1988ApJ...326..884W

THE ASTROPHYSICAL JOURNAL, **326**:884–888, 1988 March 15

FLUX DENSITIES OF ULTRACOMPACT H II REGIONS AT 7 MILLIMETERS

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Received 1987 July 9; accepted 1987 September 3

ABSTRACT

We report 7 mm continuum observations of 29 suspected ultracompact (UC) H II regions. Twenty-seven sources were detected, most of which had not previously been observed at 7 mm. These sources were found to be small (only eight were fully resolved by our 43″ beam) and bright at millimeter wavelengths (>0.5 Jy), making them easy to distinguish from associated diffuse free-free emission which can confuse single-dish observations made at centimeter wavelengths. The ionizing stars are mostly O5–O6, consistent with our detection limit of 0.5 Jy. We find that dust in UC H II regions typically absorbs more than 50% of the stellar ionizing photons. Some of the sources reported here might also serve as flux and pointing calibrators at millimeter wavelengths.

Subject headings: nebulae: H II regions — stars: formation

I. INTRODUCTION

Ultracompact (UC) H II regions are associated with sites of recent O and B star formation. Several have been mapped with high spatial resolution at radio wavelengths by Felli, Johnston and Churchwell (1980); Colley (1980); Dreher and Welch (1981); Ho and Haschick (1981); Dreher *et al.* (1984); Felli, Churchwell, and Massi (1984); Turner and Matthews (1984); Garay, Reid, and Moran (1985) and Garay, Rodríguez, and van Gorkom (1986). These observations have shown that UC H II regions are *very* small, typically 0.01 pc to 0.1 pc in diameter and have emission measures greater than 10^7 pc cm^{-6}. Ultracompact H II regions are frequently associated with older, more extended, and less dense H II regions.

Ultracompact H II regions interact with their environment in several observable ways. They are deeply embedded in dust "cocoons" which completely absorb UV and optical starlight rendering them invisible optically, but bright in the FIR. Interferometric radio continuum observations show that the ionized gas has a variety of morphologies; shell structures are seen in some (Turner and Matthews 1984; Colley 1980; Dreher and Welch 1981; Felli, Churchwell, and Massi 1984), while others have arc structures (Wood and Churchwell 1988; Garay, Rodríguez, and van Gorkom 1986). The continuum images of UC H II regions often show *very steep* brightness gradients along their outer boundaries, indicating that they are generally ionization bounded by dense molecular gas and dust. This is corroborated in a few cases where molecular absorption has been observed against the H II region. Some sources appear to have a rotating or expanding ring of ionized gas (Garay, Rodríguez, and van Gorkom 1986; Ho and Haschick 1986). Because they represent a very early stage in the evolution of massive stars and are a means to probe the interaction of stellar gravitation, radiation, possible particle winds, and magnetic fields in a star-forming region, UC H II regions have received considerable observational attention in the past few years.

Obtaining a complete picture of the interactions UC H II regions have with their environs has been hampered, however, by the small number of known sources and by incomplete observations of their flux density distributions. The first problem has been addressed by recent continuum observations made at 1.3 mm by Chini *et al.* (1986*a*, *b*; hereafter CKMG) and at 3 mm by Wood, Churchwell, and Salter (1988) which have identified several new, potential UC H II regions. But for many sources the second problem, our incomplete knowledge of their continuum spectra, remains. It is important that we rectify this situation because the radio to near-infrared flux density distribution of a source provides several valuable diagnostics of the embedded star(s), the H II region, and its dust "cocoon." The free-free (f-f) contribution to the spectrum can be used to estimate the rms electron density, electron temperature, emission measure, and UV photon flux necessary to ionize the circumstellar gas, while the infrared spectrum provides a measure of the total luminosity of the central star(s) and a basis for determining the properties (density, temperature, etc.) of the circumnebular dust cocoon. It is, perhaps, surprising that the flux distributions of these sources are not as well determined at radio and millimeter wavelengths as they are at infrared wavelengths. This is partly due to the extensive *IRAS* database and to the fact that UC H II regions are typically much brighter at FIR wavelengths than at radio wavelengths.

Here we report single-dish flux density measurements of 29 probable UC H II regions at 7 mm (43.3 GHz). We used the Nobeyama Radio Observatory[5] 45 m telescope because high spatial resolution is required to separate UC H II emission from surrounding diffuse H II emission. These 7 mm observations are a good measure of the flux of the plasma in the optically thin portion of its spectrum, and they aid in the determination of the "turnover" frequency at which the f-f emission becomes optically thin. At 43.3 GHz we are in fact only slightly past the turnover frequencies of most UC H II regions (typically in the range 10–30 GHz). Observations at 7 mm are also important because the 3 mm observations of Wood, Churchwell, and Salter (1988), and especially the 1.3 mm data of CKMG, are contaminated by dust emission, making them a poor measure of the source flux in the optically thin portion of the f-f spectrum. This research is part of a larger project which will combine these and other mm observations, cm observations made with the VLA (Wood and Churchwell 1988), and

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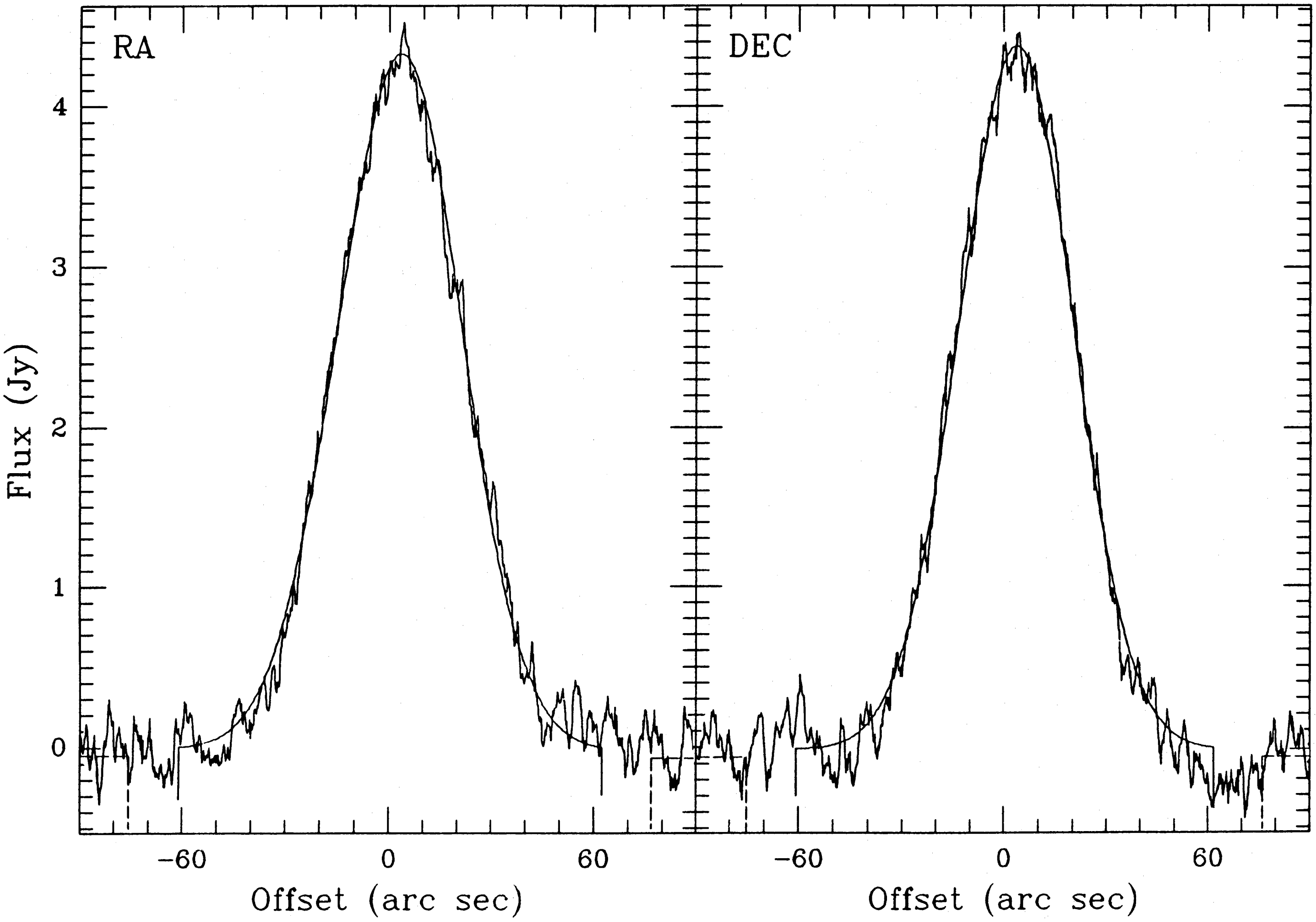

FIG. 1.—An example of a typical "cross-scan" pair. The source was scanned several times through the best known position and the average (shown here) was fitted with a two-dimensional Gaussian (*smooth curve*) to determine the true source position, flux density, and angular diameter (if resolved).

the *IRAS* database to construct models of the warm dust and ionized gas.

II. OBSERVATIONS

The observations were made using the 45 m telescope of the Nobeyama Radio Observatory on 1986 June 20–21. A general description of the 45 m telescope is found in Akabane *et al.* (1983). The single-sideband receiver had a bandwidth of 500 MHz centered on 43.3 GHz. The system temperature was ~650 K (at 70° elevation). The beam was approximately circular, with a HPBW of 43".5 at 43.3 GHz as determined from observations of Jupiter, Venus, and 3C 84 (T. Takano and M. Inoue, private communication). We employed beam switching with a throw of 6'.5. Observations were made in a "cross-scan" mode in which two scans, one aligned with the R.A. and the other with the decl. axis, were taken through the best known position of the source. Figure 1 shows a cross-scan pair for a typical source. Each scan took 25 s to complete and was typically 2' in length. The time constant for integration was chosen to ensure that the beam was well sampled. These cross-scans were repeated 10 times or until a good signal-to-noise ratio was obtained. The average of all the cross-scans for a particular source was then fitted with a two-dimensional Gaussian model (source and beam) to obtain the peak flux, source position, and angular diameter in right ascension and declination.

The pointing accuracy of the telescope is estimated to be less than 10" based on periodic observations of SiO maser sources. Pointing corrections were applied online. The zenith opacity of the atmosphere, measured at three separate times during the observations, increased smoothly from 0.10 to ~0.20 during the course of the observations due to deteriorating weather conditions. Venus and Mars were used for absolute flux calibration using the method described by Ulich *et al.* (1980). Their brightness temperatures (210 K for Mars and 400 K for Venus) were obtained by interpolating the figures in Ulich (1974) to 7 mm. We estimate ~10% accuracy in the flux calibration, not including errors in the brightness temperatures of the planets (<8%). As a check of the calibration we also observed W3(OH) at the beginning and at the end of the run and found our measured flux density to be in very good agreement (<2%) with that of Krügel and Mezger (1975).

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[1] The Nobeyama Radio Observatory (NRO), a branch of the Tokyo Astronomical Observatory, University of Tokyo, is a facility open for general use by researchers in the fields of astronomy and astrophysics.

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TABLE 1

45 m TELESCOPE OBSERVATIONS AT 43.3 GHz

				GAUSSIAN WIDTH				FLUX	
	POSITION			Observed		Deconvolved[a]			
SOURCE	α(1950)	δ(1950)	τ_{atm}	α (″)	δ (″)	α (″)	δ (″)	Peak (Jy)	Int. (Jy)
W3(OH)	$02^h23^m17\overset{s}{.}6$	61°39′04″	0.16/0.22	40	44	pt. source		3.05	
G6.55−0.10	17 57 47.4	−23 20 30	0.25	...	...	...	...	<0.5	
G8.14+0.23	17 59 59.7	−21 48 06	0.18	51	55	27	33	1.26	1.85
G5.97−1.18(M8)	18 00 36.1	−24 22 56	0.26	58	57	39	36	2.52	4.44[b]
G9.61+0.20	18 03 13.8	−20 32 09	0.24	76	30	62	<15	0.49	
G8.67−0.36	18 03 18.7	−21 37 50	0.25	40	40	pt. source		0.93	
G10.62−0.38	18 07 30.8	−19 56 26	0.24	43	40	pt. source		4.29	
G11.95−0.03	18 08 56.1	−18 36 53	0.24	47	44	19	<15	1.00	
G19.6−0.2	18 24 50.0	−11 58 28	0.21	41	46	<15	15	2.53	
G20.1−0.1A	18 25 22.9	−11 30 38	0.21	37	45	pt. source		0.97	
G23.70+0.17	18 31 10.8	−08 09 20	0.20	73	45	59	<15	0.48	
G24.47+0.49	18 31 26.6	−07 20 31	0.20	60	64	41	47	1.13	2.32
G23.43−0.21	18 31 59.9	−08 34 50	0.21	...	...	...	...	<0.5	
G29.96−0.02	18 43 27.0	−02 42 43	0.15	41	44	pt. source		2.85	
G30.53+0.02	18 44 23.8	−02 10 39	0.15	36	40	pt. source		0.81	
G32.96+0.28	18 47 56.3	−00 05 35	0.18	42	43	pt. source		2.64	
G33.9+0.11	18 50 17.0	−00 51 41	0.15	63	49	46	22	0.66	1.02
G34.25+0.15	18 50 46.0	01 11 11	0.14	44	43	pt. source		6.12	
G35.19−1.74	18 59 13.9	01 09 10	0.13	48	42	21	<15	4.02	
G45.07+0.14	19 11 00.6	10 45 56	0.23	59	46	40	<15	0.69	
G45.13+0.14	19 11 07.3	10 48 37	0.22/0.24	41	42	pt. source		4.02	
G45.45+0.06	19 11 59.2	11 03 47	0.25	44	70	<15	55	1.46	
G43.89−0.79	19 12 04.7	09 17 14	0.28	54	62	32	44	0.83	1.47
W51D	19 21 21.2	14 25 24	0.27	73	45	58	<15	7.83	
W51E	19 21 24.0	14 24 43	0.28	58	74	38	60	12.72	28.6[b]
G75.84+0.40	20 19 48.3	37 21 56	0.14/0.27	49	45	22	<15	3.43	
G75.77+0.34	20 19 49.3	37 16 19	0.15/0.28	54	57	31	37	1.43	2.31
G76.38−0.62	20 25 33.0	37 12 60	0.14/0.29	52	52	28	29	3.52	5.05
61W15	21 19 05.6	51 40 42	0.15/0.27	35	44	pt. source		0.74	

[a] "pt. source" indicates that the source was unresolved relative to our 43″ HPBW.

[b] This object is located in a complicated field and may be confused by other sources.

III. RESULTS

Twenty-nine suspected UC H II regions were observed and 27 were detected with signal-to-noise ratios greater than 5 σ. This is the first detection at 7 mm for nearly all of these sources. Table 1 gives the source name, fitted position, atmospheric opacity at the time of observation, observed and deconvolved angular diameters, and the peak and integrated flux densities corrected for atmospheric attenuation. We estimate the errors in the source positions given in Table 1 to be about 10″. The flux densities for sources observed on both days have been averaged; the difference was never greater than 20% which is within their combined errors. In these cases, two values for the atmospheric opacity are given in Table 1. All of the detected sources have small angular diameters relative to our HPBW of ~43″ as one would expect for UC H II regions, and 17 have fluxes greater than 1 Jy.

In Table 2 we derive some parameters of the exciting stars and circumstellar dust shells assuming the distances given in column (2) and that each source is ionized by a single star. In column (3) we give the Lyman continuum photon flux, N_c', required to produce the observed 7 mm flux density. Nearly all of these values correspond to ionization by O6 stars or hotter. This cut-off is a selection effect due to our sensitivity limit of 0.5 Jy (see Wood, Churchwell, and Salter 1988). We note that N_c' *underestimates* the total Lyman continuum photon flux, N_c*, produced by the central star(s) because it does not include UV photons absorbed by dust. To estimate the magnitude of this effect we list in column (4) the observed infrared luminosity, L_{IR}, given by CKMG. L_{IR} is a good measure of the total luminosity of the system since dust eventually absorbs nearly all of the stellar radiation and reemits it in the FIR. Column (5) gives the ZAMS spectral type (Panagia 1973) inferred from L_{IR}. We can also use the observed Lyman continuum photon flux, N_c', to estimate the spectral type. Based on N_c' alone, most of the ionizing stars in our sample appear to be O6 or hotter, in agreement with CKMG, but while we find few stars hotter than O6, CKMG find several. In all cases, the spectral type we estimate using N_c' is always *cooler* than that found using L_{IR} by CKMG. This difference can be attributed to absorption of stellar UV photons by dust. The fraction of ionizing photons absorbed by dust, $f_d = (1 - N_c'/N_c^*)$, is given in column (6) of Table 2. *Typically dust absorbs more than 50% of the ionizing photons.* This is a lower limit because there may be an additional contribution to the f-f emission due to associated diffuse H II which would tend to overestimate N_c' and underestimate f_d. The three sources with negative values of f_d are probably IR and radio source misidentifications; they are included here for completeness. To derive f_d we have assumed that a single star is responsible for the ionization of each source. Given the fact that the observed parameters of a system of multiple O stars are easily dominated by whichever member has the earliest spectral type, this assumption is questionable only for systems which contain nearly identical stars.

Our 7 mm fluxes are, in all cases, less than the 3 mm and 1.3 mm fluxes reported by Wood, Churchwell, and Salter

TABLE 2

DERIVED PARAMETERS

Source (1)	Assumed[a] Dist. (kpc) (2)	Log N_c' (s^{-1}) (3)	Log L_{IR}[b] ($L/L_\odot$) (4)	Sp. Ty.[c] from L_{IR} (5)	f_d (6)
W3(OH)	3.0	48.50	5.27[d]	O6.5	>0.52
G8.14+0.23	4.2	48.58	5.28	O6.5	>0.42
G5.97−1.18(M8)	1.9	48.27	4.92	O7.5	>0.42
G9.61+0.20	0.6	46.31	3.64	B1	−9.54[e]
G8.67−0.36	6.2	48.62	5.42	O6	>0.65
G10.62−0.38	6.5	49.32	6.09	O4	>0.75
G11.95−0.03	5.2	48.50	4.99	O7	>0.24
G19.6−0.2	4.5	48.78	5.42	O6	>0.50
G23.70+0.17	9.0	48.66	5.60	O5.5	>0.80
G24.47+0.49	7.6	49.19	5.93	O5	>0.63
G29.96−0.02	9.0	49.43	6.30	O4	>0.68
G30.53+0.02	13.8	49.25	5.71	O5.5–O5	>0.42
G32.96+0.28	15.6	49.87	6.39	O4	>0.12
G33.9+0.11	8.2	48.90	5.49	O6–O5.5	>0.52
G34.25+0.15	3.7	48.99	5.77	O5.5	>0.57
G35.19−1.74	3.2	48.68	5.45	O6	>0.60
G45.13+0.14	9.5	49.63	6.22	O4	>0.50
G45.45+0.06	9.7	49.20	6.16	O4	>0.81
G43.89−0.79	10.3	49.26	5.44	O6	−0.51[e]
G75.84+0.40	5.5	49.08	5.78	O5.5	>0.47
G75.77+0.34	5.6	48.93	5.65	O5.5	>0.63
G76.38−0.62	1.0	47.77	4.50	O9.5–B0	−0.48[e]

[a] From various sources given in CKMG.

[b] From CKMG except where noted.

[c] Panagia 1973.

[d] From Krügel and Mezger 1975.

[e] Negative values are probably misidentifications.

(1988) and by CKMG, respectively. In many cases the difference is greater than a factor of 5. Wood, Churchwell, and Salter (1988) also pointed out that the 3 mm fluxes they obtained were generally less than those at 1.3 mm reported by CKMG. The difference cannot easily be attributed to differences in beam sizes and resolution effects, since nearly all of the sources are unresolved. And though it might indicate a systematic error, we believe that it is more likely attributable to increasing warm dust emission toward shorter mm wavelengths. This is supported by an examination of the individual source spectra which typically peak near 100 μm about three *orders of magnitude* greater than the extrapolated f-f emission. The fluxes at 3 mm, and especially at 1.3 mm, often show an upturn toward the large 100 μm peak causing their spectra to deviate from the $\nu^{-0.1}$ power-law dependence expected for optically thin f-f radiation alone.

We conclude that observations at wavelengths *shorter* than 7 mm can be unreliable measures of the optically thin f-f radiation of the ionized gas because they often suffer from contamination due to dust emission, while on the other hand, observations at wavelengths *longer* than 7 mm made with a single dish are influenced by emission from more extended, diffuse H II, with which UC H II regions are often associated. Thus, 7 mm is an ideal wavelength at which to measure the flux of ultracompact H II regions in the optically thin portion of their spectra.

IV. SUMMARY

We have identified several new objects which appear to be ultracompact H II regions by observing known compact H II regions at 7 mm, where only the highest emission measure components are likely to be detected, and by using a telescope with sufficient spatial resolution to separate diffuse from UC H II emission. These are the first observations at 7 mm for most of the sources and they serve to bridge the gap between measurements of the optically thick and optically thin portions of the free-free spectrum.

We found the sources to be small relative to our HPBW of 43″ and relatively bright. Based on the photon flux required to ionize the gas, most of the stars appear to be O6 or hotter, though this is an underestimate due to dust absorption. It appears that dust competes effectively with the gas for stellar UV photons. If we assume that a single star is responsible for the ionization and compare the UV photon flux required to maintain the H II region (inferred from the radio continuum) with that produced by the ionizing star (inferred from the IR luminosity) we find that generally more than 50% of the ionizing photons are absorbed by dust within the H II region. Models of the ionizing gas and of the circumnebular dust cocoon would benefit greatly from higher resolution radio and IR observations; most of the sources in our sample were unresolved with our 43″ beam.

We note that flux density measurements at 7 mm are less contaminated by warm dust emission than observations at shorter wavelengths and are less influenced by associated diffuse H II emission than those at longer wavelengths. Thus 7 mm flux densities are more reliable measures of the optically thin portion of the H II region emission. In addition to their astrophysical interest, several of the sources reported here (e.g., G10.62−0.38, G29.96−0.02, G32.96+0.28, G34.25+0.15, or G45.13+0.14) may be good flux and pointing calibrators at millimeter wavelengths.

We would like to thank the director of the Nobeyama Radio Observatory for permitting this program to be scheduled on the 45 m telescope and the National Science Foundation for its generous assistance with travel expenses for D. O. S. W. Support for E. B. C. under NSF grant AST 86-05125 is also acknowledged.

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