CLASSIFICATION OF SUPERNOVA REMNANTS AND HII REGIONS FROM THEIR RECOMBINATION LINE EMISSION

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Abstract

H109α recombination line observations are used in an attempt to classify 46 galactic radio sources as either supernova remnants or HII regions. Long integrations at the H109α line frequency on two well-known supernova remnants (IC 443 and 3C 391) provide improved upper limits on the line emission from these objects. From these results the electron temperature in IC 443 is estimated to be in excess of $1 \cdot 6 \times 10^4$ K.

I. Introduction

Most of the radio sources in the Galaxy can be classified as either supernova remnants (SNR's) or HII regions on the basis of their radio spectra, polarization characteristics, and whether or not they exhibit hydrogen recombination lines (Milne 1970; Downes 1971). Milne *et al.* (1969) have established the criterion that HII regions generally have H109α recombination line intensities greater than 3% of the continuum level, and no detectable line has been found in a conclusively established SNR which does not have an HII region in the same direction. However, a number of the classifications remain uncertain, because the spectra are poorly determined and the recombination line surveys (Reifenstein *et al.* 1970; Wilson *et al.* 1970) either did not include the source or used such a short integration time that the results were inconclusive.

In this paper we present the results of searches for H109α recombination lines from 46 sources, most of which at one time or another have been considered to be possible SNR's.

II. Observations and Results

The observations were made in two separate sets: in July 1971 using the CSIRO 64 m telescope at Parkes and in February 1972 using the 42 m telescope at the Green Bank Observatory of NRAO. The 64 m telescope was equipped with an AIL parametric amplifier with a system noise temperature of 80 K and a 64-channel filter spectrometer with a resolution of 100 kHz per channel (corresponding to a velocity of $6 \cdot 0$ km s^{-1} at this frequency); the beamwidth was $4' \cdot 2$ arc. A TRG parametric amplifier with a system noise temperature of 60 K and a 413-channel autocorrelator with an effective resolution of 63 kHz was used on the 42 m telescope (beamwidth $6' \cdot 5$ arc).

The results of the survey are presented in Table 1. The galactic number of each source is given in the first column and the measured antenna temperature T_L of the

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H109α line is in column 2. Where no line was detected we have listed the line temperature as less than 2·5 times the r.m.s. noise level on that record. The r.m.s. noise for each source, which is a function of the integration time, is given in column 3. In column 4 the ratio of line temperature to continuum temperature, measured from the same observations, is given. Where a line was detected, its width to half-intensity (in kHz) and its velocity with respect to the local standard of rest are given in columns 5 and 6 respectively. The telescope used, either Green Bank or Parkes, is indicated (by G or P) in column 7. The common name is given in column 8 and our conclusion as to the nature of the source, on the evidence of these recombination line observations, is given in column 9. In a number of cases these conclusions are corroborated by spectral data and independent recombination line measurements.

The results in Table 1 generally indicate whether a given object is an SNR or not, but a few sources need specific comments.

G289·1—0·4 and G295·2—0·6

These two sources previously appeared to be exceptions to the general conclusions of Milne *et al.* (1969) in that they both exhibited almost 3% H109α line but appeared to have nonthermal spectra. Improved spectral data (Shaver and Goss 1970) show that both these sources are thermal, and our line detections confirm those of Wilson *et al.* (1970).

G310·6—0·3 and G310·8—0·4

These sources were thought to be nonthermal by Kesteven (1968), and Milne's (1969) observations suggested that at least one source in this close pair was nonthermal. From the recombination line results presented here G310·8—0·4 is definitely thermal and G310·6—0·3 is possibly nonthermal.

G337·8—0·1

No recombination line stronger than 1% of the continuum was found by Wilson *et al.* (1970) for this source. Since the continuum spectrum appeared to be thermal, Milne *et al.* (1969) suggested that it might be a high-temperature HII region. The T_L/T_C ratio of 0·02 found here is a positive detection but is lower than is usually associated with a normal HII region, while more recent continuum data (Shaver and Goss 1970) suggest that the spectrum is nonthermal. The low T_L/T_C ratio may be the result of an SNR–HII blend.

G355·2+0·1

The combination of marginal continuum data and the reported absence of H109α lines (Reifenstein *et al.* 1970) for this source led Milne *et al.* (1969) to suggest that this source was nonthermal.

G8·5—0·3, G45·5+0·1, and G78·9+3·7

The detection of lines in these sources is contrary to the results of Reifenstein *et al.* (1970) but similar to the findings of Wilson and Altenhoff (1972).

G11·2—0·4, G21·5—0·9, G74·9+1·2, and G78·3+2·5

Our results are in agreement with those of Wilson and Altenhoff (1972) but our upper limits on a possible line are somewhat lower. In G78·3+2·5, where Wilson and Altenhoff placed a lower limit of 0·04, we find a line at $T_L/T_C = 0{\cdot}018$.

TABLE 1

RECOMBINATION LINE RESULTS

(1) Galactic source number	(2) T_L (K)	(3) ΔT r.m.s. (K)	(4) T_L/T_C	(5) Half-width (kHz)	(6) Central velocity (km s^{-1})	(7) Telescope used	(8) Name	(9) Nature of source
G127·3+0·7	<0·01	0·004	<0·10			G	NRC 5	Inconclusive
G128·0−3·9	<0·01	0·004	<0·2			G	S22	Inconclusive
G130·7+3·1	<0·02	0·008	<0·003			G	3C 58	SNR
G166·1+2·3	<0·01	0·004	<0·11			G	VRO 41.05.01	Inconclusive
G180·0−1·7	<0·015	0·006	—			G	S147	Inconclusive
G189·1+2·9	<0·004	0·0015	<0·003			G, P	IC 443	SNR
G194·0−1·6	0·016	0·005	0·054	334±52	4±3	G	S34	HII region
G263·4−3·0	<0·04	0·015	<0·013			P	Vela X	SNR
G267·9−1·1	5·15	0·02	0·042	602±33	0±2	P	MSH 08−47	Calibrator
G289·1−0·4	0·27	0·052	0·060	368±45	20±3	P		HII region
G289·9−0·8	0·155	0·035	0·071	535±69	5±4	P	MSH 11−61B	HII region
G290·1−0·8	<0·03	0·01	<0·013			P	MSH 11−61A	SNR
G295·2−0·6	0·12	0·032	0·037	535±61	41±4	P	Kes 16	HII region
G299·4−0·3	0·09	0·030	0·15	418±77	−52±5	P	RCW 64	HII region
G310·6−0·3	<0·06	0·025	<0·067			P	Kes 20B	Possibly SNR
G310·8−0·4	0·135	0·036	0·110	468±70	18±5	P	Kes 20A	HII region
G337·8−0·1	0·10	0·035	0·02	435±70	−52±5	P	Kes 41	SNR plus HII region
G348·2+0·5	0·070	0·015	0·102	484±61	−14±4	P	RCW 120	HII region
G349·7+0·2	<0·02	0·008	<0·010			G		SNR
G355·2+0·1	0·90	0·020	0·110	668±81	8±5	P	NGC 6383	HII region
G359·5−0·1	<0·02	0·008	<0·005			G		SNR
G0·1+0·0	0·275	0·020	0·017	874±45	−92±3	G		Possibly a blend
G0·9+0·1	<0·02	0·008	<0·009			G	Kes 55	Nonthermal
G6·0−1·2	0·50	0·010	0·058	435±33	6±2	G	M8	Calibrator
G8·5−0·3	0·075	0·010	0·062	384±41	35±3	G		HII region
G11·2−0·4	<0·006	0·0025	<0·012			P		SNR
G13·4+0·1	0·065	0·010	0·062	1100±84	28±5	G		HII region
G20·0−0·2	<0·02	0·008	<0·022			G		Probably SNR
G21·5−0·9	<0·02	0·008	<0·017			G		Probably SNR
G31·9+0·0	<0·011	0·0045	<0·005			P	3C 391	SNR
G33·1+0·0	<0·02	0·008	<0·055			G	Kes 78	Inconclusive
G35·6−0·4	0·083	0·015	0·065	534±56	52±4	G		HII region
G35·5−0·0	<0·015	0·006	<0·019			G		SNR
G37·9−0·4	0·29	0·034	0·2	468±42	61±2 }	P	W47	HII region
G37·4−0·2	0·15	0·043	0·043	601±90	39±5 }			
G45·5+0·1	0·40	0·030	0·050	434±37	54±2	P	Kuz 47	HII region
G69·9+1·5	0·032	0·012	0·03	484±96	−61±6	G		HII region
G74·8+0·6	0·0375	0·010	0·036	334±54	0±4	G		HII region
G74·9+1·2	<0·02	0·008	<0·018			G		SNR
G78·2+1·8	0·075	0·006	0·039	368±38	1±3	G	γ Cygni	Nonthermal plus thermal background
G78·3+2·5	0·025	0·012	0·018	635±151	−10±9	G	DR 3	HII region
G78·5−0·1	0·045	0·008	0·035	418±49	−14±4	G	DR 12	HII region
G78·9+3·7	0·032	0·015	0·09	334±87	1±5	G	DR 1	Probably HII region
G79·8+1·2	0·052	0·010	0·095	518±60	−22±4	G	DR 11	HII region
G82·2+5·4	<0·015	0·006	<0·12			G	W63	Inconclusive
G93·6−0·3	<0·008	0·003	—			G	CTB 104A	Inconclusive
G117·3+0·1	<0·015	0·006	—			G	CTB 1	Inconclusive
G118·1+5·0	0·080	0·015	0·093	351±46	−8±3	G	NGC 7822	HII region

G31·9+0·0

The source 3C 391 is considered to be a definite SNR but with a significant decrease in its emission at low frequencies. Bridle and Kesteven (1971) and Caswell *et al.* (1971) have suggested a number of reasons for this change in the spectrum, a possible explanation being interstellar free–free absorption in front of the SNR.

For such a case Bridle and Kesteven predict a T_L/T_C ratio of 0·0045 for a normal line width of 30 $km\,s^{-1}$; this value is at the limit of the present data.

G37·9—0·4 and G37·4—0·2

Holden and Caswell (1969) and Milne (1970) suggested from the continuum spectrum that W47 was an SNR but we have detected a strong H109α line from two positions within this source. Our velocity for G37·9—0·4 agrees with the velocity measured by Reifenstein *et al.* (1970) at the same position; however, the apparently very much lower velocity for G37·4—0·2 should be noted.

G74·8+0·6 to G79·8+1·2

The entire Cygnus-X complex appears to be thermal, with the probable exceptions of G74·9+1·2 and the source near γ Cygni, in general agreement with the results of Wendker's (1970) analysis of the continuum spectra of the sources in this region. The beam used for the present observations of the source near γ Cygni overlapped the nearby definite HII region so that a recombination line was observed.

III. Discussion

One of the consequences of this work is that (including G78·6+1·0 from Wilson and Altenhoff 1972) the SNR classification of 13 sources in Milne's (1970) catalogue and 18 in the slightly more ambitious list of Downes (1971) is now questioned. Nine of these sources were thought to be SNR's, in the absence of adequate continuum spectra, because Reifenstein *et al.* (1970) failed to find an H109α recombination line in these directions. A conclusion that has been drawn from a comparison of the northern (Reifenstein *et al.* 1970) and southern (Wilson *et al.* 1970) H109α surveys is that the percentage of sources exhibiting no recombination line is much higher in the northern survey than in the southern survey (Altenhoff and Wilson 1970). The discovery that at least nine of these northern sources do in fact emit recombination lines corrects this discrepancy to some extent. There are large selection differences between the northern and southern H109α surveys and careful consideration of these should be made in any comparative analysis.

Some discussion on our observations of IC 443 is warranted. This object is the brightest SNR in Hα light and is therefore the one most likely to exhibit hydrogen recombination lines. We find that the observed line-to-continuum ratio in the bright north-eastern filament is $< 0\cdot003$, but of course the radio continuum includes nonthermal emission as well as free–free emission from the bright filaments. Assuming that the filaments are collisionally excited, we may use the formulae of Parker (1964*a*) to determine a ratio of the Hα emission to the free–free continuum emission as a function of electron temperature. The ratio of H109α to free–free continuum also can be determined as a function of temperature using the formulae given by Reifenstein *et al.* (1970), assuming a width for the undetected line corresponding to the 50 $km\,s^{-1}$ measured for the Hα line by Lozinskaya (1969). Combination of these values gives the ratio of Hα to H109α as a function of electron temperature. The integrated flux of the object in Hα has been measured by Parker (1963), and we can get an upper limit to the flux in H109α by using the above ratio of $T_L/T_C < 0\cdot003$

together with the total flux density at 5000 MHz given by Milne (1971). The results imply an excitation temperature of greater than 16 000 K for IC 443, which may be compared with the values found, from the low excitation lines, in the Cygnus Loop (Parker 1964*b*) and Vela X (Milne 1968), namely 17 000 K and 10 000 K respectively.

Departures from local thermal equilibrium in the populations of the higher bound levels of the hydrogen atom (Sejnowski and Hjellming 1969) will lower the electron temperature estimated from the recombination lines. However, for the moderate electron densities measured in IC 443 ($\sim 350\ \mathrm{cm}^{-3}$, Parker 1964*b*) and electron temperatures in excess of 15 000 K we should not have to increase our estimate of T_e by more than 1000 K.

In this analysis for IC 443 we have assumed that the electron temperature and the ratio of nonthermal to thermal emission both remain constant across the nebula. Presumably the relative intensity of Hα in the bright filaments where the H109α line measurements were made is higher than in the rest of the source, so that the temperature may be even higher. An increase in adopted line width will lower our estimate of the temperature, and Lozinskaya (1969) has measured Hα line widths up to 225 $\mathrm{km\,s}^{-1}$ in other parts of IC 443. However, H109α lines of this extreme width would not be detected with our limited filter bank width. Although the source IC 443 is the most likely SNR to exhibit H109α lines, the above analysis indicates that such lines are near the limit of detection and that further observations of greater sensitivity should be undertaken. However, below 25 000 K the ratio T_L/T_C is a steep function of temperature, varying approximately as T_e^{-4} in the region $15\,000 \leqslant T_e \leqslant 20\,000$ K. An increase of a factor of two in integration time would therefore be necessary to increase the lower limit on temperature from 16 000 to 18 000 K.

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