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THE RELATION BETWEEN RADIO FLUX DENSITY AND IONISING ULTRA-VIOLET FLUX FOR HII REGIONS AND SUPERNOVA REMNANTS IN THE LARGE MAGELLANIC CLOUD

M. D. Filipović[1,2], P. A. Jones[2] and G. L. White[2]

[1] *University of Western Sydney, Locked Bag 1797 Penrith South, DC NSW 1797 Australia*

[2] *Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 2121 Australia*

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SUMMARY: We present a comparison between the Parkes radio surveys (Filipović et al. 1995) and Vacuum Ultra-Violet (VUV) surveys (Smith et al. 1987) of the Large Magellanic Clouds (LMC). We have found 72 sources in common in the LMC which are known HII regions (52) and supernova remnants (SNRs) (19). Some of these radio sources are associated with two or more UV stellar associations. A comparison of the radio flux densities and ionising UV flux for HII regions shows a very good correlation, as expected from theory. Many of the Magellanic Clouds (MCs) SNRs are embedded in HII regions, so there is also a relation between radio and UV which we attribute to the surrounding HII regions.

Key words. Galaxies: Magellanic Clouds – ISM: HII regions – ISM: supernova remnants – radio continuum: galaxies – ultraviolet: galaxies

1. INTRODUCTION

HII regions are parts of the interstellar medium where the hydrogen clouds have been highly ionised by the ultra-violet (UV) light of hot stars. The radio emission from HII regions is due to thermal bremsstrahlung. Therefore, the detailed theory of the ionisation of HII regions predicts a simple relationship between UV flux of stellar associations and the radio flux of the surrounding HII region (Mezger 1972). Supernova remnants (SNRs) are also associated with groups of massive hot stars so they are often found together with HII regions.

The two Magellanic Clouds (MCs) are an ideal laboratory for such studies of HII regions, SNRs and stellar associations. Their distances are known and amount to only about one-tenth that of the Andromeda Galaxy (M31). They are thus near enough that we can make detailed studies of individual objects in them using large modern telescopes. At the same time they are far enough away that we can assume all the objects in any Cloud are at the same distance from us. Therefore, physical properties of the MCs HII regions, SNRs and stellar associations can be studied without the problems of uncertain distances and high extinction of Galactic studies. It is important to mention that the selection effects may play major role in these type of studies. Especially if given surveys are hampered by low sensitivity, poor resolution results relative to the size of studied objects.

In this paper we compare flux densities for the Large Magellanic Cloud (LMC) HII regions and SNRs from the Parkes radio surveys of Filipović et al. (1995) to the ionising UV flux for corresponding stellar associations from Smith et al. (1987). We compare these results with the theory of Mezger (1972) and Wilcots (1994).

2. IDENTIFICATION OF HII REGIONS AND SNRs IN THE LMC

Catalogues of radio sources towards the LMC at six radio frequencies are presented in Filipović et al. (1995). All these sources (483) have been classified as HII regions (114), SNRs (59) and background objects in Filipović et al. (1998a).

Smith et al. (1987) presented Vacuum Ultra-Violet (VUV) survey of the LMC obtained in two bandpasses with sounding-rocket instrumentation. The bandpasses are each ∼200 Å wide and are centered near 1500 Å and 1900 Å. The angular resolution is ∼50″. Flux densities are given for 122 stellar associations of young stars in the LMC. These 122 sources are the stellar associations in the Lucke & Hodge (1970) catalogue. From the fluxes at 1500 Å, Smith et al. (1987) have calculated ionising flux shortward of the Lyman limit assuming a temperature of 41000 K, and correcting for reddening.

The common area of the radio and VUV surveys (∼40 square degrees) lies between RA(J2000)= 04^h51^m to 05^h57^m and Dec(J2000)=$-71°40'$ to $-65°30'$. The radio positions used are from the highest Parkes radio-frequency survey in which the source appears, as the higher frequency. Parkes data have the best positions (∼20″). These positions were compared with positions from the Lucke & Hodge (1970) catalogue of the LMC stellar associations. The basic criterion for positive source identification is that radio source must lie within the listed diameter of the stellar association (Lucke & Hodge 1970; Table 1; Col. 6).

The comparison of the radio and VUV surveys resulted in the discovery of 72 sources common to both surveys from which 19 are SNRs embedded in HII regions, 52 are HII regions and one is background source. However, some radio sources consist of two or more stellar associations. The one source (B0535-6857 or LH 89/85) which is classified as a background object (Dickey et al. 1994) represents the expected chance coincidence of comparison between the two surveys. No selection effects are accounted for in this comparison since both resolution and sensitivity of both surveys are matching size of the LMC HII regions and SNRs.

Data for these 72 sources in common are presented in Table 1. Column 1 gives the radio source name and col. 2 the Lucke & Hodge (1970) stellar association. The radio flux density is given in col. 3 (also see Filipović et al. 1995). The Lyman flux predicted by the theory (see Eq. 1; Sec. 3) is given in col. 4. The Lyman ionising flux density from Smith et al. (1987) is listed in col. 5. The ratio of these two Lyman fluxes is given in col. 6 and col. 7 lists the source type adopted from Filipović et al. (1998a).

Table 1. Catalogue of the LMC radio sources identified in the VUV survey. The flag (⋆) in Col. 1 denotes complex radio regions around 30 Doradus where flux comparison is not appropriate (see text). The LH source number (Col. 2) is taken from Lucke & Hodge (1970). In Col. 7 we flag with † HII regions classified in Filipović et al. (1998a).

Radio Source Name (1)	LH Association (2)	$S_{4.75GHz}$ (Jy) (3)	Ly Flux (10^{48} ph s^{-1}) predicted from radio (4)	Ly Flux (10^{48} ph s^{-1}) from VUV (5)	Ly Flux Ratio (pred/VUV) (6)	Source Type (7)
B0450-6927	1	0.267	71.2	85.6	0.83	SNR
B0452-6722	3	0.079	21.1	16.8	1.25	HII†
B0452-6924	2	0.256	68.3	40.3	1.69	HII†
B0453-6700	4	0.049	13.1	85.0	0.15	SNR
B0454-6716	6	0.280	74.7	75.7	0.99	HII
B0454-6916	5	0.544	145.1	105.7	1.37	HII
B0456-6629	9,10,13,14	2.092	558.0	489.9	1.14	HII
B0456-6932	8	0.243	64.8	186.8	0.35	HII†
B0457-6830	12	0.610	162.7	235.7	0.69	HII
B0457-6849	11	0.124	33.1	6.9	4.79	HII†
B0503-6722	19	0.090	24.0	90.8	0.26	HII†
B0504-6906	17,16,20	0.093	24.8	21.0	1.18	HII†
B0505-6740	22	0.107	28.5	9.3	3.07	HII†
B0505-7048	24	0.145	38.8	193.3	0.20	HII†
B0505-7058	23	0.064	17.1	4.7	3.63	HII†

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Table 1. (continued)

Radio Source Name	LH Association	$S_{4.75GHz}$ (Jy)	Ly Flux (10^{48} ph s^{-1}) predicted from radio	Ly Flux (10^{48} ph s^{-1}) from VUV	Ly Flux Ratio (pred/VUV)	Source Type
(1)	(2)	(3)	(4)	(5)	(6)	(7)
B0506-6806	25	0.226	60.4	32.5	1.86	SNR
B0507-7029	26	0.146	38.9	23.5	1.66	SNR
B0510-6710	32	0.170	45.3	54.8	0.83	HII†
B0510-6857	31	1.156	308.3	91.7	3.36	HII
B0512-6720	34	0.083	22.1	48.6	0.46	HII†
B0513-6729	37,38	0.186	49.6	39.9	1.24	HII†
B0513-6925	35	0.162	43.2	125.4	0.34	HII
B0518-7117	40	0.152	40.5	19.0	2.13	HII†
B0519-6916	41	1.024	273.1	787.8	0.35	HII
B0519-6941	42	0.866	231.0	152.8	1.51	SNR
B0520-6531	43	0.505	134.7	53.4	2.52	SNR
B0521-6545	45	0.141	37.6	18.5	2.03	SNR
B0522-6757	48	0.236	63.0	115.8	0.54	SNR
B0522-6800	47,48,49	2.481	661.8	748.9	0.88	HII
B0523-6806	49	0.580	154.7	54.8	2.82	HII
B0524-7121	50	0.081	21.6	16.4	1.32	SNR
B0525-6618	52,53	1.173	312.9	269.0	1.16	HII
B0526-6731	54,51	1.214	323.8	220.3	1.47	HII
B0526-6740	55	0.294	78.4	31.0	2.53	HII
B0526-6851	58	1.197	319.3	358.6	0.89	HII
B0526-7137	56	0.044	11.7	6.1	1.92	HII†
B0527-6920	57	0.110	29.3	24.3	1.21	HII
B0528-6730	63	0.563	150.2	164.3	0.91	HII
B0528-7038	62	0.244	65.1	14.6	4.46	SNR
B0530-6655	65	0.100	26.7	22.3	1.20	SNR
B0531-7106	66,69	1.132	302.1	142.4	2.12	HII
B0532-6629	72	0.410	109.4	104.6	1.05	HII
B0532-6734	75	0.093	24.8	30.0	0.83	SNR
B0532-6743	76	1.071	285.7	394.5	0.72	HII
B0532-6833	71	0.676	180.3	248.0	0.73	HII
B0532-6841	73	0.127	33.8	48.0	0.70	HII†
B0534-6726	79	0.443	118.1	39.1	3.02	HII†
B0535-6603	83	0.701	186.9	61.3	3.05	SNR
B0535-6736	82	1.454	387.8	28.8	13.5	SNR
B0535-6857*	89,85	0.320	85.4	738.5	—	BG
B0535-6948	81	0.332	88.6	55.5	1.60	HII
B0536-6735	88	0.200	53.3	9.1	5.86	SNR
B0536-6914*	90	4.536	1210.1	203.8	—	SNR
B0536-6941	87	0.491	131.0	527.8	0.25	HII
B0537-6623	95	0.328	87.5	24.1	3.63	HII
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Table 1. (continued)

Radio Source Name (1)	LH Association (2)	$S_{4.75GHz}$ (Jy) (3)	Ly Flux (10^{48} ph s^{-1}) predicted from radio (4)	Ly Flux (10^{48} ph s^{-1}) from VUV (5)	Ly Flux Ratio (pred/VUV) (6)	Source Type (7)
B0538-6911*	99	3.571	952.5	23.1	—	SNR
B0539-6907*	100	35.79	9545.9	293.6	—	HII
B0539-6931	101	1.272	339.2	537.6	0.63	HII
B0540-6921	104	0.980	261.4	291.2	0.90	SNR
B0540-6935*	106	0.250	66.7	576.6	—	HII†
B0540-6940	103	1.939	517.2	221.8	2.33	HII
B0540-6946*	105	4.186	1116.6	9.6	—	HII
B0540-7111	107	0.081	21.6	17.8	1.21	HII†
B0541-6909*	111	0.150	40.0	185.8	—	HII
B0541-7125	110	0.077	20.5	8.7	2.36	HII
B0542-6906*	113	0.798	212.9	4.1	—	HII
B0543-6752	114	0.253	67.4	18.6	3.62	HII
B0544-6621	115	0.131	34.9	65.3	0.54	SNR
B0545-6710	116	0.246	65.6	84.2	0.78	HII
B0549-7004	117,118	0.699	186.5	169.9	1.10	HII
B0552-6815	121	0.093	24.9	34.2	0.73	HII†
B0556-6814	122	0.099	26.5	8.7	3.05	HII†

3. RADIO TO VUV SOURCE FLUX DENSITY COMPARISON

The radio flux density of HII regions is expected to be proportional to the ionising UV flux. Mezger (1972) and then Wilcots (1994) have predicted the relation between the observed radio flux density and the flux of the Lyman photons ionising the HII regions. The formula from Wilcots (1994) is:

$$F_c = 4.761 \times 10^{48} \times a(\nu, T_e) \times \nu^{0.1} \times T_e^{-0.45} \times S \times D^2 , \quad (1)$$

where F_c is given in photons per second, $a(\nu,\ T_e)$ is a factor equal to 1 in our case, ν is frequency in GHz (4.75), T_e is effective temperature of the source (in our case T_e=10000 K is assumed; Pagel et al. 1978), S is source flux density (at 4.75 GHz) in Jy and D is distance (55 kpc; Van Leeuwen et al. 1997).

The above formula has been used to estimate the flux of ionising UV photons for HII regions given the observed 4.75-GHz radio flux densities (Table 1; col. 4). These predicted UV fluxes were compared with UV fluxes (Table 1; col. 5) from Smith et al. (1987). This comparison is similar to that undertaken by Smith et al. (1987) but uses more HII regions, revised radio flux densities, a slightly different radio frequency and revised distance to the LMC.

The flux-flux comparison is shown on Figs. 1a and 1b in logarithmic scales and the HII regions show good agreement with the Mezger (1972) and Wilcots (1994) model line. For this comparison we did not include 30 Doradus, four other HII regions and two SNRs within 30 Doradus region due to the complicated spatial distribution of the 4.75-GHz emission. For these sources the radio flux densities are not reliable because the area of the source cannot be clearly defined. Also, we exclude from further study the background object (B0535-6857).

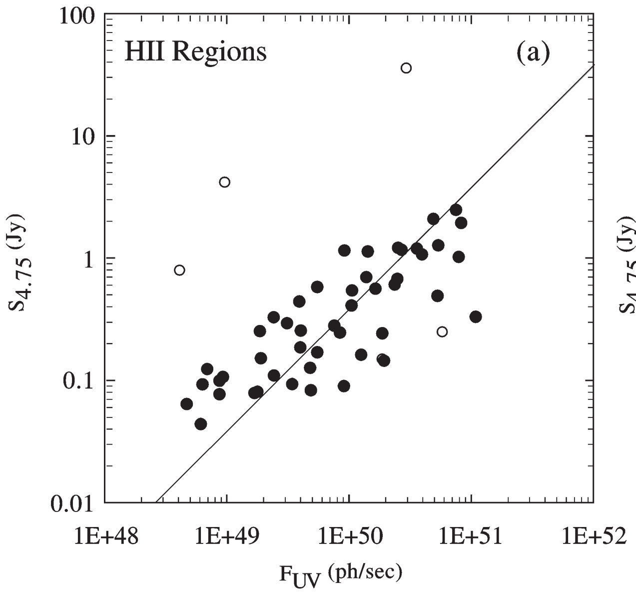

Fig. 1. *The comparison between radio and ionising fluxes (Smith et al. 1987) for 52 HII regions (a) and 19 SNRs (b) in the LMC. Filled circles (a) represent HII regions and five open circles are 30 Doradus and nearby HII regions. Filled squares (b) represent SNRs (embedded in HII regions) and two open squares SNRs near 30 Doradus where the fluxes are confused (see text). The diagonal line represents the theoretical formula (Eq. 1) of Mezger (1972) and Wilcots (1994). There is a good correlation for HII regions.*

The total observed ionising flux from all LH stellar associations ($F_{\mathrm{uvtotal}=8.3\times10^{51}\mathrm{phs}^{-1}}$),[1] is within 1% of the ionising flux predicted from corresponding radio sources ($F_{\mathrm{radiototal}=8.4\times10^{51}\mathrm{phs}^{-1}}$) [2]. However, for some individual sources there are disagreements by a factor of two or more.

We also find that ~32% of LH stellar associations (39 out of 122) do not have radio-continuum counterpart. These sources have a whole range of ionising UV fluxes ($10^{47} - 10^{51}$ ph s^{-1}) and prompt the question of their non radio-continuum appearance. Presumably, these stellar associations are not surrounded by dense hydrogen clouds and thus do not form HII regions. Similarly, some 40 out of 59 radio selected SNRs and 62 out of 114 HII regions classified in Filipović et al. (1998a) do not have corresponding stellar association in Lucke & Hodge (1970).

In order to quantify the agreement of the radio–UV correlation with the theory of Mezger (1972) we calculate the ratio (Table 1; col. 6) of ionising UV flux predicted from the radio flux by Eq. (1) (Table 1; col. 4) to the ionising flux (Table 1; col. 5) obtained from Smith et al. (1987) measurements. The distribution of the ratio for 47 (52-5) HII regions and 17 (19-2) SNRs is plotted in Fig. 2a and 2b with logarithmic bins.

For HII regions the mean of the ratio in the log domain is 0.16 with standard deviation SD=0.78, corresponding to ratio 1.17 with a scatter of factor 2.2. This is in very good agreement with the results of Smith et al. (1987). For the SNRs which have associated Lucke & Hodge (1970) stellar associations and radio fluxes (Filipović et al. 1995): we found the mean ratio (in log domain) of 0.41 and SD=1.04 corresponding to ratio 1.51 with a scatter by the factor 2.8. We interpret this as being a subset of SNRs which are embedded in HII regions. The radio emission of these sources is more likely related to the thermal surroundings of HII regions than to the non-thermal emission of the SNR.

[1] A total of all fluxes from Table 1 (col. 5)

[2] A total of all fluxes from Table 1 (col. 4)

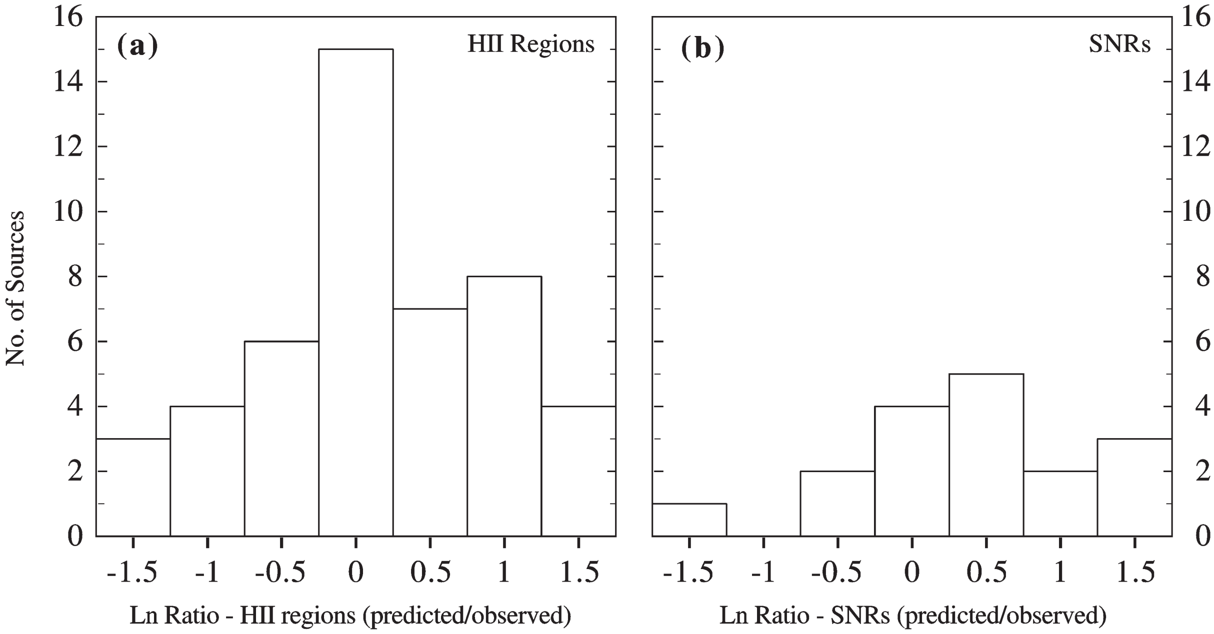

Fig. 2. *The ratio of ionising UV flux predicted from the radio emission compared to that obtained from UV observations, plotted as a histogram on logarithmic scale for (a) HII regions and (b) SNRs.*

Oey & Kennicutt (1997) compared Hα and Lyman continuum emission for 14 LMC HII regions. From the expected relation between these two wavelengths they conclude that there is a substantial leakage of ionising photons from some HII regions while other HII regions appear to be radiation-bounded. If this is the case, we would expect there to be some scatter about the Mezger (1972) relation (Eq. 1) between radio and UV-continuum. Similar results were found by Wilcots (1994) who used the Mezger (1972) relation to estimate UV ionising flux for 11 LMC and SMC HII regions from the radio fluxes of ATCA pointed observations. They compared these fluxes with the UV estimated from their Hα observations. We find, in Filipović et al (1998b), a good correlation between Hα and radio-continuum fluxes of HII regions for the MCs.

4. CONCLUSION

The comparison of Parkes radio surveys of HII regions and SNRs with the UV survey of stellar associations in the LMC has located 72 sources in common. A comparison between source radio flux densities and ionising UV flux shows a good correlation for HII regions, as expected from theory. More surprisingly, a subset of radio SNRs mostly fit the same radio-UV relation as the HII regions probably because they are in close physical relation.

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РЕЛАЦИЈА ИЗМЕЂУ РАДИО И ЈОНИЗОВАНОГ УЛТРА-ЉУБИЧАСТОГ ФЛУКСА ЗА HII РЕГИОНЕ И ОСТАТКЕ СУПЕРНОВИХ У ВЕЛИКОМ МАГЕЛАНОВОМ ОБЛАКУ

М. Д. Филиповић[1,2], П. А. Џонс[2] и Г. Л. Вајт[2]

[1] *University of Western Sydney, Locked Bag 1797 Penrith South, DC NSW 1797 Australia*

[2] *Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 2121 Australia*

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Оригинални научни рад

У овој студији представљамо поређење између Паркс радио прегледа (Филиповић са сарадницима 1995) и вакум ултра-љубичастих (VUV) прегледа (Смит са сарадницима 1987) Великог Магелановог Облака (LMC). Пронађена су 72 заједничка објекта у ВМО-у од којих су најбројнији раније класификовани ха-два HII региони (52) и остаци супернових (SNRs) (19). Неки од ових радио објеката могу се идентификовати са две или више познате УВ звездане асоцијације. Поређење густине радио флукса и јонизованог УВ флукса за HII регионе показују одличну корелацију баш као што је и теоријски предвиђено. Већина остатака супернових у Магелановим Облацима налазе су у HII регионима, тако да значајно доприносе релацији између радио и УВ у односу на околне и самосталне HII регионе.