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New high-frequency radio observations of Cygnus Loop SNR

S. Loru[1], A. Pellizzoni[2], E. Egron[2], S. Righini[3], A. Ingallinera[1], S. Mulas[4], A. Melis[2], R. Concu[2], P. Reich[5], W. Reich[5], G. Umana[1]

[1] INAF, Osservatorio Astrofisico di Catania, Via Santa Sofia 78, I-95123 Catania, Italy
[2] INAF, Osservatorio Astronomico di Cagliari, Via della Scienza 5, 09047 Selargius, Italy
[3] INAF, Istituto di Radio Astronomia di Bologna, Via P. Gobetti 101, 40129 Bologna, Italy
[4] Dipartimento di Fisica, Università degli Studi di Cagliari, SP Monserrato-Sestu, KM 0.7, 09042 Monserrato, Italy
[5]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Abstract

Cygnus Loop is one of the most well-studied middle-aged Supernova Remnants (SNRs). If on one hand its large size ($\sim 4^\circ \times 3^\circ$) makes this SNR particularly well-suited for morphological studies across the entire accessible electro-magnetic spectrum, on the other it involves technical difficulties on the radio observations and related flux density measurements, which are available in literature only up to $\sim$ 5 GHz. With the aim to study the complex morphology of the Cygnus Loop with detailed continuum radio maps at higher frequencies than those available so far, we observed the whole SNR at 8.5 GHz with the Medicina Radio Telescope and the northern-bright filament at 7.0 and 18.7 GHz with the Sardinia Radio Telescope. We studied the integrated spectrum of Cygnus Loop by using our flux density measurement at 8.5 GHz with those available in literature, and we modelled it with a simple synchrotron power-law function. Our measurement rules out any spectral steepening up to high radio frequencies, and it confirms the trend suggested by the Planck data at 30 GHz. We coupled the preliminary measurements related to the northern filament at 7.0, 8.5 and 18.7 GHz in order to study its integrated spectrum. Our data suggest a spectral steepening between around 10 and 20 GHz associated with this peculiar region.

1 Introduction

Thanks to its large size, its location well out of the Galactic plane, and its high brightness ($\sim$210 Jy at 1 GHz), Cygnus Loop is well suited for observations across the entire electromagnetic spectrum. It is a middle-age SNR (estimated age of $1 - 2 \times 10^4$ yr) with a very characteristic morphology: a large northern circular shell and a bubble-like shell located in

the southern part. The radio studies showed substantial differences in the total intensity and magnetic field configuration between these two regions, showing that the northern part of the remnant is governed by the compression of the magnetic field due to the SN explosion shock, while the southern part results most likely from shock acceleration, which is thought to act in young remnants (Green, 1984). These evidences seem to suggest that Cygnus Loop is constituted by two interacting SNRs (Uyanıker et al., 2004). However, this scenario is not supported by the morphological characteristics revealed in a recent multi-wavelength study, which explains the features of the southern shell as the result of the interaction between the remnant's shock and a low-density region, and not as a separate remnant (Fesen et al., 2018). This hypotheses could be supported by the lack of X-ray emission in the region where the interaction between the northern and the southern shells is expected.
Based on the flux density measurements, the integrated radio spectrum of Cygnus Loop is well modelled by a simple power law ($S_\nu \propto \nu^{-\alpha}$) with $\alpha = 0.40 \pm 0.06$ (Sun et al., 2006). Because of its large size and its complex morphology, Cygnus Loop has been investigated in terms of spatially-resolved spectral index studies. These highlighted variations of the spectral indices across the SNR with an upper limit of $\Delta\alpha = 0.2$. In particular, flat spectra were observed in correspondence to the brightest partial shells of the northern shell (NGC 6960 and NGC 6992) and in the southern region. Taking into account the evolutionary stage of Cygnus Loop, a synchrotron spectral break could be expected at high radio frequencies, and sensitive maps above ∼5 GHz could be crucial to investigate on this respect.
Despite this scientific interest, sensitive flux density measurements are missing at frequencies $\gtrsim$ 5 GHz, due to the technical difficulties in performing radio continuum observations of this SNR. The lack of high-frequencies radio measurements is common to almost all large and complex SNRs. The single-dish telescopes can perform this kind of observations at high frequencies, but a high sensitivity and baseline stability of the receiving system are required (Sun et al., 2006). In this context, we carried out a program dedicated to the observation of SNRs (PI: Pellizzoni) during the first Early science phase of the Sardinia Radio Telescope (SRT). We performed with SRT accurate maps of these SNRs at the three central frequencies of 1.55, 7.0, 21.4 GHz (Egron et al. 2017, Loru et al. 2019) in order to investigate the integrated spectra of the evolved SNRs W44 and IC443, and to perform spatially-resolved spectral measurements in the 1.5−7.0 GHz frequency range. Our studies revealed significant frequency- and region-dependent spectral slope variations for both sources. We observed, for the first time, a synchrotron spectral break in W44 at a frequency of 15±2 GHz. Assuming a magnetic field in the range 18−90 μG, as expected by the compression theory of the ISM magnetic field, this result provides a direct estimate for the maximum energy of accelerated CR electrons in the 6−13 GeV range, which is consistent with indirect evidence from γ-ray observations. The same study performed on IC443 showed the consistence of the SRT data with the spectral model that includes the spinning dust emission. In particular, our flux density measurement at 21.4 GHz independently supports the characteristic spectral dust emission bump in the frequency range 20−70 GHz (Onić et al., 2017), and confirms the trend suggested by the low-resolution Planck measurement at 30 GHz (Planck Collaboration et al., 2016). In view of these results in the context of single-dish imaging of extended sources, we considered Cygnus Loop a challenging and very interesting target to observe with the Italian radio telescopes. With this aim, we observed Cygnus Loop with the Medicina radio telescope

at 8.5 GHz during a dedicated observing project in 2017. We exploited the obtained map in order to obtain a sensitive flux density that is crucial to investigate a possible steepening in the integrated spectrum and to test the energy distribution of the particles accelerated in this SNR.
We also included Cygnus Loop in our 2018 observing project with SRT. The project is focused on the high-frequency and polarimetric comparative investigations on a wider sample of middle-aged and young SNRs in order to perform a precise modelling of the region-dependent continuum spectral indices and to disentangle magnetic enhancement processes from spectral variation contributions. Spectro-polarimetric observations have been performed with SRT at 7.0 GHz and in the range 18.6−24.5 GHz on two interesting regions of Cygnus Loop: the northern-bright filament (NGC 6992) and the southern shell. These observations are crucial to study region-dependent variations on spectral indices and polarisation properties, which are attributable to different acceleration mechanisms acting in these regions.

2 Observations and results

We observed Cygnus Loop with the Medicina Radio Telescope at the central frequency of 8.5 GHz between June and August 2017 (Project 14-17, PI S. Loru), for a total observing time of 80 hours. We carried out the mapping through On-The-Fly (OTF) single-dish imaging along RA and Dec. directions, by setting a bandwidth of 680 MHz during the first half of observing time and 250 MHz for the rest of the time. All the observations were performed with a speed of 4 arcmin/s, a sampling time of 20 ms and a single scan per HPBW (corresponding to $2.77'$). The total map size of $5° \times 6°$ includes the extra length/duration free from significant source contribution that is required for properly identify and subtract the baseline component. As result, we acquired 16 complete maps (RA+Dec.) that we merged in order to obtain the final map showed in Fig.1(*left*). This map is characterised by ∼240 samples per beam and a resolution of $4.8'$. We considered an elliptic extraction region centred in (RA, Dec.)=(20^h 51^m 39.058^s, $+30°$ $34'$ $45.40''$) and with semi-major and semi-minor axis of ∼2.2° and ∼1.8°, respectively, in order to calculate a flux density of 54±4 Jy.
In view of the results obtained with the Medicina radio telescope, we decided to independently investigate the emission of the two shells of Cygnus Loop. In particular we focused on the northern-bright filament and the southern shell. With this aim, we included Cygnus Loop in our 2018 observing project with SRT (2018 December-2019 May, Project 22-18, PI A. Pellizzoni) that was dedicated to the high-frequency and polarimetric observations of SNRs in $C-$band (7.0 GHz) and $K-$band (18.6−24.6 GHz). In this work, we present the preliminary results of the observations that we performed with SRT on the northern bright filament at the central frequencies of 7.0 GHz and 18.7 GHz. We performed the observations both in $C-$ and $K-$band with the maximum bandwidth available of 1.2 GHz, and the data were recorded by using the spectro-polarimetric back-end SARDARA (Melis et al., 2018) in full-stokes mode with 1024 spectral channels. For each band, we carried out OTF maps of NGC 6992 characterised by a size of $1.9° \times 1.9°$ (RA) and $1.3° \times 2.5°$ (Dec.), by setting a scanning speed of 5 arcmin/sec and a sampling time of 20 ms. Two consecutive $C-$band scans were separated by an offset of 0.01°, which implies that 4 passages were carried out per beam

on average, and about 27 samples beam^{-1} scan^{-1} were taken (taking into account that the beam size is 2.77′). The same offset was adopted for the $K-$band observations, implying in this case one passage per beam. The SRT $K-$band receiver is characterised by a 7−feed configuration, which allowed us to increase the mapping speed and then to efficiently mitigate the effects of temporal atmospheric opacity variations on the image quality (Navarrini et al., 2016). Our observations at 18.7 GHz were carried out with the $K-$band receiver in the "Best Space Coverage" configuration. This specific geometry over the whole acquisition provides a full coverage of the scanned area, carrying out for each receiver scan, 7 simultaneous, equally-spaced (spacing ∼0.86′) OTF scans for both polarisation channels. We spent ∼3.3 hours in order to carry out a complete map (RA+Dec.) of NGC 6992 both at 7.0 and 18.7 GHz. In Fig.2(*Top*), we show the preliminary images related to the calibrated maps of the nothern-filament obtained with SRT at 7.0 GHz and 18.7 GHz with a resolution of 2.7′ and 1′, respectively. In Fig.2(*Bottom-left*), we also compare the SRT map at 7.0 GHz with that obtained at 8.5 GHz with the Medicina Radio Telescope in order to clarify the SRT observing strategy and to evaluate the possible consistence of the filament's emission at the two frequencies. It is worth noting that the filament is well-detected with SRT both in $C-$ and $K-$band. We considered polygonal regions closely fitting the filament at the three frequencies of 7.0, 8.5 and 18.7 GHz in order to estimate the related flux densities.

3 Discussion and future perspectives

We coupled the sensitive flux density measurement associated with our map of Cygnus Loop at 8.5 GHz (Fig.1) with those available in the literature in order to study the integrated spectrum of Cygnus Loop. We used a simple synchrotron power-law function in order to model the integrated spectrum. The resulting spectral energy distribution is shown in Fig.1 (*right*), where it can be noticed that our measurement rules out any spectral steepening up to high radio frequencies, and it confirms the trend suggested by the Planck data at 30 GHz. Furthermore, the spectral index value obtained from the fit is consistent with the values reported in the previous studies by considering flux densities measurements up to 5 GHz.
In order to get information about the spectral behaviour of the northern filament, we coupled the preliminary flux density measurements associated with our maps at 7.0, 8.5 and 18.7 GHz. The integrated spectrum is shown in Fig.2(*Bottom-right*). Our data suggest a spectral steepening between around 10 and 20 GHz. This preliminary result is very important because it could provide a constrain on the maximum energy of the particles accelerated in this peculiar region of Cygnus Loop, where blast waves are thought that encounter molecular material. Indeed, from the γ-ray observations, a break in the particle energy spectrum is expected in the range of 1−10 GeV, but a more accurate determination of this energy from radio observations could be crucial to understand the nature of the shock and the particle acceleration mechanisms in this region.
The high-frequency radio observations allow us to assess the maximum energy of CRs accelerated in the evolved and complex SNRs like Cygnus Loop. Our aim for the future is to exploit the spectro-polarimetric data carried out during our observing project with SRT in order to complete the study of the integrated spectrum of the filament NGC 6992, and

to introduce the characterisation of its magnetic field configuration. The same work could be performed by using the data related to the southern shell of Cygnus Loop in order to investigate on possible differences on the particle acceleration mechanisms and magnetic field conditions (amplification/compression) between these interesting regions.

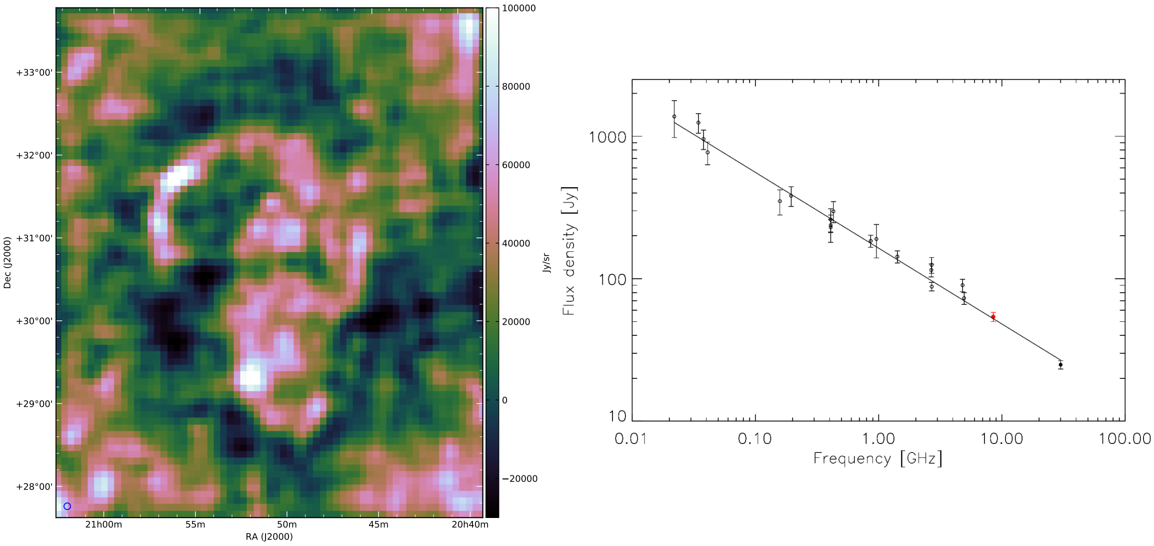

Figure 1: *Left*: map of Cygnus Loop SNR obtained with the Medicina radio telescope at 8.5 GHz. The pixel size is of 4.8′. The beam size is indicated by the green circle in the bottom left corner. *Right*: Weighted least-squares fit applied to the spectral energy distribution (SED) of Cygnus Loop for the synchrotron power-law model. The red and the black filled diamonds correspond respectively to the SRT point at 8.5 GHz and the *Planck* data.

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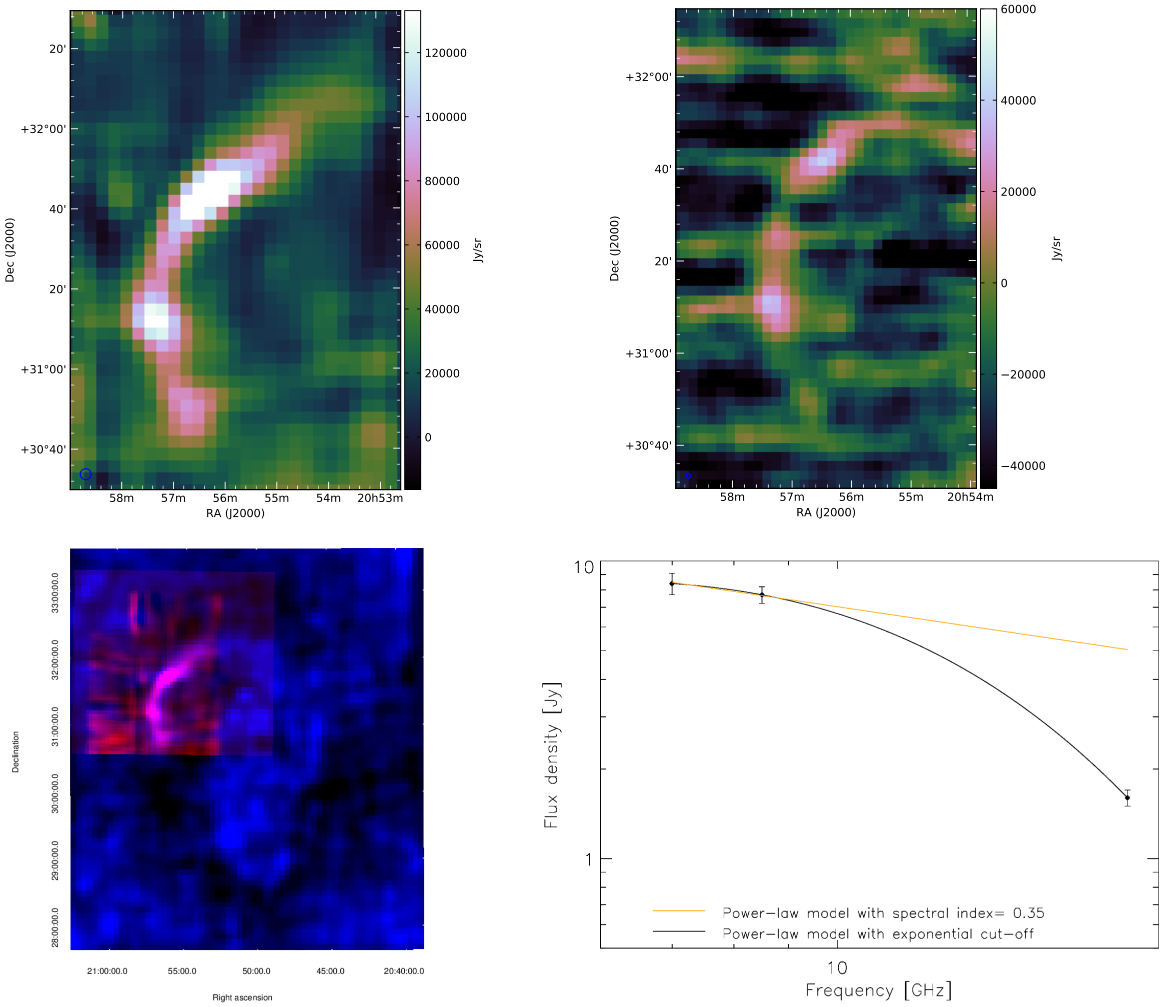

Figure 2: *Top*: image of the northern-bright filament of Cygnus Loop carried out with SRT at 7 GHz (*Left*) and 18.7 GHz (*Right*) with a resolution of 2.7′ and 1′, respectively. *Bottom*: RGB image of Cygnus Loop obtained from the Medicina data at 8.5 GHz (blue) and SRT data (red) at 7.0 GHz (*Left*). SED of the northern-bright filament related to our flux density measurements at 7.0, 8.5 and 18.7 GHz (*Right*). The black line indicates the weighted least-squares fit applied to the SED for a synchrotron power-law with an exponential cut-off model, while the orange line is obtained from the fit for a synchrotron power-law model with spectral index set on the value reported in literature of 0.35.