The molecular hydrogen content of NGC 604 and other M33 H II region complexes

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SUMMARY
We have searched six bright H II regions in M33 for H2 line emission. Previously detected fluorescent H2 emission in the first-ranked M33 H II region, NGC 604, has been mapped, allowing us to estimate the mass of its molecular cloud (of order $3 \times 10^6 M_\odot$). This result implies a ratio $N_{\text{CO}}/N(H_2)$ lower by an order of magnitude than that of galactic molecular clouds. The lack of shocked H2 in NGC 604 implies that the ionized stellar wind bubbles seen in the nebula are not interacting strongly with the molecular material. The dynamics of NGC 604 appear to be dominated by gravitational interaction. A 2-μm spectrum of NGC 604 also shows H1 and He i recombination lines from the ionized gas, as well as CO absorption in the photospheres of late-type stars, which must dominate the 2-μm continuum.

With the exception of IC 133, the other H II regions yielded only upper limits for H2 emission. IC 133 appears to contain an unusually small amount of gas and dust. The lack of H2 in the other regions is briefly discussed.

1 INTRODUCTION

The Local Group Sc II galaxy M 33 contains a number of very large and luminous H II regions. The largest and brightest is NGC 604, which in the Local Group is only surpassed by the LMC 30 Doradus complex. The ionized gas in NGC 604 consists of a 0.5 arcmin complex core surrounded by a 1.5 arcmin diffuse envelope. At the distance of M 33 (720 kpc; Madore et al. 1985), this corresponds to linear sizes of 105 and 315 pc. Both NGC 604 and the second brightest H II region NGC 595 are associated with H I mass concentrations of order $10^8 M_\odot$ (Wright 1971; Newton 1980; Deul & van der Hulst 1987).

NGC 604 contains a large number of luminous early-type stars (spectral types O and WR — Benvenuti, d’Odorico & Dumontel 1979; Conti & Massey 1981; Rosa & d’Odorico 1982) several of which are undergoing mass loss (Massey & Hutchings 1983). The total stellar luminosity of NGC 604 is a few times $10^3 L_\odot$ (Israel et al. 1972; Rice et al. 1988). The ionized gas is in violent motion with speeds of up to 100 km s$^{-1}$, and a kinetic energy content of order $5 \times 10^{51}$ erg (Rosa & d’Odorico 1982). It has been suggested that the dynamical structure of NGC 604 is dominated by stellar wind bubbles (Rosa & Solf 1984; Hippelein & Fried 1984). A weak CO signal was detected towards NGC 604 by Blitz (1985), although both carbon and oxygen (as well as nitrogen) are underabundant in NGC 604 by large factors as compared to Orion (Kwitter & Aller 1981; Dufour, Schiffer & Shields 1984).

The presence of CO emission from the dynamically active H II region NGC 604 prompted us to conduct a search for near-infrared line emission from excited molecular hydrogen. Somewhat surprisingly, this search did not result in the detection of shock-excited H2, but rather in the detection of radiatively excited H2 (Israel et al. 1988; hereafter Paper I). The mapping described below revealed the spatial extent of this emission. In turn, this result encouraged us to search other H II region complexes in M 33, notably NGC 595 and IC 133 which likewise show CO emission (Blitz 1985; Israel & Stark, unpublished data). All these objects are under-abundant at least in N and O by amounts similar to those found in NGC 604.
2 OBSERVATIONS

The NGC 604 H$_2$ observations were made in 1984 October at UKIRT, with an InSb detector (UKT 9) and a circular variable filter wheel (CVF) of resolution $\lambda/\Delta\lambda = 120$; standard chopping and nodding techniques were employed using an east–west beam separation of $2$ arcmin. All spectra were obtained with a wavelength separation between adjacent datapoints of 0.0076 $\mu$m. The uncertainty in the wavelength scale is 0.005 $\mu$m. In the 1984 observations, we readily detected the H$_2$ $1 \rightarrow 0$ Q-branch. Full $K$-band spectra (2.00–2.45 $\mu$m) were obtained with an aperture of 19.6 arcsec at six positions in NGC 604. Four positions were re-observed with an aperture of 12.5 arcsec. The extent of the excited H$_2$ was mapped by observing the $1 \rightarrow 0$ Q-branch between 2.39 and 2.46 $\mu$m with the 19.6 arcsec aperture on a grid of positions separated by 12.5 arcsec. Intensities were calibrated by observing the G dwarf HD 3029 ($K = 7.09$ mag; Elias et al. 1982) and assuming its energy distribution to be that of a 9000 K blackbody. Fig. 1(a) shows the map of integrated Q-branch intensities: Fig. 1(b) compares its distribution and the extent to that of the H$\alpha$ emission of NGC 604.

In Fig. 2 we show the averaged spectrum of the three strongest 19.6 arcsec aperture (1984) positions. The strong dip (about 25 per cent) in the continuum longwards of 2.3 $\mu$m is due to CO absorption in the atmospheres of late-type stars. Judging from the depth of the absorption, these stars are the dominant contributors to the 2 $\mu$m continuum. Since such a strong CO absorption feature is characteristic of M supergiants, NGC 604 must contain a significant population of massive evolved stars in addition to the relatively unevolved ionizing stars. In this respect, NGC 604 is very similar to the more luminous nebula 30 Doradus in the LMC (see McGregor & Hyland 1981). Although the signal-to-noise ratio in the individual spectra averaged in Fig. 2 is poor, the CO absorption appears to be strongest in the direction of component $G$ (nomenclature of Israel et al. 1982) and weakest towards components $B$ and $C$ which comprise the brightest part of NGC 604 in radio and H$\alpha$ maps.

In this 1984 spectrum, the $1 \rightarrow 0$ Q-branch of H$_2$ is quite prominent. In addition, emission due to HeI (2$^2P$–2$^1S$) at 2.06 $\mu$m, and Br$\gamma$ at 2.17 $\mu$m is seen. The spectrum has, however, insufficient signal-to-noise ratio to show unambiguously the other H$_2$ lines which the high-quality 1986 spectrum (Paper I) showed to be present, notably the $1 \rightarrow 0 S(1)$ line which has a strength of $2.5 \times 10^{-21}$ W cm$^{-2}$.

During the 1986 observing run we also used the UKIRT cooled grating spectrometer (CGS 2) with a 5 arcsec beam and a resolving power of $\lambda/\Delta\lambda = 550$ to observe the Br$\alpha$ line at the peak in the H$_2$ $1 \rightarrow 0$ Q-branch emission. For the same (19.6 arcsec) resolution as that of the CVF Br$\gamma$ measurement in Paper I, we find $F(Br\alpha) = 4.2 \pm 1.1 \times 10^{-12}$ W cm$^{-2}$ sr$^{-1}$, as compared to $F(Br\gamma) = 1.10 \pm 0.04 \times 10^{-12}$ W cm$^{-2}$ sr$^{-1}$ (Paper I) so that $F(Br\alpha)/F(Br\gamma) = 4 \pm 1$.

For our 1986 survey of $1 \rightarrow 0$ Q-branch emission of the other bright H$\alpha$ regions we again used the UKT 9 CVF with a 19.6 arcsec aperture, and obtained spectra between 2.37

Figure 1. (a) Map of the H$_2$ $v = 1 \rightarrow 0$ Q-branch emission towards NGC 604. Contours are in steps of $9 \times 10^{-22}$ W cm$^{-2}$. Lowest (dashed) contour is likewise at $9 \times 10^{-22}$ W cm$^{-2}$ and indicates the $1 \sigma$ noise level. Filled circles indicate positions observed; a reference star south-east of NGC 604 is also marked. (b) Simplified $1 \rightarrow 0$ Q-branch map superposed on an H$\alpha$ emission image of NGC 604 (courtesy H. Hippkelein and J. W. Fried). Peak H$_2$ emission is at the edge of the visual (H$\alpha$) nebula, and extends to the south-east where there is only weak (envelope) optical emission.

Figure 2. Averaged spectrum of the three strongest positions in Fig. 1, covering effectively the entire H$\alpha$ core. At 2.15 $\mu$m, the flux of HD 3029 is $6.5 \times 10^{-17}$ W cm$^{-2}$ $\mu$m$^{-1}$. 

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and 2.45 \( \mu m \) under good observing conditions. They were likewise sampled every 0.076 \( \mu m \) (0.4 resolution element). Correction for atmospheric transmission and intensity calibration was made by observing the standard star BS 8905 (F8III; \( K = 3.0 \) mag) and assuming a blackbody temperature of 5700 K. One set of integrations yielded a clear detection of emission from the radio/infrared position of IC 133 (Fig. 3). A second set of integrations taken a day later (but under less favourable weather conditions) failed to confirm this detection. We thus regard this result as tentative. All other observations yielded upper limits, including three positions in NGC 595 which contain a hint of emission at the Q-branch wavelength. The results are given in Table 1.

![Figure 3. H_2 v = 1-0 Q-branch spectrum of IC 133; see text.](image)

### Table 1. Observations of 1-0 Q-branch emission in M 33.

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<th>Object</th>
<th>( \alpha(1950) )</th>
<th>( \delta(1950) )</th>
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<td>(arcsec)</td>
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Notes: *In 19.6 arcsec aperture; not corrected for extinction. **See text.  
\( ^{\text{a}} \)Peak value; see Paper I; text.

## 3 ANALYSIS AND DISCUSSION

### 3.1 The properties of the giant molecular cloud in NGC 604

Fig. 1(b) shows that the H\(_2\) cloud dimensions are roughly comparable to those of the H\(_\alpha\) complex. The results obtained by Hippelein & Fried (1984) show that the H\(_\alpha\) emission in the direction of H\(_2\) peak emission is redshifted with respect to the rest of the nebula by about 20 \( km\ s^{-1}\); at the same time the velocity dispersion at this peak is relatively low with \( \Delta V \approx 10-15 \ km\ s^{-1} \). At the position of suspected embedded infrared continuum sources (Israel et al. 1982), we see no enhancement of H\(_2\) emission. The tongue of H\(_2\) emission seen in the north-east towards a prominent H\(_\alpha\) loop (Fig. 1b) is intriguing. Unfortunately, we have no measurements covering this loop. Note the location of the H\(_2\) peak at the edge of the bright H\(_\alpha\) image.

#### 3.1.1 Extinction to the H\(_2\) source

The optical line emission from NGC 604 suffers a mean extinction \( A_v = 0.7-1.2 \) mag (Israel & Kennicutt 1980; Hippelein & Fried 1984), while the brightest ionizing stars have \( A_v = 0.5 \) mag (including a contribution of about 0.15 mag due to the galactic foreground; Massey & Hutchings 1983). The relatively low extinction of the optical nebula and stars suggests that the bulk of the H\(_2\) emitting region is located behind the H\(_\alpha\) region complex. The bright parts of the visual nebula most likely are ionization fronts moving into the molecular cloud complex. The extinction of the H\(_2\) emission should be at least the mean extinction of the ionized gas quoted above, which corresponds to 0.1 mag or less at the wavelength of the Q-branch. At the location of the H\(_2\) peak, the extinction is somewhat higher than average: \( A_v \) \((H\alpha) = 1.5-2.0 \) mag (Israel et al. 1982; Hippelein & Fried 1984). We therefore estimate the foreground extinction of the entire H\(_2\) cloud to be \( A_{v}= 1.5 \) mag, so that \( A_{2,41} = 0.16 \) mag.

#### 3.1.2 Luminosity of the H\(_2\) emission

In Paper I, we have shown that the H\(_2\) emission from the peak position, comprising 30 per cent of the area-integrated Q-branch emission, is radiatively excited. Although we cannot entirely rule out shock excitation being important at other positions, we will proceed on the assumption that in fact all H\(_2\) emission observed towards NGC 604 is radiatively excited. The peak signals shown in Fig. 1 of Paper I, now corrected for \( A_v = 1.5 \) mag foreground extinction, yield a surface brightness \( o1 = 0 S(1) = 4.1 \times 10^{-6} \ erg \ cm^{-2} \ s^{-1} \ sr^{-1} \) and \( o1 = 0 Q = 1.1 \times 10^{-5} \ erg \ cm^{-2} \ s^{-1} \ sr^{-1} \), implying a peak surface brightness in all H\(_2\) lines \( o(H_2) = 2.5 \times 10^{-4} \ erg \ cm^{-2} \ s^{-1} \ sr^{-1} \) (Black and van Dishoeck 1987; see also Paper I). The map in Fig. 1, again corrected for foreground extinction yields a mean surface brightness \( o(Q) = 5.6 \times 10^{-6} \ erg \ s^{-1} \ cm^{-2} \ sr^{-1} \) over the area within the first solid contour. Assuming that the total H\(_2\) luminosity scales with the Q-branch luminosity, we find an integrated luminosity \( L(H_2) = 9.4 \times 10^4 L_{\odot} \) for a distance of 720 kpc. This can be compared to the total luminosity of the stars exciting NGC 604. ANS UV (Israel et al. 1982) and IRAS IR observations

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3.1.3 Size, structure and density of the giant H₂ cloud

The angular dimensions (FWHM) of the cloud, as observed in the 19.6 arcsec aperture, are approximately 37 × 24 arcsec. The deconvolved angular size corresponds to linear dimensions of 110 × 50 pc. The projected surface area of 5 × 10¹⁷ pc² is about twice the mean surface area 2.1 × 10¹⁶ pc² found for galactic giant molecular clouds (Blitz 1985). The H₂ cloud associated with NGC 604 is thus comparable to the largest galactic molecular cloud complexes. The observations made in a 12.5 arcsec aperture yield Q-branch surface brightness about 20 per cent higher than those made in the 19.6 arcsec apertures at the same position. This difference is of only marginal significance when compared to the observational error. It implies, however, that H₂ cloud clumping can only be important on scales smaller than about 4 arcsec (15 pc).

In Paper I, we considered excitation of H₂ at the peak position by essentially a point-like illuminating source. We concluded that, depending on model input assumptions, the density \( n_{\text{H}} = n(\text{H}) + 2n(\text{H}_2) \) of irradiated material is 250 < \( n_{\text{H}} < 1000 \) cm⁻³ for a separation of about 50 pc between stellar energy source and molecular cloud surface and no intervening extinction. In order to explore further the validity of that result, we consider here some alternatives. First, we assume that the UV radiation originates in 30 O stars, or small clusters with the same UV output, scattered throughout the nebula. This number is a compromise between the number of luminous blue stars identified in NGC 604 and the number of distinct Hα features seen in the nebula (cf. Benvenuti et al. 1979; Sabbadin, Raffanelli & Bianchini 1980). It reproduces the total luminosity of stars in NGC 604. Given the dimensions of the nebula, each star or cluster should dominate an area of about 25 pc (7 arcsec) radius. The main difference from the situation described in Paper I is that the same UV radiation field intensities \( I_{\text{UV}} \) are reached much closer to the stellar energy sources. This, and the lower mean surface brightness of the cloud as a whole reduce the mode distances listed in table 3 of Paper I by a factor of about 0.3. Conversely, for a mean separation of 25 pc between star and cloud, the above densities \( n_{\text{H}} \) would have to be increased by about a factor of three, to e.g. 500 < \( n_{\text{H}} < 3000 \) cm⁻³. The actual H₂ excitation situation in NGC 604 is most likely somewhere between irradiation by a point-like source and irradiation by homogeneously scattered sources, so that we find 300 < \( n_{\text{H}} < 1700 \) cm⁻³, with a 50 per cent uncertainty in this range.

We briefly return to the question of internal extinction. Extinction inside the nebula between the irradiating stars and the molecular cloud surface leads to sharply reduced UV radiation field intensities, and thereby requires larger \( n_{\text{H}} \) values for a given separation. Generally, the presence of large amounts of dust mixed with the ionized gas of H I regions does not appear very likely (cf. Caplan & Deharveng 1986; van der Hulst et al. 1988; see also Skillman & Israel 1988), but their occurrence cannot entirely be ruled out. If, unexpectedly, large internal extinctions \( A_v > 0.5 \) occur, this would lead to significantly higher cloud densities \( n_{\text{H}} > 3000 \) cm⁻³ for any reasonable separation. For the moment, however, we will ignore this possibility.

3.1.4 Excitation: the dominance of fluorescent H₂ and the early-type stars in NGC 604

To what extent radiatively excited H₂ dominates shock-excited H₂ (as follows from the line ratios listed in Paper I) can be seen by considering the surface brightness \( \sigma(S(1)) \) of the 1 − 0 S(1) line. The observed peak surface brightness is \( \sigma(S(1)) = 4.0 \times 10^{-6} \) erg s⁻¹ cm⁻² sr⁻¹ in a 19.6 arcsec aperture, while the S-line ratios do not allow a contribution of more than 15 per cent by shock-excited H₂ gas. Theoretical calculations by Shull & Hollenbach (1978) for shock-excited H₂ with \( n_{\text{H}_2} = 1000 \) cm⁻³ and \( V_s = 10 \) km s⁻¹ predict \( \sigma(3\text{S}) \) to be already ten times more than the peak value observed. Thus, either shock excitation is absent (e.g. for \( T = 2000 \) K, the column density of shocked H₂ is \( N(\text{H}_2) \approx 10^{15} \) cm⁻²), or shocked H₂ is locally present but with a rather small aperture filling factor (i.e. on a scale ≤ 20 pc as compared to our linear aperture of 70 pc). A larger aperture filling factor is possible, without causing a conflict with the observed line ratios and intensities, but only for very weak shocks (\( V_s \approx 6 \) km s⁻¹). Even in that case, however, the luminosity of shock-excited H₂ is at most 15 per cent of the total H₂ luminosity.

How can UV excitation dominate so completely, in spite of the violent motions clearly seen in the H I region? Shull & Hollenbach (1978) show that (wind) shock excitation will dominate if \( K L_{\text{w}} < 1.28 \), in which \( K \) is a UV pumping constant (Hollenbach, Chu & McCray 1976) and \( L_{\text{w}} \) is the wind luminosity in units of 10⁸ erg s⁻¹. For galactic OB stars, this condition is generally fulfilled for spectral types earlier than O8. Such stars occur in abundance in NGC 604, as do Wolf–Rayet stars (Benvenuti et al. 1979; Conti & Massey 1981; Rosa & d’Odorico 1982; Massey & Hutchings 1983). The relative weakness of shock-excited H₂ can be explained if stellar wind luminosities (i.e. mass-loss rates and terminal velocities) of the exciting stars in NGC 604 are lower by at least a factor of three than those of their galactic counterparts (cf. the discussion of LMC/SMC H₂ regions by Israel & Koornneef 1988). Such a situation is indeed observed for Magellanic Cloud stars (Hutchings 1982) and it has been modelled by Kudritzki, Pauldrach & Puls (1987) on the basis of low metallicities. As we have noted before, carbon, nitrogen and oxygen abundances in NGC 604 are very similar to those in the Magellanic Clouds and significantly lower than those in the solar neighbourhood.

3.1.5 Dynamics of NGC 604: gravitational binding

The conclusion of the previous section has an important consequence. The overall velocity dispersion of ionized gas in NGC 604 is 30 km s⁻¹ (Hippelein & Fried 1984). As in the case of other extragalactic H I regions, this large velocity dispersion is usually attributed to either a number of gas clouds moving in the overall gravitational field of the complex (Terlevich & Melnick 1981) or, with some caveats, to an ensemble of expanding windblown shells (Rosa & d’Odorico 1982; Rosa & Solf 1984; Hippelein & Fried 1984). The minor role played by shocks in the excitation of H₂ in NGC 604 suggests the first explanation to be correct.
Some of the motions seen in the ionized gas may indeed represent windblown shells, but these will involve only a relatively small fraction of all the gas present. It is unlikely that the overall dynamics and energetics of NGC 604 are dominated by expanding stellar bubbles or large-scale gas flows. Consequently we support the conclusion by Terlevich & Melnick (1981) that the observed velocity dispersion is largely due to the relative motions of individual gas clouds in the gravitational potential of the whole cloud.

3.1.6 Molecular mass of NGC 604 and CO to H₂ conversion

We estimate the mass of the molecular complex by using equation (26) of Black & van Dishoeck (1987), which essentially assumes the H₂ emitting layer to be representative for cloud conditions throughout. We find $M_{\text{cloud}}/M_\odot = 1.34 \times 10^8 n_p N_e^{-1/2}$, in which $N_e$ is the number of clouds in the area mapped. For a single, homogeneous cloud ($N_e = 1$), the density range $300 < n_H < 1700$ cm$^{-3}$ yields a molecular mass range $4 \times 10^6 < M_{\text{cloud}} < 4 \times 10^7 M_\odot$. For a representative density $n_H = 750$ cm$^{-3}$, the H₂ mass implied by the observed H₂ line emission is $M_{\text{cloud}} = 1 \times 10^6 M_\odot$. If clumping is important on scales $< 15$ pc (cf. Section 3.1.2), the H₂ mass will be lower: taking $N_e = 100$, we find $M_{\text{cloud}} = 1 \times 10^5 M_\odot$, and $\rho_{\text{cloud}} = 10$ pc. However, whereas clumping would decrease the mass derived, the presence of even modest amounts of internal extinction would increase it by similar factors. Thus, the H₂ observations suggest a molecular cloud mass of order $3 \times 10^6 M_\odot$ within a factor of three.

The molecular mass can also be estimated from the CO emission observed towards NGC 604. In a 1.1 arcmin beam, which just covers the entire H₂ cloud in Fig. 1, Blitz (1985) found a $J = 1 \rightarrow 0$ CO signal with $T_R = 0.1$ K and a velocity FWHM of $\Delta V = 13.5$ km s$^{-1}$. In the preceding section, we have argued that the velocity dispersion of NGC 604 is a response to the gravitational field rather than caused by stellar wind bubbles, so we can use the virial theorem to obtain a mass estimate. With the mean H₂ cloud radius $R(\text{H}_2) = 37$ pc and $\Delta V = 13.5$ km s$^{-1}$ (Blitz 1985), we find a virial mass $M_{\text{vir}} = 8.5 \times 10^5 M_\odot$ for the complex. However, high signal-to-noise observations in a larger (1.7 arcmin) beam show the CO profile to have a broad shoulder with $\Delta V = 30$ km s$^{-1}$, identical to the H I velocity dispersion in the same beam (Israel & Stark, unpublished data) and also to the H₂ velocity dispersion of the ionized gas (Hippelein & Fried 1984), so that this value is more realistic than the formal FWHM given by Blitz. The virial mass then becomes $M_{\text{vir}} = 4 \times 10^6 M_\odot$. This result is indeed in good agreement with the mass estimate obtained directly from the observed H₂ emission; in the following we will assume a mass $M_{\text{cloud}} = 3 \times 10^6 M_\odot$ for the cloud complex shown in Fig. 1.

The best available galactic CO to H₂ conversion N(H₂) = 2.3 × 10$^{20}$ [T$_K$ dV mol cm$^{-2}$] (Bloemen et al. 1986; Bloemen, private communication) yields only $M(\text{H}_2) \approx 2.0 \times 10^6 M_\odot$, a factor of fifteen less than derived above! Less reliable, but commonly used empirical conversions of CO signal strength to H₂ mass (e.g. the one proposed by Young & Scoville 1982) yield masses that are about twice as high, but still fall far short of the required H₂ mass. We conclude that the observed CO emission from the NGC 604 molecular cloud is less than expected from the observed radiatively excited H₂ emission by probably an order of magnitude, and that routinely used CO to H₂ conversions are not applicable to NGC 604.

This conclusion is not changed by interferometric CO observations of NGC 604 showing the presence of two small ($< 30$ pc) clouds (Boulanger et al. 1988). Their source N604-S(CO) is outside the area depicted in Fig. 1. The other object, N604-N(CO), coincides with our H₂ peak but is much smaller than the H₂ extent in Fig. 1. Most likely, it consists of relatively warm molecular material in direct contact with the star formation zone. Comparison with single dish spectra (Blitz 1985; Israel & Stark, unpublished data) indeed suggests that N604-N(CO) is only the brightest component of a larger complex; the interferometer appears to have missed an underlying more extended and less bright component containing at least half of the total CO signal.

A significant dependence of CO to H₂ conversion factors is predicted by photodissociation models (Maloney & Black 1988). In M 33 both C and O are under-abundant with respect to H (Kwitter & Aller 1981; Dufour, Schiffer & Shields 1984), decreasing the effectiveness of CO self-shielding. Thus, in the UV-rich environment of NGC 604, [CO]/[H₂] abundances and CO strengths relative to N(H₂) are expected to be appreciably lower than in the solar neighbourhood. NGC 604 metallicities are comparable to those of the Magellanic Clouds. There, Israel et al. (1986a) have shown that CO photodissociation provides a natural explanation for the weak CO emission observed. This interpretation can be tested by observations of [C I] and [C II]; in photodissociation regions we expect to find [C I]/[CO] and [C II]/[CO] ratios significantly higher than found in galactic molecular clouds where this effect is less pronounced. In general, the importance of photodissociation implies that the use of CO to H₂ conversion factors derived from galactic observations easily leads to severe underestimates of the actual H₂ mass in regions of strong UV radiation and low metallicity (such as NGC 604 and the Magellanic Clouds) and therefore should be avoided.

A mass $M = 3 \times 10^6 M_\odot$ is in the upper range of galactic giant molecular cloud masses (Sanders 1981; Dame 1983). It should be compared to the ionized mass $M(\text{H II}) = 9 \times 10^4 M_\odot$ and the neutral hydrogen mass $M(\text{H I}) = 1.6 \times 10^5 M_\odot$. The ionized and neutral hydrogen mass estimates are most likely correct within a factor of two (cf. Israel et al. 1982). Thus, in the NGC 604 complex, H II and H₁ and H₂ represent roughly 15, 30 and 55 per cent, respectively of the total hydrogen mass.

3.2 H₂ in IC 133

H₂ emission was detected, with a strength about equal to that of the NGC 604 H₂ peak, at a single position out of nine searched (Table 1; Fig. 3 but note the caveat in Section 2). Confidence in the detection is strengthened by the fact that it coincides with the position of peak radio (Israel & van der Kruit 1974; Vilaflor et al. 1986), Ha and IRAS infrared position (Rice et al. 1988). In contrast to the NGC 604 cloud, the H₂ brightness at positions neighbouring the peak drops below the detection level. The bright H₂ emission in IC 133 therefore extends over less than 20 arcsec, i.e. less than 70 pc. No H₂ emission was seen towards the central and northern Ha emission zones. The absence of a large cloud of...
detectable H$_2$ has interesting implications. To illustrate this, we first consider the stellar population of IC 133.

### 3.2.1 Stellar luminosity of IC 133

The nominal position of the detected H$_2$ is 7 arcsec (25 pc) north-west of the brightest blue stars in the nebula, B102 and B103 (Humphreys & Sandage 1980). For B103, these authors give $V = 16.2 \pm 0.2$ mag, corresponding to an absolute magnitude $M_V = -8.1 \pm 0.3$ (cf. Madore et al. 1985). The colour $(B-V) = +0.3 \pm 0.3$ mag is much too red for an early-type object, and suggests $E(B-V) = 0.8 \pm 0.3$ mag. No data are given for B102, presumably because it is a multiple object, but it appears as bright as B103. For the whole star cluster in IC 133, Humphreys & Sandage (1980) given an integrated $V_T = 14.3$ mag ($M_V = -10.0$, not corrected for extinction). The cluster was also clearly detected in the UV between 1550 and 2500 Å (Israel, de Boer & Bosman 1986b). The UV data show a weak 2200 Å feature indicating an extinction $E(B-V) = 0.05$ (galactic foreground) + 0.35 (LMC-type reddening law) = 0.4 mag (cf. Massey & Hutchings 1983). Taking this extinction and assuming the stars to radiate at 40000 K we find an intrinsic luminosity $L_\lambda = 5 \times 10^7 L_\odot$ from both the visual and the UV data. This is brought down to $L_\lambda = 1.5 \times 10^7 L_\odot$ if the stars radiate at temperatures as low as 20000 K.

### 3.2.2 Comparison of IC 133 and NGC 604

In Table 2 we compare IC 133 and NGC 604. The stellar luminosity of IC 133 is within a factor of two that of that of NGC 604. The dimensions of the cluster are roughly similar to those of the NGC 604 nebula at its weakest emission limits. However, the radio power of IC 133 is only 6 per cent that of NGC 604, and the far-infrared luminosity is about a third. The infrared radiating dust in IC 133 is considerably hotter than that in NGC 604, and the radio surface brightness of the IC 133 nebula is higher than that of (the larger) NGC 604 nebula. If the H$_2$ emission from IC 133 is radiatively excited, its observed total H$_2$ luminosity is about a quarter of that of the NGC 604 cloud.

These differences are explained (a) if the cluster in IC 133 is deficient in early-type stars, so that relatively few photons are emitted below 1200 Å, or (b) if IC 133 is extremely poor in gas and dust, so that most emitted photons escape the region without exciting a dense interstellar medium. For several reasons we prefer (b). First, Humphreys & Sandage (1980) list 68 stars in IC 133 between $V = 16.2$ and 20.5 mag of which about 50 have blue colours. Thus, the cluster does not appear to be deficient in O-type stars. Secondly, the high far-infrared colour temperature suggests efficient dust heating, consistent with an abundance of heating photons and relatively little dust. Thirdly, H$\alpha$ emission is patchy, and covers only a small fraction of the cluster surface; the radio source likewise is smaller than the cluster. Indeed, the optical appearance of IC 133 is dominated by stars rather than ionized gas. Fourthly, although the H$_2$ emission peaks in IC 133 and NGC 604 are equally strong, the effective extent of the H$_2$ emission in IC 133 is much less than that in NGC 604. The higher extinction of IC 133 implies that a larger fraction of the total dust content is in front of it, in contrast to NGC 604. Although in this way a consistent picture emerges, we find it nevertheless puzzling that the gas and dust content of IC 133 should be so low especially in view of its age (estimated at $5 \times 10^8$ years by Humphreys & Sandage 1980). This object clearly deserves further study.

### 3.3 H$_2$ in other M 33-H II regions

We searched the second brightest H II region NGC 595 for H$_2$ emission in six positions. A seventh position was centred on the nearby small, but bright H II region 46 (Boulesteix et al. 1974). In this object, emission may be present at the detection level, as well as at two positions adjacent to the main ionization fronts of NGC 595 (Table 1). Note that the UV luminosity of NGC 595 is two-thirds of that of NGC 604, while its infrared and radio luminosities are a third of that of NGC 604 (Table 2). The integrated CO signal towards NGC 595 is three-quarters of that towards NGC 604. An upper limit to the integrated H$_2$ luminosity, over the same area as the radio continuum, is $L(H_2) < 3 \times 10^7 L_\odot$.

No H$_2$ was detected towards NGC 588, IC 132 and IC 142, although our aperture completely covered the radio emitting zones, and although IC 142 has been detected in CO (Israel & Stark, unpublished data). We note that for all regions are consistent with a ratio $L_{BR}/L(H_2) < 2.5 \times 10^{-3}$. Such a dependence of $L(H_2)$ on far-infrared luminosity could be expected for radiative excitation. Also, if the radio continuum emission of the H II regions searched is a measure for the number of exciting photons emitted by their exciting stars, the radio surface brightness $\sigma_R$ indicates the strength of the radiation field in these regions. The only detections occur at relatively high values $\sigma_R = 0.1$ mJy arcsec$^{-2}$ (NGC 604, IC 133). The other objects have lower values $\sigma_R = 0.05$ mJy arcsec$^{-2}$ (NGC 589, NGC 595) and $\sigma_R = 0.025$ mJy arcsec$^{-2}$ (IC 132, IC 142). Such a result is consistent with radiative excitation of H$_2$, but only for relatively high densities $n_H > 10^3$ cm$^{-3}$ (Black & van Dishoeck 1987).

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4 CONCLUSIONS

(i) The giant extragalactic H II region complex NGC 604 is associated with a large cloud of radiatively excited molecular hydrogen of dimensions 110 × 50 pc. This is comparable to the size of the largest giant molecular cloud complexes in the Galaxy.

(ii) This cloud has densities $n_{HI} = n(H) + 2n(H_2)$ in the range $300 < n_{HI} < 1700$ cm$^{-3}$. Both the H$_2$ observations and the virial theorem applied to CO observations suggest a molecular cloud mass of order $3 \times 10^6 M_\odot$. Hydrogen in the NGC 604 complex is distributed over the different phases roughly as $M(H II) : M(H I) : M(H_2)$ = 0.3 : 0.7 : 1.0.

(iii) The molecular mass of the NGC 604 cloud is about an order of magnitude larger than indicated by the modest CO emission integral. This illustrates that the use of galactic CO to H$_2$ conversions in other galaxies may lead to significant underestimates of total molecular masses, especially in low metallicity, UV-rich environments.

(iv) The apparent absence of shock-excited H$_2$ indicates relatively weak stellar winds for the stars exciting NGC 604, probably as a consequence of its low metallicity. It is unlikely that the dynamics and energetics of NGC 604 are dominated by expanding windblown shells. The observed velocity dispersion probably represents bulk motions in the gravitational field of the complex.

(v) Relatively bright H$_2$ emission was tentatively detected in only one out of nine apertures centred on IC 133. This nebula appears to be a young object with surprisingly little gas and dust. No emission was detected from NGC 588, IC 132 and IC 142.

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