Serb. Astron. J. № 170 (2005), 101 - 110 UDC 524.354–77 : 524.7NGC4214NGC4395
Preliminary report

A SEARCH FOR CANDIDATE RADIO SUPERNOVA REMNANTS IN THE NEARBY IRREGULAR STARBURST GALAXIES NGC 4214 AND NGC 4395

B. Vukotić[1], I. Bojičić[1], T. G. Pannuti[2] and D. Urošević[1]

[1]*Department of Astronomy, Faculty of Mathematics, University of Belgrade Studentski trg 16, 11000 Belgrade, Serbia and Montenegro*

[2]*Spitzer Science Center, California Institute of Technology MS 220-6, Pasadena, CA 91125, USA*

(Received: September 15, 2003; Accepted: April 18, 2005)

SUMMARY: We present the results of a search for new candidate radio supernova remnants (SNRs) in the nearby starburst irregular galaxies NGC 4214 and NGC 4395 using archived radio observations made with the Very Large Array (VLA) at the wavelengths of 3.5 cm, 6 cm and 20 cm for NGC 4214 and 6 cm and 20 cm for NGC 4395. These observations were analyzed as part of our ongoing search for candidate radio SNRs in nearby galaxies: the goal of this search is to prepare a large sample of candidate radio SNRs for the purpose of a robust statistical study of the properties of these sources. Based on our analysis, we have confirmed the non-thermal nature of the discrete radio sources α and β in NGC 4214 and classify these sources as candidate radio SNRs based on their positional coincidences with HII regions in that galaxy. We have measured the flux densities of the two candidate radio SNRs at each wavelength and calculated corresponding spectral indices: we have also measured flux densities of two other discrete radio sources in these galaxies – ρ in NGC 4214 and #3 in NGC 4395 – which we suspect to be additional candidate radio SNRs based on their positional coincidences with other HII regions in these galaxies. However, the radio data presently available for these sources cannot confirm such a classification and additional observations are needed. We have also calculated the radio luminosities $L_{\rm radio}$ at the wavelength of 20 cm for these two candidate radio SNRs as well as the corresponding values for the minimum total energy $E_{\rm min}$ required to power these radio sources via synchrotron emission and the corresponding magnetic field strength $B_{\rm min}$. We have compared our mean calculated values for these properties with the mean values for populations of candidate radio SNRs in other starburst galaxies: while the values for $L_{\rm radio}$ and $B_{\rm min}$ are roughly comparable to the values seen in other starburst galaxies, the mean value for $E_{\rm min}$ is higher than the mean value of any other starburst galaxy. Finally, we include these two candidate radio SNRs in a discussion of the $\Sigma - D$ relation for extragalactic candidate radio SNRs and find that these sources are located on the shallower end of the master $\Sigma - D$ relation for all extragalactic SNRs as derived by Urošević et al. (2005).

Key words. galaxies: individual (NGC 4214, NGC 4395) – galaxies: ISM – galaxies: spiral – galaxies: starburst – radio continuum: galaxies – ISM: supernova remnants

1. INTRODUCTION

Radio observations of nearby galaxies have been successful in detecting and identifying a large number of candidate radio supernova remnants (SNRs) in nearby galaxies (Urošević et al. 2005). Based on published results of radio searches for these sources, over 220 candidate radio SNRs are currently known to exist in thirteen spiral and irregular galaxies located within 15 Mpc of the Galaxy (Pannuti et al. 2005, in preparation): in fact, the size of this sample is now comparable to the number of known Galactic radio SNRs (231 – Green 2004). This sample of known extragalactic candidate radio SNRs is well-suited for a thorough study of radio SNR properties in a manner which addresses known deficiencies of the sample of Galactic radio SNRs.

For example, distances to the large majority of the known Galactic radio SNRs are poorly known, and associated with these distance uncertainties are considerable uncertainties in the sizes and ages of these SNRs. In contrast, distance uncertainties to extragalactic SNRs may be reduced to uncertainties in the distance to the host galaxy. Through continued searches for extragalactic candidate radio SNRs – especially when new galaxies are considered and more sensitive observations are used – the number of known extragalactic candidate radio SNRs is certain to increase, and statistical studies of these sources will become more robust.

One remarkable result from these searches for extragalactic candidate radio SNRs is the discovery of numerous sources with radio luminosities which rival or even exceed the luminosity of the most radio-luminous Galactic radio SNR, Cas A. These extremely luminous candidate radio SNRs are generally found in spiral or irregular galaxies which are currently experiencing starburst activity: these galaxies include NGC 1569 (Greve et al. 2002), NGC 2146 (Tarchi et al. 2000), NGC 4258 (M106) (Hyman et al. 2001), NGC 4736 (M94) (Duric and Dittmar 1988), NGC 6946 (Lacey et al. 1997, Lacey and Duric 2001) and NGC 7793 (Pannuti et al. 2002). In addition to their enhanced radio luminosities, in some cases the estimates for the minimum total amount of energy required to power these radio sources via synchrotron emission exceed 10^{51} ergs, the canonical value for the mechanical energy associated with supernovae. To explain such a high energy phenomena, some authors (Paczyński 1998, Wang 1999) have invoked a model of a particularly luminous supernova known as a "hypernova," while others have suggested that these sources may be associated with gamma-ray bursts. There may also be an association between the rate of star formation for a galaxy (starburst or quiescent) and the number of luminous radio SNRs resident in that galaxy. The true nature of these sources and their relationship to the evolutionary state of their parent galaxy remains uncertain and the subject of debate.

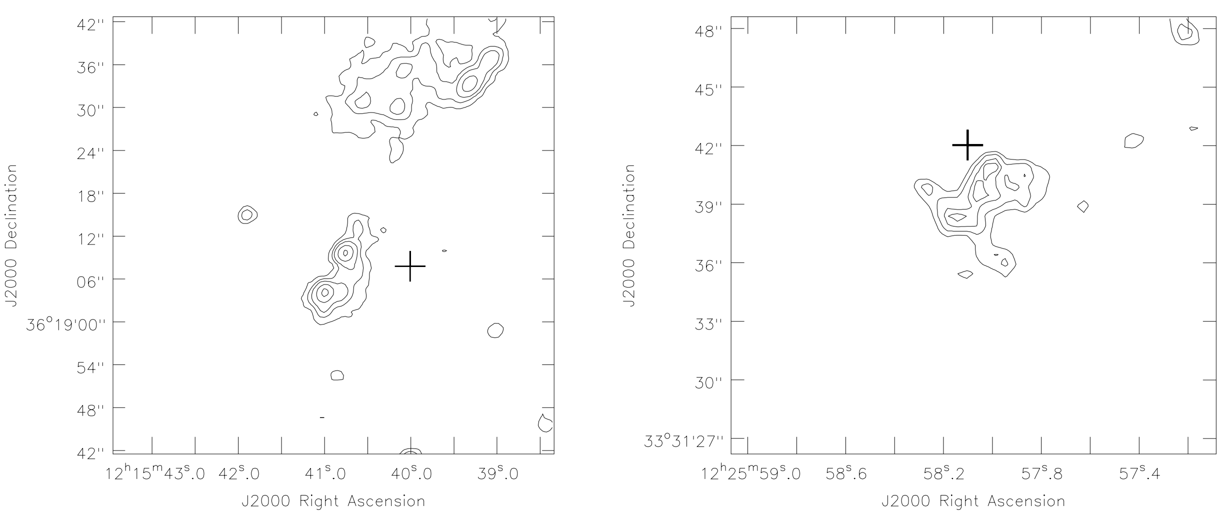

Fig. 1. *DSS optical image (in J2000.0 coordinates – courtesy of http://skyview.gsfc.nasa.gov) of NGC 4214 (left) and H_α image at 656.8 nm (in J2000.0 coordinates – Knapen et al. (2004) – courtesy of NED) of NGC 4395 (right). The positions of HII regions from Table 2 are marked with crosses and their uncertainties are 5 arcseconds. The images are overlayed with contours showing radio emission at 20 cm. Contour levels are 3.0, 6.0, 10.0, 20.0, 35.0 in units of 0.022 mJy for NGC 4214 and 3.0, 3.7, 4.5, 4.9 in units of 0.028 mJy for NGC 4395.*

Table 1. Gross Properties of NGC 4214 and NGC 4395

Galaxy	R.A. (J2000.0) (h m s)[a]	Decl. (J2000.0) (° ' ")[a]	Galactic Longitude ℓ (°)[a]	Galactic Latitude b (°)[a]	Major and Minor Axes (arcmin)[a]	Hubble Type[a]	Distance (Mpc)	Inclination Angle i (°)[b]
NGC 4214	12 15 39	+36 19 33	183.91	+36.33	8.5×6.6	IAB(s)m	4.7[c]	37
NGC 4395	12 25 49	+33 32 48	186.45	+33.55	13.2×11.0	SA(s)m	2.6[d]	38

References: [a] – NED, [b] – Tully (1988), [c] – Saha et al. (1994), [d] – Filippenko and Sargent (1989).

Table 2. Positions, Flux Densities, Spectral Indices and Associated HII Regions of the New Candidate Radio SNRs

Candidate Radio SNR	Galaxy	R.A. (J2000.0) (h m s)	Decl. (J2000.0) (° ' ")	$S_{3.5}$ (mJy)	S_6 (mJy)	S_{20} (mJy)	α	HII Region
α	NGC 4214	12 15 40.9	+36 19 04.6	1.0±0.1	1.4±0.2	2.33±0.06	-0.43±0.03	HK02[a]
β	NGC 4214	12 15 40.7	+36 19 10.0	1.0±0.1	1.2±0.2	1.84±0.06	-0.32±0.03	HK02[a]
ρ	NGC 4214	12 15 42.0	+36 19 15.2	–	<0.05	0.27±0.06	<-1.35	–
#3	NGC 4395	12 25 58.1	+33 31 39.5	–	<0.14	<0.16	–	RBD17[b]

References: [a] – Hodge and Kennicutt (1983), [b] – Roy et al. (1996).

To help increase the number of known extragalactic candidate radio SNRs and to identify additional extremely luminous sources of this type, we are gathering data from radio observations of nearby galaxies (both new and archived) to detect new candidate radio SNRs. We are complementing this analysis by also searching through the literature to identify new sources of this type as revealed by observations conducted by other authors. Recently, we have conducted a search for new candidate radio SNRs in the nearby starburst irregular galaxies NGC 4214 and NGC 4395. Both of these galaxies are known to be currently experiencing an epoch of starburst activity: the subject of this paper is to describe these new candidate radio SNRs revealed by our search and determine if these sources may serve as additional examples of extremely luminous candidate radio SNRs located in galaxies experiencing a period of starburst activity. In Fig. 1 we present a digital sky survey (DSS) optical image of NGC 4214 obtained from http://skyview.gsfc.nasa.gov and H_α image at 656.8 nm of NGC 4395 obtained from NED: the positions of the HII regions associated with the radio sources considered in this paper (Table 2) are indicated with crosses. Position uncertainties of HII regions are five arcseconds. The optical images are overlayed with contour lines showing the radio emission at 20 cm. Contour levels are 3.0, 6.0, 10.0, 20.0, 35.0 in units of 0.022 mJy for NGC 4214 and 3.0, 3.7, 4.5, 4.9 in units of 0.028 mJy for NGC 4395. In Table 1 we give general properties of NGC 4214 and NGC 4395, including Right Ascension and Declination (J2000.0), Galactic latitude and longitude, major and minor axes, Hubble Type, distance in Mpc and inclination angle.

The organization of this paper is as follows. In Section 2 we describe the radio observations of these galaxies at the wavelengths of 3.5 cm, 6 cm and 20 cm and the data reduction process. Properties of these two galaxies and previous observations of these galaxies and known discrete radio sources in these galaxies considered in this paper (including candidate radio SNRs) are discussed in Section 3. Properties of the new extragalactic candidate radio SNRs are given in Section 4, while in Section 5 we compare the properties of these sources with the properties of other candidate radio SNRs also located in starburst galaxies. We discuss the Σ-D relation for extragalactic candidate radio SNRs (including the new candidate radio SNRs in our analysis) in Section 6 and finally the conclusions of this work are given in Section 7.

2. RADIO OBSERVATIONS OF NGC 4214 AND NGC 4395

We obtained data for radio observations for NGC 4214 and NGC 4395 made with the Very Large Array (VLA[1]) from the Web-based NRAO archive (http://www.nrao.edu). NGC 4214 was observed at the wavelengths of 6 cm and 3.5 cm, while the NGC 4395 was observed at the wavelengths of 20 cm and 6 cm. The data were reduced using standard reduction techniques for gain, phase and flux calibration with the Astronomical Imaging and Processing System (AIPS++), which is a software package provided and maintained by the NRAO for interactive calibration and editing of radio interferometric data. The

[1]The VLA is a facility of the National Radio Astronomy Observatory (NRAO), which is operated by Associated Universities, Inc., under contract to the National Science Foundation.

Table 3. Properties of the Observational Data for NGC 4214 and NGC 4395

Galaxy NGC 4214	Date	VLA configuration	restoration beam size	rms (mJy/beam)
20 cm	1986 May 3	A	$\sim 2'' \times 2''$	0.022
6 cm	1997 April 20	B	$\sim 2'' \times 1''$	0.038
3.5 cm	1997 April 20	B	$\sim 1'' \times 1''$	0.030
Galaxy NGC 4395	Date	VLA configuration	restoration beam size	rms (mJy/beam)
20 cm	1990 March 03	A	$\sim 5'' \times 3''$	0.028
6 cm	1999 October 31	B	$\sim 2'' \times 1''$	0.044

final images were corrected for primary beam attenuation before undertaking flux measurements of the candidate radio SNRs. The observation of NGC 4214 at a wavelength of 20 cm was reduced by Eck et al. for the purpose of their work in Eck et al. (2002). The values for integral flux density of the sources α, β and ρ in NGC 4214 at 20 cm were measured from the fits format image obtained by Eck et al. using the MIRIAD program package for the radio data reduction.

In Table 3 we list the general properties of the observational data and final reduced images. Such as date when the observation was taken, VLA configuration, the size of the restoring beam for the final image and the rms noise level. The rms noise level was calculated as follows. We have measured the rms over a few quiet (no sources) parts of the image. Then we used the mean values of these measurements for our final value of the rms.

3. RESULTS

In Table 2 we list general properties of four discrete radio sources in these galaxies which were identified by previous surveys and appear to be positionally coincident with resident HII regions. These properties include the host galaxy, the position of the radio source (Right Ascencion and Declination in J2000.0 coordinates), flux densities at 3.5 cm, 6 cm and 20 cm ($S_{3.5}$, S_6 and S_{20}, respectively), spectral index α (defined so that $S_\nu \propto \nu^\alpha$) and the name of the associated HII region. For the purposes of measuring the flux densities we considered all our sources as point like because they were approximately the size of the restoring beam at each wavelength. Flux densities were measured over a region which was occupied by the source and above the three σ (standard deviation of the pixel values for the whole image). The errors for spectral index were calculated when plotting the flux densities vs. frequency for the purposes of obtaining the spectral index, considering the values for the flux density errors. The plots were taken in Sigma plot, the software package for plotting the various kind of data. For the flux density errors we used the 10% of the flux density values for all the values except the ones we measured from the image obtained by Eck et al. (2002). There we used the three time rms value for the final flux density error. We now give a brief description of both the host galaxies and the detected discrete radio sources.

3.1. NGC 4214 and the Discrete Radio Sources α, β and ρ

NGC 4214 is a nearby irregular starburst galaxy located at a distance of 4.7 Mpc (Saha et al. 1994): this galaxy features extensive massive star formation throughout its disk. General properties of this galaxy (particularly its high rate of massive star formation) have been discussed extensively in the literature (see Sargent and Filippenko 1991, Beck et al. 2000, and Drozdovsky et al. 2002). We note that NGC 4214 has also been the host of a Type Ib historical supernova, SN 1954A (Barbon et al. 1999). As part of a survey of radio emission from historical supernovae, Eck et al. (2002) described a radio observation made of this galaxy with the VLA at 20 cm (the rms noise level of the observation was 0.022 mJy): radio emission from SN 1954A was not clearly detected by their observation to a limiting flux density of 0.068 mJy. Eck et al. (2002) detected eleven discrete radio sources in the field of view of their observation of NGC 4214: they argued that four of these sources – α, β, η and ρ – are associated with HII regions in the galaxy. Based on our measurements of flux densities for α, β and ρ at 3.5 cm, 6 cm and 20 cm using our reduced images and the corresponding spectral indices for these sources, we claim that sources α and β are candidate radio SNRs based on their non-thermal indices and their positional associations with HII regions in NGC 4214. Source ρ may be a candidate radio SNR or (more likely, based on its steep spectral index) a background radio source. Emission was detected from this source at 20 cm but at 6 cm no emission was seen above the rms noise level of 0.038 mJy/beam. Additional radio observations with improved sensitivity are needed to properly classify this source. We do not believe that η is a candidate radio SNR because this source is actually a complex of radio sources spread over a large circular area with a diameter of 15 arcseconds on the sky. A summary of X-ray observations made of NGC 4214 with *Chandra* and *XMM-Newton* are presented by Hartwell et al. (2004): those authors found 20 discrete X-ray sources within the optical extent of that galaxy down to a limiting luminosity of approximately 3×10^{36} ergs sec^{-1} over the energy range of 0.3 – 8.0 keV at our assumed distance to this galaxy. No coincidences are seen between the discrete X-ray sources identified in that work and the three candidate radio SNRs in NGC 4214 that are discussed in this paper.

3.2. NGC 4395 and the Discrete Radio Source #3

Like NGC 4214, NGC 4395 is a nearby irregular starburst galaxy: the distance to NGC 4395 is estimated to be 2.6 Mpc (Filippenko and Sargent 1989). This galaxy features numerous bright HII regions and a Seyfert nucleus of extremely low brightness (Kraemer et al. 1999, Lira et al. 1999, Moran et al. 1999). Based on 6 cm and 20 cm observations made of NGC 4395 with the VLA, Sramek (1992) presented a study of the radio emission from a source associated with the nucleus of this galaxy. In that paper, Sramek (1992) also commented on other discrete radio sources in the field of view that were detected by the observations. One of those sources (denoted as #3) is coincident with an HII region known as RBD17 (Roy et al. 1996) and features a non-thermal spectrum: Sramek (1992) quoted a flux density of 0.24±0.04 mJy for this source at 20 cm (rms noise level of 0.036 mJy) and gave an upper limit of 0.3 mJy for its flux density at 6 cm (rms noise level of 0.120 mJy). We have remeasured flux densities at 6 cm and 20 cm for #3 and obtained only the upper limits for flux density listed in Table 2. With the present datasets it is impossible to measure a spectral index (and therefore make a robust classification) of this source as an HII region, candidate radio SNR or a background source. We claim that this source could be a candidate radio SNR based on its positional coincidence with an HII region in NGC 4395, but new, more sensitive observation of this galaxy are required to confirm or discard our assumption. Our measured flux densities at 6 cm and 20 cm for #3 are somewhat lower than the values measured by Sramek (1992). Similar to our search for X-ray counterparts for the candidate radio SNRs in NGC 4214, we have conducted a literature search for a known X-ray source which may be a counterpart to #3. Radecke (1997) describes a *ROSAT* PSPC observation made of NGC 4395 and identifies 12 X-ray sources in the field of view of the observation but no X-ray counterpart to #3 is seen. We note, however, that the limiting X-ray luminosity of the X-ray observation was approximately 2×10^{38} ergs sec^{-1} over the energy range of 0.1 – 2.4 keV, which is a much higher limiting luminosity than the limiting luminosity attained by the *Chandra* and *XMM-Newton* observations of NGC 4214 that were mentioned previously. An additional X-ray observation with sensitivity comparable to the NGC 4214 observations is necessary to compare the X-ray properties of #3 with the X-ray properties of α, β and ρ in NGC 4214 in more rigorous detail.

4. PROPERTIES OF THE NEW EXTRAGALACTIC CANDIDATE RADIO SNRS

We now consider three key properties of these new extragalactic candidate radio SNRs, namely the radio luminosity $L_{\rm radio}$, the minimum total energy $E_{\rm min}$ required to power the radio source via synchrotron emission and the corresponding magnetic field strength $B_{\rm min}$. Expressions for all three of these quantities have been derived previously using equipartition arguments by Pacholczyk (1970), and the reader is referred to that work for a detailed treatment of the subject matter. To summarize, if we assume for each candidate radio SNR a radio flux density spectrum S_ν of the form $S_\nu = \beta\, \nu^\alpha$ (where β is the flux scale factor, ν is the frequency in Hz and α is the spectral index), then the radio luminosity of a candidate radio SNR may be calculated using the equation

$$L_{\rm radio} = 4\pi D^2 \int_{\nu_1}^{\nu_2} S_\nu d\nu = 4\pi D^2 \beta \int_{\nu_1}^{\nu_2} \nu^\alpha d\nu \quad (1)$$

where D is the distance to the galaxy in which the candidate radio SNR resides. For the present work, we will assume values of 10^8 and 10^{11} Hz for the cut-off frequencies ν_1 and ν_2, which are typical values for the synchrotron spectra. Equation 1 then becomes

$$L_{\rm radio} = 4\pi D^2 \frac{S_{\nu_0}\nu_0^\alpha}{(1+\alpha)}[10^{11(1+\alpha)} - 10^{8(1+\alpha)}] \quad \text{ergs/sec} \quad (2)$$

where S_{ν_0} is the flux density in mJy from the source at the observed frequency ν_0.

Analytic relations for $E_{\rm min}$ and $B_{\rm min}$ may be derived by first considering the total energy $E_{\rm total}$ within an SNR. We define $E_{\rm total}$ as

$$E_{\rm total} = E_e + E_p + E_B, \quad (3)$$

where E_e, E_p and E_B are the energies stored in electrons, heavy particles and the magnetic field, respectively, within the SNR. Using this expression, analytic relations for $E_{\rm min}$ and $B_{\rm min}$ may be derived (Pacholczyk 1970) and expressed as

$$E_{\rm min} = c_{13}(1+\xi)^{4/7} f^{3/7} (d/2)^{9/7} L_{\rm radio}^{4/7} \quad (4)$$

and

$$B_{\rm min} = (4/5)^{2/7}(1+\xi)^{2/7} c_{12}^{2/7} f^{-2/7} (d/2)^{-6/7} L_{\rm radio}^{2/7}. \quad (5)$$

In these expressions, we have introduced the following quantities: ξ is the ratio of the energies of the heavy particles and the relativistic electrons (for this quantity we assume a value of 40 to be consistent with values for particles observed at the top of the Earth's atmosphere). f is the fraction of the radio source's volume that is occupied by the magnetic field and the relativistic particles (we assume that all of the SNRs identified in the radio surveys are in the adiabatic (Sedov) phase of expansion, and in that phase the value of f is approximately 0.25), and, d is the diameter of the candidate radio SNR, while c_{12} and c_{13} are functions which are weakly dependent on α and are tabulated by Pacholczyk (1970).

In Table 4, we list the calculated values for $L_{\rm radio}$, $B_{\rm min}$ and $E_{\rm min}$ for the sources α and β in NGC 4214. We do not have any information for the diameters of these sources: for the purposes of the calculations we have assumed diameters of 20 pc. Such a value is consistent with the observed diameters of candidate radio SNRs in the Local Group spiral galaxy M33 (Duric et al. 1995; Gordon et al. 1998, 1999): also, this value has been assumed in other calculations of SNR energetics (Duric and Dittmar 1988, Pannuti 2000, Lacey and Duric 2001). Certainly, additional optical observations of these SNRs are required to measure their diameters more precisely (and, through spectroscopic observations, confirm or refute their classifications as SNRs, as argued in the present paper). We comment that for neither of these two candidate radio SNRs does the value of $E_{\rm min}$ exceed 10^{51} ergs; therefore a "hypernova" explosion is not necessary to explain the energetics of these sources and, instead, they may be considered to be the remnants of typical supernova explosions. We compare the values for these quantities for the two new candidate radio SNRs with other candidate radio SNRs located in starburst galaxies in the next Section. An analysis of the properties of SNRs located in starburst and normal galaxies will be the subject of a future paper (Pannuti et al. 2005, in preparation).

Table 4. $L_{\rm radio}$, $B_{\rm min}$ and $E_{\rm min}$ for the New Extragalactic Candidate Radio SNRs

Candidate Radio SNR	$L_{\rm radio}$ (ergs sec^{-1})	$B_{\rm min}$ (mG)	$E_{\rm min}$ (ergs)
α	1.70×10^{36}	0.18	2.54×10^{50}
β	1.82×10^{36}	0.18	2.40×10^{50}

5. COMPARISON OF THE PROPERTIES OF THE NEW CANDIDATE RADIO SNRS WITH CANDIDATE RADIO SNRS IN OTHER STARBURST GALAXIES

In Table 5 we list values for $L_{\rm radio}$, $B_{\rm min}$ and $E_{\rm min}$ for samples of candidate radio SNRs located in four nearby starburst galaxies. Two candidate radio SNRs in NGC 2146 are believed to be hypernova remnants, based on calculated values for $E_{\rm min}$ which exceed 10^{51} ergs (Pannuti et al. 2005, in preparation): we have omitted these two anomalously energetic sources from the present discussion. We note that of the four galaxies listed in Table 5, two (NGC 1569 and NGC 2146) are dwarf irregular galaxies similar in type to NGC 4214, while the remaining two galaxies (NGC 4258 and NGC 4736) are more massive grand design spirals.

Inspection of Table 5 indicates that the mean value of $B_{\rm min}$ for the two candidate radio SNRs in NGC 4214 is comparable to the mean values derived for the candidate radio SNRs in other starburst galaxies. We note that mean value for $L_{\rm radio}$ for these two candidate radio SNRs is among the highest value for the listed galaxies while the mean value of $E_{\rm min}$ is the largest of all. It appears that in terms of these properties, the candidate radio SNRs of NGC 4214 are the most similar to the candidate radio SNR identified in NGC 2146: we note that both of these galaxies are also similar in type (that is, both are irregular starbursts). It is remarkable that the candidate radio SNRs in NGC 4214 are among the most luminous known in starburst galaxies: however, the number of clearly-identified candidate radio SNRs in starburst galaxies is still rather small, and more candidate radio SNRs need to be identified before firm statements can be made about how candidate radio SNRs in different starburst galaxies compare with one another and how candidate radio SNRs in starburst galaxies compare with candidate radio SNRs in normal galaxies.

Table 5. Mean Values for $L_{\rm radio}$, $B_{\rm min}$ and $E_{\rm min}$ for Samples of Extragalactic Candidate Radio SNRs in Nearby Starburst Galaxies

Galaxy	$N^{\dagger}$	Mean $L_{\rm radio}$ (ergs sec^{-1})	Mean $B_{\rm min}$ (mG)	Mean $E_{\rm min}$ (ergs)
NGC 1569	3	1.79×10^{35}	0.11	5.09×10^{49}
NGC 2146	1	2.37×10^{36}	0.45	1.22×10^{50}
NGC 4258	4	5.58×10^{35}	0.14	1.62×10^{50}
NGC 4736	10	2.76×10^{35}	0.11	9.61×10^{49}
NGC 4214	2	1.76×10^{36}	0.18	2.47×10^{50}

† – Number of known candidate radio SNRs in the galaxy.

6. THE Σ-D RELATION FOR EXTRAGALACTIC CANDIDATE RADIO SNRS

The $\Sigma - D$ relation for SNRs, where Σ is the radio-surface brightness and D is the diameter of an SNR, provides a convenient way to investigate the evolution of the radio-surface brightnesses of these sources with time. This relation was first proposed by Shklovsky (1960) in the form of $\Sigma = AD^{-\beta}$. Approximately four decades after Shklovsky's first derivation, the $\Sigma - D$ relation has been analyzed and modified on the bazis both theoretical studies and radio observations of Galactic and extragalactic candidate radio SNRs. Reviews on the Σ-D relation have been provided by Urošević (2002, 2003), and updated relations for Galactic and extragalactic candidate radio SNRs have been presented by Guseinov et al. (2003) and Urošević et al. (2005), respectively. As described in Section 1, the distances to many Galactic SNRs are poorly known, and there is an ensuring large uncertainty in the diameters of these sources as well. Therefore, the study of the Σ-D relation for candidate radio SNRs in nearby galaxies can take advantage of reducing distance uncertainties to the

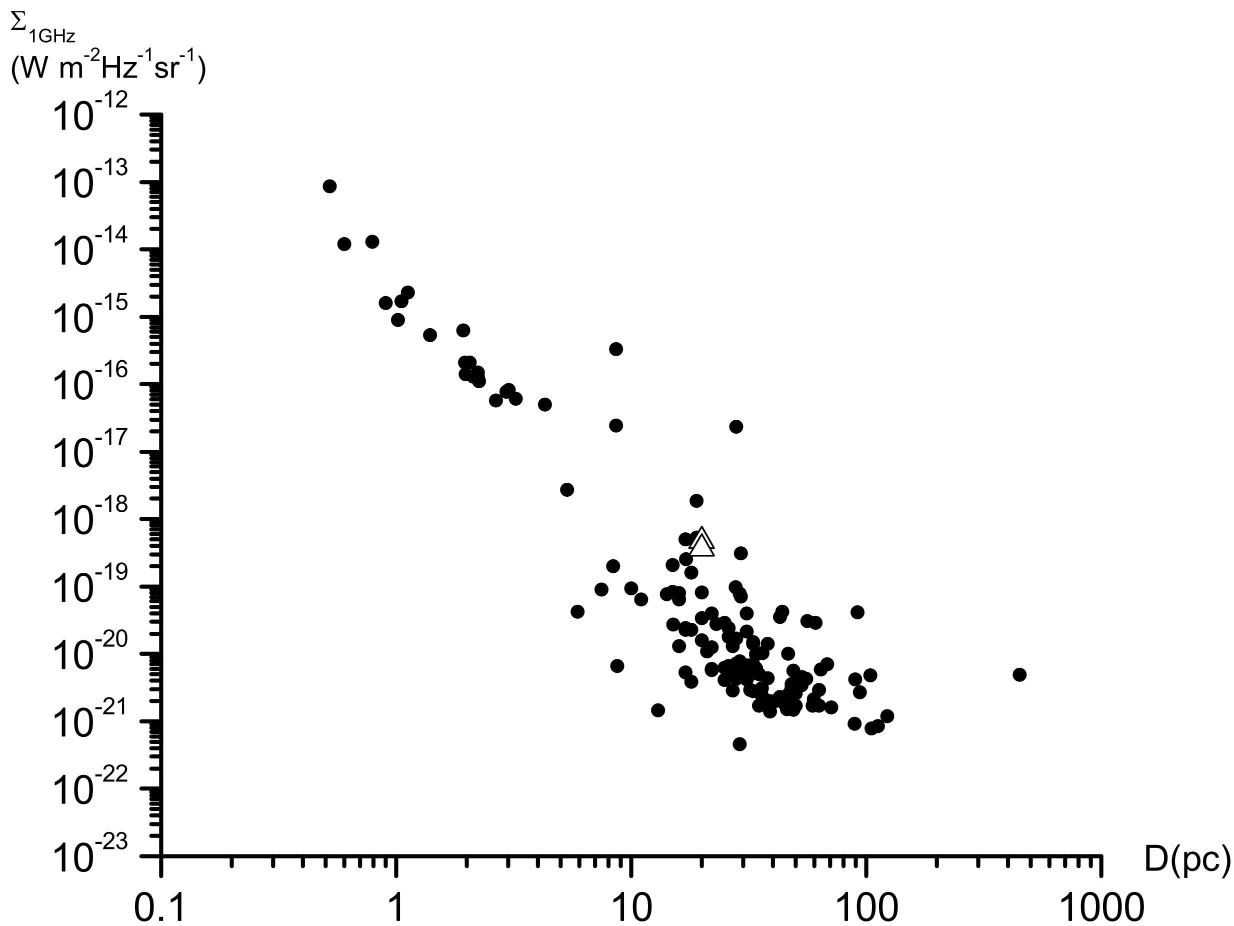

Fig. 2. *The Σ-D relation for known extragalactic candidate radio SNRs (from Urošević et al. 2005). We have added the two new candidate radio SNRs described in this paper to the original diagram and plotted these sources as open triangles. See Section 5.*

SNRs into distance uncertainties to the host galaxy: this represents a unique approach to general studies of this relation. Based on the values for S_{20} listed in Table 2, the adopted distances to the galaxies and an assumed diameter of 20 pc for each SNR, we have calculated values for Σ for each SNR at a frequency of 1 GHz and in the units of W m^{-2} Hz^{-1} sr^{-1}. We present these calculated values for the new candidate radio SNRs in Table 6.

Table 6. Surface Brightness Σ for the New Candidate Radio SNRs in NGC 4214

Candidate Radio SNR	Galaxy	$\Sigma_{1\mathrm{GHz}}$ (W m^{-2} Hz^{-1} sr^{-1})
α	NGC 4214	4.76×10^{-19}
β	NGC 4214	3.62×10^{-19}

To determine the current stages of evolution for the two candidate radio SNRs in NGC 4214, we used the surface brightnesses for these sources as listed in Table 6 and added these sources to our diagram depicting the Σ-D relation for SNRs in nearby galaxies which we presented in a previous work (Urošević et al. 2005). Our revised version of this diagram is shown in Fig. 2, where the new candidate radio SNRs α and β are plotted as open triangles, while the other candidate radio SNRs known from previous studies are plotted as filled circles. Again we print out that we have adopted a diameter of 20 pc for each source in the absence of any estimates for the true diameters of these sources (which could be conceivably obtained by optical or radio observations): without more definite estimates of the diameters of these sources, strong conclusions about the evolutionary stages of the new candidate radio SNRs based on the Σ-D relation should be avoided. However, based on inspection of Fig. 2 we do see that these two new candidate radio SNRs belong to the shallower end of the master relation with a slope of $\beta \approx 2$ (Urošević et al. 2005). Since NGC 4214 is a starburst galaxy, this result suggests that the SNRs in this galaxy are possibly more evolved, consistent with the hypothesis that this galaxy is close to a post-starburst stage of evolution. Also, it indicates that the difference in slopes seen for candidate radio SNRs from two different types of galaxies (normal and starburst) may originate from a purely "physical" evolutionary effect predicted by Duric and Seaquist (1986). This conclusion was also reached by Urošević et al. (2005) in the case of NGC 1569. As noted in Section 4, we argue that follow-up optical observations of the candidate radio SNRs in NGC 4214 will be quite useful for measuring the true diameters of these SNRs for the purposes of Σ-D studies of extragalactic SNRs as well as to search for signature shock-heated emission from such atomic species as [S II] which is commonly associated with SNRs. Indeed, observations of more extragalactic candidate radio SNRs are necessary to pursue studies of the Σ-D relation for sources in a wide variety of evolutionary stages, environments and types of host galaxies. Such studies will be a part of our future work on extragalactic candidate radio SNRs and, of course, the subject of future publications as well.

7. CONCLUSIONS

The conclusions of this paper may be stated as follows:

(1) As part of our search for new candidate radio SNRs in nearby galaxies, we have identified two new sources on the ground of the results presented in published papers: these candidate radio SNRs (denoted as α and β) are associated with the nearby starburst galaxy NGC 4214. Based on our analysis of archived radio observations made of this galaxy with the VLA at the wavelengths of 3.5 cm, 6 cm and 20 cm, we have confirmed the non-thermal nature of the radio emission from these sources and argued that these two sources are new candidate radio SNRs. We have searched in the literature for X-ray counterparts to these sources based on published lists of discrete sources associated with each galaxy: no such X-ray counterparts were found. In addition, we suspect that the radio sources ρ in NGC 4214 and #3 in NGC 4395 are also candidate radio SNRs based on their positions association with HII, regions but the present radio data available for these sources are not sufficient for a robust classification and additional radio observations with improved sensitivity are required.

(2) We have calculated values for several properties (namely $L_{\rm radio}$, $B_{\rm min}$ and $E_{\rm min}$) for the two new candidate radio SNRs and compared mean values for these properties to samples of candidate radio SNRs in several other known starburst galaxies. We find that with respect to the mean values for the candidate radio SNRs in other starburst galaxies, the mean value of $B_{\rm min}$ for the two candidate radio SNRs in NGC 4214 are comparable, the mean values for $L_{\rm radio}$ are among the highest for any starburst galaxy and the mean values of $E_{\rm min}$ are the largest of all. The radio luminosities of the candidate radio SNRs in NGC 4214 may, therefore, be the highest of any starburst galaxy but more candidate radio SNRs in other starburst galaxies need to be detected, classified and analyzed to help interpret these results in a broader context.

(3) We have included the two new candidate radio SNRs in a brief study of the Σ-D relation for extragalactic candidate radio SNRs to determine the evolutionary states of these newly-identified sources. It appears that the new candidate radio SNRs belong to the shallower end of the master relation with a slope of $\beta \approx 2$: this result suggests that the new candidate radio SNRs are possibly more evolved.

Acknowledgements – T.G.P. and D.U. thank Nebojsa Duric for many useful conversations regarding the properties of extragalactic candidate radio SNRs. T.G.P. also acknowledges useful discussions regarding starburst galaxies with Seppo Laine. B.V. and I.B. thank Christopher Eck for consigning the 20 cm images of NGC 4214. We also thank the referee for comments and suggestions which have helped to improve the quality of this paper. This research has made use of NASA's Astrophysics Data System, the SIMBAD database (which is operated at CDS, Strasbourg, France) and the NASA/IPAC Extragalactic Database (NED) (which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.) This research is part of the projects "Galactic and Extragalactic Molecular Clouds" (No. 136001) and "Structure, Kinematics and Dynamics of the Milky Way" (No. 1468) supported by the Ministry of Science and Environmental Protection of Serbia.

REFERENCES

Barbon, R., Buondi, V., Capellaro, E. and Turatto, M.: 1999, *Astron. Astrophys.*, **139**, 531.

Beck, S. C., Turner, J. L. and Kovo, O.: 2000, *Astron. J.*, **120**, 244.

Chevalier, R. A. and Fransson, C.: 2001, *Astrophys. J.*, **558**, L27.

Drozdovsky, I. O., Schulte-Ladbeck, R. E., Hopp, U., Greggio, L. and Crone, M. M.: 2002, *Astron. J.*, **124**, 811.

Duric, N. and Seaquist, E.R.: 1986, *Astrophys. J.*, **301**, 308.

Duric, N. and Dittmar, M. R.: 1988, *Astrophys. J.*, **332**, L67.

Duric, N., Gordon, S. M., Goss, W. M., Viallefond, F. and Lacey, C.: 1995, *Astrophys. J.*, **445**, 173.

Eck, C. R., Cowan, J. J. and Branch, D.: 2002, *Astrophys. J.*, **573**, 306.

Filippenko, A. V. and Sargent, W. L. W.: 1989, *Astrophys. J.*, **342**, L43.

Gordon, S. M., Kirshner, R. P., Long, K. S., Blair, W. P., Duric, N. and Smith, R. C.: 1998, *Astrophys. J. Suppl. Series*, **117**, 89.

Gordon, S. M., Duric, N., Kirshner, R. P., Goss, W. M. and Viallefond, F.: 1999, *Astrophys. J. Suppl. Series*, **120**, 247.

Green D.A., 2004, Bulletin of the Astronomical Society of India, 32, 335–370.

Greve, A., Tarchi, A., Hüttemeister, S., de Grijs, R., van der Hulst, J. M., Garrington, S. T. and Neininger, N.: 2002, *Astron. Astrophys.*, **381**, 825.

Guseinov, O. H., Ankay, A., Sezer, A. and Tagieva, S. O.: 2003, *Astron. Astrophys. Transactions*, **22**, 273.

Hartwell, J. M., Stevens, I. R., Strickland, D. K., Heckman, T. M. and Summers, L. K.: 2004, *Mon. Not. R. Astron. Soc.*, **348**, 406.

Hodge, P. W. and Kennicutt, R. C.: 1983, *Astron. J.*, **88**, 296.

Hyman, S. D., Calle, D., Weiler, K. W., Lacey, C. K., van Dyk, S. D. and Sramek, R.: 2001, *Astrophys. J.*, **551**, 702.

Knapen, J. H., Stedman, S., Bramich, D. M., Folkes, S. L. and Bradley, T. R.: 2004, *Astron. Astrophys.*, **426**, 1135.

Kraemer, S. B., Ho, L. C., Crenshaw, D. M., Shields, J. C. and Filippenko, A. V.: 1999, *Astrophys. J.*, **520**, 564.

Lacey, C. K., Duric, N. and Goss, W. M.: 1997, *Astrophys. J. Suppl. Series*, **109**, 417.

Lacey, C. K. and Duric, N.: 2001, *Astrophys. J.*, **560**, 719.

Lira, P., Lawrence, A., O'Brien, P., Johnson, R. A., Terlevich, R. Bannister, N.: 1999, *Mon. Not. R. Astron. Soc.*, **305**, 109.

Moran, E. C., Filippenko, A. V., Ho, L. C., Shields, J. C., Belloni, T., Comastri, A., Snowden, S. L. and Sramek, R. A.: 1999, *Publ. Astron. Soc. Pacific*, **111**, 801.

Pacholczyk, A. G. 1970, *Radio Astrophysics: Nonthermal Processes in Galactic and Extragalactic Sources.* San Francisco: W. H. Freeman and Company.

Paczyński, B. 1998, *Astrophys. J.*, **494**, L45.

Pannuti, T. G.: 2000, Ph.D Thesis, University of New Mexico.

Pannuti, T. G., Duric, N., Lacey, C. K., Ferguson, A. M. N., Magnor, M. A. and Mendelowitz, C.: 2002, *Astrophys. J.*, **565**, 966.

Radecke, H.-D.: 1997, *Astron. Astrophys.*, **319**, 18.

Roy, J.-R., Belley, J., Dutil, Y. and Martin, P. 1996, *Astrophys. J.*, 460, 284.

Saha, A., Labhardt, L., Schwengeler, H., Macchetto, F. D., Panagia, N., Sandage, A. and Tammann, G. A.: 1994, *Astrophys. J.*, **425**, 14.

Sargent, W. L. W. and Filippenko, A. V.: 1991, *Astron. J.*, **102**, 107.

Shklovsky, I.S.: 1960, *Astron. Zh.*, **37**, 256.

Sramek, R.: 1992, Relationships Between Active Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko, ASP Conference Series (ASP: San Francisco), vol. 31, p. 273.

Urošević, D.: 2002, *Serb. Astron. J.*, **165**, 27.

Urošević, D.: 2003, *Astrophys. Space Sci.*, **283**, 75.

Urošević, D., Pannuti, T.G., Duric, N. and Theodorou, A.: 2005, *Astron. Astrophys.*, **435**, 437.

Tarchi, A., Neininger, N., Greve, A., Klein, U., Garrington, S. T., Muxlow, T. W. B., Pedlar, A. and Glendenning, B. E.: 2000, *Astron. Astrophys.*, **358**, 95.

Tully, R.: 1988, Nearby Galaxies Catalog (Cambridge: Cambridge University Press).

Wang, Q. D.: 1999, *Astrophys. J.*, **517**, L27.

ПОТРАГА ЗА КАНДИДАТИМА ЗА ОСТАТКЕ СУПЕРНОВИХ У РАДИО ДОМЕНУ У БЛИСКИМ НЕПРАВИЛНИМ ЗВЕЗДОРОДНИМ ГАЛАКСИЈАМА NGC 4214 И NGC 4395

B. Vukotić[1], I. Bojičić[1], T. G. Pannuti[2] and D. Urošević[1]

[1]*Department of Astronomy, Faculty of Mathematics, University of Belgrade Studentski trg 16, 11000 Belgrade, Serbia and Montenegro*

[2]*Spitzer Science Center, California Institute of Technology, MS 220-6, Pasadena, CA 91125, USA*

UDK 524.354–77 : 524.7NGC4214NGC4395
Претходно саопштење

Представљамо резултате потраге за новим кандидатима за остатке супернових (ОСН) у радио домену у блиским неправилним звездородним галаксијама NGC 4214 и NGC 4395 користећи архивирана радио посматрања рађена са Very Large Area (VLA) на таласним дужинама од 3.5 cm, 6 cm и 20 cm за NGC 4214 и 6 cm и 20 cm за NGC 4395. Ова посматрања су анализирана као део потраге за кандидатима за ОСН у радио домену у блиским галаксијама која је у току: циљ ове потраге је да се припреми велики узорак кандидата за ОСН у радио домену у сврху поузданог статистичког проучавања особина ових извора. На основу наше анализе, потврдили смо нетермалну природу дискретних радио извора α и β у NGC 4214 и класификовали ове изворе као кандидате за ОСН у радио домену на основу њихове положајне блискости са HII регионима у тој галаксији. Измерили смо густине флукса два кандидата за ОСН у радио домену на свакој таласној дужини и израчунали одговарајуће спектралне индексе: такође смо измерили густине флукса два дискретна радио извора у овим галаксијама - ρ у NGC 4214 и #3 у NGC 4395 - за које сумњамо да су кандидати за ОСН у радио домену на основу њихове положајне блискости са HII регионима у овим галаксијама. Ипак, тренутно доступни радио узорци за ове изворе не могу да потврде такву калсификацију па су потребна додатна посматрања. Такође смо израчунали радио луминозности $L_{\rm radio}$ на таласној дужини од 20 cm за ова два кандидата за ОСН у радио домену као и одговарајуће вредности за минимум укупне енергије $E_{\rm min}$, потребне за напајање ових извора преко синхротронске емисије и одговарајуће јачине магнетног поља $B_{\rm min}$. Упоредили смо наше израчунате средње вредности ових карактеристика са средњим вредностима за популацију кандидата за ОСН у радио домену у другим звездородним галаксијама: док су вредности за $L_{\rm radio}$ и $B_{\rm min}$ грубо упоредиве са вредностима које се јављају у другим звездородним галаксијама, средња вредност за $E_{\rm min}$ је већа од средње вредности за било коју другу звездородну галаксију. Коначно, укључујемо ова два нова кандидата за ОСН у радио домену у дискусију о $\Sigma - D$ релацији за ван галактичке кандидате за ОСН у радио домену и налазимо да се ови извори налазе на блажем крају мастер $\Sigma - D$ релације за све ван галактичке ОСН као што је изведено у Урошевић и др. (2005).