THE UNUSUAL DISTRIBUTIONS OF IONIZED MATERIAL AND MOLECULAR HYDROGEN IN NGC 6881: SIGNPOSTS OF MULTIPLE EVENTS OF BIPOLAR EJECTION IN A PLANETARY NEBULA

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ABSTRACT

The planetary nebula NGC 6881 displays in the optical a quadrupolar morphology consisting of two pairs of highly collimated bipolar lobes aligned along different directions. An additional bipolar ejection is revealed by the hydrogen molecular emission, but its wide hourglass morphology is very different from that of the ionized material. To investigate in detail the spatial distribution of molecular hydrogen and ionized material within NGC 6881, and to determine the prevalent excitation mechanism of the H2 emission, we have obtained new near-IR Brγ and H2 and optical Hα and [N II] images, as well as intermediate resolution JHK spectra. These observations confirm the association of the H2 bipolar lobes to NGC 6881 and find that the prevalent excitation mechanism is collisional. The detailed morphology and very different collimation degree of the H2 and ionized bipolar lobes of NGC 6881 not only imply that multiple bipolar ejections have occurred in this nebula, but also that the dominant shaping agent is different for each bipolar ejection: a bipolar stellar wind most likely produced the H2 lobes, while highly collimated outflows are carving out the ionized lobes into the thick circumstellar envelope. The asymmetry between the southeast and northwest H2 bipolar lobes suggests the interaction of the nebula with an inhomogeneous interstellar medium. We find evidence that places NGC 6881 in the H II region Sh 2-109 along the Orion local spiral arm.

Key words: infrared: ISM – ISM: molecules – planetary nebula: individual (NGC 6881)

1. INTRODUCTION

Asymmetry is common among planetary nebulae (PNe) and it comes in a large variety of shapes and morphological features. On a large scale, the departure from symmetry goes from the mild asymmetry of elliptical PNe to the strong asymmetry displayed by bipolar PNe. Asymmetry in PNe is also revealed by an assortment of small-scale morphological features including the asymmetric fast low-ionization emission regions (FLIERs) of elliptical PNe, as well as point-symmetric collimated outflows and their associated blowouts and bow-shock structures. The asymmetry in PNe has been linked on many occasions to the precession of the progenitor star in a binary system. This class of PNe is not homogeneous at all, and includes PNe with multiple collimated outflows along different directions (Corradi et al. 1997) or with precessing jet-like features (Miranda et al. 1999), starfish-shaped and multipolar PNe that show point-symmetric bow-shock features (Sahai & Trauger 1998; Sahai 2000), and quadrupolar and polypolar PNe with different sets of bipolar lobes aligned along different symmetry axes (Manchado et al. 1996; López et al. 1998). Polypolar and quadrupolar PNe are especially interesting as multiple hourglass structures imply recurrent bipolar ejections which are particularly difficult to interpret in the framework of the interacting stellar wind model (Kwok et al. 1978; Balick 1987).

One of the most intriguing PNe with multiple bipolar lobes is NGC 6881. Originally classified as a quadrupolar PN, based on optical narrowband images and long-slit echelle spectra (Guerrero & Manchado 1998), NGC 6881 presents two pairs of highly collimated bipolar lobes with very similar, although not coincident, symmetry axes. The southwest lobe displays a loop-like feature that is highly reminiscent of a precessing collimated outflow, but its measured expansion velocity is low. Kwok & Su (2005) showed that the dense equatorial ring has recently changed its orientation, being aligned with the youngest pair of bipolar lobes. Therefore, there are many signs suggesting that precession and sequential events of bipolar ejections have occurred in NGC 6881. The spatial distribution of the molecular hydrogen in this nebula, as revealed by near-IR narrowband images (Guerrero et al. 2000), adds a new twist. Molecular hydrogen emission is detected in wide hourglass bipolar lobes that extend much farther than the ionized bipolar lobes. The H2 bipolar lobes may represent a bipolar ejection unrelated to the formation of the two pairs of ionized bipolar lobes.

To study carefully the spatial distributions of ionized material and molecular hydrogen in NGC 6881 and to investigate the excitation mechanism of the H2 molecule throughout the nebula, we have obtained new H2, Brγ, [N II], and Hα images, and JHK intermediate-resolution long-slit spectroscopic observations. A description of the observations is presented in Section 2 and the results are given in Section 3. The results are discussed in Section 4, and the conclusions and a short summary are presented in Section 5.

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2. OBSERVATIONS

2.1. Imaging

Narrowband near-IR images of NGC 6881 were obtained during 2006 September 9 using LIRIS (Long-Slit Intermediate Resolution Infrared Spectrograph) at the Cassegrain focus of the 4.2 m William Herschel Telescope (WHT) on Roque de Los Muchachos Observatory (ORM, La Palma, Spain). The detector was a 1k × 1k HAWAII array sensitive in the spectral range from 0.8 to 2.5 µm. The plate scale is 0.25 pixel−1 and the field of view (FOV) is 4.27 × 4.27. The narrowband filters isolated the H₂ (1−0) S(1) 1.2128 µm and Brγ 2.1658 µm emission lines. An additional narrowband filter (Kc) centered at 2.270 µm was used in order to subtract the continuum contribution from the line emission detected through the H₂ and Brγ filters. The central wavelength and bandwidth of these filters are listed in Table 1.

We obtained series of 100 s exposures on each filter for the total integration times given in Table 1. The telescope pointing was shifted by a few pixels between each exposure, rastering the nebula to different locations on the detector. Each series of observations on the object was followed by a similar series of observations on adjacent blank sky positions. Individual exposures were flat-fielded and dark-corrected, and the sky contribution was removed using the continuum Kc image. Since we did not find it necessary to scale the images, although differences in the point-spread function (PSF) of stars in the field of view required us to degrade the PSF of the H₂ image to match those of the Brγ and Kc images. The continuum subtracted H₂ and Brγ images and the Kc image are presented in Figure 1. The spatial resolution, as determined from the FWHM of stars in the FOV, is ~0.8.

Narrowband images in the [N Ⅱ] and Hα emission lines were obtained on 2006 June 30 using ALFOSC (Andalucia Faint Object Spectrograph and Camera) at the 2.56 m Nordic Optical Telescope (NOT) in the ORM. The camera is a 2048 × 2048 CCD with a plate scale of 0.19 pixel−1 and a FOV of 6.5×6.5. The [N Ⅱ] and Hα images of NGC 6881 are also presented in Figure 1. The spatial resolution, as determined from the FWHM of stars in the FOV, was 0.9.

2.2. Spectroscopy

Intermediate-resolution JHK long-slit spectroscopic observations were performed on 2004 July 2–4 using the NICS (Near Infrared Camera Spectrometer) at the 3.5 m Telescopio Nazionale Galileo (TNG) at the ORM. The NICS is a multimode instrument for IR observations (0.9−2.5 µm) that uses a HAWAII 1024 × 1024 array as detector. We used the LF camera, providing a plate scale of 0.25 pixel−1, and the 0.75 slit, with a width of 0.75 and a length of 4. Observations were obtained using the JH and Ks grisms and the long-slit was placed along the central star at P.A.s 113° and 137° (Table 2). In order to provide the means for subtracting the sky emission, the nebula was placed at different positions along the slit.

The spectra were reduced using IRAF routines of the noao.twodspec and noao.onedspec packages. The data were flat-fielded using dome flats, and the sky contribution was removed using sky spectra obtained at the same time as the nebular spectra. We used telluric sky lines for the wavelength calibration. The standard IR stars of spectral type A−A0 (Hunt et al. 1998) were used for the flux calibration. We obtained the sensitivity function by comparing the spectra of these stars with a blackbody model of temperature 9480 K, similar to the effective temperature of A0 stars. Finally, the telluric absorptions in the one-dimensional spectra of NGC 6881 were removed using the IRAF task “telluric,” applying it to stars with featureless spectra in the JHK range.

3. RESULTS

3.1. Morphology

The notable differences in the spatial distributions of ionized material and molecular hydrogen within NGC 6881 described by Guerrero et al. (2000) are specially highlighted in the H₂, Hα, and [N Ⅱ] composite picture shown in Figure 2. In NGC 6881, we can distinguish the following components.

3.1.1. The Equatorial Torus at the Central Region

The central regions of NGC 6881 contain both molecular and ionized material. This region can be described as a clumpy torus-like structure (Kwok & Su 2005) that is expanding at a moderate velocity (Guerrero & Manchado 1998). The details of the molecular and ionized material distribution in the central regions of NGC 6881, however, could not be studied properly by Guerrero et al. (2000), because of the limited spatial resolution of their near-IR images and poor continuum subtraction at this region. Our new continuum-subtracted H₂ image reveals two bright knots of H₂ emission located at the central region of NGC 6881 along its minor axis, suggesting a ring of molecular material. The relative distribution of ionized and molecular material in the central region of NGC 6881, shown in Figure 3, reveals that the H₂ emission encompasses the [N Ⅱ] emission.

Molecular hydrogen in this region survives in a thin layer surrounding the ionized torus-like structure, most likely shielded by dense material from the ionizing flux of the central star.

4 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.
Figure 1. Images of NGC6881 in the Brγ (top, left), Kc (middle, left), and [N II] (bottom, left) narrowband filters. The images in the H2 (top, right), [N II] (middle, right) and Hα (bottom, right) filters show a larger field of view than the images in the left column. The artifacts noticeable around the field stars in the continuum subtracted Brγ and H2 images are residuals of the subtraction caused by a slight mismatch of the PSF between the line and continuum images. The arrows towards the northwest of the nebula in the right panels mark diffuse emission in the H2, [N II], and Hα images associated with the northwest H2 lobe and its northwest extension. The arrow towards the south of the nebula in the H2 image marks diffuse emission unrelated to NGC6881, probably a background galaxy.
3.1.2. The Highly Collimated Bipolar Lobes

The two pairs of highly collimated bipolar lobes are mainly detected in the Brγ, [N ii], and Hα images, while the H2 emission from these lobes is weak. The northern wall of the northwest lobe is brighter than its southern wall, and the opposite applies to the southeast lobe, thus showing the point-symmetric brightness distribution typical of other bipolar PNe (e.g., K 4-55, Guerrero et al. 1996).

3.1.3. The Hourglass H2 Bipolar Lobes

Contrary to the highly collimated bipolar lobes, the open hourglass bipolar lobes of NGC 6881 are dominated by H2 emission. They show a narrow waist coincident with NGC 6881 central regions and clear limb-brightening, indicating that they are formed by a thin layer of material.

3.1.4. The Northwest Bipolar Lobe Extension

The H2 emission of the northwest hourglass lobe displays an extension that casts its emission outwards up to ∼50″ from the center of NGC 6881 along its symmetry axis. This emission is mainly detected in H2, but there are also hints of [N ii] and Hα emission (Figure 2). The H2 surface brightness of this feature is not homogeneous, but is distributed on a series of three bright bands interspersed between bands of diminished brightness. Interestingly, the bright bands can also be recognized in the Hα image. The northwesternmost tip of these bands shows a remarkable wedge-shaped morphology.

3.1.5. Large-Scale Emission

The Hα and [N ii] images of NGC 6881 show large-scale diffuse emission, with the nebula laying on a broad arc of patchy emission that crosses the FOV from the northeast to the south (Figure 1). An examination of an Hα image from the INT/WFC Photometric Hα Survey (IPHAS) of the northern Galactic plane (Drew et al. 2005) of this region reveals a complex system of filaments. NGC 6881 (l = 74°55′20″, b = +02°11′37″) is projected along the local spiral arm onto the intricate network of Hα filaments near the proximity of γ Cyg (e.g., Parker et al. 1979). In particular, NGC 6881 is projected towards the east of a large cavity of size 20′×12′ oriented along the north–south direction that forms part of the H II region Sh 2-109 (l = 79°48′, b = +00°15′).
3.2. Spectroscopic Analysis

The long-slit spectra of NGC 6881 detect continuum emission from the innermost regions and extended line emission all through the nebula. A preliminary inspection of the two-dimensional spectra reveals the variation at different locations of the nebula of important line ratios (e.g. H$_2$ 1–0 S(1)/Br$\gamma$, He i/He ii), in agreement with the different spatial distribution of emission shown by the Br$\gamma$ and H$_2$ images. Guided by these images, we have extracted spectra from four individual regions: the central region, the ionized lobes, the H$_2$-dominated hourglass lobes, and the northwest H$_2$ lobe extension. The $K$ spectra of these regions are shown in Figure 5, and the $JHK$ spectra of the ionized lobes in Figure 6. Within our limited spectral resolution, the radial velocity derived for the different regions is similar.

The measured line intensities are listed in Tables 3 and 4. The spectra and line ratios confirm that the central region is Br$\gamma$-dominated, the ionized lobes show H$_2$/Br$\gamma \sim 1$, and the outermost regions are H$_2$-dominated. He ii emission is confined to the central region, while the outermost regions show a wealth of H$_2$ lines. We note that the spectrum from the ionized lobes is most likely contaminated by emission from the H$_2$-dominated hourglass lobes.

3.3. H$_2$ Excitation

The molecule of H$_2$ can be excited by shocks or by UV fluorescence. The 1–0 S(1)/2–1 S(1) line ratio is traditionally used to diagnose the H$_2$ excitation mechanism, with a line ratio $\sim 2$ implying UV fluorescence (Black & van Dishoeck 1987),
and a line ratio \( \sim 10 \) implying shock excitation (Burton et al. 1989). The 1–0 \( S(1)/2–J S(1) \) line ratio in the different regions of NGC 6881 ranges from 5.5 up to 7.5, thus indicating that shock excitation can be the most likely dominant excitation mechanism.

In a case of pure collisional excitation, the population of \( \nu, J \rightarrow \nu', J' \) is given by

\[
g_\nu J (\nu, J) = \exp \left( - \frac{E(\nu, J) - E(1, 3)}{kT_{\text{ex}}} \right),
\]

where \( g_\nu J \) is the statistical weights. This equation can be rearranged in terms of the flux

\[
F(\nu', J') v_{1085(1)} A_{1085(1)} v_{1085(1)} = \exp \left( - \frac{E(\nu, J) - E(1, 3)}{kT_{\text{ex}}} \right),
\]

where \( A_{\nu', J', J, J', \nu} \) represents the transition probability, and \( F(\nu', J') \) is the observed flux at frequency \( v_{1085(1)} \).

The temperature can be inferred from the slope of the line fitted to the data points in Figure 7. In NGC 6881, the value of the vibrational excitation temperature, \( T_{\text{ex}}(\nu) \), is similar to this of the rotational excitation temperature, \( T_{\text{ex}}(J) \), and thus it can be concluded that shocks are the dominant excitation mechanism of \( H_2 \). The excitation temperature is 2100 K for the central region, \( 2200 \pm 100 \) K for the ionized and \( H_2 \) lobes, and \( 2700 \pm 100 \) K for the extension of the NW \( H_2 \) lobe. There is thus a trend for the temperature to increase as we move farther from the central regions of NGC 6881.

4. DISCUSSION

4.1. Ionized and Molecular Gas in NGC 6881

The \( H_2 \) emission of bipolar PNe is typically found in their equatorial rings and on the walls of their bipolar lobes, outlining closely the distribution of ionized material shown in H\( \alpha \) or \([N\,\text{ii}]\) images (Kastner et al. 1996; Guerrero et al. 2000). In NGC 6881, however, the different spatial distributions of ionized material and molecular hydrogen trace distinct nebular structures. A search in the literature shows that there are very few cases of bipolar PNe and proto-PNe in which the \( H_2 \) and \( H\alpha \) morphologies are different: CRL 2688, M 2-9, NGC 2440, NGC 7072, J 900, and Hb 12. From this short list, NGC 2440 has to be discarded as recent \( HST \) images (Proposal ID. 11090) have shown that the \( H_2 \) arc seen by Latter et al. (1995) follows the outermost \( H\alpha \) emission. In CRL 2688 (the Egg Nebula), the \( H_2 \) emission is distributed along the equatorial plane and at the tips of the bipolar lobes seen in scattered light (Latter et al. 1993; Sahai et al. 1998). The \( H_2 \) bipolar lobes of M 2-9 envelop the bipolar lobes seen in emission lines of ionized species such as \( \text{Fe}\,\text{ii} \) (Smith et al. 2005). The four-lobed shell of \( H_2 \) in NGC 7072 surrounds its elliptical ionized core, revealing the location of a
Figure 7. Excitation diagrams for the central region (top), ionized lobes (center), and H\textsubscript{2}-dominated lobes and northwest extension (bottom) of NGC 6881. The diagrams show the upper state vibration-rotation populations relative to the $v = 1, J = 3$ level plotted against the upper state energy. The linear fits to the populations of different vibrational levels find rotational excitation temperatures of 2000 K, 2100 K, and 2700 K for the central region, ionized lobes, and H\textsubscript{2}-dominated lobes and northwest extension, respectively.

4.2. Multiple Bipolar Ejections in NGC 6881

The occurrence of multiple ejections of material is common among PNe, particularly among type I multiple-shell PNe that show faint, giant haloes (Chu et al. 1987). The haloes, interpreted as the relic of late thermal-pulse episodes (Stanghellini \\& Pasquali 1995; Hajian et al. 1997), are mainly associated with elliptical or round PNe, but are rare among bipolar PNe. Recurrent bipolar ejections resulting in multiple independent pairs of bipolar lobes have been reported for only a handful of PNe. The different pairs of bipolar lobes may have similar morphology and orientation, e.g., M 2-9 (Balick 1999; Schwarz et al. 1997), but in most cases they show notable differences, either affecting their morphology and degree of collimation, e.g., Mz 3 (Guerrero et al. 2004; Santander-García et al. 2004), the orientation of their symmetry axes, e.g., M 2-46 (Manchado et al. 1996), or its ionization degree, e.g., Hb 12 (Welch et al. 1999). In NGC 6881, we find two pairs of highly collimated ionized lobes oriented along slightly different directions and a pair of H\textsubscript{2} bipolar lobes with an open hourglass morphology.

The two pairs of ionized lobes of NGC 6881, first reported by Manchado et al. (1996), have been described in detail by Guerrero \\& Manchado (1998) and Kwok \\& Su (2005). Precession is evidenced by the different symmetry axes of each pair of ionized lobes and from the alignment between the equatorial ring and the youngest pair of bipolar lobes. The sharp morphology, similar kinematical age, and different orientation of the two pairs of bipolar lobes point to a sudden collimated ejection of material that has carved out bipolar cavities into the surrounding medium. The morphology of the ionized bipolar lobes of NGC 6881 is very reminiscent of the proto-PN CRL 618 in which high-velocity jets moving along different directions (Cox et al. 2003) have produced bipolar cavities in the nebular envelope (Trammell \\& Goodrich 2002). The similarities between the two bipolar nebulae extend to the coaxial rings of the bipolar cavities and to the bright, compact knots at their tips. The collimated outflows of CRL 618 might well evolved in the future into bipolar lobes similar to those of NGC 6881.

The limb-brightened morphology of the H\textsubscript{2} lobes indicates that the material is mainly confined in their walls, thus suggesting that the bipolar lobes carry enough momentum to sweep up and press the circumstellar medium into a thin sheet. Indeed, the prevalent shock excitation of H\textsubscript{2} requires a source of momentum. It is unlikely that a current fast (~1000 km s\textsuperscript{-1}) wind from the central star would provide this momentum, as such a stellar wind would be trapped by the inner ionized lobes. Our spectra do not provide information on the expansion velocity of the H\textsubscript{2} lobes, but an upper limit can be derived assuming that the [N\textsc{ii}] emission from the loop-like structure at the edge of the southeast lobe is produced by a shock. For a planar shock to be able to produce significant [N\textsc{ii}] $\lambda$6584 Å emission, but...
low or minimal [O III] λ5007 Å emission (Guerrero & Manchado 1998), the shock velocity must not exceed ~60 km s^{-1} (Hartigan et al. 1987). Such high speed makes unlikely the origin of the momentum in the thermal pressure of hot gas within the bipolar lobes. However, the momentum of the H2 bipolar lobes must have been provided at the ejection time, either in a sudden bipolar ejection or through a stellar wind intrinsically bipolar or isotropic but collimated by an equatorial structure. The oblique shock of a bipolar lobe expanding at ~60 km s^{-1} would be able to shock excite the H2 molecules along its edge, while giving rise to [N II] and Hα emission at its tip. Such ballistic ejection may also explain the increasing H2 temperature excitation with the distance to the nebula center.

The very different collimation degree of the ionized and H2 lobes of NGC 6881 suggests that they formed during two different ejection events with substantial changes in the collimation conditions or even in the collimation mechanisms between the two episodes. The H2 lobes formed very likely by the action of an episodic wind producing an hourglass-shaped ejection, while high velocity jets ejected along close directions produced the two pairs of ionized lobes. An additional period of isotropic heavy mass loss resulting in a dense envelope is revealed by concentric arcs detected around the innermost regions of NGC 6881 (Corradi et al. 2004).

4.3. NGC 6881 and the Surrounding Interstellar Medium

The morphology of the southeast and northwest H2-dominated bipolar lobes are discrepant, with the former being smaller than the latter and showing a sharp edge at its southeastern tip. This sharp edge is spatially coincident with a [N II] loop-like feature (Figure 4), a structure that has been interpreted as a low velocity precessing jet (Guerrero & Manchado 1998), but that, in view of the perfect spatial coincidence with the southeast tip of the H2 lobe, seems more likely to mark its termination. The abrupt border of the southeast H2 lobe and the [N II] loop-like structure may be unveiled the interaction of this bipolar lobe lobe with dense material.

As we noted in Section 3.1, NGC 6881 is embedded within diffuse emission that forms part of Sh 2-109, an inhomogeneous H II region located at a distance of 1.4 ± 0.4 kpc and with a diameter of 400 ± 100 pc (Fich & Blitz 1984). In view of the hint of interaction of the southeast H2 lobe of NGC 6881 with dense material, resulting in the notably different morphologies of the southeast and northwest lobes, it is worthwhile to investigate the physical association of NGC 6881 with Sh 2-109. The distance to NGC 6881 has been estimated to be 2.5 kpc by Cahn et al. (1992) who used the Shklovsky method according to the Daub scheme. In their work, Cahn et al. used an angular radius of 2'/5 which seems inadequate as it only traces the bright, central regions of NGC 6881. This region has an angular radius ~1'/2, but if we account for the ionized bipolar lobes, then an averaged angular radius of 6'/5 has to be used. If we adopt this radius, then the revised distance to NGC 6881 using the Cahn et al. method would be ~1.5 kpc, supporting its physical association with the H II region Sh 2-109.

An inspection of IPHAS Hα images of this region reveals that the diffuse emission in which NGC 6881 is embedded constitutes the eastern wall of a large cavity-like structure. H I 21 cm line observations of the neutral gas distribution and kinematics of the region confirm that this structure is a cavity with an expansion velocity ~10 km s^{-1} (Cappa et al. 1996). The radial velocity of this H I cavity, v_{LSR} ~ +16 km s^{-1}, is very similar to the radial velocity of NGC 6881, v_{LSR} ~ +2 km s^{-1} (Guerrero & Manchado 1998). The projection of the nebula onto the H I cavity and their similar radial velocities suggest that NGC 6881 may be located within this cavity, with its H2-dominated southeast lobe hitting onto the dense material at the wall of the cavity, slowing it down and producing a sharp edge, while the northwest H2 lobe expands into the H I cavity with little opposition.

5. CONCLUSIONS AND SUMMARY

New images and near-IR spectra of NGC 6881 confirm the different distribution of ionized material and molecular hydrogen within this PN. The H2 images have resolved its central region which shows the spatial distribution expected for a ring of molecular material surrounding an innermost ionized ring. The H2 bipolar lobes share the same orientation than the ionized lobes, but they are less collimated and display a distinct hourglass morphology. The H2 emission is predominantly shock excited, both in the central ring and in the H2 bipolar lobes.

We infer a complex history formation for NGC 6881, involving important changes in the collimation mechanism of the bipolar lobes in the latest evolutionary stages. The H2 bipolar lobes are consistent with the action of a bipolar wind. The final evolution of the PN implied the ejection of episodic fast collimated outflows with changing directions that interacted with the dense circumstellar envelope ejected in a previous phase.

The southeast H2 lobe of NGC 6881 is less extended than the northwest lobe and shows a sharp edge, implying the interaction of NGC 6881 with an inhomogeneous interstellar medium. We find very likely that NGC 6881 is within a cavity in the midst of the H II region Sh 2-109.

This work is funded by grant PNAYA2005-01495 of the Spanish MEC. G.R.L. thanks the IAA for its hospitality and the support of a postgraduate scholarship from CONACyT (Mexico). We thank J. Acosta and G. Gómez for taking the LIRIS images of NGC 6881, and K. Viironen and the IPHAS team for providing us with large-scale Hα images of the region around NGC 6881. We are also grateful to E. J. Alfaro for enlightening discussion on the location of NGC 6881 within the Galaxy.

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