Origin of the near-UV light in the circumnuclear regions of Seyfert galaxies

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Abstract In order to understand better the nature of the near-UV light in Seyferts (Sy), as well as the connection between the AGN and starbursts processes, we carried out a snapshot survey among the nearest Sy nuclei with HST ACS at F330W (∼U). In a previous work (Muñoz Marín et al. 2007), we found a variety of morphologies, including star-formation dominated objects, and also other galaxies with bright filaments, biconical structure or an extended emission, which are unlikely to trace star-formation. In this work we aim to disentangle the contribution of the different processes that may contribute to the near-UV emission, focussing in the extended emission. We use a subsample of galaxies with near-UV ACS data and WFPC2 [OIII] images, as well as optical and near-IR data. From these data we create a synthetic image of the contribution of the ionised gas to be subtracted from the near-UV data. The residuals are analysed by means of photometry in the bands F330W (∼U), F547M (∼V), and F160W (∼H). By these means, we are able to disentangle the different contribution and their relative importance in most objects.

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1 Sample and Data.

For the sample we select the galaxies of our Seyfert atlas (Muñoz Marín et al. 2007; hereafter MM07), that are studied as well by Schmitt et al. (2003). In that work, the [OIII] nuclear emission is studied with HST in a sample of 60 nearby Seyfert galaxies. This last is perhaps the largest [OIII] imaging compilation of the NLR of nearby Sy, that are imaged at a resolution comparable to ours. We end up with a final sample of 15 galaxies, from which 8 are Sy2 and 7 are Sy1 (including five Sy1.5 and one 1.8 objects). We find no difference between Sy1 and Sy2 subsamples, neither respect to their mean distance (71 Mpc for Sy1, and 74 Mpc for Sy2), nor in their mean axial ratio (b/a of 0.80 for Sy1, while it is 0.74 for Sy2).

We have studied HST images of the objects in several bands: near-UV ACS (F330W), optical WFPC2 ([OIII] and F547M), and near-IR NICMOS (F160W) data. The filter F547M has the advantage that minimises the contamination by strong emission lines, and that most of the objects are imaged in this band (as it served in most cases for the continuum subtraction of the [OIII] image), what allows for a comparison between them. The third band used is NICMOS F160W, what allows for the study of two colours. This last filter has the advantage that there are data for all the objects (except for NGC 7212), and that it is so wide that we can neglect the contribution by emission lines

2 Different Components of the Near-UV Light

In MM07 we showed that star-clusters and star-formation are common in many Sy nuclei. In this work we will focus in the nature of the extended near-UV emission. There are several processes that are expected to contribute to the light in the F330W filter. The most relevant ones are:

- Stellar continuum. This is emission from the underlying stellar population of the galaxy or a possible population of unresolved star clusters. In this category are included the individual star clusters, which appear as compact, unresolved, or slightly extended objects. HST studies of starburst galaxies (e.g. Meurer et al. 1995) have identified compact knots of star-formation and a diffuse component, which is believed to originate via dissipation of ageing star clusters (Tremonti et al. 2001; Chandar et al. 2005).
- Nebular continuum. Due to the short wavelength and large width of the near-UV filter, the nebular continuum may be an important contribution at this band, in regions with ionised gas. The main contributions to this continuum are electron transitions from free to bound states, or electron-ion recombination. There is also a contribution of free-free transitions, by means of free electrons-ion interaction followed by bremsstrahlung radiation from the electrons. This last is more important at longer wavelengths, and is negligible in this case. The most important role is played by Hydrogen and Helium recombination. Another source of nebu-

lar continuum at this wavelength is the two-photon decay of the 2^2S level of HI. Assuming a fixed [OIII]/Hβ ratio of 10, it is possible to relate the total contribution of the nebular continuum through the given filter to the [OIII] flux. We will assume a temperature of the gas of 10,000 K, as well as a He abundance of 10%. Taking into account the filter width and average wavelength, we get from Osterbrock (1989), as a good approximation:

$$F_{NC,F330W} \sim 0.3 \cdot F_{[OIII]}, \quad (1)$$

where the factor above may vary between 0.375 and 0.2.

- Emission lines from ionised gas. The forbidden lines [NeV]$\lambda\lambda$3346,3426 are the only emission lines strong enough to contribute to the light through the F330W filter, at the redshift range of our sample. These high ionisation lines are expected to be strongly diluted in the presence of a bright continuum and give a rather small equivalent width. We have compiled [NeV] data from the literature for some galaxies of the sample, and completed these with measurements in nuclear STIS spectra, and literature data for other active galaxies. With this, we are able to define a reasonable range for the ratio [OIII]/[NeV], that would allow us to create a synthetic [NeV] image. We concluded that any scaling between 1/2–1/30 to the [OIII] image may be a reasonable approximation to the actual [NeV] emission, depending very much on the nature of the object.
- Scattered light from the AGN by free electrons or dust. On basis of the unified model we expect this contribution in both Sy types. Scattered light can be identified through polarimetric studies, as it is expected to be at least partially polarised. This emission is expected to correlate spatially with the [OIII] emission to a certain degree, although the correspondence is not one-to-one. The two processes have a different dependence on density and polarisation also depends on the scattering angle (line emission would roughly go with N_e^2 while polarised flux would go with $N_e \times P$ where P depends on the scattering angle. To make things more complicated, a low polarisation does not necessarily imply a low contribution from the scattered light. As a summary, the contribution of scattered light in the circumnuclear region may be important for some objects, although it is not trivial to correct for it. A detailed study of this component would need polarimetric imaging, what is beyond the scope of this work.
- Finally, light from the AGN itself in the cases in which both the continuum and the BLR are directly visible, as a point-like bright source (nuclei of Seyfert type 1 to 1.5). In these objects the nucleus has to be removed prior to any further analysis

3 Analysis and Results

We have compared the near-UV ACS images and the narrow-band continuum subtracted [OIII]λ5007 images. The [OIII] images were scaled in order to create a synthetic image of the ionised gas contribution through the filter F330W (emission of [NeV] lines plus nebular continuum). We define **f**, as the number by which we scale the [OIII] image, in order to subtract it to the flux-calibrated near UV image. We try different **f** values, looking for the one that best removes the extended emission. During this process we also refine the alignment of the images by minimising the residuals. Fig. 1 provides an example of this. In Sect. 2, we provide a range of reasonable **f** values (0.2–0.7, but most frequently expected $\sim$0.3). By this method we demonstrate that the emission of the ionised gas can explain the extended emission visible in several objects. This is the case of the filamentary structure of IC 5063, NGC 3393 or UGC 1214 (Mrk 573), as well as parts of the more diffuse emission of Mrk 6, Mrk 915, NGC 5347 and NGC 7212. These regions of ionised gas are large, extending from 100 pc to 1 Kpc from the nucleus, and in general can be accounted for with a unique scaling factor for the [OIII] image (in the range f$\sim$ 0.2–0.4).

In order to infer the nature of the residual light, we use F330W images after the synthetic ionised gas image subtraction, complemented with WFPC2 F547M and NICMOS F160W data. The photometry was performed with the IRAF task 'phot'. Depending on the morphology of each object in particular, we calculated the colour radial structure, or integrated the light in certain apertures or rings. Then we compared the results with synthetic photometry of Single Stellar Populations (see Fig. 2, together with the expected colours of a blend of an old stellar population with a bluer young (9 Ma old) stellar population or a power-law. We have found that the diffuse emission remaining after estimating and subtracting the ionised gas contribution, can be attributed to the underlying stellar population of the bulge. This is the case of objects such as IC 5063, NGC 1320, NGC 3516, UGC 1214, UGC 6100, and UGC 12138. Scattered light from the AGN does not seem to contribute in a significant fraction to the total light, in the majority of the cases, with the probable exception of the cone-shaped near-UV emission to the northwest of the nucleus in NGC 7674.

In a number of objects we find also a strong near-UV emission extending less than 100 pc from the nucleus (for example in NGC 4593). These are mostly Sy1 in which even after the best nuclear-PSF subtraction, there remains a compact but resolved emission. We do not think this is an artifact of the PSF subtraction of the nucleus, but a real feature. However, it is true that the nuclear subtraction generates uncertainties that preclude any accurate analysis of the very inner region. We have made some calculations to set an upper limit of the contribution of the ionised gas emission, indicating a different mechanism. A strong change in the ionisation factor (higher towards the centre) has not been ruled out, though.

Last, star-forming regions and super-massive star clusters stand out as compact knots in the near-UV image (F330W). They pose a significant contribution in a fraction of objects; namely, NGC 4253, NGC 5548, NGC 7212, and NGC 7674.

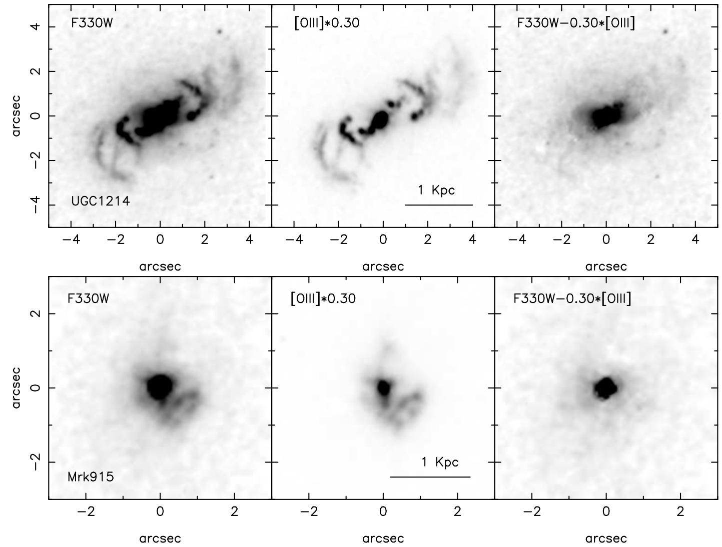

Fig. 1 Two examples of the subtraction of the ionised gas contribution. The three images are plotted with the same intensity scaling. Left: F330W ACS image convolved with WF3 PSF; middle panel: [OIII] image scaled by the indicated factor (see discussion in text); right panel: the residuals from the subtraction of the other two.

4 Conclusions

The physical regions studied in this work are between 100 pc and 1 Kpc from the Seyfert nuclei. For these regions we find that the mechanisms responsible for the near-UV emission are as varied as the morphologies observed. We have shown that emission lines and nebular continuum can explain much of the extended emission at F330W in Seyferts, especially in the cases of clear biconical and filamentary structure. The remaining diffuse light is due to the underlying bulge stellar population, in most cases. Respect to the possible starburst component, we have not found, in general, much evidence of extended unresolved young stellar populations. That would be the case of star-formation happening in a non-cluster mode or with a very high rate of cluster disruption due to the proximity of the AGN. On the contrary, the objects with nuclear star-formation in the sample are normally dominated by bright stellar-clusters. There exists the possibility that a young stellar population is completely diluted in the bulge light and we cannot detect it. For one galaxy we find clues for scattered light from the AGN. In summary, there is not a unique and dominating mechanism responsible for the near-UV emission. Each object deserves a particular study and a close inspection, as we find the most varied morphologies. A deeper study would require the use of spectroscopy, and optimally, the use of IFU data with enough resolution.

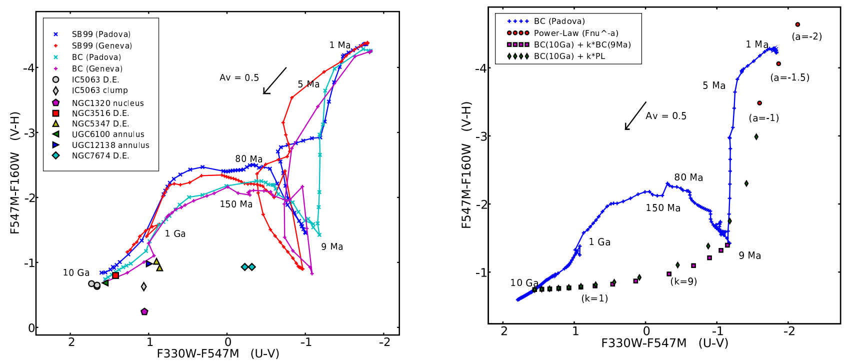

Fig. 2 **Left panel:** Evolution of the studied colours with age of several Single Stellar Population model in a (F330W–F547M) vs (F547M–F160W) diagram. The graph shows the comparison of Starburst99 (SB99) and Bruzual & Charlot 2003 (BC03) models for both, Padova 1994 and Geneva 1994 tracks. All the models have a standard Salpeter IMF function. In blue *full line*, SB99 models with Padova tracks; in cyan *dotted-dashed line*, BC03 with Padova tracks; in red *dashed line*, SB99 with Geneva tracks; magenta *dotted line* stands for BC03 models with Geneva tracks. We add the photometric results for several objects. Different colours and symbols stand for different objects and regions, which are labelled in the plot legend, in which 'D.E.' stands for diffuse emission. The photometric points are corrected for galactic extinction with the law of Cardelli et al. (1989). The reddening vector corresponding to A_V=0.5 is also plotted for reference. **Right panel:** Same colour-colour diagram showing the location of some power-law spectra, and two sequences of a young population of 9 Ma (magenta squares) and a power-law with a=-1 (green diamonds), added to a 10 Ga old stellar population. For reference, we have also plotted the reddening vector, and the evolution of a SSP model of Bruzual & Charlot (2003), with Padova tracks and Salpeter IMF.

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