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IRAS 04000+5052: A Not So Compact, Not So Metal-poor H II Region[1]

CÉSAR ESTEBAN, LUIS LÓPEZ-MARTÍN, ÁNGEL R. LÓPEZ-SÁNCHEZ, BERNABÉ CEDRÉS, AND JORGE GARCÍA-ROJAS

Instituto de Astrofísica de Canarias, Via Láctea s/n, E-38200 La Laguna, Tenerife, Spain;
cel@iac.es, luislm@iac.es, angelrls@iac.es, bce@iac.es, jogarcia@iac.es

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ABSTRACT. We present new observations of IRAS 04000+5052, a Galactic H II region that is associated with a young stellar cluster and is possibly located in the Perseus arm. We have found that contrary to previous claims, this object is not a compact metal-poor H II region. The electron density and chemical composition of the nebula are similar to those of normal H II regions of the Galactic disk. The radial velocity of the ionized gas coincides with that obtained from CO observations, indicating that the nebula is associated with a molecular cloud. Probably, the ionizing source of the H II region is a Herbig Be star of spectral type B0.5.

1. INTRODUCTION

IRAS 04000+5052 (Galactic coordinates 150°.86, −1°.12) has an *IRAS* low-resolution spectrum (LRS) spectrum and *IRAS* fluxes that are consistent with an H II region (Wang et al. 1993). Wouterloot & Brand (1989) found ^{12}CO emission in the direction of the object and calculated galactocentric and heliocentric distances of 12.04 and 3.88 kpc, respectively, (assuming a solar galactocentric distance of 8.5 kpc) for the molecular emission. This indicates that IRAS 04000+5052—if it is truly associated with the molecular cloud—is located beyond the solar circle and beyond the Perseus arm. Wang et al. (1993) found a near-infrared (NIR) variable source associated with the *IRAS* source, probably a young object embedded in the H II region. In a more recent study, Wang et al. (2002) carried out a more complete study of the object, based on NIR imagery and optical spectroscopy. These authors find an isolated high-mass protostellar infrared cluster of 15 objects associated with the *IRAS* source, where a B0.5-type star (their IRS 7 object) is the ionizing source of the H II region. Wang et al. (2002) classify IRAS 04000+5052 as a compact H II region, based on the criteria of its size and location in a star-forming molecular cloud. These authors also estimate the [N II]/Hα ratio of the nebula from Gaussian fitting of the blend of Hα and [N II] λλ6548 and 6584 lines measured in their low-resolution spectrum (∼10 Å). The [N II]/Hα ratio they find is about 1/16.3, which is the lowest value ever reported for a Galactic H II region. This result suggests that IRAS 04000+5052 is a rather peculiar metal-poor nebula and merits further investigation.

We have carried out optical spectroscopy and imagery of IRAS 04000+5052 in order to obtain a more precise determination of its chemical composition and to discover the true nature of the object.

2. OBSERVATIONS

Intermediate-resolution spectroscopy was obtained in 2002 December 27 with the ISIS spectrograph on the 4.2 m William Herschel Telescope (WHT) at the Roque de los Muchachos Observatory in La Palma, Spain. Two different CCDs were used at the blue and red arms of the spectrograph: an EEV CCD with a configuration of 4096 × 2048 pixels at 13.5 μm in the blue arm, and a Marconi CCD with 4700 × 2148 pixels at 13.5 μm in the red arm. The dichroic used to separate the blue and red beams was set at 5400 Å. The slit was 3′.7 long and 1″.03 wide. Two gratings were used, the R1200B in the blue arm and the R316R in the red arm. These gratings give reciprocal dispersions of 17 and 62 Å mm^{-1} and effective spectral resolutions of 0.86 and 3.81 Å for the blue and red arms, respectively. The blue spectra cover from λλ4456 to 5484, and the red ones from λλ5370 to 8690. The spatial scale is 0″.20 pixel^{-1} in both arms.

The slit was centered on the brightest part of the nebula, with a position angle of 90° (east-west). Three 600 s exposures were taken and combined to obtain good signal-to-noise ratio (S/N) and an appropriate removal of cosmic rays. The spectra were wavelength calibrated with a CuNe+CuAr lamp. The correction for atmospheric extinction was performed using the average curve for continuous atmospheric extinction at Roque de los Muchachos Observatory. The absolute flux calibration of the spectra was achieved with observations of the standard stars Feige 15, Feige 110, H600, and Hz 44. All the CCD frames were reduced using the standard IRAF[2] TWODSPEC reduction

[1] Based on observations made with telescopes operated on the island of La Palma by the Isaac Newton Group of Telescopes and Nordic Optical Telescope at the Spanish observatory of Roque de Los Muchachos of the Instituto de Astrofísica de Canarias.

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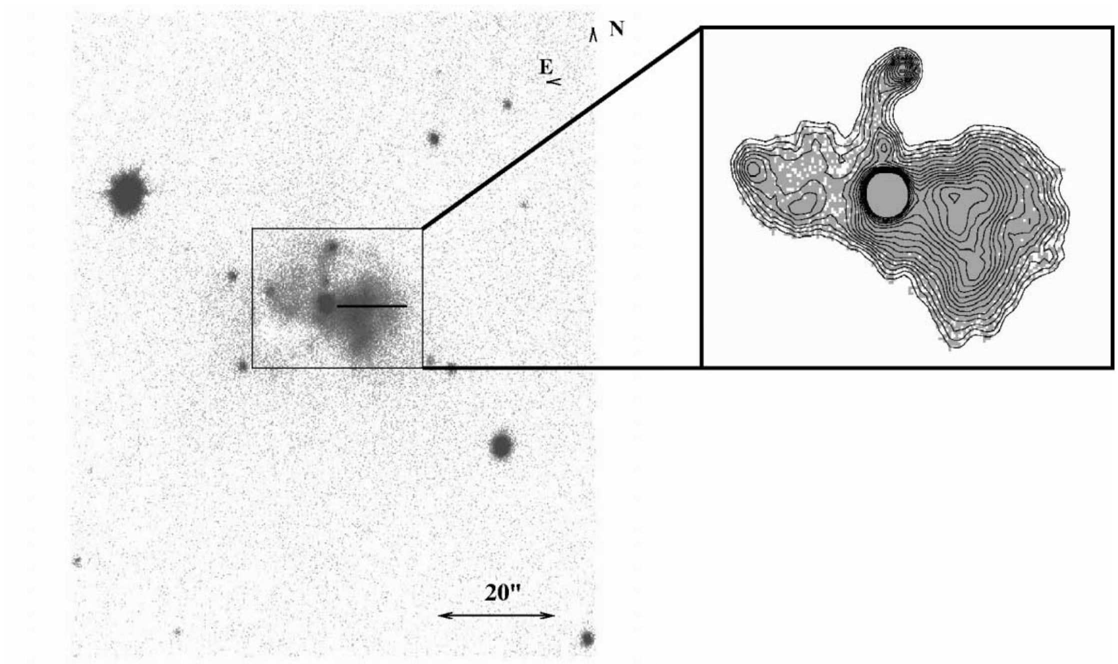

FIG. 1.—CCD Hα image of IRAS 04000+5052. The position and spatial extension of the zone from which the one-dimensional spectra have been extracted is indicated. The expanded frame on the right shows an enlargement of the central part of the continuum-subtracted image of the nebula in gray scale with contours.

package to perform bias correction, flat fielding, cosmic-ray rejection, wavelength and flux calibration, and sky subtraction.

The optical CCD images were obtained on 2004 January 21 at the 2.56 m Nordic Optical Telescope (NOT) at Roque de los Muchachos Observatory (La Palma, Spain). We used the Andalucia Faint Object Spectrograph and Camera (ALFOSC) in image mode with an E2V CCD detector (2048 × 2048 pixels) with a pixel size of 13.5 μm and spatial resolution of 0.19″ pixel^{-1}. The narrowband filters for the Hα and continuum have a full width at half-maximum (FWHM) of 33 and 51 Å, respectively. The continuum filter has its central wavelength at 6891 Å. The average seeing of the images was 1.2″. Four exposures of 300 s in Hα, and three exposures of 150 s in the continuum, were added to obtain a good S/N and an appropriate removal of cosmic rays in the final images. The images were bias-subtracted, flat-fielded, and flux-calibrated following standard procedures, making use of IRAF software, in particular the FOCAS package. The absolute flux calibration was performed using the spectrophotometric standard stars Feige 110 and HR 1544, and following the method proposed by Barth et al. (1994). Figure 1 shows the resulting Hα image of IRAS 04000+5052.

3. RESULTS AND DISCUSSION

The Hα image of the nebula (Fig. 1) shows much more detail than the broadband NIR and Brγ images published by Wang et al. (2002). IRAS 04000+5052 has a patchy structure, with the presence of dark zones and a very faint extended ionized halo. The morphology is typical of an H II region associated with a substantial amount of obscuring material and a star-forming zone.

The bidimensional spectrum shows that Hα is the brightest line of the nebula. The profile of this line is rather complex along a substantial part of the spatial extension of the nebula. This profile can be reproduced with the combination of two Gaussian components of different widths. The relative contribution of the broad component is more important at the position of the stellar continuum of IRS 7 (the variable NIR source found by Wang et al. 2002 that corresponds to the brightest star embedded in the nebula) and decreases as one gets farther from the star. This fact indicates that the broad component is produced by the light of a stellar emission feature scattered by the dust mixed with the ionized gas. In Figure 2, we show the relative contribution of the broad and narrow components of the Hα line (as well as the [N II]/Hα intensity ratio) for different slices of the spectrum along the brightest part of the nebula. The line profile was analyzed via a double-Gaussian fitting using the Starlink DIPSO software package (Howarth & Murray 1990). For each Gaussian fit, DIPSO gives the fit parameters (radial velocity centroid, integrated flux, FWHM, etc.) and their associated statistical errors. In Figure 3 we show examples of Gaussian fits in two small separate zones of the nebula. The broad (stellar) component is especially important in the zone surrounding IRS 7 (Fig. 3, *left*; and also Fig. 2). The intrinsic FWHM (corrected for instrumental profile) of the broad component is about 520 km s^{-1} in that zone. In contrast, the intrinsic FWHM of the narrow (nebular) component of Hα is typically

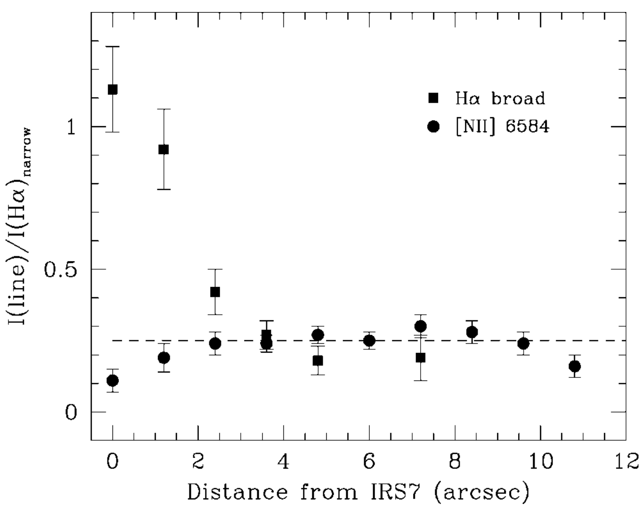

FIG. 2.—Emission-line ratios of the broad component of Hα and nebular [N II] with respect to nebular (narrow) Hα emission along part of the slit (from the ionizing star IRS 7 to the west). The spatial increments are 1″.2 long. The contribution of the broad Hα emission is more important near IRS 7, while the [N II] emission is quite constant along the slit.

of the order of 30−50 km s^{-1}. In the right panel of Figure 3 we show an example of a zone without a noticeable contribution of the broad component. The broad Hα component should be related to the reflection of a stellar emission feature produced by a circumstellar disk or strong stellar winds associated with IRS 7, the most probable ionization source of the H II region.

We extracted a single one-dimensional spectrum integrating from 2″ to 15″ to the west of IRS 7 (shown in Fig. 1) in order to estimate the physical conditions and chemical abundances of the ionized gas. We avoided the zone around IRS 7 because of the important contribution of the broad component to the total Hα flux. Figure 4 shows parts of the blue and red spectra of IRAS 04000+5052. Hβ is the only line detected in the blue spectrum, and shows a rather low S/N. Line intensities were measured integrating all the flux between two given limits and over a local continuum that was estimated by eye. In Table 1 we include the observed and dereddened line-intensity ratios with respect to I(Hβ) of the emission lines detected in the integrated one-dimensional spectrum. A relatively small contribution of the broad component of Hα is still present in this spectrum. In Table 1 we include the individual parameters of the two components of Hα. The observed line intensities have been corrected for interstellar reddening using the Whitford

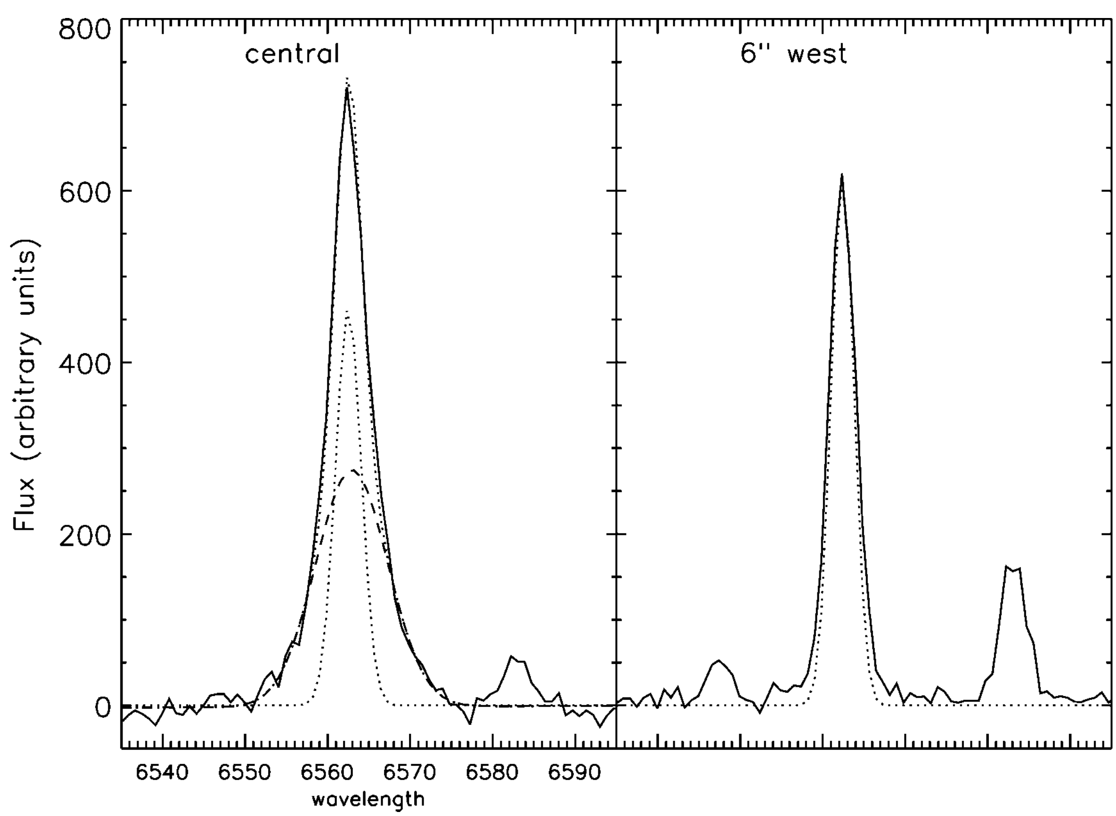

FIG. 3.—Spectra of a 1″.2 long slice passing through the central star of IRAS 04000+5052 H II region (*left*) and an off-center region 6″ to the west of the central star (*right*). The Gaussian fits to the line profiles (individual and combined) are included as discontinuous curves. The FWHM and nature of the components are given and discussed in the text. The flux is in arbitrary units, and the scaling factor used in both boxes is different.

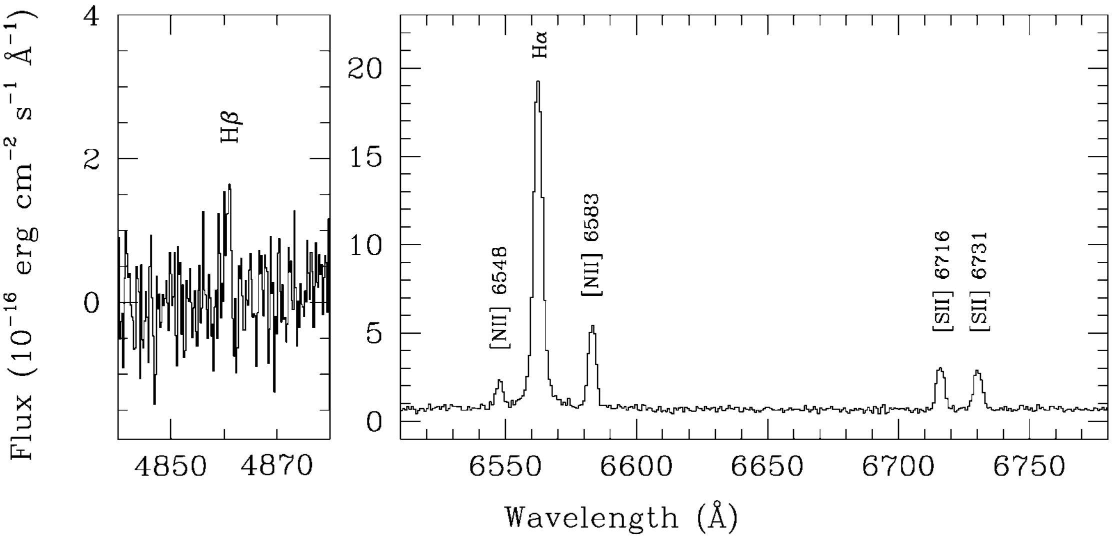

FIG. 4.—Parts of the blue (*left*) and red (*right*) spectra of IRAS 04000+5052, showing all the emission lines measured in the nebula. Hα and the [N II] doublet are clearly resolved (for comparison, see Fig. 2 of Wang et al. 2002).

(1958) law and the reddening constant $C(\mathrm{H}\beta)$. This constant has been derived from the ratio between the observed Hβ and Hα (narrow component) line intensities compared with the theoretical values expected for case B recombination using Brocklehurst (1971) and assuming an electron temperature of 10,000 K. The value of $C(\mathrm{H}\beta)$ is 3.1 ± 0.5, which corresponds to an extinction of $A_V = 6.5 \pm 1.1$ mag. Wang et al. (2002) estimate a lower limit of A_V of about 2.64 mag from their upper limit to the intensity of Hβ, which is not detected in their spectrum. In Table 1 we have also included the velocity (with respect to the local standard of rest v_{LSR}) corresponding to the centroid of the single- or double-Gaussian fitting of the lines. The reddening-corrected Hβ line flux of the one-dimensional spectrum is $3 \pm 1 \times 10^{-13}$ ergs cm^{-2} s^{-1}.

The weighted mean of the v_{LSR} of the different lines—except for that of the broad Hα component—is -30.1 ± 0.5, which is entirely consistent with the velocity obtained by Wouterloot & Brand (1989) from the ^{12}CO ($J = 1$–0) emission in the direction of the optical nebula $v_{\mathrm{LSR}} = -30.5 \pm 0.2$ km s^{-1}.

TABLE 1
LINE INTENSITY RATIOS WITH RESPECT TO $I(\mathrm{H}\beta) = 100$

Line	$f(\lambda)$	$F(\lambda)/F(\mathrm{H}\beta)$	$I(\lambda)/I(\mathrm{H}\beta)$	v_{LSR} (km s^{-1})
4861 Hβ	0.00	100 ± 35	100 ± 35	−46 ± 22
6548 [N II]	−0.34	246 ± 25	22 ± 2	−30 ± 5
6563 Hα[a]	−0.34	3190 ± 65	289 ± 6	−30.1 ± 0.6
6563 Hα[b]	−0.34	323 ± 32	29 ± 3	−8 ± 16
6584 [N II]	−0.34	794 ± 40	72 ± 4	−26 ± 2
6716 [S II]	−0.36	410 ± 28	32 ± 2	−32 ± 2
6731 [S II]	−0.36	402 ± 28	32 ± 2	−34 ± 3

[a] Nebular (narrow) component.
[b] Contribution of dust-scattered stellar Hα emission feature.

This result proves that the nebula is certainly associated with the molecular emission reported by Wouterloot & Brand (1989). These authors determined a kinematic heliocentric distance of 3.88 kpc for IRAS 04000+5052. On the other hand, Wang et al. (2002) derived a photometric distance of 4.29 kpc using the observed *K* magnitude of IRS 7, its estimated B0.5 spectral type, and their lower limit of the extinction ($A_K = 0.11 \times A_V = 0.29$ mag). Following the same procedure used by those authors, we have recalculated the photometric distance of IRAS 04000+5052 using our more precise value of $A_K = 0.72$ mag, finding a distance of 3.55 kpc, which is also fairly similar to the kinematic one. However, those authors implicitly assume $M_K \approx -3.85$ mag for their calculations, without quoting any references. We have reviewed the recent literature, finding that the absolute *K* magnitude given by Wang et al. (2002) seems to be excessively bright. Hanson et al. (1997) obtain $M_K = -1.56$ mag for a zero-age main-sequence (ZAMS) B0.5 V star, while Wegner (2000) finds an average $M_V = -2.75$ for a sample of 12 Galactic B0.5 IV−V stars with *Hipparcos* parallaxes. Using the intrinsic $V-K$ color for B0.5 V stars of -0.79 obtained by Koornneef (1983), we derive an expected $M_K = -1.96$ for this kind of star. These two determinations of the absolute *K* magnitude are about 2 mag fainter than the value adopted by Wang et al. (2002). Wegner (2000) indicates that it is common that Be stars are brighter than normal B stars of the corresponding spectral types (about 0.5 mag in the case of B0.5 stars). As we can see, the appropriate value of the absolute magnitude of the ionizing star is uncertain, and this makes it difficult to fix a precise value of the photometric distance for the object. If we assume a M_K of between -1.5 and -2.5 mag, this would imply a heliocentric distance of 1.2–1.9 kpc and suggest that the object could belong to the Perseus arm (located at ~2 kpc; see Russeil 2003). This result is contrary to the claim by Wang et al. (2002) that IRAS 04000+5052 is located beyond that spiral arm. Differences between kinematic and photometric distances are rather usual; in fact, Russeil (2003), in her recent revision of the distribution of star-forming complexes and the structure of the Galaxy, indicates that velocity anomalies are common in the Perseus arm.

Wang et al. (2002) estimate the number of Lyman continuum photons N(Lyc) that ionize the nebula, given a radio continuum flux density at 1.4 GHz obtained from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and assuming a heliocentric distance of 3.88 kpc, finding log N(Lyc) = 46.27, a value that corresponds to a ZAMS star of spectral type B0.5 (Panagia 1973). We have obtained the integrated flux from our dereddened flux-calibrated and continuum-subtracted Hα CCD image of the nebula finding a value of $6.64^{+2.34}_{-1.98} \times 10^{-11}$ ergs cm^{-2} s^{-1}. Assuming a representative value of about 1.5 kpc for the heliocentric distance (we have not considered errors for the distance in the following, because it is rather undefined), we obtain an Hα luminosity of $L_{\mathrm{H}\alpha} = 1.79^{+0.65}_{-0.54} \times 10^{34}$ ergs s^{-1}, which corresponds (assuming an ionization-bounded nebula) to log N(Lyc) = $46.12^{+0.13}_{-0.16}$ (e.g., Osterbrock 1989). This ionizing flux is consistent with a ZAMS star of spectral type B0.5, which is in (coincidental) agreement with the results of Wang et al. (2002). In addition, we consider that the central object IRS 7 can be classified as a Herbig Be star because of several facts: (1) its early B spectral type; (2) the presence of broad Hα emission related to the star; and (3) its pre–main-sequence nature (due to its association with a very young stellar cluster, an H II region, and a molecular cloud). The corresponding galactocentric distance of the object is about 9.8 kpc (assuming the Sun is at 8.5 kpc).

From Figure 4 and Table 1, it is clear that Hα and the two lines of the [N II] doublet are well resolved in our spectrum, and that the [N II] (λ6584)/Hα ratio is 0.25, which is much larger than the value of 0.06 derived by Wang et al. (2002) from a Gaussian fitting of an unresolved blend of those lines. This result refutes the statement by Wang et al. (2002) that IRAS 04000+5052 is a metal-poor nebula with the lowest [N II]/Hα line ratio known in Galactic H II regions. In contrast, our value of 0.25 coincides with the average of the [N II] (λ6584)/Hα ratio observed in a sample of 15 Galactic H II regions (Hawley 1978). On the other hand, the [N II]/Hα ratio—evaluated only for the nebular or narrow component of Hα—is almost constant along the nebula, as can be seen in Figure 2. We cannot determine the electron temperature of the ionized gas; therefore, it is not possible to obtain a direct estimation of the chemical abundances of the nebula. In any case, we can indirectly estimate the metallicity by making use of empirical calibrations. Denicoló et al. (2002) propose a calibration of the O/H ratio versus the [N II] (λ6584)/Hα ratio. Using this relation, we obtain an oxygen abundance of 12 + log (O/H) ≈ 8.70, a value that is typical of H II regions in the solar vicinity. In Figure 5 we show two diagnostic diagrams (adapted from Sabbadin et al. 1977) involving the locus

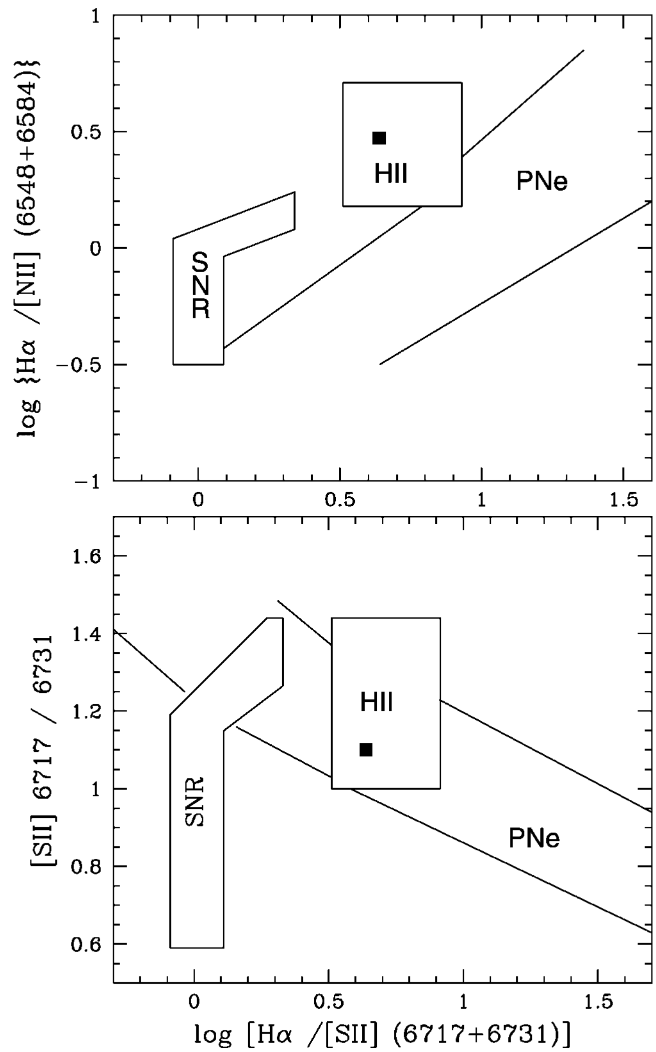

FIG. 5.—Diagnostic diagrams showing the emission-line ratios of IRAS 04000+5052, indicating the H II region nature of the object (adapted from Sabbadin et al. 1977).

of several line ratios we have observed in the nebula. These diagrams clearly indicate that IRAS 04000+5052 is radiatively excited and has a spectrum of a typical H II region, which is consistent with that suggested by its *IRAS* LRS spectrum, *IRAS* fluxes, and morphology.

The detection and measurement of the [S II] doublet at $\lambda\lambda$6716 and 6731 allows us to derive the electron density of the nebula. Using the five-level IRAF NEBULAR task (Shaw & Dufour 1995) for the analysis of emission-line nebulae, in addition to our observed [S II] λ6717/λ6731 ratio, we obtain an electron density of 540^{+400}_{-200} cm^{-3}. This density is similar to that observed from collisionally excited line ratios in other normal Galactic H II regions. For example, the central parts of the Orion nebula have electron densities between 3000 and 5000 cm^{-3} (Esteban et al. 1998), and M17 has shown between 500 and 1000 cm^{-3} (Esteban et al. 1999). Vílchez & Esteban

TABLE 2
COMPARISON OF PHYSICAL PARAMETERS

Class of H II Region	Size (pc)	N_e (cm^{-3})	Emission Measure (pc cm^{-6})	Ionized Mass ($M_\odot$)
Compact[a]	$\lesssim$0.5	$\gtrsim 5 \times 10^3$	$\gtrsim 10^7$	~1
Classical[a]	~10	~100	~100	$\sim 10^5$
IRAS 04000+5052	~0.2	540^{+400}_{-200}	$\sim 5.8 \times 10^4$	0.11 ± 0.04

[a] Reference values taken from Kurtz & Franco (2002).

(1996) obtain densities between ≤100 and 550 cm^{-3} for a sample of H II regions located toward the Galactic anticenter. From the data in Figure 1 and the adopted distance of 1.5 kpc, it is possible to estimate the approximate linear dimensions of the nebula, which are about 0.19 × 0.14 pc.

From our dereddened value of Hα flux and the diameter of the nebula, we can estimate its rms density using the usual formulae (e.g., Gurzadyan 1997), which is N_e(rms) = 950 ± 150 cm^{-3}. This value is larger than the density obtained from the [S II] doublet, but is consistent within the uncertainties, indicating that the volume filling factor of the nebula should be about 1. It is necessary to mention that the exact value of N_e(rms) is extremely dependent on the assumed distance, which is rather uncertain in this case. The corresponding ionized mass of the nebula is very small: 0.11 ± 0.04 $M_\odot$. In Table 2 we compare some physical parameters of IRAS 04000+5052 with those that are typical of compact and "classical" (normal) H II regions (Kurtz & Franco 2002). Wang et al. (2002) propose that IRAS 04000+5052 is a compact H II region, taking into account size considerations and its association with a molecular cloud, but lacking of any information about electron density. From Table 2 we can see that since the size and mass of the nebula are of orders that are typical of compact H II regions, the density is therefore consistent with the typical values of normal H II regions. We believe that the small linear size of the ionized mass of the nebula is due to the rather weak ionizing flux of the star, which is relatively cold, because of its estimated B0.5 spectral type. Therefore, we suggest that IRAS 04000+5052 should be considered a relatively normal small H II region that is ionized by a rather weak and cold ionizing source.

4. CONCLUSIONS

We present new observations of IRAS 04000+5052, a faint Galactic H II region that is associated with a small, isolated protostellar cluster probably located in the Perseus arm. We have found that this H II region is associated with a molecular cloud and that it cannot be considered a compact metal-poor H II region located beyond the Perseus arm, as proposed by Wang et al. (2002). It is ionized by a spectral type B0.5 stellar source, perhaps a Herbig Be star. Its corresponding ionizing flux is rather weak, and the size of its associated H^+ sphere is correspondingly small, with a diameter of the order of 0.2 pc. The H II region is very faint, highly reddened, and patchy, as expected, because of its association with a molecular cloud and a zone of recent star formation. The electron density of the nebula is consistent with that of typical H II regions and not of compact ones. The nebula is clearly not a metal-poor object; its [N II] (λ6584)/Hα ratio is 0.25, which is larger than the value of 0.06 previously determined by Wang et al. (2002), and is consistent with that of normal H II regions of the Galactic disk.

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