The Relation between the Large-scale Gas Dynamics, Nuclear Kinematics, and Activity in Spiral Galaxies

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Abstract. Most of the spirals discussed in the following are well-known starburst galaxies (M 82, NGC 253, etc.). In addition to their nuclear activity, which makes them so popular, the selected galaxies have several other phenomena in common, such as bars, gas outflow, and possibly nuclear rings. The relationship between those phenomena is discussed in the following. I will show that the gas dynamics in the outer and inner parts of these galaxies are strongly related to their starburst activity. Galaxy interactions as well as bars play an important role as they affect the gas flow within the disk, driving gas inwards and outwards where it accumulates at preferred resonance orbits. The inflowing gas provides the supply for the central starburst region from which gas is eventually ejected into the halo. I compare the group of nearby starburst galaxies with distant ultra-luminous galaxies (Arp 220, NGC 6240, etc.), in which strong tidal interactions cause the radial gas inflow. In both groups high-resolution H I absorption measurements reveal fast-rotating nuclear rings.

1. Introduction

In this lecture I will discuss some aspects of the relation between the large-scale gas dynamics, nuclear kinematics, and activity in spiral galaxies. The original *idea* which led to this project was the possibility of using H I absorption measurements as a tracer of nuclear rings in galaxies. The two *keys* which may help to understand the relationship are bars in galaxies and galaxy-galaxy interactions. A successful approach to this issue involves observations and theoretical N-body simulations of galaxies which complement each other.

The best tracer for the overall gas distribution and kinematics in galaxies is the 21-cm emission line of the neutral hydrogen atom (H I). Although the H I content and global spectrum of a galaxy can be measured with a single-dish telescope, for this project interferometers such as the *Australia Telescope Compact Array* (ATCA)[1] in the Southern Hemisphere and the *Very Large Array*

[1]The Australia Telescope Compact Array is part of the Australia Telescope National Facility (ATNF), a division of the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

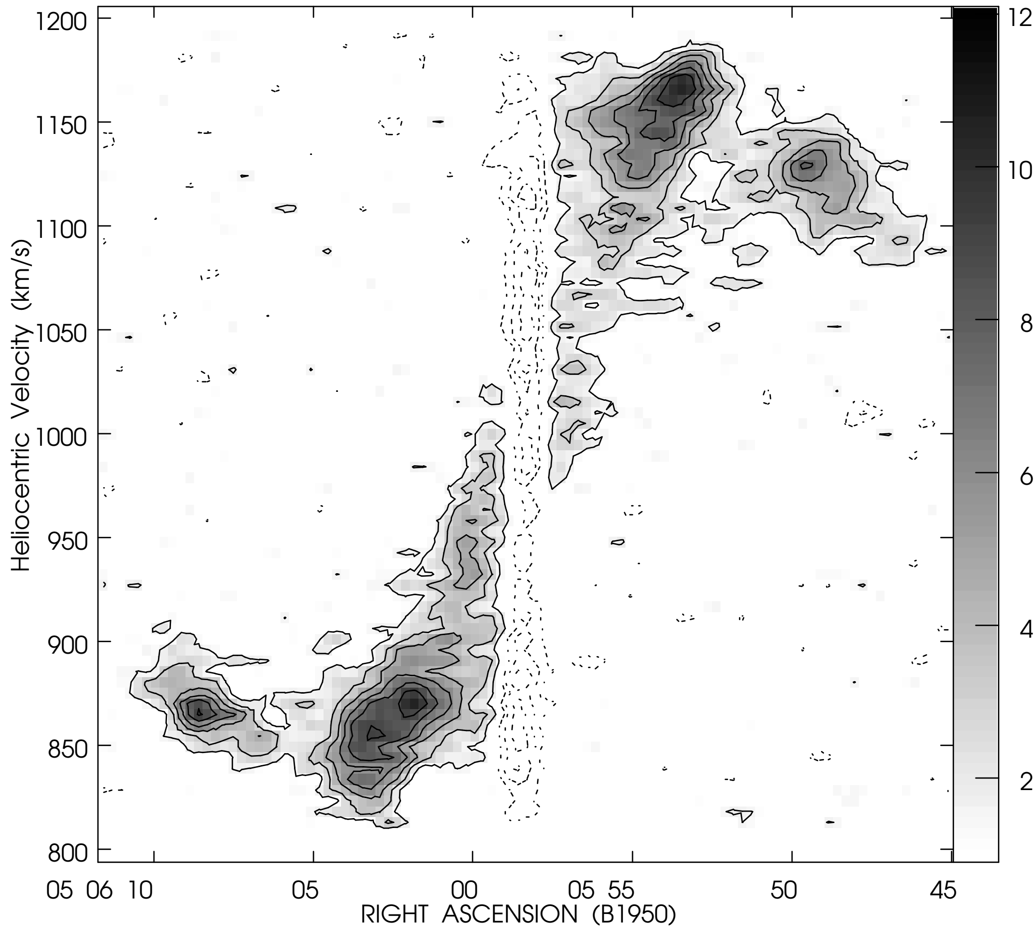

Figure 1. Major-axis position-velocity diagram of the starburst galaxy NGC 1808 (Koribalski, Dickey & Mebold 1993). We assumed a position angle of 320° (see also Fig. 5 and 6). The contour levels are −4.5, −3, −1.5, 1.5, 3, 4.5, 6, 7.5, and 9 mJy beam^{-1}. These data were taken with the VLA BnC array; the resolution is about $15'' \times 20'' \times 5$ km s^{-1}. — Note that both H I emission (solid lines) and absorption (dotted lines) cover about the same velocity range.

(VLA)[2] in the Northern Hemisphere are required to map galaxies in detail. For the brightest galaxies we can also use the H I absorption line to study the gas motions close to the centre by using the largest configurations of the existing interferometers. This method has several advantages: 1) at high angular resolution the H I emission is resolved out leaving absorption only (see Dickey 1979), 2) the H I absorption unambiguously traces the gas in front of the continuum sources, and 3) the velocity resolution is usually very high (a few $\mathrm{km\,s^{-1}}$), much higher than in the studies of optical emission lines. The obvious disadvantage is that absorption studies are limited to bright galaxies, mostly starburst or otherwise active galaxies. And even in those galaxies one has to keep in mind that the absorption depends directly on the distribution and strength of the continuum sources in the nuclear region.

A description of one of the first interferometric studies of H I absorption lines is given by Clark, Radhakrishnan & Wilson (1962) and Clark (1965).

2. The Nuclear Region: H I Absorption Measurements

Absorption by neutral atomic hydrogen in luminous spiral galaxies provides an excellent tool to study the gas kinematics in their nuclear regions. Whereas from emission studies it is difficult to interpret the observed radial velocities, absorption measurements have the advantage that the detected lines must come from the near side of the nucleus. So, red-shifts or blue-shifts relative to the systemic velocity of the galaxy, v_{sys}, unambiguously show infall or outflow of gas, respectively. Since the absorption lines are intrinsically narrow as a result of the low temperatures of the optically thick gas, typically 30 to 150 K (Dickey, Salpeter & Terzian 1979), it is surprising that numerous galaxies show H I absorption over a broad range of velocities (a few hundred $\mathrm{km\,s^{-1}}$); see e.g., Fig. 1. Some examples are found in the absorption surveys by Mirabel (1982) and Mirabel & Sanders (1988), using the Arecibo telescope, and by Dickey (1982, 1986), obtained with the large configurations of the VLA.

Interferometric studies of individual bright galaxies, e.g., NGC 253, NGC 660, NGC 1068, NGC 1365, NGC 1808, M 82, NGC 3079, NGC 3628, NGC 4945, etc. reveal H I *emission and absorption over about the same velocity range.* And many more galaxies can be added to the sample (see Table 1). It is remarkable that these are all *barred galaxies* with *high central activity* and far-infrared (FIR) luminosities of a few $10^{10}\,\mathrm{L}_\odot$ (see Tables 2 and 3), often revealing *outflow* of gas from the central region. They also frequently contain megamasers and Seyfert nuclei although the starburst activity usually dominates the total power output.

Sérsic & Pastoriza (1965) had already noted that galaxies with peculiar nuclei, e.g., NGC 1097, NGC 1365, NGC 1808, and NGC 7552 (most of them containing 'hot spots', i.e., extremely bright H II regions), are barred (SB or SAB), strongly indicating a relationship between the nuclei of galaxies and their whole structure. My main aim is to investigate further the nature of this relationship.

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[2]The Very Large Array is a facility of The Very Large Array is a facility of the National Radio Astronomy Observatory (NRAO), which is operated by Associated Universities, Inc., under Cooperative agreement with the National Science Foundation.

To understand the nuclear kinematics in these galaxies — which are probably very much alike — sensitive *high-resolution* H I observations need to be carried out which can at least partly resolve the central continuum. A summary of our high-resolution ATCA observations is given in Section 3. Section 4 contains a literature review of the sample of galaxies described above, including some of our new results, and a comparison with strongly interacting galaxies and others with broad H I absorption lines. As a summary I present a global model in Section 5.

Table 1. Some properties of the H I absorption and emission lines in the selected galaxies

Name	$v_{\rm abs}$ range	$\Delta v_{\rm abs}$	$v_{\rm em}$ range	$\Delta v_{\rm em}$	gradient	*Ref.*
	[km s^{-1}]		[km s^{-1}]		[km s^{-1} arcsec^{-1}]	
NGC 253	75–330	255	75–400	325		(a)
NGC 660	640–1050	410	675–1050	375	87	(b)
NGC 1068	760–1300	540	900–1300	400		(c)
NGC 1365	1473–1786	313	1432–1840	408		(d)
NGC 1808	820–1180	360	810–1190	380	13	(e)
NGC 3034	66–375	309	50–380	330		(f)
NGC 3079	840–1420	580	860–1420	560	500	(g)
NGC 3628	650–1080	430	670–1020	350	27	(h)
NGC 4945	380–740	360	355–750	395		(j)
Circinus	350–550	200	285–590	295		(k)
NGC 6221			1300–1650	350		(l)
NGC 7552	1500–1700	200	1460–1760	300		(l)
NGC 7582	1380–1780	400	1380–1810	430		(l)

Column (1): Galaxy name. *Columns (2)–(5):* The velocity range observed in H I absorption and emission, respectively. *Column (6):* Lower limit to the velocity gradient of the H I absorption feature, when resolved. *Column (7):* References. (a) Dickey, Brinks & Puche 1992; (b) Gottesmann & Mahon 1990; Baan, Rhoads & Haschick 1992; (c) Gallimore et al. 1994; Brinks et al. 1995; (d) Jörsäter & van Moorsel 1995; (e) Koribalski, Dickey & Mebold 1993; (f) Weliachew, Fomalont & Greisen 1984; Crutcher, Rogstad & Chu 1978; (g) Irwin & Seaquist 1991; Baan & Irwin 1995; (h) Schmelz, Baan & Haschick 1987; Wilding, Alexander & Green 1993; (j) Ables et al. 1987; (k) Koribalski & Whiteoak 1996; (l) Koribalski, Lavezzi, Dickey & Whiteoak 1996.

2.1. The Puzzle

There are mainly two questions to be addressed: 1) What causes the large velocity width (several hundred km s^{-1}) of the absorption lines detected against the nuclear regions of galaxies? 2) Why are the absorption line widths observed against the nuclear radio continuum similar to those measured in emission over the whole extent of the galaxy? The problem is illustrated well in Fig. 1 which shows a typical H I position-velocity diagram of a starburst galaxy (here NGC 1808); both the H I emission and absorption lines cover nearly 400 km s^{-1}.

To address these question one should first examine the conditions for observing neutral hydrogen gas in absorption[3]: we need *cold* atomic hydrogen gas ($T \lesssim$ 150 K) *in front* of a rather strong continuum source. Then, there are mainly two explanations for the large velocity range observed in absorption. The gas is either A) in turbulent motion or B) in a regular Keplerian orbit around the nucleus. Case A) means there are numerous cold gas clouds falling into and ejected out of the nuclear region. To explain the similar velocity range for emission and absorption the clouds are required to have maximum velocities similar to the rotation amplitude of the galaxy. This model is, e.g., strongly favoured by Mirabel & Sanders (1988) who in their paper conclude that *"... in the central regions of the most luminous infrared galaxies there must be high concentrations of turbulent atomic gas enshrouding the nuclear radio-continuum source."* Case B) requires rather high rotational velocities close to the nucleus and was therefore often rejected. But now that interferometers and VLBI techniques are used to resolve the nuclear continuum structure in galaxies those high rotation velocities have been found in nearly all cases (see Section 4). Most of the large absorption line widths can be reproduced if the rotation amplitude in the nuclear region is similar to that in the outer region of the galaxy. This requires either a rather flat rotation curve or two components with similar amplitude as for example present in the Galactic rotation curve (Dame et al. 1987). In some cases the inner part of the rotation curve has to rise toward the nucleus to explain absorption line widths much larger than the observed velocity range in emission. The extreme rotational velocities of the nuclear maser emission in NGC 4258 shows what might be happening in the centre of many starburst galaxies (see Section 4.3).

A more detailed discussion of the two cases is given by Koribalski, Dickey & Mebold (1993). In several galaxies both high rotational velocities and either infall or outflow of gas are observed.

3. Observations

In addition to detailed studies of individual galaxies like *NGC 253* (Koribalski, Whiteoak & Houghton 1995), *NGC 1808* (Koribalski, Dickey & Mebold 1993; Koribalski 1993), *NGC 4945* (Ables et al. 1987; Ott 1995), and *Circinus* (K. Jones et al. 1996, in prep.; Koribalski & Whiteoak 1996), a snap-shot survey of the brightest nearby galaxies ($F_{100\mu\rm m} \gtrsim 20$ Jy; $v_{\rm sys} \lesssim 3000$ km s^{-1}) has been carried out at declinations below $-35°$ using the largest configuration of the ATCA (Koribalski et al. 1996). The 20-cm radio continuum emission and H I were observed simultaneously. Because of the high angular resolution ($\gtrsim 6''$) the H I emission is resolved out in most cases and only H I absorption against the strongest background sources is detected. After Hanning smoothing the velocity resolution is 6.6 km s^{-1}. A large variety of nuclear structures was found

[3]H I absorption studies are used in many other areas of astronomy, e.g., in Galactic work to determine distances for pulsars, H II regions, supernova remnants, etc., and spin temperatures of the interstellar medium (ISM). In extragalactic astronomy, H I and Lyman α absorption line measurements against bright quasars can help to uncover the amount and properties of the gas in the line of sight, often out to very large distances corresponding to the early stages of galaxy evolution.

(multiple sources, such as NGC 1792; double sources, such as NGC 3883; point sources plus extended emission, such as NGC 2442, etc.) as well as broad H I absorption lines against the strongest nuclear sources.

To investigate the relationship between the processes occurring in the nuclear regions of galaxies and their large-scale dynamics follow-up observations have been carried out of several of those galaxies showing H I absorption in the snap-shot survey. For that project the rather compact 375-m configuration (to pick up faint extended emission, e.g., tidal tails and bridges between neighbouring galaxies) and the intermediate 1.5-km configuration of the ATCA were chosen; some of the preliminary results are presented here. The angular resolution varies and is given in each of the figure descriptions whereas the velocity resolution is the same as before.

4. Galaxies with Broad H I Absorption Lines

4.1. The Group of Nearby Starburst Galaxies

This section describes a group of relatively nearby spiral galaxies showing a variety of activities. The original selection criterion for this sample was the presence of broad H I absorption lines — a quite unusual criterion at first glance, but a very valuable one in the later interpretation of the overall kinematics in these galaxies. Such broad absorption lines are quite peculiar, because they indicate a large range of velocities both blue- and red-shifted in a very tiny region just *in front* of the radio continuum emission. Since such a broad H I absorption line was detected in NGC 1808 (see below) I wanted to know its origin and the relation to the surrounding medium in the galaxy.

The galaxies with broad H I absorption lines can be divided into two different groups, one consisting of relatively nearby luminous spirals (see Tables 1, 2 and 3) and the other of distant ultra-luminous mergers (see Table 4). In the following I will take a closer look at the members of the first group.

Starbursts are thought to be the result of gas accretion toward the central regions of galaxies. There are mainly two mechanisms known which can transport mass into this region: either tidal interactions or bars (see e.g., Combes 1988). I suggest that the broad H I absorption lines in the central region of most luminous spirals (see Table 1) are caused by a fast-rotating ring of cold gas. The accretion of gas in the inner region (probably near the inner Lindblad resonances) could have been induced by the bar potential of these galaxies (see e.g., Combes & Gerin 1985). Since outflow of gas from the central region is another phenomenon observed in this group of galaxies I propose a model in which the neutral gas is fuelling the nuclear starburst where it is partly ionized and then ejected by supernova explosions and stellar winds (see Section 5).

NGC 253 is a nearby edge-on galaxy and the brightest member of the Sculptor group. Its nuclear region is particularly active, revealing numerous compact radio sources (Antonucci & Ulvestad 1988), as well as bright optical and infrared emission lines. The strong and extended radio emission makes it especially suitable for H I absorption measurements (see e.g., Combes, Gottesman & Weliachew 1977; Dickey, Brinks & Puche 1992; Koribalski, Whiteoak & Houghton 1995).

Figure 2. (top) H I distribution of the starburst galaxy NGC 253.

Figure 3. (bottom) H I mean velocity field of NGC 253 (for a full description see Koribalski, Whiteoak & Houghton 1995). The data were taken with three different arrays of the ATCA (12 h each).

Gardner & Whiteoak (1974) also measured broad H_2CO and OH absorption lines. NGC 253 reveals a bar which has been detected in the near-infrared (Scoville et al. 1985; Forbes & DePoy 1992), optical (Pence 1980), and — on a much smaller scale — in the CO emission (Canzian, Mundy & Scoville 1988; see also Mauersberger et al. 1996). Various authors have also indicated the possibility of large-scale outflow of ionized gas into the halo (see Schulz & Wegner 1992, and references therein). Extended X-ray emission has been observed by Fabbiano & Trinchieri (1984) and Pietsch & Trümper (1993) using the Einstein- and ROSAT satellites, respectively.

Table 2. Some basic parameters of the selected galaxies

Name	α(2000) [h m s]	δ(2000) [° ′ ″]	Type	i [°]	v_{21} [km s^{-1}]
NGC 253	00 47 33.1	−25 17 18	.SXS5..	78	251
NGC 660	01 43 01.4	+13 38 37	.SBS1P.	65	853
NGC 1068	02 42 40.2	−00 00 48	RSAT3..	40	1137
NGC 1365	03 33 36.6	−36 08 17	.SBS3..	60	1662
NGC 1808	05 07 42.8	−37 30 51	RSXS1..	57	1005
NGC 3034	09 55 54.0	+69 40 57	.I.0../	82	203
NGC 3079	10 01 58.2	+55 40 43	.SBS5./	85	1125
NGC 3628	11 20 16.3	+13 35 22	.S..3P/	82	847
NGC 4945	13 05 26.2	−49 28 15	.SBS6*/	78	560
Circinus	14 13 10.2	−65 20 20	.SAS3*.	60	438
NGC 6221	16 52 46.7	−59 12 59	.SBS5..	43	1482
NGC 7552	23 16 10.9	−42 35 01	PSBS2..	28	1585
NGC 7582	23 18 23.3	−42 22 11	PSBS2..	64	1575

Column (1): Galaxy name. *Columns (2) & (3):* Galaxy position. *Column (4):* Galaxy type. *Column (5):* Approximate galaxy inclination. *Column (6):* Mean heliocentric radial velocity derived from H I observations.
References: All parameters except the inclination are taken from the Third Reference Catalog (RC3) by de Vaucouleurs et al. (1991). The galaxy inclination has either been taken from the H I catalog by Huchtmeier & Richter (1989) or references mentioned in the summary of the individual galaxies.

Figures 2 and 3 show the H I gas distribution and velocity field of NGC 253, respectively. The emission is distributed rather similar to the optical light and shows a rather regularly rotating spiral galaxy (Koribalski, Whiteoak & Houghton 1995). The H I absorption against the central continuum sources causes the prominent 'hole' in the centre of the distribution. The major-axis position-velocity diagram of NGC 253 is rather similar to that of NGC 1808 (Fig. 1), with one major difference: here the absorption spectrum is not quite as broad as the emission spectrum and it is asymmetric with respect to the systemic velocity (see Table 1). Whereas the large width of the absorption is most likely caused by a fast-rotating nuclear ring, the asymmetry of the line has been interpreted as due to gas outflow from the nuclear region. A detailed analysis of the H I data is in progress.

Table 3. Far-infrared flux, luminosity and derived star-formation rate

	D [Mpc]	F_{FIR} [10^{-11} W m^{-2}]	L_{FIR} [10^9 L$_\odot$]	SFR [M$_\odot$ yr^{-1}]
NGC 253	3.4	5.59 (a)	20	5.2
NGC 660	11.2	0.35 (a)	14	3.6
NGC 1068	15.2	0.97 (b)	71	18.4
NGC 1365	20.5	0.51 (a)	68	17.6
NGC 1808	10.9	0.57 (c)	21	5.5
NGC 3034	3.25	5.84 (a)	19	4.9
NGC 3079	15.6	0.25 (b)	19	4.9
NGC 3628	10.2	0.31 (a)	10	2.6
NGC 4945	6.7	3.70 (a)	52	13.5
Circinus	3.6	1.21 (d)	5	1.3
NGC 6221	17.7	0.22 (d)	22	5.6
NGC 7552	20.9	0.36 (d)	50	12.9
NGC 7582	20.7	0.25 (d)	34	8.8

Column (1): Galaxy name. *Column (2):* Adopted distance, assuming $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. *Column (3):* Far-infrared flux as calculated from the IRAS $60\,\mu$m and $100\,\mu$m fluxes. References: (a) Rice et al. 1988, (b) Young et al. 1989, (c) Danks, Perez & Altner 1990, (d) IRAS Point Source Catalog 1985. *Column (4):* Far-infrared luminosity ($\propto D^2$). *Column (5):* Star-formation rate: SFR ($M \geq 0.1$ M$_\odot$) $= 0.26 *$ column (4), see Hunter et al. (1986).

NGC 660 is a rather peculiar galaxy for which two kinematical systems exist: a nearly edge-on disk ($PA = 46°, i \approx 80°$) and an inclined polar ring or strongly warped outer disk ($PA = -7°, i \lesssim 60°$) (Gottesman & Mahon 1990; Baan, Rhoads & Haschick 1992; Combes et al. 1992). The 6-cm continuum map by Condon et al. (1982) shows quite extended emission along the inner disk with two peaks roughly $4''$ apart. H I position-velocity diagrams obtained by Gottesman & Mahon along the major axes of both systems show a broad absorption line the varying column density of which resembles the (here unresolved) continuum structure. This and the map of the integrated mean velocity dispersion shown by the authors hints at a fast-rotating nuclear ring at $PA = 46°$, thus belonging to the disk. Further, there are indications for a stellar bar (Young, Kleinmann & Allen 1988) and very tentatively for nuclear outflow (Gottesman & Mahon 1990). Baan, Rhoads & Haschick (1992) obtained both high-resolution H I and OH absorption measurements with the VLA. They found that a central disk (diameter $\sim 6''$ or 300 pc) with a large velocity gradient (see Table 1) dominates the absorption signature. The companion UGC 01195, an irregular, distorted galaxy is located $22'$ or 72 kpc away.

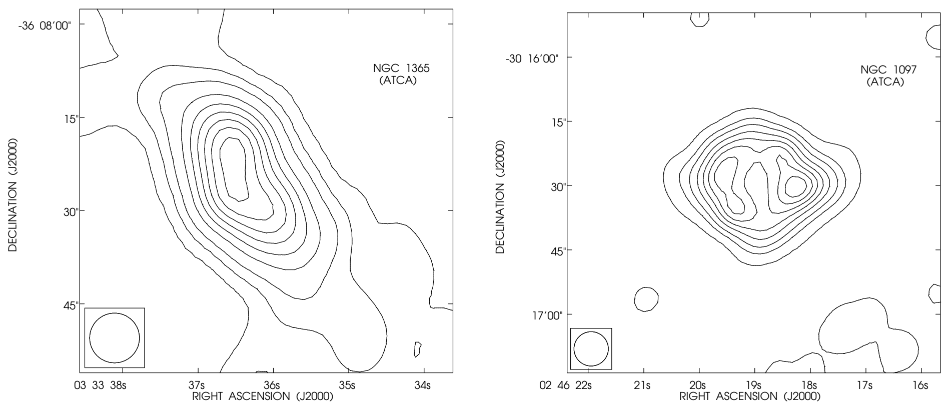

Figure 4. 20-cm radio continuum emission of the starburst galaxies NGC 1365 and NGC 1097. These data were taken with the largest array of the ATCA (snap-shot). The beam has been convolved to 8″.

NGC 1068 is a barred galaxy with a very complex nuclear region. Although it is an archetype Seyfert 2, at least half of the IR emission arises from star formation (Young, Kleinmann & Allen 1988). High-resolution (∼2″) VLA H I absorption measurements carried out by Gallimore et al. (1994) reveal several blue- and red-shifted features against the SW radio lobe and a jet as well as broad (FWHM = 128±25 km s^{-1}) double absorption lines against the radio nucleus. The absorption lines cover a total velocity range of ∼540 km s^{-1}, from ∼760 to 1300 km s^{-1}. The two lines against the core are centred at +66±12 km s^{-1} and –295±9 km s^{-1}, resulting in a mean offset from $v_{\rm sys}$ of –181 km s^{-1}. Because of this large offset Gallimore et al. reject circular orbits (which are favoured for many of the galaxies presented here), but prefer a model with two distinct, near-nuclear cloud populations, one falling into and the other flowing out of the radio core, both associated with the fuelling of and exhaust from the central engine. In case of a fast-rotating nuclear ring I would expect the radius to coincide with the inner Lindblad resonance (ILR) induced by the bar potential. It is possible that the absorption lines observed in NGC 1068 are caused by outflow and a nuclear ring as suggested for NGC 253. For comparison see also the summary of H I absorption measurements against the Seyfert galaxy NGC 4151 and the peculiar galaxy NGC 4258 in Section 4.3.

A detailed discussion of NGC 1068 and NGC 4151 is given in the chapter by Brinks & Mundell in this volume.

NGC 1365 is a southern, strongly barred spiral galaxy with no apparent companions. VLA H I observations by Ondrechen & van der Hulst (1989) show the overall gas extent of the galaxy. The central region contains a Seyfert nucleus as well as circum-nuclear radio continuum and Hα emission, indicating star formation (Saikia et al. 1994; Sandqvist, Jörsäter & Lindblad 1995). Ondrechen & van der Hulst find a strong absorption feature centred at 1570 km s^{-1}

Figure 5. (top) H I distribution of the starburst galaxy NGC 1808.

Figure 6. (bottom) H I mean velocity field of NGC 1808 (for a full description see Koribalski 1993). These data were taken with the BnC and AnB arrays of the VLA (5 h each).

with a width of only 33 km s^{-1}. But their position-velocity diagrams indicate a much broader ($\Delta v \gtrsim 200$ km s^{-1}) feature which is confirmed by Jörsäter & van Moorsel (1995) who find a total velocity width of 313 km s^{-1} for the H I absorption. Our own ATCA snap-shot observations of NGC 1365 and also NGC 1097, another strongly barred galaxy, clearly reveal H I absorption over a broad velocity range. The broad absorption features are most likely caused by a rapidly rotating ring/disk of neutral gas. For NGC 1365 a similar disk of ionized matter with a radius of 7″ has already been inferred by Lindblad (1978). NGC 1097 is in many respects very similar to NGC 1365 (see Ondrechen, van der Hulst & Hummel 1989). The continuum sources of both galaxies are displayed in Fig. 4.

NGC 1808 is a peculiar southern spiral galaxy and rather nearby example of nuclear starburst activity ($L_{\rm FIR} \approx 2{\times}10^{10}$ L$_\odot$); for a comprehensive overview see Koribalski (1993). Well known are the prominent dust filaments which emerge nearly perpendicular to its central disk (Véron-Cetty & Véron 1985; Laustsen, Madsen & West 1987), similar to those observed in M 82, indicating continuing disk-halo interactions. The nuclear region contains a number of bright 'hot spots', which are mostly interpreted as very bright H II regions (Sérsic & Pastoriza 1965; Alloin & Kunth 1979; Koribalski & Dettmar 1993). In the actual nucleus, however, Véron-Cetty & Véron drew attention to the presence of a broad Seyfert-like component of Hα with FWHM about 550 km s^{-1}. Radio observations at 6 cm reveal a number of very small ($< 1''$) compact sources in the central region, most likely to be supernovae and supernova remnants (Saikia et al. 1990).

VLA measurements of its nuclear region reveal that the broad ($\Delta v \approx$ 360 km s^{-1}) H I absorption line seen at low angular resolution is a much narrower line which shifts its centre velocity over the face of the continuum (Koribalski, Dickey & Mebold 1993). This is interpreted as a torus of cold, dense gas with a rotation velocity of ~250 km s^{-1} and radius 500 pc. The gravitational mass required to explain this fast rotation is a few times 10^9 M$_\odot$. Figures 5 and 6 display the overall H I distribution and velocity field of the galaxy NGC 1808. The central 'hole' is caused by H I absorption.

The radius and velocity of the nuclear ring are comparable to the distribution and kinematics of the optically visible 'hot spots'. The possibility of a molecular gas ring has been considered by Dahlem et al. (1990) and is also indicated in new CO(2–1) data by Aalto et al. (1994).

A stellar bar (length $\sim 3'$ or 6 kpc), which was discovered in the Hα line (Phillips 1993; Koribalski & Dettmar 1993), might be causing the gas to accumulate at the inner and outer Lindblad resonances. The inner Lindblad resonance as determined from the bar pattern speed coincides with the ring radius; the outer resonance lies just outside the pseudo-ring which is formed by the outer spiral arms.

NGC 3034 (M 82) is a typical and probably the most well-known starburst galaxy and has been extensively studied in nearly all wavelength ranges. Although M 82 is classified as a dwarf irregular galaxy, it is very similar to many of the starburst galaxies discussed here, in particular NGC 1808. High-resolution observations by Kronberg, Bierman & Schwab (1985) show that the continuum emission is concentrated into a large number of compact sources, identified as very young supernova remnants. A cylindrical outflow of dense molecular clouds and ionized gas has been observed, ejected from the disk into the halo at several hundred $\mathrm{km\,s^{-1}}$ (Nakai et al. 1987; Bland & Tully 1988). H I absorption lines shifting over the continuum source(s) clearly indicate a fast-rotating nuclear ring (Weliachew, Fomalont & Greisen 1984; Yun 1992). Telesco et al. (1991) report the detection of a bar $\sim$1 kpc long; the nuclear ring (radius $\sim$ 300 pc) lies roughly between the ILR(s) which are found at 40 and 600 pc.

NGC 3079 is a remarkable edge-on spiral galaxy. It is optically disturbed and dusty, has a Seyfert 2/LINER spectrum, an active nucleus, and starburst activity (for a summary see Baan & Irwin 1995, and references therein). Two radio lobes extending approximately along the minor axis of the galaxy — very similar to those in Circinus (see below) — suggest the presence of outflow (e.g., Duric & Seaquist 1988; Hummel, van Gorkom & Kontanyi 1983). This is also indicated by the Hα images which reveal a giant loop (Ford et al. 1986) and, on deeper images, several filaments on kpc scales (Armus, Heckmann & Miley 1990). The nuclear activity may be fuelled by an inner molecular disk (Young, Claussen & Scoville 1988) which has a radius of $\sim$400 pc. Broad H I absorption lines detected by Irwin & Seaquist (1991) probably indicate a fast-rotating ring of similar size. High-resolution VLA H I and OH absorption measurements by Baan & Irwin (1995) reveal numerous components, one of which is a rapidly rotating compact disk, extended by about 100 pc or $1\farcs25$ (see also Gallimore et al. 1994). NGC 3079 also contains the most luminous known H_2O megamaser.

NGC 3628 is a peculiar edge-on galaxy which belongs to the Leo Triplet, a nearby complex of three interacting spirals. H I observations by Rots (1978) and Haynes, Giovanelli & Roberts (1979) reveal emission in all three galaxies as well as a plume and bridge between NGC 3627 and NGC 3628. CO observations of the group have been published by Young, Tacconi & Scoville (1983). Neutral hydrogen absorption in NGC 3628 was first reported by Dickey (1982); he quotes a line width of 93 $\mathrm{km\,s^{-1}}$ (although there is a hint of faint absorption over a much larger velocity range) centred at 882 $\mathrm{km\,s^{-1}}$, close to the systemic velocity of the galaxy. VLA observations against the extended continuum of NGC 3628 by Schmelz, Baan & Haschick (1987) reveal about 10 individual H I absorption features over a velocity range of $\sim$350 $\mathrm{km\,s^{-1}}$. The velocity gradient of several strong components has been interpreted as a circular, solidly rotating disk. A very detailed study of both the H I emission and absorption in NGC 3628 has been carried out by Wilding, Alexander & Green (1993). Zhang, Wright & Alexander (1993) obtained high-resolution H I and CO measurements of NGC 3627. We obtained ATCA 20-cm radio continuum and H I snap-shot observations, but the angular resolution is rather low.

NGC 4945 is a nearby, southern, edge-on galaxy with an extremely large optical extent. Giant complexes of gas and dust in the disk give it a patchy appearance similar to NGC 253. The presence of a bar was indicated by de Vaucouleurs (1964), but further measurements are necessary to support this finding. The 'active' nucleus exhibits both starburst and Seyfert characteristics

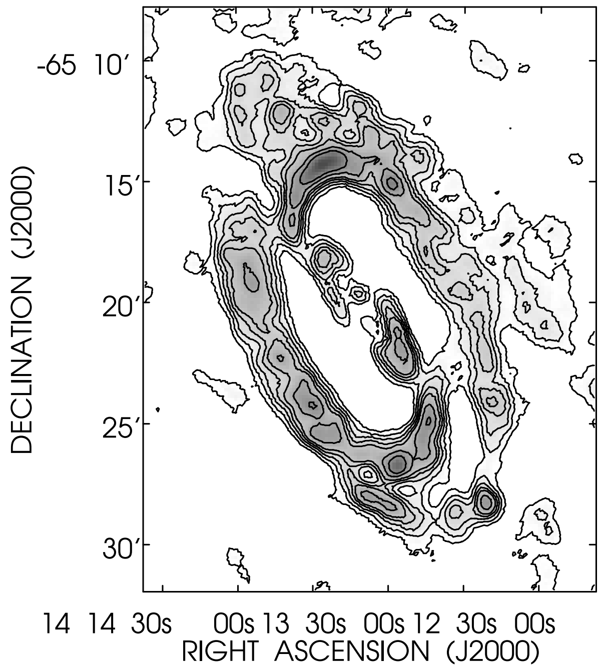

Figure 7. H I distribution of the Circinus galaxy (courtesy: K. Jones, B. Koribalski, M. Elmouttie, R. Haynes). Contour levels are 0.042, 0.063, 0.084, 0.105, 0.126, 0.169, 0.211 Jy beam^{-1} km s^{-1}. This is a very preliminary map was taken with the 750-m array of the ATCA (12 h). The angular resolution is $\sim$40″. Please note that the H I emission is extended over a much larger field than displayed.

(Whiteoak 1986). Nakai (1989) indicated the presence of optical filaments on one side of the galaxy emerging from the nuclear region toward the halo. The fan-like morphology of the outflow has a scale-height of 2 kpc and extends $\sim$10 kpc along the plane. A broad H I absorption line has been detected, but not resolved, by Whiteoak & Gardner (1976) and Ables et al. (1987). Similar broad absorption lines have also been found at other wavelengths (see Whiteoak & Wilson 1990, and references therein). Several authors find evidence for a fast-rotating molecular ring: in CO(1–0) by Bergman et al. (1992), in H_2 (2.2μm) by Koornneef (1993), and in CO(2–1) by Dahlem et al. (1993). The nuclear ring is quite thick and has a mean radius of about 100–200 pc and a rotational velocity of 200–250 km s^{-1}. A detailed study of the H I emission and absorption in NGC 4945 has recently been carried out with the ATCA by Ott (1995).

Circinus is a nearby spiral galaxy only 4° below the Galactic plane. It was found while inspecting a Schmidt plate and shortly afterwards observed in H I with the Parkes 64-m telescope. Freeman et al. (1977) measured a half-width

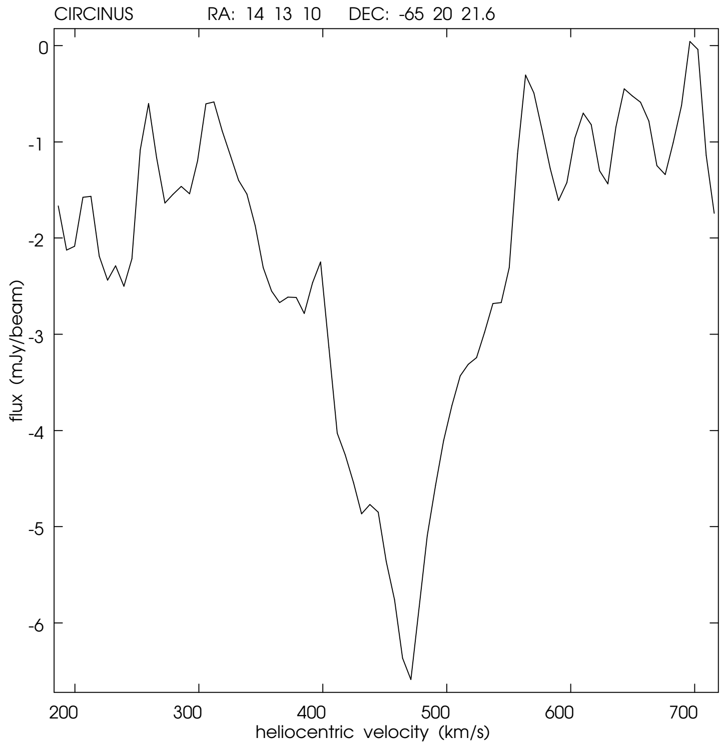

Figure 8. H I absorption spectrum toward the nuclear region of the Circinus galaxy. These data were taken with the largest array of the ATCA (Koribalski & Whiteoak 1996).

of at least $32' \times 15'$ for the H I extent of Circinus, much larger than the optical diameter ($\sim$10$'$) of the galaxy. K. Jones et al. (1996, in prep.) and Koribalski & Whiteoak (1996) only recently mapped Circinus with several configurations of the ATCA; a few preliminary results are presented here. Fig. 7 shows part of the overall H I distribution, clearly outlining the two spiral arms. The elongated central disk (length $\sim$5$'$) indicates a bar, and the central 'hole' is caused by H I absorption against the bright central region of Circinus (see Fig. 8). The nuclear activity is caused by star formation, a Seyfert 2 nucleus and giant radio lobes (perhaps associated with outflow), very similar to those in NGC 3079. Harnett et al. (1990) observed Circinus with Parkes at 1665 and 1667 MHz and found strong OH absorption lines over a velocity range of nearly 200 km s^{-1}. High-resolution ATCA measurements reveal H I absorption over about the same velocity range. The data show a shift of the line over the face of the continuum, indicating a fast-rotating nuclear ring (Koribalski & Whiteoak 1996). This is supported by Hα images taken with AAT Taurus Fabry-Perot interferometer (Fig. 9) and with the ESO New Technology Telescope (Marconi et al. 1994) showing a broken ring or spiral arms at $\sim$200 pc from the nucleus. Marconi et al. also found an O III emission cone toward the NW indicating highly ionized gas flowing out from the nuclear region.

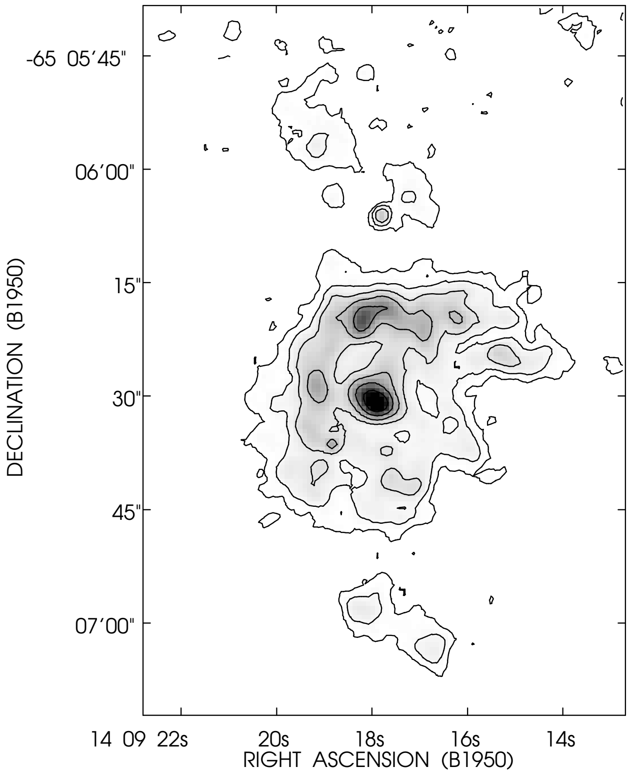

Figure 9. Hα emission from the nuclear region of the Circinus galaxy. This is a very preliminary image taken with the TAURUS-2 Fabry-Perot instrument at the Anglo-Australian Telescope (courtesy: B. Koribalski, K. Taylor, J. Whiteoak). The angular resolution is $\sim$1$''\!\!.$5.

NGC 6221 is a barred spiral galaxy which is interacting with its brightest neighbour, NGC 6215, and possibly also with two newly discovered low-surface brightness galaxies (see Fig. 10). The galaxy group lies only $\sim 10°$ below the Galactic plane which explains the rather crowded field in the optical. Recent measurements with the ATCA 375-m array revealed an H I bridge between the two major galaxies and several extensions of the gas envelope of NGC 6221 which can be attributed to tidal forces between these galaxies (B. Koribalski et al., in prep.). Detailed studies of the Hα line emission in NGC 6221 by Pence & Blackman (1984) revealed very large non-circular motions of the ionized gas, possibly as a result of tidal interactions and streaming motions along the bar. The H I distribution of NGC 6221 (Fig. 11) is quite similar to the optical emission; the central depression is caused by H I absorption which is observed over several hundred km s^{-1}. A nuclear ring is the most likely explanation regarding the similarity of this galaxy to others discussed here, but further data analysis is needed to confirm this idea. The H I velocity field looks much more regular than the Hα field which was reconstructed from several long-slit spectra. The nuclear activity is characterised by star formation and a weak Seyfert 2 nucleus.

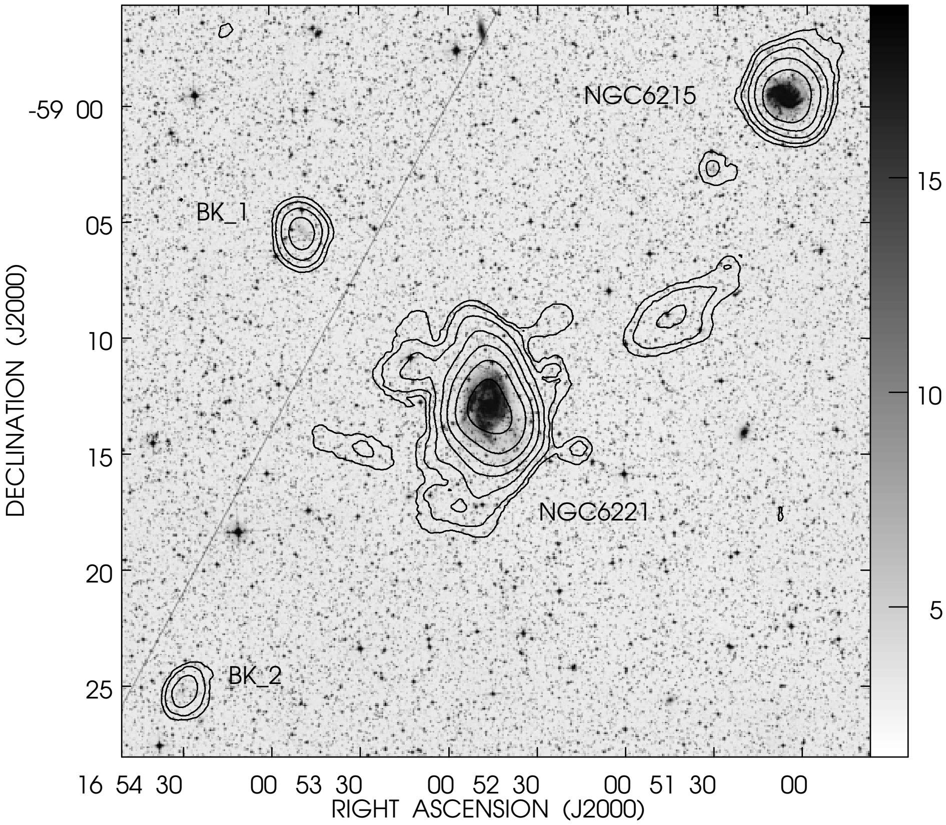

Figure 10. H I distribution (contours) of NGC 6221 and neighbouring galaxies overlaid onto the optical emission (greyscale) from the Digitized Sky Survey (DSS). The contour levels are 0.15, 0.3, 0.6, 1.2, 2.25, 4.5, and 9 Jy beam^{-1} km s^{-1}. Please note that no primary beam correction has been applied here. A tidal H I bridge is visible between NGC 6221 and its brightest neighbour, NGC 6215 ($v_{\rm sys} = 1555$ km s^{-1}). The two low-surface brightness galaxies (BK_1: $v_{\rm sys} \sim 1645$ km s^{-1} and BK_2: $v_{\rm sys} \sim 1510$ km s^{-1}) are newly discovered members of this interacting group of galaxies. These data have been obtained with the 375-m array of the ATCA (12 h). The angular resolution is about 1$'$.5.

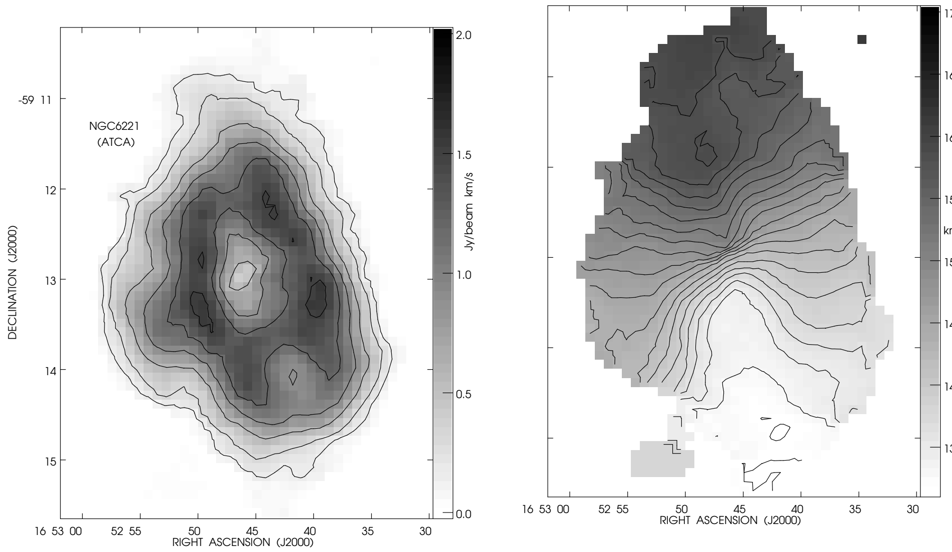

Figure 11. *Left:* H I distribution of NGC 6221. The contour levels are 0.15, 0.3, 0.6, 0.9, 1.2, and 1.5 Jy beam^{-1} km s^{-1}. *Right:* Mean H I velocity field of NGC 6221. The contour levels range from 1315 to 1615 km s^{-1}, step 15 km s^{-1}. These data have been obtained with the 1.5-km array of the ATCA (12 h). The resolution is $30'' \times 25'' \times$ 6.6 km s^{-1}.

Not much is known about NGC 6215, which is classified as a non-barred spiral galaxy of type SAS5 (RC3). Its H I emission extends from ~1450 to 1650 km s^{-1} (Fig. 10).

NGC 7552 is a prominent starburst galaxy; no active nucleus has been reported. Because of its nearly face-on inclination the strong bar is easy to identify. Although it has no close neighbours, the group of galaxies associated with NGC 7582 (see below) at a distance of ~30′ plays an important role. Forbes et al. (1994) found a 1-kpc starburst ring in NGC 7552 consisting of supernova remnants and optical 'hot spots'. We observe H I absorption against the ring and find a velocity shift of ~120 km s^{-1} between its eastern and western parts.

NGC 7582 is a barred spiral which is interacting with several bright neighbours, namely NGC 7590, NGC 7599 (see Fig. 12), and most likely also NGC 7552 (see above). Recent ATCA measurements reveal several H I bridges between the group members (B. Koribalski et al., in prep.). NGC 7582 has a Seyfert 2 nucleus, but it is clearly dominated by starburst activity as shown by strong radio emission, which probably originates from many supernova remnants, and by the presence of numerous H II regions (Morris et al. 1985). TAURUS Fabry-Perot observations of the circum-nuclear Hα emission suggest a fast-rotating disk of H II regions (diameter ~1 kpc) in the plane of the galaxy. Morris et al. also suggest

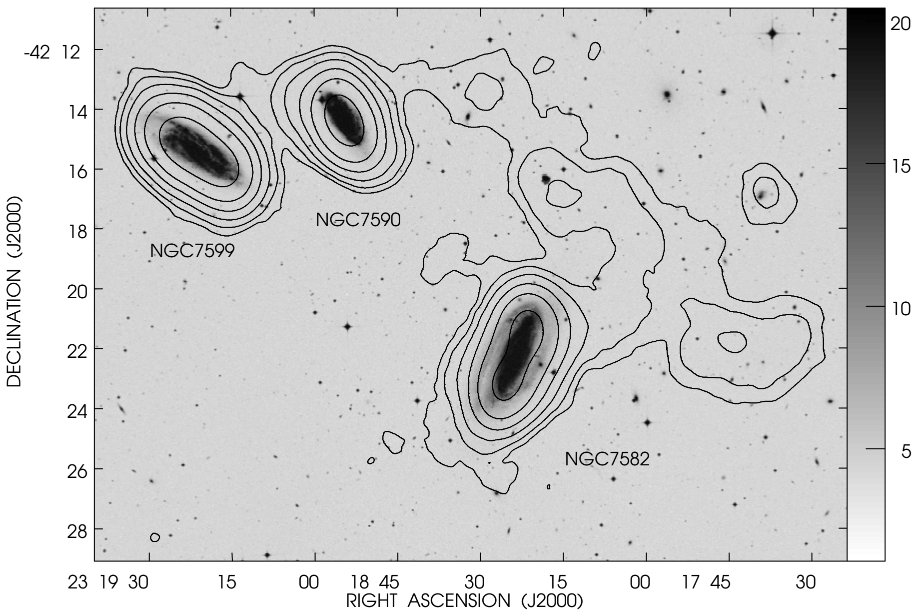

Figure 12. H I distribution (contours) of NGC 7582 and two nearby galaxies, NGC 7590 ($v_{\rm sys}$ = 1596 km s^{-1}) and NGC 7599 ($v_{\rm sys}$ = 1654 km s^{-1}) overlaid onto the optical emission (greyscale) from the Digitized Sky Survey (DSS). The contour levels are 0.15, 0.3, 0.6, 1.2, 2.25, and 4.5 Jy beam^{-1} km s^{-1}. Please note that no primary beam correction has been applied here. Several tidal tails are visible near NGC 7582, pointing toward the neighbours in the east and toward NGC 7552 which lies at a projected distance of $\sim 30'$. These data have been obtained with the 375-m array of the ATCA (12 h). The angular resolution is about $1\rlap{.}'7 \times 1\rlap{.}'3$.

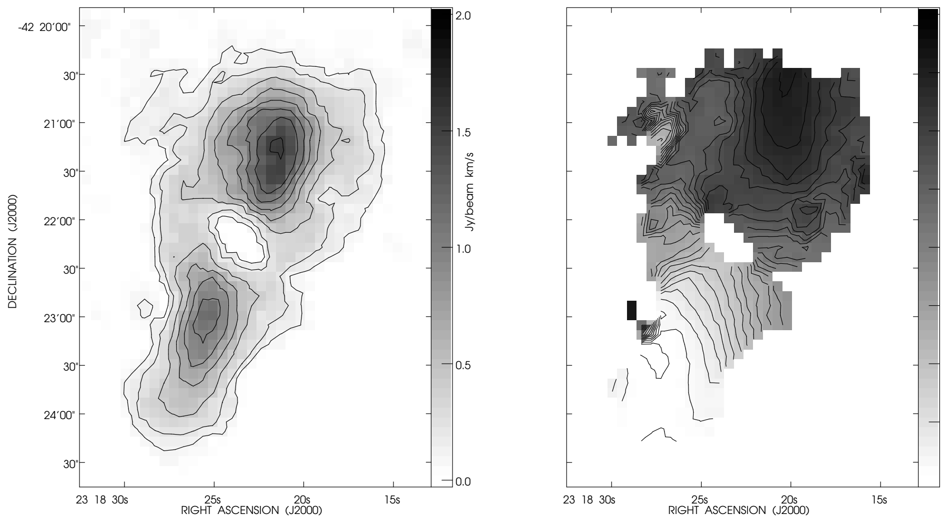

Figure 13. H I distribution and mean velocity field of NGC 7582. These data were taken with the 1.5-km array of the ATCA. The angular resolution is $38'' \times 23''$.

that blue-shifted O III line emission originates from high excitation gas expanding outwards from the nucleus in a cone. The H I distribution of NGC 7582 (see Fig. 13) is rather asymmetric (because of tidal interaction) and extends over a velocity range of at least 400 km s^{-1}. The absorption lines cover nearly the same range, but are $\sim$50 km s^{-1} blue-shifted with respect to the emission. We find the H I absorption line clearly shifting over the face of the continuum emission indicating a fast-rotating ring. Circumnuclear Hα emission, suggesting a similar feature (see above), hints at a mixture of gas phases in the nuclear region.

Recent high-resolution 8.64-GHz observations with the ATCA by Norris & Forbes (1996) suggest a double nucleus.

4.2. Strongly Interacting Galaxies

Table 4 lists a few strongly interacting or merging galaxies which also show broad H I absorption lines. These galaxies happen to be some of the nearest and more famous examples of very luminous FIR-galaxies with far-infrared luminosities of more than $10^{12}\,L_\odot$ (see also Heckman et al. 1990). They are the sites of exceedingly powerful bursts of star formation. The RC3-Type is added to show how peculiar these systems are. Several of these galaxies have also been detected in hydroxyl absorption (see e.g., Schmelz et al. 1986).

I could easily add a few more galaxies to this group (see e.g., Dickey 1982, 1986; Mirabel 1982; Heckman et al. 1983). Mirabel & Sanders (1988) find that 18 out of their 92 luminous far-infrared galaxies show H I absorption with line widths of 100–600 km s^{-1}, although some cases are very weak (e.g., U 9618, Mrk 331), and many of the detections were known before (see the references in Table 4). Interferometric studies need to be carried out to separate the H I absorption from the emission to determine more accurate line widths and centre velocities. For example, the study fails to pick up the broad absorption in the nearby polar-ring galaxy NGC 660, and there may well be others.

Table 4. Strongly interacting pairs of spirals

Name	D [Mpc]	RC3-Type	abs. line width [km/s]	*References*
NGC 520	30	.P.....	100	1,5,7
Mkn 231	160	.SAT5$P	150	1
NGC 2623	74	.P.....	525	2,5,7
NGC 3256	37	.P.....	300	10
NGC 3690/IC 694	42	.IB.9P.	300	1,5,8
IC 4553 (=Arp 220)	72	.S?....	743	2,(4),5,6,7
IC 883	92	.I..9*P	460	3,7
NGC 6240	100	.I.0.*P	700	1,3,(9)

References: (1) Dickey 1982; (2) Mirabel 1982; (3) Heckman et al. 1983; (4) Norris et al. 1985; (5) Dickey 1986; (6) Baan et al. 1987; (7) Mirabel & Sanders 1988; (8) Baan & Haschick 1990; (9) van der Werf et al. 1993; (10) English 1994.

What is happening in these galaxies? Are they scaled-up versions of the group of nearby luminous galaxies discussed in the previous section? I think the answer is *yes*. But in these galaxies the cold gas which feeds the starburst is driven inwards by strong tidal interaction or merging between galaxies (see e.g., Rieke et al. 1985), whereas in the nearby galaxies, bars and/or weak galaxy interactions may be responsible.

Are those broad absorption lines also caused by fast-rotating nuclear rings? Interferometer maps of the integrated CO emission have shown that cold gas is strongly concentrated toward the 'active' nuclei (starburst nuclei or AGN) of those systems (Sargent & Scoville 1991; Scoville et al. 1991). The kinematics, which are more clearly revealed by high-resolution H I absorption measurements, indicate that at least part of the gas rotates around the nuclei (see e.g., Baan & Haschick 1990). A very nice example is the peculiar galaxy IC 4553, where the H I and OH absorption measurements clearly indicate a fast-rotating edge-on disk close to the nucleus; the total velocity shift across the source is 145 km s^{-1} over a distance of $1\farcs9$ or ∼700 pc (Baan et al. 1987, and references therein). But there are also inward and outward motions of the cold gas. The central activity of IC 4553, which is also the best studied OH megamaser galaxy, is caused by a Seyfert 2 or starburst nucleus (see e.g., Heckman et al. 1983).

The gas distribution and kinematics in interacting systems could provide information about the merger evolution. As the interaction progresses, a large fraction of the interstellar medium (ISM) of each galaxy is expected to sink into a common centre of mass. I suggest that the cold gas is accumulated in a ring near the central source from where it is spiralling inwards, eaten up by the hungry starburst, and then partly ejected into the halo.

4.3. Other Galaxies with H I Absorption Lines

Seyfert Galaxies. NGC 4151 is a weakly-barred spiral galaxy (type PSXT2). It is also one of the best-studied examples of a nearby active galactic nucleus (AGN), and one of the original nuclei noted by Seyfert (1943). The Seyfert type is possibly intermediate between 1 and 2. Pedlar et al. (1992) investigated the

large-scale H I structure of the galaxy which covers a velocity range of about 920–1080 $\mathrm{km\,s^{-1}}$ in emission and absorption; the galaxy is viewed nearly face-on ($i \sim 20°$). They find that the most striking feature of the Hsc i emission structure is a 'fat' bar, or oval, which occupies the central 5 kpc. The distortions of the velocity field are most likely caused by the non-circular gas flows in the bar. No evidence for tidal interactions with the companions at a distance of $\gtrsim 20'$ has been found. Pedlar et al. suggest that the massive, gas-rich bar of NGC 4151 could have caused the inflow of gas to the centre (similar to the model I discuss for the nearby starburst galaxies in Section 4.1), and that the neutral hydrogen gas present within the few hundred parsec of the nucleus (as shown by the H I absorption measurements) constitutes a fuelling reservoir for the AGN.

Using the VLA B-array H I absorption toward the nuclear region of NGC 4151 was detected by Dickey (1986), with a centre velocity of 997 $\mathrm{km\,s^{-1}}$ and width of 52±15 $\mathrm{km\,s^{-1}}$. To resolve the nuclear region Mundell et al. (1995) obtained Merlin H I absorption measurements with an angular resolution of $0''.15$. They found absorption (FWHM $\sim$90 $\mathrm{km\,s^{-1}}$, centred at 993±6 $\mathrm{km\,s^{-1}}$) against the nucleus only. Several other, slightly weaker continuum sources which are part of a jet pointing toward us show no absorption. The authors therefore conclude that the neutral hydrogen disk in which the nucleus is embedded can be no thicker than 50 pc.

The H I survey of Seyfert galaxies by Heckman, Balick & Sullivan (1978) shows how the low angular resolution of even the biggest single-dish telescopes makes it nearly impossible to detect H I absorption against the nuclear continuum sources of galaxies. Out of 58 Seyfert and Seyfert-like galaxies, 25 were detected in H I emission and only three in H I absorption.

The peculiar galaxy NGC 4258: A black hole candidate. NGC 4258 is a nearby (D = 6.4 Mpc) active spiral galaxy with high luminosity H_2O maser emission. VLBI observations by Greenhill et al. (1995) and Miyoshi et al. (1995) find the masers residing in a very fast-rotating ($v_{\rm sys}$±900 $\mathrm{km\,s^{-1}}$), nearly edge-on toroid/disk of radius 0.2 pc. This provides the most compelling evidence so far for a black hole in the centre of a galaxy. — The masers are probably formed in relatively dense gas clouds that are forming new stars.

H I observations of NGC 4258 (van Albada 1978, 1980) reveal a rather flat rotation curve ($v_{\rm rot}$ $\sim$200 $\mathrm{km\,s^{-1}}$) in the outer parts of the galaxy, but a steep rise in the nuclear region. The latter prompts van Albada (1978) to speculate "that the rotational velocities near the nucleus may be significantly higher than measured, implying a larger central mass concentration." Streaming motions in the H I velocity field are attributed to the weak bar in the disk of NGC 4258 (type SXS4, see Table 2).

NGC 4258 is also well known for its anomalous arms, visible only in Hα and radio continuum, which are usually interpreted in terms of collimated nuclear outflow or jets (Cecil, Wilson & Tully 1992; Dettmar & Koribalski 1990, and references therein).

As NGC 4258, the galaxies NGC 3079, NGC 1068, NGC 4945, and Circinus each host an H_20 megamaser (apparent isotropic luminosity > 10 $L_\odot$). A position-velocity diagram of the brightest H_2O masers in the central parsec of NGC 1068 (Gallimore et al. 1996) shows a similar, but much less extreme phenomenon than NGC 4258. Other megamaser galaxies are currently investigated. Weaker H_20 masers are also known in NGC 253, M 82 and a few other galaxies (see Greenhill et al. 1990, and references therein).

Elliptical Galaxies. The nearest and most prominent radio elliptical galaxy is NGC 5128 (Cen A). H I, OH, and H_2CO absorption features have been detected near the systemic velocity of the galaxy (550 km s^{-1}). The H I absorption line extends from about 500 to 700 km s^{-1}, whereas the H I emission is much broader, extending rather symmetrically over ~500 km s^{-1} (Gardner & Whiteoak 1976, and references therein). High-resolution VLA observations by van der Hulst, Golisch & Haschick (1983) show three rather narrow absorption features, one at the systemic velocity of Cen A and the other two at +26 and +46 km s^{-1}. The red-shifted components possibly arise from clouds falling into the nucleus where they fuel the central engine; this has also been observed in several other radio elliptical galaxies (see van Gorkom et al. 1990).

Several narrow absorption features, both at the systemic velocity and at red-shifted velocities, have been observed against the nucleus of the early-type galaxy NGC 1052 (van Gorkom et al. 1986).

Other radio elliptical galaxies detected in H I absorption are NGC 315, NGC 1275, NGC 3894, NGC 5363, 3C 236, and 4C 31.06, bringing the number of detections up to eight (van Gorkom et al. 1989, and references therein).

Quasars. The first detection of H I in a quasar spectrum was made by Brown & Roberts (1973), who detected a narrow absorption line against 3C 286 at a red-shift of $z = 0.69$. H I absorption has also been detected against the QSO PKS 1157+014 (Wolfe, Briggs & Jauncey 1981) and the BL Lac object AO 0235+164 (Wolfe, Davis & Briggs 1982). For a summary see e.g., Giovanelli & Haynes (1988). Another very interesting study is that of H I absorption lines against strong radio continuum sources, many of them quasars, in the vicinity of spiral galaxies; see e.g., Corbelli & Schneider (1990) and Dickey, Brinks & Puche (1992).

Others. VLBI observations of H I absorption (3420–3590 km s^{-1}) against the active nucleus ($0''.016$ or 5 pc) of the highly luminous spiral galaxy NGC 5793 ($v_{\rm sys}$ = 3521 km s^{-1}; D = 70 Mpc) reveal several components (Gardner et al. 1992). The authors claim that these are probably caused by various clouds moving outwards, and not by a single rotating cloud complex surrounding the nucleus. But a higher sensitivity study and larger bandwidth are definitely needed to solve the issue.

Several strong absorption lines in the radio galaxy 3C 293 ($z = 0.045$) have been detected by Haschick & Baan (1985). They can resolve the broad (Δv = 480 km s^{-1}) H I absorption spectrum into more than 10 components, which can be attributed to two different structures: —a) the strongest features are part of a rapidly rotating disk surrounding the nucleus of the galaxy and —b) several high-velocity features which are either red- or blue-shifted are interpreted as clouds falling into and being expelled from the nucleus of 3C 293. The observed velocity gradient across the whole $2''\!.2$ continuum structure is 179 km s^{-1}.

Recent VLA observations of Cygnus A, the nearest powerful FR II galaxy ($z = 0.0565$), by Conway & Blanco (1995) also revealed a broad ($\Delta v = 270$ km s^{-1}) absorption line against its 15-pc nucleus. It most likely consists of two components arising from a rotating nuclear torus.

Another radio galaxy, NGC 4261 (3C 270), shows a rather narrow ($\Delta v =$ 65 km s^{-1}) H I absorption feature against its nucleus, near the systemic velocity at ~2200 km s^{-1} (Jaffe & McNamara 1994).

5. A Global Model

As a summary I present a probable model for the evolution of the nearby starburst galaxies by taking into account observations of their large-scale and nuclear gas dynamics as well as numerical simulations of gas flows in galaxies.

Since bars, which strongly influence the gas kinematics in the disk of a galaxy, can be triggered or enhanced by **galaxy interactions** (Athanassoula 1990; Gerin, Combes & Athanassoula 1990), it is necessary to study the environment of galaxies as well as their individual gas dynamics. Combes et al. (1990) show that the growing time of a bar instability (which is severely affected by various galaxy properties like e.g., the gas mass and the bulge-to-disk mass ratio) is at least $0.5\,10^9$ yr. When the bar has settled down, after about 1–$1.5\,10^9$ yr, it rotates with a high velocity. With time, the bar length grows and its pattern speed slows down slightly. All of the nearby starburst galaxies discussed here are barred and most of them show signs of tidal interaction (e.g., disturbed velocity fields, tidal tails, H I bridges). Some of the best examples are NGC 3034 (M 82), NGC 6221, and NGC 7582. Thus, it is very likely that galaxy interaction plays an important role in the **formation of bars**.

Whereas in the distant ultra-luminous galaxies like Arp 220, NGC 6240, and others (see Table 4) strong tidal interactions or merging are responsible for the central activity, the less violent starbursts in nearby galaxies like NGC 253 and NGC 1808 (see Table 2) are possibly caused by bars, or oval distortions, in the disk (Combes 1988; Heckman 1990).

The best way to analyse the overall gas dynamics in galaxies is by observing the neutral hydrogen gas. The H I velocity field, in particular, can be used to study the **streaming motions** around the bar. A good example is the barred starburst galaxy NGC 1808. Its bar is very prominent in the Hα line, which is concentrated in numerous clumps along a nearly straight line extending ~3 kpc to both sides of the nucleus. Whereas it is relatively easy to obtain velocities for the individual clumps, it is difficult to measure the velocity field of the diffuse ionized gas surrounding the bar. Although the bar is not as prominent in the distribution of the neutral hydrogen gas, the deviations from circular motions caused by the bar are immediately visible in the H I velocity field. In fact, one can nearly see the gas flowing toward the galaxy centre where it fuels the nuclear starburst.

Theoretical studies have shown that the gas orbits within a barred potential are highly elliptical and change their shape and size near the location of resonances (see e.g., Contopoulos & Grosbøl 1989). A characteristic radius in a barred galaxy is the co-rotation radius (CR) which appears to lie near or slightly beyond the end of the bar. Numerical simulations (e.g., Combes & Gerin 1985; Combes 1988) show that the gas is streaming outwards from CR to the outer Lindblad resonance (OLR) and inwards from CR to the inner Lindblad resonance (ILR). Outer (pseudo)-rings of galaxies, usually formed by the spiral arms, indicate the accumulation of gas at the OLR. The ILR regularly lies within the central few hundred parsec of a galaxy and high-resolution observations are needed to resolve the nuclear gas kinematics. H I absorption measurements with interferometers such as the ATCA and VLA have revealed ample evidence for such rings in starburst galaxies, some of which is summarised in the previous sections. The **nuclear rings** or tori are found to be rotating at very large speed, often at least as high as in the outer parts of the galaxy.

One unsolved problem for numerical simulations of gas flows in galaxies is the transport of matter into the star-forming region. Whereas the gas flow from the disk to the nuclear ring, is well explained by the presence of a bar, there has been no explanation on how the gas gets inside the inner Lindblad resonance where observations clearly show the existence of large amounts of molecular and cold atomic gas. (For a thorough discussion on numerical simulations of gas flows in galaxies see the chapter by Jan Palous in this volume.) To fuel, e.g., an M 82-class starburst interstellar masses of at least 10^8 $M_\odot$ are needed (Heckman 1990). Thus, some process must allow a substantial fraction of the ISM of a galaxy to flow right into the nuclear region where it generates and sustains the **star formation** activity and perhaps, in a more evolved stage, feeds an active nucleus (or a black hole). Stellar winds and supernova explosions eventually lead to the formation of chimneys and fountains, where ionized gas breaks out of the galactic plane, dragging neutral gas and dust (and magnetic field lines) out to large scale-heights. The **outflows** in NGC 253, M 82 and NGC 1808 are well studied examples.

Rieke, Lebofsky & Walker (1988) suggest a sequence for the evolution of a nuclear starburst in which star formation occurs first at the nucleus and then spreads over the whole nuclear region, accompanied by gas flowing out from the centre. In this sequence NGC 253 is the prototype of 'phase 3' where the nuclear star formation has ended and superbubbles break into the halo. In 'phase 4' the circum-nuclear star formation continues and the given prototype is M 82. At the end of the sequence, when star formation has ceased, stand galaxies like M 31 (Andromeda) where the emission is dominated by old stellar populations. M 31 is also a promising candidate for a black hole in the centre as the rotation velocity and the velocity dispersion strongly increases in the central few pc (see Dressler & Richstone 1988; Kormendy 1988, 1990). Maybe our Galaxy is also at the end of this sequence showing little star-formation activity, but large velocities in the nuclear disk (see Dame et al. 1987).

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