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A WINDSWEPT CLOUD CORE ADJACENT TO HH 2

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ABSTRACT

We analyze an Hα image of the HH 1/2 region of unprecedented depth. In this image, the outflows and other emission structures of this region are clearly seen. We focus on a description of the "hill', which is an approximately circular feature directly to the SW of HH 2. Through an analysis of our Hα image and IR images (obtained with the IRAC camera of the Spitzer telescope), we show that while the "hill" is consistent with previous interpretations of this object as a PDR (excited by the UV radiation of HH 2), it also shows features implying that the partially photodissociated molecular clump is embedded in an environment which is streaming from N to S. This motion might be the result of the expansion of the Orion nebula, or of an uncollimated, outwards directed flow from the central region of the HH 1/2 system.

RESUMEN

Analizamos una imagen de Hα de la región de HH 1/2 de mayor profundidad que todas las imágenes previas. En esta imagen se ven claramente los flujos y otras estructuras emisoras de esta región. Nos enfocamos en una descripción de la "colina", que es una estructura aproximadamente circular directamente al SO de HH 2. Mediante un análisis de nuestra imagen de Hα y de imágenes IR (obtenidas con la cámara IRAC del telescopio Spitzer), mostramos que si bien la "colina" es congruente con interpretaciones previas de este objeto como una PDR (excitada por la radiación ultravioleta de HH 2), también muestra estructuras que implican que la nube parcialmente fotodisociada está inmersa en un medio ambiente que fluye de norte a sur. Este movimiento podría ser el resultado de la expansión de la nebulosa de Orión, o de un flujo no colimado de la región central del sistema HH 1/2.

Key Words: evolution — HII regions — ISM: kinematics and dynamics — stars: formation

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1. INTRODUCTION

HH 1 and 2 are the best studied Herbig-Haro (HH) objects (see the review of the literature on HH 1 and 2 of Raga et al. 2011). This system is driven by a central source (Rodríguez et al. 2000) which ejects a bipolar jet system (seen in the IR, Noriega-Crespo & Raga 2012) terminating at HH 1 and 2, with a total angular size of $\approx 3'$. Two large bow shock structures, HH 401/402, located about $25'$ from the HH 1/2 source, might also be associated with the same system (Ogura 1995, Reipurth et al. 2013).

The region around HH 1/2 shows a complex structure with other IR/optical (Reipurth et al. 1993, 2000) and molecular outflows (Moro-Martín et al. 1999; Lefloch et al. 2005). We analyze a deep Hα image, which shows the large-scale structure of this region with unprecedented detail (see also Reipurth et al. 2013).

We use this image to describe the structure of the "hill", an approximately spherical region located directly to the SW of HH 2. This structure has been studied in detail by Lefloch et al. (2005), who show that the IR (molecular) and optical (atomic/ionic) emission are located at the outer edge of a centrally concentrated CO clump (detected at millimeter wavelengths). We designate this optical/infrared emission region surrounding the clump as the "rim" and denote the entire physical structure as the "hill", i.e. the CO clump plus the "rim".

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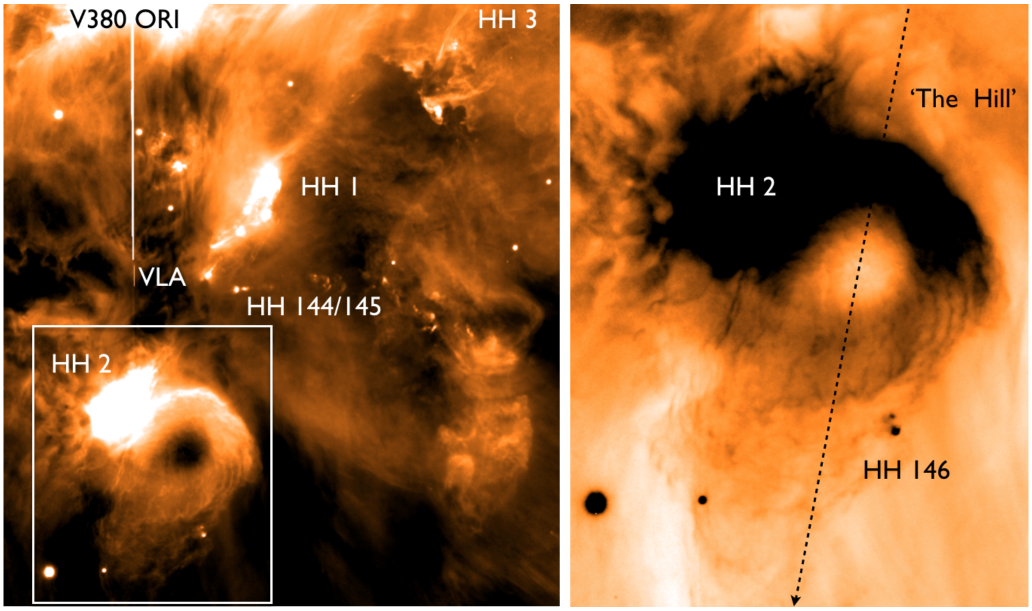

Fig. 1. The left panel shows the deepest existing Hα image of the HH 1/2 region. Complex faint details are seen in the surface structure of the L1641 cloud. It can be seen that HH 2 is skirting the side of the "hill" (see the text for a discussion). Part of HH 3 is seen on the upper right. The rectangle shows the area enlarged in the panel at right, which is a negative to show the details of the wave-like pattern on the west side of the bright rim. The dashed arrow indicates the direction away from θ^1 Ori C. North is up and East is left. The color figure can be viewed online.

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The "rim" has been successfully interpreted as a PDR (at the outer edge of the CO clump) excited by the UV radiation of HH 2 (see, e.g., Girart et al. 2002). We use our new Hα image and IR images obtained with the IRAC camera of the Spitzer space telescope to suggest new elements in the interpretation of the emission from the "rim".

The paper is organized as follows. § 2 describes the observations. § 3 describes the general features of the Hα image of the HH 1/2 region. The Hα and IR structure of the "hill" is discussed in § 4. Finally, we present our conclusions in § 5.

2. OBSERVATIONS

We have obtained the deepest existing Hα image of the HH 1/2 region, corresponding to a 1 hour exposure with SuprimeCam on the 8m Subaru telescope. For technical details, see Reipurth et al. (2013). In this image (see Figure 1), complex faint details are seen in the surface structure of the L1641 cloud.

We compare our new Hα image with the IR images of the HH 1/2 region described by Noriega-Crespo & Raga (2012). These images were obtained with the IRAC infrared camera (Fazio et al. 2004) of the Spitzer space telescope. In the present paper, we use the images obtained in the IRAC channels I1 (3.6 μm, dominated by PAHs) and I3 (5.8 μm, dominated by H_2).

3. THE HH 1/2 FIELD

The left frame of Figure 1 shows an approximately 5 $\times$ 6 arcmin field of the HH 1/2 region. This region includes the HH 1/2 outflow, HH 3 and HH 144/145 (see Reipurth et al. 1993). HH 1/2 are ejected from an optically undetected source $\approx 10''$ to the SE of the HH 1 jet (i.e., the elongated feature to the W of the "VLA" label of Figure 1). The outflow source was detected at radio wavelengths by Pravdo et al. (1985). The HH 144/145 chain of knots flows to the W of the source region, and appears to be associated with a binary companion of the HH 1/2 source. HH 3 is probably not directly associated with the other HH objects in the region.

Directly to the SW of HH 2, the striking semi-circular region is the "hill". The approximate coordinates of the center of the "hill" are 5:36:23.2, −6:47:37 (2000). This region is shown in the zoomed image in the right frame of Figure 2. Directly to the S of the hill is HH 146, composed of a pair of knots (see Reipurth et al. 1993).

It is clear that "the hill" has a general bow-shaped morphology with an approximate E/W mirror symmetry (with a brighter E side, though the

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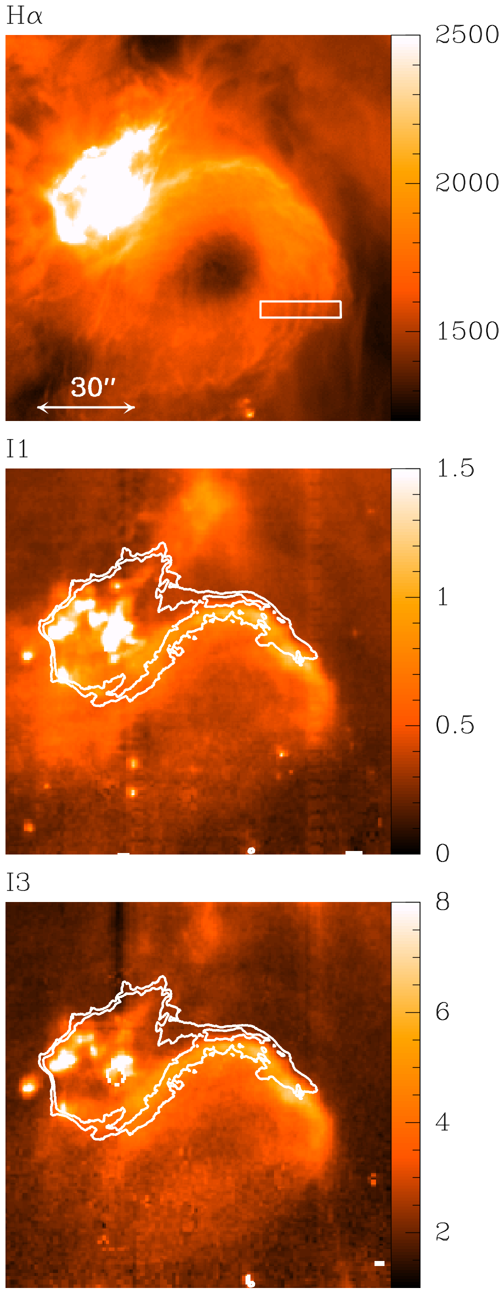

Fig. 2. Hα (top) and IRAC I1 (center) and I2 (bottom) channel maps of a region around HH 2. The angular scale of the maps is shown in the top frame. The three frames are shown with the linear color scales to the right of each frame (the Hα frame is uncalibrated, and the scales of the IRAC frames are given in mJY sterad^{-1}). On the IRAC frames we have plotted two contours of the Hα emission, in order to show that the Hα emission of the "rim" has an offset of $\approx 10''$ to the N of the IR ridge. On the top frame we show a box that encloses part of the wave-like structure observed in the SW region of the "hill". The color figure can be viewed online.

morphology of this side is confused with the emission of HH 2 itself), and a strong N/S asymmetry:

- the N region has a bright, leading filament,
- the S region has a morphology of filaments with a N-S orientation.

The "hill" has a low intensity central region.

4. "THE HILL"

In Figure 2, we show a region around HH 2 in Hα (top) and in the I1 (3.6 μm, dominated by PAHs) and I3 (5.8 μm, dominated by H_2) IRAC channels (central and bottom frames, respectively). In the IRAC maps, "the hill" has an arc-like morphology, with the "rim" pointing approximately to the N. It is clear that the Hα rim of the hill does not coincide with the IR rim, but lies outside the molecular emission seen in the IRAC maps.

Lefloch et al. (2005) present detailed millimetric (single dish) observations of the "hill", and also IR spectra/images (obtained with the ISOCAM spectral imaging instrument of the ISO satellite). They find that the ^{13}CO emission fills in the central hole of the hill, and that the H_2 and PAH emission is distributed in the arc-like structure that is seen (at higher angular resolution) in the central and bottom frames of our Figure 2.

Lefloch et al. (2005) interpret the "hill" as a PDR (a photon dominated or photodissociation region) corresponding to the outer layers of a molecular clump (observed in the CO emission) which is located close to the line of sight to HH 2 and closer to the observer than HH 2. HH 2 is proposed as the source of the FIR photons that produce the PDR. This interpretation was proposed by Girart et al. (2002), and theoretical models of the chemistry of PDRs excited by HH objects were presented by Viti & Williams (1999), Viti et al. (2003), and Girart et al. (2005). These models show that both the chemical properties (Christie et al. 2011) and the arc-like geometry of the "rim" (Raga & Williams 2000) appear to be in agreement with the theoretical predictions.

In this scenario, the "rim" would correspond to a two-layer structure of an outer photoionized (optical) region and an inner (infrared) PDR. For such an ionized layer, one can use the standard argument, based on the two equations:

$$I_{H\alpha} = \int j_{H\alpha} dl = \left(\frac{j_{H\alpha}}{n_H^2}\right) n_H^2 L \,, \qquad (1)$$

$$F_{ion} = \int n_e n_{HII} \alpha_B dl = n_H^2 \alpha_B L \, , \quad (2)$$

where the integrals are carried out along the line of sight, $j_{H\alpha}$ is the Hα emission coefficient, α_B the "case B" recombination coefficient, n_e is the electron density, while n_{HII} is the ionized hydrogen and n_H the total hydrogen density. For the second equalities one assumes a homogeneous, fully ionized layer of width L. There are of course possible projection effects which are not considered in these two equations. These equations then provide a relation between the observed Hα intensity $I_{H\alpha}$ (equation 1) and the ionizing photon flux F_{ion} (given as number of impinging ionizing photons per unit area and time, see equation 2). This relation is:

$$F_{ion} = \frac{I_{H\alpha}\alpha_B}{(j_{H\alpha}/n_H^2)} \, , \quad (3)$$

where we take $\alpha_B = 2.59 \times 10^{-13} \mathrm{cm^3 s^{-1}}$ and $j_{H\alpha}/n_H^2 = 2.83 \times 10^{-26} \mathrm{erg\ s^{-1} cm^3\ sterad^{-1}}$ (the $T = 10^4$ K values given in the book of Osterbrock 1989).

Now, from the calibrated HST Hα image of Raga et al. (2015), we calculate an average Hα intensity for the "rim" $I_{H\alpha} = 1.7 \times 10^{-5} \mathrm{erg\ s^{-1} cm^{-2} sterad^{-1}}$, which has been corrected for the $E(B-V) = 0.27$ average galactic reddening of Raga et al. (2015). With this $I_{H\alpha}$ value, from equation (3) we obtain an estimate $F_{ion} \approx 1.6 \times 10^8 \mathrm{cm^{-2} s^{-1}}$.

Could HH 2 be providing this ionizing photon flux? This can be estimated as follows. Following Raymond et al. (1988), the bright condensations of HH 2 have radii $r_0 \approx 10^{16}$ cm, shock velocities $v_s \approx 150$ km s^{-1} and pre-shock densities $n_0 \approx 1000$ cm^{-3}. Shocks of ≈ 150 km s^{-1} produce ≈ 2 ionizing photons per incident neutral H atom (see Raymond et al. 1988). Therefore, the total rate of ionizing photons produced by one of the bright condensations of HH 2 is:

$$S_{HH2} \approx 2\pi r_0^2 n_0 v_s \approx 9 \times 10^{42} \, \mathrm{s^{-1}} \, . \quad (4)$$

If HH 2 is located at a distance $D \approx 2 \times 10^{17}$cm from the "hill" (i.e., similar to the projected angular separation of $\approx 30''$), the ionizing photon flux produced by HH 2 at the position of the "rim" will be $F_{HH2} = S_{HH2}/(4\pi D^2) \approx 2 \times 10^7 \mathrm{cm^{-2} s^{-1}}$. As this estimation was done for only one of the condensations of HH 2 (which currently has 3 brighter condensations: A, H and G, see Raga et al. 2016) we would expect the total flux (produced by HH 2 as a whole) to have a value of $\approx 6 \times 10^7 \mathrm{cm^{-2} s^{-1}}$, which is close to the $F_{ion} = 1.6 \times 10^8 \mathrm{cm^{-2} s^{-1}}$ necessary to produce the observed Hα intensity of the "rim" (see above).

This estimate has been done considering a fixed separation of $\approx 30''$ from the HH 2 condensations to the "rim", while there really is a range of physical distances from the different condensations of HH 2 to different positions along the "rim" structure. The estimates of the previous paragraph therefore have to be taken only as order of magnitude estimates of the ionizing photon flux at the "rim" produced by HH 2.

The other evident candidate for producing the ionization of the "rim" is θ Ori. The ionizing photon rate of θ Ori is dominated by the contribution of θ^1Ori C, which produces $S_* \approx 10^{49} \mathrm{s^{-1}}$. If this star is at a distance $D \approx 3 \times 10^{19}$ cm (similar to the projected angular separation between HH 2 and θ Ori), the ionizing photon flux at the position of the "rim" would be $F_* = S_*/(4\pi D^2) \approx 9 \times 10^8 \mathrm{cm^{-2} s^{-1}}$, assuming that there is no significant absorption of the ionizing photons as they travel from θ Ori to HH 2. We therefore find that even if a sizeable fraction of the ionizing photons is absorbed along the way, the ionizing photon rate produced by θ Ori would be enough to produce the ionization observed in the "rim" of the "hill".

An interesting feature observed is the wave-like pattern to the SW of the "hill", seen for the first time in our ultra-deep high-resolution Hα image. This feature has a number of finger-like ridges which wrap around to the SE, partially following the shape of the "hill" (see the right frame of Figure 1).

In the Hα frame of Figure 2, we show a box enclosing part of this wave-like structure. In Figure 3 we plot the intensity integrated along the N/S axis of this box as a function of the E/W position (measured in arcseconds from the E edge of the box). We also show a sinusoidal intensity vs. position dependence with a spatial wavelength of $4''$, illustrating the fact that the observed intensity vs. position dependence has at least four peaks that coincide quite convincingly with a periodic dependence with this spatial wavelength.

It is not clear which is the process that gives rise to this quasi-periodical wave structure. Looking at Figure 1 (right panel) one sees that this wave structure is likely associated with a more extended faint region to the S of the "hill". The fact that the "hill" has a relatively sharp edge to the N and a diffuse, spatially more extended emitting region to the S can be interpreted as evidence that the molecular clump giving rise to this structure is immersed in an environment that is flowing in an approximate N-S direc-

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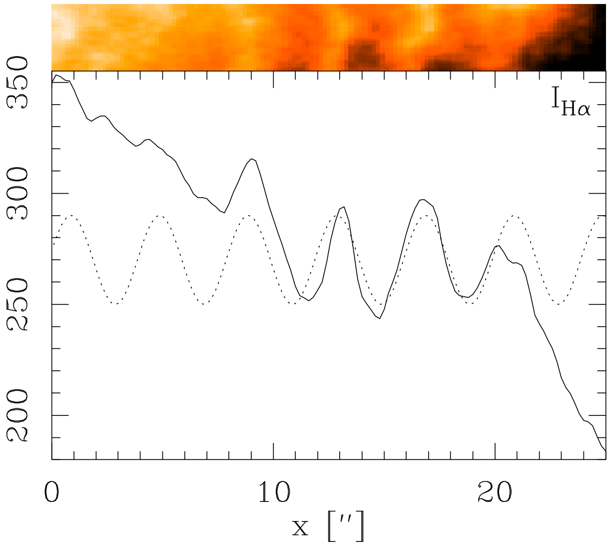

Fig. 3. Top frame: Hα emission of the region with the wave-like structure in the SW of the "hill" (corresponding to the box shown in the top frame of Figure 2). Bottom frame: Hα emission (in arbitrary units) integrated over the N/S axis of the top box, shown as a function of distance from the E edge of the box (solid line). A sinusoidal curve with a spatial wavelength of 4″ (1600 AU) is also shown (dashed line). The color figure can be viewed online.

tion. This "sharp leading edge/diffuse wake" combination is expected for the interaction between a clump and either a subsonic or a supersonic external flow (see, e.g., Hartquist et al. 1986 and Hartquist & Dyson 1993).

The implied N-S large-scale flow could be associated either with a broad, slow, wind ejected from the HH 1/2 source, or with a general expansion of M42 (the Orion Nebula, excited by θ Ori). The dashed line in Figure 1 (right panel) shows the direction toward θ^1 Ori C. The velocity of the flowing environment would have to be relatively low (of the order of a few km s^{-1}) because it would otherwise push the emitting molecular clump material to velocities which are not observed (Lefloch et al. 2005). Such a velocity for the impinging flow would be subsonic with respect to the sound speed ($\approx$ 10 km s^{-1}) of the photoionized "rim".

In simulations of the interaction between a clump and a flowing environment, it is possible to have "vortex shedding" events, which lead to the formation of quasi-periodic structures in the wake region. An example of this is found in the early stages of the simulation presented by Raga et al. (1998). The wave-like pattern shown in Figure 3 could possibly correspond to such a structure.

5. CONCLUSIONS

We present an analysis of a deep Hα image of the region around the HH 1/2 outflow, showing unprecedented detail (see Figure 1). We focus on the structure which we call the "hill", directly to the SW of HH 2.

The Hα emission of the hill shows a northern ridge, which skirts the ridge of molecular emission observed in the IR (see Figure 2). The IR emission ridge itself envelops a CO clump (see Lefloch et al. 2005). Our observations cannot distinguish whether this clump is protruding from the more tenuous background cloud or it is a disconnected, free-floating structure above the cloud surface.

The intensity of the Hα emission of the "hill" can be used to estimate the ionizing photon field that would be necessary to produce the observed emission. From the standard argument (balancing recombinations with impinging ionizing photons) we estimate an impinging ionizing photon flux $F_{ion} \approx 2 \times 10^8 \mathrm{cm}^{-2}\mathrm{s}^{-1}$. An order of magnitude estimate shows that both HH 2 and θ Ori (or the two at the same time) could be producing this required ionizing photon flux.

In our Hα map we also see a fainter region with a filamentary structure which appears to surround the W and S region of the CO clump. In the W part of this structure, there is a very remarkable wave-like structure of several parallel ridges, with a spatial wavelength of ≈ 4″, corresponding to 1600 AU at the distance of HH 1/2 (see Figure 3).

We speculate that this southern region of the "hill" is a wake resulting from the interaction between the CO clump and a surrounding environment that flows from N to S. This motion could be the result of the general expansion of M42 (the Orion Nebula), or could correspond to a broad, low velocity outflow from the central region of the HH 1/2 system. The orientation of the wake from the "hill" suggests that it forms an obstruction in the expanding HII region powered mainly by θ^1 Ori C. At the same time, the "rim" is clearly brighter on the side towards HH 2. It thus seems that the "hill" is affected by both HH 2 and θ^1 Ori C.

The traditional explanation of the molecular emission of the "hill" has been that it corresponds to a PDR produced by the UV radiation emitted by HH 2 (see, e.g., Girart et al. 2005 and Lefloch et al. 2005). While this model successfully explains the molecular emission of the "rim" (which envelops the northern region of the "hill"), it does not explain the southern, wake-like region. The existence

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of this wake implies that the "hill" molecular clump is embedded in an environment with an organized N-S flow motion. The interaction of this moving environment with the clump would definitely have an effect on the shape of the emitting region, and might also have at least some influence on the chemistry of the outer rim.

The periodic, wave-like structure observed to the S of the "hill" (see Figure 3) could yield interesting information with two possible observational approaches:

- spatially resolved, kinematic observations giving the positional dependence of the centroid and dispersion of the Hα emission (which could be done with long-slit, Fabry-Perot or 2D "integral field unit" techniques),
- obtaining a second epoch, deep Hα image.

As the image discussed here was obtained in 2006 (see Reipurth et al. 2013), if one were to obtain a second epoch image now, the resulting ≈ 12 yr timespan that would be covered would allow a detection of motions with velocities of ≈ 50 km s^{-1} or larger. As discussed in § 4, we expect considerably lower velocities for the flow impinging on the "hill", so that we would not expect proper motions to be detected. The excersise of obtaining a second epoch image might anyway prove to be interesting.

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