A YOUNG STELLAR CLUSTER WITHIN THE RCW41 H II REGION: DEEP NIR PHOTOMETRY AND OPTICAL/NIR POLARIMETRY

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ABSTRACT

The RCW41 star-forming region is embedded within the Vela Molecular Ridge, hosting a massive stellar cluster surrounded by a conspicuous H II region. Understanding the role of interstellar magnetic fields and studying the newborn stellar population is crucial to building a consistent picture of the physical processes acting on this kind of environment. We carried out a detailed study of the interstellar polarization toward RCW41 with data from an optical and near-infrared polarimetric survey. Additionally, deep near-infrared images from the 3.5 meter New Technology Telescope were used to study the photometric properties of the embedded young stellar cluster, revealing several YSO candidates. By using a set of pre-main-sequence isochrones, a mean cluster age in the range 2.5–5.0 million years was determined, and evidence of sequential star formation was revealed. An abrupt decrease in R-band polarization degree was noticed toward the central ionized area, probably due to low grain alignment efficiency caused by the turbulent environment and/or the weak intensity of magnetic fields. The distortion of magnetic field lines exhibits dual behavior, with the mean orientation outside the area approximately following the borders of the star-forming region and directed radially toward the cluster inside the ionized area, in agreement with simulations of expanding H II regions. The spectral dependence of polarization allowed a meaningful determination of the total-to-selective extinction ratio by fittings of the Serkowski relation. Furthermore, a large rotation of polarization angle as a function of wavelength was detected toward several embedded stars.

Key words: ISM: clouds – ISM: magnetic fields – open clusters and associations: individual: RCW41 – stars: formation – techniques: photometric – techniques: polarimetric

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

It is well known that sites of massive star formation are mainly found inside heavily obscured dusty molecular cores, which are commonly associated with giant molecular cloud complexes (e.g., Lada & Lada 2003; Lada 2010). Photometric studies at near-infrared (NIR) wavelengths make it possible to probe deep inside where star formation is taking place, with the very young stars frequently showing large infrared excesses due to the presence of warm dust from the associated circumstellar disks.

On the other hand, the study of the interstellar dust grain’s interaction with the local magnetic fields is a powerful tool for understanding some of the physical processes acting in such environments. In this context, magnetic fields might play a key role in star formation. In fact, several physical processes, including the initial cloud collapse by the fragmentation of early stage star-forming cores, the channeling of interstellar material via ambipolar diffusion, the disk and bipolar outflow formation, the angular momentum transport, etc., are possibly strongly affected by the strength and configuration of the local magnetic field components (Mestel & Spitzer 1956; Nakano 1979; Mouschovias & Paleologou 1981; Shu et al. 1987; Lizano & Shu 1989; Heitsch et al. 2004; Girart et al. 2009). However, it is still unknown whether magnetic fields or interstellar turbulence provide the main supporting source against the cloud collapse, ultimately defining the star formation efficiency (Padoan et al. 2004; Crutcher 2005; Heiles & Crutcher 2005; McKee & Ostriker 2007).

The formation of massive stars causes a large impact on the surrounding environment, ionizing the interstellar gas and providing a source of turbulence due to strong stellar winds and outflows from the newborn stellar population. Only recently, theoretical studies have attempted to describe a realistic view of the impact of the expansion of H II regions on the underlying structures of the magnetic field lines (Krumholz et al. 2007; Peters et al. 2010, 2011; Arthur et al. 2011). Unfortunately, mappings of the magnetic field structures along the majority of Galactic H II regions are scarcely available, although these could serve as important tests and provide additional constraints on such models of star formation.

An important method of mapping the sky-projected lines of the magnetic field using optical or NIR spectral bands is from interstellar polarization by aligned dust grains, which serves as a well known tracer. A detailed study of linear polarization toward H II regions and young stellar clusters can provide useful information regarding the structure of the Galactic magnetic field in these regions.

The Vela Molecular Ridge (VMR) is an interesting Galactic complex where star formation is taking place over a wide range of masses (Liseau et al. 1992; Lorenzetti et al. 1993; Massi et al. 1999, 2000, 2003). It is located at the Galactic plane roughly toward l ~ 265°, where one can see the presence of several large interstellar features, such as the Vela supernova remnant, the Gum Nebula, and other structures. Beyond this “local” structure, at the 1–2 kpc range, several young star clusters are found, as
well as numerous optical H II regions with several signposts of embedded star formation such as H2O masers (Braz & Epchtein 1983; Zinchenko et al. 1995).

Among these structures, a giant molecular complex extends over 20' in the southern sky. This can be identified by its strong CO emission and was first studied by Murphy & May (1991), who divided the main structure into four regions labeled A–D. Clouds toward these areas are located along a wide range of distances from 700 to ∼2000 pc (Liseau et al. 1992). According to Murphy & May (1991) regions A, C, and D are closer to us (∼1 kpc), with the cloud B being slightly more distant (∼2 kpc). Recently, a submillimetric survey carried out by Olmi et al. (2009) detected approximately 140 proto- and pre-stellar cores in the direction of cloud D.

The IRAS 09149-4743 source is an example of a young stellar cluster in this region. It is part of the cloud A and is located at an estimated distance of 1.3 ± 0.2 kpc (Roman-Lopes et al. 2009). It shows several candidate young stellar objects (YSOs), as well as two massive stars of spectral types O9 v and B0 v, as revealed by previous photometric and spectroscopic infrared surveys (Ortiz et al. 2007; Roman-Lopes et al. 2009). Several radio and infrared observations are available in the direction of IRAS 09149-4743, tracing a number of chemical elements in this region. These elements are mainly related to the existence of the surrounding H II region and the massive star-forming area. Ortiz et al. (2007) compiled a list of all observational data collected from the literature up to that date. Furthermore, Pirogov et al. (2007) reported the detection of CS, N2H+, and 1.2 mm dust continuum emissions toward IRAS 09149-4743. Specifically, the dust emissions represent an almost spherical core approximately superposed to the stellar cluster direction. Pirogov (2009) carried out further studies of these data through analysis of the cloud’s radial density profile (RDP).

Our main goals in this work are to study the stellar population of the associated massive star cluster and to investigate the structure of the interstellar magnetic field in the direction of the related H II region. These goals were carried out by combining new deep NIR imaging with optical and NIR polarimetric data of the related region. The paper is organized as follows: Section 2 describes the NIR photometric data and reduction techniques and the polarimetric observational sample. Results and analysis obtained from the photometric and polarimetric data are separately presented in Sections 3 and 4, respectively. Discussion of these results is introduced in Section 5, and the final conclusions are listed in Section 6.

2. OBSERVATIONAL DATA

2.1 Near-infrared Photometry

The raw imaging data for the IRAS 09149-4743 region were retrieved from the ESO archive. The observations comprise two separate programs with the following identifiers: 073.D-0102 (PI: Dr. Sergio Ortolani) and 080.D-0470 (PI: Dr. Ben Davies). The observing missions were conducted during the nights of 2004 May 5 and 2008 February 10 using the Sofi (Son of Isaac) NIR camera (Moorwood et al. 1998) mounted on the 3.58 meter New Technology Telescope (NTT) from La Silla/Chile.

In Figure 1(a) we use a combined Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) image of the studied region to show the surveyed area. The 2004 survey corresponds to the two small squares shown in this figure (delimited by cyan dashed lines): one centered on the stellar cluster and the other on a nearby control field. This survey, hereafter denoted “Dataset A,” corresponds to J, H, and Ks band observations using a 0.144 pixel−1 plate scale, which allows a 2.1 × 2.1 field of view. The observational strategy included 24 expositions at each of the three filters, corresponding to 12 observations of the cluster field intercalated with 12 observations of the control field. Moreover, successive observations of the same field were made by jittering the telescope by a small displacement (≈9.5, 20′, respectively.)
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Figure 1(a) the region associated with Dataset B corresponds roughly in the NE–SW direction) between each exposition. The FWHM values of point-like sources at this observational run are of $\approx 1''$.

The observational data from the 2008 survey (which we hereafter denote “Dataset B”) were obtained using the H and $K_s$ bands, with a plate scale of 0.288 pixel$^{-1}$, allowing a field of view of about 4.9 x 4.9. Four jittering positions were used, moving the telescope in the N–E–S–W directions while positioning the cluster in each of the four quarters of the frame. Using this method, a larger field could be mapped covering an area of 7.4 x 7.4 on the sky, centered on the stellar cluster. In Figure 1(a) the region associated with Dataset B corresponds to the larger square delimited by a solid line. Atmospheric conditions during this observational run allowed mean FWHM values of $\approx 0.7''$.

Images from both data sets were treated using IRAF3 (Tody 1986) tasks from the NOAO package to perform the following reduction steps: division by a flat-field frame and illumination pattern, correction of bad pixels from the frame using a bad pixel mask, correction of the “crosstalk effect,” combination of jittered images in order to create sky fields, subtraction of the sky images, combination of the sky-subtracted images, and alignment of images from different filters. The reduced images of Datasets A and B are respectively displayed in Figures 1(b) and (c). MONTAGE4 was used to create the 7.4 x 7.4 field mosaic of Dataset B (Figure 1(c)).

DAOFIND (from the DAOPHOT package) was used to locate stars peaked with 3σ above the background, and objects missed by this routine were further inserted by visual inspection. Astrometric configuration of the objects’ world coordinate system was done by using a sample of 2MASS isolated objects from the same field. Correction of the coordinates was achieved with an rms uncertainty of $\approx 0.05$ arcsec in right ascension ($\alpha$) and declination ($\delta$) for both data sets.

Point-spread function (PSF) photometry was further performed using the algorithms from the DAOPHOT package (Stetson 1987), with the following photometric parameters for each data set: PSF radius of 2.30 and fitting radius of 1.30 for Dataset A; PSF radius of 2.59 and fitting radius of 0.86 for Dataset B. Several runs of PSF fitting and stellar subtraction were performed in order to reveal and obtain magnitudes for the very close faint companions from the most crowded areas.

Photometric calibration was achieved by comparing the instrumental magnitudes with a sample of isolated, good quality photometry stars (flag “A”) at the same field from the 2MASS survey. Such comparison is shown in Figure 2 for both data sets. These diagrams show a quite good correlation, with zero point uncertainties of 0.02 mag in all photometric bands for both data sets. Individual magnitude uncertainties were computed using a quadratic sum of the instrumental errors from the PSF photometry and the calibration uncertainty.

Furthermore, approximate completeness limits were derived from the analysis of the histograms, also shown in Figure 2. These are defined as the points where the histograms deviate from the straight lines, which represent a linear fit to the logarithm of the number of objects per magnitude bin. The values obtained for Datasets A and B are $(J, H, K_s)_{\text{limit}} = (18.6, 17.4, 16.8)$ and $(H, K_s)_{\text{limit}} = (18.4, 17.8)$, respectively. Considering the above photometric limits of both data sets, an improvement of 1.6, 2.1, and 2.8 mag have been obtained in the $J, H,$ and $K_s$ bands, respectively, as compared to the earlier survey by Ortiz et al. (2007), allowing us to probe more deeply into the lower-mass stellar population.

In order to check the existence of color dependence terms to be applied to the Sofi photometry, we constructed diagrams of magnitude difference (between the Sofi and 2MASS systems) as a function of the $(J – H)$ and $(H – K_s)$ colors, as can be seen in Figures 3(a) (Dataset A) and (b) (Dataset B, the $H – K_s$ color only). As can be noticed, there is no need to apply color correction terms to the derived Sofi photometry.

The photometric results are shown in Tables 1 and 2, respectively corresponding to 530 and 2608 stars in Datasets A and B.

### Table 1

| $\alpha(\text{hms})$ | $\delta(\degree\arcmin)$ | $J$ | $\Delta J$ | $H$ | $\Delta H$ | $K_s$ | $\Delta K_s$ |
|---------------------|--------------------------|-----|------------|-----|------------|-------|------------|
| 9 16 47.94          | $-$47 57 17.8            | 9.712 | 0.022 | 8.962 | 0.015 | 8.653 | 0.026 |
| 9 17 1.91           | $-$47 56 44.7            | 10.999 | 0.020 | 9.456 | 0.018 | 8.786 | 0.016 |
| 9 16 43.49          | $-$47 56 22.9            | 10.684 | 0.021 | 9.865 | 0.015 | 9.492 | 0.026 |
| 9 17 4.34           | $-$47 55 49.5            | 12.801 | 0.020 | 10.852 | 0.018 | 9.959 | 0.016 |
| 9 16 46.67          | $-$47 57 21.2            | 12.037 | 0.022 | 10.910 | 0.015 | 10.486 | 0.026 |
| 9 16 41.89          | $-$47 56 15.4            | 14.555 | 0.038 | 12.041 | 0.015 | 10.627 | 0.026 |
| 9 16 47.05          | $-$47 56 44.0            | 12.636 | 0.021 | 11.481 | 0.015 | 11.039 | 0.026 |
| 9 17 8.72           | $-$47 57 16.1            | 12.982 | 0.020 | 11.764 | 0.019 | 11.183 | 0.016 |
| 9 16 45.57          | $-$47 56 50.0            | 12.387 | 0.021 | 11.707 | 0.015 | 11.391 | 0.026 |
| 9 16 44.89          | $-$47 55 38.6            | 13.740 | 0.021 | 12.407 | 0.015 | 11.483 | 0.026 |

Notes. The columns above respectively represent each of the objects’ equatorial coordinates ($\alpha, \delta$), as well as the $J, H,$ and $K_s$ magnitudes, together with each uncertainty ($\Delta J, \Delta H, \Delta K_s$). Values marked with * represent undetected stars (in each specific band) or saturated objects.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 2

| $\alpha(\text{hms})$ | $\delta(\degree\arcmin)$ | $H$ | $\Delta H$ | $K_s$ | $\Delta K_s$ |
|---------------------|--------------------------|-----|------------|-------|------------|
| 9 16 47.95          | $-$47 57 17.8            | *  | *          | 8.621 | 0.036 |
| 9 17 4.88           | $-$47 54 4.8             | 10.411 | 0.016 | 9.534 | 0.028 |
| 9 16 43.49          | $-$47 55 22.8            | 9.944 | 0.024 | 9.543 | 0.028 |
| 9 17 4.43           | $-$47 55 49.4            | 10.870 | 0.024 | 9.995 | 0.026 |
| 9 16 47.68          | $-$47 57 21.2            | 10.920 | 0.016 | 10.455 | 0.021 |
| 9 16 56.95          | $-$47 58 23.5            | 11.194 | 0.015 | 10.500 | 0.016 |
| 9 16 41.88          | $-$47 56 15.4            | 12.068 | 0.022 | 10.666 | 0.024 |
| 9 16 25.46          | $-$47 59 30.9            | 11.337 | 0.014 | 10.765 | 0.011 |
| 9 16 34.57          | $-$47 56 58.3            | 11.650 | 0.015 | 10.814 | 0.015 |
| 9 16 50.51          | $-$47 53 16.6            | 11.093 | 0.035 | 10.924 | 0.029 |

Notes. The columns above respectively represent each of the objects’ equatorial coordinates ($\alpha, \delta$), as well the $H$ and $K_s$ magnitudes, together with each uncertainty ($\Delta H$ and $\Delta K_s$). Values marked with * represent undetected stars (in each specific band) or saturated objects.

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3 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

4 Eletronic address: http://montage.ipac.caltech.edu/
the National Optical Astronomy Observatory—NOAO observatory, during 2010 February and April and 2011 March. The NIR data were obtained using the 1.6 m telescope of the OPD (Observatório Pico do Dias, Brazil, operated by Laboratório Nacional de Astrofísica—LNA/MCT) during 2011 April.

The polarimetric modules used in both telescopes are similar and consist basically of a rotatable achromatic half-wave retarder followed by a calcite Savart plate and a filter wheel (for a complete description of this instrument, see Magalhaes et al. 1996). The half-wave retarder can be rotated in steps of 22.5°, and one polarization modulation cycle is covered for every 90° rotation of this wave-plate. This arrangement provides two images of each object on the detector, which correspond to the perpendicular polarization beams \( f_o \) (ordinary) and \( f_e \) (extraordinary). Rotating the half-wave plate by 45° yields a rotation of 90° of the polarization direction. Thus, at the detector area where \( f_o \) was first detected, \( f_e \) is now imaged and vice versa. Combining all four intensities reduces flat-field irregularities. In addition, the simultaneous imaging of the two beams allows observation under non-photometric conditions and at the same time virtually suppresses the sky polarization component. If extended interstellar emission from the field contributes to some polarization level, this component is also automatically eliminated. Finally, each set of a polarimetric observation was performed using blocks of 8 steps of the half-wave retarder, which corresponds to a 180° rotation of the plate.

Reductions were performed in the standard manner using IRAF’s routines for both the optical and NIR data. Point-like sources were selected from the images using DAOFIND for stars peaked 5σ above the local background level, with the
saturated objects removed from the sample. The total counts for each source were computed by applying aperture photometry using the PHOT routine for several ring sizes around each star. Objects affected by cosmic rays, bad pixels, or superposition of light beams from close companions were classified as bad polarization values and were not used in our analysis.

From the difference in the measured flux for each beam, we derived the polarimetric parameters using a set of IRAF tasks specifically designed for this purpose (PCCDPACK package, Pereyra 2000). This set includes a FORTRAN routine that reads the data files and calculates the normalized linear polarization from a least-squares fit solution, which yields the degree of linear polarization ($P$), the polarization position angle ($\theta$), measured from north to east, and the Stokes parameters $Q$ and $U$, as well as the theoretical (i.e., the photon noise) and measured errors. The latter were obtained from the residuals of the observations at each wave plate position angle ($\psi_i$) with respect to the expected $\cos 4\psi_i$ curve. In further analysis of the polarimetric data, we adopted the greater value between both estimated errors.

Finally, in order to determine the reference direction of the polarizer, and to check for any possible intrinsic instrumental polarization, a set of polarimetric standard stars were observed each night. The obtained polarizations degree for the observed unpolarized standard stars proved that the instrumental polarization is negligible for both telescopes and instrumentation.

In the case of the optical survey, $V$, $R$, and $J$ Johnson–Cousins’ filters (covering different areas over the studied region) were used. Figure 4 shows a false-color image measuring about $30' \times 30'$ that corresponds to a combination of the $R$ (DSS = blue), $J$ (2MASS = green), and $Ks$ (2MASS = red) images of the RCW41 region. The extended emission seen in blue is probably mostly due to the H$\alpha$ emission of the associated H II region; the cluster objects are mainly seen in red and near the center. The polarimetric $R$-band survey (yellow box—$28' \times 28'$) covers almost the whole area, while the $V$ and $I$ bands cover about $8' \times 8'$ of the region centered on the cluster (green dashed line). Each field was observed using exposures of 300 s per half-wave plate position, and in order to cover the entire area of the $R$-band survey, a $3 \times 3$ frame mosaic mapping was conducted at the CTIO’s 0.9 m telescope. The polarized standard stars for the optical survey were selected from the catalogs compiled by Clemens & Tapia (1990) and Turnshek et al. (1990), corresponding to HD 298383, HD 111579, HD 126593, and HD 110984.
Table 3

| α_{2000}(hms) | δ_{2000}(′′′′) | Band | P(%) | σ_p(%) | θ(^°) | σθ(^°) |
|---------------|----------------|------|------|--------|-------|--------|
| 9 15 37.95 | −48 1 24.9 | R | 2.70 | 0.44 | 144.6 | 4.7 |
| 9 15 41.72 | −47 53 10.7 | R | 5.33 | 1.26 | 3.3 | 6.8 |
| 9 15 43.66 | −47 47 39.1 | R | 10.62 | 1.86 | 1.8 | 5.0 |
| 9 16 22.63 | −47 57 57.1 | V | 10.47 | 3.34 | 171.1 | 9.1 |
|               |               | I | 7.97 | 1.44 | 163.9 | 5.2 |
| 9 16 25.00 | −47 58 1.0 | R | 10.72 | 1.76 | 177.8 | 4.7 |
|               |               | I | 7.32 | 0.75 | 0.1 | 3.0 |
| 9 16 36.83 | −47 56 27.8 | V | 12.06 | 1.59 | 111.5 | 6.3 |
| 9 16 38.41 | −47 57 14.9 | V | 3.16 | 0.31 | 167.7 | 2.9 |
|               |               | R | 2.51 | 0.28 | 168.5 | 3.2 |
|               |               | I | 2.86 | 0.35 | 174.1 | 3.5 |
| 9 16 40.99 | −47 55 9.9 | V | 3.60 | 0.61 | 138.7 | 4.9 |
|               |               | R | 2.76 | 0.16 | 148.0 | 1.7 |
|               |               | I | 2.35 | 0.09 | 150.8 | 1.1 |
| 9 16 42.57 | −47 57 24.4 | V | 4.67 | 5.42 | 159.6 | 33.2 |
|               |               | R | ** ** | ** ** | ** ** | ** ** |
|               |               | I | 2.66 | 2.53 | 139.4 | 27.2 |
| 9 16 44.48 | −47 58 17.1 | V | 0.85 | 0.38 | 178.0 | 12.7 |
|               |               | R | 0.78 | 0.37 | 173.6 | 13.7 |
|               |               | I | 0.44 | 0.34 | 170.7 | 22.4 |
| 9 16 45.47 | −48 0 3.4 | H | 11.43 | 1.73 | 147.2 | 6.6 |

Notes. The columns above respectively represent each of the objects’ equatorial coordinates (α, δ), the spectral band of the polarization measurement (V, R, I, or H), the polarization degree and its uncertainty (P and σ_p), and the polarization angle with its uncertainty (θ and σθ). Polarization and angle values marked with ** represent objects that were detected in the indicated band but present bad polarization values, as defined in Section 2.2.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

3. RESULTS AND ANALYSIS FROM DEEP NIR PHOTOMETRY

3.1. Color–Color Diagrams

Valuable information regarding the nature of the cluster’s stellar population may be inferred from (J − H) × (H − Ks) diagrams, which are shown in Figure 5. They were constructed from Dataset A for objects in the cluster and control areas detected in all three bands. Represented are the unreddened

The NIR observations gathered at the 1.6 m telescope of the OPD observatory were performed using the H band of the NIR camera CamIV, which has a 4′ × 4′ field of view when mounted at this telescope. At each position of the half-wave plate, sixty 10 s images were obtained (in order to avoid the detector’s nonlinearity limit for the brighter sources), jittering the pointing by 12 arcsec between each image in a cross-pattern, resulting in 600 s of total exposure time. Two fields were mapped in this manner, one centered on the cluster and a second one shifted toward the south, therefore covering a 3.5 × 7.0 area as shown in Figure 4 by the red dash-dotted box. The NIR polarimetric standards Elias 14, Elias 25 (ρ Oph), and HD164740 were selected from Whittet et al. (1992) and Wilking et al. (1980, 1982).

The complete polarimetric survey is presented in Table 3.

Figure 5. Color–color diagrams for the cluster (a) and control (b) areas from Dataset A. Stars marked with Obj1-6 labels are objects previously studied through spectroscopic techniques (Roman-Lopes et al. 2009). The red dashed lines represent the reddening band from the standard reddening law, and the dark green lines denote the locus of CTT Stars. Different symbols and colors designate different sections from the diagram (a): the bulk of cluster’s stars are represented by gray open circles, with 1.1 < J − H < 2.2, within the reddening band; also within the reddening band are stars presenting higher (red asterisks, J − H > 2.2) and lower (pink diamonds, J − H < 1.1) extinction values; purple plus signs and orange triangles respectively designate objects toward the left and right (therefore with color excess) of the reddening band. A small dispersion of H − Ks = 0.1 beyond the limits of the reddening band is allowed to account for photometric uncertainties. All objects from the control area (b) are marked with green crosses.

(A color version of this figure is available in the online journal.)
main sequence (MS) and the giant/supergiant branch locus (shown at the bottom left by the red solid line), as obtained from Koornneef (1983) and corrected to the 2MASS photometric system using the transformation proposed by Carpenter (2001). Also, the locus of the Classical Tauri (CTT) stars (Meyer et al. 1997) is indicated in the cluster’s diagram by the solid dark green line, with the standard reddening law (Rieke & Lebofsky 1985) represented (in both the cluster and control diagrams) by the red dashed lines. Different colors and symbols are used to represent objects from different parts of the diagram.

By comparing the distribution of sources in both diagrams, we note that despite the majority of control field stars showing extinction levels similar to the cluster field stars, the objects from the cluster region present a much higher number of highly reddened objects and stars with color excess (respectively, red asterisks and orange triangles). Furthermore, by analyzing the distribution of the majority of points from the cluster’s diagram (mainly the gray open circles), we note that they are approximately distributed along a strip (indicated by the solid blue line polygon) that is roughly parallel to the CTT locus (the dark green line). On the other hand, stars from the control field are more “vertically” distributed in the diagram, resembling the reddened MS locus. This may indicate that most of the stars from the cluster region are probably pre-main-sequence (PMS) stars.

### 3.2. Mean Visual Extinction

It is possible to take advantage of the fact that the bulk of stellar objects from the cluster field lay in a distribution that is roughly parallel to the CTT line locus (blue polygon in Figure 5(a)) to estimate the mean visual extinction in the direction of the cluster. We initially assumed that the objects located inside the polygon area are CTT stars. Therefore, assuming the standard interstellar reddening law of Rieke & Lebofsky (1985), we applied the dereddening vector computing the visual extinction for each star inside the polygon. The average of these values yielded a mean visual extinction of $A_V = 7.6 \pm 2.0$. We represent in Figure 5(a) the reddened CTT locus ($A_V = 7.6$) as well as the uncertainty from this computation, i.e., the $A_V = 9.6/5.6$ CTT loci (dark green dotted lines). Although a large scattering of the CTT band is seen, we estimate that about 30% of all stars from the cluster field are located within these limits. Besides, the interstellar extinction is probably spatially non-uniform along the cluster’s region, and contamination from foreground objects is inevitable, which contributes to increasing the observed scattering.

An independent computation of $A_V$ may be inferred from spectroscopically confirmed O/B stars. According to the survey by Roman-Lopes et al. (2009), stars labeled as Obj1a, Obj2, and Obj4 in Figure 5(a) probably belong to the group of the cluster’s most massive objects (respectively, B0 V, O9 V and B7 V). Assuming that they have already reached the MS, we can obtain another value for the cluster’s mean visual extinction by dereddening their observed $(J - H)$ and $(H - Ks)$ colors, using the intrinsic colors given by Koornneef (1983) and the interstellar extinction law taken from Rieke & Lebofsky (1985). Adopting this method, we have found the following $A_V$ values, respectively, for Obj1a, Obj2, and Obj4: $7.8 \pm 1.4$, $7.0 \pm 1.8$, and $6.4 \pm 2.3$. All values are in the range 6–8 mag, which is consistent with the computation obtained from the CTT candidates method.

### 3.3. Spatial Distribution of the Cluster’s Stellar Population

Considering that the photometric properties of the cluster’s area indicate that it is composed of stellar populations with different characteristics (embedded PMS stars, foreground and background objects, stars with high extinction, etc.), it is important to study their spatial distribution relative to the cluster’s location. Figure 6 shows a false-color image of the region obtained by combining the $J/H/Ks$ images of Dataset A. Each detected star is marked with colors and symbols according to its location on the color–color diagram, as defined in Figure 5(a), with the stars designated as Obj1-6 indicated by the green labels. Some very faint stars from the field are not marked because they were not detected in all three bands and therefore were not assigned locations in the color–color diagram.

The cluster’s region is composed of two distinct structures: the main portion, which is associated with an extended emission visible mainly in the $Ks$ band and is formed by a number of objects concentrated around the Obj1a/b stars (these two central objects present an angular separation of only 1.3 arcsec and are displayed in a close-up view at the top of Figure 6); and the small subcluster region that is located 1.1 arcmin toward the SE of the main cluster’s center and hosts Obj2, which is a O9 V star (Roman-Lopes et al. 2009), presumably the most massive object in the field. According to Ortiz et al. (2007), Obj1a and Obj2 are the best candidates for ionization sources of the associated H II region.

The contours shown in the map (colored in white) are from the HNCO survey of massive Galactic dense cores by Zinchenko et al. (2000), which covers mainly the central parts of the cluster. The HNCO molecule is most easily excited radiatively (rather than collisionally) inside the molecular clouds’ densest
regions \( n > 10^6 \text{ cm}^{-3} \). It is particularly sensitive to the far-infrared radiation field from warm dust and therefore is a suitable tracer of regions at the vicinity of massive star-forming sites. As previously pointed out by Ortiz et al. (2007), the HNCO survey revealed an area supposedly swept out by stellar radiation around Obj1a/b, as well as the presence of a high-density region 30–50 arcsec NW of the central stars (Obj1a/b).

We may correlate this information with the location of stars with high extinction (marked with red asterisks). These highly obscured objects present \( A_V \) values in the range 15–35 and are most commonly found toward the north of the field shown in Figure 6. From a total of 19 high extinction objects, 16 (i.e., 84%) are located above the cyan-colored dashed line that divides Figure 6 into northern and southern halves, suggesting an extinction rising gradient in the south–north direction. Furthermore, 9 (i.e., 47%) of these stars are located within the HNCO contours, indicating the expected correlation between the high density medium and the presence of highly obscured stars. Therefore, although background stars may be present, some of these are most probably highly embedded young cluster sources and therefore deserve special attention.

There is no clear trending for objects marked with gray open circles or orange triangles, as they are scattered along the entire area. However, for pink diamonds (i.e., lower extinction stars or massive members of the cluster), there is weak evidence that an anti-correlation exists relative to the positions of high extinction stars (red asterisks): 63% of the pink diamonds (17 out of 27 stars) are located within the southern area of the image. Although it is not possible to assert this unequivocally, this fact corroborates the idea that a rising extinction gradient occurs in the south–north direction. This evidence may support the idea that interstellar material surrounding Obj1a is only beginning to be swept out (according to the structure of HNCO contours), while the area around the subcluster (which hosts the O9 v star) have already been cleaned due to the action of its strong winds.

### 3.4. Color–Magnitude Diagrams

In Figure 7 we show three color–magnitude diagrams for both the cluster and control areas. While the control field is probably composed by foreground and background MS and giant stars, the cluster’s field also contains members of the cluster itself. In order to locate the overlap region, stars from the control area (denoted by green crosses) were plotted in all diagrams. This is useful in identifying stars from the cluster area presenting photometric characteristics of contaminating objects.

Figures 7(a) \((H \times [H - K_s])\) and (b) \((K_s \times [J - K_s])\) were both created with colors and magnitudes from Dataset A, using the cluster and control areas as did in Section 3.1 (the inset in Figure 7(a) shows the cluster and control areas overplotted in a small 2MASS \(K_s\)-band image). Points from these two diagrams are plotted using the same color/symbol scheme used in Figure 5, therefore allowing us to identify the positions of the different groups previously defined in the color–color diagram. The zero-age main sequence (ZAMS; for solar metallicity) is represented by a 2MASS JHKs Padova isochrone (Bonatto et al. 2004), which is denoted by the black solid line surrounded by a gray band that accounts for the \( \pm 2.0 \) mag uncertainty in \( A_V \). As a complement, we also plotted three PMS isochrones \((t = 1, 2.5, \text{ and } 5 \text{ Myr, for solar metallicity})\) taken from young stellar evolution models by Siess et al. (2000). We used the cluster’s distance \((d = 1.3 \pm 0.2 \text{ kpc})\) and the interstellar extinction as in Section 3.2. Furthermore, an arrow corresponding to an amount of 5 mag in visual extinction was also included in each diagram.

Figure 7(c) is a \(H \times (H - K_s)\) diagram built with the \(H\) and \(K_s\) data from Dataset B, which provides a larger area around the cluster (see Figure 1). As shown by the inset, we have kept the same cluster’s area used in Dataset A (Figures 7(a) and (b)) and have chosen a different control region, encompassing a wide area at the external borders of the region covered by Dataset B (defined by the green cross-hatched area). This should allow a more complete probe of the field stellar population. Since \(J\)-band data are not available from Dataset B, a position in the color–color diagram was not assigned; therefore, we have simply used gray open circles to represent cluster stars and green crosses for objects from the control area.

By analyzing the distribution of the cluster and control stars in all three diagrams, we note some striking common features. Initially, the majority of the point sources from the cluster region appear shifted from the MS locus, being displaced to its right with higher color values, i.e., over the region where the PMS isochrones are present. This indicates that the majority of the cluster sources are probably very young stars that still have not reached the hydrogen burning phase. However, as would be expected, some objects from the cluster area are located toward the left part of the diagram, occupying the same area as the control field stars; therefore, they are probably members of the Galactic field stellar population. Also, from Figures 7(a) and (b), we can see that objects positioned toward the left side of the ZAMS are mainly those represented by pink diamonds and purple plus signs, i.e., lower extinction stars and objects with anomalous colors, indicating that such objects are likely foreground stars. On the other hand, it is evident that some of the pink diamond brighter stars (for example, Objects 1a, 2, and 4), are in fact cluster members that have already reached the MS phase.

Although the bulk of the cluster stars (represented by the circles), are located among the PMS isochrones, a certain number of objects appear distributed to the right in the diagrams, therefore presenting large \(J - K_s\) and \(H - K_s\) values. This is probably a combined effect of intrinsic infrared excess from PMS stars, non-uniform interstellar extinction along the cluster’s area, and photometric uncertainties. We specifically note those stars represented by the orange triangles, which are well displaced toward the right showing high color indexes, which is an indication of emission from circumstellar disks. Furthermore, these objects are relatively faint with \(H > 16\); therefore, they probably correspond to the very low mass component of the YSO candidate sample.

Finally, the objects represented by red asterisks (identified as objects within the reddening band, but showing high extinction levels) present some of the highest \(J - K_s\) and \(H - K_s\) values. Although some of these stars may be background sources, considering the non-uniform and clumped nature of the interstellar environment around the cluster (see, for example, the HNCO emission contours in Figure 6 and the discussion in Section 3.3), it is possible that some of them are actually highly embedded cluster PMS stars. For example, it is highly probable that Obj1b (the close companion to the central star Obj1a, marked with a red asterisk) is actually a massive YSO. This subject will be further discussed in Section 3.6.

### 3.5. The Cluster’s Evolutionary Status

The PMS isochrones from Siess et al. (2000) shown in Figure 7 may be correlated with the stellar distribution in
Figure 7. Color–magnitude diagrams using Dataset A (a: $H \times [H-K_s]$; and b: $K_s \times [J-K_s]$) and Dataset B (c: $H \times [H-K_s]$). The small 2MASS images inside diagrams (a) and (c) show the cluster and control areas used for each data set. Stars from the control areas are marked with green crosses, while cluster stars in diagrams (a) and (b) are marked with colors and symbols according to their locations on the color–color diagram (Figure 5). All stars from the cluster area in diagram (c) are denoted by gray open circles. The MS and several PMS isochrones are indicated, and the yellow line provides a statistical separation between the contaminating field stars and objects from the cluster, as shown in Figure 8. In diagram (b), the inset image shows the location of the cluster objects from the turn-on area (blue arrows), i.e., located within the blue dashed rectangle. Obj2 was saturated in Dataset B and therefore is not shown in diagram (c).

(A color version of this figure is available in the online journal.)
Figure 8. Histograms of color indexes for cluster (red solid lines) and control areas (blue dashed lines), separated by successive strips 1 mag wide. Histograms from parts (a), (b), and (c) are directly related to the distribution of the stellar population in the color–magnitude diagrams from Figures 7(a), (b), and (c), respectively. Therefore, parts (a) and (b) are both from Dataset A, representing histograms of $H - Ks$ and $J - Ks$ in magnitude divisions of $H$ and $Ks$, respectively. Histograms from part (c) are from Dataset B, where the $H - Ks$ color is used in bands of $H$ magnitude. Each value in the histograms was normalized by the total number of stars used in each field. Vertical yellow lines are used in several histograms to help identify contaminating stars from the cluster region by separating the overlapping areas between control and cluster populations (at the left of the yellow line) from the population that is mainly composed by cluster stars (at the right).

(A color version of this figure is available in the online journal.)

In order to provide more quantitative recognition of the contaminating objects, the following method has been adopted: the three color–magnitude diagrams from Figure 7 were divided in bands of 1 mag, and to every strip a histogram was constructed using the color index of each respective diagram. The results are shown in Figure 8, where histograms from parts (a), (b), and (c) are respectively related to the color–magnitude diagrams from Figures 7(a), (b), and (c). Each histogram is divided between the cluster (red solid lines) and control (blue dashed lines) populations, and bins of 0.15 mag were used. The histograms
were normalized by the total number of stars used in the color–magnitude diagrams of each area, namely: $N_{\text{tot}}(\text{Dataset A, cluster}) = 302$, $N_{\text{tot}}(\text{Dataset A, control}) = 202$, $N_{\text{tot}}(\text{Dataset B, cluster}) = 384$, and $N_{\text{tot}}(\text{Dataset B, control}) = 396$. Therefore, these diagrams represent the percentage fraction of stars within each magnitude strip and color bin.

A rough separation between the intrinsic cluster stars (mainly displaced toward the right of the histograms) and the field stellar population may be defined by the color index value where the cluster’s fractional number of stars becomes predominant relative to the control. In every histogram presenting a sufficient number of points, this value has been marked with a yellow vertical line. Therefore, it represents a separation criterion between the field stars (objects from the left of the yellow line) and the intrinsic cluster population (stars from the right of the yellow line). These values were also indicated in Figure 7 by the yellow connected dots and lines. This provides an appropriate scheme to roughly decontaminate the color magnitude diagrams, therefore allowing a clearer analysis of the isochrones’ positions relative to the distribution of possible intrinsic points from the cluster.

When analyzing Figures 7(a) and (c) (the $H \times [H - K_s]$ diagrams), we note that the yellow separation lines passes exactly between the locus related to $t = 2.5$ Myr and $t = 5.0$ Myr. Moreover, in these two diagrams, the bulk of the cluster’s points (gray open circles), which are toward the right of the yellow line, seem to roughly define a band around the $t = 2.5$ Myr isochrone.

On the other hand, the turn-on point is better defined in the $K_s \times (J - K_s)$ diagram (Figure 7(b)), as indicated by the blue dashed rectangle, which encompasses both objects that have already reached the MS and those that are currently leaving the PMS stage. Note that over the MS region, below the turn-on area in the HNCO contours (Figure 6), these sources are most likely T Tauri stars and members of the cluster.

This evidence suggests that the cluster’s mean age is between 2.5 and 5.0 Myr. Moreover, this analysis reveals that a sequential star formation scenario may have occurred within this region. The spatial location of objects from the turn-on area in Figure 7(b) (within the blue dashed rectangle) is indicated by blue arrows at the inset image in the same diagram. It is evident that most of these objects (13 out of a total of 13) are positioned closer to (or within) the subcluster, instead of on the central main cluster area (as would be expected if mass segregation processes had already taken place). Therefore, a plausible explanation for this evidence may be that the most massive objects (located at the subcluster) were formed earlier, subsequently inducing star formation at the main cluster area.

This evolutionary view is supported by the fact that the interstellar material near the subcluster seems to have already been swept out, while at the cluster area denser clumps are still present (see Section 3.3). If the multi-epoch formation hypothesis is in fact true, the large spread of cluster points on the color–magnitude diagrams toward higher color values could also be explained by an intrinsic age spread of the studied stellar population.

### 3.6. Analysis of Individual Objects with Known Spectroscopic Properties

The spectroscopic features of several specific objects previously studied by Roman-Lopes et al. (2009), may now be correlated with the objects’ positions on the color–color and color–magnitude diagrams. The same stars from that survey were renamed as Obj1-6 and are indicated in Figures 5–7.

Three of the more massive objects from the cluster—Obj1a, 2, and 4—were respectively classified as B0 v, O9 v, and B7 v-B8 v stars. Their locations on the color–magnitude diagrams (Figure 7) are consistent with stars that have already reached the MS.

Obj1b shows spectral lines characteristic of YSOs, and according to Ortiz et al. (2007), the set Obj1a+b also indicates features of warm dust, such as infrared emission beyond 5 μm (probably coming from Obj1b). In fact, this object is located within the high-extinction region of the color–color diagram, an indication of its embedded nature. Furthermore, we note that its K-band spectrum (see Figure 6 from Roman-Lopes et al. 2009) presents features that are very similar to the spectrum of T Tau Sb, the third member from the T Tau system (Duchêne et al. 2002): both sources show a large Brγ emission (which is a strong accretion signature) as well as several absorption CO overtones. This evidence suggests that Obj1b, the close companion to the massive B0 v central object (Obj1a), is a very young T Tauri star. The presence of this young object near the center of the main cluster region provides additional support for the idea that star formation within this area has been triggered by the earlier star formation activity at the subcluster, as discussed in Section 3.5.

Although the sources labeled as Obj5 and Obj6 were previously classified as late-type field stars, their positions on the color–magnitude diagrams (Figures 7(a), (b), and (c)) are consistent with a classification as T Tauri stars. Even though their spectroscopic features may be interpreted as being from typical low mass late-type stars, there have been reported observations of Class I stars with few spectroscopic signs of youth. Two examples are the IRAS 03220+3035(S) and IRAS F03258+3105 sources, from the NIR spectroscopic survey by Connelley & Greene (2010), which were classified as young YSOs, despite presenting K-band spectra only with some CO overtones in absorption and almost no Brγ emission, hence being very similar to Obj5 and Obj6. Therefore, if we also take into account their positions at the very crowded area near the cluster’s center (see Figure 6), these sources are most likely T Tauri stars and members of the cluster.

Other interesting properties are related to Obj3, which is a highly reddened source that has NIR colors corresponding to a visual extinction of $A_V > 20$, which is consistent with its spatial location among the HNCO contours (Figure 6). Although the previous analysis of its K-band spectrum showed that it could be a typical late-type background star, its position in the color–magnitude diagram suggests that it may also be interpreted as a highly reddened medium mass YSO. Careful analysis of its spectrum shows a weak set of CO absorption lines, which is usually a feature of low-mass YSOs. However, its high NIR luminosity rather suggests a more massive nature. Therefore, a valid explanation for the weakness of these lines could be due to veiling of the photosphere and CO bands by the circumstellar dust emission, as suggested by Casali & Eiroa (1995). In this case, an anti-correlation of these lines'
intensity with the NIR color excess is expected. Although more observations are necessary to fully characterize this source, this evidence indicates that Obj3 is likely a medium mass YSO from the cluster.

### 3.7. Cluster Center Determination and Radial Density Profile

In order to perform a rigorous analysis of the cluster’s RDP, it is important to determine its mean center. Therefore, we have used the \( K_s \) image from Dataset B, divided the region into bins of specific widths (5, 10, 15, and 20 arcsec), and computed the stellar density distribution. The result is shown in Figure 9, where the gray scale represents the number of stars per bin area.

The cluster’s center position for each bin width was determined through bi-dimensional Gaussian fits to the stellar density distributions, represented by the red contour maps superposed to each diagram in Figure 9. A mean value has been computed, resulting in \((\alpha_c, \delta_c) = (9^h16^m43.5^s, -47^\circ56'24.2'')\), with an uncertainty of \((0.2', 0.9')\). Although the cluster’s stars appear slightly scattered toward the south and southeast (near the subcluster), a highly peaked concentration appears around \(\alpha_c, \delta_c\), the cluster’s center.

The morphology of the RCW41 cluster’s RDP may be studied by fittings of a two-parameter King function (King 1962, 1966), which may be approximately described in terms of the central density \((\sigma_0)\) and the core radius \((R_\text{core})\). This was achieved by positioning several circumcenteric rings around the computed center, with widths of 10 arcsec each, and computing the stellar density as a function of the distance from the center \((\sigma(r))\). The obtained density profile was fitted by the following equation:

\[
\sigma(r) = \sigma_{\text{field}} + \frac{\sigma_0}{1 + (r/R_\text{core})^2}. \tag{1}
\]

The results are expressed in Figure 10(a), where the points indicate the stellar densities at each ring, and the King function fitting is denoted by the solid line together with the uncertainty curves (dashed lines) obtained from the uncertainties of the fitted parameters. Starting from the center, the stellar density decreases toward larger radii, and the point where the cluster’s density completely merges with the field density is visually identified as \(R_\text{lim}\), i.e., an approximate value for the cluster’s limiting radius.

Note that a bump extending from \(r \approx 65''\) to \(110''\) appears in this radial profile, which is due to the stellar scattering toward the southeast area (which includes the subcluster—the small blue box in Figure 10(a)). In Figure 10(b), we have removed this area from the RDP analysis (blue cross-hatched region), in order to provide a cleaner fitting only of the cluster’s main concentration, i.e., the stellar densities were computed from increasing half-rings at the northwest area of the field. The new King function is more sharply concentrated toward the center in this case, showing large decreases of 44% in \(R_\text{core}\) and 38% in \(R_\text{lim}\). The estimated value of \(R_\text{lim}\) indicates that the control areas used in the photometric analysis from the previous sections are sufficiently distant from the cluster’s main structure, therefore avoiding significant contamination.

Lada & Lada (2003) pointed out that embedded stellar clusters may be morphologically classified as hierarchical-type (with multiple peaks at the density profile, frequently found scattered over a large spatial scale) or centrally condensed-type (highly concentrated distributions, with relatively smooth RDPs). Although the density distributions show that the cluster does present some isolated stellar concentrations, the relatively smooth fit of the King function indicates that it is probably of the centrally condensed type. This structural type is a common
distributions (from the dust emission and from the stellar density) are similar in size, suggesting that the stellar system is still embedded within part of the original cloud in which star formation was initially ignited. The presence of such dense interstellar material increases the gravitational potential and therefore the physical boundary of the system, aiding in keeping the stars spatially concentrated. The centrally condensed-type stellar cluster occurs because of the interstellar gas and dust from the parental molecular cloud, which are still present in the cluster’s region and are probably beginning to be swept away due to the action of the new-born massive stars.

It is important to point out that in the above mentioned comparison, the centers of both the dust emission radial profile and the King function are not exactly the same, being separated by about ~11 arcsec. Furthermore, Pirogov (2009) adopted a much larger distance to this object (2.6 kpc), as compared to the value of 1.3 kpc spectroscopically determined by Roman-Lopes et al. (2009). However, the difference is irrelevant in this case, since we have converted the spatial dimensions to angular sizes in Figure 10.

4. RESULTS AND ANALYSIS FROM OPTICAL/NEAR-INFRARED POLARIMETRY

4.1. The Large-Scale Distribution of R-band Polarization Vectors

The R-band polarization survey covers a large area around the RCW41 region, encompassing both the stellar cluster and the ionized area, as previously shown in Figure 4. A polarization degree and angle were assigned to every point-like source detected in the field, and in this manner we have constructed a map of the H ii region showing the distribution of polarization vectors superposed to each star, as exposed in Figure 11. The vectors’ orientations indicate the predominant direction of the electric field oscillations related to the stellar light beam and, assuming the standard grain alignment mechanisms, the vectors trace the sky-projected component of the interstellar magnetic field lines (Davis & Greenstein 1951).

In this image, the size of each vector is proportional to the polarization degree (a 10% sized vector is indicated at the top-right of the graph as reference), and the vector’s colors are related to the quality of the polarization measurement: good quality measurements, with $P/\sigma_P > 3$, are shown in yellow, while lower quality data, with $3 > P/\sigma_P > 1$, are shown in red. Green circles denote objects with $P/\sigma_P < 1$ or stars with bad polarization values (i.e., affected by cosmic rays, bad pixels of the detector, or light beam superposition with close companions). Therefore, all optically detected objects from this survey are marked with either a vector or a green circle according to the above-mentioned criteria.

Since the observations were made by integrating the light of all stars from the field with the same exposure time, the classification of an individual measurement among one of these groups depends on the stellar brightness (which increases the individual signal-to-noise ratio) and also on the intrinsic polarization degree from the source (therefore, unpolarized sources naturally have greater probability to fall on the $P/\sigma_P < 1$ classification).

Considering that many stars are too obscured to be detected by the optical survey, only the brightest sources were visible. These observations are still useful in studying the large-scale properties of the magnetic field structure around the H ii region, as will be shown in the following sections. However, it is important to point

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Figure 10. (a) King profile fitting using concentric rings around the cluster’s center position. The values obtained for $\sigma_c$, $R_{\text{core}}$, $R_{\text{lim}}$, and $R_{\text{lim}}$ are expressed at the top of the diagram, and the spatial sizes of $R_{\text{core}}$ and $R_{\text{lim}}$ are indicated as dashed red circles in the $K_s$ image from Dataset B (inset). The error bars represent the Poisson uncertainties. The $\sigma_{\text{field}}$ parameter, which represents the uniform stellar density from the field, is separately computed by taking the mean value of the King function. Note that both companions). Therefore, all optically detected objects from this survey are marked with either a vector or a green circle according to the above-mentioned criteria.

(A color version of this figure is available in the online journal.)

feature of very young stellar clusters, since most of the stars have not yet dispersed throughout the field and are still heavily concentrated around the center.

Such morphology may be correlated with 250 GHz observations of the 1.2 mm dust continuum emission toward this region (Pirogov et al. 2007), which defines an almost spherical core in which the cluster is probably immersed. Based on these observations, Pirogov (2009) computed a power-law RDP of the dust emission, which is shown in Figures 10(a) and (b) by the thick yellow line (the peak emission was adjusted to match the maximum value of the King function). Note that both...
Figure 11. Distribution of R-band polarization vectors at the RCW41 region. The image is a 30 × 30 arcmin RGB combination of the DSS R band (blue), the 2MASS Ks band (green), and MSX 8.2 μm emission (red). Note the large mid-IR ring or bubble (red) surrounding the blue-colored ionized area. The embedded cluster is located nearly at the center of the region. Vector sizes are proportional to the polarization degrees and colors are related to the data quality, as specified above the diagram. Green circles denote objects with poor (P/σP < 1) or bad polarization values. Gray lines are the IRAS 100 μm contours, showing the 128, 170, 240, 500, and 1000 MJy sr⁻¹ emission levels.

(A color version of this figure is available in the online journal.)

out that, considering the 1.3 kpc distance to the cluster, a fraction of these stars are foreground objects; therefore, their observed polarization levels are possibly mainly caused by interstellar components unrelated to the RCW41 region. These properties will be further analyzed in Section 4.2.

The background image used to produce Figure 11 shows interstellar structures related to the star-forming region extending into a large area around the embedded stellar cluster. The image is an RGB combination of the DSS R-band image (blue), showing optically visible stars and the ionized region (the Hα emission is within the spectral region defined by the R band); the 2MASS Ks image (green), indicating the location of several obscured stars visible only in the NIR, including the associated stellar cluster, nearly at the image’s center; and the MSX 8.2 μm mid-infrared emission (red), showing mainly the radiation from the warm dust and polycyclic aromatic hydrocarbons (PAHs).

A striking feature seen in this image is that the mid-infrared emission (red) defines a great ring or bubble of warm dust and PAHs that encompasses the ionized area denoted by the extended emission in blue. This structure suggests that UV radiation from massive stars and high energy photoionized electrons from inside the HII region heats the dust grains and excites the PAHs from the surrounding environment, generating the “envelope” type of emission. It is not uncommon to find mid-infrared emission of PAHs at the outer edges of HII regions, as revealed, for example, by the Spitzer GLIMPSE survey of the Galactic plane (Churchwell et al. 2006, 2007). Some mixture between the R-band and mid-infrared emission is seen in the direction of the cluster, where several interstellar filaments extend almost radially from it. Such morphological structure will be further analyzed in Section 4.5.

Additional interesting information is provided by the IRAS 100 μm emission, which is attributed to the colder dust component and is represented in Figure 11 by the gray contours. Note that the 100 μm emission shows a peak almost centered on the cluster’s area and that the outer contours (especially the 170 MJy sr⁻¹ isophote) roughly follow the morphology of the hot dust ring from the mid-infrared radiation, suggesting the existence of a cold dust “cocoon” around the entire area.

Comparing the global distribution of polarization vectors with the direction of the Galactic plane (the b = 0° line), we note that both directions are not correlated. All-sky optical polarization surveys have shown that, particularly along the
Galactic plane, polarization vectors tend to present an overall horizontal orientation, i.e., parallel to the plane (Mathewson & Ford 1970; Axon & Ellis 1976; Heiles & Crutcher 2005). However, as noted by the latter authors, the polarization vectors lose this tendency on the magnetic “poles,” located at \( l \approx (80^\circ, 260^\circ) \). The VMR is located along one such “pole” (the RCW41 cluster is at \( l = 270:3 \)); therefore, the correlation between polarization vectors and the Galactic plane direction is indeed not expected.

The distribution of polarization vectors presents some characteristics that can be related to the features of the \( \text{H} \text{ii} \) emission region. Note that toward the ionized area, and especially near the cluster, the vectors’ sizes are small when compared to the outer vectors. This evidence indicates a decrease in polarization degree toward the center of the region. Furthermore, at the right side of the field, a global bending of the vectors’ directions is seen both at the area’s bottom-right and top-right portions, roughly following the curvature of the \( \text{IRAS} \) 100 \( \mu \text{m} \) emission contours in these regions. Such properties will be further analyzed in Section 4.3.

It is important to point out that, since a fraction of the sample is composed of YSOs with infrared excess, some of these sources may contribute to a contaminating polarized emission from the circumstellar disk. However, the large-scale correlated pattern of polarization angles seen in the map may not be explained by intrinsic polarization. The overall characteristics are best described by interstellar polarization due to dust dichroic absorption, with some possible scatter in polarization angles due to individual disk emission from some sources.

Figure 12 shows histograms of polarization angle and polarization degree divided by different \( P/\sigma_P \) intervals. The Gaussian fits to the angle histograms show that the dispersion (indicated by the FWHM lines) of the \( 3 > P/\sigma_P > 1 \) data

4.2. Correlation with 2MASS Photometry

Since the individual stellar distances for the polarimetric survey are not available, we take advantage of the 2MASS data to approximately infer the foreground, background and intrinsic cluster’s populations. Given that the \( \text{H} \text{ii} \) region is located at 1.3 kpc from the Sun, it is important to evaluate if the interstellar polarization of objects from such a distance range are significantly affected by the nearby structures along the same line of sight. Therefore, the goal is to identify, at least statistically, foreground objects and analyze their polarization levels in comparison with the typical values from the field.

Figures 13(a) and (b) show respectively the \((J - H) \times (H - K_s)\) color–color and the \(P_R \times (J - H)\) diagrams using the \(R\)-band polarimetric sample and the associated 2MASS data. Figure 13(a) shows that the bulk of the polarimetric points present \((J - H)\) values in the range 0.5–1.1 mag, in contrast with the previous photometric analysis (Figure 5), in which it was shown that stars both from the cluster and control regions are somewhat more reddened. This is probably due to a combination of two factors: (1) the earlier analysis was carried out in a much smaller area, concentrated on the cluster, where the \(A_V\) values are statistically higher; and (2) the polarimetric survey is optically limited, and therefore only the brightest sources were detected.

Figure 13(b) shows that, for those objects having \((J - H) \geq 0.9\), there is almost no star presenting \(P_R < 1\%). This effect is emphasized by the vertical \((J - H = 0.9)\) and horizontal \((P_R = 1\%)\) green dashed lines in this diagram. This is a suggestion that objects obscured by the molecular cloud (and therefore located behind or within it) show a minimum polarization level equal to 1%. As a consequence, stars presenting polarization values below this limit are probably foreground objects. Such points are marked with green crosses and define a thick band around the unreddened MS locus in the color–color diagram (Figure 13(a)), further evidence that they are mainly foreground rather than absorbed stars. Moreover, their spatial location on the field is uniform (Figure 13(c)), as expected for a randomly distributed group of foreground objects along the line of sight.

We conclude that although a small polarization level due to foreground structures is probably included in the stellar light for most of the objects in the observed field, this level is small when compared to the typical polarization levels found for the region (which is mainly between 2% and 6%, as suggested by the polarization distribution given in Figure 12). In fact, Santos et al. (2011) have shown that in the directions near \( l \sim 260^\circ \) over the Galactic plane, polarization degrees in the \(V\) band are smaller than 1% at least up to a distance of 400 pc from the Sun. Therefore, it is expected that a major fraction of the polarization vectors for the observed field indeed map the magnetic field lines within the \( \text{H} \text{ii} \) region.

By analyzing Figure 13(a), we note that a group of points (marked with orange asterisks) are located above a small gap at \((J - H \approx 1.1)\) within the reddening band of the color–color distribution. The \(A_V = 7.6\) MS reddened locus (as calculated
for the cluster; Section 3.2) is superposed to these points, showing that these stars are reddened by the molecular cloud and therefore are probably either background or embedded objects. Their spatial distribution is also shown in Figure 13(c). Open circles, which comprise the main group of stars from the field, have typical polarization degrees above the 1% level for foreground objects and typical $J - H$ values below the 1.1 estimated limit for background and embedded stars. Therefore, this group is probably composed by a mixture of foreground, background, and mainly embedded objects in the HII region.

### 4.3. Large-scale Mean Polarization Degree and Angle Maps

In order to analyze further the evidence that the degree of polarization is lower inside the HII region, we have chosen an approximate center of the ionized area (based on the $R$-band extended emission, represented by the blue color in the image shown in Figure 11), and studied the behavior of the mean polarization as a function of this radial distance from the center. This analysis is displayed in Figure 14(a). Beginning from the selected center position ($\alpha, \delta_{2000} = (9 16 42.9, -47 59 48)$), several circumcentric rings of increasing radius were built; inside each ring, the $Q$ and $U$ Stokes parameters from individual objects (with $P/\sigma_P > 1$) were averaged, therefore allowing us to compute the mean polarization value associated with that ring and its associated standard deviation. Three different ring widths were used in this analysis (0.75, 1.00, and 1.25 arcmin), and the results are identified with distinct symbols in Figure 14(a). Therefore, each mean polarization value was plotted as a function of the angular distance from the chosen center.

A sharp increase in mean polarization degree (from $\approx 2.8\%$ to $\approx 3.9\%$) was found at a distance of $\sim 7.8$ arcmin from the center of the HII region (corresponding to $\sim 2.9$ pc, assuming that the cluster is located at 1.3 kpc from the Sun). Such distance is denoted by an orange circle in the RCW41 image of Figure 14(a). By comparing the position where the polarization degree increases (with respect to values inside the HII region) with the MSX 8.2 $\mu$m mid-infrared emission (red), we find striking evidence that such a position roughly corresponds to the warm dust and PAHs “bubble” that encloses the ionized gas. Given this evidence, we have attempted to build a “mean polarization image” of the RCW41 region based on the $R$-band survey. To achieve this result, we have divided the spatial region where the polarimetric data are distributed into $50 \times 50$ intervals of equal width. Considering each observation inside a specific division, a mean polarization value was computed (only objects having $P/\sigma_P > 1$ were used). In order to account for cases where no stars were available inside a particular division, a smoothing routine was applied, returning the same image but averaged locally by using a small box that runs through the entire array. The result is shown in Figure 14(b), where the polarization image is superposed on the actual picture of the RCW41 HII region. Redder colors correspond to lower polarization levels while bluer colors indicate higher polarization levels, as specified by the color bar given at the top of the diagram. The location of the cluster (and the associated subcluster) and the ring where mean polarization is found to sharply increase are also indicated.

Note that nearby the cluster (and slightly toward the northeast of it), we find an area where polarization mean values are lower in comparison with typical values for the field, presenting $P \lesssim 2\%$ (marked in red). Furthermore, toward the left and bottom side of the area (southeast), we find a large region where the polarization degree is higher ($P \sim 6\%$, marked in dark blue). This region marks the transition border between the inner and outer sides of the southeast part of the HII region and is probably responsible for the sharp increase in polarization detected in Figure 14(a).

Two models may be proposed to explain the decrease of polarization toward the ionized region: (1) Given that temperature values of the local interstellar medium and the radiation field from hot stars are probably higher inside the HII region, it is

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5 The SMOOTH function from IDL (Interactive Data Language).
expected that mechanisms of grain alignment are disturbed by the turbulent medium, hindering the alignment efficiency and therefore providing lower $P$ values. Polarization efficiency may also be affected if the intensity of the magnetic field inside the photoionized area is intrinsically weaker, which may be true if field lines have been pushed aside by the expansion of the H\textsc{ii} region. (2) Dust grains have been swept away from inside the H\textsc{ii} region due to the action of intense stellar winds from the newborn stars, therefore resulting in a lower dust column density and consequently lower $P$ levels. Obviously, if the second model is true, a similar decrease in interstellar extinction as a function of the distance from the center would be expected. Further discussion on the distinction between the two models will be carried out in Section 5.

We also constructed a “mean polarization angle image,” using the same procedures described above. The result is shown in Figure 14(c), where yellow and red colors represent vectors slanted to the right and blue colors are regions with mean polarization angles slanted to the left (with respect to the vertical orientation). By this diagram, we are able to highlight global changes in polarization angle with respect to the typical values found in the field. In fact, we note that toward the bottom right of the image (southwest), a large area marked with green/yellow/red colors indicates a global slanting of the polarization vectors toward the right. Furthermore, such regions seem to roughly follow the outer contour of the ionized area, indicated by the circle in Figure 14(a). Such inclination of the polarization vectors may also be seen in Figure 11, as pointed out earlier in Section 4.1.

This structure suggests that the physical processes that generated the H\textsc{ii} region, followed by the expansion of the ionized area, caused a global deflection of the original magnetic field lines in the field. Such deflection of the magnetic field lines around the expanding ionization front is most prominent toward
the southwest area surrounding the H\textsc{ii} region, as exposed in Figure 14(c). As an example, Matthews et al. (2002) described another region where a similar distortion of magnetic field lines was observed toward NGC 2024, with polarization vectors being swept due to the expansion of the associated H\textsc{ii} region. Tang et al. (2009) also described a similar effect toward G5.89, a \(~0.01~\text{pc sized ultra-compact H \textsc{ii} region} at a much earlier evolutionary stage (\(~600~\text{years}), already displaying significant distortion of the magnetic field lines as a consequence of the expansion of a shell-like structure.

4.4. Wavelength Dependence of Polarization and Determination of the Total-to-selective Extinction Ratio

It is possible to take advantage of the polarimetric survey in multiple spectral bands to analyze specific properties of the dust particles along this region. For instance, the grain size distribution directly influences the underlying interstellar law, which is generally assumed to follow a standard behavior. Therefore, such analysis will enable us to directly test this hypothesis, at least in the direction of the cluster and nearby surroundings, where V, R, I, and H polarization data overlap (see Figure 4).

It is well known that an empirical law known as the Serkowski relation may be used to describe the spectral dependence of the interstellar polarization (Serkowski et al. 1975):

\[ P_\lambda = P_{\lambda_{\text{max}}} \exp \left[ -K \ln^2 \left( \frac{\lambda_{\text{max}}}{\lambda} \right) \right], \]

where the typical value of the parameter K is 1.15 and \( P_{\lambda_{\text{max}}} \) and \( \lambda_{\text{max}} \) denote respectively the maximum polarization value and the wavelength where such a maximum point is reached. Furthermore, it is also known that when stellar light trespasses different dust layers with different grain alignment conditions, it is possible that the resulting beam will present a spectral dependence of the polarization angle, usually represented as a rotation of \( \theta \) with respect to \( \lambda^{-1} \) (Gehrels & Silvester 1965; Coyne 1974; Messinger et al. 1997).

By analyzing the overlap region between the polarimetric surveys in the V, R, I, and H bands, we have selected stars with VRIH or at least VRI observations, where the requirement \( P/\sigma_P > 3 \) was fulfilled in all observed bands. Our polarimetric sample contains 34 objects meeting these conditions. Values of \( P_{\lambda_{\text{max}}}, \lambda_{\text{max}} \), and a measurement of the rotation of the polarization angle were obtained for each of these stars. As an example, Figure 15(a) illustrates the results obtained for one of them, i.e., the \( P \times \lambda^{-1} \) graph (along with the adjusted Serkowski curve) and the \( \theta \times \lambda^{-1} \) diagram, also showing the fitted values for this particular case.

Figure 15(b) shows a diagram of \( (P/P_{\lambda_{\text{max}}}) \times (\lambda_{\text{max}}/\lambda) \), where the individual \( P_{\lambda_{\text{max}}} \) and \( \lambda_{\text{max}} \) fitted values were used together with the polarimetric data for the available bands. Red circles indicate polarimetric data to which the fitting was performed only with the VRI bands, while blue circles include the H band. Note that, comparing the points with the position of the Serkowski curve, there is a larger dispersion toward lower \( \lambda \) values (i.e., toward the V band). This is an expected effect since the signal-to-noise ratio of the polarimetric measurement for a particular embedded object is supposed to be smaller toward bluer colors. However, the overall fitted points form a band around the Serkowski curve, therefore revealing a quite good adjustment.

We estimated the ratio of the total-to-selective extinction, \( R_V \), by applying the well known relation between this parameter and \( \lambda_{\text{max}} \) (Serkowski et al. 1975; Whittet & van Breda 1978; Whittet 2003),

\[ R_V = (5.6 \pm 0.3)\lambda_{\text{max}}. \] (3)

Figure 16(a) shows a histogram of the obtained \( R_V \) values, indicating that most of them are concentrated between \(~2.5 and \(~3.5. By adjusting a Gaussian fit to this distribution, the peak value suggests a mean ratio of the total-to-selective extinction of \( R = 2.96 \pm 0.42 \), which agrees with the standard value of 3.09 for the typical interstellar grains. This finding supports the distance of 1.3 \pm 0.2 kpc for the embedded stellar cluster, obtained through spectroscopic techniques (Roman-Lopes et al. 2009). Furthermore, it corroborates the position of the PMS isochrones and MS locus in the color–magnitude diagrams from the photometric analysis (Sections 3.4 and 3.5), since the standard interstellar law was assumed in those cases.

Figure 16(b) shows an \( R(\text{DSS})/Ks(2MASS) \) composed image of the RCW41 region, with the local R-band polarization vectors distribution and colored symbols indicating the objects from the multi-band analysis. Different colors for the symbols are related to different strips of \( R_V \) values (divided in intervals of 0.5, as specified above the image), and the symbols indicate different intervals of the polarization angle rotation \( (\Delta \theta) \), where \( \square \) represents a small rotation level—between \(~5 and \( S^\circ/\mu\text{m}^{-1} \)—and \( \times \) and \( \diamond \) denote high rotation levels of \(~40 < \Delta \theta'^{\circ}/\mu\text{m}^{-1} \) and \(~20 < \Delta \theta'^{\circ}/\mu\text{m}^{-1} \) < 40, respectively.

Note that there is no spatial concentration of specific \( R_V \) or \( \Delta \theta \) values over the observed area. Although most of the \( \Delta \theta \) values show low rotation levels, a great \( \Delta \theta \) dispersion is found,
The small-scale distribution of $H$-band polarization vectors.

The $H$-band polarimetric survey is focused on the RCW41 cluster (Figure 4), and since most of the objects in this area are highly obscured in the visual wavelengths, the NIR survey provides a much greater number of polarization vectors at least in a region of a few parsecs around the star-forming locus.

Figure 17 shows the distribution of the $H$-band polarization vectors surrounding the stellar cluster, superposed on an RGB combination of the $H$ and $Ks$ images (respectively blue and green, from SofI’s Dataset B), and the 5.8 $\mu$m image (red) collected using the Infrared Array Camera (IRAC) onboard Spitzer. The morphology of the mid-infrared extended emission is dominated by several conspicuous filaments emanating almost radially from the cluster. These structures resemble the pattern previously noted in the MSX 8.2 $\mu$m emission (Figure 11), but obviously with a much higher resolution, allowing the distinction of individual filaments near the cluster.

Polarization vectors are plotted with different colors according to the data quality (blue vectors have $P/\sigma_P > 3$ while yellow vectors represent data with $3 > P/\sigma_P > 1$), and green circles denote lower-quality polarization measurements. We also adopted in this case criteria to roughly separate contaminating field stars from cluster members, based on the fact that the polarimetric survey in the $H$ band reaches an approximate photometric limit at $H = 16$. We found this information by correlating the polarimetric data with photometric Dataset B and analyzing the $H$ magnitude distribution for the polarimetric sample. Therefore, by studying the color–magnitude diagram of Figure 7(c), we note that up to $H < 16$, the contaminating stars are dominant if $H - Ks \lesssim 0.5$ and $H \gtrsim 13.5$. Stars with such photometric characteristics are marked with a purple square in Figure 17, indicating that these are possibly field stars. A consistent trend in this diagram is that the number of field stars within the cluster is small, compared to the outer regions of the image, where this number increases.

The first striking evidence found in the distribution of polarimetric vectors is that the polarization angle dispersion is much greater than in the $R$-band large-scale survey. This is probably an indication of the existence of a largely turbulent medium near the cluster. In fact, if we analyze the histogram of polarization angles for the entire $H$-band sample (Figure 18, top panel), we can see that the entire range of possible angles is covered. However, a peak is reached at angles similar to those in the large-scale distribution, i.e., at $\theta \sim 160^\circ$, suggesting that even in smaller scales there is an underlying trend to follow the global scale pattern. Furthermore, no major differences are noted between the distributions of the good quality ($P/\sigma_P > 3$, blue) and the low-quality data ($3 > P/\sigma_P > 1$, yellow). The polarization degree distribution (Figure 18, bottom panel) shows that the majority of stellar objects present $P_H$ values within 1%–4%.

Even when considering the large angle dispersion, we find that along even smaller regions within the area of Figure 17, some local trends may be unveiled, especially toward the interstellar filaments seen in 5.8 $\mu$m extended emission. In order to reveal these underlying features, we have selected six sub-areas, mainly encompassing the most prominent filaments, as

\[ \Delta \theta = 5^\circ \text{rad} \]
Figure 17. H-band polarization vector map of an area of approximately $3.5 \times 7.0$ encompassing the RCW41 stellar cluster. The image is an RGB combination of the $H$ and $K_s$ images from the SofI’s Dataset B NIR survey (respectively, blue and green) and the 5.8 μm image from Spitzer’s IRAC (red), showing several filaments bent toward the cluster. Blue vectors, yellow vectors, and green open circles respectively represent data with $P/\sigma_p > 3$ (good quality), $3 > P/\sigma_p > 1$ (lower quality), and $P/\sigma_p < 1$ (also indicating bad polarization data). Stars marked with open purple squares are possible contaminating field objects, presenting the following photometric features: $H - K_s < 0.5$ and $H > 13.5$. Histograms denote the distribution of polarization angles for objects within each of the white dotted areas labeled 1–6 (blue and yellow lines from the histograms also denote, respectively, good and lower-quality data). The peak of each Gaussian fit is defined as the mean polarization orientation from that specific field. This mean angle is used to draw a grid inside each selected area, therefore denoting the mean local polarization orientation along that line of sight.

(A color version of this figure is available in the online journal.)

indicated by the white dotted quadrangles marked with the labels 1–6. Considering the polarization vectors within each of these areas, the associated histograms of polarization angles were built with objects marked as possible contaminating field stars removed from the analysis. The distributions are also shown in Figure 17, linked to each respective area, and the good quality ($P/\sigma_p > 3$) and low-quality data ($3 > P/\sigma_p > 1$) are indicated respectively by the blue and yellow histograms. Gaussian fits were applied to each distribution, and the peak of the adjusted function corresponds to the main trend of the polarization angles within that area. By using this main value, a white dotted grid was drawn within each area, therefore corresponding to the local predominant polarimetric orientation.

We note that along the majority of the chosen areas, the main polarization direction seems to be consistent with the direction of the associated filament. Such a trend is especially evident toward areas 2, 3, and 4. This occurs specifically toward area 2, although only eight vectors contribute to the histogram, and all of them are oriented parallel to the filament, presenting polarization angles around $\approx 110^\circ$. Such orientation is almost perpendicular to the main trend for the large-scale pattern, indicating a clear correlation with the local filament structure. Toward areas 1 and 6, a small difference seems to exist between the main polarization angle and the filament direction, although the orientation pointing in the direction of the cluster is evident. The existence of substructure or superposed filaments with different orientations along the line of sight may contribute to this displacement. Over area 5, which encompasses both the subcluster and a part of the main cluster region, an orientation pointing toward the cluster is also evident.

We conclude that, despite the large angle dispersion, magnetic field lines on a small scale seem to be deflected inward, pointing toward the cluster and probably connected to the direction of the large 5.8 μm filaments from the Spitzer survey. The polarization angle dispersion is indeed expected to exist in such a dynamic star-forming region, where strong stellar winds from massive objects and possibly outflows from newborn lower mass stars should play important roles as sources of turbulence in...
the surrounding interstellar medium. As a consequence, grain alignment efficiency and magnetic field lines are supposed to be affected, therefore characterizing a higher dispersion of the polarization orientations.

5. DISCUSSION

5.1. Comparison of the Magnetic Field Structure with Theoretical Studies on the H ii Regions’ Expansion

Simulations conducted by Peters et al. (2010) describe the collapse of a massive molecular cloud followed by the formation of a small stellar cluster, which ionizes the accretion flow and causes the H ii region to expand. Spitzer (1978) first described the evolution of a photoionized region around an ionization source in a uniform medium and provided an analytic solution to the expansion of the H ii region. However, several physical mechanisms, such as heating and cooling, turbulence, the effects of ionizing and non-ionizing ultraviolet radiation, X-rays, and magnetic fields, must be considered in order to provide a realistic view of the expansion process.

Arthur et al. (2011) carried out simulations of this type considering the effects of a previously magnetized medium. Comparison of these simulations on non-magnetized and magnetized environments provides similar results in terms of the general morphology of the H ii regions, therefore suggesting that the presence of magnetic field lines does not significantly impact resistance to the expansion of the ionized area, although this influence is most evident when considering the morphology of small-scale features, such as globules and interstellar filaments.

On the other hand, such expansion is expected to impact greatly the overall shape of the magnetic field lines. The main results from these simulations have shown that after the expansion of the H ii region, a dual behavior of the field’s morphology may be noticed when comparing the inside and outside regions of the ionized area: outside the H ii region (i.e., in the location of the neutral gas, following its borders), magnetic field lines tend to lie along the ionization front, forming a ring around the ionized area; inside the H ii region (i.e., within the ionized area), magnetic field lines are expected to lie perpendicular to the ionization front, therefore pointing toward the ionization source.

These qualitative predictions are consistent with the results of the large and small-scale polarimetric surveys of the RCW41 region introduced in Sections 4.1, 4.3, and 4.5. The R-band surveys have revealed that magnetic field lines bend along the borders of the H ii region toward some areas (Figures 11 and 14), which is consistent with the interpretation of magnetic field lines being pushed aside due to the expansion of the region, therefore lying along the ionization front on the neutral areas.

Moreover, our H-band polarimetric survey showed that, although a large angle dispersion is evident over the entire area, the mean polarization direction resembles a radially oriented field toward the cluster, roughly following the direction of several filaments from the mid-infrared Spitzer image. This is consistent with the theoretical prediction that inside the ionized area, field lines are expected to lie perpendicular to the ionizing front. Assuming that the main ionizing sources in the region are Objects 1a and 2 (from Figure 6), as suggested by Ortiz et al. (2007) and Roman-Lopes et al. (2009), magnetic field lines should point toward these targets, which is indeed obtained from the polarization vectors mean orientation (which points mainly toward Obj1a).

Such a radial pattern is not noticed from the large-scale R-band map, although a large portion of this survey is composed of the ionized region inside the H ii region. Furthermore, a perfect ring of polarimetric vectors is obviously not formed along the borders of the ionized area, as predicted by the simulations of the magnetic field lines. However, it is important to point out that the polarimetric survey is not a simple sky-projected slice of the H ii region. Rather, it represents the integrated effect of linear polarization due to different interstellar structures superposed along the line of sight. For example, if we imagine the H ii region roughly as an expanding sphere, such an expansion will be noticed spatially in the sky but will also occur in the line-of-sight direction. The expansion of the outer borders will push and pull interstellar material in our direction, causing the observations of the ionized region to be composed by the sky-projected, integrated polarizing effect due to the outer borders and the ionized region (if the observed star is located behind the H ii region). Therefore, the large-scale observations of the ionized region should account for this effect, and the radial pattern is not expected to be detected.

However, even when considering such effects, an indication of the dual behavior of the polarimetric vectors’ orientations inside and outside the ionized area is certainly noticed when analyzing the R-band and H-band polarization data. These observations give support to the results from the simulations, which provide similar qualitative predictions, at least when studying the specific environment of the RCW41 region.

5.2. The Origin of the Low Polarization Values within the H ii Region

In Section 4.3 we showed that overall lower R-band polarization degrees are detected inside the H ii region, especially near the cluster.
Therefore, it seems that the observed decrease in polarization degree inside the H II region is probably caused by a lower polarization efficiency of the local interstellar medium. This may be explained by an intrinsic suppression of the alignment of dust grains with respect to the interweaving magnetic field lines, which is expected given the dynamic and turbulent conditions of such an interstellar environment.

Furthermore, in the simulations performed by Arthur et al. (2011), it was shown that the intensity of magnetic fields in the photoionized area is lower ($B = 0.1−10 \mu G$) when compared with the neutral areas from the border of the H II region ($B = 10−30 \mu G$). This is probably explained by the fact that the expansion of the ionized region causes the magnetic field lines to be pushed aside and therefore removed from inside the area, weakening the magnetic field in this location. If this is the scenario occurring in RCW41, a further depletion of polarization efficiency would be expected, contributing to the lower $P$ values detected near the cluster.

5.3. The Turbulent Component of the Magnetic Field Toward RCW41

The polarimetric data set toward RCW41 is entirely suitable to apply a method that aims to estimate the turbulent contribution to the magnetic field lines, relative to its uniform component (Hildebrand et al. 2009). It is based on the assumption that the interstellar magnetic field $B(x)$ is composed of a large-scale structured field $B_0(x)$, together with a turbulent component $B_t(x)$. Initially, the procedure consists basically of computing the second-order structure function of the polarization angles $\langle \Delta \Phi^2(l) \rangle$, hereafter SF, which is defined as the average value of the squared difference in polarization angles between two points separated by a distance $l$ (see Equation (5) in Falceta-Gonçalves et al. 2008). The square root of this quantity is denominated the angular dispersion function (ADF), and provides information on the dispersion of polarization angles as a function of the length scale toward a specific interstellar area.

Hildebrand et al. (2009) pointed out that within the range $\delta < l \ll d$ (where $\delta$ and $d$ are the correlation lengths respectively characterizing $B_t(x)$ and $B_0(x)$), the SF is composed by a constant turbulent contribution (denoted by $b$); a smoothly increasing contribution with respect to the length $l$, as expected from the uniform field (the slope of this linear behavior is represented by $m$); and an almost constant contribution due to measurement uncertainties ($\sigma(l)$). Being statistically independent, these factors must be added quadratically, leading to

$$\langle \Delta \Phi^2(l) \rangle \approx b^2 + m^2 l^2 + \sigma^2(l).$$  \hspace{1cm} (4)

The ratio of the turbulent to large-scale magnetic field strength is related to the quantity $b$ through the following expression:

$$\left( \frac{B_t^2}{B_0^2} \right)^{1/2} \approx \frac{b}{\sqrt{2-b^2}}.$$  \hspace{1cm} (5)

Therefore, by constructing the SF (and computing the measurement uncertainties $\sigma(l)$) using the polarization angles, it is straightforward to apply a linear fit with Equation (4) and determine the $b$ factor (by the intercept at $l = 0$).

Using the polarization angles from the $R$ and $H$ polarimetric data sets, we have computed the SF, as well as the mean measurement uncertainties $\sigma(l)$. Thereafter, the ADF was built for each case, as shown in Figures 20(a) and (b), which are respectively related to the $R$- and $H$-band polarization data. Prior...
to calculating the ADF, the factor \( \sigma^2(l) \) was subtracted within each bin of the SF as suggested in Equation (4) (therefore, the value of each bin in Figure 20 is \( \sqrt{\langle \Delta \phi^2(l) \rangle - \sigma^2(l)} \)). In Figures 20(a) and (b), bin widths of 2 and 0.25 arcmin, respectively, have been used. Only the first six points of the ADF (denoted by blue open circles) are used in the linear fit of Equation (4), in order to guarantee the validity of the \( l \ll \lambda \) regime, and the fitted function is represented by the red dashed line. The ratio of the turbulent to large-scale magnetic field strength, which is shown at the top of each diagram. (A color version of this figure is available in the online journal.)

Figure 20. Angular dispersion functions (ADFs) constructed by using the polarization angles from the R-band (a) and the H-band (b) polarimetric data sets. Each bin (respectively, of widths 2 and 0.25 arcmin) has already been corrected due to the mean measurement uncertainties. The red dashed lines denote the curve obtained through the linear fit of the SF using the first six points on each case (blue circles). The turbulent contribution \( b \) is determined by the interception of this curve at \( l = 0 \), being subsequently used to compute the ratio of the turbulent to the large-scale magnetic field strength, which is shown at the top of each diagram.

6. CONCLUSIONS

Using two sets of NIR photometric data collected using the SofI camera at the NTT 3.5 m telescope, we have characterized the stellar population of a deeply embedded stellar cluster related to the RCW41 H\( \alpha \) region. Furthermore, through optical (\( V, R, \) and \( I \) bands) and NIR polarimetric observations (\( H \) band) obtained, respectively, with similar polarimetric modules at the 0.9 m telescope on CTIO/Chile and the 1.6 m telescope on OPD/Brazil, we have built linear polarization maps of the star-forming area. Our main results from both techniques are as follows:

1. Analysis of photometric colors of cluster stars in comparison with field stars shows that a number of the cluster objects present color excess, which is typically associated with circumstellar disks of young PMS stars. The cluster also presents several highly reddened objects (\( A_V > 20 \) mag).

2. A mean visual extinction of \( A_V = 7.6 \pm 2.0 \) is estimated for the cluster objects based on the location of the majority of the stars on the color–color diagram, which roughly defines a band parallel to the reddened locus of CTT stars. This is corroborated by an independent \( A_V \) computation using MS stars from the cluster.

3. The morphology of the cluster is divided between a main portion and a subcluster. There seems to exist a correlation between the locations of the highly obscured objects with the HNCO contours, which are mostly concentrated toward the north of the cluster’s main part. Therefore, these are probably highly embedded objects, and a local rising extinction gradient in the south–north direction is probably present near the cluster. This evidence supports the idea that the interstellar material surrounding Obj2 (a O9\( v \) star at the subcluster, presumably the most massive object in the field) has already been swept out, while near the main portion, gas and dust are still beginning to be affected, according to the HNCO contours.

4. The color–magnitude diagrams of the cluster stars show that the majority of the objects are displaced toward higher color values, indicating that these stars are mainly young objects, also presenting color excess and non-uniform interstellar extinction. Comparison with PMS isochrones provide a mean cluster age between 2.5 and 5.0 Myr. Stars from the turn-on region (more massive) are mostly concentrated near the subcluster, suggesting that this area was formed earlier, subsequently triggering star formation at the main portion of the cluster. Results from item (3) corroborate this hypothesis.

5. The nature of some objects previously observed through NIR spectroscopy was reviewed. Obj\( 1b \), the close companion to the massive B0\( v \) central object, is highly reddened and presents spectroscopic features similar to T Tau Sb, and is therefore a very young T Tauri star. Objects 3, 5, and 6 were previously identified as late-type field stars, although their positions in the color–magnitude diagrams are consistent with the T Tauri classification. Examples of young objects with similar spectral features have been found. Specifically, Obj3 is highly reddened (\( A_V > 20 \)) and very luminous, with spectral features that may be consistent...
with a medium mass YSO. Its weak CO absorption lines may be explained due to veiling from the circumstellar dust emission.

6. Using the density distribution of stars in the field, the cluster’s center was determined to be at \((\alpha_c, \delta_c)_2000 = (9^h16^m43.5, -47^\circ56'24.2')\). A two-parameter King function was adjusted to the RDP, considering both the entire area around the cluster and a second fit where the portion encompassing the subcluster was removed, providing a much sharper profile. The general morphology shows that although some stellar scattering exist toward the south, the main cluster is probably of the centrally condensed type. This shape is correlated to the spherical and similarly sized cloud core in which the cluster is immersed, as observed from the 1.2 mm dust continuum emission toward RCW41.

7. The R-band polarimeter survey of a large area encompassing the entire \(\text{H}\alpha\) region, was used to build images of mean polarization degree and position angle. A radial analysis starting from the center of the ionized area revealed a sharp increase in polarization degree roughly coinciding with a conspicuous interstellar ring detected at the MSX 8.2 \(\mu\text{m}\) emission, which delimits the ionized area. This evidence reflects a global decrease in polarization degree inside the \(\text{H}\alpha\) region, mainly near the cluster, which is most probably due to low grain alignment efficiency caused by the turbulent environment and weak magnetic fields in this area.

8. The image of mean polarization angles exhibits large areas, mainly toward the southwest of RCW41, where polarization angles are slanted outward, following the borders of the ionized area. Such slanting coincides with the limits of the region indicated by the MSX 8.2 \(\mu\text{m}\) emission and is reflected in the structure of the ionization front. Such slanting coincides with the limits of the region indicated by the MSX 8.2 \(\mu\text{m}\) emission and is supported by simulations of the expansion of \(\text{H}\alpha\) regions, which predicts that the magnetic field lines at the neutral gas outside the limits of the region tend to lie parallel to the ionization front.

9. The \(H\)-band polarimetric survey, focused on a smaller area toward the cluster, shows that, although a large dispersion of polarization angles is present, a mean pattern may be noticed: polarization vectors roughly follow the direction of several interstellar filaments, emanating radially from the cluster as revealed by the Spitzer 5.8 \(\mu\text{m}\) image. Therefore, the mean orientation is roughly perpendicular to the ionization front, a result that is also in agreement with the predicted morphology of the magnetic field lines inside the ionized area, from simulations of expanding \(\text{H}\alpha\) regions.

10. By combining polarimetric optical data (\(V, R, \text{ and } I\)) and the NIR \(H\) band, the Serkowski function was fitted toward several stars mainly near the cluster. A large rotation of polarization angles was noticed toward some stars, revealing that the light beam has probably trespassed different interstellar layers along the line of sight. The total-to-selective extinction ratio was computed toward each of the fitted objects, and a mean value of \(R = 2.96 \pm 0.42\) was obtained, in agreement with the standard 3.09 value for the typical interstellar medium extinction law.

11. Through the statistical correlation analysis (computing the ADFs using the \(R\)- and \(H\)-band polarimetric data sets), we showed that the ratio of the turbulent to large-scale magnetic field strength is \((20.2 \pm 0.5\%)\) when the entire area surrounding the \(\text{H}\alpha\) region is considered, and \((53 \pm 1\%)\) if only the area near the cluster is taken into account. The higher turbulence level within the cluster area reinforces the hypothesis that the low polarization values at this region occur due to the lower polarization efficiency.

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