Chapter 3

Molecular Gas in Double Barred Galaxies

I. The Diverse Morphology and Dynamics of NGC 2273 and NGC 5728

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Abstract

Double bars have been proposed as a means of transporting molecular gas past inner Lindblad resonances into the nuclear regions, where it can fuel active or starburst nuclei. Thus far, the existence of double bars has been determined by isophote twists seen in the near infrared, which could probe the bulge properties of these galaxies rather than the disk properties. We have observed two double bar galaxy candidates (NGC 2273 and NGC 5728) in $^{12}$CO $J=1-0$ with the Caltech Millimeter Array. Despite the similar near infrared images of the two galaxies, we see rather different nuclear morphologies in the CO maps. NGC 2273 shows evidence of a nuclear bar misaligned from the main stellar bar by $\sim 90^\circ$, and aligned with the near infrared isophote twists observed by Shaw et al. (1993). NGC 5728 shows an arc of CO clumps that peaks just to the south-west of the dynamical center and curves to the south-east where it follows the dust lane to the south. Models of double-barred galaxies suggest that these galaxies should contain a large fraction (5-10%) of their mass in the form of molecular gas. Our calculations suggest that NGC 2273 and NGC 5728 contain sufficient amounts of gas, but NGC 5728 is contains a smaller fraction (6%) than NGC 2273.
(20%). If the dissipative nature of the gas has been overestimated in the models, the gas mass fraction could explain why we see a nuclear bar in NGC 2273 and no such structure in NGC 5728. The lack of a nuclear bar in the CO maps of NGC 5728 may be evidence that it is in a later stage of evolution. Bar dissolution may have just begun, and the gas has responded first, which may explain why we see a nuclear bar in the near infrared images of NGC 5728, but not in the CO maps.

Galaxies: starburst – galaxies: active – galaxies: ISM – galaxies: kinematics and dynamics – galaxies: nuclei

3.1 Introduction

The nuclei of barred spiral galaxies are often the setting for extraordinary events such as starbursts, molecular rings, inflow, and even Seyfert activity. The need to understand the mechanisms driving these phenomena has inspired a great number of observations and computer simulations. Models suggest that bars in galaxies can drive molecular gas into the nucleus where it can fuel the vigorous star formation activity that would otherwise exhaust the molecular gas content on timescales much shorter than observed (e.g. Combes 1994). Bars can only drive molecular gas inward until it reaches the Inner Lindblad Resonance (ILR; see Fig. 3.1), where it will accumulate into a ring that will halt the inflow. To overcome this, Shlosman, Frank, & Begelman (1989) proposed that the ring may become unstable and form a secondary bar inside the radius of the ILR, which could allow gas to reach much farther into the nucleus and possibly be the driving mechanism behind Seyfert nuclei.

Recent near infrared (NIR) surveys reveal isophote twists in the central regions of barred galaxies which may be the signature of this ‘bar within a bar’ (e.g. Mulchaey, Regan, & Kundu 1997). There are three mechanisms which can account for NIR isophotal twists
Figure 3.1: Schematic Diagram of a Double-Barred Galaxy
Schematic diagram of how a large scale bar (Main Bar) passing through a disk can transport material towards the nucleus of the galaxy. It is difficult for simulations to transport material all the way to the center because it tends to get trapped at the Inner Lindblad Resonance (ILR). This figure shows the Inner Bar that may form interior to the ILR and transport material all the way to the nucleus.
(Elmegreen et al. 1996). The first mechanism (hereafter called Model 1), proposed by Shaw et al. (1993), suggests the isophote twists are the result of an inner stellar bar triggered by a dissipative gaseous component and misaligned from the main bar. Their numerical simulations suggest that in the presence of two ILRs a nuclear ring can become elongated perpendicular to the main bar (along the x2 orbits). Gas dissipation steals angular momentum which can cause the inner part of the perpendicular gaseous ring to become more aligned with the main bar, resulting in the appearance of an elongated nuclear ring that leads the main bar. This gas ring exerts a torque on the stellar component of the bar, pulling it out of alignment also. The whole system would then rotate with the same angular frequency, with the inner gaseous ring and nuclear stellar bar leading the main bar. The second mechanism (hereafter Model 2) suggests that the twists are the result of a kinematically distinct inner bar (Friedli & Martinet 1993). Their N-body simulation (with stars and gas) suggests gas inflow along the bar can accumulate enough mass that the inner part of the gas bar can become nearly self-gravitating and decouple from the main bar. The inner bar may rotate with a pattern speed of up to 6 times that of the main bar. The third mechanism (Model 3) suggests that the NIR isophote twists may be the result of a triaxial stellar bulge (Kormendy 1979).

These models can be tested through observations of the molecular gas morphology and dynamics. Model 1 would exhibit an inner gaseous bar that leads the inner stellar bar slightly, but has the same rotation speed as the main bar. Model 2 would show a gaseous inner bar that is rotating with a different pattern speed than the main bar. Thus, molecular gas dynamics should allow us to distinguish between these models. Model 3 is associated with the stellar bulge. Since there is very little gas in the bulge compared to the disk of a galaxy, the isophote twists should not be visible in the CO maps. Both the first and second

\footnote{Note: Shaw et al. (1993) suggest that the NIR isophote twists are not the result of a distinct nuclear bar, but simply a distortion of the main bar. For ease of comparison with the other models, we will, however, also refer to this main bar distortion as a nuclear bar.}
models require the galaxy contain about 5-10\% gas (by mass) in order to produce long-lived nuclear bars. Without this large gas fraction, there is not enough dissipation in the models, and the observed structures do not last long enough to be as common as they are observed to be (Shaw et al. 1993; Friedli & Martinet 1993).

This paper presents observations taken with the Caltech Millimeter Array of two galaxies that exhibit such NIR isophote twists: NGC 2273 and NGC 5728. NGC 2273 is a SB(r)a galaxy that has a Seyfert 2 nucleus, nuclear star formation (Mulchaey, Wilson, & Tsvetanov 1996), and a nuclear ring of dust ($r \approx 5\arcsec$; Yankulova 1999). It has a recession velocity of 1841 km s$^{-1}$ (de Vaucouleurs et al. 1991) which implies that it is 24.5 Mpc away (assuming $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). It also has three outer rings which appear to be made by separate sets of spiral arms at $r \approx 0\fdg4$, 1\fdg1 and 1\fdg0. HI observations indicate that it is not very gas rich for a barred spiral galaxy with such a wide variety of nuclear activity (van Driel & Buta 1991). This observation is supported by the $^{12}$CO $J=1-0$ spectra taken by Young & Devereux (1991), who find very narrow CO linewdths and conclude that most of the molecular gas must be contained in the central few arcseconds of the nuclei of NGC 2273. Color maps of the inner regions of NGC 2273 suggest that there is a reddened ring of dusty material ($r \approx 5\arcsec$) surrounding a region of high ionization (Yankulova 1999). NGC 5728 is a southern hemisphere barred spiral galaxy classified as SAB(r)a that also contains a Seyfert 2 nucleus. Its recession velocity of 2788 km s$^{-1}$ (de Vaucouleurs et al. 1991) suggests it is located at a distance of 37.2 Mpc. Color maps indicate the galaxy contains two blue rings of recent star formation, one in the nucleus ($r \approx 5\arcsec$; Wilson et al. 1993) and one near the main bar ends ($r \approx 55\arcsec$; Schommer et al. 1988). Two dust lanes emerge from just outside the nuclear ring and run parallel to the main bar of the galaxy. Table 3.1 summarizes the properties and adopted parameters for these galaxies. These two galaxies were chosen as targets for this study because of the similarity in their nuclear and large scale morphologies; both galaxies are classified as Seyfert 2 galaxies and contain nuclear rings (which suggest
Table 3.1: Adopted Properties of NGC 2273 and NGC 5728

<table>
<thead>
<tr>
<th>Property</th>
<th>NGC 2273</th>
<th>NGC 5728</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.A. (2000.0)</td>
<td>06(^{h})56(^{m})08(^{s})7</td>
<td>14(^{h})42(^{m})24(^{s})0</td>
<td>1</td>
</tr>
<tr>
<td>Dec. (2000.0)</td>
<td>+60°50′43″1</td>
<td>−17°15′10″8</td>
<td>1</td>
</tr>
<tr>
<td>Classification</td>
<td>SB(r)a</td>
<td>SAB(r)a</td>
<td>2</td>
</tr>
<tr>
<td>Optical Diameter</td>
<td>3′3</td>
<td>3′1</td>
<td>1, 2</td>
</tr>
<tr>
<td>Nuclear Ring Diameter</td>
<td>~10″</td>
<td>~10″</td>
<td>3, 4</td>
</tr>
<tr>
<td>Outer Ring Diameter (s)</td>
<td>0′7, 2′2, 3′/1</td>
<td>55″</td>
<td>4, 5</td>
</tr>
<tr>
<td>Inclination</td>
<td>41°</td>
<td>48°</td>
<td>2, 4</td>
</tr>
<tr>
<td>Main Bar PA</td>
<td>~115°</td>
<td>~38°</td>
<td>4, 6</td>
</tr>
<tr>
<td>NIR Isophote Twist PA</td>
<td>~45°</td>
<td>~90°</td>
<td>6, 7</td>
</tr>
<tr>
<td>Heliocentric Velocity</td>
<td>1841 km s(^{-1})</td>
<td>2788 km s(^{-1})</td>
<td>2</td>
</tr>
<tr>
<td>Assumed Distance</td>
<td>24.5 Mpc</td>
<td>37.2 Mpc</td>
<td>8</td>
</tr>
<tr>
<td>Linear Scale</td>
<td>1″ = 120 pc</td>
<td>1″ = 180 pc</td>
<td>8</td>
</tr>
</tbody>
</table>

(1) NASA/IPAC Extragalactic Database; (2) de Vaucouleurs, de Vaucouleurs, Corwin, Buta, Paturel, & Fouque 1991; (3) Yankulova 1999; (4) Schommer et al. 1988; (5) van Driel & Buta 1991; (6) Mulchaey, Regan, & Kundu 1997; (7) Shaw et al. (1993); (8) Assumes \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\)

the presence of an ILR), and, most importantly, both galaxies exhibit the NIR isophote twists thought to be the signature of a nuclear bar as discussed above.

In §3.2 we discuss the observations and data reduction techniques. In §3.3.1 and §3.3.2 we discuss the molecular gas distribution and dynamics, respectively. In §3.4 we discuss the molecular gas mass determined from the \(^{12}\)CO \(J=1−0\) flux in comparison with the amount of molecular gas required by the models to produce the observed features. In §3.5 we compare our results to models of double barred galaxies, previous observations of these galaxies, and to observations of other galaxies. The paper is summarized in §3.6.

3.2 Observations and Data Reduction

We have observed the barred galaxies NGC 2273 and NGC 5728 in \(^{12}\)CO \(J=1−0\) (115.3 GHz) using the Caltech Millimeter Array. For NGC 2273 we have 3 tracks, two in the low-
resolution (L) configuration, and one in the high-resolution configuration (H). For NGC 5728 we have four tracks (two H, one L, and one in the equatorial (E) configuration). Preliminary calibration was done using the calibration package MMA (Scoville et al. 1993). Only baselines with a coherence >0.5 were used. The quasars 0642+449 and 1334–127 were used for gain calibration and Neptune and 3C273 were used for flux calibration.

For NGC 2273, we used $\alpha(2000) = 06h50m08.7$, $\delta(1950) = +60^\circ 50' 45'' 1$ for the pointing center and the spectrometer was centered at $V_{kr} = 1841$ km s$^{-1}$. For NGC 5728 we used the pointing center of $\alpha(2000) = 14h42m24.0$, $\delta(2000) = -17^\circ 15'10''8$ and a recession velocity of $V_{kr} = 2930$ km s$^{-1}$. In both cases, the spectrometer had a bandwidth of 240 MHz which corresponds to a velocity coverage of $\sim 620$ km s$^{-1}$. The frequency resolution was 2 MHz, which gives a velocity resolution of 5.2 km s$^{-1}$ at 115 GHz; however, we have binned the data to a resolution of 10.4 km s$^{-1}$ to increase the signal to noise ratio.

For map making we used the data reduction software MIRIAD (Sault, Teuben, & Wright 1995). Data with unusually high visibilities were clipped, the maps were naturally weighted and the inner quarter CLEANed to 1$\sigma$. The resulting synthesized beam is 3$''0 \times 2''5$ (PA=$21^\circ$) for NGC 2273 and 4$''5 \times 3''0$ (PA=$-12^\circ$) for NGC 5728. The rms noise in the maps is 3.09 Jy/beam km s$^{-1}$ for NGC 2273 and 2.65 Jy/beam km s$^{-1}$ for NGC 5728. The maps cover a 60$'' \times 60''$ area, but only the regions with significant emission are shown in Figures 3.2 and 3.5.
3.3 Molecular Gas Distribution, Dynamics, and Comparisons to Models

3.3.1 Morphology

Figure 3.2 shows the NIR image (top panel) of Mulchaey, Regan, & Kundu (1997) as well as the integrated intensity $^{12}$CO $J$=1–0 map (bottom panel) for NGC 2273. In the NIR image the contours start at 17 mag arcsec$^{-2}$ ($K_S$ band) and are in 0.5 mag increments, while in the CO map contours start at 3.1 Jy/beam km s$^{-1}$ and increase in steps of 3.1 Jy/beam km s$^{-1}$ (1$\sigma$). The CO emission is integrated over the velocity range where we see emission, namely from 1669 km s$^{-1}$ to 1981 km s$^{-1}$. The $^{12}$CO $J$=1–0 integrated intensity map (Fig 3.2) shows a small bar-like structure (P.A. $\sim$40°) that is approximately perpendicular to the main bar of the galaxy (P.A. $\sim$115°). Comparing the size of the CO bar with the synthesized beam, we see that the bar is resolved along its major axis, but may not be fully resolved along its minor axis. The integrated intensity map also shows finger-like structures protruding to the north and south of the CO bar. Assuming trailing spiral arms, these fingers line up with the leading edge of the main galactic bar.

The integrated intensity map only shows a two-dimensional view. If we want to see the details of how the molecular gas is distributed, we need to use the velocity information. The channel maps (Fig. 3.3) show that the CO bar is actually three dynamically separate clumps that merge into a bar-like structure when we average the emission over all channels. In order to emphasize the three individual clumps, we have used the clumpfind algorithm (Williams, de Geus, & Blitz 1994) and plotted the individual clumps in Fig. 3.4. The two clumps near the ends of the CO bar are brighter than the central peak, which suggests that molecular gas may be flowing in along the main bar, but is actually being collected into clumps which are presumably the location of the ILR. Similar CO morphologies have been seen in other barred galaxies such as the ‘twin peaks’ galaxies of Kenney et al. (1992) and
Figure 3.2: NIR and CO Images of NGC 2273
Integrated intensity map of $^{12}$CO $J=1-0$ emission in NGC 2273. The CO map of NGC 2273 shows a nuclear bar aligned with the NIR isophote twists of Mulchaey et al. (1997). This result suggests that in NGC 2273, these NIR isophote twists are the result of a true nuclear bar. The fingers of emission to the north and south of the nuclear CO bar suggest evidence of inflow onto the inner bar along the leading edge of the main bar. The rms noise in the map is 3.1 Jy/beam km s$^{-1}$ and the contour levels for the CO integrated intensity map start at $1\sigma$ and increase in steps of $1\sigma$. The beam size of $3'' \times 2.5''$ with a PA of $21^\circ$ is shown in the lower left corner.
the nearby starburst galaxy M82 (e.g., Shen & Lo 1995). We will discuss the importance of these similarities in §3.5.

The NIR image of NGC 2273 (top panel Figure 3.2; Mulchaey, Regan, & Kundu 1997) shows isophote twists in the inner $10 \times 10''$ misaligned from the main bar by $\sim 90^\circ$. The $^{12}$CO $J=1-0$ integrated intensity map (bottom panel; Figure 3.2) shows a nuclear bar that aligns with the NIR isophote twists. This result rules out the triaxial bulge explanation of the NIR isophote twists for NGC 2273 (Model 3; Kormendy 1979). The models of Shaw et al. (1993) predict that we should see the nuclear molecular component leading the nuclear isophote twists observed in the NIR by up to $20^\circ$. The models of Friedli & Martinet (1993) predict that the gaseous nuclear bar leading the gaseous stellar bar by up to $10^\circ$. In NGC 2273, there is no clear evidence that the gaseous inner bar is leading the stellar inner bar by any significant amount. However, this observation does not rule out either model, since Shaw et al. (1993) and Friedli & Martinet (1993) predict deviation angles between the gaseous and stellar bars as small as $5^\circ$, which is smaller than we can measure accurately from the maps.

Figure 3.5 shows the $I$-band image (top panel) of Prada & Gutiérrez (1999) as well as the integrated intensity $^{12}$CO $J=1-0$ map (bottom panel) of NGC 5728. The CO contours start at 1.3 Jy/beam km s$^{-1}$ and increase in steps of 1.3 Jy/beam km s$^{-1}$ (0.5$\sigma$). The emission is integrated over the velocity range of 2650 km s$^{-1}$ to 2980 km s$^{-1}$. The $^{12}$CO $J=1-0$ map of NGC 5728 (Fig. 3.5) does not show an obvious nuclear bar as seen in NGC 2273. It contains several individual clumps of emission that seem to form an arc with a radius of $6''$. If this arc is part of a molecular ring, then the CO ring is not aligned with the galactic center, nor is it aligned with the ring structure surrounding ionization cones seen in the HST images by Wilson et al. (1993). The brightest peak in the CO map of Fig. 3.5 is located $\sim 2''$ to the SW of the brightest peak seen in the VLA and H$\alpha$ maps of Schommer et al. (1988). The smaller CO clumps that run counter-clockwise to the SE of the brightest
Figure 3.3: CO Channel Map of NGC 2273
The CO bar seen in Fig. 3.2 is actually comprised of three separate clumps. The contour levels are 0.04, 0.06, 0.08 ... Jy/beam (2, 3, 4 ... $\sigma$). The plus sign indicates the map center. The panels are shown at 31.2 km s$^{-1}$ intervals and are binned to 31.2 km s$^{-1}$ wide bins.
Figure 3.4: Individual CO Clumps in NGC 2273
This figure shows the output from the clumpfind algorithm. It shows the three main clumps of CO emission that combine to produce the bar seen in the integrated intensity map (Fig.3.2).
peak line up with the dust lane that runs out of the nucleus and along the main bar of the galaxy (Schommer et al. 1988). We reserve discussion of the physical interpretation of these features for §3.5.2.

At first glance, it appears that our CO map is offset from the galaxy center (marked with a ‘+’ in Fig. 3.5) determined by Schommer et al. (1988). It should be noted that the spectral lines in the nucleus of NGC 5728 cover such a large range of velocities that we have missed velocities lower than 2630 km s\(^{-1}\). The H\(\alpha\) maps of Schommer et al. (1988) show that there are some velocities as low as 2600 km s\(^{-1}\) and as high as 3010 km s\(^{-1}\) in the nucleus of NGC 5728. The lowest velocity regions are located to the north-east of the dynamical center, so if there is strong CO emission at 2600 to 2630 km s\(^{-1}\), we will have missed it in our maps, perhaps creating the observed non-symmetric appearance. There is definitely evidence of bright CO emission near the low velocity end of our spectrometer. It can be seen as a faint peak in Fig. 3.5 at RA = 14^h_4^m_2^s, \(\delta = -17^\circ 15'07''6\) (it is the NE clump that was used in the dynamical mass calculation of §3.3.2).

To test whether the asymmetry seen in the CO map of NGC 5728 is caused by the exclusion of the lowest 30 km s\(^{-1}\) of the spectral data, we cropped the highest 30 km s\(^{-1}\) from the spectra and recreated the moment maps. This process reduces the intensity of the brightest peak to the west of the dynamical center, but the peak is still more than twice as bright as the emission peak on the north-east side of the dynamical center. Thus, it is likely that the asymmetric appearance of the CO maps is real, and not an artifact of missing low velocity emission.

The NIR image of NGC 5728 Shaw et al. (1993) shows isophote twists in the nuclear region similar to those of NGC 2273, but our CO map of NGC 5728 shows no clear evidence for the existence of a nuclear bar. This result suggests that in NGC 5728, the NIR isophote twists may not be the result of the nuclear bar, but may be caused by a triaxial stellar
Figure 3.5: NIR and CO Images of NGC 5728

The top panel shows the NIR image of NGC 5728 by Prada & Gutiérrez 1999. The lower panel is the $^{12}$CO J=1–0 integrated intensity map for the nucleus of NGC 5728. Note that we do not see an inner bar as we do for NGC 2273. The emission appears be asymmetric with respect to the dynamical center of the galaxy (marked by the +) determined by Schommer et al. 1988. The rms noise in the map is 2.65 Jy/beam km s$^{-1}$, and the contours start at 0.5σ and increase in steps of 0.5σ. The beam size is $4.5'' \times 3''$ with a PA=−12° and is shown in the lower left corner. The × symbols indicate the clumps used to determine the dynamical mass discussed in §3.3.2.
bulge as predicted by Kormendy (1979). We give a more detailed discussion of the possible causes of the NIR isophote twists in §3.5.2.

### 3.3.2 Dynamics

The position-velocity diagram (Fig. 3.6) taken along the axis of the CO bar in NGC 2273 shown in Fig. 3.2 indicates that the bar is rotating at approximately $570 \text{ km s}^{-1} \text{ kpc}^{-1}$ ($870 \text{ km s}^{-1} \text{ kpc}^{-1}$ deprojected). Since we have no detections beyond the inner bar shown in Fig. 3.2, and there are no rotation curves published for the inner $1'$, we cannot determine yet if the CO inner bar is kinematically distinct as predicted by Model (2) or if it is rotating at the same angular frequency as the main bar as predicted by Model (1).

Assuming Keplerian rotation, we have

$$M_{\text{dyn}} = \left( \frac{V_{\text{circ}}}{\sin i} \right)^2 \left( \frac{R}{G} \right)$$

where $M_{\text{dyn}}$ is the mass interior to radius $R$, $V_{\text{circ}}$ is the circular velocity of the material at radius $R$, $i$ is the galaxy’s inclination and $G$ is the gravitational constant. Contributions from non-circular velocities can only cause deviations of approximately 30% in the calculated mass (e.g. Sakamoto et al. 1999). Using Figure 3.4 to obtain velocities at the bar ends, and assuming the inclination to be $41^\circ$, we find the dynamical mass of the nuclear molecular bar to be $1.6 \times 10^9 \ M_\odot$.

The channel maps of NGC 5728 (Figure 3.7) show a much less ordered appearance. Careful examination of the velocity of the clumps suggests that the southern-most clump has the highest recession velocity and the velocities of the clumps decrease as you move clockwise around the arc (ignoring the CO emission associated with the dust lane to the far south). This is consistent with the velocity field determined by the H$\alpha$ maps of Schommer et al. (1988). The CO emission is very clumpy with some of the features seen in the integrated intensity map of Figure 3.5 being made up of numerous CO features that are
Figure 3.6: Position-Velocity Plot Along the CO Bar of NGC 2273
Position-velocity diagram for a slice along the major axis of the CO bar in Fig. 3.2. It rotates as a solid body with a projected angular frequency of 570 km/s/kpc. Contours indicate 10%, 20%, 30% ... of the peak. Positive offsets are toward the north-east end of the bar.
3. THE DIVERSE MORPHOLOGY AND DYNAMICS OF NGC 2273 AND NGC 5728

separated in velocity space. The brightest peak is actually a superposition of many less bright peaks at different velocities. There is no evidence in our CO maps of NGC 5728 for a bar interior to the ring as reported by Prada & Gutiérrez (1999), so naturally we cannot confirm the reports that this inner bar may be counter-rotating.

Our CO data for NGC 5728 are not sufficient to create a high quality position-velocity map as we did for NGC 2273, but we can use the channel maps to determine the position and velocity for the two bright clumps that lie along the major axis of NGC 5728 and straddle the dynamical center\(^2\). Using the same equations as for NGC 2273, we calculate a dynamical mass of \(6.3 \times 10^9 \, M_{\odot}\) for the inner 8\(''\) of NGC 5728.

Thus far we have concentrated our comparisons predominantly on the models of double barred galaxies that are comprised of both stars and gas. There is another class of models that attempt to explain nuclear NIR isophote twists using purely stellar orbits (Maciejewski & Sparke 2000). It is known that there are different classes of orbits in a barred potential. The two important ones are the x1 family that runs parallel to the bar major axis, and the x2 family, that runs perpendicular (e.g., Athanassoula 1992). It was thought that the x2 orbits of the large scale bar near the nucleus could form the x1 orbits of the smaller nuclear bar and the corotation radius of the nuclear bar could correspond to the ILR of the large scale bar. In this picture, the nuclear bar must always be aligned perpendicular to the main bar. Friedli & Martinet (1993) rule out this model by studying a large sample of double-barred galaxies, since they found that not all the observed offset angles between the nuclear bar and the main bar can be explained by inclination effects. Recently, Maciejewski & Sparke (2000) find that there exists orbits in which particles in a double-barred potential remain on closed orbits and may form the building blocks of long-lived double-barred galaxies without

\(^2\)The north east peak is at RA = 14\(^h\)42\(^m\)24\(^s\), \(\delta = -17\(^\circ\)15\('\)07\(''\)6 and has a central velocity of 2660 km s\(^{-1}\). The south west peak is at RA = 14\(^h\)42\(^m\)23\(^s\)75, \(\delta = -17\(^\circ\)15\('\)13\(''\)0 and has a central velocity of 2960 km s\(^{-1}\). These points are indicated in Figure 3.5 by x's.
Figure 3.7: CO Channel Map of NGC 5728

Note how there is not strong evidence for large scale ordered motion. The large plus sign indicates the galaxy center determined by Schommer et al. (1988). The smaller plus signs mark the locations of the peaks used to calculate the dynamical mass. Contours levels are 0.04, 0.06, 0.08, ... Jy/beam (1.5, 2.3, 3 ... σ). The panels are shown at 20.8 km s⁻¹ intervals and are binned to 20.8 km s⁻¹ wide bins.
the need for a gaseous component. The particle nature of this model renders it untestable with our molecular gas observations, since it is unlikely that molecular gas will orbit in a particle-like manner. We mention it here solely as a possible explanation as to why NGC 5728 shows nuclear bars in the NIR images, but not in the CO maps.

3.4 Molecular Gas Mass and Gas Mass Fraction

We use the CO flux over the entire nuclear bar of NGC 2273 to estimate the molecular gas mass in the nuclear region. We adopt

\[ M_{\text{gas}} = 1.6 \times 10^4 \left( \frac{D}{\text{Mpc}} \right)^2 \left( \frac{S_{\text{CO}(1-0)}}{\text{Jy km s}^{-1}} \right) \left( \frac{X}{X_{\text{Gal}}} \right) \]

(Wilson 1995), where \( D \) is the distance to the galaxy, \( S_{\text{CO}(1-0)} \) is the \(^{12}\text{CO} J=1-0\) flux, \( X \) is the CO-to-\( \text{H}_2 \) conversion factor compared to the Galactic value \((X_{\text{Gal}})\). The constant at the start of the equation contains a factor of 1.36 to account for other elements besides hydrogen. For lack of evidence to the contrary, we adopt the Galactic value of the CO-to-\( \text{H}_2 \) conversion factor of \( 3 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1} \) (Scoville & Sanders 1987) for the galaxies studied in this paper. The total CO flux for the nuclear CO bar of NGC 2273 is 48.6 Jy km s\(^{-1}\), which corresponds to a molecular mass of \( 4.7 \times 10^8 \text{ M}_\odot \). If we repeat this calculation using only the region interior to the locations used in the dynamical mass calculation (\( \sim 1 \) kpc along the length of the CO bar) we measure a flux of 38.0 Jy km s\(^{-1}\), which corresponds to a molecular mass of \( 3.6 \times 10^8 \text{ M}_\odot \). This mass constitutes approximately 20% of the nuclear bar’s dynamical mass (§3.3.2).

Of course, the estimate for the molecular gas mass is only a lower limit since the interferometer is insensitive to the large scale structure that may be present in the nuclear regions of this barred galaxy. Single dish \(^{12}\text{CO} J=1-0\) spectra of the inner 55\(''\) of NGC 2273 taken by Young et al. (1995) show a flux of 137 \( \pm \) 24 Jy km s\(^{-1}\), suggesting that our interferometry maps may be missing up to 65% of the CO emission. Also important is
the effect of the uncertainties in the individual measurements used to calculate this ratio. For example, in §3.3.2, if we assume that $V_{\text{circ}}$, $i$, and $R$ each have a conservative $\sim 10\%$ uncertainty, this results in a $\sim 25\%$ uncertainty in $M_{\text{dyn}}$. Similarly for the molecular gas mass, if we assume a $\sim 10\%$ uncertainty for each measured value, we obtain an uncertainty in $M_{\text{gas}}$ of $\sim 20\%$. The final value for the ratio $M_{\text{gas}}/M_{\text{dyn}}$ is $20\pm 6\%$.

Yankulova (1999) find that the nuclear ring of NGC 2273 is very dusty and calculate the mass of this dust to be $\sim 10^5 \, M_\odot$. Comparing this to our molecular gas mass, we find that the gas-to-dust ratio is approximately 3600 in the center of this Seyfert 2 galaxy. This ratio is higher than found for nearby spiral galaxies ($M_{\text{gas}}/M_{\text{dust}} \sim 1000$; Devereux & Young 1990). It may not be surprising that the ratio of gas to dust is higher in the center of this barred galaxy, where we might expect an increase of nuclear molecular gas (caused by inflow along the bar) as well as a decrease in dust due to the strong ionizing nuclear source (Yankulova 1999).

The CO flux for the inner $8 \times 8\arcsec$ of NGC 5728 is 25.6 Jy km s$^{-1}$, which indicates a molecular mass of $5.7 \times 10^8 \, M_\odot$. Using our dynamical mass data we find that the molecular gas in the nucleus of NGC 5728 constitutes 9% of the total mass. We believe that our determination of the dynamical mass in such a complicated environment is likely unreliable. Our dynamical mass determined in §3.3.2 is lower than the value determined by Rubin (1980) through model fits of the velocity data over the entire galaxy. Due to the complexity of our data and the simplicity of the models assumed in §3.3.2, we will adopt the value determined by Rubin (1980). She finds the total dynamical mass of the galaxy in the inner $10\arcsec$ diameter (1.8 kpc) is $\sim 1 \times 10^{10} \, M_\odot$. This estimate lowers the mass fraction of molecular gas to $6\pm 2\%$. Again, this result is a lower limit because the interferometer will miss large scale structure. There are no single dish $^{12}\text{CO}$ $J=1-0$ spectra for NGC 5728 published, so we cannot directly estimate the flux missed by our interferometric maps. Single dish $^{12}\text{CO}$ $J=2-1$ spectra of the inner $22\arcsec$ of NGC 5728 (Petitpas & Wilson, in prep.) show fluxes
of 62 Jy km s\(^{-1}\). Assuming a \(^{12}\)CO \(J=2-1/J=1-0\) ratio of 0.7 (Sakamoto et al. 1995) we obtain a \(^{12}\)CO \(J=1-0\) flux of 89 Jy km s\(^{-1}\). Comparing this to the CO flux in the interferometric map of 30 Jy km s\(^{-1}\) for this region, we find that the interferometric maps are missing \(\sim 67\%\) of the flux detected by a single dish.

A requirement of both the models of Shaw et al. (1993) and Friedli & Martinet (1993) is that the entire galaxy contain \(\sim 5-10\%\) molecular gas by mass. Friedli & Martinet (1993) found that they could also create nuclear bars if the total (atomic + molecular) gas to total mass ratio is 10\%, or if 2\% of the total mass interior to 1 kpc (diameter) is molecular. Shaw et al. (1993) only require that 4-6\% of the entire galaxy mass be gaseous. The high gas contents in these two models are required to provide enough dissipation so that the nuclear ring can become phase shifted out of its stable orbit and collapse into a nuclear bar. Both galaxies meet the molecular gas mass requirements of the models, yet only NGC 2273 shows evidence for a nuclear molecular bar. It is interesting that we find \(\sim 20\%\) gas (by mass) in the nucleus of NGC 2273, where we see a nuclear bar, yet we only see \(\sim 6\%\) (by mass) in NGC 5728, where we see no evidence in our CO maps for a nuclear bar. This comparison suggests that perhaps the models of Shaw et al. (1993) and Friedli & Martinet (1993) are correct, but the parameters they adopted to model the gas dissipation may not be correct. For example, if they were to decrease the amount of dissipation in the gas slightly, it is possible that they could still create nuclear CO bars in galaxies that contain 20\% gas, yet galaxies with lower mass fractions such as NGC 5728 would not have enough dissipation to create long-lived nuclear bars.

A recent interferometric \(^{12}\)CO \(J=1-0\) survey by Sakamoto et al. (1999) suggests that typical gas mass fractions range from 0.9\% to 31.5\% in the inner 500 pc radius of a sample of 17 galaxies, with no apparent correlation with galaxy type. Since we have used the same techniques to determine the gas mass fraction, it is worthwhile to compare our results with those of a larger sample. For NGC 2273, we calculate the molecular gas mass fraction over
the entire length of the bar for which we see emission in the position velocity plot (Figure 3.6), which corresponds to the inner 720×720 pc. For NGC 5728, we measured the molecular gas mass fraction over an area of 8×8′ which corresponds to the inner 1.4×1.4 kpc. NGC 2273 has a nuclear gas mass fraction of 20% and NGC 5728 has 6% molecular gas. Sakamoto et al. (1999) find evidence that HII nuclei have higher ratios of gas to dynamical masses (∼18% average) compared to Seyfert and LINER galaxies (∼6% average). NGC 5728 is in agreement with the previously observed range for its type of nuclear activity, while NGC 2273 seems to have a higher molecular gas fraction than the other Seyfert 2 galaxies in the sample obtained by Sakamoto et al. (1999). A distinct classification of NGC 2273 into one particular category is difficult in light of current observations which suggest that, in addition to its Seyfert 2 activity, NGC 2273 is undergoing nuclear star formation (Mulchaey, Wilson, & Tsvetanov 1996). These observations suggest that NGC 2273 may be an intermediate object that should fall somewhere between the HII and Seyfert 2 classifications of Sakamoto, Okumura, Ishizuki, & Scoville 1999, in which case it is in the expected intermediate range of gas mass fraction for such an object. In any case, our observed gas mass fraction for NGC 2273 does not compromise the results of Sakamoto et al. (1999).

3.5 Discussion

3.5.1 Comparison to Previous Studies of NGC 2273

It has long been known that bars are a good way to transport material into the nuclear region of a galaxy (e.g. Combes 1994) by allowing material to flow inward along the leading edge of the bar. Indications of such an inflow are visible in the CO map of NGC 2723, seen as fingers extending NW and SE from the top and bottom (respectively) of the CO bar. This observation suggests that inflow along the main bar of NGC 2273 is depositing
material onto the ends of the nuclear bar seen in the CO maps. This material would then be free to flow along the nuclear bar into the central regions, and could possibly supply the nucleus with enough material to sustain the observed Seyfert and starburst activity.

The channel maps of NGC 2273 show that the bar seen in the integrated intensity maps is actually composed of three separate structures. These structures are barely spatially resolved in our maps (if at all), but they are clearly resolved in velocity (as seen in Fig. 3.3). Similar nuclear CO distributions have been seen previously in regular (non-double) barred galaxies such as NGC 5383 and M82 (Sheth et al. 2000; Neininger et al. 1998). In NGC 5383, Sheth et al. (2000) see bright CO emission from “twin peaks” that coincide with the ILR radius, as well as a central concentration near the nucleus. High resolution observations suggest that the nuclear structure of NGC 5383 is actually a nuclear spiral when viewed with the Hubble Space Telescope (Sheth et al. 2000), which casts some doubt on the identification of nuclear bars with lower resolution, ground-based images.

HST images (Malkan, Gorjian, & Tam 1998) and narrow-band color maps (Yankulova 1999) of NGC 2273 show that the nucleus contains a ring elongated in the same direction as our nuclear CO bar. The HST (WFPC2, F606W) images show a central bright spot and indications of what may be flocculent spiral arms and a ring. The bright blobs at the ends of the nuclear CO bar correspond with the edges of the ring seen by Malkan, Gorjian, & Tam (1998) and Yankulova (1999). It is likely that this ring indicates the location of the ILR of the main bar, and thus, our nuclear bar ends occur at the ILR radius as predicted by the models of Friedli & Martinet (1993) and Shaw et al. (1993). If we assume that the corotation radius of the nuclear bar occurs near the ILR of the main bar (Pfenniger & Norman 1990; see Fig. 3.1), then the CO peaks at the ends of the nuclear bar are analogous to the condensations that collect at the corotation resonance of large-scale bars (Garcia-Burillo et al. 1998). This result suggests that nuclear bars may share many of the same properties as large-scale bars and that modeling nuclear bars may be done using scaled-
down versions of the large-scale barred potentials that are currently used in barred galaxy models.

3.5.2 Comparison to Previous Studies of NGC 5728

HST images of the nucleus of NGC 5728 show what appears to be an off-center ring of young stars circling two ionization cones that seem to originate from a point ~3" west-north-west (~60°) from the center of our maps (Wilson et al. 1993). These images also show a bar-like structure that is oriented at a position angle of ~90° which Wilson et al. (1993) suggest may be comprised of older stars. Our CO map shows no bright emission peak at the vertex of the ionization cones of the HST maps. The bright and faint CO peaks (used in §3.3.2 to determine the dynamical mass) that straddle the map center are roughly perpendicular to the ionization cones. The other peaks in the maps (curving to the south) are associated with the dust lanes that run along the leading edge of the main bar (Schommer et al. 1988). Our CO maps also do not show any strong evidence of a bar structure oriented at PA = ~90° which might correspond to the bar suggested by the NIR images of Shaw et al. (1993). If we assume that the clumps (marked by ×’s in Figure 3.5) that straddle the dynamical center (indicated by the +) correspond to similar nuclear bar end enhancements as seen in NGC 2273 (Figure 3.2) then the nuclear CO bar in NGC 5728 would be leading the stellar nuclear bar seen in the NIR images by ~45°. This angle is greater than the offsets predicted by Shaw et al. (1993) and Friedli & Martinet (1993) for which a 20° maximum offset is predicted. If the nuclear stellar bar is counter rotating as reported by Prada & Gutiérrez (1999), then the nuclear CO bar is trailing the main bar, which is not predicted in any of the models discussed in this paper.

Unfortunately, the integrated intensity maps and the channel maps of the nucleus of NGC 5728 show no conclusive evidence for a nuclear bar in our data either aligned or misaligned with the NIR isophote twists. This result suggests that if the NIR isophote
twists of Shaw et al. (1993) are the result of a nuclear bar, it is mostly stellar and contains little molecular gas. This observation counters the finding of Shaw et al. (1993) and Friedli & Martinet (1993) whose models require that these nuclear bars contain lots of molecular material in order to provide enough dissipation.

3.5.3 Comparison with Other Nuclear Barred and NIR Isophote Twist Galaxies

Considering all barred galaxies (not just the ones containing NIR isophote twists) there are currently nine barred galaxies that show evidence for a nuclear molecular bar (Devereux et al. 1992; Kenney et al. 1992; this work). It seems that the identification of a gaseous nuclear bar may be ambiguous: there may be confusion between what is considered a “twin peak” galaxy and what is considered a nuclear bar. Unresolved twin peak galaxies will appear as galaxies with a nuclear CO bar. For example, NGC 3351 is classified as a twin peak galaxy by Kenney et al. (1992) but considered to have a nuclear CO bar by Devereux, Kenney, & Young (1992). Twin peak galaxies are believed to be caused by gas collecting at an ILR as it flows inward along the leading edge of the main bar of a galaxy (Kenney et al. 1992). These galaxies are thought to be preventing molecular gas from reaching all the way into the nucleus, while nuclear bar galaxies are thought to assist molecular gas flow into the nucleus by transporting it interior to the ILR (Kenney et al. 1992; Shlosman, Frank, & Begelman 1989). We will need a larger sample of galaxies containing unambiguous nuclear bars so we can determine their properties in comparison to twin peak galaxies.

From the NIR surveys that have detected the isophote twists originally thought to be the signature of a nuclear bar (e.g. Mulchaey, Regan, & Kundu 1997; Shaw et al. 1993; Wozniak et al. 1995; Jarvis et al. 1988; Elmegreen et al. 1996; Friedli & Martinet 1993), only a handful of galaxies have high resolution CO maps published: NGC 4736, NGC 6951, NGC 5728, and NGC 2273 (Sakamoto et al. 1999; Kenney et al. 1992; this work). NGC
2273 and NGC 6951 contain two peaks at the ILR radius with more CO emission interior to these peaks. CO maps of NGC 4736 show what may be a weak twin peak structure, with a bright central concentration (Sakamoto et al. 1999). NGC 5728 has a bright, off-center peak of emission, with other emitting regions that do not seem to line up with other features or the ILR radius. Only NGC 5728 does not show evidence for a twin peaked or bar structure elongated in the same direction as the nuclear NIR isophote twists.

To explain why there is no nuclear CO bar in NGC 5728, we need to examine the time evolution of the models. The models of Shaw et al. (1993) were only run until they reached a steady state, so comparisons of our CO maps with the predictions for the lifetimes of nuclear bars is not possible. Friedli & Martinet (1993) show that after the nuclear bar forms, it usually remains present for over 5 turns of the nuclear bar (approximately 2 turns of the main bar; ~500 Myr). The double-bar phase can transport the molecular gas inward, which eventually results in the disruption of the nuclear bar; often even the large-scale bar is disrupted by bulge growth (Pfenniger & Norman 1990) or central mass concentration (Hasan & Norman 1990) which changes the barred gravitational potential into a more spherical potential. In this picture, NGC 5728 may represent a older double-barred galaxy that has already undergone a molecular nuclear bar stage which has modified the gravitation potential through the creation of a high mass central object (perhaps the cause of the jets seen in the HST images of Wilson et al. (1993)). The molecular gas could have responded to the change in the potential faster than the stellar component, which may explain why we see evidence for a nuclear bar in the NIR images but not in the CO maps.

Additional support for this scenario is found when we consider the star formation activity of each of these galaxies. NGC 2273 and NGC 6951 have active nuclear star formation and the CO maps show a strong CO bar and a distorted twin peak structure with faint central concentration, respectively (Kohno et al. 1999; Kenney et al. 1992). In NGC 4736, there is evidence for a recent starburst phase, and the CO maps show a weak twin peaked structure
Table 3.2: Properties NIR Isohote Twist Galaxies

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>M_{gas}/M_{dyn}</th>
<th>Nuclear Activity</th>
<th>CO morphology</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2273</td>
<td>20%</td>
<td>Star formation, Seyfert 2 activity</td>
<td>Obvious bar/triple peaks</td>
<td>1, 2</td>
</tr>
<tr>
<td>NGC 4736</td>
<td>2%</td>
<td>Star formation in ring outside nucleus, LINER</td>
<td>Central peak, weak signs of twin peaks?</td>
<td>3, 4</td>
</tr>
<tr>
<td>NGC 5728</td>
<td>6%</td>
<td>Evidence of past star formation, Seyfert 2</td>
<td>Non-centralized peaks, no bar?</td>
<td>1, 5</td>
</tr>
<tr>
<td>NGC 6951</td>
<td>29%</td>
<td>Star formation</td>
<td>Twin (triple?) peak/ elongated ring?</td>
<td>6</td>
</tr>
</tbody>
</table>

1) this paper; 2) Mulchaey, Wilson, & Tsvetanov (1996); 3) Sakamoto, Okumura, Ishizuki, & Scoville (1999); 4) Kinney, Bohlin, Calzetti, Panagia, & Wyse (1993); 5) Wilson, Braatz, Heckman, Krolik, & Miley (1993); 6) Kohno, Kawabe, & Vila-Vilaró (1999)

as well as a bright central concentration (Kinney et al. 1993; Sakamoto et al. 1999). A summary of these observations is given in Table 3.2. These results suggest that NGC 2273 and NGC 6951 may be in a earlier stage of evolution, where the nuclear molecular bar is still visible. NGC 4736 may be just finishing its double bar phase and the molecular gas (and stars) are beginning to return to a single barred galaxy phase. NGC 5728 may have been finished with its double bar phase for quite a while. The molecular gas has lost its nuclear barred appearance, while the stars have not. The models of Friedli & Martinet (1993) show no evidence for the evolutionary sequence proposed here. Their models suggest that the gas and stars in a nuclear bar behave similarly on timescales of a few million years; thus if evolution is responsible for the variation in nuclear stellar and CO morphologies and the models are correct, then it is unlikely that we should see such a variety in our small sample of galaxies.

Another explanation for the variety of CO morphologies may be that there are different physics at work in the molecular gas in each galaxy. It is interesting that the NIR images of all four galaxies look remarkably similar, while the CO maps look remarkably different. The similarity in the NIR images suggests that the stellar distribution in these galaxies is
similar. The differences in the CO morphology suggest that there is something different about the molecular gas in each galaxy, which causes it to respond differently to the galactic stellar potential. We are in the process of obtaining multi-line CO data at the JCMT in order to place constraints on the molecular gas temperatures and densities in a sample of starburst and non-starburst Seyfert 2 galaxies, which may help shed some light on the different CO morphologies observed in the double barred galaxies.

3.6 Summary

We have mapped the barred galaxies NGC 2273 and NGC 5728 in $^{12}\text{CO} \ J=1-0$ with the Caltech Millimeter Array. These galaxies are known to contain NIR nuclear isophote twists, which are thought to be the signature of a nuclear bar. The main results are summarized as follows:

1) In NGC 2273 we see a nuclear molecular bar approximately perpendicular to the large scale galactic bar. The CO bar is aligned with the NIR isophote twists suggesting that in NGC 2273, the twists are caused by the presence of a real nuclear bar, and are not the result of a triaxial stellar bulge. Such a feature is predicted by the simulations of NIR isophote twist galaxies by Shaw et al. (1993) and Friedli & Martinet (1993). Friedli & Martinet (1993) predict a kinematically distinct nuclear bar that rotates with a pattern speed greater than the main bar, while Shaw et al. (1993) predict that the nuclear structure will have the same pattern speed as the main bar. Unfortunately, the lack of a detailed rotation curve for the inner regions of NGC 2273 prevents us from determining if the nuclear bar is kinematically separate from the rest of the galaxy.

2) In the nucleus NGC 5728 we see a series of clumps of emission that do not seem to align with any of the features previously observed at other wavelengths. CO emission is detected coincident with the dust lane to the south of the nucleus. The peak of the CO map
is not aligned with the galactic center, nor is it located at the center of the offset nuclear ring seen in the HST images of Wilson et al. (1993). We do not see evidence for a nuclear bar in the CO maps, which suggests that, if there is a real nuclear bar in the nucleus of NGC 5728, it must contain little or no molecular gas. This result is contrary to current simulations of double barred galaxies, which require large amounts of dissipative material to produce long-lived nuclear bars. It is possible that the NIR isophote twists in NGC 5728 are caused by either a triaxial stellar bulge or are scattered light from the jets observed in the HST images of Wilson et al. (1993).

3) We have calculated the molecular gas mass over the entire nuclear bar of NGC 2273 and find that it contains $4.7 \times 10^8$ M$_\odot$ of molecular gas. The inner 1.4×1.4 kpc of NGC 5728 contains $5.7 \times 10^8$ M$_\odot$ of molecular gas. Assuming Keplerian motion, we find that the dynamical mass of the inner 10'' of NGC 2273 is $1.9 \times 10^9$ M$_\odot$, which translates into a molecular gas mass fraction of 20% for NGC 2273. Adopting the dynamical mass value determined by Rubin (1980) we calculate the molecular mass fraction to be 6% for NGC 5728.

4) Comparing our observations to models of double-barred galaxies, it seems that both galaxies contain sufficient molecular gas for the models of Shaw et al. (1993) and Friedli & Martinet 1993. However, we only see a nuclear gas bar in NGC 2273. One possibility is that the gas dissipation in the models may be overestimated. Reducing the viscosity of the gas in the models could permit nuclear bars to form in galaxies with a 20% gas mass fraction, but not in galaxies with 6% gas mass fraction.

5) Another possible explanation for the differing CO morphologies may be galaxy evolution. When comparing our results with other double barred galaxies, we find evidence that NGC 5728 may represent an older double-barred galaxy in the final stages before nuclear bar dissolution. It is possible that the inflow has already modified the galactic potential, and the molecular gas has responded to the changes before the stellar component. This
may explain why we see a nuclear bar in the NIR images of NGC 5728, but not in the CO maps.

6) The similarity in the NIR images and the differences in the CO maps suggest that the molecular gas may have different physical properties in each galaxy, which allows it to respond differently in similar gravitational potentials. These differences could be the result of nuclear starburst activity heating the gas, which could make it less viscous. Multi-line data are currently being obtained to test this hypothesis.

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