On the classification of ultra-compact nuclear rings

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Abstract. Ultra-compact nuclear rings (UCNRs) can be defined as those galactic circumnuclear rings with a radius inferior to 200 parsecs [1]. Because very high spatial resolution is needed, this population has not been studied systematically until now. One important issue that has to be solved is whether UCNRs have an origin similar to larger circumnuclear rings, which are related to inner Lindblad resonances, or whether they have a different origin. We present the first results of a survey performed on 487 galaxies imaged by HST, to find and characterize UCNRs. These results include the detection of new rings as well as the confirmation of rings that were already known. We present a list of 23 reliably detected UCNRs and discuss their origin.

1. Introduction

Star-forming nuclear rings, almost exclusively found in barred galaxies [2], are attributed to shock focusing of gas near the location of one or more inner Lindblad resonances (ILRs; [3, 4, 5], see also ref. [6, 7] for reviews). Their sizes, of typically ~ 1 kpc, allow them to be easily resolved in ground- and space-based observations. On the other hand, high resolution imaging with the Hubble Space Telescope (HST) has led to the detection of several unusually compact circumnuclear star-forming regions. These rings, with a radius smaller than 200 pc, have been defined as ultra-compact nuclear rings (UCNRs) [1].

Previous studies have detected the latter kind of rings in several galaxies, including IC 342 [8], NGC 864 [9], NGC 1079 [10], NGC 2903 [11], NGC 2985 [1], NGC 3245 [12], NGC 3379 [13], NGC 4450 [14], NGC 4579 [15, 1], two in NGC 4800 [1], NGC 4826 [11], NGC 5236 [11] and NGC 5248 [16, 17, 18].

In this proceedings paper we present a systematic search for UCNRs. We performed a survey that included all the $B_T \leq 12.5$ galaxies that are not edge-on and for which the nuclear region has been imaged by HST.

2. Sample selection

Our sample is based on that defined in ref. [19] to survey ‘dwarf’ Seyfert nuclei in nearby galaxies. Those authors selected all the galaxies from the Revised Shapley-Ames Catalog of Bright Galaxies (RSA; [20]) and the Second Reference Catalogue of Bright Galaxies (RC2; [21]) with $B_T \leq 12.5$ mag and $\delta \geq 0\,\text{deg}$. $B_T$ is the apparent total $B$ magnitude reduced to the RC3 system [22]. Twelve additional objects of special or historical interest were added to the sample. The statistical completeness of the sample was as defined for the RSA and is thought to end near

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1 Three Rings for the Elven-kings under the sky, Seven for the Dwarf-lords in their halls made of stone, Nine for Mortal Men doomed to die...
$B_T = 12.0 \text{ mag}$. To this sample of 503 galaxies we added a similar selection done in the southern celestial hemisphere: we selected all the galaxies with $B_T \leq 12.5 \text{ mag}$ in the Third Reference Catalogue of Bright Galaxies (RC3; [22]). The RC3 contains galaxies brighter that 15.5 mag, which implies that we have no problems with completeness in the southern hemisphere. Our final selection was of 893 galaxies.

As we are looking for UCNRs, that usually lie in the galactic plane, we removed from this list of 893 galaxies all those that were classified as edge-on in the RC3, and we also removed from our selection all galaxies with an axis ratio smaller than 0.35 ($i > 70 \text{ deg}$).

We then retrieved ACS, FOC, NICMOS, and/or WFPC2 images from the HST archive which included the nuclear regions of our non edge-on galaxy sample. All the galaxies that have not been observed by HST were removed from the sample because the resolution reached by ground-based telescopes does not allow us to detect UCNR at the distances of most of the galaxies. We also removed the local group dwarfs. The final sample has 487 objects with morphological types ranging from giant elliptical galaxies to irregular dwarf galaxies.

In Fig. 1 we show histograms of the distribution of Hubble morphological types, as obtained from LEDA. As we can see in that figure, elliptical galaxies are very well represented in our sample. Most of the galaxies (90%) are closer than 40 Mpc which means that we can reliably detect rings with diameters around 100 pc or less. Disk galaxies, where Lindblad resonances may occur, are also common in our sample, especially in the Sa–Sc range. On the other hand, very late-type galaxies occur in small numbers, due to the fact that they commonly are small irregular galaxies that are fainter than our $B$ magnitude cut-off. The distance distribution of the galaxies peaks in the bin 15–20 Mpc, at the distance of the Virgo cluster.

**Figure 1.** Distribution of Hubble types in the sample. Barred galaxies are shown in the double-hatched histogram and unbarred galaxies in the single-hatched one.
3. Data processing
UCNRs can be traced by dust, if they are not star-forming, and by emission lines or UV emission if they are. They can also be seen in colour-index maps due to the blue absorption in the case of dust UCNRs or due to the blue light excess in star-forming UCNRs.

3.1. Structure maps
The structure map technique [23] allows one to observe the distribution of structure, and in particular of dust, in a galaxy on scales larger than the point spread function (PSF), using only one image in a single filter. We used synthetic PSFs which were created with the Tiny Tim software [24]. We used images through green or red optical filters to apply the structure map operator.

3.2. $H\alpha$ images
We used $H\alpha$ ACS and WFPC2 images taken through the narrow-band filters $F656N$ or $F658N$, and continuum images taken through a red broad-band filter. In the few cases where images taken through both $H\alpha$ filters were available in the archive, we chose the $F658N$ image, because the $H\alpha$ line of our sample galaxies is better centred in its passband. The images used for the continuum subtraction were in most of the cases the same ones from which we derived the structure maps. The procedure used to remove the continuum is explained in refs. [25, 26].

3.3. Paa images
We downloaded the NICMOS Paa narrow filter images from the archive. There are two ways to remove the continuum component in Paa images depending on which images are available in the archive. In case of having broad-band imaging in IR at a wavelength close to Paa the procedure is the same than as for $H\alpha$. The wide filter images used for continuum subtraction are taken with $F110W$ ($\sim J$) or $F160W$ ($\sim K$) filter. In some cases, the sets of images are made up of an $F187N$ and an $F190N$ image. At zero redshift Paa, at a wavelength of 1874.5 nm, is centred on $F187N$ and while a galaxy is moving away from us because of the cosmological redshift, this frequency shifts to longer wavelengths in such a way that most of the Paa emission falls into the $F190N$ filter for galaxies with $v > 3000km\cdot{s}^{-1}$. For galaxies with velocities lower than this threshold we directly subtracted the $F190N$ image from the $F187N$ image after multiplying the $F190N$ image by a number ranging from 0.9 to 1.0 due to its slightly greater efficiency. This value was calculated in each case by plotting the counts from continuum emission areas in one filter against those in the other one, fitting a line, and using its slope to find a correction factor. For galaxies with greater velocities we performed the inverse operation ($F190N-F187N$).

3.4. Colour-index images
Most of the colour index images were made using filters close to $V$ and $I$ from ACS and WFPC2. We first aligned the images and then we performed the operation $V - I = -2.5\log V/I$ to get the colour index image. In some cases when we had no $V$ or $I$ image, we produced $I - J$, $I - H$, and $J - H$ images instead.

3.5. UV images
We also downloaded ACS, FOC, and WFPC2 UV images because it is sometimes easier to detect UCNRs at these wavelength because they usually contain many star-forming regions. No processing was needed for these images.
4. Results and discussion
UCNRs are found in all the morphological types except in irregular dwarf galaxies, but do not have uniform properties. Here we present an initial classification of UCNR and discuss their possible origins:

4.1. Star-forming UCNRs
Star-forming UCNRs show strong evidence of star formation such as clumps of Hα and/or Pα emission, and/or strong UV emission. They are usually fed by spiral arms and, analogous to larger nuclear rings, may be related to the ILRs due to bars or to galaxy-galaxy interactions (see for an example [25]). All the rings of this kind that we have found are located in spiral galaxies, except for those in NGC 3245 and NGC 4459, which are lenticular, so we infer that this kind of UCNR is more frequent in disk-dominated galaxies than in spheroid-dominated galaxies. The star-forming UCNRs we have found are shown in Fig. 2.

4.2. Dust UCNRs
Dust UCNRs are detected as dust features and they are either not emitting, or only weakly emitting, in Hα, Pα or UV, which indicates that there is no massive star formation. All these galaxies are early-type: NGC 3379 and NGC 4371 are SB0 galaxies and the others are ellipticals. NGC 3379 has a considerable flux of Hα emission but the UCNR is much clearer in the structure map. Moreover, being in a galaxy of morphological type $T = -4.8$ there is probably almost no extinction except for the self-absorption within the ring, so the ring may in fact be much fainter than other rings for which we have measured the Hα emission. These galaxies show no evidence of spiral arms fuelling the UCNR. Dust UCNRs are thus more frequent in galaxies dominated by spheroids. They may well consist of material coming from stellar winds that settles in a disk in which the viscosity is strong enough to deplete the inner part and feed the black hole. Rings in an elliptical galaxy should be short-lived (see ref. [27] for a more detailed discussion of these
Figure 3. Dust UCNRs. The images are 500 pc on a side. North is up and East is left.

Figure 4. NGC 2787. The images are 500 pc on a side. North is up and East is left. The arrows indicate the dust ring in the left image and the ionization ring in the right one.

issues). On the other hand, a triaxial spheroid is able to sustain stable UCNRs. All the dust UCNRs we have found are shown in Fig. 3, except the one in NGC 2787, which will be described in the next subsection.

4.3. Ionization UCNRs
This kind of UCNRs are not made by a ring of material, but by the glowing of the inner part of a disc surrounding an AGN that ionizes it. This is seen in the lenticular galaxy NGC 2787 (Fig. 6) where the ring seems to be connected the inner part of a polar disk of dust. Ionization UCNRs are merely apparent rings.

5. Conclusions
UCNRs are found in all kinds of galaxies except in very late-types. We have found dust UCNRs in around 3% of the spheroid-dominated galaxies and star-forming UCNRs in 4% of the galaxies with a disk. Dust UCNRs may consist of dust coming from stellar winds that is trapped in stable orbits around the black hole, whereas star-forming UCNRs are most probably related to ILRs set up by a bar or a past interaction, in analogy with their larger counterparts, the (circum)nuclear rings.

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