the so-called ‘generic surveys’, a small number of SKA1 surveys that provide maximum commensality to a wide range of scientific objectives, at an early date. The concept is still under debate among the SKA Scientific Working Groups and among those proposed there is the survey of the Galactic Plane to be conducted with SKA1-MID at band 5 (5 to 14 GHz), with a planned sensitivity of 0.04 mJy/beam and a resolution of 1 arcsec. If conducted, this survey will enable the study of all visible SNRs, likely including many missing ones. Analogue surveys are proposed for SKA1-LOW. In this case, the better *uv* coverage at short spatial frequency will allow a very accurate measurement of the SNR flux density, hence a precise reconstruction of its SED.

## 5. Summary and conclusions

The advent of the SKA and the CTA will allow a great result in a major improvement in the study of Galactic SNRs as sites where cosmic rays are produced. Both radio and

$\gamma$-ray emissions are a probe of the local plasma conditions and provide us insights on the fundamental phenomena resulting in particle acceleration. The work on two Galactic SNRs presented here suggests that high-resolution radio observations, possible with next-generation radio instruments, will be a formidable tool to enlarge the sample of Galactic SNRs that can be studied in great detail. Such an opportunity will be naturally offered by SKA and its precursors. The science preparation phase with these new facilities is currently ongoing and many results will come shortly. In the next future, radio and $\gamma$-ray observatories will provide us a clear portrait of SNRs, better refining their role as cosmic accelerators. In particular with radio and $\gamma$-ray observations we will able to determine if SNRs are indeed the main contributors for Galactic cosmic rays or if other sources must be considered.

## References

Aharonian, F., Buckley, J., Kifune, T., & Sinnis, G. 2008, *RPPh*, 71, 096901

Bell, A. R. 2013, *APh*, 43, 56

Cristofari, P., Gabici, S., Casanova, S., Terrier, R., & Parizot, E. 2013, *MNRAS*, 434, 2748

DeLaney T., Koralesky, B., Rudnick, L., & Dickel, J. R. 2002, *ApJ*, 580, 914

Dubner, G. & Giacani, E. 2015, *A& AR*, 23, 3

Frail, D. A., Goss, W. M., & Slysh, V. I. 1994, *ApJ*, 424, L111

Gaensler, B. M. & Slane, P. O. 2006, *ARAA*, 44, 17

Giacani, E., Smith, M. J. S., Dubner, G., & Loiseau, N. 2011, *A& A*, 531, A138

Green, D. A. 2014, *BASI*, 42, 47

Ingallinera, A., Trigilio, C., Umana, G., Leto, P., Agliozzo, C., & Buemi, C. 2014, *MNRAS*, 445, 4507

Norris, R. P., *et al.* 2011, *PASA*, 28, 215

Riggi, S., *et al.* 2016, *MNRAS*, 460, 1486

Umana, G., *et al.* 2015, *MNRAS*, 454, 902

Wang, L., Cui, X., Zhu, H., & Tian, W. 2015, *PoS: aska.conf*, 64