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EMISSION NEBULAE: STRUCTURE AND EVOLUTION – A BRIEF REVIEW OF THE RESULTS

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Abstract. We describe in this paper some of the most important results achieved by the researchers who participate in the project "Emission nebulae: structure and evolution", financed by the Ministry of Education, Science, and Technological Development of the Republic of Serbia. Most of these results pertain to the radio and hydrodynamical evolution of the supernova remnants (SNRs), to the appearance of their radio-spectra in continuum, to the computation of the equipartition of the energy density of the magnetic field and of the energy density of the ultra-relativistic particles and to the optical detection of emission nebulae in nearby galaxies. In addition, we also present the results of other very interesting and important research, more or less connected to the process of charged particle acceleration at collisionless shocks in Space.

1. INTRODUCTION

Since its beginning, the project "Emission nebulae: structure and evolution", that is supported by the Ministry of Education, Science, and Technological Development of the Republic of Serbia, has gathered researchers from several different institutions: the Department of Astronomy at the Faculty of Mathematics of Belgrade University, the Astronomical Observatory of Belgrade, and the Physics Department at the Faculty of Sciences of the University of Novi Sad. Our group consists of the following members: Dejan Urošević (project principal investigator), Bojan Arbutina, Dragana Ilić, Tijana Prodanović, Branislav Vukotić, Dušan Onić, Milica Vučetić (maiden name Andjelić), Aleksandra Ćiprijanović, Marko Pavlović, Vladimir Zeković, Jovana Petrović and Petar Kostić. In addition, some of our dear foreign associates are M. Filipović (Western Sydney University), T. G. Pannuti (Department of Earth and Space Sciences, Space Science Center, Morehead State University, USA), D. Leahy (Department of Physics and Astronomy, University of Calgary, Canada), O. Salvatore (INAF Osservatorio Astronomico di Palermo), K. Stavrev and N. Petrov (National Astronomical Observatory Rozhen, Institute of Astronomy, Bulgarian Academy of Science, Bulgaria), Ü. D. Göker and E. N. Ercan (Department of Physics, Boğaziçi University, Turkey), I. Bojičić (Department of Physics, Macquarie University, Sydney), A. Moiseev and A. Smirnova (Special Astrophysical Observatory of the Russian Academy of Science), O. Egorov (Department of Radioastronomy, Lomonosov Moscow State University, Moscow), G. Zaharijaš (University of Nova Gorica), B. D. Fields (University of Illinois at Urbana-Champaign), V. Pavlidou (University of Crete), J. Beacom (Ohio State University), and many others.

The theoretical research, as well as the results obtained by the observations conducted by astronomers from our project and in cooperation with fellow colleagues from several different institutions from abroad, are mainly focused on emission nebulae, particularly on SNRs. This paper reviews some of the recent results of our investigations.

2. SUPERNOVA REMNANTS AS PARTICLE ACCELERATORS

Supernova remnants are formed after the so-called supernova explosion. In fact, a strong collisionless shock wave is created ahead of the ejected material from the supernova explosion. SNRs strongly influence the interstellar medium (ISM) through which they expand. On the other hand, the ISM has a great impact on their evolution. These spectacular objects are the most powerful Galactic sources of electromagnetic radiation (prominent at low as well as at high frequencies). A forward shock that spreads through the ISM, the compressed ISM and ejecta, the reverse shock, and in some cases pulsar and its wind nebula (plerion), are all sometimes visible, in the case of a relatively young remnant.

SNRs are responsible for the creation of cosmic-rays, so that they represent the most efficient particle accelerators in our galaxy, as well as in other galaxies throughout the Space (see e.g. Urošević 2014 for a review). Particles that repeatedly cross the powerful shock front (that moves through the ISM) can gain energy via the so-called first-order Fermi mechanism or diffusive shock acceleration (DSA) process (Fermi 1949; Bell 1978a,b; Blandford & Ostriker 1978; Reynolds, Gaensler, & Bocchino 2012). This is the most probable and efficient mechanism for a production of high energy particle ensemble in SNRs. It actually produces the non-thermal ensemble of charged particles which in the simplest test-particle case has a power-law energy distribution. The particle energy spectral index, derived from the theory is in a good accordance with the observations. It seems that SNRs are efficient particle accelerators possibly up to the so-called knee in the cosmic-ray particle spectrum.

2. 1. RADIO CONTINUUM EMISSION FROM SUPERNOVA REMNANTS

Whenever there are ultra-relativistic charged particles moving in the external global magnetic field we can expect a production of synchrotron radiation. In that sense, the radio-continuum spectra of SNRs are generally mainly shaped by the (non-thermal) synchrotron emission. For a standard value of the mean Galactic magnetic field (order of μG), GeV electrons are responsible for the observed synchrotron emission at higher radio-frequencies, and TeV electrons for X-rays.

The analysis of the integrated radio up to microwave continuum of SNRs is very important as any possible deviations from the known theoretical predictions can give us new insights into physics behind the observed radiation. Observational verification of several different theoretical models (such as non-linear particle acceleration effects in young SNRs, questions related to the significant intrinsic thermal bremsstrahlung emission from the SNRs expanding in a dense environment of molecular clouds, contribution of different dust emission processes linked to the SNRs, etc) rely on a good quality (reliable flux density estimates at so much as possible different continuum frequencies) of the high-frequency part of the radio, as well as the microwave continuum of SNRs (see the following papers for more details: Onić et al. 2012; Onić 2013; Onić 2015; Onić & Urošević 2015; Onić, Urošević, & Leahy 2017). This is connected with serious observational problems due to the transparency issues regarding the Earth's atmosphere. Recent observations of the microwave sky by the space telescopes such as *Wilkinson Microwave Anisotropy Probe* and *Planck Space Telescope* have opened a new window into the analysis of continuum emission from the SNRs.

For example, in the case of young SNRs, we expect that the effects of the non-linear DSA process can cause a concave up synchrotron spectrum (Reynolds & Ellison 1992; Jones et al. 2003; de Looze et al. 2017). Actually, a non-linear DSA theory predicts that the particle energy spectrum steepens at low energies and flattens at higher energies. To that end, we have analyzed the radio to microwave continuum emission of famous SNR Cas A. The results of this analysis show that the shape of the known spectrum of Cas A is very well represented by a simple model that includes the effects of the (non-linear DSA) synchrotron curvature, as well as of the thermal absorption at lowest radio-frequencies, and a simple, one-component thermal dust emission at the highest continuum microwave-frequencies (see Onić & Urošević 2015 for details).

Another example is related to the group of SNRs with flat radio-spectral indices. Generally, there are several possible explanations for such a flat radio-continuum spectra: significant imprints of the Fermi II (stochastic) acceleration mechanism, contribution of the secondary electrons left over from the decay of charged pions (if an SNR is interacting with a molecular cloud environment), simple thermal contamination, the intrinsic thermal bremsstrahlung radiation from the SNRs (see Schlickeiser & Fürst 1989; Ostrowski 1999; Uchiyama et al. 2010; Onić 2013 for more details about these explanations).

In Figure 1, the radio to microwave continuum of the mixed-morphology (Rho & Petre 1998) SNR IC 443 is shown. The thermal absorption, that is linked to the SNR (see Castelletti et al. 2011 for more details) is behind the low-frequency turnover. The results of the analysis also show that the thermal dust emission, as well as the apparent bump, possibly due to the spinning dust emission, very well explain the SNR's radiation in the analyzed frequency range (see Onić et al. 2017 for a detailed discussion; but see also Egron et al. 2017, for an alternative description).

Finally, we would also like to stress the importance of furthering our understanding of the dynamics and emission processes from the mixed-morphology SNRs, in general.

2. 2. EQUIPARTITION CALCULATION

It is apparent that magnetic field plays an important part in various related phenomena in ISM (collisionless shock-formation and compression, particle acceleration, radiation, etc). Each of the four forms of ISM (thermalized particles, cosmic-rays, radiation, and the magnetic field) contain similar energy density of about 1 eV cm^{-3} in the vicinity of the Sun. The determination of the magnetic field strength in the ISM is one of the most complicated tasks of modern astrophysics. In fact, only a few methods, that are very limited in their applicabilities, have been proposed so far.

Apart from the Zeeman effect and the so-called Faraday rotation, the equipartition or minimum energy calculation is a widespread method for estimating magnetic field strength and energy contained in the magnetic field and cosmic-rays by using only the radio-synchrotron emission of the, particular source (Pacholczyk 1970; Duric 1990; Govoni & Feretti 2004; Beck & Krause 2005). It should be noted that the

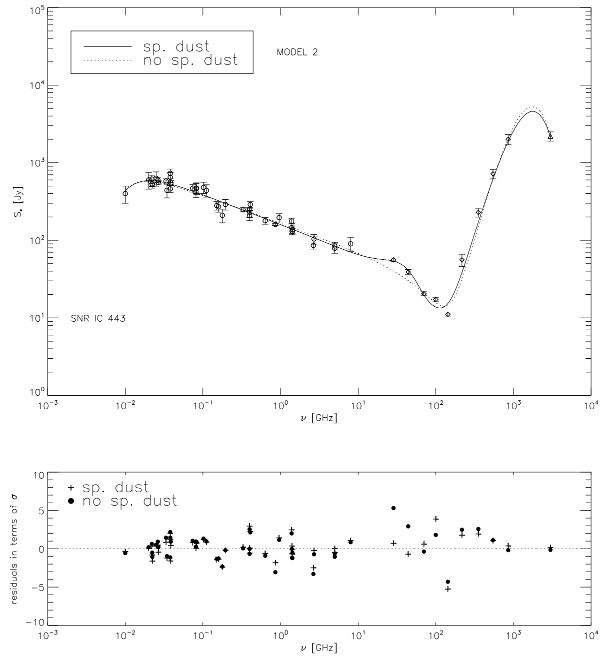

Figure 1: The weighted least-squares fit to the known, radio to microwave continuum, of the SNR IC 443 (taken from Onić et al. 2017). Solid line represents the fit when the so-called spinning dust emission is included in the model, while dashed line correspond to the fit without spinning dust emission, made for a comparison.

assumption of equipartition (constancy in order of magnitude) between the energy density of cosmic-rays and the energy density of magnetic field is, actually equivalent to the minimum energy requirement. Despite its approximate character, this method remains a useful tool, especially when there are no other estimates of a magnetic field.

Incorporating the theory of DSA process, a newly modified equipartition calculation for estimating magnetic field strengths and energetics in SNRs, with spectral indices in [0.5, 1] range is derived by our group (see Arbutina et al. 2012,2013 for a thorough description of a model and its application). In addition, the web application for calculation of the magnetic field strengths and energetics in the SNRs is created and is available for free usage[1].

2. 3. SIMULATIONS

The physical justification of the equipartition between the energy density of cosmic-rays and the energy density of magnetic field is usually questioned. On the other hand, the new results of our group, based on the 3D hydrodynamic simulations of SNR evo-

[1] Available at `http://poincare.matf.bg.ac.rs/~arbo/eqp/`.

lution, coupled with a non-linear DSA model of particle acceleration and accompanied magnetic field amplification (MFA), seems to suggest, that (equi)partition between cosmic-rays and magnetic fields really does exist, in all but the youngest SNRs (see Urošević, Pavlović & Arbutina 2017 for much more details).

Our simulations also provide the evidence that evolved SNRs, at the end of the Sedov phase of evolution, especially those embedded in a rarefied ambient medium, can maintain equipartition similar to those in the ISM (see Figure 2). In that sense, SNRs are likely responsible for maintaining the known equipartition between cosmic-rays and magnetic fields in the ISM. In addition, we can say that the equipartition is a physically justified assumption especially between the cosmic-ray electrons and the magnetic fields in evolved SNRs, in the Sedov phase of evolution. In that sense, the equipartition between the electron component of cosmic-rays and magnetic field can be used for calculation of the magnetic field strength directly from observations of synchrotron emission from SNRs.

In Figure 2, the results of our simulations, for two representative SNRs, one expanding in the high-density environment (HB 3), and another spreading in the rarefied medium (G1.9+0.3), are presented. In our future work, we will extend the analysis to a much larger sample of SNRs.

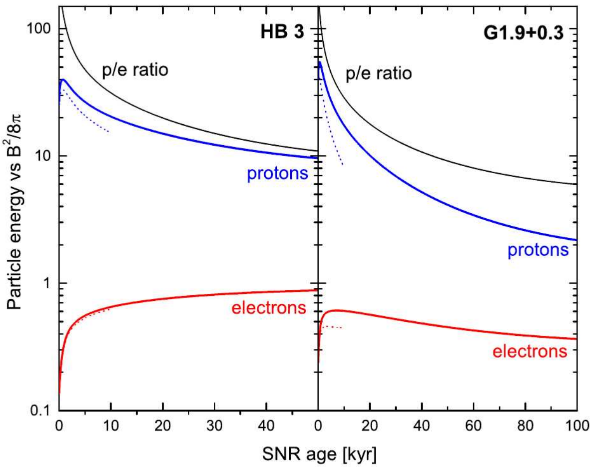

Figure 2: Temporal evolution of the ratio between cosmic-ray proton (electron) kinetic energy density and magnetic field energy density at the SNR shock front, represented with thick blue (red) lines. Dotted lines represent previous ratios in the case when Alfén drift is included in numerical model. Simulation parameters are carefully tuned to reproduce current observational properties of the two particular SNRs, namely SNR HB 3, evolving in dense medium and the youngest known Galactic SNR G1.9+0.3, evolving in a rarefied medium. We also give the ratios between proton and electron kinetic energy densities during the lives of the SNRs (thin black line).

In addition, the radio evolution of the youngest known Galactic SNR G1.9+0.3 is investigated by using the 3D hydrodynamic modeling and non-linear kinetic theory of cosmic-ray acceleration in SNRs (see Pavlović 2017 for much more details). The current age of the SNR is estimated to be slightly over 120 yr. It expands in an ambient medium of number density of around 0.02 cm^{-3}. Our numerical model predicts increasing radio-emission from the SNR during the free expansion phase, reaching its maximum value around the age of 600 yr, and then decreasing during late free expansion and in the beginning of Sedov phase. Interestingly, it seems that we are currently witnessing approximately the fastest radio-emission increase than it will ever be. In addition, the steep radio-spectral index (steeper than linear DSA theory prediction of 0.5) for this, young SNR is explained only by the means of efficient non-linear DSA process and accompanying strong MFA. Finally, in a light of a new γ-ray observatories, we show that it may be visible in TeV γ-rays by future instruments including the *Cherenkov Telescope Array*.

3. COLLISIONLESS SHOCKS AS PARTICLE ACCELERATORS

Collisionless shock waves are very important phenomena as they represent the places of a particle acceleration in Space. The SNRs are linked to the collisionless shock waves that expand through the ISM. The formation of such a shock wave, particle acceleration and magnetic field amplification are coupled processes and we do not fully understand the physics behind these phenomena yet (Nikolić et al. 2013). Our group is interested in these issues, particularly in possible resonant microinstabilities that trigger such colissionless shock-formation and evolution (Zeković 2017).

We are not just interested in the SNRs but also in some other, more exotic candidates for significant particle acceleration sights in the Universe. These include the so called tidal cosmic-ray population, formed by the tidal shock waves that result from the galactic interactions. Furthermore, the existence of hypothetical structure-formation cosmic-rays, produced by the large-scale accretion shocks during the process of large-scale structure-formation is also part of our research (see Fields, Pavlidou & Prodanović 2010; Prodanović, Bogdanović & Urošević 2013 for more details).

Galactic interactions and mergers have been known to give rise to the tidal shocks and disrupt morphologies especially in the smaller of the interacting components. These shocks can also heat the gas and dust and will inevitably accelerate charged particles and result in a so-called tidal cosmic-ray population, in addition to standard galactic cosmic-rays. Both, tidal heating and additional non-thermal radiation will affect the so-called far-infrared (FIR) to radio correlation of these systems (a well-established empirical connection between a continuum radio and dust emission of star-forming galaxies, that is often used as a tool in determining star-formation rates). We were interested to check the hypothesis that the FIR-radio correlation is not stable in interacting galaxies, but rather evolves as the interaction/merger progresses. From the analysis of a sample of 43 infrared bright star-forming interacting galaxies at different merger stages, we have found that the FIR-radio correlation parameter and radio-emission spectral index vary noticeably over different merger stages and behave as it would be expected from our hypothesis (see Donevski & Prodanović 2015 for much more details).

We would also like to mention that our researchers are involved in some other investigations that will not be further elaborated here (see Dobardžić & Prodanović 2014,2015; Ćiprijanović 2016,...). For instance, some of them include very interesting topics in γ-ray astronomy, as well as in nucleosynthesis of light, primordial, elements

(D, Li) (that is part of the COST action project ChETEC – Chemical Elements as Tracers of the Evolution of the Cosmos).

4. $\Sigma - D$ RELATIONS AND RADIO OBSERVATIONS OF SUPERNOVA REMNANTS AND PLANETARY NEBULAE

From the very beginning of our project, we have been interested in the study of the theoretical and empirical radio $\Sigma - D$ relations for the SNRs. This research is important for understanding the evolution of the synchrotron radiation from SNRs and related phenomena occurring at collisionless shock waves. Additionally, this kind of a relation is often used for determining distances to SNRs in the Milky Way (Shklovsky 1960).

The $\Sigma - D$ relation depends on different properties of the supernova explosion (the explosion energy, mass of the ejected matter), as well as on the properties of the the ISM (density, magnetic field strength, etc). One of the main drawbacks of this relation is the severe data scatter, that basically occurs due to the spread in the relevant parameters, in addition to the measurement uncertainties and selection effects.

We have applied a robust analysis of the collected data sample for the calibration of empirical radio $\Sigma - D$ relation, with various fitting methods. Our Monte Carlo simulations verified that the slopes of the empirical $\Sigma - D$ relation should be determined by using the so-called orthogonal regression, because of its good performances for data sets with severe scatter (see Urošević et al. 2010; Pavlović et al 2013,2014; Bozzetto et al. 2017 for more details).

The random resampling for reconstruction of the probability density function (PDF) of ($\Sigma - D$ relation) calibration data points in the fitting plane was also applied by our researchers. The resulting PDF can be used to estimate distance-related properties. This PDF-based method for calibration can provide more accurate and more reliable calculations than those obtained by standard linear fitting procedures (see Vukotić et al. 2014 about this new PDF-based method for distance calibration without using standard fitting procedures).

Furthermore, we have analyzed the impact of ISM structure on the slope of the radio $\Sigma - D$ relation assuming the fractal ISM structure. It has been found that the empirical radio $\Sigma - D$ slopes, being steeper than the ones derived from theory, might be partly explained with the fractal structure of the ambient medium into which the SNRs expand (see Kostić et al. 2016 for more details).

The $\Sigma - D$ relation for the SNRs, as a useful distance determination tool, can be significantly improved if the radio-evolution is better understood. Numerical simulations should provide a better understanding of underlying physics and explanation of the observed statistical properties (see Pavlović et al. 2017 for a detailed discussion and new results).

In addition to the $\Sigma - D$ relation for the SNRs, we were also interested in the theoretical and empirical radio $\Sigma - D$ relation for planetary nebulae. We have derived both theoretical and calibrated the empirical $\Sigma - D$ relation for different samples of planetary nebulae (see Urošević et al. 2009; Vukotić et al. 2009,2014; Leverenz at al. 2017 for more details).

Finally, we participate in the overall, detailed theoretical interpretation of the particular observations of the emission nebulae (i.e. from the Magellanic clouds and from our own galaxy), which are performed by our colleagues from the Western Sydney University in Australia. The analysis of the shape of the radio-continuum spectrum and position of the SNR in the so-called $\Sigma - D$ diagram, complemented with the calculation of the magnetic field strength, enables us to determine the evolutionary status of a remnant (see also Payne et al. 2008; de Horta et al. 2012; Bozzetto et al. 2012a,b; de Horta et al. 2013; Bozzetto et al. 2013, 2014a,b; Crawford et al. 2014).

5. OPTICAL OBSERVATIONS OF EMISSION NEBULAE IN NEARBY GALAXIES

The researchers from our project are also interested in the optical observations of the emission nebulae in the nearby galaxies (such as the nearby spiral galaxy IC 342, Holmberg IX dwarf galaxy, dwarf galaxy NGC 3077, elliptical galaxy NGC 185, etc). The most of our observations were conducted by the 2m RCC-telescope at the National Astronomical Observatory (NAO) Rozhen in Bulgaria. Furthermore, members of our group participate in a joint project of the Serbian Academy of Sciences and Arts and the Bulgarian Academy of Sciences called "Optical search for supernova remnants and H II regions in nearby galaxies (M81 group and IC 342)". In addition, we are also engaged in the collaboration with colleagues from Turkey, regarding the observations of galaxies NGC 1569, NGC 6946, IC 1613 with 1.5m telescope of Tübitak National Observatory. Our plans, for the near future, include the observations by the so-called Milanković telescope at the Astronomical Station Vidojevica in Serbia. Finally, we have recently participated in the long slit spectroscopic observations of emission nebulae in NGC 185 with our Russian colleagues, as a complement to our previous photometric observations. The observations were conducted using the 6m telescope of Special Astrophysical Observatory of the Russian Academy of Sciences.

The actual search for new SNRs and H II regions (candidates) is often based on the analysis of optical observations with narrow band [S II] and Hα filters (see Arbutina et al. 2009; Andjelić 2011; Andjelić et al. 2011; Vučetić et al. 2013, 2015b for a thorough discussion). It is known that optical spectra of SNRs have elevated [S II] to Hα emission line ratios, as compared to the spectra of normal H II regions (Matonick & Fesen 1997; Blair & Long 2004). This emission ratio has been used to differentiate between shock heated SNRs (collisional excitation inducted by shocks) and photoionized nebulae. Of course, the Balmer-dominated SNRs, which are thought to be related to type Ia supernovae, will be missed by optical searches using this [S II]/Hα criterion.

As the star-formation in nearby galaxies can be mapped at high-resolution, even with small telescopes, besides the identification of new emission nebulae, we are interested in the star-formation rates (SFRs), derived from Hα flux. It is very important to eliminate Hα flux contaminants when calculating SFRs from Hα emission. We have analyzed the contribution of the Hα flux from the SNRs to the total Hα flux and its influence on the derived SFR. The average SNR contamination to the total Hα flux and derived SFRs for a particular set of nearby galaxies (18 of 25 galaxies with optically detected SNRs, excluding the Milky Way) was found to be around 5% (see Vučetić et al. 2015a for more details). Due to the observational selection effects, the SNR contamination of SFRs obtained represents only a lower limit.

6. CONCLUSIONS

As we have already mentioned earlier, the researchers participating in the project "Emission nebulae: structure and evolution", supported by the Ministry of Education, Science, and Technological Development of the Republic of Serbia, have achieved many interesting results related to different phenomena in the ISM of Milky Way and nearby galaxies, and to processes of particle acceleration at collisionless shocks in Space. We plan to continue our ongoing research and to extend the list of our existing collaborators in the future.

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