UPDATED $\Sigma - D$ RELATIONS AND MAIN RADIO LOOPS AS SUPERNOVA REMNANTS[1]

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Updated $\Sigma - D$ relations (relations between the surface brightness (Σ) and the diameter (D)) for supernova remnants (SNRs) were used for investigation of the origin of the main galactic radio loops (Loop I, II, III, IV). In this paper, test results affirm the SNR hypothesis of the radio loops origin. With loop affixation, the updated $\Sigma - D$ relations become more complete in comparison with the original relations and they result by flatter slopes – $\beta \approx 2$.

1. Introduction

1.1. Radio Loops

For more than three decades, it is known that some radio spurs can be joint into a small circle. The set of spurs belonging to the same small circle is referred to as a loop. By early seventies, four major galactic loops were recognized. They can be seen clearly in an all-sky radio continuum picture.

Although our understanding of these intriguing objects still contains a considerable number of loose ends and question marks, the supernova theory of their origin acquired an enhanced respectability and mostly thanks to the extensive observations of X-ray emission from Loop I. Discovery of analogous HI and X-ray loop features (e.g. Heiles 1979, Nousek et al. 1981, Egger & Aschenbach 1995, 1996) suggests that large shells may be a rather common and important feature of the interstellar medium. Such observations seem to be particularly relevant at the present time regarding the suggestions that old supernova remnants probably shape the character of the major fraction of the interstellar medium (McKee & Ostriker 1977).

The SNR radio loops hypothesis originated in the work by Brown et al. (1960). At the time, it wasn't still detected that some spurs are placed on the approximately small circles of the celestial sphere since all discussions considered the North Polar Spur (NPS) – main part of Loop I – clearly visible in the earliest radio-continuum surveys. The first radio loop model supporting the SNR hypotesis belongs to Berkhuijsen et al. (1971). It is based upon the geometry of radio loops (expressly circular (Salter 1970); later on, it was confirmed in the paper by Milogradov-Turin & Urosevic (1997)), gradients of the brightness that are steeper from the outer side of the ridge – the area of the brightest part of the spur, HI regions attached to the outer edges of the remnants, runaway stars and spectral indices typical of non-thermal objects. All the above mentioned characteristics are observable in the radio range of the spectrum.

These pioneer investigations led to many more others that supported the SNR radio loops hypothesis (e.g., Salter 1983, Kosarev et al. 1994, Egger & Aschenbach 1995, 1996, Sembach et al. 1997). Naturally, there were other models which explained the origin of radio loops in completely different manner (e.g. Mathewson 1968, Sofue 1977, 1994). Mathewson (1968) considered the hypothesis of loops unification. He noted that the spur ridges and regions of strong radio polarization follow the "flow patterns" of the optical polarization vectors and concluded that the spurs and loops are tracers of the helical magnetic field structure of the local spiral arm. Sofue (1977) proposed a completely different theory for Loop I. This came about almost as a by-product of his ideas on the formation of the 3 kpc expanding spiral arm. He envisaged isotropic MHD waves from the Galactic center propagating through the halo and disk of the Galaxy and showed that these would converge with high efficiency into a ring in the disk. For his model, at $t > 10^8$ yr, some 80% of the energy of waves would converge in the disc at about 3.5 kpc, while the remainder would expand quasispherically into the halo forming an immense shell structure. Sofue (1994) again explained NPS as an object of Galactic dimensions. The origin of NPS is a gigantic explosion that took place

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near the galactic center. Strong shock wave caused by the explosion expelled the shell into the halo.

1.2. Basic Evolution Theories of SNRs' Radio Radiation and Radio Loops

There are two basic evolution theories of the SNRs' radio radiation: Shklovsky theory (1960a,b) and van der Laan theory (1962a,b). Main difference between these two is the following: according to van der Laan, the magnetic field is created by compression of the interstellar magnetic field (due to the interaction between a shock wave and the envelope rejected by the explosion) and SNR radiates from the edge of the cloud whereas the magnetic field remains constant with expansion of the remnant; contrary to that opinion, the Shklovsky theory claims that the whole expanding sphere is radiating and the magnetic field (frozen in it) decreases with the square of radius. It is evident that the radio loops model (assuming that the loops are local SNRs) should be supported by the van der Laan theory due to the shell-like remnant and the constant magnetic field that should extend to greater dimensions easily. Spoelstra (1972, 1973) compared the parameters received from his polarization observations of the radio loops (also, showing the loops are nearby objects) with the parameters given by van der Laan theory and reached a "reasonable" fitting. Only at first glance, the Shklovsky theory is not convenient as an explanation of the nature of the radio loops, but if we use updated $\Sigma - D$ relations, loops can be explained as the supernova remnants.

1.3. $\Sigma - D$ Relation

The relation between the surface brightness Σ and the diameter D (so-called $\Sigma - D$ relation) is a convenient method for investigation of the radio brightness evolution of supernova remnants (SNRs). Shklovsky (1960a) theoretically analyzed synchrotron radiation of the spherical expanding nebula and the $\Sigma - D$ relation is a result of that theoretical analysis. It has a form:

$$\Sigma = AD^{-\beta}. \tag{1}$$

The updated theoretical derivation of this relation for the shell-like SNR is performed by Duric & Seaquist (1986, hereafter D&S). Structure of the derivation is similar to Shklovsky's, but instead of the Fermi's accelerating mechanism, they adopted the Bell's (1978). Bell formulated a model in which acceleration of particles was produced by repeated scattering of particles across a shock front. Turbulence downstream from the shock (convection zone) provides the scattering in the upstream direction. As particles propagate upstream, ahead of the shock, they excite Alfven waves if the shock is super-Alfvenic. They are scattered by the waves, and some find their way downstream again. The particles have finite probabilities of repeating the cycle, the probability being directly proportional to the particle velocity. This leads to a power-low distribution in energy for the accelerated particles and a number density which is a function of the shock velocity. The magnetic field model D&S used is based on the research of Gull (1973) and Fedorenko (1983). Gull proposed the model in which the ambient magnetic field is amplified in the convection zone and that it provides the environment in which relativistic electrons can radiate efficiently. Fedorenko formulated a model in which magnetic field B is changed with D according $B \propto D^{-x}$, where $1.5 \leq x \leq 2$.

The observations started to confirm the existence of $\Sigma - D$ dependence in the form the Shklovsky theory had anticipated previously. The first empirical $\Sigma - D$ relation was derived by Poveda & Woltjer (1968). Using $\Sigma - D$ relation, Shklovsky (1960b) presented a way for determing the distances to SNRs as surface brightness is the quantity not dependent upon the distance to the radio source. Milne (1970) derived an empirical $\Sigma - D$ relation and calculated distances to all observed SNRs in our galaxy (there 97 of them).

Further, this relation was a subject of many investigations in an attempt to precisely determine the specific set of calibrators and therefore to achieve a better $\Sigma - D$ relation. The basic criterion for the choice of calibrators is a reliable distance to the remnant. Most studies done during 1970s and the early 1980s are of this kind. Better observations enabled more precise calculations of the distances to the calibrators and their number increase. Critical analyses of this relation have started since the discoveries by Allakhverdiyev et al. (1983a,b) and continue with the researches of Green (1984) and Allakhverdiyev et al. (1986a,b). Inaccurate calculation of the distances to certain calibrators is the basic deficiency of the relations derived in this manner, i.e. there are not enough remnants with precisely calculated distances necessary for the derivation of the proper $\Sigma - D$ relation (Green, 1984). Also, the interstellar medium where a supernova exploded must be taken into consideration. Allakhverdiyev et al. (1983a,b; 1986a,b) showed that it makes sense to derive the relation only for shell-like remnants. $\Sigma - D$ relations were not an interesting research topic in late 1980s and early 1990s. Research in this field was discontinued

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since the "attacks" on the $\Sigma - D$ relation for as long as one decade. Once again, Green (1991) showed that calibrators are too scattered on the $\Sigma - D$ diagram so that no valid relation can be derived. Everything remains so until the papers Case & Bhattacharya (1998, hereafter C&B). Their relation is the updated $\Sigma - D$ relation for galactic SNRs. Thirty seven galactic shell-like remnants with reliably calculated distances were taken as calibrators. Whenever the kinematic method was required for determination of the distances to the calibrators, the new rotation model of our galaxy was applied to their calculation. This model is based on the values of galactic constants $R_\odot = 8.5$ kpc and $V_\odot = 220$ km/s. Two $\Sigma - D$ relations were derived. The first one is referring to all thirty seven remnants and the other one to thirty six remnants (without Cas A remnant extremely dispersed from the fit line). C&B considered the second relation (case of thirty six calibrators) more representative since Cas A isn't the most ordinary SNR in comparison to other galactic, shell-like remnants. Flatter slope relation ($\beta = 2.38 \pm 0.26$) was derived in the case of thirty-six calibrators, and C&B concluded that this result shows good agreement with $\Sigma - D$ relations for other galaxies.

Construction of extragalactic $\Sigma - D$ relations is very convenient because all calibrators are approximatly at the same distance. Therefore, the distance determination problem a particular remnant does not exist, if the distance to the galaxy is known. Once a SNR is identified, that SNR becomes calibrator. However, we detect the greater number of SNRs only in the nearby galaxies (LMC, SMC, M31, M33). As the distance to the galaxies increases, fewer SNRs can be observed. Also, extragalactic data-sets don't have the "mulmquest bias"; this bias is an inevitable, undesired characteristic of the Galactic data-set.

Updated extragalactic relation was derived for nearby galaxy M33 (Urosevic, 2000). We have used a new sample (Gordon et al., 1999) of radio-selected and optically confirmed supernova remnants in M33 (53 SNRs were identified). For 36 good resolved calibrators, we have got a very flat slope $\beta = 1.82 \pm 0.22$ (on 1 GHz).

In this paper, radio loops are affixed to C&B and to 36 calibrators from M33 and the variations of the quotient β are examined. The results of these tests could confirm the SNR origin of radio loops.

2. Analysis and Results

If we accept surface brightness (at 1 GHz) and diameters (in pc) for four main radio loops from the Berkhuijsen

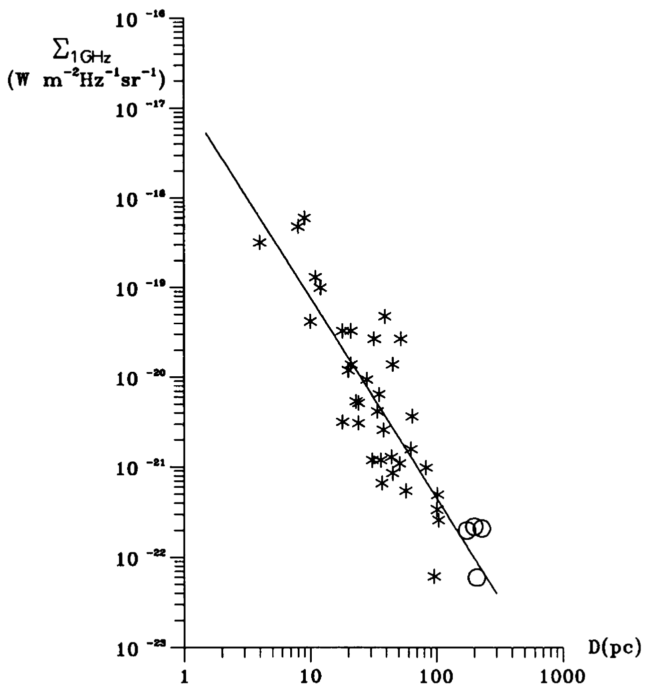

Fig. 1. $\Sigma - D$ diagram at frequency of 1 GHz. C& B calibrators are represented by asterisks and loops by circles

(1986) study, and affix them to the set of the initial 36 C& B calibrators, the following relation is derived by the best fit method:

$$\Sigma_{1\mathrm{GHz}} = 1.31^{+1.46}_{-0.69} \times 10^{-17} D^{-2.23 \pm 0.20}. \qquad (2)$$

All forty objects defining relation (2) are of equal statistical weight. Quotient variation $\Delta\beta$=0.15 is easily noticeable as well as the fact that it corresponds to the interval predetermined by this quotient's error. This means that affixation of the loops to other calibrators alters the slope of the original relation keeping it in the permitted range of values. This test was done by Berkhuijsen (1973) only that at the time the latest empirical relation of Ilovaisky & Lequeuix (1972) was taken as the initial one. In her test, the variation of β quotient in the case of the equal statistical weights $\Delta\beta \approx 1$. Original calibrators were supplemented with Loop I and Origem loop.

$\Sigma - D$ diagram associated with relation (2) defined for thirty six calibrators along with four main radio loops is showed in Fig. 1.

If we have affixed loops to the 36 calibrators from the M33 galaxy, then we will obtain the relation:

$$\Sigma_{1\mathrm{GHz}} = 1.00^{+0.79}_{-0.44} \times 10^{-17} D^{-2.02 \pm 0.16}. \qquad (3)$$

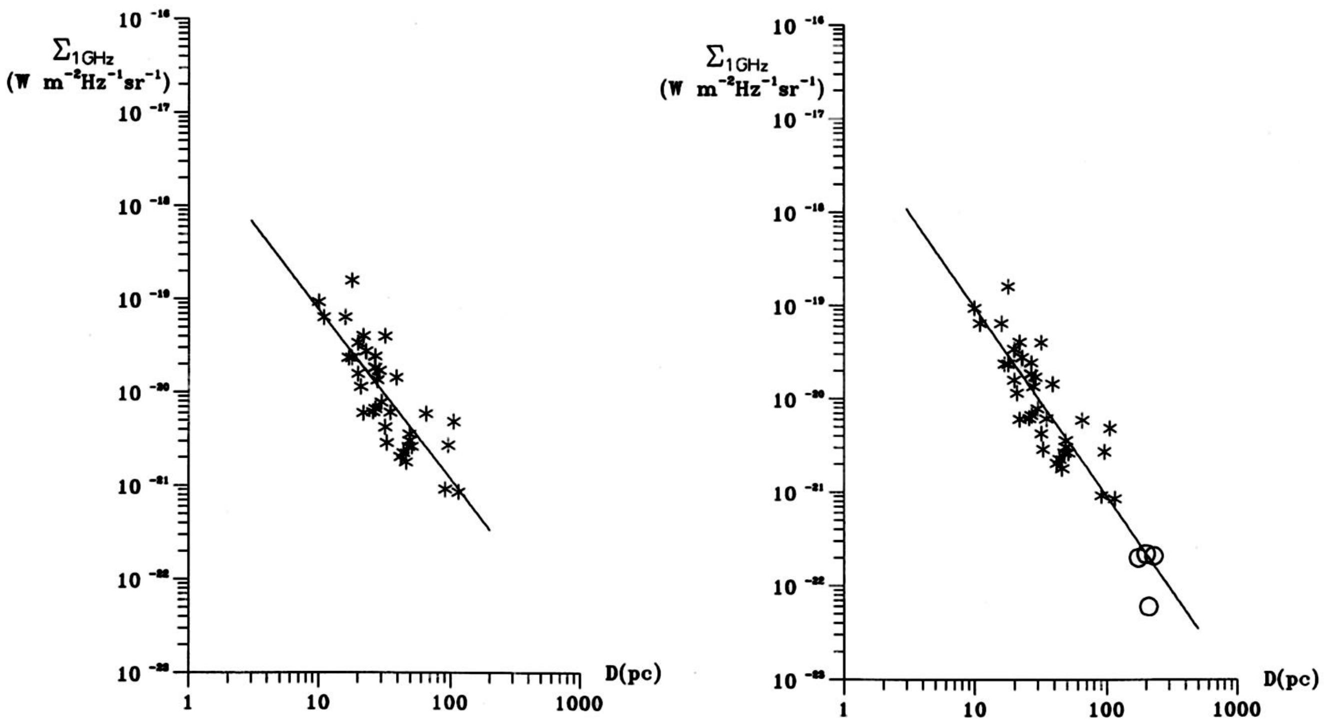

Fig. 2. $\Sigma - D$ diagrams at a frequency of 1 GHz. Calibrators from M33 galaxy are represented by asterisks and loops by circles

Again, the calibrators defining relation (3) are of equal statistical weight and the quotient variation $\Delta\beta = 0.20$ means that affixation of the loops to other calibrators alters the slope of the original relation keeping it in the permitted range of values.

$\Sigma - D$ diagrams associated with original relation for 36 calibrators from M33 galaxy and with relation (3) defined for 36 M33 calibrators along with 4 main radio loops are showed in Fig. 2.

3. Discussion

With loop affixation, the fit quality for the test of C&B relation is rising up by 5% (from 71% to 76%). Scattering is noticeable but basically explained by the facts that remnants are evolving in a different interstellar medium, they have different energy of explosions, unreliably calculated calibrators distances, possibility that the set of calibrators contains supernova remnants of Type I and Type II at the same time (e.g. Dickel et al. 1993). Loops are occupying the lower right area of $\Sigma - D$ diagram (see Figures 1 and 3) and balancing the relation. Errors of quotients A and β are reduced with loop affixation. Loop IV has smaller diameter than the average diameter defined by relation (2).

C&B $\Sigma - D$ diagram for thirty six calibrators with in-drawings of main loops is shown in Fig. 3. Loop IV is at the fit line which means it is an ordinary remnant considering $\Sigma - D$ dependence. It is obvious from Fig. 3 that Loop I (diameter 230 pc) is closer to the line than Cas A (the drawing is also attached to the diagram). It leads to the conclusion that Loop I is more normal remnant than the supernova remnant Cas A, considering the connection between surface brightness and the remnant diameter. Since Loop I is the loop with the largest diameter, the fact it is more normal means that the other three loops are more normal, too. Besides, Cas A isn't the only remnant away from the fit line. Another five calibrator remnants are showing more distant from the fit line (W51, CTB37A, Kes67, CTB37B, and G349.7+0.2). It means that, for their brightness, these remnants have larger diameters than Loop I has for its brightness. Remnants SN1006, CTA1 and G156.2+5.7 are more distant too, but from the left of the fit line, i.e., in the minimum diameter area.

For the test of the M33 relation, the fit quality is rising up by 15% (from 67% to 82%). As in a case of C&B relation, scattering is noticeable. Loops are balancing relation very well. This balancing is better than in the case of C&B relation (for C&B relation, the fit quality is rising up by 5%, for M33 relation – 15%!). On Fig. 2,

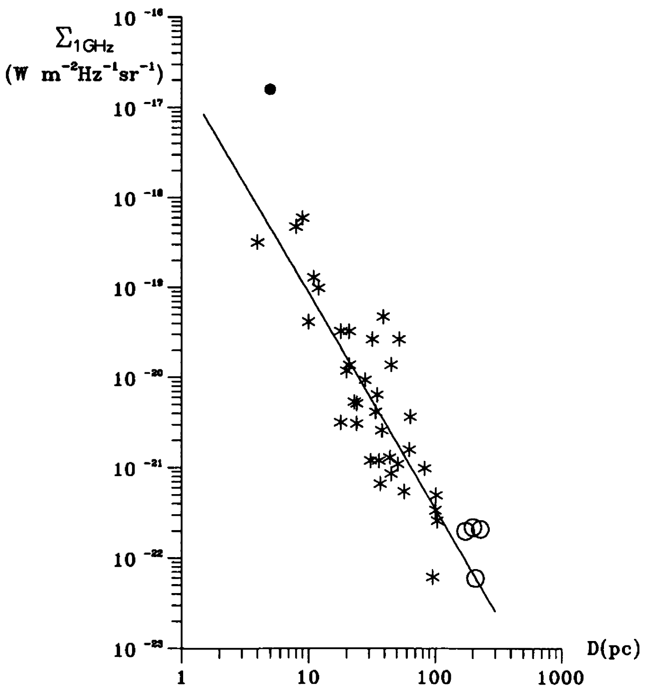

Fig. 3. $\Sigma - D$ diagram at a frequency of 1 GHz is showing C&B dependence derived using thirty six calibrators with in-drawings of main loops and Cas A remnant. Asterisks are representing C&B calibrators, circles are representing loops, and the full circle stands for Cas A remnant

we can see the "empty space" on the $\Sigma - D$ diagram between M33 calibrators and radio loops. Gordon et al. (1999) sample was not detected low brightness and big diameter SNRs, because the M33 galaxy is not so close to us, and therefore VLA telescopes could not detect that sources. In future, with a grow up of a observational technique, we will be able to detect low brightness SNRs (like loops) and probably β will increase to 2. If we compare tests of these two relations, we deduce: (1) if in original relation $\beta < 2$, β will be increasing after loops affixation and (2) if in original relation $\beta > 2$, β will be decreasing after loops affixation. These tests results are supported $\beta \approx 2$ (e.g. Mills, 1983; Mills et al., 1984; C&B; Urosevic, 2000). Theoretical $\Sigma - D$ relation doesn't predict $\beta = 2$ (e.g., from the Shklovsky model, $\beta = 6$; from D&S model, $2.75 \leq \beta \leq 3.5$). If we suppose the spherical expanding of the SNR with constant luminosity – L_ν (independent of the SNR diameter), the relation is as follows:

$$\Sigma_\nu \propto L_\nu D^{-2}. \tag{4}$$

If we have got $\beta = 2$ for the empirical relation, theoretical $\Sigma - D$ relation in D&S form doesn't exist. Theoretical relation gets the trivial form (4). In future, with detection of a greater number of the low brightness galactic and especialy extragalactic SNRs, theoretical relations will have much better interpretation. That results will explain does or does the not theoretical $\Sigma - D$ relation exist.

4. Conclusion

All the above stated can be concluded as follows: low brightness and large diameters of the main loops shouldn't be a problem present ever since the loop discovery. Such a test result is supporting the SNR origin of the radio loops. We have obtained better $\Sigma - D$ relations affixing radio loops. Therefore, we deduce that radio loops present SNRs which were needed for the calibration of the valid $\Sigma - D$ relation. Detection of a greater number of the SNRs which are similar to the radio loops will affirm (or not) the existence of the theoretical $\Sigma - D$ relation.

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МОДЕРНІЗОВАНІ $\Sigma - D$-СПІВВІДНОШЕННЯ І ГОЛОВНІ РАДІОКОНТУРИ ЯК ЗАЛИШКИ СПАЛАХУ НАДНОВОЇ

Д. Уросевиц

Р е з ю м е

Модернізовані $\Sigma - D$-співвідношення (співвідношення між світністю поверхні Σ та діаметром D) для залишків спалаху наднової було використано для дослідження походження головних галактичних радіоконтурів (Контури I, II, III, IV). Аналіз результатів підтвердив гіпотезу про походження радіоконтурів як залишків спалаху наднової. З петльовим додатком удосконалені $\Sigma - D$-співвідношення стають повнішими порівняно з вихідними і дають обнадійливий результат для кута нахилу площини — $\beta \approx 2$.

МОДЕРНИЗИРОВАННЫЕ $\Sigma - D$-СООТНОШЕНИЯ И ГЛАВНЫЕ РАДИОКОНТУРЫ КАК ОСТАТКИ ВСПЫШКИ СВЕРХНОВОЙ

Д. Уросевиц

Р е з ю м е

Модернизированные $\Sigma - D$-соотношения (соотношения между светимостью поверхности Σ и диаметром D) для остатков вспышки сверхновой были использованы для исследования происхождения главных галактических радиоконтуров (Контуры I, II, III, IV). Анализ результатов подтвердил гипотезу о происхождении радиоконтуров как остатков вспышки сверхновой. С петлевым приложением усовершенствованные $\Sigma - D$-соотношения становятся более полными в сравнении с исходными и дают обнадеживающий результат для угла наклона плоскости — $\beta \approx 2$.