THE DISTRIBUTION OF DARK MATTER
IN A RINGED GALAXY

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ABSTRACT

Outer rings are located at the greatest distance from the galaxy center of any feature resonant with a bar. Because of their large scale, their morphology is sensitive to the distribution of the dark matter in the galaxy. We introduce here how study of these rings can constrain the mass-to-light ratio of the bar, and so the percentage of dark matter in the center of these galaxies.

We compare periodic orbits integrated in the ringed galaxy NGC 6782 near the outer Lindblad resonance to the shape of the outer ring. The non-axisymmetric component of the potential resulting from the bar is derived from a near-infrared image of the galaxy. The axisymmetric component is derived assuming a flat rotation curve. We find that the pinched non-self-intersecting periodic orbits are more elongated for higher bar mass-to-light ratios and faster bars. The inferred mass-to-light ratio of the bar depends on the assumed inclination of the galaxy. With an assumed galaxy inclination of $i = 41^\circ$, for the orbits to be consistent with the observed ring morphology the mass-to-light ratio of the bar must be high, greater than 70% of a maximal disk value. For $i = 45^\circ$, the mass-to-light ratio of the bar is $75 \pm 15\%$ of the maximal disk value.

Since the velocity field of these rings can be used to constrain the galaxy inclination as well as which periodic orbit is represented in the ring, further study will yield tighter constraints on the mass-to-light ratio of the bar. If a near maximal disk value for the bar is required, then either there would be little dark matter within the bar, or the dark matter contained in the disk of the galaxy would be non-axisymmetric and would rotate with the bar.

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1. INTRODUCTION

Outer rings are located at the greatest distance from the galaxy center of any feature resonant with a bar. Because of their great distance from the galaxy center, their morphology should be sensitive to the distribution of the dark matter in the galaxy. Since they are resonant with the bar they are also sensitive to the mass-to-light ratio of the bar. These rings provide a unique opportunity to constrain the mass-to-light ratio of the luminous stellar matter in a galaxy, thus telling us about the dark matter distribution. Although the morphology of outer rings has been used to constrain bar pattern speeds (Byrd et al. 1994), it has not yet been used to constrain the dark matter distribution.

Disk mass-to-light ratios have been almost exclusively measured by axisymmetric fits to observed rotation curves (e.g. Kent 1987a, Kent 1987b, Broeils & Courteau 1997, Begeman 1991, Sackett 1997b) and are commonly done by requiring the disk to be as massive as possible, as in the “maximal disk” model. Disk mass-to-light ratios determined in this manner are model dependent (see Sackett 1997a) and are affected by a variety of assumptions such as the dark matter halo profile assumed and the bulge/disk decomposition method. In this paper, by measuring the gravitational force of a non-axisymmetric component, the bar, which is necessarily a disk component, we can constrain the disk mass-to-light ratio in a way that is independent of the radial distribution of the dark matter, and does not require the assumption (of the “maximal disk” model) that the disk is as massive as possible within the limits set by the rotation curve.

Three classes of rings can be seen in normal barred galaxies. Nuclear rings located inside the bar, inner rings which envelop the bar, and outer rings which surround the bar. The simulations of Schwarz 1981 first demonstrated that outer rings develop in the ISM near the Outer Lindblad Resonance (OLR) of the bar. Outer rings are classified (following Buta & Crocker 1991) as R1-type or R2-type rings, where R2-type rings are oval and aligned parallel to the bar and R1-type rings resemble an oval with dimples at the points where the ring is closest to the bar. When the rings contain spiral structure, they are classified as pseudo-rings and are denoted R1’ or R2’ rings. The two types of rings have morphology closed related to the two families of closed orbits near the OLR (e.g. see Contopoulos & Grosbøl 1989 or Kalnajs 1991). The bar in these galaxies causes many stellar orbits in the plane of the galaxy to intersect themselves. Because gas can shock, it cannot remain in these orbits, so it collects in orbits that are near the periodic orbit families which are not self-intersecting (Schwarz 1981). For an excellent review on the properties of ringed galaxies see Buta & Combes 1996.

In this paper we examine the sensitivity of the ring shape of an R1’ ringed galaxy to the mass-to-light ratio of the bar. The non-axisymmetric component of the gravitational potential is derived from a J band image of the galaxy. The morphology of the ring is compared to periodic orbits near the OLR for different bar mass-to-light ratios. Using this comparison we place limits on the mass-to-light ratio of the bar, and so on the distribution of the dark matter in the galaxy.
NGC 6782 is the best example of an R1-type ringed galaxy found to date in the OSU galaxy survey. In a catalog of southern ringed galaxies (Buta 1995) the galaxy is classified as R1′SB(r)0/a. Buta 1995 shows this galaxy as a nice example of an R1′ ringed galaxy and demonstrates that the outer ring is prominent in a $B-I$ color map and so is quite blue. Byrd et al. 1994 show NGC 6782 as an example of a galaxy that resembles their slow pattern speed simulations. The R1′ ring in NGC 6782 has a radius of $\sim 60''$ which corresponds to 15kpc assuming a distance to the galaxy of 50 Mpc ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

The galaxy was observed in the near infrared $J,H$ and $K$ bands and in the visible $B,V$ and $R$ bands. These data are a preliminary part of a survey being carried out at the Ohio State University of $\sim 220$ galaxies (Frogel et al. 1996). The survey’s goal is to produce a library of photometrically calibrated images of late-type galaxies from 0.4 to 2.2$\mu$m. For notes on the observation and reduction techniques see Pogge et al. 1997, or for individual examples Quillen et al. 1994, and Quillen et al. 1995. All the images were observed at the Cerro Tololo Interamerican Observatories. The $BVR$ images were observed at the 0.9m telescope on 1995 October 25 using the Tek#2 1024 $\times$ 1024 pixel CCD with a spatial scale of 0.40/pixel. Total on source exposure times were 30, 15 and 10 minutes for $B,V$ and $R$ respectively. The $JHK$ images were observed at the 1.5m telescope on 1995 October 31 and 1995 Nov 2 using the NICMOS 3 256 $\times$ 256 pixel infrared array with a spatial scale of 1.16/pixel. Total on source exposure times were 15 minutes at $J$ and $H$ and 29 minutes at $K$ band. The infrared images were observed during photometric conditions and were calibrated on the CTIO/CIT system using standard stars listed by Carter & Meadows 1995. The optical images were observed during clear but non-photometric conditions.

Figure 1 shows $B$ and $J$ band images of the galaxy and an $R/B$ color map. In the $B$ band image (Figure 1a) the classic figure 8 shape of the R1-type ring can be seen. The ring has some spiral structure which causes the ring to be brighter on its north-east and south-west sides than on its north-west and south-east sides. This means that the ring does not have perfect mirror symmetry about its major axis. The pinches near the bar ends can be more clearly seen in the brighter north-east and south-west sides of the ring.

3. THE FORM OF THE GRAVITATIONAL POTENTIAL

To integrate orbits in the plane of the galaxy we require an estimate of the gravitational potential. We assume that the potential in the plane $\Phi(r,\theta)$ is a sum of two components, an axisymmetric one, $\Phi_0(r)$, and a component $\Phi_2(r)$ proportional to $\cos 2\theta$,

$$\Phi(r,\theta) = \Phi_0(r) + \Phi_2(r) \cos(2\theta)$$  \hspace{1cm} (1)

where $\theta$ is the azimuthal angle in the plane of the galaxy and $r$ is the radius. We take the bar to be aligned along the axis with $\theta = 0$. 
3.1. The Axisymmetric Component

The axisymmetric component of the potential should be consistent with the rotation curve of the galaxy at the location of the outer ring. At the location of the outer ring in NGC 6782, dark matter is expected to contribute to the rotation curve. We therefore could not use a potential derived solely from the light distribution as did Quillen et al. 1994 & Quillen 1997 which were dynamical studies of bars in the central few kpc of galaxies.

Unfortunately, there is no published rotation curve for NGC 6782. Few ringed galaxies have measured rotation curves at large radii. However those few that have been observed, have rotation curves that are nearly flat. For example, the rotation curve of ESO-509-98 is very flat (Buta et al. 1996), and the HI velocity field shows the rotation curve of NGC 3351 (of similar morphological type) to be nearly flat (A. Bosma private communication). Simulations of outer rings produce more realistic shaped rings in model galaxies with flat rotation curves (Byrd et al. 1994). In our orbit integrations, for the axisymmetric component of the potential, $\Phi_0$, we therefore assume a logarithmic form consistent with a flat rotation curve. $\Phi_0$ is determined by one parameter, the circular velocity, which we estimate from the Tully-Fisher relation (see below). We include scaling factors in all values which depend upon this velocity so that when the actual circular velocity is known, these values can be corrected.

Near infrared images are superior to visible images for dynamical studies because of their reduced sensitivity to extinction from dust and because they are dominated by light from an older cooler stellar population that is more evenly distributed dynamically and a better tracer of the stellar mass in the galaxy than the bluer, hotter stars (e.g. Frogel 1988; Frogel et al. 1996). We use the $J$ band image to determine the gravitational potential due to the luminous stellar component of the galaxy. The $J$ band image was used because the sky is flatter outside the bar than it is in the $H$ band image and because it has higher signal to noise than the $K$ band image. The color $J - K = 1.0 \pm 0.05$ is constant across the bar, though the bulge of the galaxy ($r < 7''$) is redder with $J - K = 1.06 \pm 0.05$. The height of the rotation curve from the luminous stellar matter (traced in $J$ band) allows us to define a maximal disk, and show that at the ring a significant dark component is needed to have a realistic flat rotation curve.

3.2. Galaxy Inclination

Before the gravitational potential due to luminous stellar matter can be generated from the infrared image, we must correct for the inclination of the galaxy. A statistical study of R1' ringed galaxies found that these rings have observed axis ratios of $q_0 = 0.74 \pm 0.08$ and position angles on the sky with respect to the bar of $\theta_0 = 90^\circ \pm 9^\circ$ (Buta 1995). Buta 1995 found that R1' rings are very nearly perpendicular to the bar and are elongated. Gas simulations of these rings support Buta 1995's finding for the ring alignment (Byrd et al. 1994). We therefore assume that the ring is perpendicular to the bar. This assumption reduces the degrees of freedom so that the major
axis position angle is fixed by a choice for the inclination of the galaxy.

Another constraint on the galaxy inclination is obtained from the outermost detected isophotes. We constructed a sum of the $B, V$ and $R$ images weighted inversely by the noise in each band so as to maximize signal to noise in the outer regions of the galaxy. An outer isophote is displayed in Figure 1d. This isophote has major axis oriented at a position angle of $\sim -45^\circ$ and has an axis ratio of $\sim 0.9$. This suggests that the galaxy is not highly inclined. Since early-type galaxies are less often warped than late-type galaxies (Bosma 1991), it is unlikely that the galaxy is warped at large radii. We therefore corrected for the inclination, $i$ (where a face-on galaxy has $i = 0^\circ$), of the galaxy using various inclinations and their accompanying position angles (see Table 1). Deprojected images of the galaxies at these inclinations are shown in Figure 2.

The inclination $i = 41^\circ$ causes the ring in the plane of the galaxy to be rounder or to have a larger axis ratio than for $i = 35^\circ$. Inclinations higher than $45^\circ$ cause the outer isophotes of the galaxy (see Figure 1d) to be very elliptical, or have an axis ratio smaller than 0.8 (see Table 1 for axis ratios). These outer isophotes are not aligned with any feature in the galaxy so they should be close to circular. Inclinations higher than $45^\circ$ also cause the ring to be either aligned parallel to the bar or to be almost round (for $i = 49^\circ$, the ring axis ratio is $\sim 1.0$). This would be inconsistent with the statistics of of R1' rings compiled by Buta 1995. For inclinations lower than $35^\circ$, the bar and the ring cannot be perpendicular. It is therefore unlikely that the inclination of the galaxy is outside the range $35^\circ < i < 45^\circ$.

After correcting for inclination, the gravitational potential in the plane of the galaxy traced by the luminous stellar matter was determined by convolving the $J$ image of NGC 6782 with a function that depends on the vertical structure of the disk (Quillen et al. 1994). Before convolution stars were removed from the $J$ image. The disk is assumed to have density $\propto \text{sech}(z/h)$ (following van der Kruit 1988) where $z$ is the height above the plane of the galaxy and $h$ is the vertical scale height. The resulting potential is insensitive to the choice of vertical function for functions such as $\text{sech}$, $\text{sech}^2$ and exponential with equivalent $\langle z^2 \rangle$ (Quillen 1996). Since the galaxy is distant, a small vertical scale height was used $h = 0''5$. Quillen 1996 found that doubling the vertical scale height results in raising the $\Phi_2$ component of the gravitational potential by $\sim 10\%$. We have deliberately made $h$ small because the seeing in the images causes artificial smoothing equivalent to increasing the size of $h$.

### 3.3. What Do We Mean by a Maximal Disk?

Figure 3 shows the rotation curve derived from the axisymmetric component of the potential generated from the $J$ image for the different galaxy inclinations. The horizontal line shown in Figure 3 is the circular rotational velocity computed using the Tully-Fisher Relation. For an $H$ band total magnitude of 8.87 measured from our $H$ band image, we compute a circular velocity of 320 km s$^{-1}$ using the relation given in Pierce & Tully 1992. All subsequent values given in this paper
will be in units with respect to this circular velocity. This circular velocity is also what we used for
the flat rotation curve axisymmetric component of the potential in our orbit integrations at the
location of the ring. The rotation curves shown in Figure 3 assume a distance of 50 Mpc \((H_0 = 75\ km\ s^{-1}\ Mpc^{-1})\) to the galaxy and a mass-to-light ratio of \(M/L_J = 1.23 \left(\frac{v_c}{320 \ km \ s^{-1}}\right)^2 \left(\frac{50 \ Mpc}{D}\right)\) or
using the color of the bar \(M/L_K = 0.69 \left(\frac{v_c}{320 \ km \ s^{-1}}\right)^2 \left(\frac{50 \ Mpc}{D}\right)\) in solar units (see Worthey 1994)
where \(L_J\) and \(L_K\) are the luminosities in the \(J\), and \(K\) bands and \(v_c\) is the true (not yet measured)
circular velocity of the galaxy.

For a “maximal disk” the rotation curve is attributed as much as possible to be from the
visible components so that the halo could have a hollow core. (Some authors call a “maximal disk
solution” one with a smooth halo that extends into the nucleus of the galaxy). The mass-to-light
ratio listed above for the disk is what we take to give a “maximal disk”. This mass-to-light ratio
was chosen so that the rotation curve generated from the \(J\) band light reaches above the circular
velocity predicted from the Tully-Fisher relation. Once the true circular velocity for the galaxy
has been observed, the mass-to-light ratio for the maximal disk can be rescaled. Because the three
dimensional nature of the bulge was not properly taken into account in estimating the potential,
the rotation curve is higher (by 10 – 20\%) than it should be in the central 0 – 20''. This is why
we have chosen the mass-to-light ratio such that the rotation curve is somewhat higher than the
circular velocity near the galaxy nucleus (see Figure 3).

We note that the rotation curve generated from the light drops with increasing radius. At the
radius of the ring (\(\sim 60 – 70''\) or 15 – 17kpc), a significant fraction of the mass must be from dark
matter. Matter outside of our image which we do not detect exerts a radial force outwards, so
that the rotation curve predicted from starlight should be even lower at large radii than we show
in Figure 3.

### 3.4. The Non-Axisymmetric Component of the Gravitational Potential

The non-axisymmetric component of the potential should be due solely to the bar of the
galaxy. Since the bar is in the disk of the galaxy, our inaccurate treatment of the bulge of the
galaxy does not affect our measurement for \(\Phi_2(r)\) (defined in equation 1). If luminous matter
outside the image is axisymmetric then once again, our estimate for \(\Phi_2(r)\) is not affected by
neglecting this matter. This means that our orbit integrations which use only the \(\Phi_2\) component
derived from the luminous matter are not affected by our inaccurate treatment of the bulge and
outer disk. Higher order Fourier components of the potential are neglected since at the ring they
are negligible.

The magnitude of the \(\Phi_2\) component measured from the potential due to luminous matter is
shown in Figure 4 for the various inclinations assumed and for the maximal disk mass-to-light ratio
discussed above. The \(\Phi_2\) component drops off quickly with radius as expected for a quadrupolar
potential term. Also shown in Figure 4, an exponential function

$$
\Phi_2(r) = A \exp (-r/a),
$$

was fit to these $\Phi_2$ components. The numerical values for these fits are listed in Table 1. These numbers show the strength of the non-axisymmetric component of the potential from the bar for the maximal disk, (corresponding to the rotation curves shown in Figure 3). For the higher inclinations $\Phi_2$ component is substantially stronger because the bar becomes longer once deprojected. The exponential scale length of $\Phi_2$, $a$, is also larger for the higher inclination case (see Table 1). In the next section we discuss the effect of changing the disk mass-to-light ratio (and so the bar strength) on the morphology of the R1′ ring.

4. MODELING THE RING

We integrate orbits in the plane of the galaxy for a gravitational potential with axisymmetric component consistent with a flat rotation curve and circular velocity determined from the Tully-Fisher relation. The non-axisymmetric component of the potential is derived from exponential fits to the $\Phi_2$ components generated from the $J$ band image for the various galaxy inclinations assumed. In our integrations we vary the strength of the bar by adjusting the mass-to-light ratio of the $J$ band image and by keeping the circular velocity fixed. What we call the maximal disk corresponds to the mass-to-light ratios for the rotation curves shown in Figure 3 and the $\Phi_2$ components shown in Figure 4 with fitting parameters listed in Table 1. Varying the mass-to-light ratio of the disk corresponds to multiplying $\Phi_2$ by a constant that is less than 1. Since the maximal disk mass-to-light ratio is determined by our assumption for the circular velocity (see discussion above), our results are not affected by the fact that actual circular rotational velocity is not known. Periodic orbits (or orbits that are closed in the frame in which the bar is stationary) in the plane of NGC 6782 were found by numerical integration as in Quillen et al. 1994.

In Figure 5 we show periodic orbits near the OLR for the maximal disk for a galaxy inclination of $41^\circ$. We see that the inner periodic orbits are more pinched near the bar, and have a rounder appearance. The outer orbits are more elongated and less pinched near the bar. Points in Figure 5 (and subsequent figures) are shown at equal timesteps along the orbit so that the gas density in the orbit should be high in the pinches near the bar. Correspondingly the speed of the gas decreases in the pinches. Measurement of the velocity field in the ring should constrain the degree of cuspiness of the orbits. As pointed out by Kalnajs 1991 the gas in the ring cannot be in an orbit that intersects itself or that has loops. We therefore only consider orbits that are not self-intersecting. For the orbits shown in Figure 5a, the radius of corotation is $37.7''$ and the bar angular rotation rate or pattern speed is $35.0 \text{ Gyr}^{-1} \times \left(\frac{v_c}{320 \text{ km s}^{-1}}\right) \left(\frac{50 \text{ Mpc}}{D}\right)$. For our rotation curve, this pattern speed places the radius of corotation just past the end of the bar as predicted theoretically and inferred from observations of bars. Figure 5 shows that the maximal disk provides a good fit to the morphology of the ring for a galaxy inclination of $i = 41^\circ$. In the
following sections we explore the sensitivity of the ring morphology to the bar strength, the bar pattern speed and the galaxy inclination.

4.1. Varying the Strength and Pattern Speed of the Bar

Figure 6 shows comparisons between periodic orbits with the same apogee for different bar strengths and pattern speeds at a galaxy inclination of $i = 41^\circ$. All figures compare an orbit shown in Figure 5a that has a maximal disk mass-to-light ratio with a similar orbit for either lower bar mass-to-light (Figure 6a), faster bar (Figure 6b) or both (Figure 6c). Figure 6a shows the comparison for two bars with the same pattern speed. We note that the weaker bars have rounder less pinched orbits of the same apogee. Figure 6b a comparison between a slow and a faster bar with the same bar strengths. We can see that the faster bar has a more elongated and strongly pinched orbit of the same apogee. In Figure 6c we can see that by decreasing the bar strength and increasing the bar pattern speed, differences in the shapes of orbits with the same apogee can be minimized.

Weakening the bar potential at the location of the ring (equivalent to decreasing the disk mass-to-light ratio) to less than 70% of the maximal disk value causes the pinched orbits to be rounder and less pinched than the observed ring. We find that it is not possible to consistently match the morphology of the ring by raising the bar pattern speed in a weaker bar, since this decreases the radius of corotation to within the bar ends. For the orbits shown in Figure 5 (and the solid line in Figure 6abc) the corotation radius lies just outside the end of the bar at a radius of $37.7''$. The faster bar (with corresponding orbit shown as open points in Figure 6c) which would fit the ring morphology places the radius of corotation at $33.1''$ which lies within the end of the bar, a situation which is not thought to be theoretically possible (Contopoulos et al. 1989). As a result we find that for an assumed inclination of $i = 41^\circ$ the bar mass-to-light ratio must be greater than 70% of the maximal disk value.

4.2. Changing the Galaxy Inclination

For a lower galaxy inclination of $i = 35^\circ$ the strength of the $\Phi_2$ component is about half as large of that with $i = 41^\circ$ at the location of the ring (see Figure 4). As expected from the previous section it is not possible to match the ring morphology with the periodic orbits without increasing the mass-to-light ratio past what we have defined as the maximal disk value or decreasing the radius of corotation to a radius smaller than the bar length. Figure 7 shows orbits integrated for a maximal disk mass-to-light ratio with a bar corotation radius of $32.2''$. Orbits with larger apogees than shown in Figure 7 become self-intersecting with small loops at their minor axes and are probably unstable. The non-self-intersecting periodic orbits are too round to match the observed ring morphology. It is not possible to resolve the problem by raising the bar angular rotation rate
since this would place the radius of corotation within the end of the bar.

It would be possible to have a stronger bar or a larger mass-to-light ratio with a more carefully estimated maximal disk value at $i = 35^\circ$. For example if the rotation curve of the galaxy decreases with radius near the ring then the maximal disk value for mass-to-light ratio could be higher. The ring enveloping the bar which is quite blue (see Figure 1c) may contain a large gas mass. Including this gas mass increase the strength of the non-axisymmetric component ($\Phi_2$) of the potential and so cause the periodic orbits near the OLR to be more elongated. In short we find that for an assumed inclination of $i = 35^\circ$ the bar mass-to-light ratio must be greater than the maximal disk value assumed here.

For higher galaxy inclinations, the outer ring becomes rounder and the bar lengthens (see Figure 2). A mass-to-light ratio lower than the maximal disk value is required to match the observed morphology of the ring. In Figure 8 we show periodic orbits for a galaxy inclination of $45^\circ$ that resemble the morphology of the ring for a mass-to-light ratio that is 75% of the maximal disk value. Since the average radius of the ring is larger for this galaxy inclination than for lower inclinations, the bar angular rotation rate must be lower. Mass-to-light ratios lower than 60% again cause the ring to be too round to match the morphology of the ring. Higher mass-to-light ratios than 90% eliminated the R1 periodic orbits (the resonance was very strong) at the radius of the ring for pattern speeds that kept the corotation radius outside the bar ends. As a result we find that for an assumed inclination of $i = 45^\circ$ the bar mass-to-light ratio must be within $75 \pm 15\%$ of the maximal disk value.

It is extremely unlikely that the galaxy inclination is much higher than $45^\circ$ since at $50^\circ$ the ring is almost round and the outer isophotes of the galaxy are even more elongated (see Figure 2).

5. SUMMARY AND DISCUSSION

5.1. Underlying Assumptions

We have assumed the following in modeling the R1' outer ring in NGC 6782:

1) The ring morphology consists of gas in periodic non-self intersecting orbits near the Outer Lindblad Resonance, and spiral structure in the ring does not cause the morphology to deviate significantly from these periodic orbits.

2) The bar is perpendicular to the ring. This allowed us to determine the position angle for a given galaxy inclination.

3) The rotation curve is flat.

4) The $\Phi_2$ non-axisymmetric component of the potential is only due to the bar as seen in the $J$ band image (gas is neglected) and does not twist (equation 1).
5) The maximal disk mass-to-light ratio is well estimated from the axisymmetric component of the $J$ band generated potential.

Many of these assumptions can be constrained with a velocity field that can determine the inclination and measure the rotation curve of the galaxy. However the first assumption listed above is of particular concern. Strong spiral structure in the ring will cause the gas to deviate from the periodic orbit families explored here. While it is not unreasonable to expect that the gas is close to the periodic orbits (in the same way gas in the Milky way is primarily undergoing circular motion despite its spiral structure), future work should both study R1 ring galaxies with minimal spiral structure and investigate the role of the spiral structure in these rings.

5.2. Summary and Discussion

In this paper we have explored the shape of the periodic orbits near the Outer Lindblad resonance in a ring galaxy using a non-axisymmetric gravitational potential based upon a near-infrared image of the bar. We find that the shape of the non-self-intersecting periodic orbits at the OLR is affected by the strength of the non-axisymmetric component $\Phi_2$ of the gravitational potential. A stronger bar (corresponding to a larger $\Phi_2$) or a faster bar result in more elongated orbits at the radius of the ring.

Using the above assumptions, and comparing outer ring morphology of NGC 6782 with the integrated non-self-intersecting periodic orbits we find that the bar mass-to-light ratio can be constrained given an assumed galaxy inclination. For a galaxy inclination of 41° we find that a bar mass-to-light ratio greater than 70% of the maximal disk value is needed to match the ring morphology. It is not possible to match the morphology of the ring with a weaker and faster bar since this places the bar corotation radius within the end of the bar. For $i = 45°$ we find a mass-to-light ratio of $75 \pm 15\%$ of the maximal disk value matches the morphology of the ring. For $i = 35°$ a value larger than the maximal disk value assumed here is required. A larger mass-to-light ratio could be allowed if a large gas mass is found in the ring enveloping the bar (increasing the $\Phi_2$ component of the potential), or if the rotation curve decreases near the ring.

Larger galaxy inclinations are unlikely for the following reasons: 1) The ring becomes round or aligned with the bar which is not supported by statistics of R1-type rings (Buta 1995). However, NGC 6782 could be a special case. 2) The outer isophotes of the galaxy become significantly elongated. Deeper images showing the shapes of the isophotes past the ring may help to constrain the inclination angle of the galaxy.

We note that here that the method considered here places a constraint on the the strength of the non-axisymmetric ($m = 2$) component of the potential from the bar. Since the bar is necessarily a disk component this leads directly to a constraint on the disk mass-to-light ratio. Once the rotation curve is observed the morphology of the ring gives a constraint on the disk mass-to-light ratio which is independent of any assumptions about the halo or dark matter.
distribution. As a result a measured rotation curve would allow us to measure the core radius of the dark matter halo using our values for the mass-to-light ratio. A measured rotation curve will also enable us to place a value on the maximal disk mass-to-light ratio assumed here and check whether our assumption of a flat rotation curve is a good one.

Modeling of an observed velocity field in the ring will make it possible to measure the mass-to-light ratio of the bar with more precision than with a purely morphological comparison as done here. Velocities observed along the major axis of the ring should constrain the inclination of the galaxy. Highly pinched orbits have slow speeds in their pinches, as inferred from small spacing in the equal time step points shown in Figures 5-8. The velocity field should also therefore limit which particular orbits are represented in the ring. The asymmetry of the velocity field will also constrain the degree of deviation from the periodic orbits caused by spiral structure in the ring.

We also plan to observe other ring galaxies to find if high mass-to-light ratios are required generally. Modeling of galaxies with different orientations should help resolve the uncertainties caused by projection.

Gas simulations of rings could be studied to discover how well closed orbits match the gas morphology in these systems, which particular orbits collect gas, and how close outer rings are to being perpendicular to their bars. The effect of spiral structure on the morphology of the ring should also be studied.

If a near maximal disk value for the bar mass-to-light ratio is indeed required (as suggested here) then either the inner parts of galaxies have little dark matter, or the dark matter contained in the disk of the galaxy is non-axisymmetric and rotates with the bar. The second possibility implies that the “conspiracy of shapes” suggested by Sackett et al. 1994 extends into the bar, and would lend support to the idea that dark matter halos are flattened (Sackett et al. 1994; Olling 1996), since if the dark matter rotates, it should be flattened.

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Fig. 1.— a) Grayscale $B$ band image of NGC 6782 overlayed with contours of the bar 0.5 mag apart. The image is uncalibrated so we do not know the absolute scale. b) $J$ band contours of the bar. The brightest contour is at 15.5 mag/arcsec$^2$ and the difference between contours is 0.5 mag/arcsec$^2$. c) B/R color map similar to that shown by Buta 1995. d) Low surface brightness contour in an image that is a noise weighted sum of the $B, V$ and $R$ band images. Note the change in angular scale between this figure and the other figures. We note that this outer isophote is almost round suggesting that the galaxy is not highly inclined.

Fig. 2.— Deprojected $B$ band images for the inclinations and position angles listed in Table 1. Note that the higher the galaxy inclination the rounder the ring and the longer the bar. The position angles have been chosen so that the bar is approximately perpendicular to the ring. These images have been rotated so that the bar has a major axis at $PA \approx 90^\circ$ which is the same as that observed in the original image. a) $i = 35^\circ$. b) Same as a) but for $i = 41^\circ$. c) Same as a) but for $i = 45^\circ$. d) Same as a) but for $i = 49^\circ$.

Fig. 3.— The rotation curves from the axisymmetric component of the $J$ band generated gravitational potential using the mass-to-light ratio described in the text as ‘maximal disk’. Rotation curves for galaxy inclinations of $i = 35^\circ$ and $45^\circ$ have been plotted as solid lines. There is little difference between them. The horizontal dotted line represents a flat rotation curve with a circular velocity of 320 km/s predicted using the Tully-Fisher relation. Once the true circular velocity, $v_c$, of the galaxy is observed, the mass-to-light ratio for the maximal disk should be rescaled. For a non-maximal disk the rotation curve resulting from the luminous stellar matter would be lower than that shown here.

Fig. 4.— The amplitude of the non-axisymmetric component $\Phi_2$ from the bar of the $J$ band generated gravitational potential for the maximal disk. The solid lines are for galaxy inclinations of $i = 45^\circ$, $41^\circ$ and $35^\circ$ in order of decreasing height. Once the true circular velocity, $v_c$, of the galaxy is observed, the mass-to-light ratio for the maximal disk should be rescaled. The dotted lines are exponential fits to these curves with strengths and scale lengths listed in Table 1. $\Phi_2$ is substantially weaker for the lower galaxy inclinations.

Fig. 5.— Comparison of periodic orbits with the morphology of the ring at a galaxy inclination of $i = 41^\circ$. a) Grayscale of the deprojected galaxy. b) Periodic orbits near the Outer Lindblad Resonance. The mass-to-light ratio of the bar in units of percent of the maximal disk value (MD) and the corotation radius ($r_{cr}$) are printed in the right hand corner of the plot. Points are plotted at equal timesteps in the rotating frame in which the bar is still. Note that speeds are slower in the pinches near the bar ends. The dotted circle shows the location of the Outer Lindblad Resonance. The maximal disk provides a good representation for the morphology of the ring.
Fig. 6.— a) The effect of varying the bar strength on the shape of the orbits with the same apogee for a galaxy inclination $i = 41^\circ$. A periodic orbit for the maximal disk (solid line) compared to a similar orbit for weaker bars with mass-to-light ratios that are 70% and 50% as large as the maximal disk value (open points). These orbits are derived from bars with the same corotation radii. The dotted circle shows the location of the Outer Lindblad Resonance. Bar strengths, in units of percent of the maximal disk value (MD), and the corotation radii ($r_{cr}$) are printed in the upper right hand corners of the plots. b) The effect of varying the bar pattern speed on the shape of the orbits with the same apogee. A periodic orbit for the maximal disk (solid line) compared to a similar orbit with the same bar mass-to-light ratio but a faster bar. c) By increasing the speed and decreasing the strength of the bar differences in the orbit shapes can be minimized. A pinched non-self-intersecting orbit for the maximal disk (solid line) compared to a similar orbit (open points) for a faster and weaker bar.

Fig. 7.— Comparison of periodic orbits with the morphology of the ring at a galaxy inclination of $i = 35^\circ$. a) Grayscale of the deprojected galaxy. b) Periodic orbits near the Outer Lindblad Resonance. The mass-to-light ratio of the bar in units of percent of the maximal disk value (MD) and the corotation radius ($r_{cr}$) are printed in the right hand corner of the plot. Points are plotted at equal timesteps in the rotating frame in which the bar is still. The dotted circle shows the location of the Outer Lindblad Resonance. The maximal disk value for the mass-to-light ratio produces non-self-intersecting orbits that are insufficiently elongated to be consistent with the morphology of the ring.

Fig. 8.— Comparison of periodic orbits with the morphology of the ring at a galaxy inclination of $i = 45^\circ$. a) Grayscale of the deprojected galaxy. b) Periodic orbits near the Outer Lindblad Resonance. The mass-to-light ratio of the bar in units of percent of the maximal disk value (MD) and the corotation radius ($r_{cr}$) are printed in the right hand corner of the plot. Points are plotted at equal timesteps in the rotating frame in which the bar is still. The dotted circle shows the location of the Outer Lindblad Resonance. The mass-to-light ratio of 75% of the maximal disk value provides a good representation for the morphology of the ring. c) Same as b) but with a weaker bar.
Table 1. Galaxy Orientation and Exponential Fits to $\Phi_2$

<table>
<thead>
<tr>
<th>Inclination</th>
<th>PA$^j$</th>
<th>$A$ (km s$^{-1}$)$^2$</th>
<th>$a$ (arcsec)$^k$</th>
<th>Outer Axis Ratio$^l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>35°</td>
<td>$-58^\circ$</td>
<td>$3.78 \times 10^4$</td>
<td>17.5</td>
<td>1.0</td>
</tr>
<tr>
<td>41°</td>
<td>$-45^\circ$</td>
<td>$3.51 \times 10^4$</td>
<td>22.5</td>
<td>0.83</td>
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<tr>
<td>45°</td>
<td>$-32^\circ$</td>
<td>$3.63 \times 10^4$</td>
<td>24.3</td>
<td>0.76</td>
</tr>
<tr>
<td>49°</td>
<td>$-25^\circ$</td>
<td>$3.40 \times 10^4$</td>
<td>26.3</td>
<td>0.70</td>
</tr>
</tbody>
</table>

$^i$Galaxy major axis Position Angle required for the bar to be perpendicular to the ring at the given inclination.

$^j$For a maximal disk mass-to-light ratio (see equation 2). Once the true circular velocity, $v_c$, of the galaxy is known these numbers should be multiplied by $\left(\frac{v_c}{320\text{ km s}^{-1}}\right)^2$.

$^k$Exponential scale length of $\Phi_2$ (see equation 2).

$^l$Axis ratio of the deprojected outer isophote shown in Figure 1d.