Are circumnuclear (starburst) rings important in the evolution of the central kiloparsec?

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Abstract. Circumnuclear starburst rings are effective barriers against gas inflow. The large ‘pile-up’ of gas leads to distinct star forming events in the rings of NGC 5248 and NGC 6951. In our work, the rings are distinctly seen as the locations where the bulk of the central kiloparsec star formation in the last 2 Gyr has taken place. This in turn has direct implications for the large scale bars that have driven the formation of the circumnuclear rings in these galaxies. They have to be at least as old. The system of large-scale bar and circumnuclear ring has therefore ample time to stop gas inflow on the scale of the last 100 pc. The stars formed in the ring will help build the (pseudo-)bulge and eventually alter the gravitational potential.

1. Introduction
Gas inflow to the nuclear regions of a galaxy is an important factor in the secular evolution of said galaxy. Not in the least since gas inflow is a necessary factor in fueling AGN. However, between the 1 kpc scale and the final parsec are still many mechanisms, such as asymmetries in the gravitational potential, that can hinder or induce gas inflow. Large scale stellar bars are the prime component in driving gas at the 100’s of parsec scales. This was also discussed by Combes (this series).

Bar perturbations in the gravitational potential of the galactic disk induce gravitational torques on the material in the disk. Gas, being a collisional entity, will experience angular momentum changes due to these gravitational torques. Between the co-rotation (CR) radius and inner Lindblad resonance (ILR) radius of the large scale bar gas will loose angular momentum and flow inward. These non-circular motions can be seen at the dust and gas lanes along the leading edges of bars. The location of the resonances is set by the bar pattern speed and the rotation of the galaxy disk. At the ILR the gas gets stalled in its inward motion and settles again on circular orbits, unless another mechanism is present that exerts a new pull on the gas. The ‘pile-up’ of gas at the ILR is more commonly known as a circumnuclear ring.

CO observations of circumnuclear rings in various nearby galaxies have shown that the rings contain large reservoirs of molecular gas \((10^8-10^9 M_\odot)\). Such an amount of molecular gas on settled orbits must lead to strong star forming events. Indeed, many circumnuclear rings are very visible in H\(_\alpha\) (e.g. Mazzuca et al. 2008), indicating current star formation. To understand what the influence of star formation in the circumnuclear rings on the secular evolution of their host galaxies can be, we need to investigate the amount and manner of the star formation in the circumnuclear rings.

In my contribution I focused on the star formation in the circumnuclear rings of NGC 5248 and NGC 6951. These two galaxies both have circumnuclear rings driven by a large scale bar. Both galaxies are nearby (15.6 and 24.1 Mpc, resp.) and host well visible circumnuclear rings in CO and H\(_\alpha\) (Jogee et
2. Star formation in the ring

In galaxies where circumnuclear rings are driven by a large scale bar the ‘amount’ of star formation is directly related to the life time of the bar.

The ‘manner’ of star formation may also be dependent on the large scale bar. The dust/gas lanes of the bar are connected to the circumnuclear ring at two distinct positions. Two modes of star formation have been proposed that deal with this fact. They are called the ‘popcorn’ and ‘pearls-on-a-string’ model, respectively. In the popcorn scenario, first put forth by Elmegreen (1994) gas density in the circumnuclear ring builds up across the ring until the gas density is high enough that the gas fragments and starts forming stars. Several of these star formation events might occur over time and without pattern within the ring, hence the designation ‘popcorn’. The ‘pearls-on-a-string’ model by comparison proposes an azimuthal age gradient to the star formation in the circumnuclear ring. Since the large scale bar connects to the circumnuclear ring via the gas and dust spiral arms at its leading edge, the gas density at the ring contact points must therefore be preferred locations for gas overdensities. In the ‘pearls-on-a-string’ scenario these overdensities would lead to star formation occurring primarily at those locations. As the system rotates over time, an azimuthal stellar age gradient in the circumnuclear ring will be created (Böker et al. 2008).

3. Full view on the ring’s stellar population

We wish to obtain a full view of the stellar content in the rings of NGC 5248 and NGC 6951, in order to understand the star formation. We do not wish to constrain ourselves solely on star clusters, but turn to integral field spectroscopy to observe the full stellar content of the ring.

Both galaxies were observed with the SAURON instrument as part of a larger campaign (Dumas et al. 2002, Maoz et al. 2001, Van der Laan et al. 2011, Van der Laan in prep. (a) & (b)) as well as in other tracers.

**Figure 1.** Example of the PPXF/GANDALF fitting of a single SAURON spaxel. The observed spectrum is given in black, the spectral fit in red, the residual in green and the fitted emission line spectrum in blue (offset from zero). Flux is in arbitrary units. The wavelength is in [Å] and is in the observed frame.
Figure 2. Spatial distribution of the fraction of stellar mass younger than the indicated age. From the top-left to bottom-right this age is 100 Myr, 200 Myr, 400 Myr, 800 Myr, 1 Gyr, 2 Gyr.

2007) between 2001 and 2004. Individual exposures with the SAURON instrument cover a field of view of about 41" × 33", with spaxels of 0′.94, a spectral resolution of 4.2 Å and sampling of 1.15 Å spectra extending from 4780 Å up to about 5350Å. After calibration, individual exposures were recentered (using a direct image of the galaxy as a reference) and merged, by projecting each data cube on a common grid with 0′.82 spaxels. The rings in both galaxies are fully included within the field of view and well resolved at this angular resolution.

The main strength of IFU data is that we are not limited to only the star clusters, but obtain light from all stars in the ring, also old(er) populations if they are present. Also by utilizing the full available spectral range, we are able to overcome a larger extinction range, which interfere with photometric observations and obscure older star clusters.

We assume that the total stellar content emitting in each spaxel can be split into a combination of single-stellar population (SSP) fractions. We obtained SSP spectra from MILES (Vazdekis et al. 2010). We assumed a Kroupa IMF and instantaneous formation and match the spectral resolution of the model to our data. The SSP spectra span lifetimes from 65 Myr to 15Gyr, with time steps that are selected to follow stellar evolution. The strongest drivers of the fit will be the Hβ and Mgβ absorption lines, which increase and decrease with age, respectively.

We use the spectral fitting codes PPXF (Cappellari & Emsellem 2004) and GANDALF (Sarzi et al.
GANDALF enables us to correctly deal with the emission lines from the gas that is present in the ring. Among the strongest emission lines we expect is also the H\textbeta emission line. If we do not account for it, gaseous H\textbeta emission could fill the stellar absorption line and we would desensitize our results against young stellar populations. We further fit for the [OIII] doublet at 5000Å and [NI] at 5200Å. A representative example of the fitting of a single spaxel is shown in Figure 1.

In Figure 2 and 3, the preliminary results for NGC 5248 and NGC 6951 are shown. From the fitting we obtain the fraction of flux in each SSP. We can convert this into fraction of mass per SSP by using the known M/L ratio for each SSP. We have obtained the presented results by summing over age.

In both galaxies the circumnuclear ring is immediately visible in the younger age bins. In NGC 5248 the ring has a near uniform azimuthal fraction of young stars. In NGC 6951 the highest < 75 Myr mass fractions are seen at two locations that are close to the bar contact points mentioned previously. As we include more age bins the stellar mass fraction in the rings increases, while the stellar mass fraction in- and outside the ring stays low. This can be seen up to 800 Myr/2 Gyr in NGC 5248 and 2 Gyr in NGC 6951. By 4 Gyr the fraction of ‘young’ stars is no longer distinct between ring and the rest of the central region.
4. Implications for the evolution of the central kiloparsec
Our results show that the circumnuclear rings have existed as distinct star formation events in the central regions of these galaxies for approximately 2 Gyrs. This has several direct implications.

- The rings in both NGC 5248 and NGC 6951 are visible in ‘fraction of young stars’ out to an age of 2 Gyr. Therefore, for the last 2 Gyr gas has been driven to these locations, where it encountered a barrier to further inflow, i.e. a resonance. This means that the large scale bar that leads to the resonance must have been in place for at least 2 Gyr.

- The width of the young stars fraction in NGC 6951 is similar to the CO distribution as presented in Van der Laan et al. 2011. Therefore, the location of the resonances in this system cannot have significantly changed in the last 2 Gyr. Which also means that the large scale bar can’t have significantly changed strength in that time. For NGC 5248 this is less clear, as the CO distribution shows a spiral pattern (Van der Laan et al., in prep (a)).

- At 2 Gyr the stellar mass fraction in the rings are close to 1 in both galaxies. This implies that the star formation was so numerous as to outshine any previous stellar populations that were present at this location before the circumnuclear ring was formed.

- The ‘manner’ of star formation in circumnuclear rings remains ambiguous. In NGC 5248 the youngest stars are distributed nearly uniform throughout the ring, which corresponds to the ‘popcorn’ model. In contrast, in NGC 6951 the youngest stars are located at 2 positions related to the contact points with the large scale bar, which would be the ‘pearls-on-a-string’ model.

5. Conclusions
Circumnuclear rings form effective barriers against inflow. Since they are large reservoirs of molecular gas ($10^8$-$10^9 M_\odot$), they must be strongly star forming. We investigate what the full influence of circumnuclear rings on the secular evolution of the galaxy is, in particular in the central kiloparsec, by looking at the amount and manner of the star formation in the circumnuclear rings of NGC 5248 and NGC 6951. By using the SAURON integral field spectrograph we are able to probe the full stellar content of the rings.

We find that the rings are distinct star formation regions in the central kiloparsecs of these galaxies, where all, or at least the vast majority, of all star formation in the last 2 Gyr has taken place. This places direct implications on the life time of the large scale bar that drives the resonances in this system; it has to be at least as old to explain these results.

With these life times for the large scale bar and circumnuclear ring and the amount of stellar mass added to the ring in the last 2 Gyr, we conclude that circumnuclear rings are an important mechanism to alter the stellar distribution in the central regions and lead to the (further) formation of the (pseudo-)bulge.

References
[1] Böker, T., Falcón-Barroso, J., Schinnerer, E., Knapen, J. H., & Ryder, S. 2008, , 135, 479
[2] Cappellari, M., & Emsellem, E. 2004, , 116, 138
[3] Combes, F. 2011, arXiv:1111.4770
[4] Dumas, G., Mundell, C. G., Emsellem, E., & Nagar, N. M. 2007, , 379, 1249
[5] Elmegreen, B. G. 1994, , 425, L73
[6] Jogee, S., Shlosman, I., Laine, S., et al. 2002, , 575, 156
[7] Mazzuca, L. M., Knapen, J. H., Veilleux, S., & Regan, M. W. 2008, , 174, 337
[8] Maoz, D., Barth, A. J., Ho, L. C., Sternberg, A., & Filippenko, A. V. 2001, , 121, 3048
[9] Sarzi, M., Falcón-Barroso, J., Davies, R. L., et al. 2006, , 366, 1151
[10] van der Laan, T. P. R., Schinnerer, E., Boone, F., et al. 2011, , 529, A45
[11] van der Laan, T. P. R., et al., in prep. (a)
[12] van der Laan, T. P. R., et al., in prep. (b)
[13] Vazdekis, A., Sánchez-Blázquez, P., Falcón-Barroso, J., et al. 2010, , 404, 1639