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Starbursts in barred spiral galaxies

II. Molecular and optical study of three Wolf-Rayet galaxies*

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Abstract. We have searched for dense molecular gas in three barred spiral galaxies with young starbursts, NGC 3049, 5430 and 6764, which are known Wolf-Rayet galaxies. We detected HCN in the latter two, and CS was marginally detected in NGC 6764.

The dense molecular gas contents of the three galaxies are compared to those of other galaxies and to other indicators of star formation. The HCN luminosities (relative to the CO and far infrared ones) in these galaxies with very young starbursts are consistent with those observed in galaxies with older starbursts and in normal galaxies, and so are our upper limits to the CS intensities (relative to CO).

The starburst ages evaluated from our spectrophotometric observations are in the range 3.4 to 6.0 Myr. A circum-nuclear ring is apparent on our images of NGC 5430, the galaxy with the oldest central starburst; this galaxy also has the widest molecular lines. The central star formation rates derived from the Hα luminosity are consistent with those expected from the global FIR luminosities, and are correlated with the HCN luminosities.

Finally, an independent estimate of the H_2 column density is obtained by optical spectrophotometry; it leads to a H_2 column density to CO intensity ratio which is about 2 to 3 times lower than the standard value, because the CO intensities of the three galaxies are higher than average, relative to their far infrared fluxes.

Key words: galaxies: individual : NGC 3049; NGC 5430; NGC 6764 – galaxies: ISM – galaxies: starburst – radio lines: galaxies

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* Based on observations obtained at the 2 meter telescope of Observatoire du Pic du Midi, the 1.93 meter telescope of Observatoire de Haute-Provence, both operated by INSU (CNRS), and at the 30 meter radiotelescope on Pico Veleta, operated by IRAM.

1. Introduction

Despite numerous studies of starburst galaxies, many questions remain about the starburst phenomenon, its triggering and evolution. Gravitational interactions and mergers seem to play a major role in triggering starbursts, but violently interacting galaxies are not necessarily the seat of starbursts (Bushouse 1986) and most starbursts seem to be isolated (Contini 1996, Coziol et al. 1996b). Numerical simulations have shown that the bar plays a major role in this process, by efficiently funneling molecular clouds toward the inner few kiloparsecs of galaxies (Noguchi 1988, Friedli & Benz 1993). This is confirmed by radio continuum observations (e.g. Puxley et al. 1988). However, the link between bar and far infrared luminosity (which traces young massive stars) in starburst galaxies remains controversial (Hawarden et al. 1996).

Molecular clouds obviously play a crucial role in the process of star formation, and their properties have been extensively studied, via millimeter observations of the CO molecule. A strong far infrared (FIR) luminosity has generally been a successful criterion for detection of the molecule in external galaxies, confirming the link between the two indicators of star formation. A CO–$N(H_2)$ conversion factor has been proposed (Strong et al. 1988) and validated by observations of normal as well as starburst galaxies (e.g. Sage et al. 1990); further studies have shown that it depends on metallicity (Wilson 1995, Arimoto et al. 1996). But its validity has recently been questioned (e.g. Nakai & Kuno 1995).

It has recently been emphasized that CO only traces low-density molecular gas and several searches for dense ($n(H_2) > 10^4$ cm^{-3}) molecular clouds in normal and starburst galaxies, generally selected to be strong CO emitters, via detection of HCN, CS, HCO^+, and other molecules, have been initiated (e.g. Mauersberger et al. 1989, Nguyen-Q-Rieu et al. 1992, Helfer & Blitz 1993, Aalto et al. 1995). It turns out that bulges of normal as well as starburst galaxies contain large quantities of dense gas, and that a threshold in the surface density of dense gas

Table 1. Basic data and global parameters of the three galaxies. D is the distance, B_{tc} is the apparent corrected blue magnitude and i is the inclination. The logarithms of total HI mass, and of far infrared and blue total luminosities are given in the last three columns

Galaxy	Type	Coordinates (J2000) α	δ	D (Mpc)	B_{tc} (mag)	i (°)	M(HI) log($M_\odot$)	L_{FIR} log($L_\odot$)	L_B log($L_\odot$)
NGC 3049	SBb	$09^h54^m49\overset{s}{.}7$	$+09°16'19''$	19.6	12.97	50.6	9.10	9.31	9.57
NGC 5430	SBb	$14^h00^m45\overset{s}{.}7$	$+59°19'42''$	42.7	12.43	51.7	9.58	10.63	10.46
NGC 6764	SBbc	$19^h08^m16\overset{s}{.}7$	$+50°55'54''$	35.6	11.89	50.1	9.65	10.23	10.52

does not seem to be required for violent star formation (Helfer & Blitz 1993).

In view of these mixed results, we have adopted a global view on starbursts in galaxies, based on multi-wavelength observations of a large and homogeneous sample of barred starburst galaxies. Such an approach should enable us to establish quantitative relationships between the properties of starbursts (age, star formation rate and initial mass function), the neutral (atomic and molecular) gas content and the morphology of the host galaxies. It has in fact already given rise to new and original results (Contini et al. 1995, Contini 1996, Contini et al. 1997, Coziol et al. 1996a).

In this paper, we combine millimetric observations of the dense molecular gas with optical images and long-slit spectroscopy of a few examples of very young starbursts galaxies, namely Wolf-Rayet galaxies, in order to investigate the properties of the dense gas of these galaxies in relation to their optical properties. The images provide morphological and photometric information on the central regions and the bar, and the spectra are used to determine the starburst ages and star formation rates as well as an independent estimate of the column density of H_2. A preliminary report on this research project has been published by Contini et al. (1996).

2. The starburst phenomenon in Wolf-Rayet barred galaxies

Wolf-Rayet galaxies are characterized by the presence of a large (10^2 to 10^3) number of Wolf-Rayet stars, which can only be explained by a very recent starburst episode, between 3 and 6 Myr old (Vacca & Conti 1992, Maeder & Meynet 1994), and probably with a nearly flat initial mass function (Contini et al. 1995). A large number of very massive ($M > 30 M_\odot$) OB stars, which are the progenitors of Wolf-Rayet stars, are likely to form under rather unusual circumstances; one might thus expect the interstellar medium of this type of galaxies to be different from those of galaxies with older and/or more moderate starbursts.

We selected our sample from the catalogue of Conti (1991). In order to optimize detection of the molecular lines, we chose three barred galaxies with a low redshift and a large far infrared flux, NGC 3049, 5430 and 6764. Fundamental parameters for the three galaxies, derived from the Lyon Meudon Extragalactic database (LEDA), are presented in Table 1.

Wolf-Rayet galaxies do not form a homogeneous class of galaxies, and span a wide range in luminosity, size and morphological type; in this respect, the three selected galaxies do show differences. NGC 5430 and 6764 are giant galaxies, whereas NGC 3049 is of low luminosity. The starburst of NGC 6764 occurs in the center of the galaxy, but the Wolf-Rayet regions of NGC 3049 and 5430 are extranuclear, the former is 2.5″ South-West of the nucleus along the bar, the latter at the South-Eastern end of the bar (12″ East and 18″ South of the nucleus). The two latter galaxies are also Markarian galaxies (Mkn 710 and 799 respectively). One property shared by all three galaxies (and by most known Wolf-Rayet barred spiral galaxies; Contini et al. 1995) is their high inclination.

3. Observations and data reduction

The radio observations were obtained at the IRAM 30 meter radiotelescope on November 27 and 28, 1994. We observed in single sideband at three frequencies simultaneously, CO(2→1) at 230.5 GHz with the 1.3mm (230G1) SIS receiver, CS(3→2) at 147.0 GHz with the 2mm receiver, and HCN(1→0) at 88.6 GHz with the 3mm SIS receiver. Upper sideband rejection was 10 to 15, 7 to 9 and 30 dB for CO, CS and HCN respectively. As backends, we used an autocorrelator for CO and filter banks of 512 1-MHz channels for the two other lines. The beamwidth of the 30 meter antenna is 27, 16 and 11″ and the main beam efficiency 0.75, 0.52 and 0.39 in order of increasing frequency (Kramer & Wild 1994). The weather was remarkably good during the run, with average zenith opacities of 0.08 at 88 and 147 GHz and 0.17 at 230 GHz. The average system temperatures were 220, 320 and 400 K in order of increasing frequency. The observations were made in wobbler mode with a throw of 2 to 4 arcmin. Pointing was done on quasars every 2 or 3 hours and found to be stable; focus was done on planets near sunrise and sunset. On-off integration times were about 3.5 hours for NGC 3049 and the Wolf-Rayet region of NGC 5430, and over 5 hours for the centers of NGC 5430 and 6764.

We checked the calibration of the CO brightness temperatures of NGC 5430 and 6764 by observing the source IRC+10216. For NGC 3049, we observed W51E1, but the predicted lines were not seen (presumably because the catalogued lines arose in the USB at the time the catalogue was done), and the calibration could not be tested; the brightness temperatures and derived integrated intensities are thus uncertain by about 30%. It was not necessary to calibrate the HCN brightness tem-

Table 2. Heliocentric radial velocities (V), line widths (FWHM) and integrated intensities (I) of the molecular lines and HI data

Galaxy	CO(2 → 1)			HCN(1 → 0)			CS(3 → 2)	HI	
	V (km s^{-1})	FWHM (km s^{-1})	I_{CO} (K km s^{-1})	V (km s^{-1})	FWHM (km s^{-1})	I_{HCN} (K km s^{-1})	I_{CS} (K km s^{-1})	V (km s^{-1})	FWHM (km s^{-1})
NGC 3049	1500±1	73±3	9.2±0.3			<0.3	<3.2	1494	199
NGC 5430	2981±1	389±3	81.6±0.5	2985±17	248±29	1.4±0.2	<2.5	2965	313
(NW)	2893±1	141±2	38.4±0.5						
(SE)	3069±1	131±2	43.2±0.5						
WR region	3074±3	97±5	6.1±0.5			<0.5	<0.9		
NGC 6764	2431±1	148±2	25.6±0.5	2422±11	139±25	0.8±0.2	(1.0)	2416	276

peratures, since USB rejection was good at the corresponding frequency. The observations were reduced with CLASS.

CCD images of the three galaxies were obtained during two runs at the 2 meter telescope of Observatoire du Pic du Midi, with a 1000×1000 Thomson CCD (pixel size 0.20″ on the sky). Images of NGC 3049 and 5430 were obtained in January of 1992, with respective exposure times 20 and 30 min. in V and 15 and 20 min. in R. Images of NGC 6764 were obtained in August of 1992, with exposure times 40 min. in B and 20 min. in V.

The calibration of the zero point of the magnitude scale was done by indirect procedures. The photometric constants in V were obtained by the measure of stars from the Guide star Catalogue (GSC) or using published aperture photometry (Longo & de Vaucouleurs 1983). For NGC 5430, we fitted our R surface brightness profile to the r-Gunn profile of Kent (1985), taking into account the color equations between Johnson and Gunn's photometric systems. We also verified that the total magnitude of each galaxy agreed reasonably well with published values. The accuracy of the zero point is thus 0.1 mag.

The spectroscopic observations were obtained in January 1992 and June 1996 at the 1.93 meter telescope of Observatoire de Haute-Provence, with the Carelec spectrograph (Lemaître et al. 1990), at a spectral resolution of 260Å/mm. During the first run, we took one 30 min. spectrum of NGC 3049 along the major axis. The slit width was 2.2″. For flux calibration, we observed the standard stars GD 140 (Massey et al. 1988) and BD +26 2606 (Oke & Gunn 1983). In the second run, we took six 25 min. spectra of NGC 5430 and 2 of NGC 6764. The slit width was 2.8″, and the standard star for flux calibration was HD 192281. The spectra were reduced with MIDAS.

4. Results

4.1. Molecular line profiles

The molecular line profiles are presented in Fig. 1. HCN was detected in the centers of NGC 5430 and 6764, but not in the Wolf-Rayet region of NGC 5430, nor in NGC 3049. CS was marginally detected in the center of NGC 6764 only. The heliocentric radial velocities, line widths and integrated intensities in each line of the three galaxies were estimated by fitting gaussians or saddle-shapes to the profiles; they are summarized in Table 2, where the HI velocities and linewidths are also given for comparison. The integrated intensity in each line is $I = \int T_{\rm mb} dv$, where $T_{\rm mb}$ is the main-beam temperature. The quoted uncertainties on the integrated intensities are internal and do not take into account pointing and calibration inaccuracies. For undetected lines, we give a 2σ upper limit of the integrated intensity. The integrated intensities must be multiplied by 4.89, 4.73 and 4.77 (at 88, 147 and 230 GHz respectively) in order to be converted to Jy km s^{-1}. Since NGC 5430 and 6764 are fairly distant compared to most galaxies where HCN has been detected, the HCN integrated intensities given in this paper are among the lowest ever reported.

Our detection of CO in NGC 3049 is the first one reported for this galaxy. The CO line profile of NGC 3049 is in fact not perfectly gaussian; it shows an excess of gas at higher velocities. It is presumably due to the bright HII region centered 8″ to the North-East.

The central CO(2→1) profile of NGC 5430 has previously been observed by Krügel et al. (1990), with the same instrument; the profile and integrated intensity are in good agreement with ours. They also observed the CO(1→0) and ^{13}CO(1→0) lines in the center of this galaxy. In the center of NGC 5430, the CO line profile is double peaked. This is the typical signature of a gaseous disk or ring. Such a structure is very likely associated with the nuclear hot-spots seen in our V–R color map (Fig. 2).

In the Wolf-Rayet region of NGC 5430, CO has a mean velocity of 3074 km s^{-1}, which means that the South-East is receding, and that the near side of the galaxy is the Eastern side. The fact that this region, which is 19.3″ from the center, has the same mean velocity ($\simeq$ 3070 km s^{-1}) as the high velocity peak of the central profile indicates that most of the bar is in the differentially rotating part of the galaxy.

The high-velocity peak of CO is larger than the low-velocity one. The HI profile (Roth et al. 1991) of this galaxy is also asymmetric, but the highest peak is at the other end of the profile; there appears to be less neutral hydrogen where there is more CO, on the SE side of the galaxy, where the HII region with Wolf-Rayet emission lies. Another surprising related fact is that

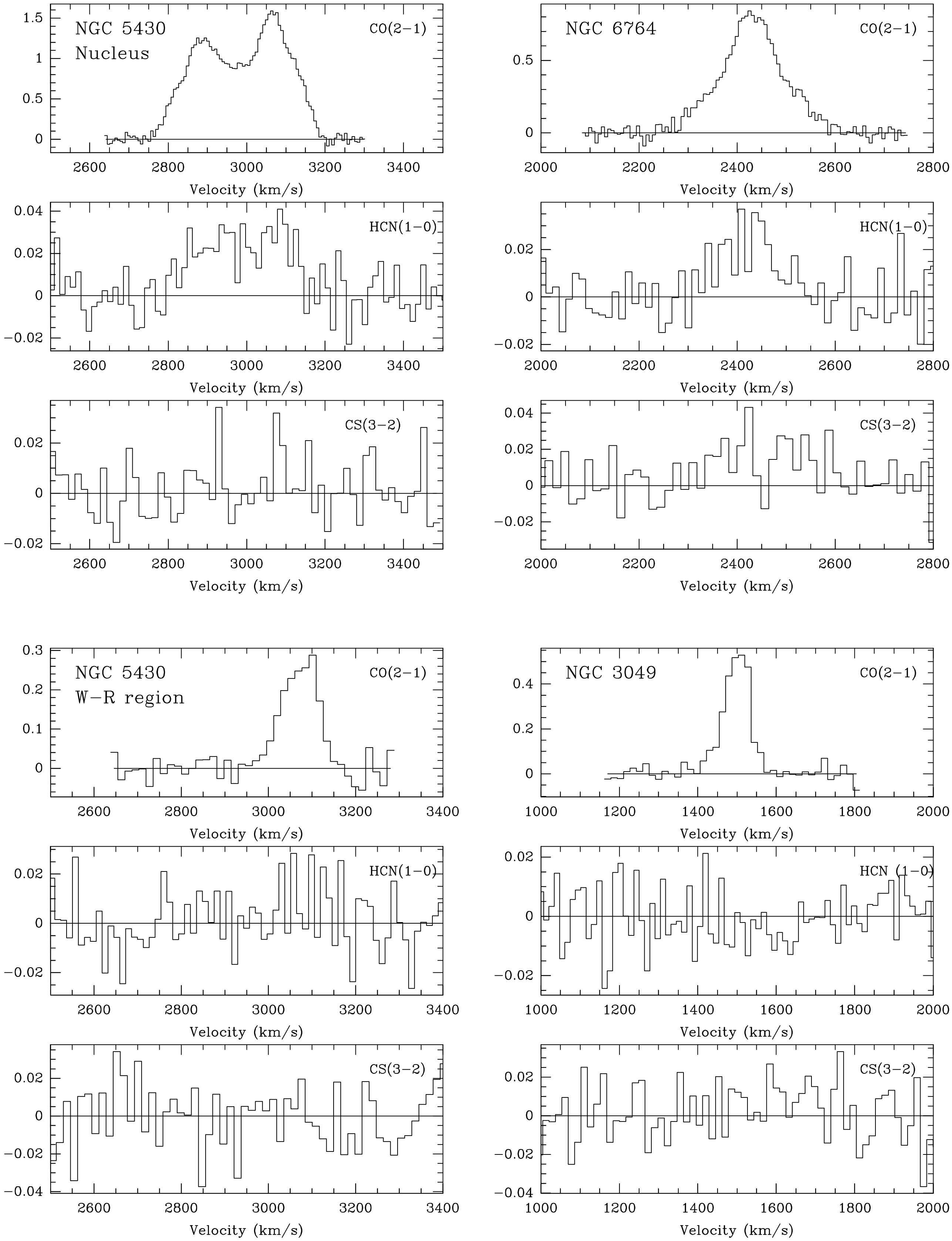

Fig. 1. Molecular line profiles (in Jy) of the three lines in the three galaxies. Top left: center of NGC 5430, bottom left: WR region of NGC 5430, top right: NGC 6764, bottom right: NGC 3049. For each galaxy, we present from top to bottom the CO(2→1), HCN(1→0) and CS(3→2) profiles

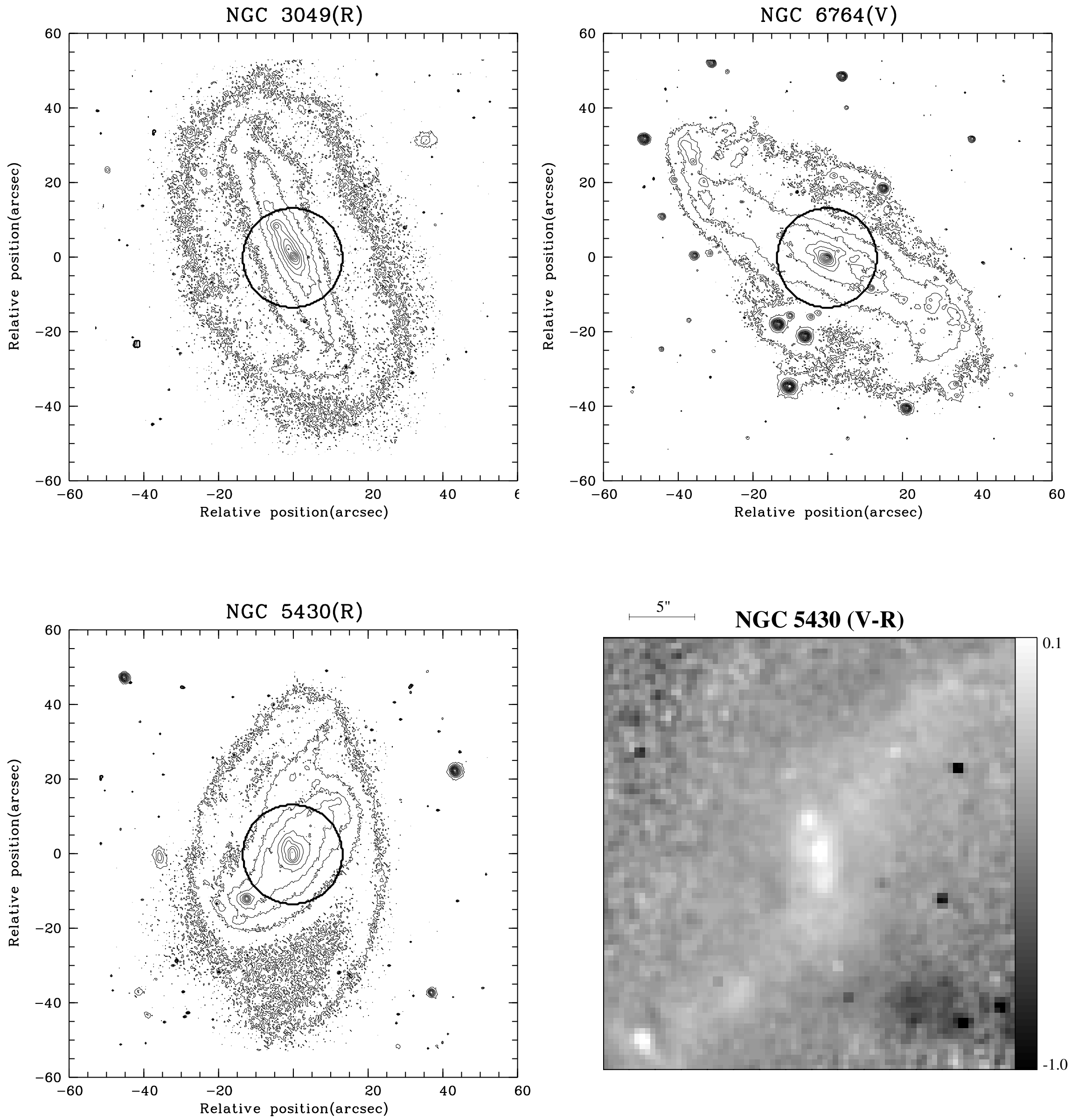

Fig. 2. Isophote maps for the R band of NGC 3049 and NGC 5430 and the V band of NGC 6764. The spacing of the isocontours is 0.5 mag. The faintest isophote levels are 22, 21 and 22.5 mag arcsec^{-2} respectively. The size of the HPBW at 87 MHz is indicated by a circle. The lower right panel shows the V–R color map of the innermost region of NGC 5430. On this map, the lower left bright spot is the Wolf-Rayet region. North is up and East to the left

the FWHM of the CO line is *larger* than that of the HI line (389 vs 313 km s^{-1}), because high velocity HI is definitely lacking.

The central CO(2→1) profile of NGC 6764 has been published by Eckart et al. (1991), also using the IRAM 30 meter antenna; they find a rather high integrated intensity of 35 K km s^{-1} compared to ours, perhaps because they used a slightly different position. The CO profile of this galaxy is similar to that of NGC 3049, and indicates that the molecular gas is in solid-body rotation in the central 11″ of this galaxy as well. CO(1→0) also appears to have a constant velocity gradient across the bar (Eckart et al. 1991), in agreement with the results of Rubin et al. (1975) for the ionized gas [1].

4.2. Optical properties

The geometrical and photometric properties of the three galaxies were obtained by fitting ellipses to the isophotes of the CCD images in the two bands, using a method described in Wozniak

[1] in that paper, East and West must be interchanged (Rubin, private communication).

et al. (1995), and analyzing the resulting surface brightness and ellipticity profiles.

NGC 3049 has a very thin bar ($b/a \sim 0.18$), of constant surface brightness, and a small bulge. The apparently elongated nucleus ($r < 10''$) shows isophotes which are twisted by the HII region close to the nucleus. The separation between the nucleus and this spot is 2.5″. There is a bright spot of star formation in the North-East (labeled "b" by Mazzarella & Boroson 1993). An inner ring surrounds the bar.

NGC 5430 displays an elongated nucleus. This shape is due to at least two bright spots on a circumnuclear ring. This ring is clearly visible on the V–R color map (Fig. 2). Its semi-major axis is 3.5″. The V–R colors of the nucleus and the spots are respectively ~ 0.2 and ~ 0 to -0.1 while in the bar outside the dust lanes it is ~ -0.3. The Wolf-Rayet region has almost the same color as the nucleus (V–R ~ 0.25). The bar does not have a constant surface brightness, contrary to those of the two other galaxies. There is also a 3-armed spiral structure, the southern arm being more elongated than the opposite one.

NGC 6764 has a thin bar of roughly constant surface brightness and a small bulge, like NGC 3049. The ellipticity of the bar increases outward to a maximum of 0.8, but its position angle remains constant.

4.3. Star formation rate and age of the starbursts

We used long-slit spectra to estimate the spectrophometric properties of six starburst regions located in our three Wolf-Rayet galaxies. For each starburst we measured the reddening coefficient $C_{\mathrm{H}\beta}$, the absolute dereddened Hα intensity $I(\mathrm{H}\alpha)$, the Hβ equivalent width W(Hβ), and the oxygen abundance, O/H, which is a metallicity indicator. The procedure for analyzing our low-dispersion spectra is described in Contini (1996) and Contini et al. (1995). The results are given in Table 3.

The Hα luminosity $L(\mathrm{H}\alpha)$ can be used to estimate the star formation rate (Kennicutt 1983), because it is directly proportional to the number of ionizing photons produced by massive and hot OB type stars (Osterbrock 1989). The predicted central star formation rates are 0.7, 8.4 and 3.7 $M_\odot$ yr^{-1} for NGC 3049 (including the NE and SW knots), NGC 5430 and NGC 6764 respectively, to be compared with the mean value of 4 $M_\odot$ yr^{-1} for the *total* star formation rate in normal Sb-Sbc galaxies (Kennicutt 1983).

In starburst galaxies, the integrated FIR luminosity L_{FIR} is mostly due to dust heated by UV radiations from young stars, rather than by absorption of visible radiation from older stars in the disk. It can thus also be used to estimate the star formation rate, and good correlations have been found between $L(\mathrm{H}\alpha)$ and L_{FIR} for samples of IRAS galaxies (Devereux & Young 1991, Sauvage & Thuan 1992, Coziol 1996). In a sample of 79 barred starburst galaxies, Contini (1996) found a nearly linear relation between $L(\mathrm{H}\alpha)$ in the center of the galaxies and their global L_{FIR} with $L(\mathrm{H}\alpha) \propto L_{\mathrm{FIR}}{}^{0.92}$. Our three Wolf-Rayet galaxies follow this relation quite closely, given the uncertainties on the absolute intensities. This means that, although the central star formation rates of our three galaxies are high compared to those in normal spirals, they are average compared to those of other barred starburst galaxies.

Table 3. Spectrophotometric data and derived starburst ages in the 3 galaxies. $I(\mathrm{H}\alpha)$ is in 10^{-14} erg s^{-1} cm^{-2}.

NGC	Region	(″)	$I(\mathrm{H}\alpha)$	W(Hβ) (Å)	$C_{\mathrm{H}\beta}$ (mag)	O/H (⊙)	age (Myr)
3049	NE	8.0	12	–16	0.74	1.7	5.6
	C	0.0	20	–29	0.32	1.2	4.7
	SW	2.5	30	–38	0.23	1.3	3.4
5430	C	0.0	103	–5	1.63	1.3	6.0
	SE	22.0	37	–41	0.56	1.2	4.0
6764	C	0.0	75	–21	0.87	0.8	5.2

There has been some confusion in the literature about the nature of the nuclear activity of NGC 6764 (see Contini et al. 1996 for the various classifications). Our new spectra clearly show that the center as well as the circum-nuclear region are the seat of LINER activity.

We estimated the ages of the starbursts by comparing our spectrophotometric data with predictions of the evolutionary synthesis model of Cerviño & Mas-Hesse (1994). A good accuracy ($\pm$ 0.5 Myr) is obtained by using W(Hβ), for a given value of O/H.

In NGC 3049, the starburst age increases from 3.4 Myr in the Wolf-Rayet region (SW) to 5.6 Myr in the most distant (NE) of the bright HII regions along the bar. The metallicity is roughly constant along the bar, and the internal extinction is more important along the bar than in the nucleus, presumably because of dust. NGC 5430 also experienced two starbursts in the recent past, one in the Wolf-Rayet region at the end of the bar (SE), 4 Myr ago, and one in the nucleus (C), about 6 Myr ago (with a larger uncertainty of about 1 Myr, due to the uncertainty on the metallicity). Finally, the age of the starburst in the nucleus of NGC 6764 is 5.2 Myr. The derived ages in the starbursts of the three Wolf-Rayet galaxies are listed in Table 3.

5. Dense molecular gas contents in Wolf-Rayet galaxies

We detected HCN(1→0) in the center of NGC 5430 and of NGC 6764, but not in NGC 3049, and CS(3→2), although marginally, in NGC 6764 only. In order to evaluate quantitatively whether these galaxies, which have unusually young starbursts, are also unusual in their dense molecular gas contents, we compare our measurements with those published for other surveys of HCN and CS in external galaxies.

In the following discussion, we make the simplifying assumption that the luminosity of these lines is a measure of the mass of dense ($n(H_2) > 10^4$ cm^{-3}) gas. Although this assumption is debatable (Aalto et al. 1995), it is generally adopted in most studies of this kind, implicitly, or explicitly by a model (e.g. Solomon et al. 1990).

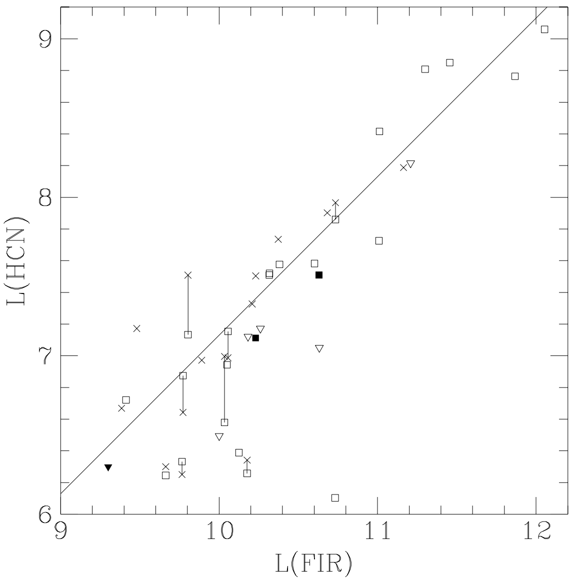

Fig. 3. HCN luminosity (in K km s^{-1} pc^2) vs far-infrared luminosity (in $L_\odot$). Filled squares: NGC 5430 and 6764; filled triangle: NGC 3049 (upper limit in HCN); open squares and crosses: high resolution (26″ HPBW) and low resolution (56 to 63″ HPBW) data from the literature; open triangles: upper limits (in HCN luminosity) from the literature. Data for the same galaxy observed in both modes are linked by a vertical line

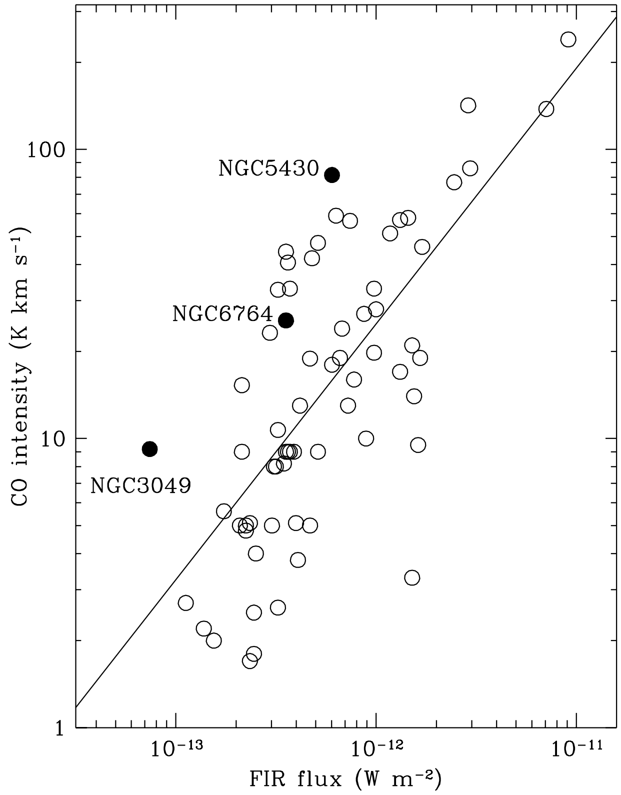

Fig. 4. CO intensity (in K km s^{-1}) vs far-infrared flux (in W m^{-2}). Filled circles: NGC 3049, 5430 and 6764; open circles : comparison samples of Braine & Combes (1992) and Contini et al. (1997). The diagonal line is a least-squares fit to the data of the comparison samples

5.1. $L_{\rm HCN}$ *vs* $L_{\rm FIR}$

We first compare the HCN luminosity of the galaxies with their total far infrared luminosity, $L_{\rm FIR}$. In other words, we compare the mass of dense gas from which stars are born to the number of recently formed stars.

To this end, we use the HCN surveys of Nguyen-Q-Rieu et al. (1992), Helfer & Blitz (1993), and Solomon et al. (1992), and HCN observations of individual galaxies, NGC 4945 by Henkel et al. (1994), and NGC 3256 by Casoli et al. (1992). The comparison with our results is given in Fig. 3, which shows the dependence of the HCN luminosity on total far-infrared luminosity. The comparison samples are divided into two categories, high resolution (26″ to 28″ HPBW) and low resolution (56″ to 63″ HPBW) observations. The extranuclear Wolf-Rayet region of NGC 5430 is not plotted because the comparison samples only concern central regions of galaxies.

The diagonal line is a linear fit (with slope unity) to the data in the region where there indeed seems to be a correlation ($L_{\rm FIR} > 10^{10.2}$ $L_\odot$). As no marked differences between the two comparison samples appear on this diagram, at least above the quoted limit, we assume that all the HCN emission is unresolved, even by the smaller beam. All the nearby galaxies (NGC 253, M33, M82), are below this limit, and some of them are probably resolved.

This correlation should be viewed with caution, as it might reveal more about the way the sample was selected (and about the Malmquist bias) than about physical properties of the galaxies. It can nevertheless be used to compare the *relative* behavior of the different galaxies. Our two detected galaxies are just below the diagonal line, and so is the upper limit derived for NGC 3049. This means that *the HCN luminosities of our galaxies with young starbursts are not unusually high*, and that NGC 3049 was not detected because it is probably just below the detection capabilities of the instrument; the noise on the HCN spectrum of NGC 3049 in Fig. 1 is at a level of $T_{\rm mb}$ = 2mK.

5.2. $I_{\rm HCN}$ *vs* $I_{\rm CO}$

Another way of testing whether the dense molecular gas content of our galaxies is unusual is to measure the intensity ratio of HCN to CO, which provides an estimate of the molecular gas density. We compare the values of this ratio in our galaxies with those in the sample of galaxies with unremarkable nuclear properties of Helfer & Blitz (1993). We cannot use our CO(2→1) observations to this end, since the corresponding beam is much smaller than that of HCN. Instead, we use the CO(1→0) observations of Krügel et al. (1990) for NGC 5430 ($I_{\rm CO}$ = 49.8 K km s^{-1}) and of Eckart et al. (1991) for NGC 6764 ($I_{\rm CO}$ = 25 K km s^{-1}). The latter should be taken with caution, since we disagree with their measure of CO(2→1) in the same galaxy.

The ratios I_{HCN}/I_{CO} are 0.028 and 0.032 for NGC 5430 and NGC 6764 respectively. This is significantly (at least 3σ) below the mean value of 0.078 for other IRAM observations of bulges of galaxies (see Table 3 of Helfer & Blitz 1993). These ratios are in fact much closer to the value of 0.026 found in the disk of our own Galaxy (Helfer & Blitz 1997) or that of 0.03 to 0.06 in the disk of M51 (Kohno et al. 1996).

However, Helfer & Blitz (1993) noticed that the HCN–CO line ratio depends on the beam size, and is smaller for a larger beam. One could thus raise the objection that the HCN–CO ratio for a given beamwidth is distance dependent, if HCN is probably more centrally concentrated than CO, and that our ratios are underestimated, since our galaxies are fairly distant.

But the velocity widths of HCN and CO are the same in NGC 6764, indicating a comparable spatial extent of both molecules. HCN should thus perhaps be viewed as distributed in a dense core *and* in a diffuse disk; this is the case for M51 (Kohno et al. 1996), NGC 1068 (Helfer & Blitz 1995) and NGC 6946 (Helfer & Blitz 1997). Furthermore, our beam ($27''$) is rather small compared to that of smaller antennas (56 to $63''$) used in some HCN surveys, and the distance effect, if any, should appear at larger distances than those of our galaxies. We thus do not think that our two line ratios are underestimated, and we confirm that the HCN to CO line intensity ratios of the two galaxies are rather low compared to those of other galaxies observed with the same instrument.

The non detection of HCN in the Wolf-Rayet region of NGC 5430 can be explained if, disregarding the different beamwidths for the two molecules, one assumes that the HCN intensity ratio between the center and the Wolf-Rayet region is the same as the CO intensity ratio. For the latter, we found a value of 13.

5.3. I_{CO} *vs FIR flux*

We found above that the HCN to CO intensity ratio of our galaxies is well below average. This suggests that their CO intensity must be unusually high, since their HCN luminosity is normal. To check this possibility, we compare the CO intensities (relative to the FIR emission) of our galaxies with those of two other samples. The CO(1→0) integrated intensities of our galaxies are plotted vs their FIR flux on Fig 4, together with those of 52 galaxies of Braine & Combes (1992; see their Fig. 5a) and of 24 young starburst galaxies observed by Contini et al. (1997). On this figure, our three galaxies occupy the upper boundary; they indeed have a higher CO(1→0) intensity than average (by a factor 2.5 to 4) for their FIR flux. We have verified that the same is true for the CO(2→1) intensities.

5.4. I_{CS} *vs* I_{HCN} *and* I_{CO}

We now turn to the contents of CS in our galaxies. Helfer & Blitz (1993) find a ratio of 2.4 between the integrated intensities of HCN(1→0) and CS(2→1) in their sample. A ratio of that order is consistent with the marginal detection in NGC 6764, and with the non detection in NGC 5430. Intensity ratios of CS(2→1) to CO(1→0) of 0.03–0.06 have been quoted in the literature (Sage et al. 1990, Helfer & Blitz 1993). Using once more CO(1→0) intensities from the literature, and assuming that CS(3→2)/CS(2→1) is close to unity, we again find that our results are consistent with expectations. One should keep in mind that these are order of magnitude estimates only, since our detection of CS in NGC 6764 is marginal.

Table 4. Column density of H_2 and CO–$N(H_2)$ conversion factors (in units of 10^{20} cm^{-2} (K km s^{-1})$^{-1}$)

NGC	$C_{H\beta}$ (mag)	A_V (mag)	$N(H_2)$ 10^{20}cm^{-2}	α/α_{gal}	$N(H_2)/I_{CO}$ obs.	stand.
3049	0.32	0.68	10.6	0.78	1.00	2.3
5430	1.63	3.48	50.1	0.81	1.00	2.4
6764	0.87	1.88	43.5	1.03	1.73	3.1

6. The column density of H_2 and the CO–$N(H_2)$ conversion factor

We take advantage of the fact that molecular and optical spectroscopy are available for our galaxies to compare two methods for estimating the CO–$N(H_2)$ conversion factor, a quantity of major importance for estimating the amount of hydrogen in molecular form in galaxies.

In the extinction method, one takes the ratio of two quantities directly related to the galaxy. The average column density of H_2 between us and the center of a galaxy with metallicity Z (in units of $Z_\odot$) can be derived from (Bohlin et al. 1978):

$$N(H_2) = 9.35 \times 10^{20}\ A_V\ Z^{-1} (\mathrm{cm^{-2} mag^{-1}}) \quad (1)$$

assuming a standard ratio of total to selective absorption of 3.1, that the column density of atomic hydrogen is negligible in the center of the galaxy, and that the amount of dust, and thus of extinction, increases with metallicity (Mauersberger et al. 1996, their Appendix B). The column density averaged over the entire extent of the bulge will be $2N(H_2)$.

A_V, the total extinction in V (in magnitudes), is computed from $C_{H\beta}$ and the following relation (Miller & Mathews 1972):

$$A_V = 2.5\, C_{H\beta}\, \frac{\delta m_V}{\delta m_\beta} = 2.136\, C_{H\beta}. \quad (2)$$

Finally, $C_{H\beta}$ and (O/H) (as metallicity indicator) are given in Table 3 for many star formation regions of the three Wolf-Rayet galaxies. Mean values over the central region are adopted.

The results are presented in Table 4, where $N(H_2)$ is derived from the total extinction in V, α/α_{gal} is the correction factor for metallicity (Wilson 1995, Arimoto et al. 1996) and $N(H_2)/I_{CO}$ is the conversion factor. The "observed" value of the conversion factor was derived by the extinction method, from $N(H_2)$ and I_{CO} estimated in each galaxy, assuming a standard intensity ratio CO(2→1)/CO(1→0) of 0.87 (Braine & Combes 1992) for optically thick gas in NGC 3049, and using the CO(1→0) intensities given in Sect. 5.2 for the two other galaxies. The "standard" value (predicted by the γ-ray method and assuming virial equilibrium) is the one of Strong et al. (1988), multiplied by $\alpha/\alpha_{\rm gal}$ to correct for metallicity effects in the galaxy (Wilson 1995, Arimoto et al. 1996). The conversion factor predicted by the extinction method is between 2 and 3 times smaller than that predicted by the γ-ray method.

7. Discussion

We have searched for dense molecular gas in three galaxies, NGC 3049, 5430 and 6764, which share the following common properties. They are the sites of very young ($\simeq$ 5 Myr) starbursts, as evidenced by the presence of Wolf-Rayet stars and by our age determinations, they have a large far-infrared flux, they are barred and highly inclined.

HCN has been detected in NGC 5430 and 6764, CS in the latter galaxy only. The HCN/FIR luminosity ratios of the two galaxies appear to be normal, confirming the trend noticed by Helfer & Blitz (1993) for normal and starburst galaxies. The upper limit to that ratio for NGC 3049 is also consistent with that trend. The measured intensities of CS or upper limits are also normal relative to that of CO and HCN in the same galaxies, when compared to other surveys of CS in external galaxies. If large amounts of dense molecular gas are required for star formation in burst mode, they no longer exist 5 Myr after the burst has started, presumably because they have been used up to form stars and/or ionized by the intense radiation emanating from massive hot stars.

We also find that the HCN/CO integrated intensity ratios are rather low relative to the mean value found in other surveys of HCN in external galaxies. This is due to the fact that our three galaxies have an unusually high CO integrated intensity relative to their FIR flux, compared to other galaxies, *including ones with young starbursts*. In other words, this higher than usual CO intensity is not a general property of galaxies with young starbursts.

The standard CO–$N(H_2)$ conversion factor overestimates the amount of molecular hydrogen by a factor 2 or 3 in our three Wolf-Rayet galaxies. But again, our galaxies have unusual CO intensities. This standard factor is thus probably valid for starburst galaxies in a statistical way, with a large uncertainty for individual estimates.

Can the optical properties of our galaxies provide an explanation for their molecular line properties? The *central* star formation rates in the three galaxies, estimated by the luminosity of the Hα line, are not unusual among starburst galaxies, because they are all proportional (with the right factor) to the *global* star formation rates estimated by the FIR luminosities. The FIR luminosity and that of Hα in the center are highest in NGC 5430 and lowest in NGC 3049, reflecting the pecking order for the luminosities in the molecular lines. This is another confirmation that the latter are not unusual in very young starbursts.

We note that NGC 5430, the galaxy with the oldest starburst, also has a circum-nuclear ring. Its presence is consistent with the fact that most of the bar is in differential rotation (Sect. 4.1), as such rings form where the rotation becomes differential (Lesch et al. 1990). The timescale of ring formation (a few 10^8 yr) is much larger than the age of the central starburst (6.0 Myr) of NGC 5430, and of the young star clusters (some less than 10 Myr) recently detected in other circum-nuclear rings by the *Hubble Space Telescope* (Maoz et al. 1996). The absence of such a structure in NGC 3049 and 6764 should thus not be attributed to the fact that their central starbursts are younger, but to dynamical properties, as their bars appear to be rigidly rotating.

One interesting property of NGC 5430 revealed in the present paper which deserves to be explored further is the fact that the CO and HI velocity profiles are asymmetric in opposite ways; there is relatively less HI where there is more CO. One possible reason for this asymmetry is a more efficient conversion of HI to H_2 in the Wolf-Rayet region which may explain the existence of the young starburst at that end of the bar. A detailed comparison of the relative distributions of HI and CO in starburst galaxies would certainly lead to a better understanding of the transformation of the gas before and during starbursts.

Finally, we point out that the linewidths of the CO lines are correlated to the central starburst ages of the three galaxies. This is a general property of young starbursts, which has been discovered by us (Contini et al. 1997).

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