IRAS 04000+5052: A not so compact, not so metal-poor H II region [1]

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ABSTRACT

We present new observations of IRAS 04000+5052, a Galactic H II region associated with a young stellar cluster and possibly located at the Perseus arm. Contrary to previous claims, we have found that 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 B0.5 spectral type.

Subject headings: H II regions – ISM:abundances

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[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 in the Spanish Observatory of Roque de Los Muchachos of the Instituto de Astrofísica de Canarias.

1. Introduction

IRAS 04000+5052 (Galactic coordinates: 150.86, -1.12) has an IRAS LRS spectrum and IRAS fluxes consistent with an H II region (Wang et al. 1993). Wouterloot & Brand (1989) found ^{12}CO emission in the direction of the object and calculate 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 really 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, Wei, & Hu (2002) have 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] 6548 and 6584 Å lines measured in their low-resolution spectrum ($\sim$ 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 disentangle the true nature of the object.

2. Observations

Intermediate-resolution spectroscopy was obtained in 2002 December 27, with the ISIS Spectrograph at the 4.2 m William Herschel Telescope (WHT) of 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 4096 $\times$ 2048 pixels of 13.5 μm in the blue arm and a Marconi CCD with 4700 $\times$ 2148 pixels of 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 4456 to 5484 Å and the red ones from 5370 to 8690 Å. 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 seconds exposures were taken and combined to obtain good signal-to-noise 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 by observations of the standard stars Feige 15, Feige 110, H 600 and Hz 44. All the CCD frames were reduced using the standard *IRAF*[2] TWODSPEC reduction package to perform bias correction, flat-fielding, cosmic-ray rejection, wavelength and flux calibration, and sky subtraction.

The optical CCD images were obtained in 2004 January 21 at the 2.56 m Nordic Optical Telescope (NOT) at Roque de los Muchachos Observatory (La Palma, Spain). We used the ALFOSC (Andalucia Faint Object Spectrograph and Camera) in image mode with a E2V CCD detector (2048 × 2048 pixels) with a pixel size of 13.5 μm and spatial resolution of 0.19″ pixel^{-1}. The narrow-band 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 seconds in Hα and 3 exposures of 150 seconds in the continuum were added to obtain a good signal-to-noise ratio 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 (Figure 1) shows much more detail than the broad-band 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 by the combination of two Gaussian components of

[2]IRAF is distributed by NOAO, which is operated by AURA, under cooperative agreement with NSF

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 goes 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 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 different zones of the nebula. The broad (stellar) component is specially important in the zone surrounding IRS 7 (Figure 3, left; and also Figure 2). The intrinsic (corrected for instrumental profile) FWHM 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 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 onedimensional spectrum integrating from 2 to 15 arcsec to the west of IRS 7 (shown in Figure 1) in order to estimate the physical conditions and chemical abundances of the ionized gas. We avoided the zone around IRS 7 because 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 signal-to-noise ratio. Line intensities were measured integrating all the flux between two given limits and over a local continuum estimated by eye. In Table 1 we include the observed and derredened line intensity ratios with respect to I(Hβ) of the emission lines detected in the integrated onedimensional 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 (1958) law and the reddening constant, $C(H\beta)$. This constant has been derived from the ratio between the observed Hβ and Hα –narrow component– line intensities as 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 $C(H\beta)$ is 3.1±0.5, which corresponds to an extinction of $A_V = 6.5 \pm 1.1$ magnitudes. Wang et al. (2002) estimate a lower limit of A_V of about 2.64

magnitudes 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 onedimensional spectrum is $3\pm1 \times 10^{-13}$ erg cm^{-2} s^{-1}.

The weighted mean of the v_{LSR} of the different lines –except 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 to the optical nebula, $v_{LSR} = -30.5\pm0.2$ km s^{-1}. 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 of 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 a $M_K \approx -3.85$ mag for their calculations without quoting any reference. We have revised the recent literature finding that the absolute K magnitude given by Wang et al. (2002) seems to be excessively bright. Hanson, Howarth, & Conti (1997) obtain $M_K = -1.56$ mag for a ZAMS B0.5 V star. On the other hand, 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 of B0.5 V stars of -0.79 obtained by Koornneef (1983) we derive an expected $M_K = -1.96$ for this kind of stars. These two determinations of the absolute K magnitude are about two magnitudes 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 difficult to fix a precise value of the photometric distance for the object. If we assume a M_K between -1.5 and -2.5 mag, this would imply a heliocentric distance between 1.2 and 1.9 kpc, and that the object could belong to the Perseus arm (located at about 2 kpc, see Russeil 2003). This result is contrary to the claim of 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 its 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 ionizes the nebula considering the 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, 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 $6.64^{+2.34}_{-1.98}$ 10^{-11} erg cm^{-2} s^{-1}. Assuming a representative value of the heliocentric distance of about 1.5 kpc (we have not considered errors for the distance in the following because it is rather undefined), we obtain an Hα luminosity of $L_{\mathrm{H}\alpha} = 1.79^{+0.65}_{-0.54} \times 10^{34}$ erg s^{-1}, which corresponds –assuming an ionization-bounded nebula– to log N(Lyc) = $46.12^{+0.13}_{-0.16}$ (i. e. Osterbrock 1989). This ionizing flux is consistent with a ZAMS star of B0.5 spectral type, in –accidental– 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 attending to several facts: a) its early B spectral type; b) the presence of broad Hα emission related to the star; c) 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 at 8.5 kpc).

From Figure 4 and Table 1 it is clear that Hα and the two lines of [N II] doublet are well resolved in our spectrum, and that the [N II](6584 Å)/Hα ratio is 0.25, 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](6584 Å)/Hα ratio observed in a sample of 15 Galactic H II regions (Hawley 1978). On the other hand, the [N II]/Hα ratio –valuated only for the nebular or narrow component of Hα– is almost constant along the nebula, as it can be seen in Figure 2. We cannot determine the electron temperature of the ionized gas and, 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 making use of empirical calibrations. Denicoló, Terlevich, & Terlevich (2002) propose a calibration of the O/H ratio vs. the [N II](6584 Å)/Hα ratio. Using this relation we obtain a oxygen abundance of 12 + log(O/H) $\sim$ 8.70, a value typical of H II regions of the solar vicinity. In Figure 5, we show two diagnostic diagrams (adapted from Sabbadin, Minello, & Bianchini 1977) involving the locus 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, consistently with that suggested by its IRAS LRS spectrum, IRAS fluxes, and morphology.

The detection and measurement of the [S II] doublet at 6716 and 6731 Å allows to deriving the electron density of the nebula. Using the five-level program for the analysis of emission-line nebulae included in IRAF NEBULAR task (Shaw & Dufour 1995) and

our observed [S II] 6717/6731 ratio we obtain an electron density of 540^{+400}_{-200} cm^{-3}. This is a density 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 between 500 and 1000 cm^{-3} (Esteban et al. 1999). Vílchez & Esteban (1996) obtain densities between $\leq$100 cm^{-3} and 550 cm^{-3} for a sample of H II regions located toward the Galactic anticenter. From 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 pc $\times$ 0.14 pc.

From our dereddened value of the Hα flux and the diameter of the nebula we can estimate its root mean square density using the usual formulae (i.e. Gurzadyan 1997), which is N_e(rms) = 950$\pm$150 cm^{-3}. This value is larger than the density obtained from the [S II] doublet but consistent within the uncertainties, result that indicates that the volume filling factor of the nebula should be about 1. It is necessary to remark that the exact value of N_e(rms) is extremely dependent on the assumed distance, which is rather uncertain in this case. The corresponding ionized mass of the nebula is very small: 0.11$\pm$0.04 M$_\odot$. In Table 2 we compare some physical parameters of IRAS 04000+5052 with those 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 attending to 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 the order of those of typical compact H II regions, the density is consistent with the typical values of normal H II regions. We consider that the small linear size an 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 consider that IRAS 04000+5052 should be considered a relatively normal small H II region 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 associated with a small and isolated protostellar cluster probably located at 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 it was proposed by Wang et al. (2002). It is ionized by a stellar source of B0.5 spectral type, 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 due to 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. Definitively, the nebula is not a metal–poor object, its [N II](6584 Å)/Hα ratio is 0.25, larger than the value of 0.06 previously determined by Wang et al. (2002) and consistent with that of normal H II regions of the Galactic disk.

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Table 1: Line intensity ratios with respect to I(Hβ) = 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

Table 2: Comparison of physical parameters

Class of H II Region	Size (pc)	N_e (cm^{-3})	EM (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)

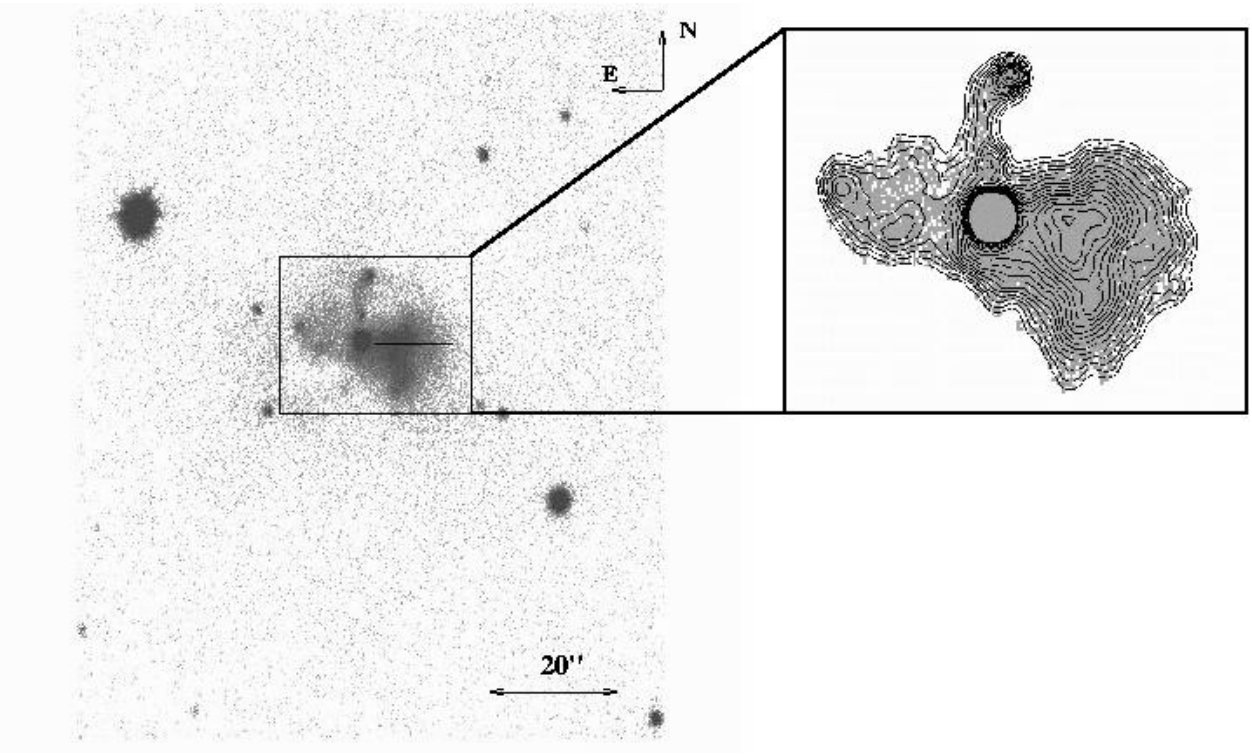


Fig. 1.— CCD Hα image of IRAS 04000+5052. The position and spatial extension of the zone from which the one-dimensional spectra have been extracted is indicated. The box on the right shows an enlargement of the central part of the continuum-subtracted image of the nebula in gray scale with contours.

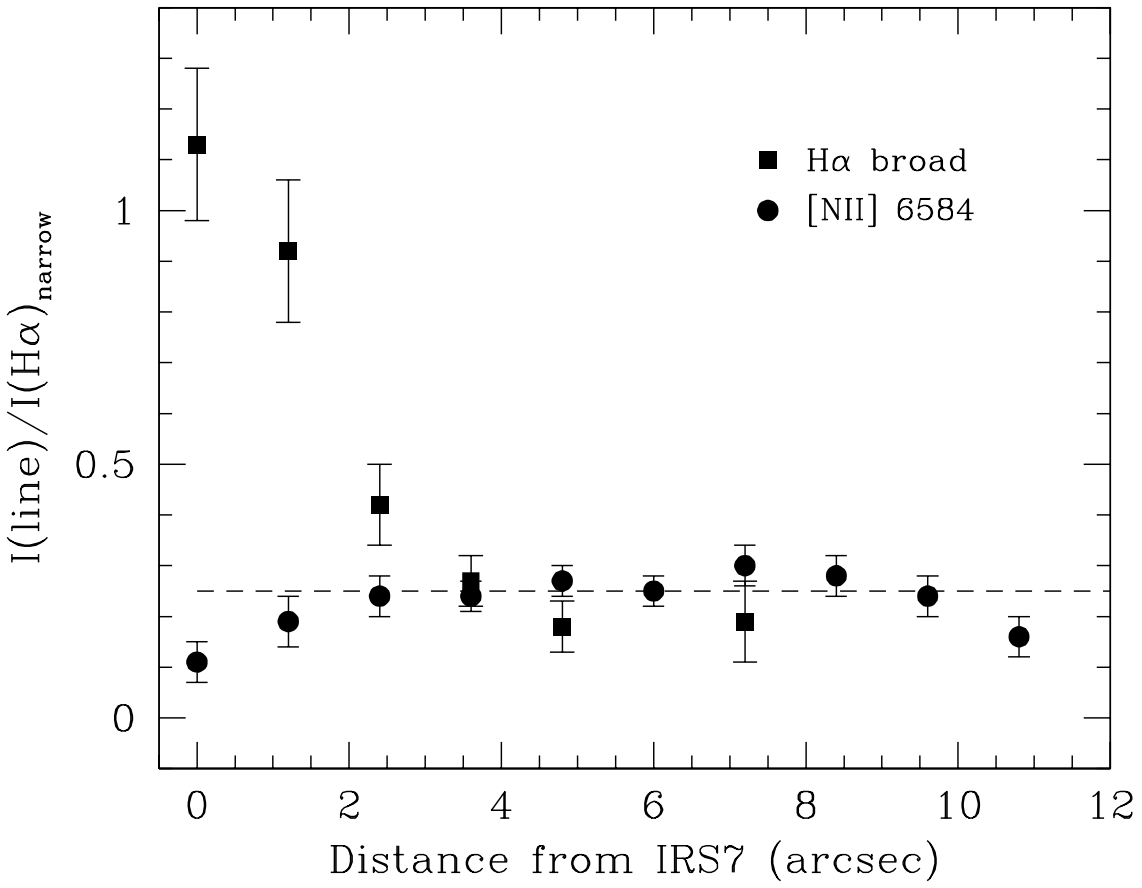


Fig. 2.— Emission line ratios of the broad component of Hα and nebular [N II] with respect to nebular –narrow– Hα emission along part of the slit (from the ionizing star IRS 7 to the west). The spatial increments are 1.2″-long. The contribution of the broad Hα emission is more important near IRS 7 while the [N II] emission is quite constant along the slit.

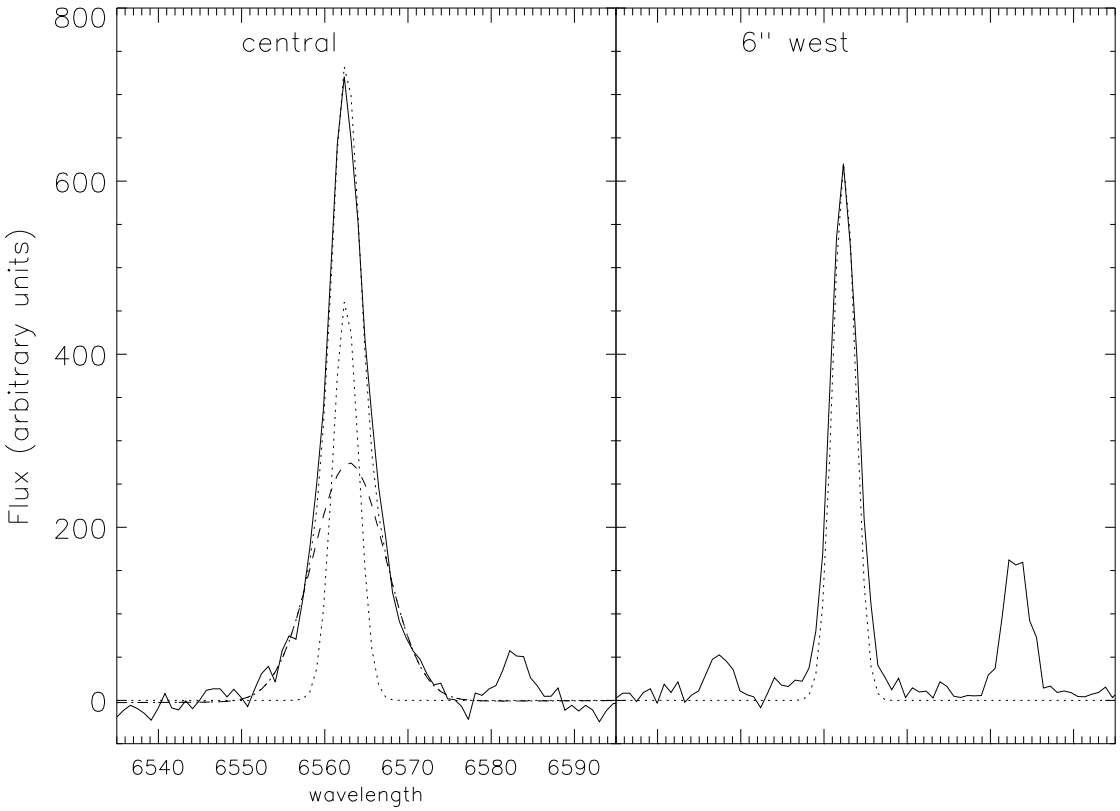


Fig. 3.— Spectra of a 1.2″-long slice passing through the central star of IRAS 04000+5052 H II region (left) and an offcenter region 6 arcsec to the west of the central star (right). The Gaussian fits to the line profiles –individual and combined– are included as discontinuous curves. The FWHM and nature 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.

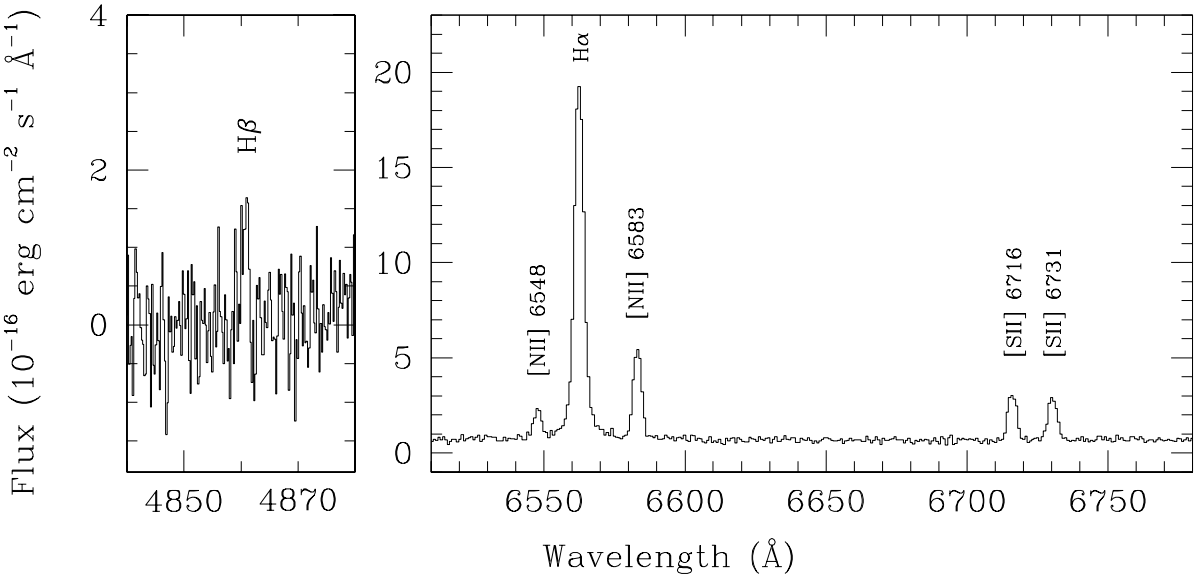


Fig. 4.— Parts of the blue (left) and red (right) spectra of IRAS 04000+5052 showing all the emission lines measured in the nebula. Hα and the [N II] doublet are clearly resolved (see Figure 2 of Wang et al. 2002 for comparison).

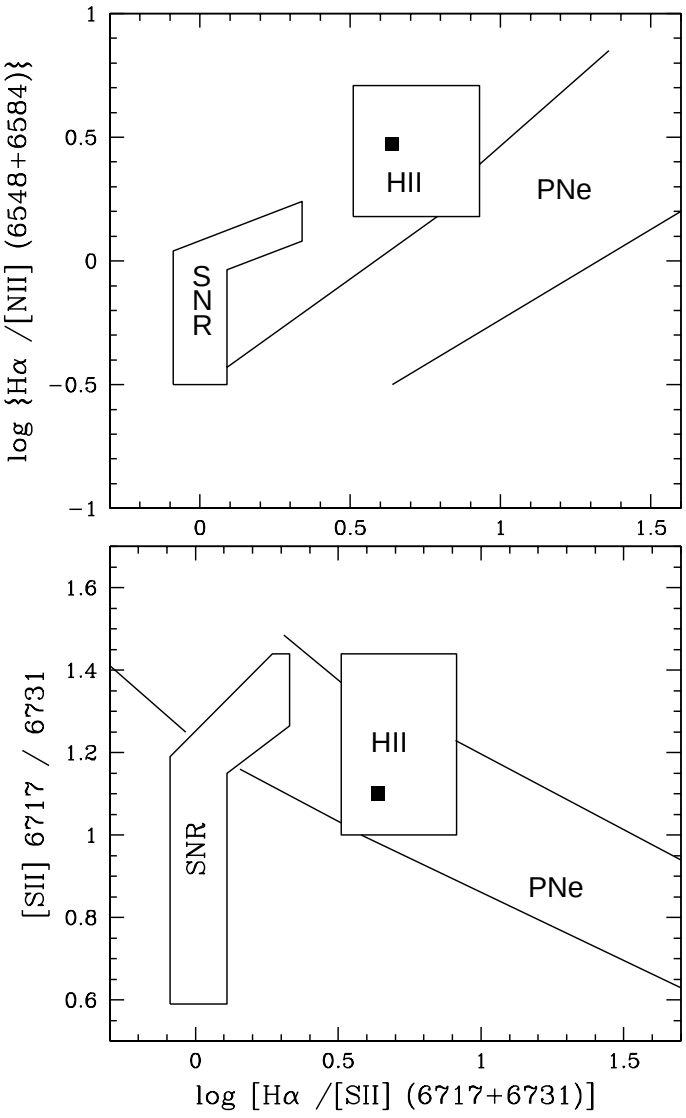


Fig. 5.— Diagnostic diagrams showing the emission line ratios of IRAS 04000+5052 indicating the H II region nature of the object (adapted from Sabbadin et al. 1977).