An uncatalogued optical H II region in the outskirts of the Galaxy

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Abstract. We present NOT optical observations of a clump ($l = 127.9435^\circ, b = +1.8298^\circ$) embedded in an extended, irregularly shaped, diffuse optical nebula. This condensation shows an emission-line spectrum typical of classic H II regions. Although its location on the sky coincides with a nearby extended photoionized region recently identified by Cichowolski et al. (2003) in radio data from the Canadian Galactic Plane Survey (CGPS), the systemic velocity of this $\approx 1^\circ$-sized H II region, $V_{\text{LSR}} = -71 \pm 12$ km s$^{-1}$, poses it far out in the Galaxy, beyond the Perseus arm. The location of this region in the Galaxy is supported by H I structures visible at comparable radial velocity on CGPS data. We argue that this H II region might belong to an outer Galactic arm. The emission line ratios of the surrounding extended nebula, whose radial velocity is consistent with that of the small H II region, are typical of photoionized gas in the low density limit. Smaller clumps of comparable surface brightness are visible within the optical boundaries of the extended, faint nebula. After comparison of the optical data with far infrared and radio observations, we conclude that this nebula is an H II region, $\sim 70$ pc in size, probably photoionized by an association of OB stars and surrounded by a ring of neutral hydrogen.

Key words. ISM: H II regions – ISM: individual objects: IRAS 01342+6358 – ISM: individual objects: IRAS 01330+6351

1. Introduction

Galactic H II regions offer the opportunity of investigating and understanding the details of star formation processes. Furthermore, the identification of H II regions is of interest to trace the spiral structure of our Galaxy, which is still a matter of debate (e.g. McClure-Griffiths et al. 2004; Russell 2003, and references therein).

During our searches for galaxies beyond the Galactic plane – based on visual inspection of Palomar Observatory Sky Survey plates of both first and second generation (e.g., Seeberger et al. 1996; Weinberger et al. 1999) – we have identified an extended and irregularly shaped nebula, not previously catalogued, which shows a number of brighter condensations that are either embedded or projected onto it. The whole object is extended over about half a degree on the sky, while the bright condensations are much more limited in size, the brightest and largest one, located at $l = 127.9435^\circ, b = 1.8298^\circ$, having a major axis of $\approx 1^\circ$. Its morphology happens to be similar to that of the giant ($\sim 2^\circ \times 2^\circ$ in extent) H II region IC 1805 (also known as W4), ionized by the association Cas OB6 and located at a distance of 2.35 kpc (Massey et al. 1995).

Two IRAS peaks of emission, listed in the IRAS Point Source Catalogue as IRAS 01342+6358 and IRAS 01330+6351, are present in the same region of the sky and were identified and measured as actually extended FIR sources by Fich & Terebey (1996). Observations of one of these sources, IRAS 01342+6358, during the CS(2−1) survey of ultracompact (UC) H II regions (Bronfman et al. 1996) left the source undetected, therefore its radial velocity and kinematic distance could not be determined. Recently, Cichowolski et al. (2003) gave evidence that the extended FIR emission is associated with an extended thermal source of radio emission. They argued that this structure is physically related to a “hole” in the H I distribution observed at a systemic velocity of $\sim 29.5$ km s$^{-1}$, and traces gas photoionized by the nearby O star HD 10125. However, they do not provide any direct measurement of the radial velocity (and therefore distance) of the ionized material. To our knowledge, no spectroscopic observations of this ionized region have been published to date.

In this paper we present for the first time $R$-band photometry and optical spectroscopy of a portion of the optical extended nebula spatially coincident with the extended FIR and radio emission, including the $\sim 1^\circ$-size brighter condensation cited above. Beside investigating the physical properties of this “condensation”, that is revealed as a classic H II region,

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* Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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we derive its radial velocity and try to establish whether this region is related to the surrounding extended nebula and associated to the extended photoionized region recently identified by Cichowolski et al. (2003).

2. Observations and measurements

The optical data were obtained in November 1999 at the Nordic Optical Telescope (NOT) with the faint object spectrograph and camera ALFOSC and consist of a 330 s $R$-band exposure covering a field of view of $\sim 5' \times 5'$ and a 1800 s long-slit spectrum taken along the major axis of the bright optical condensation (position angle $= 165^\circ$). Both the image and the spectrum have a spatial scale of 0.188 pixel$^{-1}$. The seeing during the observations was $\sim 0'0.8$. The long-slit spectrum was taken with a 1"-wide slit and has a dispersion of 1.483 Å pixel$^{-1}$ and a spectral resolution of $\sim 6.5$ Å over the wavelength range $\lambda 3833-6857$ Å, as evaluated from the FWHM of comparison lines. $R$-band images of a Landolt (1992) standard field for photometric calibration and long-slit spectra of the spectrophotometric standard star BD$+28^\circ4211$ were taken three and two times, respectively, during the same night. Standard reduction steps were performed with the available IRAF$^1$ packages. The 2σ limiting magnitude and surface brightness of our $R$-band image are $R = 23.88$ mag, $\mu_R = 24.74$ mag arcsec$^{-2}$.

$^1$ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

$^2$ MIDAS is developed and maintained by the European Southern Observatory.

2.1. Photometry

Since the diffuse nebula, as visible in the Digitized Sky Survey image (Fig. 1), extends over about half a degree on the sky, we could image only a portion of it, which completely filled the ALFOSC field-of-view. This fact prevented us from any estimation of the real sky-background, as well as an evaluation of the average surface brightness of the most diffuse portion of the nebula. Therefore, we only were able to evaluate the magnitude and surface brightness of the bright condensations falling within our field-of-view. A bidimensional polynomial fit to the sky-background (thus including the contribution from the more diffuse part of the nebula) was obtained with MIDAS$^2$ on the $R$-band image after masking (IRAF task IMEDIT) of badly saturated stars in the field and subtraction of the unsaturated stars through a fit to a model point spread function (obtained with the DAOPHOT package within IRAF). These operations were necessary because of the relatively strong contamination by stars, owe to the low Galactic latitude of the target. Photometric measurements of the clumps within the nebula were performed on the background-subtracted, free of stars, image by use of both circular apertures completely encompassing the visible clumps and polygonal apertures following the outermost visible contours. Both methods gave similar values of total magnitudes. The polygonal apertures were used to estimate the surface brightness. The measured values are given in Table 1. The whole structure, except for a filamentary extension to the north, fits into $\approx 2/3$ of a circle $\sim 15^\prime.8$ in radius. In other words,
considering the H\textsc{i} column density out to velocities around \(-30\) km s\(^{-1}\). Therefore we estimate for the observed source an internal extinction \(E(B-V) \lesssim 0.5\) mag.

The classic diagnostic emission-line ratios (Table 3) we measured are all typical of photoionized H\textsc{ii} regions (e.g. Galarza et al. 1999, and references therein). No evidence of ionization by shocks was found. Unfortunately the lack of a detectable [O\textsc{iii}] \(\lambda4363\) line prevented us from estimating the electronic temperature of the ionized gas, therefore we assumed a canonical value for H\textsc{ii} regions, \(T_e = 10^4\) K and derived the electronic density \(N_e\) from the ratio of the [S\textsc{ii}] \(\lambda\lambda6716, 6731\) lines. We found \(N_e\) values in the range \(1.7 - 2.4 \times 10^2\) cm\(^{-3}\) (Table 2), which are characteristic of classic H\textsc{ii} regions and at least one to two orders of magnitude lower than values typical of compact or UCH\textsc{ii} regions (e.g. Franco et al. 2003, and references therein). The total spectrum of the H\textsc{ii} region is shown in Fig. 3. The presence of very strong [O\textsc{i}] \(\lambda\lambda6300, 6364\) night-sky lines prevented us from establishing with certainty the presence or absence of [O\textsc{i}] emission from the nebula. However, a comparison of the [O\textsc{i}] lines on- and off-source along the slit seems to indicate that these emission lines are absent or extremely weak on the spectrum of the source. Therefore, we conclude that oxygen is almost fully ionized in this region indicating that the partially ionized zone of the nebula, where O\textsc{i} is present, is probably a very thin layer, as expected in case of ionizing stars of OB spectral types.

2.3. Spectroscopy: Radial velocity determination

The inspection of the spectrum before the background subtraction, allowed us the detection of the H\alpha emission-line (and of most other emission lines at lower signal level) all along the slit. Since the extended nebula occupies the whole field-of-view, we conclude that this emission, well outside the visible boundaries of the H\textsc{ii} region described above, stems from the extended, low surface brightness nebula filling the field of view. Therefore, we measured the position of the H\alpha line in 10 pixel bins along the whole slit, in order to establish whether the...
bright H\textsc{ii} region and the surrounding nebula of excited gas are only projected onto each other or have comparable radial velocities, i.e. are spatially coincident. Radial velocity measurements were based on the H\textalpha line, since this is by far more intense than all other detected emission lines, and thus gives a better accuracy. To estimate the error in radial velocity measurements and detect/correct for possible systematic errors, we measured the [O\textsc{i}] sky-lines in the same apertures all along the slit. We actually found a systematic error in radial velocity with a well defined, regular trend along the slit, being nearly zero in the central part of the frame (where the spectrum of the bright H\textsc{ii} region is located) and increasing when moving toward the borders. The trend was confirmed also by the measurement of other sky-lines within the wavelength range. Radial velocities measured in each 10-pixel bin were corrected for the relevant systematic error\(^3\). The dispersion of position measurements of the brightest sky-lines around their expected values, within each 10-pixel bin, gives an estimate of the uncertainty of the radial velocities. This is about 12 km\ s\(^{-1}\). The systemic velocity of the H\textsc{ii} region, obtained by averaging the radial velocities measured within its borders (as visible in the R-band image and in the H\textalpha profile), is \(V_{\text{LSR}} = -71\) km\ s\(^{-1}\). The extended part of the nebula exhibits a comparable value (within measurement errors) of radial velocity, on average \(V_{\text{LSR}} = -60\) km\ s\(^{-1}\). We conclude that the two structures are physically associated and not purely overlapping because of projection effects. In principle, part of the detected H\textalpha line might stem from other intervening Galactic nebulae along the line-of-sight or from diffuse Galactic H\textalpha emission. In fact faint diffuse Galactic H\textalpha emission appears to cover almost the entire sky (Reynolds 1990). The resolution of our spectra would not allow to unambiguously separate a different velocity, weaker H\textalpha component, which would appear in narrow blend with the observed line. However, we do not observe any hint of a second component in the line profile (e.g. double peaks, wings, humps, etc.), therefore we argue that the emission line component at the observed \(V_{\text{LSR}} = -60\) km\ s\(^{-1}\) is (if not the only) the dominant one along the line of sight. Additionally, as we show below, the spectrum of the extended nebula is typical of classic H\textsc{ii} regions, therefore significantly different from the spectrum of diffuse warm ionized interstellar gas (Reynolds 1990).

Following the method outlined by Brand & Blitz (1993) and using their best fit of the Galactic rotation curve and our measurement of \(V_{\text{LSR}}\), we estimated the distance of the photoionized nebula. We assumed the position of the bright clump as representative of the center of the nebula, and used the radius of the clump (\(16\)\(^{\circ}\)) as an indication of the positional error. We used for the Sun the IAU-recommended values of Galactocentric distance and circular velocity, i.e. \(R_0 = 8.5\) kpc and \(\Theta_0 = 220\) km\ s\(^{-1}\). We found a heliocentric

\(^3\)The spectral resolution does not allow us to separate the geocoronal H\textalpha line. However, since this line is at rest with respect to Earth like all other night-sky-lines, the correction involving the use of the [O\textsc{i}] sky-lines implicitly takes into account the geocoronal line as a radial velocity zero-point. As an additional remark we note that the emission-line ratios typical of H\textsc{ii} regions measured in Sect. 2.4 suggest that the contribution of the geocoronal line to the observed H\textalpha emission is marginal in this spectrum.
Table 3. Diagnostic emission-line ratios.

<table>
<thead>
<tr>
<th>Object Id.</th>
<th>log ([O III]/Hβ)</th>
<th>log ([N II]/Hα)</th>
<th>log ([S II]/Hα)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part 1</td>
<td>0.02</td>
<td>0.39</td>
<td>0.94</td>
</tr>
<tr>
<td>Part 2</td>
<td>0.50</td>
<td>0.51</td>
<td>0.55</td>
</tr>
<tr>
<td>Part 3</td>
<td>0.66</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>Part 4</td>
<td>0.50</td>
<td>0.48</td>
<td>0.58</td>
</tr>
<tr>
<td>Part 5</td>
<td>0.67</td>
<td>0.45</td>
<td>0.54</td>
</tr>
<tr>
<td>Part 6</td>
<td>0.77</td>
<td>0.43</td>
<td>0.48</td>
</tr>
<tr>
<td>Part 7</td>
<td></td>
<td>0.44</td>
<td>0.49</td>
</tr>
<tr>
<td>Total</td>
<td>0.58</td>
<td>0.47</td>
<td>0.54</td>
</tr>
</tbody>
</table>

distance \(d = 8.2^{+2.1}_{-1.8}\) kpc. Since the semi-major and semi-minor axes of the nebula, as visible on the DSS2 image, are 15′.8 and 14′4, this translates into an approximate diameter of 72 pc. At \(d \approx 8.2\) kpc and \(b \approx +1.83\) this H II region is located at \(z \approx 260\) pc.

2.4. Spectroscopy: Physical properties of the extended nebula

To understand the nature of the extended nebula, we also analyzed the trend of the emission-line ratios along the slit. We found no substantial variation of the diagnostic emission-line ratios, i.e. the low surface brightness extended nebula as well shows typical characteristics of classic H II regions. The only difference between the fainter and the brighter parts of the nebula falling in the slit resides in the ratio of the [S II] λ6716, 6731 lines, which in the fainter parts increases to values \(>2\), indicating that the extended nebula is in the low density limit, with \(N_e < 10\) cm\(^{-3}\). The total foreground extinction measured all along the slit, as shown in Fig. 4, does not differ substantially from that derived above for the bright clump, ranging from \(-0.5\) to \(-2.3\) mag with an average value \((E(B-V)) = 1.2 \pm 0.3\) mag. The H\(\alpha\) emission measure calculated for the region of the bright clump falling within the slit, after reddening correction, is \(EM \approx 6.94 \times 10^3\) pc cm\(^{-6}\), while the value found for the adjacent parts of the extended nebula is \(EM \approx 5.33 \times 10^3\) pc cm\(^{-6}\). We exclude the possibility that the low surface brightness nebula is a region of diffuse ionized gas (DIG) both on the basis of its H\(\alpha\) \(EM \gg 100\) pc cm\(^{-6}\) and of its [S II]/H\(\alpha\) ratio, which is usually found to be considerably higher in DIG than in classic H II regions (see, e.g., Galarza et al. 1999).

Assuming on average an \(EM \approx 5.3 \times 10^3\) pc cm\(^{-6}\) in the brighter area of the extended nebula (\(~334\) arcmin\(^2\), as estimated on the DSS2 image), considering negligible the contribution of the fainter parts of the nebula, and using the distance determined above, we obtained a rough estimate of the total (extinction-corrected) H\(\alpha\) luminosity, \(L(H\alpha) \approx 1.1 \times 10^{38}\) erg s\(^{-1}\). This luminosity is equivalent to a total number of ionizing photons \(Q_{ion} \approx 7.7 \times 10^{49}\) photons s\(^{-1}\) (Kennicutt 1998). The estimated \(Q_{ion}\) could be produced by a single ionizing star of spectral type between O5.5Va and O3V, according to values tabulated by Vacca et al. (1996, their Tables 5 to 7). However, the corresponding radius of the Strömgren sphere would be \(~6.2\) pc, much smaller than the observed radius (\(~36\) pc) of the ionized nebula. We argue that, as an alternative, the necessary amount of ionizing photons could be emitted by an association of lower luminosity OB stars. As an example, about 50 stars of spectral types between O9V and B0.5V would produce a total amount of ionizing photons similar to our estimated values. This interpretation could account for the relatively large size of the Strömgren sphere. Additionally, we note that the Strömgren sphere radii given by Vacca et al. (1996) are calculated assuming a hydrogen density \(N_H = 10^2\) cm\(^{-3}\) and therefore are significantly smaller than those tabulated by Osterbrock (1989) under the assumption of \(N_H = N_e = 1\) cm\(^{-3}\). Our spectral analysis showed that, while the bright clump has \(N_e \approx 2 \times 10^2\) cm\(^{-3}\), the surrounding nebula is in the low-density limit, \(N_e < 10\) cm\(^{-3}\). This fact might contribute to explain the discrepancy between the observed size of the ionized region and the tabulated values of Strömgren sphere radii. Our conclusion is that the nebula can probably be ionized by a few to a few tens of OB stars.

3. Comparison with FIR and radio emission

In order to derive additional information on the observed nebula, we compared the optical images (both DSS2 images and our own R-band exposure) with FIR emission from IRAS data and radio emission available from several sources in the literature and from archival data of the CGPS in the same region of the sky. Contour maps of the 60 \(\mu\)m emission, reconstructed from IRAS raw data available at the Groningen IRAS server, after correction for zodiacal emission, are shown in Fig. 5, overplotted onto the DSS2 R-band image of a 2′′ \(\times\) 2′′ field centered at the position of the H II region. As already noticed by other authors (Fich & Terebey 1996), besides the two sources listed in the IRAS Point Source Catalogue,
extended emission is clearly visible. A striking coincidence of such an extended emission with the extended nebula visible in the DSS image strongly suggests that the two features are correlated. This spatial coincidence is even better visible in Fig. 6, where a 1° × 1° DSS image centered on the optical source is overlapped with the contours of a 60 μm high resolution image obtained by processing the IRAS data with a program based on the maximum entropy algorithm MeMSys5 (Bontekoe et al. 1994). In particular the two strong sources IRAS 01342+6358 and IRAS 01330+6351 are coincident with the two main sub-features visible in the optical nebula. The bright H II region we identified within the extended nebula lies in close vicinity of the peak of IRAS emission at the center of the field. The spatial coincidence of the extended FIR emission with the extended radio continuum emission detected by the CGPS has already been shown by Cichowolski et al. (2003). Additionally, we notice a remarkable similarity between the radio and optical substructures of the extended nebula, as can be seen by comparing the CGPS radio map at 1420 MHz (Fig. 7) with the DSS image of the nebula (Fig. 1, left). Finally, the radio source NVSS J013746+641452, ~80″ in extent, with integrated flux density of 20.7 ± 2.5 mJy at 1.4 GHz, detected by Condon et al. (1998), coincides, within the positional error, with the bright optical clump, which shows a comparable extent in the R-band image. In view of these spatial coincidences, we suggest that all the above features in the optical, radio, and FIR are related one another. Given the radial velocity measured for the H II region and surrounding ionized nebula, the above considerations would pose all the above structures at Galactocentric distance ≈15 kpc (i.e. heliocentric distance 8.2 kpc), in contrast with the considerably smaller distance proposed by Cichowolski et al. (2003), based on structures detected in the H I 21 cm line at $V_{\text{LSR}} \sim -29.5$ km s$^{-1}$.

The examination of the 21 cm data from the CGPS archive gives further support to our interpretation. In fact, the plot of brightness temperature in the direction of the H II region (Fig. 8) shows a secondary depression in the H I distribution at $V_{\text{LSR}} \sim -70$ km s$^{-1}$, in good agreement with our measured radial velocity. The H I 21 cm-line image at the position of the extended nebula shows a hole in the H I distribution in clear correspondence of the ionized gas visible in the radio-continuum
and optical images. The size and boundaries of the “hole” are in good agreement with those of the ionized nebula, with a “ring” of neutral hydrogen largely surrounding the photoionized gas. This correspondence is well visible in several velocity channels in the range \( -64 \) to \(-71 \) km s\(^{-1}\) (especially at \(-67 \) km s\(^{-1}\)) and is shown in Fig. 9, where the radio-continuum at the position of the nebula is compared to the 21 cm-line map, averaged over the velocity interval \(-65.8 \) to \(-69.1 \) km s\(^{-1}\). These velocities are in good agreement (within measurement errors) with the radial velocities obtained from the optical spectrum of the nebula.

4. Conclusions

We have performed \(R\)-band photometry and optical spectroscopy of an emission nebula located \( \sim 2^\circ \) above the Galactic plane with the main aims to examine the physical conditions of its gas and establish its location within the Galactic structure. It was also our intention to establish whether the observed optical structures in this region of the sky are physically connected to one another or are rather distinct structures seen in projection along the line-of-sight.

Our data indicate that the bright condensation \( \sim 1' \) in size has typical emission-line ratios of a classic \( \text{H} \ II \) region. The radial velocity of the observed \( \text{H}\alpha \) line suggests that the \( \text{H} \ II \) region is located far out in the Galaxy, well beyond the Perseus arm. We speculate that it might belong to the outer arm of the Galaxy. Actually, indications of the presence of spiral arm tracers in the second Galactic quadrant at distances up to \( 11 \) kpc have been reported by several authors (see, e.g. Kimeswenger & Weinberger 1989, and references therein). In particular, Kimeswenger & Weinberger (1989), collecting a number of different spiral arm tracers, gave evidence of the existence of an outer spiral arm, bending above the Galactic plane in the second quadrant (see also the structure of the Galactic warp shown e.g. by Wiedemair 2001), at distances comparable to the kinematic distance of the \( \text{H} \ II \) region discussed in this work.

The presence of a depression in the \( \text{H} I \) profile along the line-of-sight to the \( \text{H} \ II \) region at velocities in agreement with those measured from our optical spectra further supports our interpretation. Additionally, we observe fainter emission lines also from the extended optical nebula that completely fills our field-of-view. The radial velocity of these emission-lines is in agreement with that of the identified \( \text{H} \ II \) region, within the measurement errors. Once again the diagnostic emission-line ratios are typical of classic \( \text{H} \ II \) regions. These facts support the idea that the bright clump and the irregularly shaped, extended optical nebula are physically related and constitute a center-brightened \( \text{H} \ II \) region. Considerations on the emission measure, apparent size, and estimated distance of the nebula lead to conclude that its gas is ionized by an association of a small number of OB stars. A comparison between the DSS2 image of this extended nebula and the 60 and 100 \( \mu \)m IRAS images reveals a striking spatial coincidence of the structures and, even more strikingly, its optical substructures are well reproduced by substructures visible in the 1420 MHz continuum. This is in contrast with the recent work of Cichowolski et al. (2003), who give some evidence of the association of these FIR sources and their radio-continuum counterparts with a nearby (distance \( \sim 3 \) kpc) region photoionized by the O star HD 10125. Although the arguments given by Cichowolski et al. (2003) look convincing, they are not supported by direct radial velocity measurements of the ionized gas. Indeed, the correspondence we find between a “hole” in the \( \text{H} I \) distribution at velocities around \(-67 \) km s\(^{-1}\) and the extended radio-continuum emission appears much tighter than the correspondence with an \( \text{H} I \) “hole” at \(-29.5 \) km s\(^{-1}\) suggested by Cichowolski et al. (2003). In the light of our observations, we argue that both the FIR sources and the radio-continuum emission are rather associated with the more distant (\( d \) \( \sim 8.2 \) kpc) photoionized nebula we have identified.

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Fig. 8. Average \( \text{H} I \) emission spectrum within a \( \sim 30' \times 30' \) box centered at the position of the optically bright clump.

Fig. 9. Left: radio continuum image at 1420 MHz, centered at the position of the ionized nebula, overlaid with a contour indicating the extent of the nebula and its peak of brightness. Right: \( \text{H} I \) 21 cm map of the same region, averaged over the velocity range \(-65.8 \) to \(-69.1 \) km s\(^{-1}\) and overlaid with the contour of the radio-continuum emission. Darker gray levels indicate lower brightness.
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