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A HIGH RESOLUTION SEARCH FOR SMALL SCALE STRUCTURE IN SHARPLESS HII REGIONS AT 4.995 GHz. THE CATALOGUE

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To increase the sample of known small scale radio emission features in HII regions, a 6 arcsec resolution survey of 77 Sharpless HII regions was made with the Westerbork Synthesis Radio Telescope at 4.995 GHz. Strip scan distributions were obtained for 103 fields, with a limiting flux density of 30 mJy. Of this sample, 51 fields were reobserved more extensively and two-dimensional maps were obtained. From these maps, positions and flux densities of several new sources were determined. A list of all observed fields and the peak flux density detected in each field is given. The position, maximum size and flux density of all sources with $S_\nu > 25$ mJy are given. These basic lists are presented as an aid to observers looking for interesting objects to observe at optical, infrared and radio wavelengths. A more complete analysis of the fields will appear in a later paper.

Key words: HII regions – radio observations – high resolution

INTRODUCTION

In this paper the results of a systematic search for compact radio sources associated with the HII regions listed in the Sharpless (1959) catalog are presented. This search was carried out with the Westerbork Synthesis Radio Telescope (WSRT) at a frequency of 4.995 GHz ($\lambda = 6$ cm). The primary motivation for this study was to enlarge the sample of compact HII regions. With this larger sample it should be possible to make some statistical conclusion concerning the early phases of the evolution of an HII region.

One of the main question to be answered is where are the compact HII regions located and what is their relationship with respect to the other indicators of recent star formation. The solution to this problem is important in testing the two following hypotheses on the manner in which star formation proceeds: 1) the expansion of an evolving HII region triggers the formation of new stars (Hjellming 1970, Israel *et al.* 1973, Habing *et al.* 1975, Elmegreen and Lada 1977); 2) the formation of massive stars leads to the destruction of the dense neutral cloud material and halts further star formation (Herbig 1962).

If the first hypothesis is true, then compact HII regions should be located inside or near evolved HII regions. If the second one is true, then there should be no association between compact and evolved features. Finally, a question related to the two hypotheses is whether compact components are isolated objects or they always form in groups. Some evidence for the later has been presented by Harten (1976) and Israel (1976).

It is obvious that a large sample of objects must be studied before any definite conclusion about the two hypotheses can be made. Although a fair number of HII regions have been searched in the past for presence of compact components, we believe that the existing material is incomplete and suffers from strong selection effects. Ideally one would like to have a survey of the galactic plane at a frequency of 5 GHz, a sensitivity of at least 0.1 Jy and a resolution of a few arcsec. Such a survey does not exist and it is unlikely that it will be undertaken due to the large amount of time and effort needed.

The existing surveys have been made: a) at lower frequencies, b) with poorer angular resolution (~ 10 arcmin) and c) with poor sensitivity (~ 1 Jy). Such surveys are sensitive mainly to larger (> 10 arcmin), low density ($n_e = 5 - 500$ cm^{-3}) HII regions where self absorption by the gas is not important.

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Unfortunately, any weak compact components are lost due to the poor resolution and sensitivity. Only the brightest compact components (*e.g.* in W3 and NGC 7538) have been discovered through these surveys.

Searches for compact components in areas of the sky near known indicators of stars formation, other than radio HII regions, (H_α emission stars, T Tauri stars, IR point sources or CO "hot spots") have not been very successful and few new compact sources have been detected. Thus it appears that the chances of detecting isolated components with flux densities > 1 Jy at 15 GHz are quite small (Churchwell *et al.* 1969).

Recent work by the authors and others have shown that compact features are often associated with small, visible HII regions, many of which are Sharpless objects. These results indicated that a systematic survey of the Sharpless objects with known radio emission was needed.

A survey of this type was conducted by Felli *et al.* (1974) using the Stanford five element interferometer, at a wavelength of 2.8 cm. Of the 140 regions surveyed, 7% contained new compact features and 15% contained features at the limit of the noise (1.2 Jy).

In the present search, with a factor 40 better in sensitivity and a much higher spatial resolution, we have selected areas inside HII regions listed in the Sharpless catalogue which show a peak in the radio continuum emission studied by Felli and Churchwell (1972).

If an HII region was larger than 10 arcmin and did not show any prominent peak in the lower resolution data, only the central maximum was observed. This introduces a bias since we have selected the areas of higher surface brightness for our observations. Sources near the equator were given lower priority because of the degraded resolution of the synthesized beam. We did not include any source which had previously been observed with the WSRT at 6 cm. Unfortunately, the area near the center of the Galaxy ($0° < \ell < 90°$) was not completely sampled due to lack of available telescope time.

The combination of this work with other recent works done with the WSRT by the authors and others, provides a sample of approximately 150 HII regions. This sample is large enough to enable us to study some of the problems regarding compact components and their relationship with more evolved HII regions. A detailed study of individual regions and a discussion of some of the statistical properties of compact HII regions as well as their relationship to more evolved HII regions will be discussed in two subsequent papers. The present paper provides a short summary of the results of the survey and it is intended as an aid to those planning future observations of HII regions.

OBSERVATIONS

The observations were made using the Westerbork Synthesis Radio Telescope at a frequency of 4.995 GHz. The telescope and its operation have been described by Baars and Hooghoudt (1974) and Casse and Muller (1974). The standard calibration and reduction procedures were used (Högbom and Brouw 1974, van Someren Greve 1974). Table 1 gives the basic parameters of the observations.

The observing was done in two stages. In the initial stage, Spring 1975, each selected field was observed near meridian transit for a period of 20 minutes, yielding a "single cut" in the *u,v* plane. The data were time averaged and a one-dimensional Fourier transformation was made. In this way we were able to observe a large number of potentially interesting areas and to check for the presence of small scale structures. The single cut observations were equivalent to scanning an 11 arcmin area in right ascension with a 6 × 660 arcsec fan beam. To improve the detection of sources with extensions larger than 15 arcsec, we also made a second Fourier transform of the original data with a resolution of 12 arcsec in right ascension.

In the second stage of the observations, the latter half of 1975 and throughout 1976, we reobserved each field that showed a peak flux density $\geqslant 30$ mJy in the single cut data. During this stage, each source was observed at five different hour angles (at $\delta < 20°$ only three-hour angles could be observed). These multicut data were then Fourier transformed in two dimensions, yielding an ultimate angular resolution of 6.6×6.6 cosec δ over a field of view 11 arcmin in diameter. The Fourier transforms were carried out using slow Fourier transforms in a specially designed programme, Slofour, written by one of us (Harten 1974). Several

HII regions are larger than the field of view and we tried to cover them in adjacent observations. However, lack of observing time has prevented us from always achieving this goal and compact components may have been missed in such cases

Our method of observation and data reduction leads to several limitations on the data and its usage. First, since only a limited number of discrete cuts were available and the *u,v* plane was not covered continuously, large sidelobe levels of the synthesized beam occurred. It was necessary to correct for the effects of the sidelobes, using the "clean" method (Högbom 1974). All data were cleaned to a level of 20 mJy and restored using a Gaussian beam of the same size as the synthesized beam. Secondly, large extended fields with a smooth brightness distribution will not be properly represented due to our incomplete sampling in hour angle and baseline. Thirdly, the incomplete sampling, combined with a low signal-to-noise ratio can cause the clean programme to work improperly, since artificial sources may occur at grating or sidelobe locations and a pattern of closely spaced point-like objects in regions of relatively smooth emission may be created. This problem was clearly present in S209 and S226. In these cases, the individual peaks were not treated as individual sources. In most cases it was possible to correct for these problems by examining the uncleaned maps. When we were reasonably but not completely certain that a source was real, we indicated it in the tables. Similarly, we may have missed a few weak sources that occurred near grating or sidelobes. All sources listed in this paper are either isolated or at least two to three times the level of the surrounding emission.

If a region is smaller than two arcmin, the shape is hardly distorted and we will have detected most of the flux density. For larger sources, the grating responses and the associated zero level shifts in the maps distort the source shape while the finite minimum baseline of the observations allows us to measure only a small fraction of the total flux density of the object.

To check the limitations of our data and our reduction procedures, we included the object S90 in our survey. A complete synthesis of this object has recently been published by Israel (1976). The object does not contain any compact features and consists of a smooth low brightness region with a brighter arc superimposed. Our observations were able to detect only the brightest ridge of emission corresponding to the broad maximum in Israel's map. We were unable to determine either the total extent or the basic shape of the low brightness emission. This indicates that our search is not very sensitive to moderately extended smooth objects.

An important difference between the single and multi-cut data is that the noise has different effects. In the single cut data each baseline has an equal noise contribution. This noise when transformed in the Fourier transform leads to false large and small scale components of comparable intensity. This is quite important to keep in mind since generally one is tempted to attribute only small scale variations to the noise and large scale variations to the astronomical source. In the multi-cut data the same argument applies to each baseline; however, the short baseline data is more closely packed in the *u,v,* plane that the longer baseline data. This results in a lower effective noise in the shorter baseline data. Thus, the largest contribution to the noise has a small scale size. Any low brightness, large scale features are more likely to be real in these maps.

DISCUSSION

Table 2 gives the summary of the observational results. For the non-detections, the coordinates given in columns 2 and 3 are those of the field centre (FC in the "comments" column) used for the observations and the upper limit to the flux density given in column 4 is the maximum flux density per beam area detected in the observed field with a fan beam of 6 arcsec × 11 arcmin.

In a few cases a peak flux density larger than the noise was found in the observed field, but the source was not reobserved because believed to be a non-thermal one. In these cases the peak flux density per beam area (PEAK in column 4) is given.

For the detected sources, the position, flux density (corrected for the primary beam attenuation), and size are given. Several of the detected sources are at low declination and, because of the decreased resolution, only a crude check of the source extent in the N-S direction can be given.

The broadened, B ($20'' < \Theta < 60''$), sources are those which have minimal instrumental effects and in which the measured flux density is probably close to the true flux density of the source. The extended, E ($\Theta > 60''$), sources may be attenuated by the interferometric antenna pattern and we are probably measuring only the fraction of the total flux density contained in the small scale structures. Also given in column 6 is the name of the Sharpless source in which the field is located. It should be understood that the Sharpless name should be used only as a reference, because the larger Sharpless objects are not completely covered by our observations.

In the 103 fields searched a total of 47 sources were detected in 34 different Sharpless objects, 19 of which are unresolved.

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Table 1 Observational parameters

Frequency of observations (GHz)	4.995
Wavelength (cm)	6
HPBW primary beam (arcmin)	11.3
HPBW synthesized beam (arcsec)	$6.6 \times (6.6/\sin(\delta))$
Radius of first grating response (arcmin)	2.8
Shortest spacing (wavelengths)	1200
FWHM of a gaussian source with a visibility of 0.5 at shortest spacing (arcmin)	$1.3 \times (1.3 \times \sin(\delta))$
r.m.s. noise per 20 minute observation (mJy)	30

Table 2 Summary of observational results

N.	R.A. (1950)	Dec. (1950)	Flux (mJy)	Size (arcsec)	Field	Comments
1	19^h 09^m 17.6^s ± .3	16° 47′ 31″ ± 3	29 ± 5	10* × 34*	S 80	B
2	19 09 16.9 ± .3	16 46 46 ± 3	52 ± 5	10* × 34*	S 80	B
3	19 22 19.9 ± .3	20 41 30 ± 3	535 ± 50	16 × 30	S 83	B
4	19 21 56.3 ± .3	20 37 46 ± 3	325 ± 70	50 × 78	S 83	B, arc of emission
5	19 41 10.7 ± .3	23 13 10 ± 3	25 ± 5	10* × 25*	S 86	
6	19 44 13.7 ± .2	24 27 58 ± 2	240 ± 20	21 × 39	S 87	B
7	19 44 15.9 ± .2	24 28 48 ± 2	45 ± 10	10* × 25*	S 87	B
8	19 44 33.8	28 00 00	< 18		S 92	FC
9	19 26 19.9	31 21 43	< 21		S 94	B, FC
10	19 57 09.8 ± .3	31 13 32 ± 3	320 ± 30	55 × 62	S 98	
11	19 58 25.0 ± .3	35 04 16 ± 3	46 ± 10	10* × 19*	S101	Displaced from H II
12	20 32 18.8 ± .3	45 27 04 ± 3	36 ± 6	10* × 14	S112	
13	20 32 15.8 ± .3	45 27 43 ± 3	25 ± 5	12 × 15	S112	Weak
14	20 33 28.5 ± .3	46 55 33 ± 3	33 ± 5	10* × 14*	S115	
15	20 33 21.3 ± .3	46 55 40 ± 3	56 ± 10	16 × 44	S115	
16	20 43 49.0	45 04 59	< 16		S117	FC
17	20 49 07.9	44 12 00	36 (Peak)		S117	B, FC
18	20 51 31.9	43 30 00	< 21		S117	FC
19	20^h 52^m 00.0^s	44° 13′ 59″	106 (Peak)		S117	FC, Non thermal source
20	20 53 41.0	43 40 59	< 22		S117	FC
21	20 55 19.9	43 18 00	< 19		S117	FC
22	21 02 27.8	49 41 06	< 26		S120	B, FC
23	21 03 35.4 ± .3	49 27 55 ± 3	125 ± 20	42 × 44	S121	B
24	21 36 30.0	50 06 11	< 27		S124	FC
25	21 39 10.1	50 10 01	< 26		S124	FC
26	21 41 00.0	50 10 01	< 24		S124	B, FC
27	21 51 33.9	47 07 01	< 21		S125	FC, slightly offset from optical nebula
28	21 27 07.4 ± .3	54 24 10 ± 3	200 ± 40	12 × 12*	S127	B
29	21 27 04.7 ± .3	54 23 28 ± 3	125 ± 40	10* × 36	S127	
30	21 27 06.4 ± .3	54 24 34 ± 3	53 ± 20 120 ± 40	10* × 12*	S127 S127	Envelope
31	21 27 31.4 ± .3	54 18 36 ± 3	95 ± 40	10* × 12*	S127	Possible grating confusion
32	22 21 10.0	56 07 00	51 (Peak)		S132	FC
33	22 18 56.0	55 55 00	< 24		S132	FC
34	22 15 40.0	55 18 00	< 24		S132	FC
35	22 15 20.0	55 12 00	< 24		S132	FC
36	22 22 20.0	55 27 00	< 26		S132	FC
37	22 30 52.7 ± .2	58 12 49 ± 2	550 ± 50	8 × 9	S138	
38	22^h 17^m 12.0^s	63° 01′ 55″	< 18		S140	FC
39	22 26 51.6 ±1.0	61 22 18 ±20	200 ±100	180 ×180	S141	Size limited by grating
40	22 45 32 ± 1	57 48 00 ±30	350(1) ±300	180 ×180	S142	E
41	22 45 31.9	57 05 42	< 14		S142	FC
42	22 45 31.9	57 37 05	< 13		S142	FC
43	22 44 12.0	57 47 06	< 17		S142	FC
44	22 46 51.8	57 47 06	< 28		S142	FC
45	22 47 31.0 ± .2	59 39 00 ± 2	2400 ±100	40 × 34	S146	E
46	22 54 13.2 ± .2	58 15 21 ± 2	550 ± 50	30 × 36	S148	E
47	22 55 55.9	62 15 00	< 16		S155	FC
48	22 55 00.0	62 20 00	< 19		S155	FC
49	22 56 40.0	62 30 00	< 21		S155	FC
50	23 39 48.8	60 40 59	< 11		S166	FC
51	23 33 13.1 ± .3	64 35 52 ± 3	110 ± 40	112 × 70	S167	B
52	23 59 00.0	64 19 59	< 17		S170	FC
53	00 18 31.9	61 26 53	< 17		S173	FC
54	00 49 40 ± 3	56 18 00 ±60	390(1) ±300	600 ×360	S184	E, Two arcs part of same source
55	00 50 20 ± 3	56 19 00 ±60				
56	01 05 38.5 ± .3	62 51 39 ± 3	140 ± 30	29 × 24	S186	B
57	01 27 00.0	58 07 01	< 17		S188	FC
58	02 47 31.0	62 00 00	< 15		S196	FC
59	02 46 12.0	59 29 35	< 21		S198	FC
60	02 45 30.0	60 15 00	< 20		S199	FC
61	02 49 30.0	60 30 00	< 15		S199	FC
62	02^h 53^m 40.1^s	60° 25′ 01″	< 24		S199	B, FC
63	02 53 00.0	60 10 01	< 20		S199	FC
64	02 59 22.4 ± .3	60 16 12 ± 3	780 ± 50	150 ×180	S201	E, Size limited by grating
65	03 19 08.7 ± .1	54 35 58 ± 1	100 ± 10	10 × 10	S203	B
66	03 19 14.1 ± .2	54 35 06 ± 2	25 ± 5	10* × 10*	S203	
67	03 48 24.0	53 16 01	< 19		S205	FC
68	04 07 17 ± 2	51 01 00 ±60	3500 ±100	180 ×180	S209	E, Size limited by grating
69	04 27 13.9	52 22 59	< 18		S210	FC
70	04 55 00.0	47 55 41	< 18		S217	FC
71	04 52 29 ± 2	47 18 55 ±10	160(1) ±100	180 ×150	S219	
72	04 26 57.4 ± .2	35 09 56 ± 2	165 ± 10	12 × 17	S222	B
73	04 26 58.4 ± .3	35 09 36 ± 4	30 ± 10		S222	Southern Extension
74	05 20 47.3	40 34 59	< 18		S225	FC
75	05 07 36.4 ± .2	37 55 37 ± 3	450 ±50	120 × 90	S226	E
76	05 12 55.0	34 28 59	< 23		S229	FC
77	05 36 00.0	35 45 00	40 (Peak)		S231	FC, Bright optical part of nebula not in the field
78	05 19 20.9	34 00 00	< 13		S236	FC
79	05^h 18^m 30.0^s	33° 39′ 00″	< 15		S236	FC
80	06 01 41.0	30 11 53	< 20		S241	FC, Bright optical nebula not in field
81	05 48 44.9	27 01 19	< 22		S242	FC
82	06 05 28.1	21 37 59	33 (Peak)		S247	FC
83	06 05 56.9	15 40 59	< 22		S261	FC
84	06 06 37.0	15 45 00	< 21		S261	FC
85	06 05 21.3 ± .3	15 44 40 ±10	35 ± 5	10* × 40*	S261	
86	06 13 00.0	14 16 59	< 27		S267	B, FC
87	06 07 49.0	13 22 30	< 18		S268	FC
88	06 06 49.9	13 00 00	< 20		S268	FC
89	06 09 00.0	13 34 59	< 26		S268	FC
90	06 11 00.0	13 09 00	318 (Peak)		S268	FC
91	06 07 23.6 ± .3	12 49 10 ±20	28 ± 5	10* × 40*	S270	
92	07 26 18.0	13 21 00	< 14		S274	FC
93	05 32 48.0	-04 54 29	< 26		S279	FC, Only one of two bright regions sampled
94	06 31 44.9	02 30 29	< 24		S280	FC
95	06 32 29.0	02 40 01	< 19		S280	FC
96	06 35 32.9	01 27 54	< 19		S282	B, FC
97	06 35 54.0	00 45 00	< 21		S283	B, FC
98	06 42 54.0	00 21 00	< 23		S284	FC
99	06^h 52^m 42.0^s	00° 25′ 59″	< 17		S285	FC
100	06 52 15.6 ± .3	-04 30 30 ±30	45 ± 10	10* ×120*	S286	
101	06 57 01.0	-04 45 00	< 15		S287	FC
102	07 06 09.8 ± .3	-04 13 03 ±30	620 ± 60	10 × 60*	S288	B
103	07 06 09.6 ± .3	-04 11 10 ±30	44 ± 5	5* × 60*	S288	B
104	06 53 05.0	-07 57 00	< 24		S291	FC
105	07 02 05.0	-10 22 59	< 20		S292	FC
106	07 14 11.0 ± .3	-09 19 24 ±30	32 ± 5	10* × 60*	S294	
107	07 14 06.6 ± .3	-09 19 48 ±30	30 ± 5	10* × 60*	S294	B
108	07 00 18.0	-11 22 59	< 18		S295	FC
109	07 02 53.0	-12 14 24	< 19		S297	B, FC
110	07 16 12.2 ± .2	-13 10 05 ±30	37 ± 8	10* × 40*	S298	
111	07 16 20.6 ± .6	-13 06 22 ±30	30 ± 5	10* × 40*	S298	Possible grating confusion
112	07 07 33.6 ± .3	-18 30 00 ±30	40 ± 8	10* × 40*	S301	E
113	07 29 29.0	-16 54 18	< 20		S302	FC
114	07 27 56.0 ± .3	-18 26 13 ±30	28 ± 5	10* × 40*	S305	E
115	07 28 07.9	-18 56 42	< 18		S306	FC
116	07 33 22.0 ± .3	-18 39 05 ±30	270 ± 40	36 × 42	S307	B
117	07 33 32.0 ± .3	-18 44 59 ±30	100 ± 20	14 × 40*	S307	B
118	07 29 57.7 ± .3	-19 20 58 ±30	40 ± 10	10* × 40*	S309	

* Unresolved by beam, size is an upper limit estimate.

(1) Flux determined from fringe visibilities.

FC = Field centre: i.e. the coordinates are those of the field centre of the observations.