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MOLECULAR HYDROGEN EMISSION IN THE WOLF-RAYET NEBULA NGC 2359

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ABSTRACT

We report the first direct detection of molecular hydrogen emission in the interstellar medium in the vicinity of a Wolf-Rayet (W-R) star. The spatial distribution of the excited molecular gas associated with NGC 2359 is filamentary and lies mainly on the border of the ionized gas, as traced by optical emission lines such as Hα or [O III] λ5007. The typical 1–0 $S(1)$ H_2 brightness in the filaments is 5×10^{-5} ergs s^{-1} cm^{-2} sr^{-1} and the total 1–0 $S(1)$ H_2 luminosity detected is $\sim 4\ L_{\odot}$. The detected line flux in the 1–0 $S(1)$ transition of H_2 at $\lambda = 2.122\ \mu$m could equally be explained by shock excitation or by fluorescence from the strong ultraviolet flux of the W-R star. The morphological distribution of the H_2 filaments is not inconsistent with either mode of excitation. Although the ubiquity of this phenomenon needs to be confirmed, the relatively high level of 1–0 $S(1)$ H_2 emission detected in this W-R nebula indicates that hot stars could potentially contribute a significant fraction of the total H_2 emission of young starburst galaxies.

Key words: circumstellar matter — ISM: bubbles — ISM: individual (NGC 2359) — stars: individual (HD 56925) — stars: Wolf-Rayet

1. INTRODUCTION

Wolf-Rayet (W-R) stars, because of their advanced evolutionary state and dense stellar winds [$\dot{M} = (0.8\text{–}8) \times 10^{-5}$ $M_{\odot}$ yr^{-1}, Abbott & Conti 1987; $v_{\infty} = 1000$–3000 km s^{-1}, Prinja, Barlow, & Howarth 1990] play an important role in physically shaping the interstellar medium and in its chemical and kinematic evolution. Although they are few in number, there is no doubt that their impact is significant, as they input into the interstellar gas approximately 50% of the total wind energy provided by all stellar types taken together, at least in the solar vicinity (Abbott & Conti 1987). In addition, they supply a copious amount of gas enriched by either hydrogen or helium burning products, which has a definite impact on the abundance of elements such as ^{4}He, ^{12}C, ^{17}O, and ^{22}Ne (Maeder 1992). Furthermore, as a W-R star represents the stage in massive star evolution that immediately precedes the supernova explosion, the study of the composition, density distribution, and kinematics of the interstellar gas in the vicinity of this type of star will yield a better understanding of the initial conditions in the interstellar medium prior to a supernova explosion.

Perhaps the most spectacular examples of the interaction between the winds of these hot stars and the interstellar medium are the W-R nebulae consisting of ionized gas observed in lines such as Hα and [O III] λ5007. They have been classified into three different types according to their formation mechanism: diffuse, radiatively excited H II regions, ejecta-type nebulae, and windblown bubbles (Chu 1981). In addition, neutral hydrogen voids and shells thought to be associated with the ionized gas have been discovered around several W-R stars in our Galaxy (e.g., Niemela & Cappa de Nicolau 1991 and references therein; Dubner et al. 1992; Arnal 1992; Arnal & Cappa 1996; Cappa et al. 1996).

NGC 2359, one of the first three W-R nebulae to be identified by Johnson & Hogg (1965), is the prototype windblown bubble. Its distance has been estimated by many authors (see Goudis et al. 1994 for a summary) as ranging from 3.5 to 6.9 kpc. For the remainder of this paper, we will adopt a distance of 5 kpc. Abundance studies by several authors (Peimbert, Torres-Peimbert, & Rayo 1978; Talent & Dufour 1979; Esteban et al. 1990) have demonstrated that the nebula shows very little chemical enrichment from processed stellar material. NGC 2359 appears to consist of two distinct parts. The first is a U-shaped diffuse H II region that is thought to have been created by the O star ancestor of the W-R star (Dufour 1989). Within this region, which is seen most strikingly in [N II] λ6584 (Schneps & Wright 1980), lies the filamentary bubble blown by the wind of the WN4 star HD 56925 (= WR 7 in the catalog of van der Hucht et al. 1981). This slightly egg-shaped nebula, which can readily be observed in Hα or [O III], is colliding with the diffuse H II region on its east side. Beyond this diffuse H II region, the optical nebula is partially obscured by a molecular cloud detected in CO (Schneps et al. 1981). The part of the nebula that is obscured is revealed by high-resolution 20 cm VLA observations by the same authors. Three distinct molecular clouds have been identified: The first borders the south part of the U-shaped nebula and is observed to have the same velocity as the ambient interstellar medium around the nebula ($V_{LSR} = 55$ km s^{-1}; see below). The second bounds the bubble and the U-shaped nebula on their east side and is moving at $V_{LSR} = 37$ km s^{-1}. This cloud is therefore thought to be compressed and accelerated by the windblown bubble. Finally, the third cloud, which is located in the southeast, has a velocity of $V_{LSR} = 67$ km s^{-1} and is probably either foreground or background.

The kinematics of this nebula has been extensively studied and was found to be rather complex. Schneps & Wright (1980; see also Schneps et al. 1981) were the first to recognize that the emission from the Hα or [O III] lines have three distinct origins: diffuse emission from the large H II region and, from the bubble, both stationary thick filaments and a thin expanding membrane that is overrunning them. The systemic velocity of the ambient gas is $V_{LSR} \sim 55$ km s^{-1}, as measured by several authors ($v = +56 \pm 5$ km s^{-1}, Georgelin & Georgelin 1970; $v = +55 \pm 25$ km s^{-1}, Lozinskaya 1973; $v = +53 \pm 8$ km s^{-1}, Pişmiş, Recellas-Cruz, & Hasse 1977; $v = +52 \pm 3$ km

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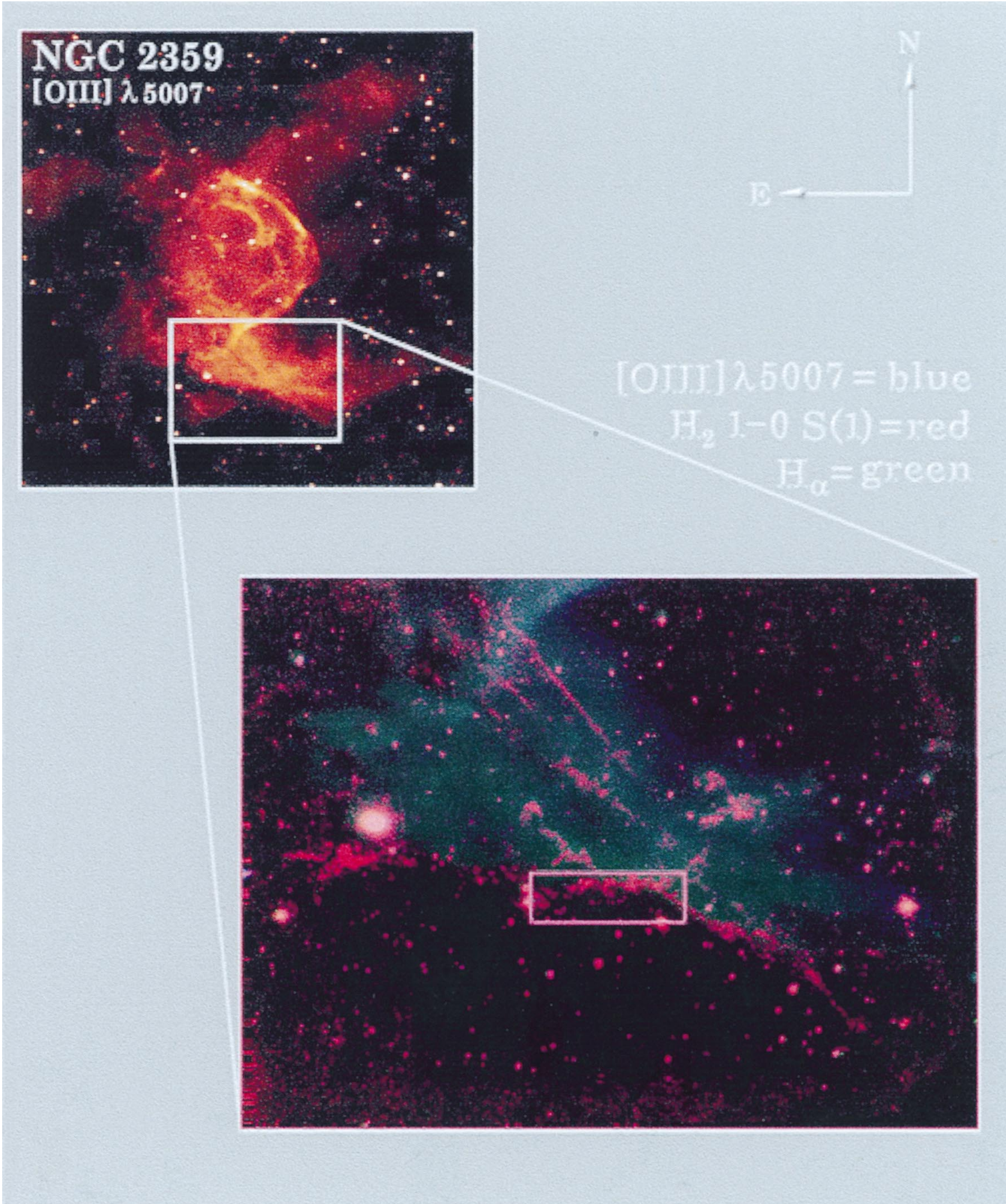

FIG. 1.—[O III] λ5007 image of NGC 2359 from Miller & Chu (1993). The total field of view is approximately $13' \times 13'$. The detail is a three-color image of the south part of the W-R nebula NGC 2359. The red corresponds to a mosaic of H_2 emission, the blue to [O III] λ5007, and the green to Hα. The field of view of this image is $4'.5 \times 3'.4$.

s^{-1}, Treffers & Chu 1982; $v = +54 \pm 5$ km s^{-1}, Goudis, Hippelein, & Münch 1983; $v = +52 \pm 3$ km s^{-1}, Goudis et al. 1994). The bubble expansion velocity was estimated to be 18, 30, 15–30, and 26 km s^{-1}, respectively, by Treffers & Chu (1982), Goudis et al. (1983), Chu (1988), and Goudis et al. (1994).

The value of the total mass of this windblown bubble is still very controversial. Schneps et al. (1981) estimated the mass of ionized gas to be $\sim 16\ M_\odot$ (for a distance of 5 kpc), but Van Buren (1986), based on dynamical arguments, suggests that it might have a neutral component, and that the total mass of the bubble is, in fact, much higher than revealed by just the ionized gas. In an attempt to detect a possible molecular component to the bubble in NGC 2359, we have obtained a series of narrowband H_2 images covering most of the optical nebula. The observations are described in § 2, and our findings are discussed in the context of the present models for this windblown bubble in § 3. In § 4, we summarize our results.

2. OBSERVATIONS AND DATA REDUCTION

We observed NGC 2359 in 1993 September/October with the Canada-France-Hawaii Telescope (CFHT) on Mauna Kea, Hawaii, using the Montreal Infrared Camera

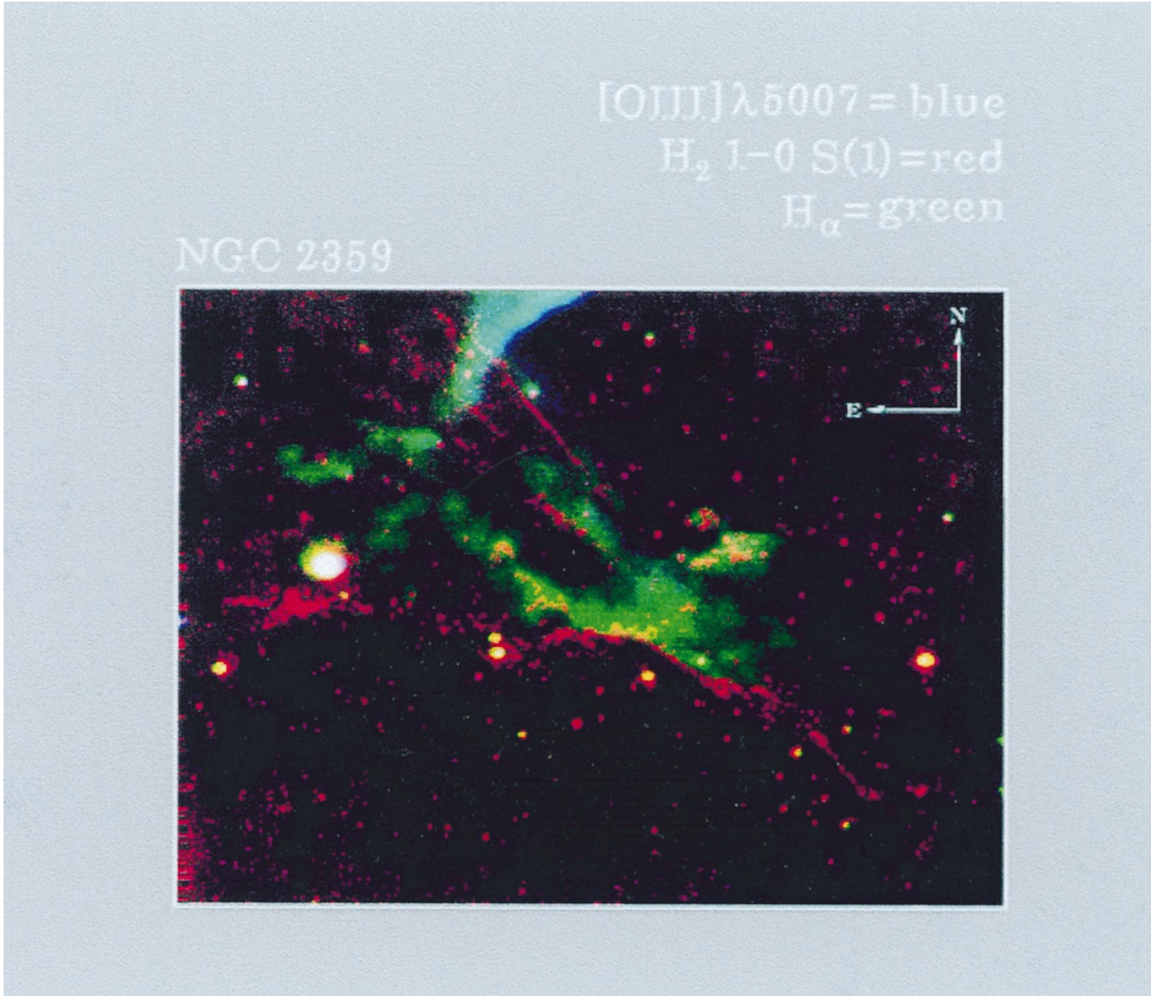

FIG. 2.—Same as in the detail of Fig. 1, but with the color contrast adjusted in such a way that only the brightest levels of optical emission are visible

(MONICA), which is equipped with an HgCdTe NICMOS detector from Rockwell International (Nadeau et al. 1994). With the setting used for the observations, the pixel scale of the detector was 0\".25, and therefore, the 256 × 256 pixels of the camera corresponded to a field of view of approximately 1′ × 1′. A preliminary scan of the entire 5′ × 7′ optical nebula was made using a narrowband ($\Delta\lambda/\lambda = 1\%$; $\lambda_c = 2.122\ \mu$m) H_2 filter centered on the 1–0 $S(1)$ transition. Relatively strong emission was discovered in the south part of the diffuse U-shaped H II region. Further observations were therefore concentrated in this area. In total, five 60 s scans were made, with a total area covered of 4\'.5 × 3\'.4. Approximately 100 images were combined to form the final mosaic, which is presented as part of a three-color image in the detail of Figure 1. We have also obtained K-band and Brγ mosaics of the nebula, but no significant emission was detected.

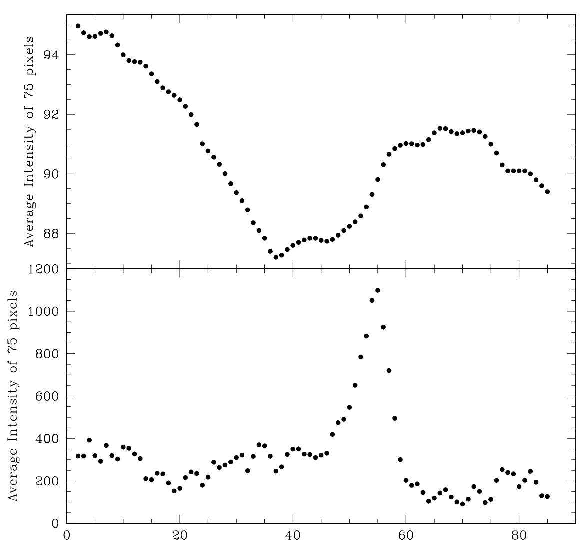

FIG. 3.—Perpendicular cut across the northmost H_2 filament. *Top*, mean Hα flux of 75 pixels along the filament, as a function of position; *bottom*, the same, but for the H_2 flux. The intensity units are arbitrary.

Before creating the final H_2 mosaic, each individual image was reduced in the following way: First, a median sky image was formed from the image being treated and three images on each side. After subtracting the sky from the image, it was divided by the flat field and corrected for geometric distortion. We also corrected for the variable sky transmission by using stars in the overlap regions of adjacent images. It was not necessary to subtract the continuum from the line images, since the nondetection of any significant flux in the K-band or Brγ images indicates that the contribution from continuum emission is negligible. Finally, once the mosaic was complete, we used UKIRT faint standards 8 and 9 (Casali & Hawarden 1992) to carry out the flux calibration.

3. RESULTS

In the montage of Figure 1, we show (*top left*) a global view of the optical nebula taken with an [O III] $\lambda5007$ filter. The white box in the south part of the U-shaped nebula indicates the region where the infrared observations were concentrated. These are presented in the detail, showing a three-color image of the south part of NGC 2359. The H_2, Hα, and [O III] $\lambda5007$ emission is coded in red, green, and blue, respectively. All three intensity scales are logarithmic. The optical images used to create Figure 1 were kindly provided by Miller & Chu (1993). This figure shows that the excited H_2 component of NGC 2359 consists of long filaments that generally do not coincide with strong Hα or [O III] emission but, rather, are located on the immediate border of the ionized gas or in regions of very low ionized flux. H_2 emission has also been detected in the north part of the nebula, but we have not taken sufficiently long exposures for significant quantitative results to be obtained. Therefore, for the remainder of this paper, we will concentrate on the images of the south part of the nebula.

The brightest filaments exactly follow the south border of the U-shaped nebula, but there is also H_2 emission within it. In particular, there are three filaments oriented in the northeast-southwest direction that fall in regions of very low optical Hα or [O III] emission. The northmost filament is amazingly straight; it is not clear what can produce such a structure. It has no special orientation with respect to the W-R star. At the north tip of these three filaments lies a very faint curl-shaped structure. Note that this, together with the three filaments, was also detected in the light of [N II] $\lambda6584$ by Schneps & Wright (1980). In fact, the entire H_2 flux distribution we have detected is extremely similar to the distribution of [N II] $\lambda6584$ in this region. Those authors have interpreted the [N II] emission as indicating the location of the ionization front.

Also intriguing is the X-shaped structure observed in H_2 and located just below the center of the three-color image. The lower section of the X is part of a longer filament that borders the optical emission. A clue to the origin of the upper part of the X is obtained by examining Figure 2, in which we show the same three-color image with the color contrast adjusted in such a way that only the very brightest Hα and [O III] emission is visible. This figure strongly supports the suggestion made by Schneps & Wright (1980) that the bright arc-shaped structure just below the main bubble is actually part of another bubble that is colliding with the main W-R nebula. The south part of this second bubble is revealed in bright Hα (*green*) emission superposed on H_2 emission, which forms the upper part of the X mentioned above (*yellow arc*). This south part of the bubble was not recognized in previously published optical images, as it was always confused with lower level emission from the U-shaped nebula. In Figure 2, it can be seen that the upper arc-shaped structure below the main W-R bubble is in fact composed of a mixture of Hα and [O III] emission (*turquoise*), except in the very inner part, which is seen only in [O III] (*blue*).

Although it is difficult to distinguish in the reproduction of Figure 1, another interesting characteristic of the H_2 emission is that it does not completely fill the region of low optical emission but, rather, is concentrated on its northwest border, toward the direction of the W-R star. The same statement can be made for the curl-shaped structure at the northeast tip of the filaments. As an example, Figure 3 shows a cut perpendicular to the northmost H_2 filament. We show the average intensity of 75 pixels along this filament of Hα in the top panel, and H_2 in the bottom panel, on a distance of 90 pixels perpendicular to the filament. It can be seen that the excited molecular gas is located in a much more narrow region than the Hα trough, and that it is not centered within it. Instead, it seems to be located on its northwest border.

The typical 1–0 $S(1)$ H_2 surface brightness in the filaments is 5×10^{-5} ergs s^{-1} cm^{-2} sr^{-1}, with maximum values reaching 40×10^{-5} ergs s^{-1} cm^{-2} sr^{-1}. This is comparable to what has been detected in planetary nebulae and supernova remnants (Graham, Wright, & Longmore 1987; Graham et al. 1993). In order to estimate the total 1–0 $S(1)$ H_2 luminosity in our field, we first removed the stars from our mosaic. This was done by fitting each star with a Gaussian and replacing it with a smooth background. Then we plotted a histogram of the number of pixels with a given intensity in the range -100 to $+100$ using 200 bins (1 ADU s^{-1} for each bin). This histogram consists of noise together with the H_2 emission from the nebula. The latter is, of course, always positive. We assumed the noise to be symmetric, and used the negative part of the histogram to perform a spline fit to the curve. We then created a positive mirror curve to the fitted negative spline. Finally, we subtracted the fitted curve and its mirror counterpart from the original histogram curve. The remainder is the emission from the H_2 gas. For a distance of 5 kpc, we estimate the integrated 1–0 $S(1)$ H_2 luminosity for this region to be $\sim 4\,L_\odot$.

4. DISCUSSION

4.1. H_2 *Excitation Mechanism: Shocks or Fluorescence?*

The Hα/[N II] and Hα/[S II] line ratios clearly show that the ionized gas at various positions in the nebula, including positions close to where the H_2 has been detected, is photoionized rather than shock-excited (see Goudis et al. 1994). It is therefore natural to ask whether fluorescence by UV photons from the W-R star could excite the H_2 gas.

Black & van Dishoeck (1987) have calculated detailed models of fluorescent excitation of H_2 in interstellar clouds. We will use their Figure 5, in which they plot the total H_2 emission ($I_{\rm tot}$) as a function of the ultraviolet scaling factor of the radiation field ($I_{\rm UV}$) for clouds of various densities, to determine whether the necessary conditions are satisfied for NGC 2359.

From our observed flux in the 1–0 $S(1)$ transition, we estimate the total flux emitted in the H_2 lines to be $I_{\rm tot} = 3 \times 10^{-3}$ ergs s^{-1} cm^{-2} sr^{-1}. This was determined by adopting model 14 of Black & van Dishoeck (1987), in which the 1–0 $S(1)$ line is found to contribute 1.6% of the total H_2 line emission.

The UV scaling factor of the stellar radiation field corresponds to the ratio of the number of nonionizing UV photons reaching the cloud to the number of UV photons in the background radiation. It can be written as

$$I_{\rm UV} = 310 \left(\frac{N_{\rm UV}}{10^{48}\ {\rm s}^{-1}}\right)\left(\frac{d}{1\ {\rm pc}^{-2}}\right),$$

where $N_{\rm UV}$ is the number of nonionizing photons capable of exciting H_2 and d is the distance between the star and the emitting gas. We also adopted a mean background of UV photons of 2.7×10^{11} photons s^{-1} m^{-2}, as measured by Draine (1978) for the solar neighborhood.

From the model atmospheres of Kurucz (1979), Puxley, Hawarden, & Mountain (1990) estimated the number of H-ionizing photons and the number of corresponding non-ionizing photons capable of exciting H_2 (N_{UV}; between 912 and 1108 Å) for stars of different temperatures. For the purpose of our study, it will be sufficient to assume that the radiation field of our W-R star can be approximated by the models of Kurucz (1979). Esteban et al. (1993) have calculated the number of ionizing photons emitted by the W-R star HD 56925 [$(5\text{–}13) \times 10^{48}$ s^{-1}]. From Puxley et al. (1990) we find that this is similar to a star of $\sim$40,000 K, and that the corresponding number of nonionizing photons is roughly 8×10^{48} s^{-1}. With the adopted distance to the star of 5 kpc, we estimate the distance between the star and the H_2 gas in the brightest filament (*d*) to be approximately 5 pc. From these values, we obtain a UV scaling factor of $\sim$100.

These values do not, in fact, correspond to any valid cloud model presented in Figure 5 of Black & van Dishoeck (1987). However, this model assumes that we are viewing the interstellar cloud "face on." For optically thin emission, if we observe it at an angle, we must multiply the calculated H_2 flux by a geometric enhancement factor, because of the longer optical path. With a modest value of $\sim$5, we can easily explain the observed flux with an interstellar cloud having a density of approximately 1000 cm^{-3}, which is close to the value for the south cloud estimated by Schneps et al. (1981) from their CO observations. Note that this corresponds only to an average density; the density in the filaments could be much higher, in which case a smaller geometric enhancement factor would be required. Therefore, it is clear that UV fluorescence is a valid candidate for the excitation mechanism of the observed molecular gas.

One can also ask whether the observed spatial distribution of the H_2 emission is compatible with the excitation mechanism of the H_2 gas being UV fluorescence. Black & van Dishoeck (1987) demonstrated that fluorescent H_2 emission increases with density and decreases with the square of the distance from the exciting star. This can possibly explain why we do not detect any H_2 radiation in the molecular cloud located immediately to the east of the bubble. Indeed, Schneps et al. (1981) found that the mean density of the molecular cloud to the east is 3 times lower than that in the south of the nebula, which is consistent, at least qualitatively, with our nondetection of H_2 emission.

In this scenario, we suggest that the H_2 filaments we are seeing within the U-shaped nebula are areas of higher density. The higher extinction would explain why the ionized gas is not visible in these regions (or why it is not ionized), and self-shielding by the high-density gas would ensure that the H_2 molecules are not dissociated by the intense ultraviolet radiation field of the W-R star. Self-shielding could also explain why the excited H_2 gas we observe is only located on the northwest border of the filament. But if fluorescence is indeed the excitation mechanism of the molecular gas, one can then wonder what has produced such a filamentary density distribution in the first place. It has been suggested that the filaments in the wind-blown bubble were a consequence of the interaction of the bubble with clumps in the surrounding interstellar medium. Perhaps these have a similar origin and are a consequence of the work of the ancestor O star wind on the surrounding interstellar medium.

However, the filamentary structure is also reminiscent of what is observed for supernova remnants (e.g., Graham et al. 1991), in which shocks are identified as the excitation mechanism of the molecular gas. Following Graham et al. (1991), the total 1–0 *S*(1) H_2 flux can be written as

$$I_{1-0\,S(1)} = 9.0 \times 10^{-6}\left(\frac{n_{H_2}}{100\ \mathrm{cm^{-3}}}\right)\left(\frac{v_s}{25\ \mathrm{km\ s^{-1}}}\right) \times \left(\frac{1}{\cos\theta}\right) \mathrm{ergs\ s^{-1}\ cm^{-2}\ sr^{-1}}\ .$$

Using a typical density of 10^3 cm^{-3}, a slow shock velocity of $\sim$15 km s^{-1}, and a small geometric enhancement factor of $\sim$2.5, we estimate that a partly dissociating shock is indeed capable of reproducing the observed 1–0 *S*(1) H_2 flux. However, shocks should also produce considerable levels of [Fe II] 1.644 μm emission, which we have not detected in an image consisting of five 60 s circular variable filter observations of the brightest filament located in the pink box in the detail of Figure 1. This is a surprising result, as the ratio of [Fe II] to H_2 1–0 *S*(1) is usually much greater than unity (e.g., Graham et al. 1987) for shocks while, in our case, we estimate it to be smaller than 0.14 (3 σ). One possible explanation for the lack of [Fe II] emission is the presence of the strong UV flux from the W-R star, which could prevent the recombination of Fe behind the shocks, in which case we should expect significant emission from [Fe III]. Just as the fluorescent H_2 emission, the H_2 emission from shocks also scales with the density, and therefore, this can once again explain why we do not detect anything on the east side of the bubble. In this model, the regions of low optical emission would also be zones of higher density in which the H_2 has survived the intense UV flux through self-shielding. The relatively slow-moving shocks would be working their way through the dense filaments in the northwest-southeast direction and, in so doing, excite the H_2 molecules. The fact that the excited gas is only located on the northwest border of the Hα trough would indicate that the shock has not moved beyond this point yet. The shock would have to be nonradiative, as line ratios show that the gas observed in the optical is photoionized.

There is also the possibility of a combined scenario in which the H_2 filamentary structure was shaped by the passage of a shock front in the past but is presently being excited by the UV photons from the W-R star. Once again, the regions we have detected in H_2 flux would then trace the zones of higher density. Finally, the only satisfactory way in this case to determine which H_2 excitation mechanism dominates is to gather spectroscopic information and measure H_2 line ratios. In addition to clearly identifying the dominant mode of excitation, these line ratios will also allow us to determine which type of shock is present.

Schneps & Wright (1980) suggested that there might be a second ionizing star in this region located in the south part of the U-shaped nebula. They proposed that this star is blowing a bubble that is colliding with the W-R bubble, creating the bright curved structure seen at the top left of the three-color image of Figure 1. Figure 2 strongly supports this suggestion, and H_2 gas is seen to border the south part of the secondary bubble (*yellow arc*). The additional star is located very close to the H_2 gas we have detected and, therefore, may contribute significantly to the excitation of the molecular gas.

4.2. *Origin of the* H_2

One of the main questions that remains to be answered about this nebula concerns its history and formation mechanism. The mass of ionized gas has been estimated from the 20 cm radio flux by Schneps et al. (1981) to be ~ 16 $M_\odot$ (for a distance of 5 kpc). Based on this mass, Treffers & Chu (1982) estimate that the kinetic energy in the shell is much less than 1% of the kinetic energy in the wind of the W-R star integrated over the lifetime of the shell, which is more than a factor of 20 smaller than predicted by windblown-bubble theory (Weaver et al. 1977). Treffers & Chu (1982) conclude that the bubble is in a momentum conservation phase, and that energy losses have occurred. Schneps et al. (1981) propose that the nonmoving dense filaments of the bubble may have been the result of interactions of the expanding tenuous bubble with small inhomogeneities in the external interstellar medium. In support of this hypothesis, Goudis et al. (1983) find that the [O III] lines are much broader in the filaments than in the expanding bubble, which is consistent with a postshock-phenomenon interpretation. Goudis et al. (1994) went on to suggest that the radiative losses occur at the boundaries between clumps and shocked wind flows (see Hartquist & Dyson 1993).

The alternative interpretation is that a large fraction of the bubble mass consists of neutral material, and that the kinetic energy obtained from the ionized gas is underestimated by a large factor. Van Buren (1986) presents a dynamical estimate of the kinetic efficiency parameter and of the radial momentum conservation parameter that takes into account the neutral material, and finds values much closer to those predicted by theory for energy-conserving bubbles. He therefore suggests that a shell of neutral H I or H_2 gas might be found associated with the ionized gas. This is possible if the ionization front is trapped inside the windblown bubble. By comparing the number of Lyman continuum photons from the W-R star with the number of recombinations in the shell, Van Buren (1986) estimates that the ionization front could easily be trapped for NGC 2359.

In support of this suggestion, Marston (1991) has presented *IRAS* observations of this nebula. From pointed 50 and 100 μm fluxes he detects dust heated at 33 K, mainly in the region to the south of the bubble. He estimates the mass of the dust to be 1.35 $M_\odot$. For a normal gas-to-dust ratio of ~ 100, this indicates that the mass of the shell is much higher than the 16 $M_\odot$ measured from ionized gas. Using 135 $M_\odot$ for the total mass of the shell, Marston (1991) finds that the bubble's kinetic efficiency parameter and the radial momentum conversion parameter are consistent with the energy-conserving case. The small difference can be accounted for by energy losses in the clumpy interstellar medium.

Our observations were aimed at attempting to detect the molecular component of the bubble predicted by Van Buren (1986). The brightest filament seems to follow the general shape of the U-shaped nebula in the south part, probably indicating the position of the border of the neighboring molecular cloud. The distribution of the very weak emission we have detected in the north part also seems to follow this pattern, although higher signal-to-noise ratio data are required to confirm this. High spatial resolution observations in CO would clearly establish the limits of the molecular cloud. The filaments located within the U-shaped optical nebula most likely trace areas of higher density in which the molecular hydrogen has not been dissociated. The strong ultraviolet radiation from the W-R star photoionizes the matter inside the U-shaped nebula and excites the H_2 molecules on its border or in the denser parts within it by fluorescence. Alternatively, slow shocks could be moving away from the star, exciting the H_2 gas on their way.

The location of this W-R nebula next to a dense molecular cloud has clearly had a profound influence on its present appearance. Nebulae around massive stars are generally thought to evolve according to the so-called three-wind model. First, the star begins its life as an O star and blows a hole in the surrounding medium that can reach 50 pc in size. These are frequently associated with the H I voids and shells detected at radio frequencies (e.g., Niemela & Cappa de Nicolau 1991 and references therein; Dubner et al. 1992; Arnal 1992; Arnal & Cappa 1996; Cappa et al. 1996). Then there is a phase of slower but much denser wind when the star undergoes a red supergiant (RSG) or luminous blue variable (LBV) phase, depending on its initial mass. Finally, when the star reaches its W-R phase the wind once again becomes fast, though less dense, and sweeps up the material ejected from the previous evolutionary phase. In some cases, this windblown bubble can overtake the RSG or LBV ejecta and burst through.

In the case of NGC 2359, the boundary conditions vary in different locations around the star, and therefore the evolution of the surrounding nebula should be slightly different. The star is located immediately to the west of the border of a dense molecular cloud, detected by Schneps et al. (1981). On its west side the bubble can easily expand, but on its east side it runs into the molecular cloud. Therefore, in its main-sequence phase, the star probably blew and ionized a hole that had a much larger extent on its west side than on its east or south side because of the large density contrast. Dufour (1989) suggests that this gave rise to a blister-type nebula, which is the suggested origin of the U-shaped H II region. It would be interesting to try to detect very faint Hα emission on the west side of the U-shaped nebula. Later, depending on its initial mass, the star underwent an RSG or LBV phase with a very high mass-loss rate but a very low terminal velocity. Assuming a typical expansion velocity of $\sim$10–25 km s^{-1}, the wind would reach a distance of $\sim$1–2.5 pc in a lifetime of $\sim 10^5$ yr. Depending on the extent of the cavity on the east side, this material could be distributed roughly symmetrically around the star. Finally, the star entered its W-R phase and blew the relatively spherical filamentary 3 pc bubble that is visible today. Inhomogeneities in the circumstellar material generated the nonmoving, dense filaments that are seen, together with the thin membrane of the bubble. The yet unsolved question of the mass of the W-R bubble is critical, as the model described above would only be acceptable if the mass of the W-R nebula were found to be relatively modest.

In the scenario described above, the molecular gas we have detected would be part of the ambient interstellar medium swept up by the star when it was on the main sequence (O star). The molecular hydrogen could be either fluorescent or shock-excited. We have not, however, detected a molecular component directly associated with the W-R windblown bubble. This does not exclude the existence of a neutral component to it, as it is possible that the hydrogen molecules have been dissociated by a shock or by the strong ultraviolet flux from the star. In this context, 21 cm H I observations would be complementary to the observations presented here, and are extremely important to establish the real mass of the W-R bubble.

4.3. *O and W-R Nebulae as an Extragalactic* H_2 *Source*

It is well known that many galaxies are strong 1–0 $S(1)$ H_2 emitters. It is generally thought that the sources of this emission are diverse, ranging from young stellar objects such as Orion to supernova remnants and planetary or reflection nebulae. Can H_2 emission from hot star nebulae (O or W-R), such as that presented here, be a significant contributor to the observed extragalactic flux? Fischer et al. (1987) and Puxley, Hawarden, & Mountain (1988, 1990) have shown that UV fluorescence from hot stars is indeed a viable mechanism to explain the H_2 emission in some active galactic nuclei and starburst galaxies. However, emission from an *individual* O or W-R star had not previously been detected. Assuming that the level of H_2 emission detected from NGC 2359 is typical, is it sufficiently high to constitute a significant fraction of the measured extragalactic sources?

As a test, we will examine the case of the prototypical W-R galaxy He 2-10. This galaxy is a blue compact dwarf in which features resembling W-R bands were first detected by Allen, Wright, & Goss (1976). Later, Conti (1991) defined the W-R galaxy class and published the first catalog with 37 members. In order to be included in this class, emission-line galaxies only need to satisfy a single criterion: displaying broad He II λ4686 emission. This indicates that these galaxies harbor a large number of W-R stars.

Vacca & Conti (1992) present long-slit ($1''.5 \times 101''$) optical spectra of 10 W-R galaxies, including He 2-10. From the observed luminosity in the C IV λ5808 and He II λ4686 lines, they estimate the number of WC and WN stars in the nucleus of the galaxy to be $\sim$400 and $\sim$293, respectively. Using a method developed by Vacca (1991) based on the number of ionizing photons required to produce the observed recombination spectrum, they find that the number of main-sequence O stars is $\sim$4400. The total number of hot stars in the nucleus of He 2-10 is therefore $\sim$5100.

Lumsden, Puxley, & Doherty (1994) present infrared spectroscopy of the nucleus of He 2-10. They find a total 1–0 $S(1)$ H_2 emission of $(6 \pm 0.4) \times 10^{-18}$ W m^{-2} in a $3'' \times 6''$ slit. For NGC 2359, we find a total 1–0 $S(1)$ H_2 luminosity of $\sim 4\ L_\odot$, which corresponds, for a distance of 5 kpc, to a flux of 16×10^{-22} W m^{-2}. Adopting this as a typical value, the estimated 5100 hot stars could contribute as much as 8×10^{-18} W m^{-2}, or a value of the same order of magnitude as the total detected 1–0 $S(1)$ H_2 flux from the nucleus of He 2-10.

Because of their short evolutionary timescales, it is very likely that massive stars are still located relatively close to their parent molecular clouds. Therefore, unless the hydrogen molecules are mostly dissociated, the stars have good chances of exciting the surrounding H_2 molecules either by UV fluorescence or by shocks from windblown bubbles. The W-R stars themselves are few in number compared with O stars and, therefore, only contribute about 10% of the total massive star input. Clearly, a more systematic study of Galactic hot stars is required to determine how widespread H_2 emission is in the vicinity of W-R and OB stars.

5. CONCLUSIONS

We have presented IR line emission observations of the W-R nebula NGC 2359. We report the first direct detection of emission from H_2 gas in the vicinity of a W-R nebula and propose that the observed filamentary distribution of molecular gas traces regions of higher density either on the border of the neighboring molecular cloud or in denser areas of nondissociated H_2 molecules within the region mainly composed of ionized gas. The excitation mechanism could be either ultraviolet fluorescence or shocks, and the spatial distribution of the H_2 is not inconsistent with either mechanism. The present data, unfortunately, do not allow us to determine the relative importance of the two possible excitation mechanisms, because both can explain the observed level of 1–0 $S(1)$ H_2 flux. Spectroscopic observations of several H_2 transitions with the aim of calculating specific line ratios are required to achieve this.

In view of the relatively high level of H_2 emission detected in NGC 2359, hot star nebulae have the potential of contributing a significant fraction of the total H_2 emission observed in emission-line galaxies, particularly in those displaying recent starburst activity. It is, however, essential to establish the ubiquity of this phenomenon among Galactic O and W-R stars in order to be able to judge its importance on extragalactic scales.

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