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Star Formation in the Central Regions of Galaxies

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Summary. Massive star formation in the central regions of spiral galaxies plays an important role in the dynamical and secular evolution of their hosts. Here, we summarise a number of recent investigations of the star formation history and the physical conditions of the gas in circumnuclear regions, to illustrate not only the detailed results one can achieve, but also the potential of using state-of-the-art spectroscopic and analysis techniques in researching the central regions of galaxies in general. We review how the star formation history of nuclear rings confirms that they are long-lived and stable configurations. Gas flows in from the disk, through the bar, and into the ring, where successive episodes of massive star formation occur. Analysing the ring in NGC 7742 in particular, we determine the physical conditions of the line emitting gas using a combination of ionisation and stellar population modelling, concluding that the origin of the nuclear ring in this non-barred galaxy lies in a recent minor merger with a small gas-rich galaxy.

1 Introduction

Starbursts, defined as relatively short periods of enhanced massive star formation (SF) activity, are important events in the evolution of galaxies. They enhance the luminosity of the host galaxy, facilitating the detection of those at larger distances, can transform significant quantities of gas into stars, can cause metal injection into, and mixing of, the interstellar medium, and can help the secular evolution of galaxies (e.g., reviews by Kormendy & Kennicutt 2004; Gallagher 2005). We focus here on a particular class of low-luminosity starbursts occurring in nuclear rings in spiral galaxies, which allow the detailed study of their SF histories and of the physical properties of the gas in the circumnuclear region.

2 Cold gas flowing in and feeding the starburst

The centres of many spiral galaxies show evidence of massive SF, often organised into a nuclear ring or pseudo-ring. Such rings are found in 20% of spiral galaxies (Knapen 2005), are thus relatively common, and almost always occur within a barred host (Knapen 2005). Dynamically, nuclear rings are thought to trace the position of the inner Lindblad resonances (ILRs), where gas driven in under the influence of the large bar slows down (Knapen et al. 1995, hereafter K95, and references therein). M100 (NGC 4321) is a prominent, relatively face-on spiral galaxy with a moderately strong bar, at a distance of 16.1 Mpc (so 1 arcsec corresponds to 70 pc). M100 hosts a well-known nuclear ring with prominent massive SF, which is located near a pair of ILRs induced by the bar (K95).

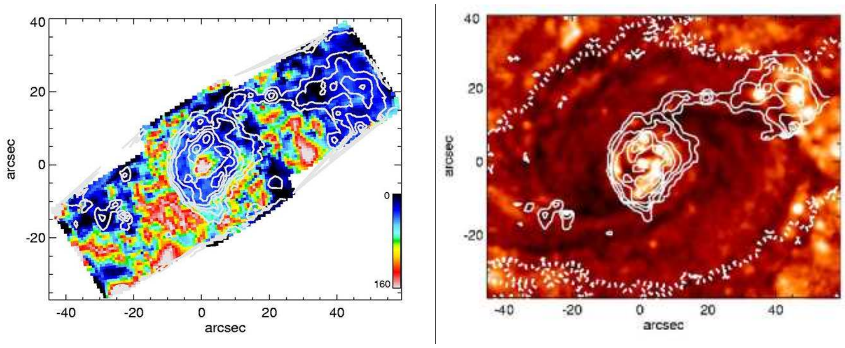

Fig. 1. *Left:* SAURON gas velocity dispersion in the central region of M100 (in km s^{-1}), with, overlaid, contours of Hβ line emission at relative levels [0, 0.05, 0.1, 0.2, 0.5, 1, 2, 3]. *Right: B-R* image with the location of the bar indicated by a K_s band contour (thick dashed line) at 18.3 mag arcsec^{-2}; Hβ emission line contours as in the *left* panel. Reproduced with permission from Allard et al. (2005).

We have obtained integral-field spectroscopic data with SAURON (Bacon et al. 2001) on the William Herschel Telescope (WHT) of the central region of the barred spiral galaxy M100 (Allard et al. 2005, 2006). These data allow us to derive maps of emission line intensities, line strength indices, and the gas velocity dispersion across the circumnuclear region. Fig. 1 shows how the Hβ emission traces the nuclear ring, broken into hotspots of emission.

The gas velocity dispersion map (Fig. 1, *left* panel) shows clearly that the ring has lower dispersion than the underlying disk, and is thus cooler, exactly where the strongest Hβ emission occurs. This happens within the ring, but in the bar the cold gas is aligned and offset from the dustlanes (Fig. 1, *right* panel). This is confirmation of the gas inflow model of nuclear ring formation, as the low dispersion traces cold gas flowing into the area through the dustlanes, and accumulating into the ring under the influence of the ILRs. Instabilities within this gas then trigger significant massive SF (Allard et al. 2005).

3 Star formation histories: evidence for multiple bursts

3.1 M100

The SAURON observations described in the previous Section not only allow analyses of the kinematics and of the emission line characteristics, but also an in-depth study of the SF history of the circumnuclear region of M100 (Allard et al. 2006). For this, we extracted Hβ, Mgb and Fe5015 absorption line indices across the field of view, where the latter two were subsequently combined into one, MgFe= $\sqrt{\mathrm{Mg}b \cdot \mathrm{Fe5015}}$, which minimises the effect of differing abundance ratios across the galaxy (Falcón-Barroso et al. 2002). The indices vary with time for a single burst stellar population (SSP): the Hβ absorption line index first rises, reaching a peak at an age of around 250 Myr, then decreases gradually, whereas the MgFe index rises monotonically with age.

Comparing SSP model predictions with the data points measured for the nuclear ring and centre of M100 shows that whereas the nucleus can be fitted well and yields an age of some 3 Gyr, the nuclear ring points cannot be fitted at all because the Hβ index values are much lower then expected for any reasonable SSP (Allard et al. 2006). We thus introduce a family of composite models, which are characterised by a combination of an old underlying bulge and/or disk contribution and a series of much more recent SF events. We estimate the age of the bulge/disk as 3 Gyr from our fit of an SSP model to the nuclear data point. Adding a number of recent bursts, 100 Myr apart, and starting a couple of hundred Myr ago so that the latest burst occurs now (to yield the observed Balmer line emission) then produces a grid of model lines, illustrated in Fig. 2, which straddle the observed nuclear ring data points.

Our proposed model (Allard et al. 2006) not only fits the data, but is also phenomenologically attractive: it stipulates the formation of the underlying bulge/disk component and the current SF activity in the ring, but also the long-lived nature of the ring, albeit not constantly forming stars at the same high rate as observed now. Our modelling thus confirms a picture in which the bar in M100, a stable configuration, constantly channels gas into the nuclear region, where it concentrates in the nuclear ring until it reaches a density high enough to collapse gravitationally, and enter the next starburst phase. That phase will last a relatively short time, until either the gas runs out or the negative feedback from the massive SF stops the formation of further stars, after which the process of accretion followed by instability to SF can start again.

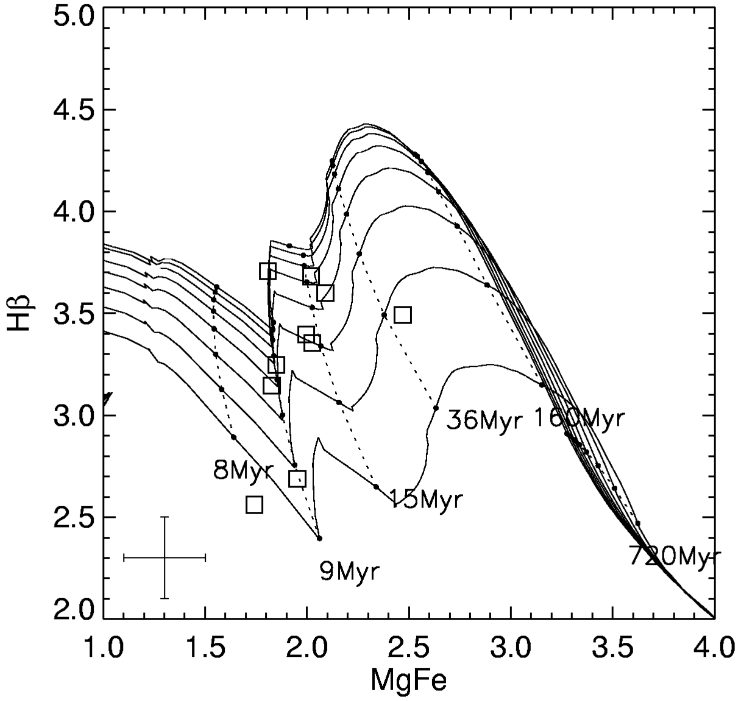

Fig. 2. Measured Hβ and MgFe indices for different points in the nuclear ring of M100 (squares), compared to a family of models which give the time evolution (indicated, in Myr) of the indices in an SSP. The models are combinations of an old ($\sim$ 3 Gyr) bulge/disk population with one (bottom) to eight (top) discrete SF episodes within the last $\sim$0.5 Gyr, separated by 100 Myr. From Allard et al. (2006).

3.2 Other nuclear rings

The model described above for M100 yields a good fit to the data, as well as a convincing interpretational framework which ties the origin and dynamics of the nuclear ring to its SF properties. M100 is often seen as a prototype of a barred galaxy hosting a nuclear ring, and to confirm this further, we analysed the SF history of a sample of seven more nuclear rings (Allard et al. 2007). This analysis is based on long-slit spectra obtained with the ISIS spectrograph on the WHT, covering a wide wavelength range from which we could extract values for the Hβ, MgFe, HδA, and D(4000) line indices for selected points in the rings, as well as in the nuclei of the host galaxies.

We find that the nuclear data points can be reproduced well by a single old SSP model, yielding, as in the case of M100, ages of a couple of Gyr for the underlying bulge and/or disk component. In none of the eight sample galaxies the nuclear ring data points can be fitted by such a model, reproducing again the results for M100 (Sect. 3.1; Allard et al. 2006).

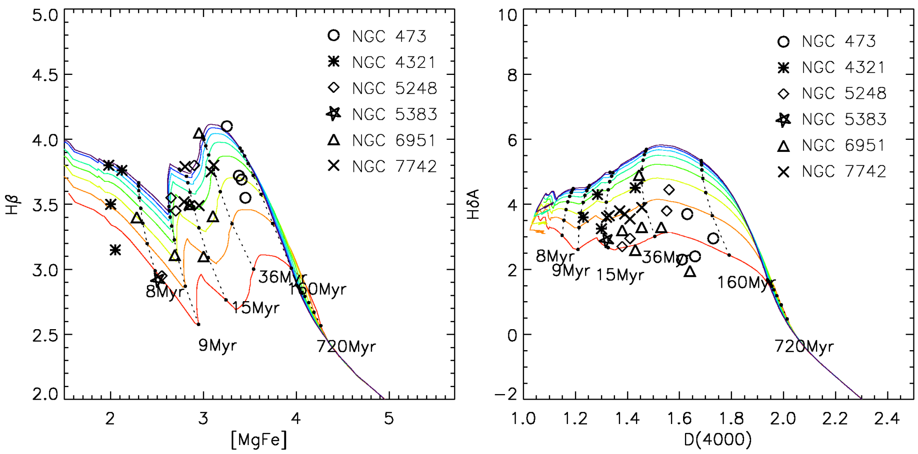

Fig. 3. Evolution of the indices Hβ vs. MgFe (*left*) and HδA vs. D(4000) (*right*) for a family of eight composite stellar population models, compared to the nuclear ring data points measured from ISIS long-slit spectra for six galaxies. The different model lines refer to models with one (bottom) to eight (top) discrete SF episodes within the last ∼0.5 Gyr, separated by 100 Myr. From Allard et al. (2007).

Figure 3 shows how we can fit the data points for six of the galaxies with composite SSP models very similar to the ones developed for M100. We can thus generalise our conclusion that most nuclear rings are stable configurations, with recurrent episodes of massive SF, the latest of which we are witnessing. The use of the HδA vs. D(4000) plot (Fig. 3), made possible by the wider wavelength range of the ISIS observations compared to the SAURON data set, allows us to exclude with a high degree of certainty a model in which the nuclear ring is only a one-off massive SF event, preceded merely by the SF which formed the bulge and/or disk, some 3 Gyr ago. Such a model could, at a stretch, still explain the M100 SAURON data, but can now be excluded.

The galaxies NGC 4314 and NGC 7217 can be explained by a model representing an old underlying bulge/disk component, of some 10 Gyr old, and only one, current, burst of massive SF. This would imply that the nuclear rings in these galaxies are new to forming massive stars, at least at their current position. So either they have only now entered the first episode where their gas clouds are unstable against gravitational collapse, or the rings have shrunk, and previous SF events have happened at slightly larger radii (Benedict et al. 2002), not covered by our data points as plotted in Fig. 3 (Allard et al. 2007).

4 Physical conditions of the gas: the case of NGC 7742

Another important aspect in deciphering the history and properties of nuclear rings, and, perhaps more importantly, in recognising the role they can play in tracing the evolution of their host galaxy, is the study of the physical properties of the ionised gas. This can be done by using diagnostic emission line diagrams, such as those introduced by Veilleux & Osterbrock (1987), which plot the ratio between two blue emission lines against that between two red lines, ensuring that the effects of dust on the diagnostics are limited.

We have recently started a programme to use integral-field spectroscopy (IFS) measurements of the circumnuclear regions of galaxies to disentangle not just their SF histories, but also the physical conditions of the gas, in order to constrain the history of these regions and to model the interplay between them and their host galaxies. As a first step, and as a feasibility study, we have combined blue (SAURON, from Falcón-Barroso et al. 2006) and red (DensePak on the WYIN telescope) IFS data of the nuclear ring region in the non-barred galaxy NGC 7742 (Mazzuca et al. 2006). The fields of view of the instrument cover the ring nicely, and the combination of wavelength ranges means that we can deduce information on most of the lines traditionally used in emission line diagnostics.

NGC 7742 is one of the few known cases where the galaxy hosting a star-forming nuclear ring contains no significant bar. The origin of such rings may lie in a previously existing, but now dissolved, bar, in a weak oval, or in a past or present interaction or minor merger (see Knapen et al. 2006 for a literature overview and examples). NGC 7742 is known to have counterrotating gas and stars in the central region (e.g., de Zeeuw et al. 2002), which immediately points to an interactive past.

Our IFS data yield, first of all, a low value for the electron density, N_e, of order $10\,\mathrm{cm}^{-3}$, in the ring region, as derived from the ratio of the [S II] lines at 6716 and 6731 Å (assuming $T = 10^4\,\mathrm{K}$, see Mazzuca et al. 2006). The knowledge of this value allows us to model other line ratios, such as those of [O III] $\lambda5007\,\text{Å}/\mathrm{H}\beta$, [N II] $\lambda6583/\mathrm{H}\alpha$, or [N II] $\lambda6583$/[S II] $\lambda\lambda6716, 6731$Å, as shown in Fig. 4. In that figure, the different points in and around the ring are indicated by shade and shape, as reproduced in the inset which shows an Hα image of the region, and with the points with the lowest [O III] $\lambda5007\,\text{Å}/\mathrm{H}\beta$ ratios corresponding to those located in the ring.

The left panel of Fig. 4 shows a comparison with a set of MAPPINGS III shock and SF models (Kewley et al. 2001), which confirms that SF is the dominant ionisation mechanism within the ring, but that shock ionisation is important both in- and outside the ring. It also indicates that there is little azimuthal variation in line ratios around the ring. The right panel of Fig. 4 yields valuable information on the metallicity, which we find to be very near solar in the nuclear ring region (as indicated by the drawn line going through the nuclear ring points, which is at $Z = Z_\odot$).

So what conclusions can we draw about the origin of the nuclear ring? The non-barred nature of its host, NGC 7742, and the counterrotation observed in the central region might indicate that some past interactive event is responsible. For the similar non-barred nuclear ring host galaxy NGC 278, a past minor merger is indeed what we proposed as origin for its ring on the basis of

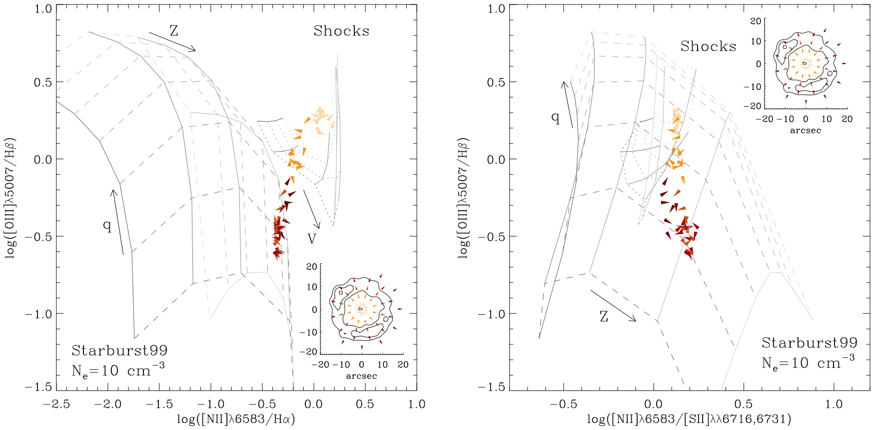

Fig. 4. Diagnostic diagrams of [OIII]λ5007/Hβ vs. [NII]λ6583/Hα (*left*) and [OIII]λ5007/Hβ vs. [NII]λ6583/[SII]$\lambda\lambda$6716, 6731 (*right*). Data points are shown by filled triangles, and the inset shows the location of these points in the ring region, with the contours showing the Hα emission of the circumnuclear ring. Darker symbols refer to points at larger radii; they are oriented according to their position angles. In each panel, MAPPINGS III starburst or shock models are shown by the grid of solid and dashed lines or of solid and dotted lines, respectively. Reproduced with permission from Mazzuca et al. (2006).

the severely disturbed morphology and kinematics of its atomic gas (Knapen et al. 2004). NGC 7742 has a companion galaxy, NGC 7743, but that seems too far away and of too regular morphology to be a candidate for a recent interaction. A minor merger with a small gas-rich galaxy, as in the case of NGC 278, seems the most likely, but this would undoubtedly lead to an influx of low-Z gas, seemingly at odds with our near-solar metallicity measurement.

Here is where the SF history models as described above (Sect. 3) come to our aid: the multiple bursts of SF, for which we found evidence there, would have enriched the gas to near-solar metallicity on timescales which are completely consistent with those modelled above (Mazzuca et al. 2006). We thus conclude that indeed a past minor merger has caused the asymmetry in the gravitational potential which lies at the origin of the nuclear ring. To confirm this further, we are presently pursuing HI observations of NGC 7742: our model predicts non-regular HI morphologies and velocity fields.

5 Closing remarks

The results highlighted here illustrate the use of integral-field spectroscopic analysis techniques to study key aspects of circumnuclear regions of galaxies: their detailed SF histories, and their physical conditions. We have found strong evidence for the stability and longevity of nuclear rings, which we model to form massive stars episodically, for the past 0.5 Gyr or so. Using the nuclear ring in the non-barred galaxy NGC 7742 as a showcase for our techniques, we find low electron densities, SF-dominated ionisation and near-solar metallicity in the ring. We postulate that a minor merger with a small gas-rich galaxy has led to the nuclear ring, and that the episodic SF in the ring, as modelled above, has enriched the infallen metal-poor gas to its current metallicity.

Our results show the importance of nuclear rings, being stable, long-lived structures which transform significant amounts of disk gas into inner-kpc stars. The techniques we have outlined here can be applied more widely than to nuclear rings, though, and should lead to important insights on, e.g., nuclear starbursts, or the zones surrounding AGN or composite nuclei.

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