Stellar Nuclear Rings in Barred Galaxies: Fossils of Past Circumnuclear Starbursts?

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Abstract. We have found four barred S0 galaxies — NGC 936, NGC 3945, NGC 4340, and NGC 4371 — which contain smooth, luminous, purely stellar nuclear rings within their bars. These rings have little or no dust, no evidence for recent star formation, and are approximately the same color as surrounding bar and bulge. Thus, they are probably the aged remnants of bar-driven circumnuclear starburst episodes similar to those seen in barred galaxies today.

Using kinematic data from long-slit spectroscopy, we construct rotation and resonance curves for two of the galaxies. In both cases, the nuclear rings appear to be located near or at the inner inner Lindblad resonances of the large-scale bars.

We also discuss the difficulties inherent in detecting and identifying such rings, and show some of the surprising ways in which stellar rings can distort galaxy isophotes and ellipse fits.

1. Introduction

Nuclear rings are circular or elliptical rings of gas and dust, typically ~ 1 kpc in size, found inside the bars of nearby galaxies; they are believed to result from the interplay of bar-driven gas inflow and bar resonances (e.g., Athanassoula 1992; Piner, Stone, & Teuben 1995). They are often sites of vigorous star formation. However, the fate of star-forming nuclear rings — what happens after the gas is consumed and star formation ceases — is currently unclear; since to date almost no “fossil” nuclear rings are known (the extremely small, blue ring found by van den Bosch & Emsellem 1998 in NGC 4570 is a possible exception).

We have recently found evidence for four such rings, in the SB0 galaxies NGC 936, NGC 3945, NGC 4340, and NGC 4371. The sizes of these rings — 600 to 900 pc in radius and 9–12% the size of the respective bars — are consistent with those of typical “young” nuclear rings (Buta & Crocker 1993). These rings are detected only as smooth distortions of the stellar isophotes; there is no evidence for significant dust or recent star formation.

2. Finding Fossil Nuclear Rings

Young (i.e., gas-rich and star-forming) nuclear rings are rather easy to see, particularly in color maps (e.g., Buta & Crocker 1993). But an old ring can be much
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harder to detect, since it may not show up in color maps and may be hard to discern against a bright bulge. Figure 1 shows a simplistic model galaxy, consisting of a de Vaucouleurs bulge of ellipticity 0.25 and a Gaussian ring of ellipticity 0.6. The ring distorts the isophotes in two ways: it makes the isophotes more elliptical at its radius, and the isophotes are rounder and “boxy” just inside the ring. Looking at just the isophotes, or at isophotal ellipse fits, it would not be clear what causes such a distortion; it could be mistaken for, e.g., a nuclear bar. However, the presence and shape of the ring is easily recovered through unsharp masking (bottom half of figure). The similarity to the real galaxy NGC 4371 is striking.

3. Morphology and Color of Nuclear Rings

In three of the galaxies (NGC 936, NGC 4340, and NGC 4371), the rings are smooth, elliptical, and aligned with the outer galactic disk: they appear to be intrinsically circular. In NGC 3945, the ring seems intrinsically elliptical, and shows signs of spiral (possibly $m = 4$) structure. In both NGC 3945 and NGC 4340, small secondary bars, not aligned with the large-scale primary bars, are found inside the nuclear rings. This pairing of nuclear rings and inner bars is also seen in galaxies with young nuclear rings (e.g., Wozniak et al. 1995).

Color maps show that rings are essentially “colorless”: they are indistinguishable from the surrounding bulge and bar stellar population, and are thus probably old and dust-free. The ring in NGC 4371 may be an exception, since it is (slightly) bluer than its surroundings; however, this could also be caused by a faint dust ring outside the stellar ring (cf. Wozniak et al. 1995).

4. Bar Resonances

Modeling of gas flow in barred galaxies (Athanassoula 1992; Piner, Stone, & Teuben 1995) shows that gaseous nuclear rings are closely associated with the inner Lindblad resonance(s) (ILRs) of large-scale bars. We can define approximate locations for such resonances in our galaxies by using kinematic information from long-slit spectroscopy; this lets us see whether the stellar nuclear rings are also associated with ILRs.

For NGC 4340, we use the major-axis velocities of Simien & Prugniel (1997) to derive a frequency curve (Figure 2, top). We use our (unpublished) bar-axis velocities, which extend to larger radii, to estimate the outer bars rotation speed: we assume that corotation is at 1.1–1.3 times the bar length, as appears to be the case for those SB0 galaxies with known bar pattern speeds (e.g., Merrifield & Kuijken 1995; Gerssen, Kuijken, & Merrifield 1999; Elmegreen et al. 1996). The points where the bar pattern speed is equal to $\Omega - \kappa/2$ are possible locations of the bars ILR(s). We do the same for NGC 3945 (Figure 2, bottom), using Kormendys (1982) major-axis rotation curve, although our estimate of the bar pattern speed is more uncertain due to the fact that the rotation curve does not extend past the outer bar radius.

For both NGC 3945 and NGC 4340, it appears that the nuclear rings lie near or at the inner ILR of the primary bars. This strengthens our identification of these rings as the stellar remnants of gaseous, star-forming nuclear rings.
Figure 1. Left: model image consisting of a moderately elliptical $R^{1/4}$ bulge and a more elliptical ring, with isophotes above and unsharp mask below. Right: central 4 x 4 kpc of SB0 galaxy NGC 4371, with $R$-band isophotes above and unsharp mask below.
Figure 2. Resonance curves for NGC 4340 and NGC 3945. Vertical dashed lines mark the deprojected sizes of inner bars and nuclear rings in each galaxy; the horizontal gray bands show the estimated ranges of outer-bar pattern speeds. Possible locations of inner Lindblad resonances (ILRs) are where the estimated bar pattern speed $= \Omega - \kappa/2$ (where the $\Omega - \kappa/2$ curves cross the pattern-speed bands).

The resonance curves also indicate that the inner bars in both of these double-barred galaxies end at or inside the inner ILRs. This is consistent with theories of double-barred galaxies where corotation of the faster-rotating inner bar coincides with one of the outer bars ILRs (Pfenniger & Norman 1990; Maciejewski & Sparke 2000).

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