H I in nearby low-luminosity QSO host galaxies

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ABSTRACT

We searched for 21 cm H I emission in a sample of 27 previously CO detected nearby galaxies hosting low-luminosity quasi-stellar objects (QSOs). In this paper we investigate the relationship between the H I and infrared properties of these host galaxies, compare the atomic and molecular gas content and look for connections to the optical and FIR properties. The single dish observations have been made with the Effelsberg 100-m telescope with a beam size of 9.5'. The sample objects have been drawn from a wide-angle survey for optically bright QSOs (HES), which have declinations $\delta > -30^\circ$ and redshifts up to $z = 0.06$. 12 host galaxies from the sample have been detected in the H I 21 cm emission line. Eight of them have a spiral geometry, whereas the other four are bulge dominated and probably of elliptical type (E/S0). Three of the objects seem to be in a phase of merging/interaction. The neutral atomic gas masses range from $1.1 \times 10^9 M_\odot$ up to $3.8 \times 10^{10} M_\odot$. The median H I gas mass in the whole sample is of the order of $11.4 \times 10^9 M_\odot$, which is a factor of two higher than the H I content of our galaxy. We find no strong correlation between H I mass and IR luminosity. The objects agree well within the expectations from the Tully-Fisher relation. In the color-color diagram we find all sources in the estimated locations. With the non-detected sources we clearly sample an upper envelope of this mass distribution.

Key words. galaxies: active – radio lines: galaxies – galaxies: nuclei – galaxies: Seyfert

1. Introduction

Molecular gas is the fuel for any activity process, whether it is in the form of vigorous bursts of star formation or an intensively accreting super massive central black hole (active galactic nuclei, AGN). The study of its morphology and kinematics is of key importance to understand the fueling mechanisms that keep the activity alive over cosmologically significant time scales. As important as studying the ongoing activity processes is studying the trigger that leads to it in the first place. It is assumed that galaxy interaction thereby plays a dominant role, initializing the transport of gas from the outer parts of the involved galaxies into their centers and so igniting the starburst and/or AGN activity. Sanders et al. (1988) already suggested early on that there might be even an evolutionary sequence between the onset of starburst and AGN activity with starbursts as precursors for AGN. This hypothesis is mainly based on the remarkable resemblance between luminous starburst galaxies (so called ultra-luminous-infrared-galaxies, or ULIRGs) and galaxies with a pronounced AGN signature (so called QSO host galaxies), such as their enormous amounts of molecular gas. However, while ULIRGs often exhibit significant signs of galaxy interaction, this is not necessarily true for QSO host galaxies. In fact, optical studies on QSO host galaxies (e.g., Bahcall et al. 1997; Boyce et al. 1998) find the majority to be rather morphologically normal without any clear signs of a past or ongoing interaction, though ~50% of their sample live with (projected) nearby companions. Much effort has been invested in studying the molecular gas emission in QSO host galaxies (e.g., Scoville et al. 2003; Krips et al. 2006a,b; Bertram et al. 2007). Atomic hydrogen, on the other hand, tracing the cold atomic molecular gas, may be a much better indicator for galaxy interaction. Only little is known so far on the atomic gas content in QSO host galaxies. Lim & Ho (1999),

Lim et al. (2001) and Ho et al. (2008a,b) present one of the first studies of H I emission in nearby QSO host galaxies. They find that while most of their observed sources show signs of a past or ongoing tidal interaction, they do not yet physically merge with another galaxy. This is in contrast to the proposed sequence by Sanders et al. (1988) in which QSOs are thought to be the merging or merged descendants of ULIRGs. In this paper we present the study of neutral atomic hydrogen in 27 nearby low-luminosity quasi-stellar objects. The observations are part of an ongoing project aimed at enhancing the statistics on nearby QSOs.

In Sect. 2 we describe the sample selection, Sect. 3 reports on the observations and data reduction. The results of the observations and the conclusions/discussion follow in Sects. 4 and 5.

Unless otherwise stated, $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ are assumed throughout the paper.

2. The sample

We have selected a volume limited sample of sources. As the sole selection criterion an upper redshift limit of $z < 0.06$ was applied. This value has been set to ensure the observability of the important diagnostic CO (2–0) rotation vibrational band head absorption line in the *K*-band. The sources have been selected from the Hamburg/ESO survey of optically bright QSOs (HES; Wisotzki et al. 2000). These 27 sources, with a declination $\delta > -30^\circ$ (by means of the observability from the Effelsberg 100-m telescope), have been searched for CO emission with the IRAM 30 m telescope on Pico Veleta (Spain) and SEST (Swedish ESO-Submillimeter Telescope) in La Silla (Chile). 27 objects (Table 1) were detected in $^{12}\text{CO}(1-0)$ and $^{12}\text{CO}(2-1)$ (see Bertram et al. 2007). They feature recession velocities in the range $2500 \text{ km s}^{-1} < v < 18\,000 \text{ km s}^{-1}$. Bertram et al. (2007) confirmed that the majority of galaxies hosting

Table 1. List of sources observed at 21 cm.

Object	RA(2000)	Dec(2000)	Seyfert ^a	Morphological ^b	v_0 (LSR)	z	D_L	$t_{\text{obs, on}}^c$	Cali- ^d	Resolution ^e	rms noise
	[h] [m] [s]	[°] ['] ["]	type	type	[km s ⁻¹]		[Mpc]	[min]	brators	[km s ⁻¹]	[Jy]
HE 0021–1819	00:23:55.3	–18:02:50		E, C	15 954	0.053	215.4	60	1, 1	1.3	0.008
HE 0040–1105	00:42:36.8	–10:49:21	Sy 1.5	E, C	12 578	0.042	169.6	60	1, 1	0.3	0.013
HE 0045–2145	00:47:41.3	–21:29:27		S	6403	0.021	86.0	60	2, 1	5.2	0.004
HE 0114–0015	01:17:03.6	+00:00:27		E, C, poss. M	13 682	0.046	184.3	90	2, 1, 1	1.3	0.006
HE 0119–0118	01:21:59.8	–01:02:25	Sy 1.5	E	16 412	0.055	221.5	60	1, 1	2.1	0.007
HE 0150–0344	01:53:01.4	–03:29:24		M	14 329	0.048	193.3	90	1, 3, 1	16.5	0.004
HE 0212–0059	02:14:33.6	–00:46:00	Sy 1.2	E, C	7921	0.026	106.2	60	2, 3	8.2	0.004
HE 0224–2834	02:26:25.7	–28:20:59		M, C	18 150	0.060	245.4	60	1, 1	8.0	0.003
HE 0227–0913	02:30:05.4	–08:59:53	Sy 1	S	4914	0.016	65.8	30	2	2.6	0.007
HE 0232–0900	02:34:37.7	–08:47:16	Sy 1	R, M, C	12 886	0.043	173.7	60	2, 1	32.0	0.002
HE 0253–1641	02:56:02.6	–16:29:16	Sy 2	S	9580	0.032	128.9	30	1	0.3	0.019
HE 0433–1028	04:36:22.2	–10:22:33	Sy 1	S	10 651	0.036	143.1	60	1, 1	2.1	0.007
HE 0853–0126	08:56:17.8	–01:38:07	Sy 1	E, C	17 899	0.060	242.1	60	1, 1	0.3	0.017
HE 0949–0122	09:52:18.9	–01:36:44	Sy 1.5	E	5905	0.020	79.1	60	4, 3	4.1	0.016
HE 1011–0403	10:14:20.6	–04:18:41	Sy 1	S, C	17 572	0.059	237.6	30	1	0.3	0.021
HE 1017–0305	10:19:32.9	–03:20:15	Sy 1	S, C, poss. M	14 737	0.049	199.0	30	1	0.3	0.018
HE 1029–1831	10:31:57.3	–18:46:34	Sy 1	S, C	12 112	0.040	163.1	60	3, 1	16.0	0.001
HE 1107–0813	11:09:48.5	–08:30:15		E	17 481	0.058	236.3	30	1	0.3	0.021
HE 1108–2813	11:10:48.0	–28:30:03	Sy 1.5	S	7198	0.024	96.5	90	4, 1, 1	0.3	0.017
HE 1126–0407	11:29:16.6	–04:24:08	Sy 1	S, C	18 006	0.060	243.7	30	1	0.3	0.020
HE 1237–0504	12:39:39.4	–05:20:40	Sy 1	S	2531	0.008	33.6	30	4	4.1	0.008
HE 1248–1356	12:51:32.4	–14:13:17	Sy 1	S, C	4338	0.015	58.2	60	4, 3	2.1	0.002
HE 1330–1013	13:32:39.1	–10:28:53	Sy 1	S, C	6744	0.023	90.4	90	1, 3, 3	16.5	0.006
HE 1353–1917	13:56:36.7	–19:31:44	Sy 1	S	10 472	0.035	140.7	60	1, 1	0.3	0.017
HE 2222–0026	22:24:35.3	–00:11:04		E	17 414	0.058	235.5	30	1	0.3	0.019
HE 2233+0124	22:35:41.9	+01:39:33	Sy 1	S, C	16 913	0.056	228.5	30	1	0.3	0.018
HE 2302–0857	23:04:43.4	–08:41:09	Sy 1.5	S, C	14 120	0.047	190.4	90	1, 1, 1	8.0	0.002

^a Taken from the NED; ^b E denotes elliptical morphology; S represents a spiral morphology; M stands for possible mergers or merger remnants; R denotes ringed objects; C marks galaxies with other extragalactic sources within a projected distance of up to 340 kpc; ^c total integration time spent on the source; ^d 1 – Holmberg I; 2 – UGC 2345; 3 – Sextans B; 4 – NGC 4303; ^e spectral resolution of the spectra shown in Fig. 1.

low-luminosity QSOs are rich in molecular gas. In 2007 and 2008 we searched this subsample for 21 cm HI emission. This sample complements the study of Ho et al. (2008a). But contrary to their sample our sources have positions further to the south.

A more detailed description of the “nearby QSO sample” can be found in Bertram et al. (2007).

3. Observations and data reduction

The observations of the HI 21 cm emission line were carried out with the Effelsberg 100-m telescope in 2007 and 2008. The 18–21 cm (1.29–1.72 GHz) two-channel *L*-band HEMT facility receiver was used as the frontend, in conjunction with the 8192-channel-autocorrelator (AK 90) and the Fast Fourier Transform Spectrometer (FFTS) as backends. With bandwidths of 10 MHz (AK 90) and 20 MHz (AK 90 + FFTS), centered on the redshifted rest frame frequency for each galaxy, we were able to obtain data with velocity ranges Δv from ~ 4200 to $\sim 21\,000$ km s⁻¹ and a velocity resolution between 0.2577 and 2.061 km s⁻¹, depending on the backend and settings. The measurements were done in position – switch mode with 5 mn on and 5 mn off the source positions, with an off – position 45' away. This provides the advantage of better baselines and the reduction of atmospheric influences. The beam efficiency was ~ 1.15 for a beam size of 9.5' at 21 cm. The on-source integration times range between 30 and 90 minutes. Daily pointing checks were performed using sources from the Effelsberg Catalog of pointing and flux density calibration (Ott et al. 1994). As flux calibrators we used

Holmberg I, NGC 4303, Sextans B and UGC 2345 (fluxes taken from Tift & Huchtmeier 1990 and from Springob et al. 2005).

The Effelsberg 100-m telescope site is known for exhibiting low level radio frequency interference (RFI) in the 21 cm band. However as the RFI signals are situated well outside the range of the expected central velocity or can be filtered out, these disturbances have no influence on the observational results.

The data were reduced and analyzed with the CLASS package of IRAM's GILDAS¹ software. All spectra have been averaged, when applicable. To obtain a better signal to - noise ratio, most of the spectra were Hanning smoothed. For data taken on different dates the subscans of each observation were calibrated with respect to a suitable flux calibrator (see Fig. 1 and Table 1). Baselines were fitted and subtracted from each subscan individually before resampling and averaging of the spectra. Another baseline fit was performed after the final resampling and averaging of all available data for the source. All polynomial fits to the baselines have been of the order of one. The errors ΔI for the given intensities I were determined following the procedure from Bertram et al. (2007). The geometric average of the line error ΔI_l and the baseline error ΔI_b were taken into account.

4. Analysis

The galaxies observed during this survey do not form a complete sample, but the results can still be used to improve our knowledge of the population of nearby AGNs. In order to derive the

¹ <http://www.iram.fr/IRAMFR/GILDAS>

Fig. 1. H I spectra of detected host galaxies from the “nearby QSO sample” observed with the Effelsberg 100-m telescope and optical DSS images. The images in the middle extend over 2' and the ones to the right contain 9.5', which is roughly the size of the beam at 21 cm. North is up and east to the left. Each source is identified by its HES name (*top left corner* of the spectrum) and the redshift (*top right corner*). The spectral resolution of the spectra in this figure range from 0.3 km s⁻¹ up to 32 km s⁻¹. If regions in the spectrum are affected by RFI (Radio Frequency Interference) and are not used for baseline-fitting and noise estimates, they are set to zero intensity.

Fig. 1. continued.

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Table 2. Summary of the H I properties.

Object	v_0 (LSR)	$I_{\text{H I}}^a$	W_{50}^b	LS ^c	$M_{\text{H I}}$	M_{dyn}	$M_{\text{tot, gas}}$	$L'_{\text{CO}}/M_{\text{H I}}$	L_{IR}	f	Σ_M	$M_{\text{H I}}/L_{\text{IR}}$	$M_{\text{H I}}/L_{\text{B}}$
	[km s ⁻¹]	[Jy km s ⁻¹]	[km s ⁻¹]		[10 ⁹ M _⊙]	[10 ¹⁰ M _⊙]	[10 ¹⁰ M _⊙]	[$\frac{\text{K km s}^{-1} \text{ pc}^2}{M_{\odot}}$]	[10 ¹⁰ L _⊙]		[M _⊙ pc ⁻²]	[M _⊙ /L _⊙]	[M _⊙ /L _⊙]
HE 0045	6 403	3.29 ± 0.13	180.8	↑↑ _A	5.7 ± 0.2	7.1	11.5	0.13	8.10	0.6	20.0	0.08	1.2
HE 0150	14 329	2.70 ± 0.28	263.0	↑↑ _A	23.8 ± 2.5	45.0	26.8	0.02	11.10	0.9	27.0	0.21	4.9
HE 0212	7 921	1.97 ± 0.18	206.4	^ _A	5.3 ± 0.5	3.3	11.7	0.09	4.07	1.1	121.6	0.13	0.4
HE 0224	18 150	2.64 ± 0.26	271.0	□ _A	37.5 ± 3.7	90.8	41.5	0.01	10.50	0.3	20.3	0.34	3.8
HE 0227	4 914	2.58 ± 0.16	193.9	□	2.6 ± 0.2	0.9	3.4	0.07	1.08	1.0	466.9	0.24	0.7
HE 0232	12 886	3.31 ± 0.40	559.0	^ _A	23.6 ± 2.8	46.9	56.6	0.18	18.50	0.8	114.9	0.13	0.8
HE 0949	5 974	5.88 ± 0.46	181.4	^ _A	8.7 ± 0.7	3.5	9.5	0.01	–	1.5	58.0	–	1.7
HE 1029	12 112	1.05 ± 0.10	241.0	↑↑	6.6 ± 0.6	24.2	17.2	0.20	21.20	0.9	14.4	0.05	0.6
HE 1237	2 531	7.55 ± 0.36	355.5	↑↑	2.0 ± 0.1	67.5	2.82	0.05	1.44	0.9	1.00	0.14	1.2
HE 1248	4 338	0.78 ± 0.03	119.5	^ _A	1.2 ± 0.2 ^d	5.7	2.2	0.08	1.29	1.4	2.6	0.12	3.5
HE 1330	6 744	1.84 ± 0.35	180.4	↑↑	3.6 ± 0.7	16.1	5.0	0.05	–	1.0	6.3	–	1.6
HE 2302	14 120	1.39 ± 0.18	338.0	↑↑ _A	11.9 ± 1.5	130.7	19.7	0.08	–	1.3	4.7	–	1.1
Non-detections													
HE 0021	15 889	<2.03	222.7		<22.2		<2.4	>0.01	–			–	<4.1
HE 0040	12 390	<1.58	222.7		<10.7		<1.3	>0.03	–			–	<4.2
HE 0114	13 672	<1.75	222.7		<14.0		<1.7	>0.03	–			–	<2.5
HE 0119	16 291	<1.42	222.7		<16.5		<2.7	>0.08	24.6			<0.07	<1.0
HE 0253	9 470	<2.58	222.7		<10.1		<1.5	>0.06	4.90			<0.21	<2.2
HE 0433	10 658	<2.21	222.7		<10.7		<2.9	>0.21	22.7			<0.05	<1.1
HE 0853	17 930	<1.03	222.7		<14.3		<2.1	>0.06	–			–	<1.5
HE 1011	17 388	<0.56	222.7		<7.5		<1.5	>0.12	–			–	<0.2
HE 1017	14 985	<1.22	222.7		<11.4		<1.6	>0.05	9.88			<0.12	<1.2
HE 1107	17 088	<1.03	222.7		<13.6		<1.8	>0.04	–			–	<0.8
HE 1108	7 199	<0.50	222.7		<1.1		<0.9	>0.85	10.4			<0.01	<0.1
HE 1126	17 988	<1.83	222.7		<25.7		<3.4	>0.04	–			–	<0.5
HE 1353	10 388	<2.44	222.7		<11.4		<1.7	>0.07	–			–	<4.7
HE 2222	17 431	<1.22	222.7		<15.9		<1.7	>0.01	–			–	<3.7
HE 2233	16 933	<2.93	222.7		<36.1		<4.0	>0.01	–			–	<4.4

^a Upper limits and errors represent 3 σ values; ^b for the non-detections, values of W_{50} correspond to the median value of all detected sources; ^c line shape: ^ represents a triangular shaped line profile; A stands for asymmetries in the line profiles; spectra with □ show a boxy line profile; ↑↑ mark line profiles of a double-horn shape; ^d this detection was already confirmed by follow-up observations with the VLA. The obtained value for the H I mass is $\sim 1.0 \times 10^9 M_{\odot}$ (König et al. 2009).

atomic neutral hydrogen gas mass $M_{\text{H I}}$, the following formula (e.g., Shostak 1978) was applied:

$$M_{\text{H I}} = 2.36 \times 10^5 D_L^2 \int S_{\nu} dv M_{\odot}. \quad (1)$$

D_L denotes the luminosity distance in Mpc and $\int S_{\nu} dv$ the flux integral in Jy km s⁻¹. For a comparison we measured the dynamical mass via

$$M_{\text{dyn}} = \frac{v_{\text{H I}}^2 r}{G} M_{\odot} \quad (2)$$

($v_{\text{H I}}$ is the velocity width from which 90% of the H I line emission arises and r is the estimated H I radius) under the assumption of a disk geometry in virial equilibrium, which is appropriate for gas rich objects. Since the size of the H I extension is not known we estimated the area of the sources from the DSS images (Fig. 1) by circular apertures. These apertures were centered on the nucleus of each galaxy. The optical radius was taken as the value where the counts of the galaxy emission in the DSS image were 3 σ larger than the background. This radius was multiplied by the factor for the median $r_{\text{H I}}/r_{\text{opt}}$ of 1.50 from Haan et al. (2008), and assuming a circular area we then derived the area by $A = \pi r^2$ which in turn was used for the determination of the dynamical mass. As expected the values for M_{dyn} are up to two orders of magnitude larger than the H I masses determined from the integrated intensity (Table 2). The infrared luminosity

was determined from the IRAS fluxes (12, 25, 60 and 100 μm fluxes were taken from the IRAS Faint Source Catalog, Moshir et al. 1990) and with the following formulae (Sanders & Mirabel 1996):

$$F_{\text{IR}} = 1.8 \times 10^{-14} (13.48 f_{12} + 5.16 f_{25} + 2.58 f_{60} + f_{100}) \frac{\text{W}}{\text{m}^2} \quad (3)$$

$$L_{\text{IR}} = 4\pi D_L^2 F_{\text{IR}} L_{\odot}. \quad (4)$$

These results are summarized in Table 2. Given are the integrated line intensity $I_{\text{H I}}$ (Col. 3), the line width at half maximum intensity W_{50} (Col. 4), an estimate on the line shape (Col. 5), the atomic neutral hydrogen mass $M_{\text{H I}}$ (Col. 6), the dynamical mass deduced from the H I data (Col. 7), the total hydrogen gas mass of the host galaxy (Col. 8), as well as the molecular to atomic gas mass fraction (Col. 9) and the infrared luminosity L_{IR} (Col. 10).

5. Results and discussion

In Fig. 1 we show the obtained H I spectra together with the associated DSS images of the region with a diameter of 2' and 9.5' around the source position. The images should serve as a means to estimate the source confusion. The spectrum of HE 1248–1356 is remarkable in the sense that the velocity range 4200–4350 km s⁻¹ shows strong CO emission (see Bertram et al. 2007) but no H I emission. As this source has a close companion (see

Fig. 2. H I mass as a function of infrared luminosity for the nearby QSOs. Stars represent the sample from this paper. Squares and triangles represent sources taken in order to enhance the statistics from Ho et al. (2008a): squares represent the sources from the Ho sample itself and triangles represent a literature sample assembled by Ho et al. (2008a). Filled squares and triangles mark available values for L_{IR} , whereas open ones with arrows represent upper limits of L_{IR} or M_{HI} . Whereas filled stars for our sample represent H I and CO detected sources and unfilled ones denote upper mass limits for the CO but not H I detected sources. Arrows show upper limits for mass and infrared luminosity.

the DSS images), it is possible that the H I gas was partially more disturbed/stripped/disrupted, by the companion. This could cause the “one-sidedness” of the spectrum indicating that the part of the host galaxy moving towards us has less neutral atomic hydrogen than the one receding. Why wasn’t the CO affected? It could just be that the disturbance was only affecting the more outwards lying H I gas and not yet the molecular CO in former times. Since then H I was converted into H_2 (CO) and the H I line in its present shape could be a remnant signature. The coordinate labels of RA and Dec (J2000), as well as the flux in Jy and the velocity in km s^{-1} are indicating the scales. Each source name is denoted above the spectrum. The H I properties and results are summarized in Table 2: Integrated line intensities cover a range from 0.5 up to 7.6 Jy km s^{-1} . The intensity upper limits and errors for non-detections represent 3σ values. The line widths (W_{50}) are of the order of hundreds of km s^{-1} . The sources HE 0232–0900 ($W_{50} = 559 \text{ km s}^{-1}$) and HE 2302–0857 ($W_{50} = 338 \text{ km s}^{-1}$) are two special cases: They both have extraordinary large line widths both in CO (FWZI: 597 km s^{-1} and 653 km s^{-1} , from Bertram et al. 2007) and H I emission. The H I line emission detected from HE 2302–0857 is even more extraordinary if we look at the full width at zero intensity (FWZI) of the H I line, with a width of 616 km s^{-1} , which is comparable to the line width (FWZI) in CO ($\Delta v_{\text{CO}} = 653 \text{ km s}^{-1}$), although the galaxy is not seen edge-on. For HE 0232–0900 however the H I line is narrower than the CO line. This indicates that the outer regions of the galactic disk were stripped from H I, or are simply depleted from the atomic gas component. As the DSS images (Fig. 1) show a peculiar morphology of this object it is also possible that the current geometry is due to a previous interaction/merger with another galaxy. The H I masses range between 1.1 and $37.5 \times 10^9 M_{\odot}$, whereas the upper limits for the dynamical masses have values from 0.9×10^{10} up to $1.3 \times 10^{12} M_{\odot}$.

Figure 2 shows a plot of the atomic hydrogen mass versus infrared luminosity containing sources from this work and the work of Ho et al. (2008a). In comparison to Ho et al. (2008b) we concentrate more on the radio – IR properties, rather than the optical H I relations. The position of the objects in this graph are in good agreement with the work of Young et al. (1989) about infrared bright galaxies: In general galaxies with high IR

luminosities have high neutral atomic hydrogen masses. Although their work places an emphasis on even more nearby sources ($D_L = 36.3 \text{ Mpc}$), the mean luminosity distance for the enlarged sample (this work + Ho et al. 2008a) plotted here was 219.5 Mpc . The comparison of these results shows no evolutionary effect in redshift due to M_{HI} or L_{IR} (see also Table 3 and Haan et al. 2008). The comparison between the molecular gas content (taken from Bertram et al. 2007) and the atomic one results in a median fraction of $L'_{\text{CO}}/M_{\text{HI}} = 0.06$ for our sample (including the upper limits for the non-detections). Maiolino et al. (1997) measured a value of 1.79 for their $M_{\text{H}_2}/M_{\text{HI}}$ (for galaxy types up to Sy 1.5). Since we are not sure if Bertram et al. (2007) and Maiolino et al. (1997) used the same CO - to - H_2 conversion factor we simply compare the L'_{CO} - to - M_{HI} ratios. The median $L'_{\text{CO}}/M_{\text{HI}}$ value given by the data of Maiolino et al. (1997) results in 0.14, which is about a factor of two higher than the value obtained for our sample. Since the median CO luminosity L'_{CO} is about the same in both samples, $5.55 \times 10^8 M_{\odot}$ for Maiolino et al. (1997) and $5.40 \times 10^8 M_{\odot}$ (CO data taken from Bertram et al. 2007), the galaxies in their sample are less rich in atomic hydrogen than the ones in this study. In a more recent publication Haan et al. (2008) compiled a study of H I properties in AGN host galaxies taken from the NUGA sample. We compared these sources, which lie a step lower in redshift range ($D_L = 6.6 \dots 53.9 \text{ Mpc}$, see Table 3), with our sample. They find more ring structures and dynamically disturbed H I disks in LINERs than in Seyfert host galaxies. Since our sample consists only of Seyfert galaxies we just account for part of the Haan sample.

The distribution of data points in Fig. 2 shows that we are sampling an upper envelope of the $M_{\text{HI}}/L_{\text{IR}}$ distribution. The sources that we detected in H I emission are those that have the largest amount of atomic hydrogen, compared to the molecular gas mass, in their hosts. This could be an explanation for the lack of more H I detections in this work. Upper limits of the non-detected sources show, that with deeper and longer integrations we would be able to correct for this deficiency in our observations.

In Fig. 3 we compare the H I and the CO intensities of the detected sources in our sample. Similar to Fig. 2 it is obvious from

Table 3. Sources from Haan et al. (2008).

Object ^a	RA(2000) [h] [m] [s]	Dec(2000) [°] ['"] ["]	v_{hel} [km s ⁻¹]	D_L [Mpc]	H I line width [km s ⁻¹]	CO line width [km s ⁻¹]	CO -Ref.	f	L_{IR} [10 ¹⁰ L _⊙]	Σ_M [M _⊙ pc ⁻²]
NGC 3147	10:16:53.65	+73:24:02.7	2820	40.9	430	420	1	0.98	21.5	1.81
NGC 3627	11:20:15.03	+12:59:29.6	727	6.6	431	409	2	0.95	86.6	2.82
NGC 4569	12:36:49.80	+13:09:46.3	-235	16.8	396	385	3	0.97	21.2	1.34
NGC 4826	12:56:43.69	+21:40:57.5	408	4.1	372	373.75	4,5,6,7	1.00	86.8	0.43
NGC 5953	15:34:32.39	+15:11:37.7	1965	36	349	230	1	0.66	25.0	0.94
NGC 6574	18:11:51.23	+14:58:54.4	2282	38	340	350	1	1.03	35.7	1.88
NGC 6951	20:37:14.09	+66:06:20.3	1424	24.1	338	380.2	8	1.12	34.8	1.71
NGC 1961	05:42:04.80	+69:22:43.3	3934	53.9	767	731	9	0.95	20.1	12.84
NGC 3368	10:46:45.74	+11:49:11.8	897	8.1	399	365	10	0.91	24.4	1.33
NGC 3718	11:32:34.85	+53:04:04.5	994	17.0	465	470	11	1.01	5.38	1.74
NGC 4321	12:22:54.90	+15:49:20.6	1571	16.8	291	200 ^c	12	0.69	50.5	2.91
NGC 4579	12:37:43.52	+11:49:05.5	1519	37	374	380	13	1.02	15.1	1.26
NGC 4736	12:50:53.06	+41:07:13.7	308	4.3	284	270	5	0.95	126	1.53
NGC 7217	22:07:52.38	+31:21:33.4	952	16.0	326	320	14	0.98	15.8	2.13
NGC 2782	09:14:05.11	+40:06:49.2	2562	37.3	246	260	1	1.06	20.8	3.29
NGC 5248	13:37:32.07	+08:53:06.2	1153	15	311	300	5	0.96	45.7	2.33

^a Taken from Haan et al. (2008); ^b references: 1 – Young et al. (1995); 2 – Sage (1993); 3 – Boselli et al. (1995); 4 – Helfer et al. (2003); 5 – Nishiyama & Nakai (2001); 6 – Casoli & Gerin (1993); 7 – Aalto et al. (1991); 8 – Kohno et al. (1999); 9 – Tutui & Sofue (1997); 10 – Braine et al. (1993); 11 – Pott et al. (2004); 12 – Sakamoto et al. (1995); 13 – Sofue et al. (2003); 14 – Combes et al. (2004); ^c uncertain.

Fig. 3. H I flux vs. CO intensity (taken from Bertram et al. 2007). Crosses mark the upper limits of H I non-detected sources. Filled circles represent the intensities for detected sources. Each object is identified by a number, which is related to the source name given in the figure legend.

Fig. 3 that we have sampled an upper envelope of the H I mass distribution. If we consider only the certain H I detected sources from this work then a high H I mass is present almost independently of the molecular mass content. Remarkable about this plot is, that the two sources with the largest CO intensity values (HE 0433–1028 and HE 1108–2813) are not detected in atomic hydrogen. This could mean that most of the available neutral atomic gas was already converted to molecular gas, i.e. H₂ (CO). The number of upper limits in the H I line strength is larger for galaxies with low molecular gas content. This implies that a correlation may be present, such that low molecular gas mass also implies a low atomic gas mass. On a statistical basis the H I detection fraction above and below the median value of the molecular gas masses (taken from Bertram et al. 2007) could give a

hint for the confidence limit of this trend in our sample. The median value results in $M_{\text{H}_2} = 2.10 \times 10^9 M_{\odot}$. Then we studied the distribution of the H I masses of the sources above the median of the molecular gas mass and below it. The median H I mass above the median molecular gas mass is $M_{\text{H I}} = (9.24 \pm 4.84) \times 10^9 M_{\odot}$ and the median H I mass below the median molecular gas mass is $M_{\text{H I}} = (2.22 \pm 0.56) \times 10^9 M_{\odot}$. These calculations do not take the non-detections into account. We defined estimated values for error bars by determining the median deviation from the medians of the H I masses. Taking these error bars into account, we find that the sources above the median molecular mass also have the larger H I masses, the sources below the median molecular gas mass have lower H I masses. Within the error bars the two populations of H I detected sources do not overlap. Nonetheless

our sample is very small and hence not suitable for making statistically significant statements.

5.1. Source confusion

We can not exclude the possibility of source confusion (see Fig. 1). The half power beam width (HPBW) at 21 cm is 9.5'. Since the whole beam lobe is (reduced) sensitive for radio signals out to twice the primary beam diameter, an H I rich galaxy at, the appropriate red shift, can cause disturbances out to angular distances of up to 18'. Asymmetries in the line profiles could possibly indicate the presence of companions or phases of merging that influence the host galaxies. One help to shed light on this matter may also be provided by the DSS images (see Fig. 1). Here we can look for indications for interactions or companions within a field of view representing the 9.5' Effelsberg beam size. An outstanding example for this circumstance is the source HE 0150–0344. Its H I spectrum shows two emission lines close in velocity. In the DSS image the source shows an elongated structure with two peaks, indicating two very close by sources. With the large Effelsberg beam we are not able to distinguish between the objects. Due to the close proximity of the sources interferometrical data would be needed to achieve the differentiation. Source confusion has a strong influence on the line shape, as well as on the line width, as mentioned earlier. Two objects, which exhibit emission at the observed frequency, close in redshift, hence also in recession velocity would cause a broadening of the studied emission line (always under the assumption that the two objects are galaxies). Therefore the target source would feature a much broader line width than it shows in reality (see Fig. 1, HE 0150–0344). This would then cause wrong numbers for the observed intensity and the resulting gas mass. Cross-checking with other observational tools, for e.g., optical images, is therefore essential to get the right result.

5.2. Morphology

A comparison of the shape of the spectra shows good agreement between line shape and associated morphology in e.g., the optical (Fig. 1, Tables 1, 2): for 11 of the 12 detected sources (the exception is HE 1248–1356) we find that the morphology from the optical DSS images and the line shape determined from the H I spectra are the same. But one has to remark that the asymmetry of the line shape in some of the spectra makes it difficult to achieve an accurate differentiation. From the optical DSS images (Fig. 1) we find spiral morphology in 15 (55%) host galaxies, elliptical morphology in 11 (41%) host galaxies and a ring morphology in 1 (4%) host galaxy. In 33% of the sources the H I spectra show triangular shaped line profiles, that is expected for turbulent line-of-sight dispersion (as in elliptical galaxies), and 67% have boxy or double-horn shaped line profiles, which is an indicator for emission from an inclined, rotating disk (as in spirals). In comparison Haan et al. (2008) find that 44% of the sources in their AGN sample are of spiral morphology, 28% are centrally peaked, 22% ringed and 5% of their host galaxies show a warped geometry. This hints at a preference for spirals in terms of morphological properties of QSO host galaxies. In their Seyfert subsample a slight excess of galaxies with a spiral geometry is evident.

In 1980 Dressler discovered a morphology-density ($T-\Sigma$) relation for galaxies: the fraction of elliptical like (E + S0) galaxies increases strongly with increasing local galaxy density, whereas the numbers of spiral galaxies decrease (see e.g., Table 1 in

Pimbblet 2003). In good agreement with further studies of this relationship he also derives values for different environments: from galaxies in the field over poor and rich groups to clusters. Furthermore Dressler et al. (1997) report a redshift evolution in the $T-\Sigma$ relation: an additional increase of the fraction of S0 galaxies with redshift whilst the number of elliptical galaxies stays nearly constant. The distribution of spiral, elliptical (E) and lenticular (S0) galaxies in our H I data is comparable to the numbers for field galaxies or poor groups. Dressler et al. (1985) expand the statistical studies of clusters by also looking at emission line galaxies. They find a much higher emission line frequency in field galaxies than in cluster galaxies. AGN occur at a rate of ~5% in field galaxies whereas in clusters only ~1% of the galaxies harbor an AGN. Martini et al. (2006) searched for low-luminosity AGN in low redshift clusters. They determined an AGN fraction of ~5%, in clusters arguing that through X-ray emission more AGN towards lower luminosities can be identified. They concluded that if the AGN fraction in the field is indeed 5 times the AGN cluster fraction they would identify ~25% of the field galaxy population to show characteristics of AGN. On the other hand, Popesso & Biviano (2006) find an average AGN fraction of 18% in clusters. They, too, argue that their estimate includes low-luminosity AGN, probably missed in previous studies. Scaling the $T-\Sigma$ relation from Dressler (1980) to AGN this would, by a strong simplification, mean that most AGN in our sample reside in host galaxies of spiral morphological type, whereas in clusters the fraction of AGN in elliptical and lenticular hosts would increase significantly.

For analytical purposes we introduce an estimate for the compactness of gas confined to the host galaxies within our sample by the derivation of the fraction of the CO line width to the H I line width as follows:

$$\text{compactness } f = \frac{v_{90}(\text{CO})}{v_{90}(\text{H I})}. \quad (5)$$

v_{90} is the velocity width from which 90% of the emission arises. We show the values for the compactness in Table 2. We want to study the distribution of CO and H I in the host galaxies with this quantity f . We assume that H I is found all over the place. If CO is mostly limited to the central inner region, filling the flat part of the rotation curve, f will be smaller than 1. For $f = 1$ the line widths in both emission lines should be equally large. Galaxies with compactness factors $f > 1$ have broader line widths in CO than in H I. As we see a large fraction of objects with companions or signs of interactions f may be used as an additional indicator for dynamical peculiarities (due to merging or disturbance). But as the beam size for the 21 cm observations was very large, other galaxies within the beam size contribute to the detected emission. Here the exceptional host galaxies HE 0232–0900 and HE 2302–0857, with their very broad emission lines at 21 cm have to be mentioned again. No clear trend could be seen in Fig. 4. There we plotted the infrared luminosity against the determined compactness of each object. All sources from Haan et al. (2008) have compactness factors close to one, except for NGC 5953 and NGC 4321, which show factors $f < 1$ (Table 3). Usually a compactness factor close to one is expected as the CO distribution normally reaches the maximal rotation velocity. In this sense our sample is exceptional. For example the sources HE 0045–2145, HE 0224–2834, HE 0949–0122, HE 1248–1356 and HE 2302–0857 exhibit compactness factors strongly differing from a value of $f = 1$. But as the fraction of objects with companions and/or indications for mergers or interactions is extraordinary high in this source sample a compactness of $f < 1$, together with the line shape, may also provide early hints for

Fig. 4. Infrared luminosity L_{IR} vs. compactness f . Filled circles represent the H I detected sources from this work, filled stars however represent detected objects from the sample of Haan et al. (2008). Unfilled symbols with arrows mark sources with upper limits for their infrared luminosities. Each detected object from this work is identified by a number, which is related to the source name given in the figure legend.

distortions in the outer regions of the host galaxies. The best example for this issue is HE 0224–2834. The small compactness of 0.3 means that the atomic gas is much more extended than the molecular gas. The asymmetry in the shape of the H I line tells us that there are distortions in the outer H I disk. The comparison to the optical DSS images shows that we are right, HE 0224–2834 has a close companion and it shows morphological signs of interaction. The same holds true for HE 0045–2145: Its line shape is asymmetrical, the compactness factor is only 0.6 and in the DSS images there is another galaxy close by. Hence the H I distribution can serve as an early indicator for interactions. The compactness for objects with spiral features seems to be lower (the CO emitting regions have a smaller extension than H I emitting ones) as they have a larger outspread than the ones showing an elliptical geometry.

As another analytical tool we use the surface mass density:

$$\Sigma = \frac{M_{\text{H I}}}{\text{area}} \left[M_{\odot} \text{pc}^{-2} \right]. \quad (6)$$

The area of the sources again was estimated from the DSS images (Fig. 1, see Sect. 4 again for the description of the area extraction process). The sample sources show areas between 55 and 76 000''² resulting in Σ values of 1.0 up to 434 $M_{\odot} \text{pc}^{-2}$. The median surface mass density, not taking the non-detections into account, is of the order of 20.1 $M_{\odot} \text{pc}^{-2}$, which is a factor of two lower compared to the value estimated for the Milky Way (50–75 $M_{\odot} \text{pc}^{-2}$, Romano et al. 2000). The data from Haan et al. (2008) however result in an even lower average surface mass density of 1.77 $M_{\odot} \text{pc}^{-2}$. Here the assumption of circular morphology leads to an overestimation of the area: We use the maximum H I radius and assume a circular morphology of the host galaxy. Since the galaxies usually are not circular but more elliptical or exhibit other structures we make an imprecise assumption of the morphology. This leads to significantly smaller surface mass densities for the sources than expected.

In Fig. 5 we show blue magnitude M_b vs. rotation velocity v_{rot} . This plot of the Tully-Fisher relation allows us to test the quality of the $FWHM$ values (W_{50}) for the emission lines. No severe outliers are seen that could not be explained as a

consequence of the inclination. As the inclinations for the sources in this sample are not defined, we can only assume a range of rotation velocities. By inserting graphs for the Tully-Fisher relation from literature sources (see e.g., Sakai et al. 2000; Ziegler et al. 2002) we can estimate where our host galaxies should be found in this graph. Since the majority of the 45° points as well as the value for the median are located to the left of the literature Tully-Fisher functions our objects should feature lower inclination angles of about 30°, which is in good agreement with our assumption of a nearly face on inclination for low luminosity AGN.

5.3. IRAS color-color diagram

Figure 6 represents an IRAS color-color diagram of the sources from this sample after Helou (1986), overlaid with the computations of Desert (1986). Our sample sources fit well into the model by Desert (1986). The location of our sample sources in the IRAS color-color plot shows that almost all of them exhibit signs which are typical for starburst dominated hosts that have elevated dust temperatures i.e. show bright 60 μm emission compared to their 100 μm emission, and show faint 12 μm emission compared to their 25 μm emission. The far-IR color is particularly sensitive to foreground Galactic “cirrus” emission, which can cause artificially small values of $f_{\nu}(60)/f_{\nu}(100)$. Only 2 objects (HE 0150–0344, HE 0212–0059) are dominated by the 100 μm emission implying lower dust temperatures. They have colors that are often found for elliptical galaxies. A visual inspection of their images shows that an identification with an elliptical host is plausible. Objects to the upper left of this plot are thought to be starburst galaxies.

6. Conclusions

We present results on the neutral atomic gas content of 27 nearby low-luminosity QSO host galaxies. 12 of the target sources were detected in H I emission. The atomic gas masses cover a range from $1.1 \times 10^9 M_{\odot}$ up to $3.8 \times 10^{10} M_{\odot}$ with a median mass of the order of $6.2 \times 10^9 M_{\odot}$. Considering the upper

Fig. 5. Blue magnitude M_B vs. rotation velocity v_{rot} . The median value is plotted as an empty star. The dashed lines show functions for the Tully-Fisher relation from the literature (Schöniger & Sofue 1997; Sakai et al. 2000; Ziegler et al. 2002). The H I detected sources from this work are coded with grey-scale. Each object is identified with its name given in the figure legend.

Fig. 6. IRAS color-color diagram according to Helou (1986). The underlying model was taken from Desert (1986). Filled circles show H I detected sources from this work, unfilled ones mark H I non-detected sources with available IRAS fluxes. Arrows are indicators for upper limits. Each object is identified by a number, which is related to the source name given in the figure legend. The location of our sample sources in the plot shows that almost all of them are starburst dominated hosts that have high dust temperatures (sources to the *upper left*). The galaxies to the lower right of the plot have colors that are often found for elliptical galaxies. The two sources HE 0150–0344 and HE 0212–0059 are such objects. These objects are dominated by the 100 μm emission implying lower dust temperatures.

limits for non-detections this value changes to $11.4 \times 10^9 M_{\odot}$. Taking this median H I mass for the whole sample into account, the atomic hydrogen mass is a factor of two higher for our sample than the H I content of the Milky Way (Hartmann & Burton 1997, $M_{\text{HI}} = 5.5 \times 10^9 M_{\odot}$). Though it is not possible to discuss the nature of the objects without high resolution imaging in more detail, we were able to draw some interesting conclusions with the help of the profiles of the H I spectra and optical DSS images. For several galaxies we found possible companions in the vicinity, as well as indications for merger/interactions. We find

no distinct correlation between the IR luminosity of a galaxy and its H I gas content. In general galaxies with high IR luminosities have high neutral atomic hydrogen masses. The compactness for objects with spiral features seems to be lower (the CO emitting regions have a smaller extension than H I emitting ones) as they have a larger outspread than the ones showing an elliptical geometry. Only for our sample there are CO and H I measurements done for the sample together. For other samples, like e.g., for the Haan et al. sample, there exist CO measurements with different telescopes/techniques in the literature by separate authors. To

our knowledge an estimated number of about 50 sources have HI and CO data taken. Therefore our sample contributes to the, at the moment, rather small contingency of hosts with atomic and molecular masses. The observed median surface mass density is about a factor two lower than the values for our Milky Way ($50\text{--}75 M_{\odot} \text{pc}^{-2}$). From the Tully-Fisher relation we deduced a median inclination of $\sim 30^{\circ}$, in good agreement with the assumption of nearly face-on morphology. Interferometrical data through follow-up observations for two out of the twelve HI detected sources have been obtained. For the other ten sources these follow-up observations are in planning.

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