January 10, 1996

The H II Region Complex G5.48-0.24: Radio Continuum, H I, and CO Observations

Bon-Chul Koo, *Seoul National University*

Kee-Tae Kim, *Seoul National University*

Ho-Gyu Lee, *Seoul National University*

Min S. Yun, *University of Massachusetts - Amherst*

Paul T P Ho

THE H II REGION COMPLEX G5.48–0.24: RADIO CONTINUUM H I, AND CO OBSERVATIONS

BON-CHUL KOO,¹ KEE-TAE KIM,¹ HO-GYU LEE,¹ MIN-SU YUN,² AND PAUL T. P. HO³

Received 1995 April 3; accepted 1995 July 14

ABSTRACT

We have carried out VLA radio continuum (6 and 20 cm), VLA H I 21 cm line, and ¹³CO $J = 1-0$ line observations of the Galactic H II region G5.48–0.24. We present the continuum maps at 21 cm with $\sim 50''$ resolution and at 6 and 20 cm with $\sim 5''$ resolution. The radio continuum maps show that the H II region is composed of a bright component immersed in a diffuse emission of $\sim 6'$ (or 21 pc) radius. The bright component has a compact (0.7 pc) core surrounded by an extended (3.4 pc) halo. According to Wood & Churchwell (1989), the compact core has an ultracompact (0.04 pc) subcomponent. The rms electron density of the diffuse emission is 7 cm^{-3} and it increases roughly by a factor of 10 from one structure to the next small-scale structure. The observed radio continuum flux, half of which is contributed by the diffuse emission, requires an ionizing star of O5 ZAMS. If we consider the direct absorption of ionizing stellar photons by dust within H II regions, the bright component alone requires an O5 exciting star.

The brightness of the diffuse continuum emission decreases steeply along its western boundary and gradually at other directions. The VLA H I 21 cm line maps show that there is an H I cloud in contact with the steep western boundary. The ¹³CO line observations show that there is a giant molecular cloud associated with the H II region. The bright component of the radio continuum emission coincides with the dense core of the molecular cloud. Therefore, G5.48–0.24 appears to be an H II region-molecular cloud complex where the formation of massive stars occurred recently. The radio continuum structures of largely different dynamical ages (e.g., 4×10^3 – 2×10^6 yr) may indicate that either the sequential star formation is proceeding, or G5.48–0.24 is a blister-type H II region.

Subject headings: H II regions — ISM: individual G5.48–0.24 — ISM: structure — radio continuum: ISM — radio lines: ISM

1. INTRODUCTION

G5.48–0.24 is a Galactic H II region detected in the 6 cm survey of Altenhoff et al. (1978) using the Effelsberg 100 m telescope. It is listed as a compact (2'9) source with peak flux density of 1.3 Jy. The source has been also observed in later surveys made with the same telescope at 11 cm (Reich et al. 1984) and at 21 cm (Reich, Reich, & Fürst 1990). The listed sizes and flux densities, however, show large differences; $\sim 5'$ and 2.04 Jy (11 cm) and $\sim 11'$ and 3.15 Jy (21 cm). Wink, Altenhoff, & Mezger (1982) made radio continuum observations at 2, 3, and 6 cm using the same telescope, and derived the source radius of $42''$ and the mean electron density of 180 cm^{-3} . They also found a subcomponent of $16''$ radius with a larger (680 cm^{-3}) electron density using a three-element interferometer. Recently, Wood & Churchwell (1989, hereafter WC89) made VLA observations with $0''.4$ resolution, and have detected an ultracompact ($\sim 1''.4$) component with high ($\sim 1 \times 10^4 \text{ cm}^{-3}$) electron density.

Hence, although it appears in the catalog of ultracompact H II regions (Churchwell 1990), the results of previous observations suggest that G5.48–0.24 has a complicated structure. At a distance of 12.5 kpc (assuming $R_\odot = 8.5 \text{ kpc}$), which has been derived from H110 α emission and H₂CO absorption line studies (Downess et al. 1980), the reported sizes range from 0.08 pc to 40 pc. In this paper, we show that G5.48–0.24 is indeed a large H II region complex with associated atomic and molecular clouds. In § 2, we describe the H I 21 cm line, radio

continuum, and ¹³CO observations. In § 3, we present the continuum maps and derive the physical parameters of G5.48–0.24. The continuum maps show the detailed structure between $5''$ and $15'$ (or between 0.3 and 50 pc) scale. In § 4, we summarize the results of H I and CO observations and derive the physical parameters of the associated atomic and molecular clouds. In § 5, we discuss the *IRAS* observations of G5.48–0.24 and compare the infrared results with our radio continuum results. In § 6, we discuss the nature of G5.48–0.24. Finally, in § 7, we summarize the paper.

2. OBSERVATIONS

2.1. H I 21 cm Line Observations

H I 21 cm line observations were made using the Very Large Array (VLA) of the National Radio Astronomy Observatory⁴ in the D configuration on 1991 March 4. The field center was $(\alpha_{1950}, \delta_{1950}) = (17^{\text{h}}55^{\text{m}}50^{\text{s}}, -24^\circ24')$. The flux and bandpass calibrators were 3C 286 and 3C 48, which were assumed to have flux densities of 14.84 and 16.03 Jy (at 1.423 GHz), respectively. The phase calibrator was 1748–253 and its bootstrapped flux was 1.17 ± 0.01 Jy. Only right circular polarization was observed. With on-line Hanning smoothing, the 128 channel correlator with a bandwidth of 3.125 MHz provided a velocity resolution of 5.153 km s^{-1} and a velocity coverage of 660 km s^{-1} . The calibrator frequency was shifted $\pm 3.125 \text{ MHz}$ with respect to the source frequency in order to avoid Galactic H I 21 cm line in the band. The data were edited

¹ Department of Astronomy, Seoul National University, Seoul 151-742, Korea.

² Astronomy Department, Caltech 105-24, Pasadena, CA 91125.

³ Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

⁴ The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1
SUMMARY OF VLA CONTINUUM OBSERVATIONS

PARAMETER	20 cm		6 cm
	1991 Mar 4 ^a	1991 Oct 18, 1992 Feb 3	1992 Feb 3, Jun 29
Central wavelength (cm).....	21.12	20.14	6.173
Array	D	A/B + B/C	B/C + C/D
Field center	(17 ^h 55 ^m 50 ^s , -24°24')	(17 ^h 56 ^m 06 ^s , -24°21')	(17 ^h 56 ^m 06 ^s , -24°21')
Bandwidth (MHz).....	0.74	100	100
On-source time (minutes).....	150	80	80
Baseline range (km)	0.025-1.03	0.081-16.7	0.034-4.92
Synthesized beam	72" × 37" × -3°	6".1 × 4".5 × 52°	6".1 × 4".5 × 52°
1 σ noise (mJy beam ⁻¹)	1.2	0.15	0.12

^a H I 21 cm emission line observation. Continuum data have been extracted from the line-free channels.

and calibrated following the standard VLA programs in AIPS (the Astronomical Image Processing Software).

The 21 cm continuum map was obtained from the line-free channels, and has an equivalent bandwidth of 0.74 MHz (see Table 1). The H I 21 cm line images have been obtained by subtracting the continuum emission in the *uv* plane. The strong CLEAN components of the continuum emission were first subtracted using the AIPS task UVSUB and then the residual continuum emission were subtracted using UVBAS. The final images have been CLEANed using the AIPS task MX.

2.2. VLA Continuum Observations

The VLA D array 21 cm continuum map revealed that G5.48-0.24 has a bright, compact (~2') component immersed

in an extended (~10'), diffuse emission (see Fig. 1). In order to explore the detailed structure of the compact component, we carried out continuum observations using the VLA configurations with longer baselines. Since the source is at low declination, we used the hybrid configurations where the north arms are extended. We chose the "scaled-array" at 20 and 6 cm, which makes the comparison between the 20 and 6 cm maps easy. The observational parameters are summarized in Table 1.

The flux calibrator was 3C 286, which was assumed to have flux densities of 14.64 Jy (1.465 GHz) and 7.53 Jy (4.885 GHz). The phase calibrator was 1748-253, and its bootstrapped fluxes were 1.19 ± 0.01 Jy (1.465 GHz) and 0.49 ± 0.02 Jy (4.885 GHz). The data of individual arrays at each band were

FIG. 1.—21 cm image of G5.48-0.24 made with the VLA D array. Contour levels (in 5 mJy beam⁻¹) are -1, 1, 2, 3, 5, 10, 20, 50, and 100.

edited and calibrated separately. The calibrated uv data sets for different hybrid configurations were merged to generate a uv data base for each band. The uv data were then self-calibrated. The final image has been CLEANed using MX. The 20 and 6 cm images have been convolved to have an identical beam ($6''.1 \times 4''.5$, P.A. = 52°) for comparison.

2.3. $^{13}\text{CO } J = 1-0$ Line Observations

The $^{13}\text{CO } J = 1-0$ (110.20137 GHz) observations were made using the 14 m telescope of the Taeduk Radio Astronomy Observatory between 1993 October and 1994 March. The telescope has a FWHM of $45''$ and a beam efficiency of 0.45 at 110 GHz. Typical system temperature was 700 K. A 256 channel filterbank with 1 MHz frequency resolution and spacing was used. The velocity was centered at $v_{\text{LSR}} = +75 \text{ km s}^{-1}$, so that the velocity coverage was $v_{\text{LSR}} = -274$ – $+421 \text{ km s}^{-1}$. A rectangular area bounded by $l = 5^\circ 09' - 41'$ and $b = -0^\circ 37' - +0^\circ 00'$ has been mapped at $1'$ spacing. The spectra were obtained by position switching to $(l, b) = (5^\circ 25', \pm 2^\circ)$. Two reference positions were used to reduce baseline fluctuations. The on-source integration time was 1 and 2 minutes for the outer and inner fields, respectively. Typical rms noise level is 0.1 K per channel. During the observing run, we regularly monitored the standard source M17 at ($18^{\text{h}}17^{\text{m}}31^{\text{s}}.0$, $-16^\circ 13' 05''$) and M17SW at ($18^{\text{h}}17^{\text{m}}26^{\text{s}}.5$, $-16^\circ 14' 54''$). Their peak antenna temperatures (when position-switched to $+30'$ in azimuth) were $6.3 \pm 0.6 \text{ K}$ and $8.6 \pm 0.8 \text{ K}$, where the error bars are the 1σ fluctuations. Hence, the flux measurement is accurate to about 10%.

3. RADIO CONTINUUM RESULTS

3.1. Morphology and Physical Parameters

The VLA 21 cm D array map in Figure 1 shows that G5.48–0.24 is composed of a slightly resolved bright component embedded in a diffuse structure of $\sim 10'$ (or 36 pc) size. The bright component is elongated ($\sim 2' \times 1'$) along the N-S direction, roughly parallel to the western boundary of the diffuse emission. The diffuse structure has a steep cutoff along its western boundary, while its brightness decreases gradually in other directions. There are three relatively strong ($> 1.5 \text{ mJy beam}^{-1}$) ridges, each of which is $7'$ long and appears to be

connected to the bright component. Also, note that there is a small ($\sim 1'$) extrusion from the bright component to the north-east direction. This extrusion coincides with an infrared source (see § 5.1).

Figures 2a and 2b are the VLA 20 and 6 cm high-resolution images, which show the detailed structure of the bright component in Figure 1. They show that at $1'$ scale the source is again composed of a strong compact component embedded in an extended structure. The compact component is located in the southern part of the extended structure and is elongated along the east-west direction. The brightness of the extended structure generally decreases from the compact component. But there are also several local intensity peaks. There is no noticeable difference in morphology between the 20 and 6 cm maps.

For convenience, we separate the continuum emission into three components: core, halo, and plateau. The core is the densest part in Figures 2a and 2b. The halo is the extended structure in Figures 2a and 2b. The core and halo constitute the bright component in Figure 1. The plateau is the diffuse emission in Figure 1. These three components are indicated in Figure 3, which shows the distribution of the 20 cm brightness temperatures along the E-W and N-S cuts crossing the peak position. The N-S cut (with a position angle of $+20^\circ$) is parallel to the western boundary of the plateau emission, while the E-W cut is perpendicular to it. The brightness temperature T_b has been computed from

$$T_b = \frac{S_\nu \lambda^2}{2k_B \Omega_{\text{sb}}}, \quad (1)$$

where S_ν is the flux density, k_B is the Boltzmann constant, and Ω_{sb} is the solid angle of the synthesized beam (see Table 1). Figure 3 shows that each component is well defined; T_b varies gradually in each component, but it varies abruptly between components. The peak brightness temperatures are 143 and 2080 K in VLA-D and A/B + B/C arrays, respectively.

The radio continuum parameters of the three components are summarized in Table 2. The peak position of the core agrees with that, ($17^{\text{h}}55^{\text{m}}58^{\text{s}}.650$, $-24^\circ 20' 43''.24$) or $(l, b) = (5^\circ 475', -0^\circ 243')$, of the VLA 6 cm A array observations with $0''.4$ resolution (WC 89). The 6 cm integrated flux density of the

TABLE 2
RADIO CONTINUUM PARAMETERS OF G5.5–0.24

Parameter	Core	Halo	Plateau	Total
Observed				
Peak position	$(17^{\text{h}}55^{\text{m}}58^{\text{s}}.8, -24^\circ 20' 43'')$			
Size	$15''.0 \times 10''.6^{\text{a,b}}$	$\sim 2''.7 \times 1''.8$	$\sim 16'' \times 11''$	$\sim 16'' \times 11''$
20 cm peak flux density (Jy beam^{-1})	0.103	...	...	0.103
6 cm peak flux density (Jy beam^{-1})	0.131	...	...	0.131
20 cm integrated flux density (Jy)	$0.535 \pm 0.013^{\text{a}}$	0.82 ± 0.09	1.45 ± 0.27	2.80 ± 0.25
6 cm integrated flux density (Jy)	$0.534 \pm 0.017^{\text{a}}$	0.80 ± 0.07	...	> 1.33
Derived				
$\bar{R}_S$ (pc)	0.70	3.4	21	21
u (pc cm^{-2})	58	66	77	96
$\bar{n}_e$ (cm^{-3})	750	86	7.0	9.8
$M_{\text{H II}}$ ($M_\odot$)	24	320	6100	6400
N_L ($10^{49} \text{ photons s}^{-1}$)	0.92	1.4	2.2	4.5

NOTE.—Flux densities are the values after the primary beam correction.

^a Computed from a Gaussian fitting.

^b Size at 20 cm. At 6 cm, it is $13''.7 \times 9''.7$.

FIG. 2.—(a) 20 cm image of G5.48-0.24 made with the VLA A/B and B/C arrays. Contour levels (in $0.5 \text{ mJy beam}^{-1}$) are -1, 1, 2, 4, 7, 10, 15, 25, 50, 100, and 200. (b) 6 cm image of G5.48-0.24 made with the VLA B/C and C/D arrays. Contour levels are same as in (a).

FIG. 3.—One-dimensional distributions of the 20 cm brightness temperature T_b across the peak positions in the VLA-D (left) and the VLA hybrid (right) images. The N-S cut is along the line with a position angle of 20° , while the E-W cut is perpendicular to it. Three components of the continuum structure (see text), i.e., core, halo, and plateau, are labeled.

core is 4.3 times that of WC 89's. The integrated flux densities agree well with previous low-resolution observations. For example, the sum of the 6 cm fluxes of the core and halo (1.33 ± 0.07 Jy) agrees well with 1.45 Jy of Wink et al. (1982) who, based on their single-dish observations with 2.6 resolution, derived the flux by fitting a Gaussian distribution with FWHM = $57''$. Likewise, our total 20 cm flux density (2.8 Jy) agrees reasonably well with 3.1 Jy of Reich et al. (1990) who obtained the flux by fitting a Gaussian distribution of 12.2×10.6 .

From the integrated flux densities in Table 2, the spectral index α , defined as $S_\nu \propto \nu^\alpha$, is $\alpha = -0.08 \pm 0.08$ for the bright component (core+halo). This agrees with $\alpha = -0.1$ of the optically thin thermal free-free emission. At the peak position, however, the flux density at 20 cm is smaller than that at 6 cm. This is due to the significant optical depth at 20 cm. For the physical parameters of the core (see Table 2), the optical depth at 6 cm is 0.024 whereas it is 0.30 at 20 cm. We derive the physical parameters of the core and halo from the 6 cm results, and those of the plateau from the 20 cm results. We assume that the emission from the plateau is also thermal. Although there is no direct evidence, its diffuse and extended emission suggests a thermal origin.

The derived physical parameters are summarized in Table 2, where $\bar{R}_S$ is the geometrical mean radius, u is the excitation parameter, $\bar{n}_e \equiv (u/\bar{R}_S)^{3/2}$ is the rms electron density, $M_{\text{H II}}$ is the mass of the ionized hydrogen, and N_L is the Lyman continuum photon luminosity necessary for the ionization (see § 5.2). We used the formulae for a spherically symmetric H II region with radius $\bar{R}_S$ to compute u and $M_{\text{H II}}$ (Schraml & Mezger 1969). We adopted $T_e = 6000$ K, which was determined by

Wink et al. (1982) from their H90 α and continuum observations. N_L is calculated from a formula given by Rubin (1968), and it does not depend on the geometry of the H II region. Note that N_L in Table 2 is 20 times that of WC89.

3.2. Other Sources in the Field

In Figure 1, we see several other continuum sources; three extended and three compact. The extended source at ($17^{\text{h}}57^{\text{m}}5$, $-24^\circ05'$) coincides with the compact H II region G5.89-0.39 (or W28 A2) which has been studied in detail at many wavelengths (see Harvey et al. 1994, and references therein). Figure 1 suggests an extended structure around the compact H II region. A sensitive observation might be interesting. The other two extended sources, one at ($17^{\text{h}}54^{\text{m}}5$, $-24^\circ20'$) and another at ($17^{\text{h}}56^{\text{m}}0$, $-24^\circ05'$), can be identified in the 11 cm Bonn survey (Reich et al. 1984) but they are not cataloged. Three compact sources are listed in Table 3. The parameters are derived from Gaussian fits. The positional uncertainty from Gaussian fits is less than $1''.8$ in R.A. and $1''$ in declination. Sources 2 and 3 are cataloged in the 11 cm Bonn survey, and source 3 is also cataloged in the 21 cm Bonn survey (Reich et

TABLE 3
OTHER COMPACT SOURCES IN THE FIELD

Number	Position (α_{1950} , δ_{1950})	21 cm flux density (Jy)	Size
1	($17^{\text{h}}54^{\text{m}}57^{\text{s}}$, $-24^\circ33'53''$)	0.067	unresolved
2	($17^{\text{h}}55^{\text{m}}02^{\text{s}}$, $-24^\circ09'43''$)	0.15	$81'' \times 65''$
3	($17^{\text{h}}55^{\text{m}}31^{\text{s}}$, $-24^\circ36'42''$)	0.61	$101'' \times 72''$

al. 1990). The reported fluxes from Bonn are 0.19 Jy (21 cm) for source 2 and 1.06 Jy (11 cm) and 0.90 Jy (21 cm) for source 3. The fluxes of source 3 are considerably different from 0.61 Jy in Table 3. The difference could be either due to the time variability of the source or due to the incomplete background subtraction in the Bonn surveys.

4. H I AND CO RESULTS

4.1. H I Results

Figures 4a–4d are the H I channel maps near the systematic velocity ($v_{\text{LSR}} = +22.0$ – $+22.9$ km s $^{-1}$) of the H II region which has been determined from radio recombination lines (Downes et al. 1980; Wink et al. 1982). Although the channel maps are confused by the foreground emission, we can still identify an H I cloud to the west of G5.48–0.24. The cloud is centered at $v_{\text{LSR}} = +25 \pm 3$ km s $^{-1}$ and appears mainly in Figures 4b and 4c. In Figure 4b, the eastern boundary of the cloud coincides with the steep western boundary of G5.48–0.24, whereas, in Figure 4c, the cloud extends to the east slightly beyond the bright component of G5.48–0.24. The absence of H I 21 cm line emission toward the plateau structure of G5.48–0.24 cannot be due to absorption because the 21 cm continuum brightness temperature ($\lesssim 5$ K) of the plateau is much less than the typical spin temperature of the 21 cm line. (It is true that, in interferometric observations, H I gas, if its distribution is smooth, can generate absorption features even if the background continuum source has a brightness temperature less than the spin temperature. But as can be seen in Figure 4 the H I cloud associated with G5.48–0.24 certainly has structures observable in VLA-D array, and therefore, its morphology except toward the bright continuum component should have hardly been affected by the absorption.) Instead, it implies that the H I cloud is in contact with the western boundary of the H II region.

The geometrical relationship between the H I cloud and G5.48–0.24 is more clearly seen in Figure 4e, where the H I map has been obtained by integrating the emission between $v_{\text{LSR}} = +15.0$ and $+30.5$ km s $^{-1}$. We blanked out those pixels with intensity less than 0.01 Jy beam $^{-1}$. Figure 4e suggests that the steep western boundary of G5.48–0.24 probably represents an ionization front propagating into the H I cloud, which appears to have a size comparable to that of the H II region. There is some H I gas superposed on the H II region. The absorption feature toward the bright component of G5.48–0.24 implies that the superposed H I gas is in front of G5.48–0.24. Hence, most of the gas originally in the eastern portion of the H I cloud, except some at the front, appears to be ionized. The physical parameters of the H I cloud have been derived from Figure 4e and are summarized in Table 4. In Table 4, $\bar{R}$ is the geometrical mean radius and $M_{\text{H I}}$ is the mass of the H I cloud obtained by assuming that the 21 cm line emission is optically thin. It should be noted that the mass and density of the H I cloud could be much greater than those in Table 4 because the VLA-D array cannot see structure larger than $\sim 15'$ and also because CLEAN does not recover the total fluxes of extended structures.

4.2. CO Results

Figure 5 shows the ^{13}CO spectrum toward the radio continuum peak. The spectrum is complex because of molecular clouds along the line of sight. But near the velocity of the H II region ($v_{\text{LSR}} \simeq +22$ km s $^{-1}$), we see a well-defined strong

TABLE 4
PHYSICAL PARAMETERS OF H I AND MOLECULAR CLOUDS

Parameter	Derived Value
H I Cloud	
$\bar{R}$ (pc)	22
v_{center} (km s $^{-1}$)	$+25 \pm 3$
Δv_{FWHM} (km s $^{-1}$)	~ 15
$M_{\text{H I}}$ ($M_{\odot}$)	1900
$\bar{n}_{\text{H}}$ (cm $^{-3}$)	1.8
Molecular Cloud	
Peak position	(17 $^{\text{h}}$ 56 $^{\text{m}}$ 01 $^{\text{s}}$, -24° 20.5')
$\bar{R}$ (pc)	16
v_{center} (km s $^{-1}$)	$+21.8 \pm 0.3$
Δv_{FWHM} (km s $^{-1}$)	7.2
M_{vir} ($M_{\odot}$)	1.7×10^5
$\bar{n}_{\text{H}_2}$ (cm $^{-3}$)	150

($T_{\text{A}}^* = 1.2$ K) line. By integrating over the line, we obtain Figure 6e. Individual channel maps are also shown in Figures 6a–6d. There are several things to note in Figure 6. First, the cloud is elongated ($10' \times 6'$) along the NW–SE direction and the bright component of the H II region is located within the dense core of the molecular cloud. The agreement both in position and velocity strongly supports that the cloud is associated with G5.48–0.24. Secondly, there is no obvious correlation between the morphology of the diffuse radio continuum and that of the molecular cloud. The diffuse emission extends well beyond the molecular cloud and the steep western boundary of the H II region does not match the distribution of molecular gas. Hence, it is not the molecular cloud but the H I cloud that is in contact with the diffuse ionized gas.

Table 4 summarizes the physical parameters of the molecular cloud. We have taken $\int T_{\text{A}}^* dv = 4.0$ K km s $^{-1}$ as the boundary of the cloud. The virial mass M_{vir} is computed from (see, e.g., Spitzer 1978)

$$M_{\text{vir}} = \frac{5\bar{R}c_{\text{tot}}^2}{G}, \quad (2)$$

where $c_{\text{tot}} \simeq \Delta v_{\text{FWHM}}/(8 \ln 2)^{1/2}$ is the effective sound speed. The physical parameters in Table 4 are close to those of a typical giant molecular cloud in the Galaxy (Scoville & Sanders 1987).

5. INFRARED EMISSION FROM G5.48–0.24

5.1. Infrared Sources within G5.48–0.24

G5.48–0.24 is a strong far-infrared source and has been catalogued as IRAS 17559–2420 in IRAS Point Source Catalog (PSC) and also as X1755–243 in IRAS Small Scale Structure Catalog (1988, hereafter SSSC). It is the bright radio component (i.e., core and halo) that appears as a strong infrared (IR) source. The diffuse plateau emission is not apparent in IR. This is shown in the pictures on the left column of Figure 7, which are the 12, 25, 60, and 100 μm images obtained from the IRAS Sky Survey Atlas (ISSA). The IR emission associated with the diffuse radio component is expected to be weak. For example, at 60 μm , the expected surface brightness from the observed 21 cm brightness temperature is $\lesssim 100$ MJy sr $^{-1}$, using the correlation between the two found in other H II regions (see, e.g., Broadbent, Haslam, & Osborne 1989; Moon

FIG. 4.—(a–d) VLA H I channel maps at 5.153 km s^{−1} velocity interval. The central velocities are labeled on the top right corner of each figure. Contour levels (in 0.1 Jy beam^{−1}) are −4, −3, −2, −1, −0.7, −0.5, −0.3, 0.3, 0.5, 0.7, and 1. Negative contours are marked as dotted lines. (e) Distribution of H I gas (*gray map*) compared with the VLA D array 21 cm contour map. Gray scale varies linearly from 0.01 to 0.2 Jy beam^{−1}. The H I gas distribution has been obtained by adding three channel maps (a–c). The pixels with brightness less than 0.01 Jy beam^{−1} have been blanked out before addition.

FIG. 4.—Continued

FIG. 4.—Continued

& Koo 1994). On the other hand, the background intensity toward G5.48–0.24 varies between 300 and 400 MJy sr^{−1}. Hence, the absence of noticeable IR emission associated with the diffuse component is not surprising.

The angular resolution of ISSA plates is 4′–5′ and the IR structure of the bright component cannot be seen. Images with higher angular resolution can be obtained by using a maximum correlation method (Aumann, Fowler, & Melnyk 1990) and the pictures on the right column of Figure 7 show such HIRES (high-resolution) images of G5.48–0.24. Angular

resolution varies over the field and the beam size at the position of G5.48–0.24 is marked at the bottom right corner of each picture. The HIRES images show that there are at least four IR sources superposed on G5.48–0.24. We call them IRS 1 to IRS 4 (see Fig. 7) IRS 1 and IRS 2 are weak and they are not apparent in ISSA images. IRS 3 is the strongest and corresponds to IRAS 17559–2420. IRS 4 is located at 130″ (or 8 pc at a distance of 12.5 kpc) to the northeast of IRS 3 and cannot be separated from IRS 3 at 60 or 100 μm. IRS 3, IRS 4, and the diffuse emission around them constitute X1755–243 in SSSC.

Table 5 summarizes some parameters of the IR sources. Peak positions of IRS 1 to IRS 4 are those at 12 μm. For X1755–243, the position is from SSSC. Flux densities of IRS 1, IRS 2, and X1755–243 are computed by integrating over pixels brighter than 2 times the rms uncertainty in the background intensity. Color-corrections have not been applied considering the large uncertainties associated with the background subtraction. Flux densities of IRS 1 and IRS 2 at long wavelengths could not be determined because the sources are weak. The flux densities of X1755–243 in Table 5 agree with those listed in SSSC within uncertainty: 79(B) Jy, 174(F) Jy, and 1620(A) Jy at 12, 25, and 60 μm, respectively. (The letters A, B, and F imply that the flux quality is high, intermediate, and low, respectively.) Flux densities of IRS 3 are those listed in PSC. For IRS 4, flux density has been determined only at 12 μm by fitting a Gaussian distribution. At longer wavelengths, accurate flux densities could not be determined because of the confusion with IRS 3. But, from Figure 7, it is clear that IRS 4 is much bluer than IRS 3. IR luminosities (L_{IR}) of IRS 3 and X1755–243 are obtained by integrating flux densities between

FIG. 5.—¹³CO $J = 1-0$ line profile at the radio continuum peak ($\alpha_{1950} = 17^{\text{h}}56^{\text{m}}01^{\text{s}}$, $\delta_{1950} = -24^{\circ}20'5''$).

FIG. 6.—(a–d) ^{13}CO channel maps at 2.72 km s⁻¹ velocity interval. The central velocities are labeled on the top-right corner of each figure. Contour levels are evenly spaced, with an antenna temperature interval of 0.25 K, starting at 0.5 K. The position of the radio continuum peak is indicated by a white star. (e) Distribution of ^{13}CO gas compared with the VLA D-array 21 cm contour map. Gray scale varies linearly from 2.7 to 14 K km s⁻¹. The ^{13}CO gas distribution has been obtained by adding four channel maps (a–d). Note that the bright radio component coincides with the dense core of the molecular cloud.

FIG. 6.—Continued

FIG. 6.—Continued

12 and 1300 μm . We used 7 Jy at 1300 μm (Chini, Krügel, & Wargau 1987).

The peak position of IRS 3, or IRAS 1759-2420, agrees with the radio continuum peak. According to the near-IR (1-5 μm) observations of Chini et al. (1987), however, the peak is located at $\approx 13''$ (0.8 pc) to the north of the radio continuum peak. The positional offset is significantly greater than the claimed uncertainty ($4''$). An accurate infrared astrometry is required to determine relative peak positions. In any case IRS 3 corresponds to the bright radio component (core and halo). The natures of the other IR sources are uncertain. IRS 1 is possibly an H II region based on its flux density ratios, e.g., $S_{25}/S_{12} = 3$ and $S_{60}/S_{25} = 7$ (Hughes & MacLeod 1989). IRS 4, as we mentioned at the end of § 3.1, appears to have an associated radio continuum. But its IR color appears to be

much bluer than IRS 3. High-resolution IR observations are required to reveal the natures of these sources.

5.2. Dust Absorption and Infrared Luminosity

Infrared emission associated with H II regions comes from dust heated by the same stars that excite the H II regions. Stellar UV photons, unless the H II region is density bounded, deposit most of their energy to dust within H II regions either through direct absorption or through the ionization and recombination of hydrogen. For H II regions embedded inside molecular clouds, stellar photons longward of the Lyman limit are also absorbed by dust within the molecular cloud. Hence, all the stellar energy will end up in IR and the observed IR luminosity L_{IR} of an H II region may be considered as a good

TABLE 5
INFRARED SOURCES SUPERPOSED ON THE G5.48-0.24 COMPLEX

Name	Peak Position (α_{1950} , δ_{1950})	S_{12} (Jy)	S_{25} (Jy)	S_{60} (Jy)	S_{100} (Jy)	L_{IR} ($10^6 L_{\odot}$)
IRS 1	(17 ^h 55 ^m 56 ^s .1, -24°25'30")	1.2 (0.3)	3.9 (0.7)	27 (8)	...	...
IRS 2	(17 55 56.1, -24 16 30)	2.4 (0.7)	1.6 (0.5)	...	...	...
IRS 3 ^a	(17 55 59.4, -24 20 45)	24 (1.4)	194 (19)	1050 (>210)	2170 (390)	0.77
IRS 4	(17 56 04.9, -24 19 00)	12 (0.6)	...	...	...	...
X1755-243 ^b	(17 55 57.2, -24 20 03)	60 (5)	283 (7)	1630 (60)	2670 (280)	1.0

NOTE.—Flux densities are derived in this work except for IRS 3. Errors quoted in the parenthesis are the 1σ uncertainty in the background surface brightness multiplied by the solid angle of the source.

^a Listed as IRAS 17559-2420 in *IRAS PSC*. Flux densities are from *PSC*.

^b Extended source including IRS 3 and IRS 4. Source name and position are from *IRAS SSSC*.

FIG. 7.—(left) ISSA images of G5.48–0.24. The bright source near the field center is IRAS 17559–2420 (or X1755–243) corresponding to G5.48–0.24. Angular resolution is $4''$ – $5''$. Contour levels are 3.5, 4, 5, 7, 10, 20, and 50 times C , where $C = 10, 12, 90$, and 450 MJy sr^{-1} for 12, 25, 60, and 100 μm , respectively. (right) IRAS HIRES images of G5.48–0.24. Four IR sources superposed on G5.48–0.24 are labeled as IRS 1 to IRS 4. Contour levels are 10, 20, 40, 70, and 100 times C , where $C = 1, 1, 5$, and 20 MJy sr^{-1} for 12, 25, 60, and 100 μm , respectively.

estimate of the luminosity of exciting star(s) (see, e.g., Habing & Israel 1979).

According to Table 5, the IR luminosity of the bright radio component (i.e., IRS 3) is $L_{\text{IR}} = 7.7 \times 10^5 L_{\odot}$. If the IR luminosity is provided by a single star, then by interpolating the table given by Panagia (1973), the total Lyman continuum photon luminosity of the *exciting star* is $N_L^* = 5.2 \times 10^{49} \text{ s}^{-1}$ corresponding to an O5 star. On the other hand, according to Table 2, the total Lyman continuum photon luminosity required to maintain ionization of the bright component is $N_L = 2.3 \times 10^{49} \text{ s}^{-1}$, corresponding to an O5.5 star (Panagia 1973). N_L is less than N_L^* presumably because dust within the H II region absorbs some significant fraction of ionizing photons. The fraction of Lyman continuum photons absorbed by dust is $f_d = 1 - N_L/N_L^* \simeq 0.56$. This factor is significantly less than 0.95 of WC 89, but similar to that of other compact H II regions (Garay et al. 1993). The large f_d of WC89 is due to their small radio continuum flux.

If the IR luminosity is provided by a stellar cluster, then N_L^* would be smaller than that of a single star because of low-mass, nonionizing stars. For a cluster with initial mass function of Miller & Scalo (1979) and with a minimum stellar mass of $0.6\text{--}16 M_{\odot}$, $N_L^* \simeq 1\text{--}2 \times 10^{49} \text{ s}^{-1}$ (Garay et al. 1993). Note that unless the stellar cluster contains only massive stars, N_L^* is less than N_L necessary for the observed radio continuum flux. Hence, although there are uncertainties in the computed N_L^* , the observed radio and IR fluxes seem to be consistent with the excitation either by a single massive star or by a cluster of massive stars.

In G5.48–0.24, as in most other H II regions, Ly α photons are not enough to explain the observed IR luminosity of G5.48–0.24. The IR excess (IRE), which is defined as the ratio of the observed IR luminosity L_{IR} to the Ly α luminosity L_{α} (see, e.g., Aller 1984), is $\text{IRE} = 7.9$ where $L_{\alpha} = 0.98 \times 10^5 L_{\odot}$ is obtained from the 6 cm flux density (see Aller 1984 or Garay et al. 1993). Hence, Ly α photons account for only 13% of the heating. The fractional heating due to the direct absorption of ionizing photons is $f_d P = 0.34$, where $P = 0.6$ is the fractional energy of Lyman continuum (Panagia 1973). Hence, apparently half ($\sim 53\%$) of the IR luminosity is due to the absorption of photons longward of Lyman limit. These fractional heating rates are consistent with the results in other compact H II regions (Antonopoulou & Pottasch 1987; Garay et al. 1993).

It should be emphasized that the above discussion applies only to the bright radio component of G5.48–0.24. In order to extend the discussion to the whole H II region, we need to know the IR property of the diffuse plateau component which is difficult because of the background emission.

6. DISCUSSION

G5.48–0.24 has radio-continuum structures of greatly different length scales: a compact (0.7 pc) core, a small extended (3.4 pc) halo, and a large (21 pc) plateau. The VLA observation with higher angular resolution has revealed structures even at smaller scales, an ultracompact ($\bar{R}_s \simeq 0.04$ pc) core (WC 89). The rms electron density increases roughly by a factor of 10 from one structure to the next small-scale structure. Therefore, each structure must be expanding into the more extended structure. If we use the sound speed ($\sim 10 \text{ km s}^{-1}$) of ionized gas as a characteristic expansion velocity, then the dynamical ages of these structures range from 4×10^3 to 2×10^6 yr.

The very different ages lead us to suspect that the diffuse plateau structure would be an unrelated H II region along the

line of sight. For the other structures, the chances are small because of their small angular sizes. We consider the possibility *unlikely*, however. According to our results in § 4, the plateau structure is certainly associated with an H I cloud. The systematic velocity of the H I cloud is almost identical to that of the molecular cloud where the bright radio component is embedded. Hence, the plateau structure, the bright radio component, and the atomic and molecular clouds are all considered to be parts of the G5.48–0.24 complex.

An explanation for structures of largely different scales is that they are created by separate, but spatially and temporally ordered exciting stars. It has been suggested that massive stars once formed within giant molecular clouds (GMCs) can induce the formation of new massive stars in adjacent region of GMCs (Blaauw 1964; Elmegreen & Lada 1977). The expanding H II regions created by massive stars compress the adjacent gas layer to be gravitationally unstable and to form new stars. An H II region that fits into the scenario of this sequential star formation would be NGC 7538 complex (or S158), where compact and ultracompact H II regions are immersed in a classical optical H II region of 3 pc radius (Israel, Habing, & de Jong 1973; Israel 1977; Campbell & Persson 1988; see Blaauw 1991 for other examples of much larger scales).

It is plausible that G5.48–0.24 is one of such H II region-molecular cloud complexes where the sequential star formation is proceeding. The dynamical age of the plateau structure implies that the preceding generation of massive stars was formed 2×10^6 yr ago. These stars, with $N_L = 2.2 \times 10^{49} \text{ s}^{-1}$ according to Table 2, have been driving an ionization-shock front into the molecular cloud. At 3×10^5 yr ago, which is the timescale of the halo, a new generation of stars started to form within the bright radio component. The relatively short dynamical age ($\sim 7 \times 10^4$ yr) of the core may indicate that the star formation has occurred over a finite time interval. On the other hand, the ultracompact core may be produced by an O star moving through the molecular cloud, in which case its dynamical age ($\sim 4 \times 10^3$ yr) is much shorter than its true age (WC 89; Mac Low et al. 1991; Van Buren & Mac Low 1992).

Alternatively G5.48–0.24 may belong to the “blister-type” H II regions, which are the H II regions formed near the edges of molecular clouds and which have blistered the skin of molecular clouds to form core/halo structures (Israel 1978). A blister-type H II region with morphology similar to G5.48–0.24 is S142 (Joncas et al. 1985). The dynamical evolution of blister-type H II regions has been studied in some detail (Icke 1979; Tenorio-Tagle 1979; Bodenheimer, Tenorio-Tagle, & York 1979; Whitworth 1979; see also review by Tenorio-Tagle 1982, and references therein). The evolution of blister H II regions differs from that of “classical,” spherically symmetric H II regions in that the blister H II regions experience the so-called “champagne” phase. The champagne phase starts when the ionization front overtakes the boundary of molecular cloud and ionizes the diffuse intercloud gas. The large pressure difference drives an isothermal shock into the ionized intercloud gas while a rarefaction wave propagates into the dense ionized cloud gas. A supersonic flow of ionized gas streaming away from the molecular cloud, i.e., the champagne flow, is set up.

In the blister model of G5.48–0.24, the exciting source of the large plateau region is located within the bright radio component. The plateau structure could be either the result of champagne flow or could be mainly the photoionized ambient diffuse gas initially there. The age of G5.48–0.24 is less than

$R_{\max}/v_{\exp} \sim 1 \times 10^6$ yr, where $R_{\max}$ (≈ 30 pc) is the extension of the diffuse emission from the core and $v_{\exp}$ (≈ 30 km s $^{-1}$) is the characteristic expansion velocity of the champagne flow (Bodenheimer et al. 1979). Again, the complex morphology within the bright component may be interpreted as an indication of the star formation over a finite time interval.

In summary, the exciting source of the plateau structure could be either within the diffuse component or within the bright component. In the former, the morphology fits into the scenario of the sequential star formation where the plateau structure is created by a preceding generation of massive stars whereas the bright component is created by newly formed massive stars. In the latter, the morphology fits into the blister model where massive stars formed near the edge of molecular cloud have blistered the skin of the cloud. Radio recombination line studies which yield the velocity structure might be useful to understand the nature of G5.48–0.24.

7. SUMMARY

We have shown that G5.48–0.24, which has been known as an ultracompact H II region, is indeed a large H II region-molecular cloud complex. It has a bright radio H II region of 3.4 pc radius, partly embedded within the dense core of a molecular cloud. It also has a diffuse emission that extends to ~ 30 pc from the core. Our results show that the study of the diffuse emission is essential to understand the nature of G5.48–0.24. Among other ultracompact H II regions studied by WC 89, those with large ratio of the single-dish to the high-resolution VLA fluxes are expected to have such diffuse, extended structures. The observations of these H II regions using the VLA configurations with shorter baselines are recommended.

We summarize below the main results of this paper:

1. The Galactic H II region G5.48–0.24 is composed of three components: core, halo, and plateau. The radio continuum brightness varies abruptly between these components. The size and mean electron density of the core are 0.70 pc and 750 cm $^{-3}$. The size increases by a factor of 5–6 and the mean electron density decreases by a factor of 0.11–0.08 between components. Each component contributes 20%, 30%, and 50% to the total flux density. The total Lyman continuum luminosity required for the ionization of G5.48–0.24 is $N_L = 4.5 \times 10^{49}$ photons s $^{-1}$, which corresponds to an O5 ZAMS.

2. Four IR sources superposed on G5.48–0.24 are identified using the *IRAS* HIRES images. The strongest source IRS 3 (or *IRAS* 17559–2420) coincides with the bright radio component. The natures of other three sources are uncertain. The luminosity of IRS 3 implies that, within the bright radio component, the fraction of Lyman continuum photons directly absorbed by dust is 0.56. This direct absorption accounts for 34% of the observed IR luminosity. Ly α heating accounts for only 13%. The remaining 53% comes from dust in surrounding neutral medium heated by stellar photons longward of Lyman limit.

3. We have detected an H I cloud in contact with the steep western boundary of the H II region. The mass of the cloud is $\sim 1900 M_\odot$ according to our VLA-D array observation. If the cloud has an extended ($\geq 15'$) structure, the total mass could be much greater than this.

4. We have detected a molecular cloud of $1.7 \times 10^5 M_\odot$ associated with G5.48–0.24. The radio continuum peak is located within the molecular cloud core. There is no obvious correlation between the radio continuum morphology and shape of the molecular cloud.

5. G5.48–0.24 has radio-continuum structures of greatly different length scales, e.g., 0.04–21 pc including the ultracompact component detected by WC 89. The dynamical ages of these structures range from 4×10^3 to 2×10^6 yr. The structures with very different dynamical ages may be created by the sequentially formed massive stars: the large plateau structure created by a preceding generation of massive stars and the bright component created by newly formed massive stars. Alternatively, the composite structure may be created by massive stars formed near the edge of a molecular cloud and have blistered the skin of the cloud. Radio recombination line studies might be useful to understand the nature of G5.48–0.24.

We thank the staff of the Joint *IRAS* Science Working Group and the National Science Data Center for providing the HIRES images and the *IRAS* Sky Survey Atlas Data. We also thank Ed Churchwell for his helpful comments. This work was supported in part by the Korean Astronomical Observatory Research Fund.

REFERENCES

- Aller, L. H. 1984, *Physics of Thermal Gaseous Nebulae* (Dordrecht: Reidel)
- Altenhoff, W. J., Downes, D., Pauls, T., & Schraml, J. 1978, *A&AS*, 35, 23
- Antonopoulou, E., & Pottasch, S. R. 1987, *A&A*, 173, 108
- Aumann, H. H., Fowler, J. W., & Melnyk, M. 1990, *AJ*, 99, 1674
- Blaauw, A. 1964, *ARA&A*, 2, 213
- . 1991, in *The Physics of Star Formation and Early Stellar Evolution*, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 125
- Bodenheimer, P., Tenorio-Tagle, G., & Yorke, H. W. 1979, *ApJ*, 233, 85
- Broadbent, A., Haslam, C. G. T., & Osborne, J. L. 1989, *MNRAS*, 237, 381
- Campbell, B., & Persson, S. E. 1988, *AJ*, 95, 1185
- Chini, R., Krügel, E., & Wargau, W. 1987, *A&A*, 181, 378
- Churchwell, E. 1990, *ARA&A*, 2, 79
- Downes, D., Wilson, T. L., Bieging, J., & Wink, J. 1980, *A&AS*, 40, 379
- Elmegreen, B. G., & Lada, C. J. 1977, *ApJ*, 214, 725
- Garay, G., Rodríguez, L. F., Moran, J. M., & Churchwell, E. 1993, *ApJ*, 418, 368
- Habing, H. J., & Israel, F. P. 1979, *ARA&A*, 17, 345
- Harvey, P. M., Lester, D. F., Colomé, C., Smith, B., Monin, J. L., & Vauglin, I. 1994, *ApJ*, 433, 187
- Hughes, V. A., & MacLeod, G. C. 1989, *AJ*, 97, 786
- Icke, V. 1979, *ApJ*, 234, 615
- IRAS* Small Scale Structure Catalog 1988, prepared by G. Helou & D. Walker (Washington: GPO)
- Israel, F. P. 1977, *A&A*, 59, 27
- Israel, F. P. 1978, *A&A*, 70, 769
- Israel, F. P., Habing, H. J., & de Jong, T. 1973, *A&A*, 27, 143
- Joncas, G., Dewdney, P. E., Higgs, L. A., & Roy, J. R. 1985, *ApJ*, 298, 596
- Mac Low, M. M., Van Buren, D., Wood, D. O. S., & Churchwell, E. 1991, *ApJ*, 369, 395
- Miller, G. E., & Scalo, J. M. 1979, *ApJS*, 41, 513
- Moon, D.-S., & Koo, B.-C. 1994, *J. Korean Astron. Soc.*, 27, 81
- Panagia, N. 1973, *AJ*, 78, 929
- Reich, W., Fürst, E., Steffen, P., Reif, K., & Haslam, C. G. T. 1984, *A&AS*, 58, 197
- Reich, W., Reich, P., & Fürst, E. 1990, *A&AS*, 83, 539
- Rubin, R. H. 1968, *ApJ*, 154, 391
- Schraml, J., & Mezger, P. G. 1969, *ApJ*, 156, 269
- Scoville, N. Z., & Sanders, D. B. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach, & H. A. Thronson, Jr. (Dordrecht: Reidel)
- Spitzer, L., Jr. 1978, *Physical Processes in the Interstellar Medium* (New York: Wiley)
- Tenorio-Tagle, G. 1979, *A&A*, 71, 59
- . 1982, in *Regions of Recent Star Formation*, ed. R. S. Roger & P. E. Dewdney (Dordrecht: Reidel)
- Van Buren, D., & Mac Low, M. M. 1992, *ApJ*, 394, 534
- Whitworth, A. 1979, *MNRAS*, 186, 59
- Wink, J. E., Altenhoff, W. J., & Mezger, P. G. 1982, *A&A*, 108, 227
- Wood, D. O., & Churchwell, E. 1989, *ApJS*, 69, 831 (WC 89)