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A molecular outflow in the Circinus galaxy*

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Abstract. From previous work on the Circinus galaxy we postulated that $\approx 50\%$ of the molecular gas in this type 2 Seyfert nucleus is distributed in a sub-kiloparsec circumnuclear ring, probably associated with the ongoing star-burst. In addition to this, we postulated the possible presence of a molecular outflow along the galaxy's minor axis. In this work we use a modified version of the routine used previously (Curran et al. 1998), in order to model this feature. From our results we believe that a 90° wide outflow, which constitutes $\approx 40\%$ of the molecular gas within the central ± 600 pc, extends to a distance of $\approx \pm 500$ pc along the rotation axis of the ring with a maximum velocity of $\approx 190\ \mathrm{km\,s^{-1}}$. The bulk velocity, which is somewhat lower than this, gives an estimate of $\gtrsim 10^7 \mathrm{L_\odot}$ for the mechanical luminosity of the outflow. Armed with a model of the molecular gas distribution, and the fact that the large scale molecular ring appears to be perpendicular to the outflow/radio jets, we modelled how the CO luminosity varies with ring and outflow inclination i.e. Seyfert type. Our results show that in the case of a ring+outflow system, we expect very little difference in the luminosities of a face-on and an identical edge-on system. In the case of a ring only distribution however, we do expect, due to "hole" in the gas, slightly more emission from a sufficiently close edge-on system, but still not enough to account for the differences in CO luminosities which have been observed between type 1 and type 2 Seyferts. This result supports the notion that something more than mere orientation comes into play when explaining these differences, thus having major implications for the unified theories of active galactic nuclei.

Key words: Galaxy: evolution – galaxies: active – galaxies: individual: Circinus galaxy – galaxies: ISM – galaxies: kinematics and dynamics

1. Introduction

The Circinus galaxy is a highly inclined spiral galaxy lying close to the galactic plane (Freeman et al. 1977). The luminous H_2O maser activity (Gardner & Whiteoak 1982; Greenhill et al. 1995; Greenhill et al. 1997) in the galaxy suggests the presence of an active galactic nucleus (AGN). The galaxy is also host to nuclear star-burst activity (Harnett et al. 1990; Moorwood et al. 1996) and the presence of visible and near infra-red coronal lines (Oliva et al. 1994), an X-ray reflection dominated spectrum (Matt et al. 1996) and broad polarised Hα (Oliva et al. 1998) suggest the presence of a hidden Seyfert nucleus, thus making Circinus the closest example of a star-burst/Seyfert 2 galaxy.

From previous work on the molecular gas within the central Circinus galaxy (Curran et al. 1998), we determined, from ^{12}CO $J = 2 \rightarrow 1$ observations, that in addition to the presence of a molecular ring, there may exist a molecular outflow emanating along the minor axis from the core of the galaxy. Previously we determined the dynamical and kinematical properties of the ring via a routine which modelled the central gas distribution (Curran 1998).

In the first part of this paper we present the results of an outflow model of the minor axis feature and compare the results obtained with those previously estimated. The second part of the work is concerned with applying the complete model of the molecular gas distribution in order to measure the central CO emission from a similar molecular gas distribution, but inclined at 90° to that in Circinus. By comparing the emission from this system we hope to measure how, *for a given galaxy*, we expect the central CO luminosity to vary with orientation, thus allowing us to determine if we expect a statistical difference in the CO luminosity between type 1 and type 2 Seyferts (as noted by Heckman et al. 1989; Sahai et al. 1991) when observed with a filled telescope beam.

2. Recap of the minor axis feature

Previously (Curran et al. 1998), we were able to obtain a satisfactory model of the molecular ring believed to be in orbit around the nucleus of Circinus. The ring accounts for 50% of the total molecular emission (within the central 560 pc). By subtracting the model ring from the raw data we were able to deduce the presence of what appeared to resemble an outflow (Fig. 6, Curran et al. 1998) and estimate the following properties:

1. The position angle is $\mathrm{PA_c} \approx -56°$ ($\approx 304°$) towards the NW (approaching) and $\approx 124°$ towards the SE (receding).

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* Based on results collected at the European Southern Observatory, La Silla, Chile

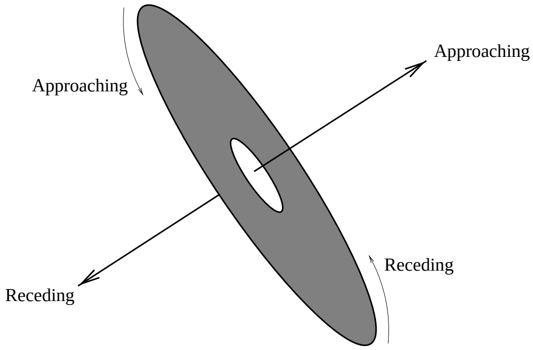

Fig. 1. The direction of rotation of the ring and the direction of outflow as viewed from Earth. Both the outflow and the ring extend to $\approx \pm 600$ pc along their respective planes

From this we were able to conclude that the ring/galactic disk is orientated so as to obscure the SE portion of the previously observed one-sided[1] ionised outflow (Harnett et al. 1990; Marconi et al. 1994; Elmouttie et al. 1995; Veilleux & Bland-Hawthorn 1997), with which the molecular outflow shares a common (approximate) orientation, Fig. 1.

2. The maximum outflow speed is $|v_{\rm c}| \approx 350$ km s^{-1}, being in good agreement with the velocity determined for a possible molecular outflow previously observed towards the NW (Elmouttie et al. 1997).
3. As with the ionisation cone (Veilleux & Bland-Hawthorn 1997), the conical angle is large, CA$\gtrsim 90°$.
4. The outflow extends to $\approx \pm 600$ pc from the centre position.

3. Modelling a molecular outflow

3.1. Model parameters

3.1.1. Introduction

An outflow was modelled according to a modified version of the routine described in Curran (1998), which allowed the addition of a "conical outflow" to the disc/ring. The outflow is modelled as the hat of a one pixel thick cone and defined via a position angle (PA$_{\rm c}$), an inclination angle ($i_{\rm c}$), a conical angle (CA), an outflow velocity[2] ($v_{\rm c}$), an extent from the origin ($r_{\rm c}$) and a relative intensity ($I_{\rm c}$). This is defined per pixel, and as in the ring model, can be varied along the cone. We found that, however, a constant intensity (over each of the two half cones) was sufficient in obtaining a match to the observed spectra. Finally, the model is "observed", as previously, according to the required HPBW.

3.1.2. The model

Previously, as mentioned in Sect. 2, the feature was estimated to have a maximum possible outflow speed of 350 km s^{-1}. Such high velocities, however, cannot be dominant near the edges of a wide (CA$\sim 90°$) outflow since these would appear to be Doppler shifted in the observed data. Since no such Doppler shifts are observed, there are two exclusive possibilities:

1. A fast narrow outflow.
2. A slower wider outflow.

Testing these possibilities, it became clear that a compromise between the two seemed to be the case, i.e. where the outflow has an intermediate velocity. This model (Table 1) still had a wide opening angle so, in order to account for the observed radial velocities, we postulate that a relatively high velocity is present close to the outflow axis but this decreases with increasing angular distance. We discuss this further after summarising the model parameters in the next paragraph.

Table 1. Summary of the outflow properties along the axis. The values obtained are explained in the main text

Quantity	SE	NW
Right ascension (1950)	$14^h09^m17^s.5 \pm 1$	
Declination (1950)	$-65°06'19'' \pm 4''$	
PA$_{\rm c}$	$120° \pm 20°$	$300° \pm 20°$
$i_{\rm c}$	$-12° \pm 10°$	$168° \pm 10°$
CA	$90° \pm 5°$	
$v_{\rm c}$ [km s^{-1}]	190 ± 10	-190 ± 10
$r_{\rm c}$ at 4 Mpc	$\approx \pm 500$ pc	
$I_{\rm c}$	5 K	3 K

In Fig. 2, we show the spectra resulting when this model is observed with a $22''$ (CO $2 \rightarrow 1$ at SEST[3]) beam, superimposed upon the observed CO $2 \rightarrow 1$ spectra, and in Table 1 we list the outflow properties according to the model. Here the right ascension and declination are quoted for the central position of the galaxy according to Freeman et al. (1977) with our uncertainties in right ascension and declination added; these are due mainly to the absolute pointing errors, typically $3''$ (the relative errors are considerably smaller), which are significantly larger than the model errors. The position and inclination angles appeared to coincide with that of the rotation axis of the molecular ring and so we initially set these accordingly while constraining the other parameters. The values for the conical angle, velocities, extent ($25'' \pm 3''$), relative intensities and finally the inclination and position angles were constrained using a routine which gave a ratio between the r.m.s. of the model residuals and the r.m.s. of the noise; the *residual-to-noise ratio*, thus enabling us to choose between models which gave similar by-eye results, i.e. appearing as in Fig. 2. Returning to the velocity/conical angle issue, as seen from Table 1, the velocity of the outflow is $\approx 190 \pm 10$ km s^{-1}, giving a maximum radial velocity[4] of

[1] Only the NW portion of the ionisation cone is generally observed, although our previous work suggests that the molecular outflow is strongest in the SE.

[2] As with the disc/ring model, approaching gas is assigned a negative velocity and receding gas a positive velocity.

[3] The Swedish-ESO Sub-millimetre Telescope is operated jointly by ESO and the Swedish National Facility for Radio Astronomy, Onsala Space Observatory, Chalmers University of Technology.

[4] The value of $\approx 190 \pm 10$ km s^{-1} was obtained directly from the model, but it should be kept in mind that any uncertainties in the inclination must be considered when discussing projected velocities.

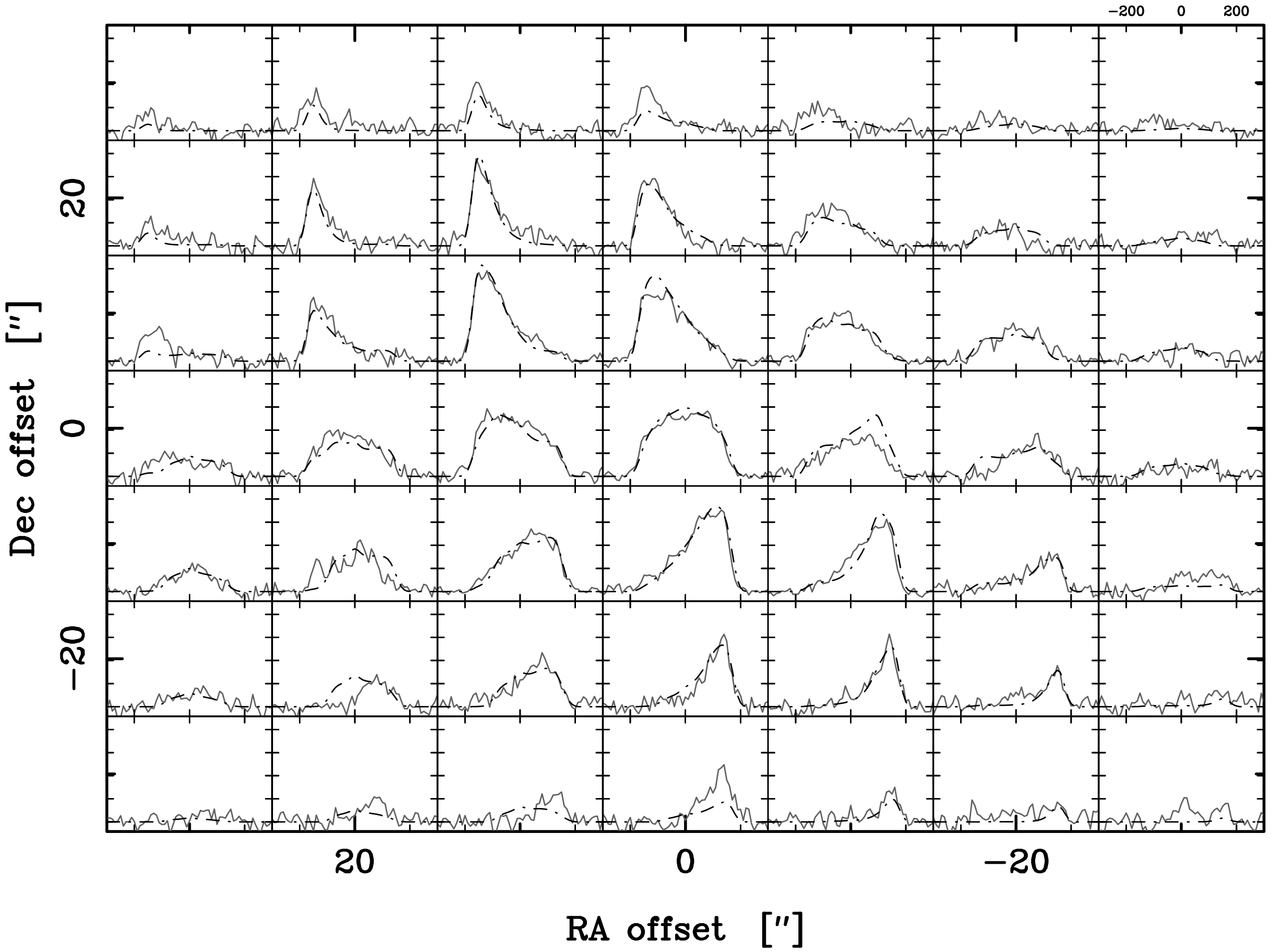

Fig. 2. The optimum model (broken-dotted) spectra superimposed upon the observed spectra (full). The velocity resolution is 10 km s^{-1} and the intensity scale is $T_{\rm A}^{*}$

$\approx 160\pm30$ km s^{-1} (for $\Delta i_{\rm c}=\pm10^{\circ}$ and $\Delta{\rm CA}=\pm5^{\circ}$), at the nearer edge of the NW cone, where the inclination is maximum. This is somewhat higher than the $\approx 90\,^{+20}_{-10}$ km s^{-1} we estimate from the observed bulk radial velocity of $\lesssim 73$ km s^{-1} (Curran et al. 1998)[5], but high speed components are evident in the CO $2\rightarrow1$ maps. So since this "wide-intermediate-speed" model gives a satisfactory fit to the observed data (Fig. 2), we suggest that, in order to produce the lower observed velocities, the gas is indeed ejected along the axis with this speed but perhaps decreases in velocity with increasing angular distance to the extent that the bulk of the gas has a lower velocity. This idea is consistent with the work of Morris et al. (1985); Hjelm & Lindblad (1996) who postulate such a decrease in velocity in order to account for the low velocity gas in ionisation outflows. So this result is perhaps what we would expect if the ionised and molecular gas is ejected from the nucleus by the narrow (15°) jet present in Circinus (Elmouttie et al. 1995), and in fact, for the approaching edge, an outflow of velocity -190 km s^{-1} at the edge of a 21° wide cone will give an observed radial velocity of -73 km s^{-1}.

In the case of the orientation parameters, we quote in Table 1 an uncertainty of $\pm20^{\circ}$ and $\pm10^{\circ}$ for the values of position and inclination angle, respectively. The errors are defined by a 10% increase in the residual-to-noise ratio.

When we sum the model spectra intensities we find that the complete model constitutes 87% of the total 1.38×10^{8} K km s^{-1} pc^{2} emitted from the central $\approx 60''\times60''$, whereas the ring only model could only account for 53% of this. Approximating these values, because of the two poor non-peripheral matches (discussed below), we estimate the molecular gas structure in the central $\approx 60''\times60''$ to consist of being $\approx 50\%$ from the ring, $\approx 40\%$ from the outflow and the remaining $\approx 10\%$ from surrounding gas which is, for the most part, dynamically unrelated to the ring/outflow structure. This leads to a molecular mass estimate of $\sim 0.3-1.4\times10^{9}{\rm M}_{\odot}$, with the range being a result of the uncertainty in the Galactic conversion ratio (Strong et al. 1988) as applied to Circinus (Curran et al. 1998). We would, however, place our estimate at the lower end of this range since Sakamoto et al. (1998) suggest a gas mass fraction of $\lesssim 10\%$ in Seyfert galaxies (although we are uncer-

[5] This estimate is quoted for the nearer edge of the NW cone, which gives a minimum estimate for the velocity, although the $\lesssim 73$ km s^{-1} permits velocities of $\lesssim 130\,^{+80}_{-30}$ km s^{-1} (for $\Delta i_{\rm c}=\pm10^{\circ}$ and $\Delta{\rm CA}=\pm5^{\circ}$) at the further (receding) edge.

tain what to expect in the outflow), thus making the conversion ratio one fifth of its canonical value. Taking this lower value for the gas mass and assuming a constant bulk outflow velocity of ≈ 90 km s^{-1} (estimated from the observed bulk radial velocity of $\lesssim 73$ km s^{-1}, Curran et al. 1998) over the $\gtrsim 10^6$ years[6] to reach 500 pc, the mechanical luminosity is calculated to be $L_{mech} \gtrsim 10^7 L_\odot$. This is tapped from the AGN luminosity of $\sim 5\times10^9 L_\odot$, calculated radiatively by Moorwood et al. (1996).

3.1.3. Un-matching spectra

Returning to the poor matches between the model and observed spectra at map coordinates (20,-20) and (-10,0), a discrepancy in the latter position had previously been noted by Curran (1998) when checking the quality of the observed data, which may have been marred by a baseline error. This discrepancy became apparent when examining the data deconvolved by a MEM routine; the *Statistical Image Analysis* (SIA) routine (Rydbeck et al. 1993; Rydbeck 1999), which checks the consistency of the spectra by comparison with adjacent spectra. This is particularly effective if the data is as densely spaced as ours (Curran et al. 1998). The consistency between the SIA and model results confirms the validity of both routines to the analyses of our data. It should be kept in mind that both function *independently* of each other; only the synthesised telescope beam used to "observe" the model and the de-convolved SIA spectra is the same.

To conclude, although the value of such detailed modelling may be doubtful, there is no escaping the fact that, on the whole, the model does successfully simulate the observed spectra, with the poorly matching spectra having being predicted by the SIA routine to be of lower quality. As well as this, since the publication of the ring model (Curran et al. 1998), further observations of the molecular gas in Circinus yield a ring structure with similar parameters as well as, interestingly, obtaining the same inclination for the radio continuum (Elmouttie et al. 1998a). This result combined with the SIA results (Curran et al. 1998) gives us confidence in the ring model, which is considerably more complicated than that for the outflow.

3.1.4. Alternative models

Although it was the appearance of the two features lying along the galaxy's minor axis in Fig. 6. of Curran et al. (1998) which initially prompted us to consider them the result of an outflow, other possibilities should be considered. One such possibility is that the features are the result of a molecular bar orientated close to the minor axis.

Circinus is believed to house a large scale atomic bar which possibly terminates in the molecular ring, expected to be located close to the inner Lindblad resonance (ILR) (Jones et al. 1999). Since this bar has a position angle of $225°$, it lies close to the major axis of the ring and main galaxy body, and so a molecular component of this cannot account for the features along the minor axis. However, nuclear bars with a wide range of orientations are known to exist in some galaxies (Freeman 1996). For example, Kenney et al. (1991) observe a CO bar in M101 orientated at $\sim 25°$ to the large scale stellar bar; a larger offset of $90°$ is seen in NGC 3351 by Devereux et al. (1992). The presence of such a bar in Circinus has the merit that if it were highly inclined (i.e. in the galactic plane) it could produce the observed velocities from low de-projected velocities[7], although in order to do this and produce the observed size, the bar would be extended far beyond the canonical 1 kpc length (Devereux et al. 1992; Freeman 1996)[8], this rules out the possibility of a highly inclined bar being located within the ring. Although such an extended bar terminating in an ILR could explain the "break" (i.e. the fact that there are two distinct features rather than one lying along the minor axis), we find the idea of a $\gtrsim 2$ kpc molecular bar lying perpendicular of a ~ 5 kpc atomic bar (Jones et al. 1999) somewhat incredible. Alternatively, a bar with a similar inclination to the proposed outflow would account for the feature according to the expected ≈ 1 kpc length, this, however, reintroduces the need for similarly high de-projected velocities, and as with in the case of NGC 3079, which like Circinus is a type 2 Seyfert possessing radio lobes, we find the idea of the gas being driven out of the plane by a nuclear jet more agreeable than that of a molecular bar tilted in this direction (Irwin & Sofue 1992).

Considering the bar possibility further, a signature of the presence of a bar is a twisting in the position angle of the kinematic axis. Examples of this can be seen in the barred spiral NGC 1365 (Teuben et al. 1986; Lindblad et al. 1996) and on the large scale in Circinus (Jones et al. 1999). Examining the observed velocity contours, Fig. 3, and acknowledging that the map is only about four beam diameters to a side, we see that the iso-velocity contours exhibit no serious twists and that they change direction more as if opening out from a compact flow. Similar trends are also seen in the SIA map which is deconvolved to a resolution of $\approx 10''$. Also regarding the velocity structure, Fig. 2, although these spectra are fairly noisy, we see none of the prominent double features expecting from a rotating bar in the minor axis spectra. So considering the presence of two, as opposed to one, minor axis features, the required length/orientation and velocity structure, we must conclude that the observed data do seem to be better represented by an outflow rather than a bar.

As well as the bar scenario there exists other possible explanations for the presence the minor axis features. Namely, the radio jets shocking the interstellar medium at these locations, or recombination at the limits of the ionisation cone, where conditions have become favourable for molecules. So all we can confidently say from our data is that, upon removal of the ring model from the *observed* data, the CO gas does indeed appear

[6] This is reasonable since the star-burst associated with the formation of the AGN (Hernquist 1989; Elmegreen 1994; Vila-Vilaró et al. 1995) is $\sim 10^7$–10^8 yr old (Marconi et al. 1994; Davies et al. 1998).

[7] It is difficult to visualise, however, how the low bar velocity could couple to the ring which has a speed of ≈ 150 km s^{-1} at this radius (Curran et al. 1998).

[8] A bar in the plane of the ring would have a de-projected length of 5 kpc.

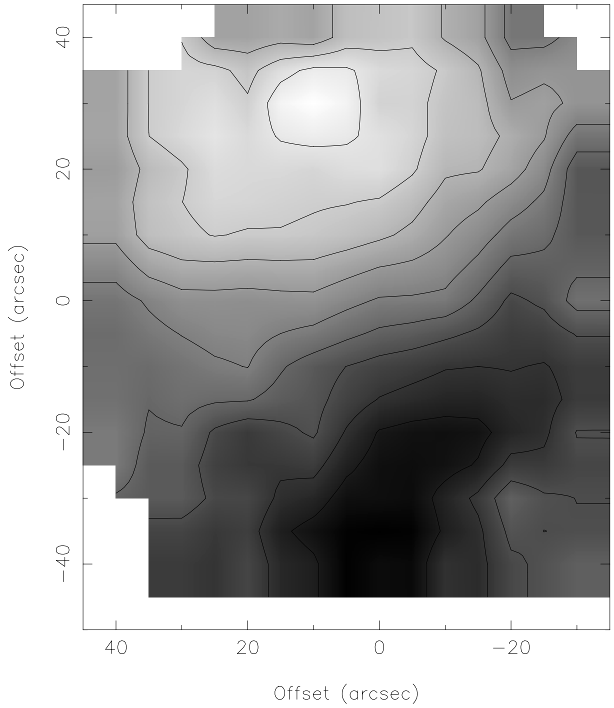

Fig. 3. The observed CO $2 \rightarrow 1$ first moment map. The peak velocities are -117 km s^{-1} (white) and 113 km s^{-1} (black). The contour increment is 12 km s^{-1}

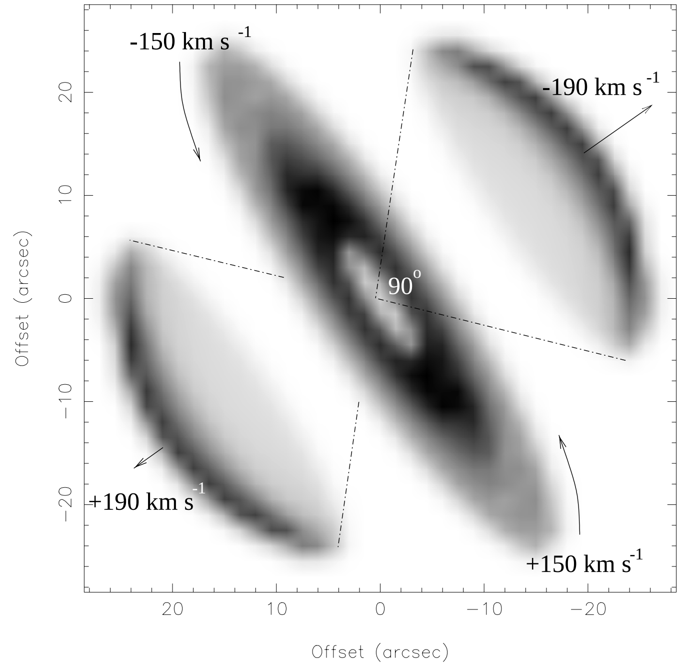

Fig. 4. A grey scale of the ring+outflow model according to the eastern intensity distribution (Sect. 3.3). The scale at 4 Mpc is $10'' \approx 200$ pc

to be present in two distinct features lying along the minor axis (Curran et al. 1998). Also, we obtain a fit to the observed spectra using a model based on a conical outflow i.e. a shell expanding from a compact region. Although, as with the ring, we shall have to wait on the availability of interferometric mapping of this source in order to truly confirm this result.

3.2. Summary

Since we have satisfactorily modelled the outflow with a hollow cone sharing the same approximate orientation ($PA_c = 295°$) and opening angle ($\approx 100°$) as the ionisation cone (Veilleux & Bland-Hawthorn 1997), we visualise the molecular outflow as possibly being funnelled by the small scale dusty molecular torus (Sect. 3.3) and ejected along with the jet/ionisation cone (Davies et al. 1998; Dopita et al. 1998), which it subsequently surrounds. A layer of dust liberated from near the nucleus (Dopita et al. 1998) possibly provides the necessary insulation between the molecules and ionised material.

This enveloping of the (NW) ionisation cone by the molecular outflow is also suggested by the recent observations of the cone by Elmouttie et al. (1998b):

1. The inclination angle derived for the molecular outflow ($-12° \pm 10°$) lies within the, admittedly large, range of that derived for the ionisation cone, i.e. between $-90°$ and $40°$.
2. The ionisation cone extends to between 400 and 520 pc, depending upon the inclination. For an inclination of $-12° \pm 10°$ the length of the ionisation cone is $510\ ^{+10}_{-30}$ pc, i.e. the same as for the molecular outflow.
3. The position angle of the ionisation cone axis is $305°$, being in good agreement with the axis of the molecular outflow (Table 1) and molecular ring axis (Curran et al. 1998).
4. The opening angle of the ionisation cone is $\lesssim 66°$. This is somewhat less than that of the molecular outflow but does not contradict the possibility that the molecules envelope the ionised matter. Note that for this opening angle, the observed bulk radial speed of $\lesssim 73$ km s^{-1} permits velocities of $\gtrsim -103$ km s^{-1} and $\lesssim 203$ km s^{-1} for the approaching and receding edges of the NW molecular outflow, respectively.
5. The outflow speed of the ionised material is between 150 and 200 km s^{-1}, thus appearing to co-move with the fastest component of the molecular gas.

These results lend weight to the argument that the two outflows are indeed connected. The only, but significant, possible disagreement with the results of Elmouttie et al. (1998b) is the fact that the NW lobe of the ionisation cone appears to be receding, whereas, in common with the polarised radio lobes (Elmouttie et al. 1995), this portion of the molecular outflow is approaching. Elmouttie et al. (1998b) do, however, note blue-shifted gas in the ionisation cone and attribute this to a mass inflow. We suggest that this blue-shift is due to the outflow approaching as opposed to such an inflow, which would require the presence of a strong bar (Gerin et al. 1988; Benedict et al. 1996; Regan et al. 1997), although, in common with their results, there is a red-shifted region observed in the SIA CO $2 \rightarrow 1$ map of Curran et al. (1998). The molecular ring+outflow structure is summarised in Fig. 4.

Returning to Sect. 2, we see that the outflow properties, as derived from the modified model, lie within the parameter ranges as previously estimated by Curran et al. (1998). As with the molecular ring, we note an asymmetry between the opposing regions of the outflow, with the outflow being more luminous in the SE. This is also as noted from the residuals (Fig. 6) of Curran et al. (1998), and is as in the case of the radio continuum emission observed at 843 MHz (Harnett et al. 1990). Elmouttie et al. (1995) observe the radio lobe to be strongest towards the NW although, as in the case of the optical observations (Marconi et al. 1994), this is probably due to these higher frequencies (1.5 and 2.3 GHz) being obscured by the molecular disk which is expected to be coplanar with the disk of the galaxy (McLeod & Rieke 1995), Fig. 4.

3.3. *Differences expected in the molecular emission between type 1 (Sy1) and type 2 (Sy2) Seyfert galaxies*

According to unified models of AGNs (Antonucci & Miller 1985; Krolik & Begelman 1986; Antonucci 1993), the absence of broad lines in some Seyfert (type 2) galaxies is accounted for by invoking the presence of a sufficiently inclined small scale dusty molecular torus which obscures the type 1 Seyfert nucleus, nested in all Seyferts. This implies that the observed differences between these two classes are determined *solely* by the orientation of the torus relative to the observers line-of-sight to the nucleus. Heckman et al. (1989), however, have found that in Sy2s the observed ratio of the CO luminosity, $L_{\rm CO}$, as a fraction of the blue luminosity is a factor of two greater than for Sy1s. Further, Sahai et al. (1991) find that for the Sy2s, $L_{\rm CO} \propto {L_{\rm blue}}^2$, while being directly proportional to $L_{\rm blue}$ for Sy1s. This could be a consequence of an intrinsic difference between the two classes, thus, at the very least, modifying the unified schemes of AGNs.

In the case of Circinus, the CO ring is probably associated with the 200 pc radius star-burst ring observed in Hα by Marconi et al. (1994) and, as mentioned previously, the molecular outflow and ring rotation axis appear to share the same position angle as the continuum and Hα outflows (Harnett et al. 1990; Veilleux & Bland-Hawthorn 1997), which are probably funnelled by the obscuration (Antonucci & Miller 1985). Thus our results lend weight to the argument that the obscuring torus may be a dense component of a continuous structure (Fosbury et al. 1999; Conway 1999) which spans all the way from the atomic gas on kpc scales to consequently feed the molecular gas to $\gtrsim 100$ pc scales (Shlosman et al. 1990; Friedli & Martinet 1993; Shaw et al. 1993) which in turn ultimately feeds the central engine (Krolik & Begelman 1988).

If this is the general case, we can test how the emission from the molecular structure in Circinus would appear if it were inclined perpendicular to its actual orientation, thus providing a clue if the differences noted by Heckman et al. (1989) could be explained through aspect alone. Since we believe that, in addition to the expected molecular ring (e.g. Myers & Scoville 1987; Harnett et al. 1990; Plante et al. 1991; Irwin & Sofue 1992; Dahlem et al. 1993; Kohno et al. 1996), there exists an outflow in Circinus, which may or may not be a common Seyfert feature (e.g. Irwin & Sofue 1992), we feel that, in order to be truly general, any distribution which hopes to model the gas at various orientations must have the option of including such an outflow. Now that we are armed with a model which gives a satisfactory fit to the observed data, it is trivial to incline this by 90°, thus simulating the spectra we would obtain from Circinus were it a "Seyfert type 1". Heckman et al. (1989) observed the centre position of their sample galaxies in CO $1 \rightarrow 0$ with the 12 m telescope at NRAO, thus having a HPBW of $55''$. Naturally, for a galaxy apparently small enough in comparison with the beam we expect the total emission to be largely independent of the orientation of the CO structure[9]. This is not expected to be the case, however, when observing apparently large galaxies (i.e. those which fill the telescope beam) since in the Sy1 case (CO ring face-on) the central position will coincide with the "hole" in the ring, whereas in the Sy2 (CO ring edge-on) case the full path length through the ring will be observed.

It seems reasonable to assume that a symmetrical model will provide a more general case, and so we chose arbitrarily the eastern model i.e. the (north) eastern portion of the ring and the (south) eastern portion of the outflow (Sect. 3.2) for the standard molecular gas distribution. In order to show how the (central) model profiles change with orientation, the central spectra for the ring only and ring+outflow models observed at various inclinations with a CO $2 \rightarrow 1$ beam are shown in Figs. 5 and 6, respectively.

As seen from Fig. 6, if an outflow is present in a low inclination system we expect a distinctive 3-component profile; a narrow central component from the disc (Fig. 5) and two Doppler shifted components from the outflow. Referring to previous CO surveys in Seyfert galaxies (Heckman et al. 1989; Maiolino et al. 1997; Papadopoulos & Seaquist 1998), we fail to find any clear detections of such features. In these surveys, the signal-to-noise ratios of the Sy1s (or more accurately non-Sy2s) are too low in order to distinguish any possible outflow features from the noise. Of the detections, only Mrk 231 is listed in the NASA/IPAC Extragalactic Database as a Sy1 with the remaining galaxies being given an intermediate class (Osterbrock 1981); NGCs 3227, 4051, 6814 as Sy1.5, NGC 7469 as Sy1.2 and NGC 5033 as Sy1.9! From these models we note that beyond a molecular ring inclination of $\approx 40°$, the central profile starts to resemble that of a Sy2. This is seen in the observed profiles of the above mentioned sources, and according to the results of Maiolino & Rieke (1995), the large scale molecular ring is expected to cause some degree of obscuration above these disk inclinations, thus making such galaxies appear as type 1.8 or 1.9 Seyferts, i.e. nearly edge-on. The presence of a dusty molecular outflow may also cause such a dimming of the narrow and broad line regions.

Since Dopita (1998) postulates that, due to the depletion of accreting gas, the opening angle will increase as the system evolves, we modelled the system with such a widened outflow. Our aim is to estimate the spectrum expected from a Sy1 with

[9] Optical depth effects might change this.

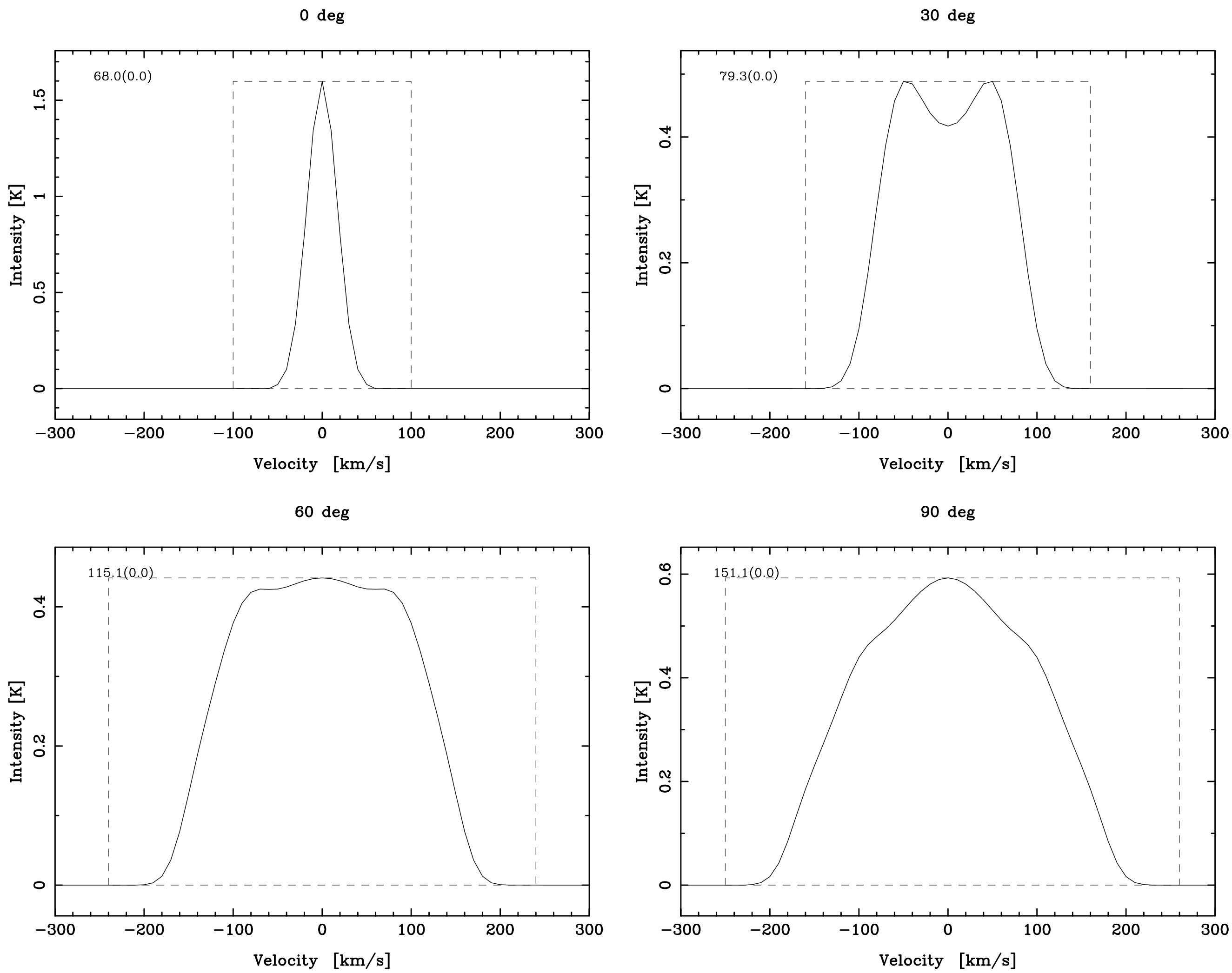

Fig. 5. The ring model observed at various inclinations with a $22''$ beam. The integrated intensities (top left in each frame) are given in K $\mathrm{km\ s^{-1}}$ and the velocity resolution is 20 $\mathrm{km\ s^{-1}}$

an outflow, as opposed to simply a "face-on Sy2". The results are summarised in Fig. 7.

As seen from Fig. 7, even if the outflow is wide, we still expect it to be apparent in a system of low inclination. Since we have no details on how the gas is depleted, the intensity of the contribution from the ring in comparison with the outflow should not be taken too literally. Indeed it is perfectly possible that Sy1s exhibit no such molecular outflows due to this very same depletion of the accreting gas (Dopita 1998). When we compare Fig. 7 with the CO $2 \rightarrow 1$ spectrum obtained from the (true) Sy1 NGC 4593[10], we see that features at $\pm \approx 140\ \mathrm{km\ s^{-1}}$ to a central feature of $\approx 2500\ \mathrm{km\ s^{-1}}$ cannot be ruled out. So in summary, all we can say at this point is that it would be of great interest to obtain a high signal-to-noise profile of a truly face-on system in order to see if the 3-component profile is indeed observed.

Returning to the question on the differences in molecular gas abundances between the two Seyfert classes, in order to quantify the beam filling factor, the ratio of the optical size of the major axis (de Vaucouleurs et al. 1991) of Circinus was compared to that of each sample galaxy of Heckman et al. (1989). The telescope beam was then scaled accordingly in order to simulate Circinus at different apparent sizes (i.e. distances). It should be noted that when we apply this to the sample, the beam filling factor depends upon the size as well as the distance to the galaxy. Thus by setting Circinus to the same apparent diameters we are assuming that the extent of the CO emission is directly proportional to the optical size of the galaxy. This may not generally be true but at least this method will provide information on how the emission changes as a function of orientation *only* for a given apparent size. In addition to the standard model, we produced a map of the edge-on model by changing the inclination of the ring from 78° to 168° and the inclina-

[10] Obtained during a survey of Seyferts which we are currently undertaking with which we plan to compare the results with Figs. 5, 6 and 7, although as with the previous surveys, the signal-to-noise ratios may prove too low in order to yield unambiguous results.

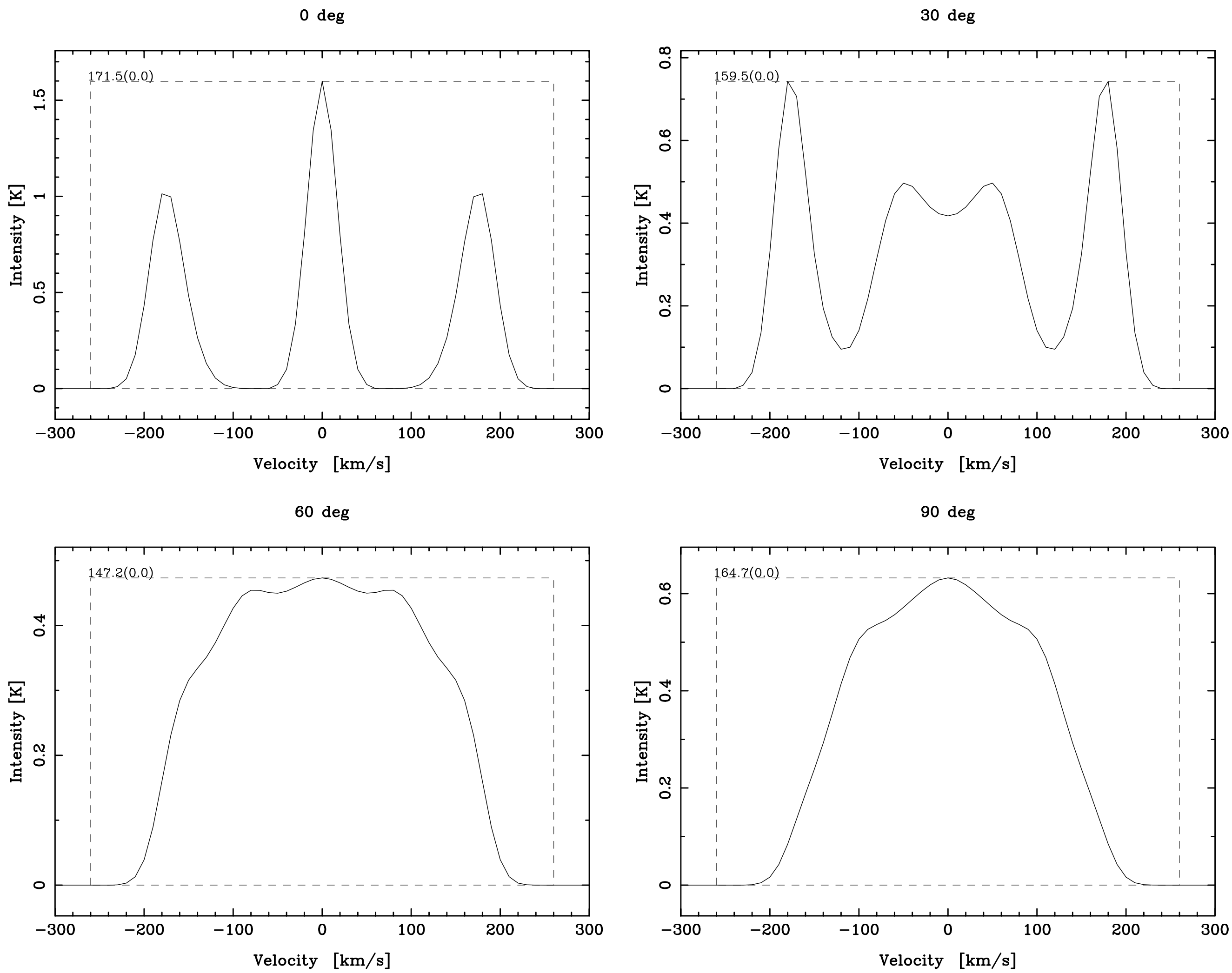

Fig. 6. The ring+outflow model observed at various (ring) inclinations with a $22''$ beam. The integrated intensities (top left in each frame) are given in K $\mathrm{km\ s^{-1}}$ and the velocity resolution is 20 $\mathrm{km\,s^{-1}}$

tion of the outflow from -12° to 78° (changing the signs of the rotation and outflow velocities accordingly). These where then convolved, over the maximum available $180'' \times 180''$ model size (giving $\int T\,dv = 2760$ K $\mathrm{km\ s^{-1}}$), with the beam widths required to simulate Circinus at the required apparent size. The important results are summarised in Table 2, where we compare the edge-on with the face-on intensities for both a ring only and a ring+outflow structure.

As seen from the "largest" 5 galaxies of the Heckman et al. (1989) sample (Table 2), there does appear to be a correlation between the simulated intensity and the inclination of the ring, although this dependence appears to be absent with the additional presence of a molecular outflow. In order to investigate this further we "observed" truly edge-on ($i = 90°$) and face-on ($i = 0°$) rings[11] at the beam-widths listed in Table 2. The results are summarised in Table 3 and Fig. 8.

[11] That is, assuming that molecular outflows are not common to Seyfert galaxies (at least to Sy1s, since the omission of an outflow does not change the edge-on results to nearly the same degree, Table 2).

Table 2. The integrated intensities [K $\mathrm{km\ s^{-1}}$] from the central positions of the almost face-on (Sy1) and almost edge-on (Sy2) models at various beam-widths. The HPBW of $55''$ (CO $1 \rightarrow 0$ at the NRAO) is scaled so as to give Circinus the apparent major axis of the galaxy listed. In this and Table 3, the first entry applies to Circinus observed with a CO $2 \rightarrow 1$ beam at SEST

HPBW	Apparent Size	Ring		Ring + Outflow	
		Sy2	Sy1	Sy2	Sy1
22	Circinus	143	70	160	169
34	NGC 1365	84	59	113	121
36	NGC 5033	78	56	107	114
54	NGC 1068	41	35	63	66
55	Circinus	40	34	62	64
100	NGC 0931	14	13	23	23
105	NGC 2273	12.2	11.7	20.3	20.5
350	Mrk 273	1.15	1.15	1.98	1.98

As seen from Table 3, a "face-on Circinus" would have to be observed with a beam-width exceeding $100''$, i.e. at $\gtrsim 8$ Mpc

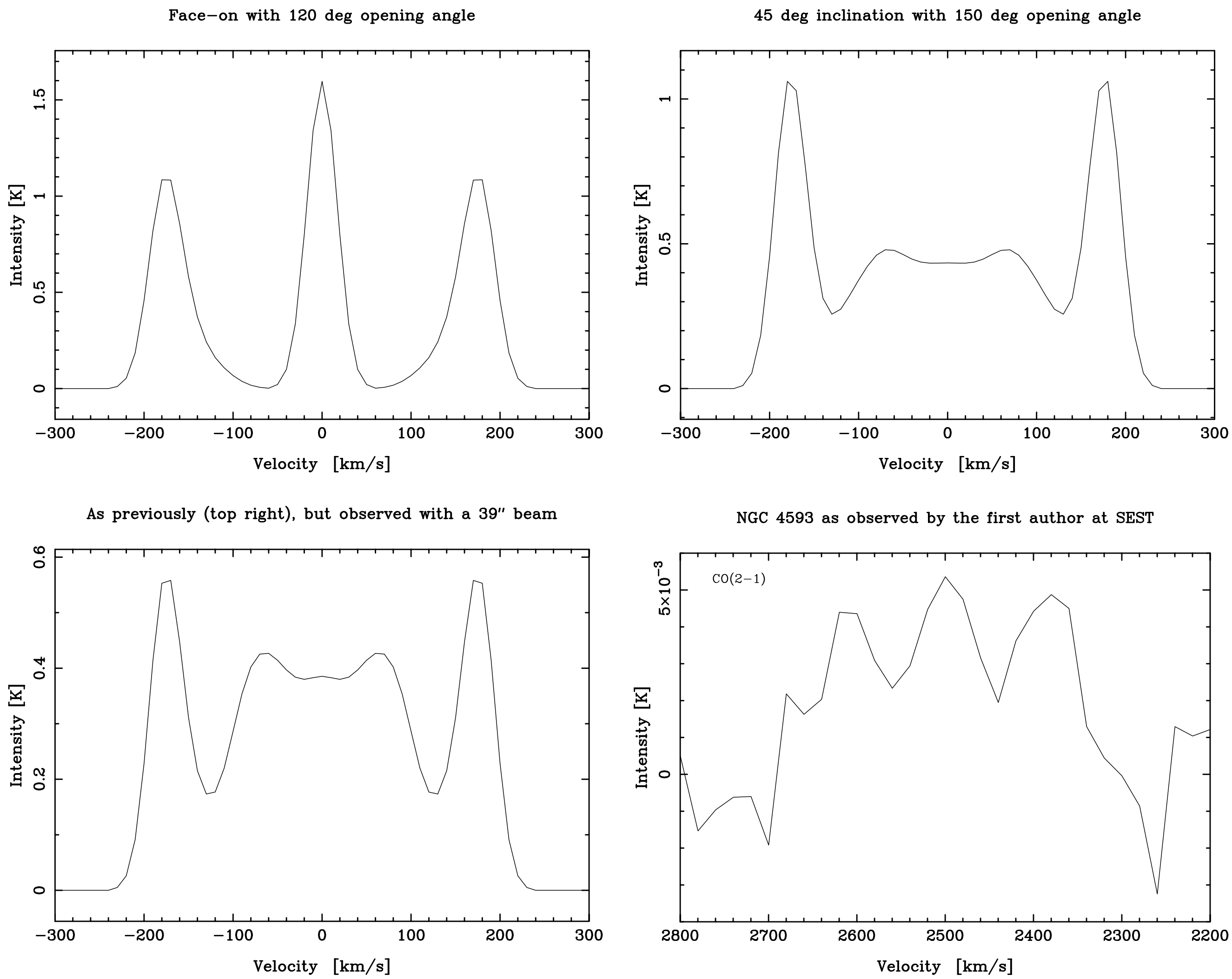

Fig. 7. The model ring with a wide outflow at various inclinations and an observed Seyfert 1 spectrum. In order to account for the results of Dopita (1998), we tested outflows with large opening angles and all the model profiles, as well as the observed one, are shown with the usual velocity resolution of 20 km s^{-1}. It is possible that Sy1s generally have less molecular gas than Sy2s (discussed in the main text), but since we have no information on whether this would result in a change in the relative abundance between ring and outflow, we have retained the values of the intensities. The third profile (bottom left) resulted from a model "observed" with a $39''$ beam, thus scaling the model to the same apparent optical major axis of NGC 4593 as observed in CO $2 \rightarrow 1$ at SEST

in CO $1 \rightarrow 0$, in order to obtain the same (to two significant figures) central intensity as from an "edge-on Circinus". This was also the case with the slightly inclined version of the galaxy, Table 2. Also as previously, we see that the differences in central intensities between the face-on and edge-on cases increase with decreasing beam-width (i.e. distance), Fig. 8.

In order to see if it was at all possible to obtain double the luminosity from an edge-on ring than from one orientated face-on, we selected a source of "average" size from the sample of Heckman et al. (1989) and modelled this with increasing "hole" sizes in the molecular ring. For this we chose Arp 220 since this has a heliocentric redshift of 5400, i.e. close to half the value for Mrk 231; the furthest source in which CO was detected. In order to scale accordingly so as to place Circinus at the same apparent size with a CO $1 \rightarrow 0$ beam, we convolved the model maps to a HPBW of $253''$. The results are summarised in Table 4.

These results show that for an "average" source, the observed difference in luminosities of Heckman et al. (1989) cannot be accounted for through mere inclination alone. Whereas when the source is close, i.e. observing Circinus with a CO $2 \rightarrow 1$ beam, the observed difference is easily obtained ($L_{\rm CO(Sy2)} \geq 2L_{\rm CO(Sy1)}$ for $r_i = 140$ pc), the observed difference cannot be obtained even for a hole of 540 pc radius i.e. within 20 pc of the outer edge of the bulk CO emission (Curran et al. 1998). This result supports the conclusion of Heckman et al. (1989) that there must be a higher abundance of CO in Sy2s than in Sy1s.

To summarise, we find on the grounds of geometry alone, that the CO luminosity of a given Seyfert 2 will only be dou-

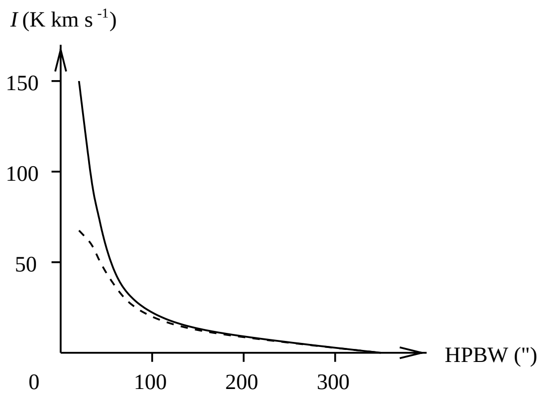

Fig. 8. The variation of central intensity with HPBW for an edge-on (full line) and a face-on (broken line) molecular ring

Table 3. The integrated intensities [K $\mathrm{km\,s^{-1}}$] from the central positions of the face-on and edge-on ring models at various beam-widths

HPBW	Apparent Size	Edge-on	Face-on
22	Circinus	151	68
34	NGC 1365	86	58
36	NGC 5033	79	56
54	NGC 1068	42	35
55	Circinus	40	34
100	NGC 0931	14	13
105	NGC 2273	12.2	11.7
350	Mrk 273	1.15	1.15

Table 4. The integrated intensities expected from the central position of the molecular ring in Circinus at face-on and edge-on inclinations. The beam has been scaled so as to give Circinus an apparent optical major axis of 1.5 arc-minutes. r_i is the value of the ring's inner radius in parsecs and I_{22} and I_{253} refer to the central intensities as "observed" with a $22''$ and a $253''$ beam, respectively

r_i [pc]	I_{22} [K $\mathrm{km\,s^{-1}}$]		I_{253} [K $\mathrm{km\,s^{-1}}$]	
	Face-on	Edge-on	Face-on	Edge-on
140	68	151	2.28	2.38
280	36	88	1.44	1.51
420	14	34	0.6	0.7
540	3	8	0.15	0.17

ble that of its face-on counterpart if it has no outflow (or any additional structure e.g. a bar), present and for beam widths of $\lesssim 20''$, i.e. observing the CO $2 \rightarrow 1$ transition in a ring with the apparent size of that in Circinus with a 15 m telescope. This difference would be even less had we modelled the intermediate Seyfert types which account for the majority of the Sy1 detections of Heckman et al. (1989). This leads us to conclude that the observed differences of Heckman et al. (1989) are due to something more than mere aspect, especially if such molecular outflows are a common feature in Seyfert galaxies. These authors themselves attribute this to a low CO luminosity (as opposed to a high blue luminosity) in the Sy1s of the sample. This is confirmed by Hunt et al. (1997) who have noted, from near-IR and colour images, that Sy2s appear to be bluer than Sy1s and star-burst galaxies. Some evidence (e.g. Pogge 1989) suggests that as well as the difference in orientation (Antonucci 1993), in general Sy1s may be the more evolved Seyfert class with significantly lower star formation rates (Moorwood 1996).

With regard to other surveys, Maiolino et al. (1997) find no dependence on the amount of CO $1 \rightarrow 0$ with respect to Seyfert type. They do, however, find that Sy2s tend to have higher starburst activity than Sy1s and attribute this to the obscuring material of the torus still being funnelled down from the global scale via a 100 pc scale torus, ultimately providing the obscuration in a Sy2 nucleus (Maiolino & Rieke 1995). This again suggesting that Sy1s are the more evolved class. Returning to the question of the molecular gas abundance, Papadopoulos & Seaquist (1998), using a similar sample to Heckman et al. (1989) and through CO line ratios, also find (as with Rigopoulou et al. 1997) no relationship between molecular gas abundance and Seyfert type, thus leaving this issue of relative gas abundances far from resolved.

4. Summary

Using a modified version of the model described in Curran (1998) we have modelled the CO $2 \rightarrow 1$ transition along the SE–NW direction in order to account for the residuals from the molecular ring model of Curran et al. (1998). As with these previous results, we suggest that the bulk of these residuals arise from a molecular outflow along the minor axis of the galaxy. The derived parameters, which agree with those previously predicted (c.f. Curran et al. 1998), are:

1. The outflow is directed along the rotation axis of the molecular ring.
2. The velocity of the outflow along this direction is $\approx 190\ \mathrm{km\,s^{-1}}$, although the bulk of the gas may fall to speeds of less than 90 $\mathrm{km\,s^{-1}}$ at the outflow edges.
3. The opening angle is $\approx 90°$ and the outflow extends to $25'' \pm 3''$, i.e. ≈ 500 pc at 4 Mpc.
4. Unlike the ionisation cone (Marconi et al. 1994; Veilleux & Bland-Hawthorn 1997; Elmouttie et al. 1998b), the outflow is bi-conical with the strongest component towards the SE.

As previously noted, the molecular outflow appears to be coincident with the ionisation cone, this being confirmed by the recent observations of Elmouttie et al. (1998b). Since the outflow, which is modelled as a hollow cone, provides a satisfactory fit to nearly all of the non-peripheral spectra and the mechanical luminosity does not exceed that of the AGN, our results may suggest that the outflow is funnelled by a small scale structure (i.e. the obscuring torus) while surrounding the ionised gas ejected from the core.

In addition to providing a close fit to the observed spectra, the results of the model seem to agree with those predicted by the *Statistical Image Analysis* routine, thus increasing our confidence in the model results.

Regarding alternatives to the outflow model, we rule out the possibility that the residuals may be due to the presence of a molecular bar rather than an outflow on the grounds:

1. The bar would be perpendicular to the large scale atomic bar observed in Circinus.
2. The velocity field of the gas doesn't clearly exhibit the usual twists in the kinematic axis, although it should be kept in mind the ring is not quite edge-on and the mapped region is only about four beams wide.
3. Admittedly although they are relatively noisy, there appear to be none of the double peaked features expected from bar rotation dominant in the spectra along the minor axis.

Although these points cannot absolutely rule out the bar hypothesis, accounting for them introduces more complications than when explaining the observed features with a simple conical outflow model. Such a molecular outflow has also been observed in the type 2 Seyfert NGC 3079.

Finally, by inclining the molecular gas structure in Circinus so as to view it normal to its actual orientation, we find that (at least in the case of Circinus) when observed with a beam wider than $\approx 10\%$ of the optical major axis ($\gtrsim 2$ kpc for Circinus), that we should expect no difference in the total CO luminosity between a Seyfert 1 and a Seyfert 2 on grounds of geometry alone. For beams narrower than this, we do expect, due to the hole in the ring being apparent at low inclinations, the emission from a Seyfert 2 to be slightly higher but not to the degree as noted by Heckman et al. (1989). Even this result only applies when the outflow is absent (although possibly only in the type 1 Seyfert case), and although the properties of any such molecular outflow, may be intrinsically different in a Seyfert 1, there is still no solid evidence, at present, to suggest that it may be absent. Although saying this, Heckman et al. (1989) outline a scheme in which type 1 Seyferts are in general the more evolved Seyfert class, and thus have less molecular gas present. This raises the possibility that outflows in type 1 nuclei may be considerably weaker than in their less evolved counterparts. In order to test this, we propose high signal-to-noise observations of systems of very low inclination in order to verify the presence or absence of a molecular outflow.

Although other surveys find no such differences (Maiolino et al. 1997; Rigopoulou et al. 1997; Papadopoulos & Seaquist 1998) in molecular gas abundances between Seyferts classes, we must conclude, that if the results of Heckman et al. (1989) are statistically sound, then the measured difference in molecular gas abundance between Seyfert types is due to something other than simple geometry. This scenario supports the results of Dopita (1998) who suggests that in addition to the orientation, the age of and the accretion rate onto the central black hole must be considered in order to unify various types of active galactic nuclei.

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References

Antonucci R.R.J., Miller J.S., 1985, ApJ 297, 621
Antonucci R., 1993, ARA&A 31, 473
Benedict G.F., Smith B.J., Kenney J.D., 1996, AJ 111, 1861
Conway J., 1999, HI Absorption from a Circumnuclear TORUS in the Hidden Quaser Cygnus A. In: Carilli C., Radford S., Menton K., Langston G. (eds.) Highly Redshifted Radio Lines. ASP Conference Series, in press
Curran S.J., Johansson L.E.B., Rydbeck G., Booth R.S., 1998, A&A 338, 863
Curran S.J., 1998, Licentiate thesis, Chalmers University of Technology
Dahlem M., Golla G., Whiteoak J.B., et al., 1993, A&A 270, 29
Davies R.I., Forbes D.A., Ryder S., et al., 1998, MNRAS 293, 189
de Vaucouleurs G., de Vaucouleurs A., Corwin H.G., et al., 1991, Third Reference Catalogue of Bright Galaxies. Springer-Verlag, New York
Devereux N.A., Kenney J.D., Young J.S., 1992, AJ 103, 784
Dopita M.A., Heisler C., Lumsden S., Bailey J., 1998, ApJ 498, 570
Dopita M.A., 1998, Proc. Astron. Soc. Aust. 14, 230
Elmegreen B.G., 1994, ApJ 425, L73
Elmouttie M., Haynes R.F., Jones K.L., et al., 1995, MNRAS 275, L53
Elmouttie M., Krause M., Haynes R.F., Jones K.L., 1998a, MNRAS 300, 1119
Elmouttie M., Koribalski B., Gordon S., et al., 1998b, MNRAS 297, 49
Elmouttie M., Haynes R.F., Jones K.L., 1997, Proc. Astron. Soc. Aust. 14, 140
Fosbury R.A.E., Vernet J., Villar-Martin M., et al., 1999, Optical Continuum Structure of Cygnus A. In: Best P., Lehnert M. (eds.) KNAW colloqium on: The Most Distant Radio Galaxies. Reidel, Amsterdam, in press
Freeman K.C., Karlsson B., Lyngå G., et al., 1977, A&A 55, 445
Freeman K.C., 1996, Barred Galaxies: Scientific Overview. In: Buta R., Crocker D.A., Elmegreen B.G. (eds.) IAU Colloquium No. 157: Barred Galaxies. ASP Conference Series, San Francisco, p. 1
Friedli D., Martinet L., 1993, A&A 277, 27
Gardner F.F., Whiteoak J.B., 1982, MNRAS 201, 13p
Gerin M., Nakai N., Combes F., 1988, A&A 203, 44
Greenhill L.J., Jiang D.R., Moran J.M., et al., 1995, ApJ 440, 619
Greenhill L.J., Ellingsen S.P., Norris R.P., et al., 1997, ApJ 474, L103
Harnett J.I., Whiteoak J.B., Reynolds J.E., Gardner F.F., Tzioumis A., 1990, MNRAS, 244 130
Heckman T.M., Blitz L., Wilson A.S., Armus L., Miley G.K., 1989, ApJ 342, 735
Hernquist L., 1989, Nat 340, 687
Hjelm M., Lindblad P., 1996, A&A 305, 727
Hunt L.K., Malkan M.A., Salvati M., et al., 1997, ApJS 108, 229
Irwin J.A., Sofue Y., 1992, ApJ 396, L75
Jones K.L., Koribalski B.S., Elmouttie M., Haynes R.F., 1999, MNRAS, 302, 649
Kenney J.D.P., Scoville N.Z., Wilson C.D., 1991, ApJ 366, 432
Kohno K., Kawabe R., Tosaki T., Okumura S.K., 1996, ApJ 461, L29
Krolik J.H., Begelman M.C., 1986, ApJ 308, L55
Krolik J.H., Begelman M.C., 1988, ApJ 329, 702
Lindblad P.A.B., Lindblad P.O., Athanassoula E., 1996, ApJ 313, 65

Maiolino R., Rieke G.H., 1995, ApJ 454, 95
Maiolino R., Ruiz M., Rieke G.H., Papadopoulos P., 1997, ApJ 485, 552
Marconi A., Moorwood A.F.M., Origlia L., Olivia E., 1994, ESO messenger 78, 20
Matt G., Fiore F., Perola G.C., et al., 1996, MNRAS 281, L69
McLeod K.K., Rieke G.H., 1995, ApJ 441, 96
Moorwood A.F.M., Lutz D., Olivia E., et al., 1996, A&A 315, L109
Moorwood A.F.M., 1996, Space Sci. Rev. 77, 303
Morris S., Ward M., Whittle M., Wison A.S., Taylor K., 1985, MNRAS 216, 193
Myers S.T., Scoville N.Z., 1987, ApJ 312, L39
Oliva E., Marconi A., Cimatti A., Alighieri S.D.S., 1998, A&A 329, L21
Oliva E., Salvati M., Moorwood A.F.M., Marconi A., 1994, A&A 288, 457
Osterbrock D.E., 1981, ApJ 249, 462
Papadopoulos P.P., Seaquist E.R., 1998, ApJ 492, 521
Plante R.L., Lo K.Y., Roy J.-R., Martin P., Noreau L., 1991, ApJ 381, 110
Pogge R.W., 1989, ApJ 345, 730
Regan M.W., Vogel S.N., Teuben P.J., 1997, ApJ 482, L143
Rigopoulou D., Papadakis I., Lawrence A., Ward M., 1997, A&A 327, 493
Rydbeck G., Wiklind T., Cameron M., et al., 1993, A&A 270, L13
Rydbeck G., 1999, A&A, in preparation
Sahai R., Sundin M., Claussen M.J., Rickard L.J., 1991, A survey of CO emission from Southern Seyfert Galaxies. In: Combes F., Casoli F. (eds.) IAU Symposium No. 146: Dynamics of Galaxies and Their Molecular Cloud Distributions. Reidel, Dordrecht, p. 327
Sakamoto K., Okumura S.K., Ishizuki S., Scoville N.Z., 1998, BAAS 192, 6609
Shaw M.A., Combes F., Axon D.J., Wright G.S., 1993, A&A 273, 31
Shlosman I., Begelman M.C., Frank J., 1990, Nat 345, 679
Strong A.W., Bloemen J.B.G.M., Dame T.M., et al., 1988, A&A 207, 1
Teuben P.J., Sanders R.H., Atherton P.D., van Albada G.D., 1986, MNRAS 221, 1
Veilleux S., Bland-Hawthorn J., 1997, ApJ 479, L105
Vila-Vilaró B., et al., 1995, A&A 302, 58