

Sub-arcsec mid-IR observations of NGC 1614: Nuclear star formation or an intrinsically X-ray weak AGN?

M. Pereira-Santaella,^{1,2*} L. Colina,^{1,2} A. Alonso-Herrero,³ A. Usero,⁴ T. Díaz-Santos,⁵ S. García-Burillo,⁴ A. Alberdi,⁶ O. Gonzalez-Martin,⁷ R. Herrero-Illana,⁶ M. Imanishi,⁸ N. A. Levenson,⁹ M. A. Pérez-Torres^{6,10} and C. Ramos Almeida¹¹

¹Centro de Astrobiología (CSIC/INTA), Ctra de Torrejón a Ajalvir, km 4, E-28850 Torrejón de Ardoz, Madrid, Spain

²ASTRO-UAM, UAM, Unidad Asociada CSIC

³Instituto de Física de Cantabria, CSIC-Universidad de Cantabria, E-39005 Santander, Spain

⁴Observatorio Astronómico Nacional (OAN-IGN)-Observatorio de Madrid, Alfonso XII, 3, E-28014 Madrid, Spain

⁵Núcleo de Astronomía de la Facultad de Ingeniería, Universidad Diego Portales, Av. Ejército Libertador 441, Santiago, Chile

⁶Instituto de Astrofísica de Andalucía, Glorieta de las Astronomía, s/n, E-18008 Granada, Spain

⁷Centro de Radioastronomía y Astrofísica (CRyA-UNAM), 3-72 (Xangari), 8701 Morelia, Mexico

⁸Subaru Telescope, 650 North A'ohoku Place, Hilo, Hawaii 96720, USA

⁹Gemini Observatory, Casilla 603, La Serena, Chile

¹⁰Centro de Estudios de la Física del Cosmos de Aragón, E-44001 Teruel, Spain

¹¹Instituto de Astrofísica de Canarias, Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain

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ABSTRACT

We present new mid-infrared (mid-IR) N -band spectroscopy and Q -band photometry of the local luminous IR galaxy NGC 1614, one of the most extreme nearby starbursts. We analyse the mid-IR properties of the nucleus (central 150 pc) and four regions of the bright circumnuclear (diameter ~ 600 pc) star-forming (SF) ring of this object. The nucleus differs from the circumnuclear SF ring by having a strong 8–12 μm continuum (low 11.3 μm PAH equivalent width). These characteristics, together with the nuclear X-ray and sub-mm properties, can be explained by an X-ray weak active galactic nucleus (AGN), or by peculiar SF with a short molecular gas depletion time and producing an enhanced radiation field density. In either case, the nuclear luminosity ($L_{\text{IR}} < 6 \times 10^{43}$ erg s $^{-1}$) is only <5 per cent of the total bolometric luminosity of NGC 1614. So this possible AGN does not dominate the energy output in this object. We also compare three star formation rate (SFR) tracers (Pa α , 11.3 μm PAH, and 24 μm emissions) at 150 pc scales in the circumnuclear ring. In general, we find that the SFR is underestimated (overestimated) by a factor of 2–4 (2–3) using the 11.3 μm PAH (24 μm) emission with respect to the extinction corrected Pa α SFR. The former can be explained because we do not include diffuse polycyclic aromatic hydrocarbon (PAH) emission in our measurements, while the latter might indicate that the dust temperature is particularly warmer in the central regions of NGC 1614.

Key words: galaxies: active – galaxies: individual: NGC 1614 – galaxies: nuclei – galaxies: starburst – infrared: galaxies.

1 INTRODUCTION

Ultraluminous and luminous infrared galaxies (ULIRGs) are objects with infrared (IR) luminosities (L_{IR}) between 10^{11} and $10^{12} L_{\odot}$ (LIRGs) and $> 10^{12} L_{\odot}$ (ULIRGs). Locally, objects with such high

IR luminosities are unusual. However, between $z \sim 1$ and 2, galaxies in the LIRG and ULIRG luminosity ranges dominate the star formation rate (SFR) density of the Universe (Le Flok'h et al. 2005; Pérez-González et al. 2005; Caputi et al. 2007; Magnelli et al. 2011). Therefore, the study at high angular resolution of local LIRGs provides a unique insight into extreme SF environments similar to those of high- z galaxies near the SFR density peak of the Universe (Madau & Dickinson 2014).

* E-mail: mpereira@cab.inta-csic.es

NGC 1614 (Mrk 617) is the second most luminous galaxy within 75 Mpc ($\log L_{\text{IR}} = 11.6$; Sanders et al. 2003) and according to optical spectroscopy its nuclear activity is classified as composite (Yuan, Kewley & Sanders 2010). It is an advanced minor merger (3:1–5:1 mass ratio; Väisänen et al. 2012) located at 64 Mpc (310 pc arcsec⁻¹) with long tidal tails. Its bolometric luminosity is dominated by a strong starburst in the central kpc (Alonso-Herrero et al. 2001; Imanishi et al. 2010), and, so far, there is no clear evidence of an active galactic nucleus (AGN) in NGC 1614 (Herrero-Illana et al. 2014).

The central kpc of NGC 1614 contains a compact nucleus (45–80 pc), which dominates the near-IR continuum emission, and a bright circumnuclear SF ring (diameter~600 pc), which is predominant in Pa α (Alonso-Herrero et al. 2001) and other SF indicators like the polycyclic aromatic hydrocarbon (PAH) emission (Díaz-Santos et al. 2008; Väisänen et al. 2012), cold molecular gas (König et al. 2013; Sliwa et al. 2014; Xu et al. 2015), and radio continuum (Olsson et al. 2010; Herrero-Illana et al. 2014). In addition, García-Burillo et al. (2015) found a massive cold molecular gas outflow ($3 \times 10^7 M_{\odot}$; $\dot{M}_{\text{out}} \sim 40 M_{\odot} \text{ yr}^{-1}$) which can be powered by the SF in the ring.

A bright obscured AGN is discarded by X-ray observations (Pereira-Santaella et al. 2011; Herrero-Illana et al. 2014). However, previous mid-IR *N*-band imaging of NGC 1614 showed that the compact nucleus has a relatively high surface brightness (Soifer et al. 2001; Díaz-Santos et al. 2008; Siebenmorgen et al. 2008). Therefore, these observations suggest an enhanced mid-IR luminosity to SFR (as inferred from the observed Pa α luminosity) ratio in the nucleus (Díaz-Santos et al. 2008), which might indicate the presence of an active nucleus. However, without high angular resolution spectroscopy no detailed studies were possible.

In this paper, we present the first high angular resolution (~ 0.5 arcsec) *N*-band (7.5–13 μm) spectroscopy of the nucleus and surrounding star-forming ring of NGC 1614, as well as *Q*-band 24.5 μm imaging using CanariCam (CC) on the 10.4 m Gran Telescopio CANARIAS (GTC). First, we describe the new observations in Section 2. The extraction of the spectra and photometry, and a simple two-component modelling are presented in Section 3. We explore the AGN or SF nature of the nucleus in Section 4, and in Section 5, the reliability of several SFR tracers at 150 pc scales is discussed. The main conclusions are presented in Section 6.

Throughout this paper we assume the following cosmology $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{m}} = 0.3$, and $\Omega_{\Lambda} = 0.7$ and the Kroupa (2001) IMF.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Mid-IR imaging

We obtained *Q*-band diffraction limited (0.5 arcsec) images of NGC 1614 using the Q8 filter ($\lambda_c = 24.5 \mu\text{m}$, width at 50 per cent cut-on/off of $\Delta\lambda = 0.8 \mu\text{m}$) of CC (Telesco et al. 2003) on the 10.4 m GTC during 2014 December 2. These observations are part of the ESO/GTC large programme 182.B-2005 (PI Alonso-Herrero). The plate scale of CC is $0.08 \text{ arcsec pixel}^{-1}$ and its field of view is $26 \text{ arcsec} \times 19 \text{ arcsec}$, so it covers the central 6 kpc of NGC 1614.

Three exposures were taken with an on-source integration of 400 s each. To reduce the data we used the REDCAN pipeline (González-Martín et al. 2013). It performs the flat-fielding, stacking, and flux calibration of the individual exposures. The three reduced images were then combined after correcting the different background levels (right-hand panel of Fig. 1). For the flux calibration the standard star

HD 28749 was observed. It is relatively weak at 24.5 μm (1.2 Jy; Cohen et al. 1999) so the absolute calibration error of our *Q*-band observations is ~ 20 per cent.

To check the flux calibration, we also compared the integrated flux of NGC 1614 in our 24.5 μm image ($6.0 \pm 0.9 \text{ Jy}$) with the *Spitzer*/MIPS 24 μm flux ($5.7 \pm 0.3 \text{ Jy}$; Pereira-Santaella et al. 2015). Both values are in good agreement.

In addition, *N*-band imaging of this galaxy was previously obtained using *Gemini*/T-ReCS in the Si2 filter ($\lambda_c = 8.7 \mu\text{m}$, $\Delta\lambda = 0.8 \mu\text{m}$). This image was published by Díaz-Santos et al. (2008) and it is shown in the middle panel of Fig. 1. The angular resolution of this observation estimated from the calibration star image is 0.4 arcsec.

2.2 Mid-IR spectroscopy

We obtained *N*-band spectroscopy (7.5–13 μm) of NGC 1614 with GTC/CC on 2013 September 8 and 2014 January 5. The low spectral resolution ($R \sim 175$) grating was used. These observations are also part of the ESO/GTC large programme 182.B-2005. The nucleus of NGC 1614 was observed with a slit of 0.52 arcsec width using two perpendicular orientations (PA, position angles 0° and 90°). The approximate location of the slits is overplotted in the middle panel of Fig. 1. The on-source integration time for each of the slit orientations was 1200 s.

The standard star HD 28749 was observed in spectroscopy mode to provide the absolute flux calibration and telluric correction. From the two-dimensional spectrum of the standard star, we derive that the angular resolution, ~ 0.5 arcsec, is approximately constant with the wavelength both nights. That is, the spectroscopy was not obtained in diffraction limited conditions.

The data were reduced using the REDCAN pipeline. Flat-fielding, stacking, wavelength calibration, and flux calibration of the exposures are performed by this software. The spectra were extracted using a custom procedure (see Section 3.1) instead of the default REDCAN extraction.

3 ANALYSIS AND RESULTS

3.1 Image modelling and spectral extraction

The *HST*/NICMOS Pa α image of NGC 1614 (Alonso-Herrero et al. 2001, see fig 1) revealed that the angular separation between the nucleus and the star-forming ring is 0.5–0.7 arcsec, which is comparable to the angular resolution of the CC *Q*-band imaging and *N*-band spectroscopy. Therefore, to disentangle the emission produced by the different regions we modelled the mid-IR image with the highest resolution (i.e. the 8.7 μm T-ReCS image) with GALFIT (Peng et al. 2010). Imanishi et al. (2011) published *Q*-band imaging of NGC 1614 at 17.7 μm . In this image, the emissions from the SF ring and the nucleus are not as clearly separated as in the CC 24.5 μm image, probably due to the slightly worse angular resolution (0.7 arcsec; Asmus et al. 2014).

We used six Gaussian spatial components (nucleus, north, south, east, west, and diffuse) convolved with the point spread function (PSF), to reproduce the 8.7 μm image (see Fig. 2). These components are motivated by the Pa α morphology (Fig. 1) and is the minimum number of components needed to reproduce the mid-IR images. The position and full width half-maximum (FWHM) of these components are listed in Table 1. According to this decomposition, the ring is located ~ 0.6 arcsec away from the nucleus

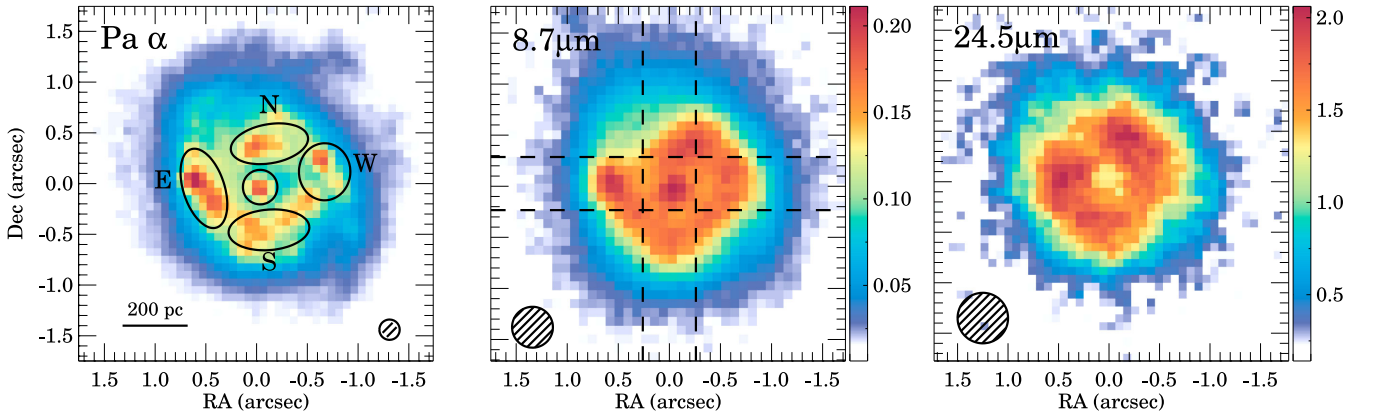


Figure 1. *HST*/NICMOS continuum subtracted Pa α (left; see also Alonso-Herrero et al. 2006), T-ReCS 8.7 μm (middle; see also Díaz-Santos et al. 2008), and CC 24.5 μm (right) images of the nuclear regions of NGC 1614. The 24.5 μm image was smoothed using a 1.5 pixel Gaussian. The position and width of the two slit orientations are plotted in the middle panel (dashed lines). The hatched circles indicate the angular resolution of the images (FWHM). For the 8.7 and 24.5 μm images the colour scale is in Jy arcsec^{-2} units. The locations of the regions used for the spatial decomposition are indicated in the left-hand panel.

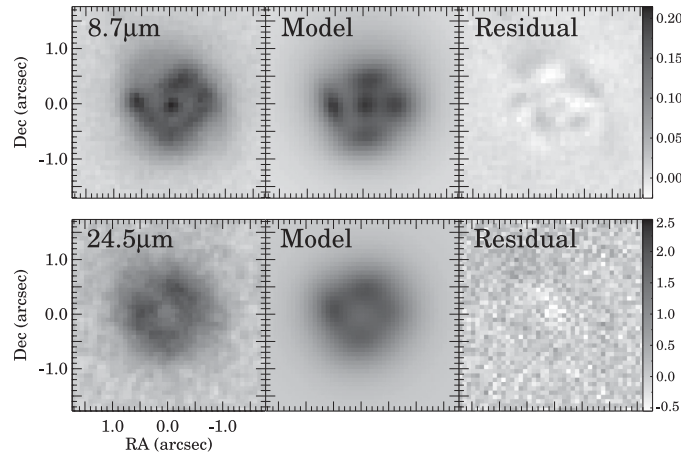


Figure 2. GALFIT models of the T-ReCS 8.7 μm (top panels), and CC 24.5 μm (bottom panels) observations of the nuclear regions of NGC 1614. The observed image, the best model and the residuals are shown in the left-hand, middle, and right-hand panels, respectively. The colour scale is in Jy arcsec^{-2} units.

Table 1. Spatial decomposition nuclear region and circumnuclear ring of star formation of NGC 1614.

Region	d^a (arcsec)	FWHM ^b (arcsec)
Nucleus	–	0.21
Diffuse	–	2.4
N	0.52	0.73
S	0.59	0.72
E	0.60	0.54
W	0.61	0.45

Notes: ^aAngular distance between the nucleus and the component.
^bDeconvolved FWHM.

(190 pc) and has an FWHM of $\sim 0.5\text{--}0.7$ arcsec (160–220 pc). The residuals of the model are less than 20 per cent (Fig. 2).

To extract the fluxes from the CC *Q*-band image, we used GALFIT fixing the relative positions and widths of these components, but allowing their intensities to vary (see Fig. 2 and Table 2).

Similarly, we used this information to extract the CC *N*-band spectra. For each wavelength, we generated a synthetic image taking into account the CC *N*-band PSF, and then we simulated the two slit orientations (PA 0° and 90°) to obtain the one-dimensional

spatial profiles. We varied the intensities of the different regions to reproduce simultaneously the observed N–S and E–W profiles at each wavelength. The resulting spectra are plotted in Fig. 3. The fluxes at 10 and 12 μm , and the 11.3 μm PAH flux and equivalent width (EW) are listed in Table 2.

3.2 Spectral modelling

For the five selected regions, we decomposed the *N*-band spectra together with the 24 μm photometry using a two-component model consisting of a modified blackbody with $\beta = 2$ and a PAH emission template. The latter is derived from the *Spitzer*/IRS starburst template presented by Smith et al. (2007) after removing the dust continuum emission (see Pereira-Santaella et al. 2015 for details). We excluded the low-atmospheric transmission spectral ranges marked in Fig. 3 for the fitting.

The blackbody temperature and the intensities of the blackbody and the PAH template are free parameters of the model. In addition, we let the relative strength of the 11.3 μm PAH feature free during the fit since the strength of the different PAH features varies both in starbursts (Smith et al. 2007) and Seyfert galaxies (Diamond-Stanic & Rieke 2010).

Table 2. Spatially resolved measurements of NGC 1614.

Region	$f_{\nu}(10 \mu\text{m})^a$ (mJy)	$f_{\nu}(12 \mu\text{m})^a$ (mJy)	$f_{\nu}(24.1 \mu\text{m})^b$ (Jy)	11.3 μm PAH ^c ($10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$)	EW _{11.3 μm^d ($10^{-3} \mu\text{m}$)}	$f_{\nu}(\text{Pa } \alpha)^e$ (mJy)
Nucleus	120 ± 8	210 ± 20	<0.5	3.2 ± 0.6	79 ± 8	2.2
N	91 ± 10	390 ± 30	1.7 ± 0.6	12.7 ± 0.2	220 ± 5	5.2
S	81 ± 10	390 ± 50	1.6 ± 0.4	9.3 ± 0.5	170 ± 3	5.0
E	61 ± 6	130 ± 10	2.0 ± 0.7	13.2 ± 0.3	500 ± 20	5.5
W	73 ± 20	280 ± 30	0.6 ± 0.3	14.2 ± 0.4	350 ± 10	4.6

Notes: 3σ upper limits are indicated for non-detections. The uncertainties do not include the ~ 10 – 15 per cent absolute calibration error. All the wavelengths are rest frame. ^aThe monochromatic 10 and 12 μm fluxes are measured in the CC spectra of each region (see Section 3.1). ^b24.1 μm fluxes derived from the CC Q -band imaging (see Section 3.1). ^cFlux of the 11.3 μm PAH feature. ^dEW of the 11.3 μm PAH. ^ePa α flux measured in the continuum subtracted $F190N$ NICMOS images (Alonso-Herrero et al. 2006). To convert to flux units, these values should be multiplied by $1.56 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ mJy}^{-1}$.

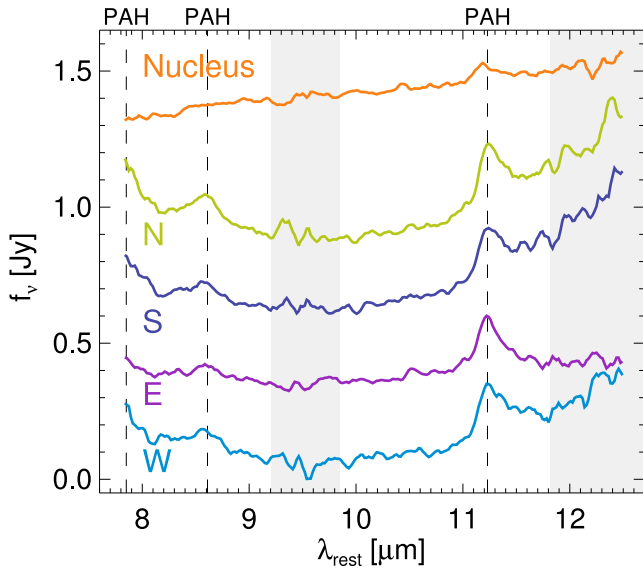


Figure 3. Mid-IR CC spectra of the nucleus and different regions in the star-forming ring. The nuclear (orange), north (green), south (dark blue), and east (purple) spectra are shifted by 1.3, 0.8, 0.55, and 0.3 Jy, respectively. The vertical lines mark the wavelength of the 7.7, 8.6, and 11.3 μm PAH features (dashed line). The shaded grey regions mark low-atmospheric transmission spectral ranges.

We calculated the warm dust mass using the following relation

$$M_{\text{dust}} = \frac{D^2 f_{\nu}}{\kappa_{\nu} B_{\nu}(T_{\text{dust}})}, \quad (1)$$

where D is the distance, f_{ν} the observed flux, κ_{ν} the absorption opacity coefficient, and $B_{\nu}(T_{\text{dust}})$ the Planck's blackbody law, all of them evaluated at 10 μm . We assumed $\kappa_{10 \mu\text{m}} = 1920 \text{ cm}^2 \text{ g}^{-1}$ (Li & Draine 2001).

The results of the fits are shown in Table 3 and Fig. 4. The mid-IR emission of the SF ring regions are well fitted by a combination of a PAH component, which dominates the emission below 9 μm , and a warm ($T \sim 110$ K) dust continuum component which dominates the emission at longer wavelengths. By contrast, the nuclear 8–13 μm spectrum is completely dominated by a warmer ($T \sim 160$ K) dust component.

4 THE AGN OR SF NATURE OF THE NUCLEUS

The nature of the nucleus (central 150 pc) of NGC 1614 is not well established. In part, this is because it is surrounded by a circum-

Table 3. Results from the modelling of the CC data.

Region	$\frac{7.7 \mu\text{m PAH}}{11.3 \mu\text{m PAH}}$ ^a	$T_{\text{dust}}^{\text{warm}}$ ^b (K)	$M_{\text{dust}}^{\text{warm}}$ ^c ($10^3 M_{\odot}$)
Nucleus	1.7 ± 0.2	160 ± 8	0.2 ^{+0.3} _{-0.05}
N	3.6 ± 0.5	110 ± 3	7.6 ^{+6.7} _{-3.4}
S	3.1 ± 0.4	109 ± 4	8.9 ^{+3.2} _{-2.3}
E	2.9 ± 0.5	108 ± 6	6.3 ^{+1.8} _{-4.3}
W	3.3 ± 0.6	115 ± 3	3.9 ^{+2.2} _{-1.3}

Notes: ^aRatio between the intensities of the modelled 7.7 and 11.3 μm PAH features (Section 3.2). ^bTemperature of the warm dust component detected in the mid-IR. ^cMass of the warm dust (see Section 3.2 for details).

nuclear ring with strong star formation (ring SFR $\sim 40 M_{\odot} \text{ yr}^{-1}$; Alonso-Herrero et al. 2001), which masks the relatively weak nuclear emission when observed at lower angular resolutions.

In the high angular resolution (0.11 arcsec) *HST*/NICMOS images, the nucleus is slightly resolved and shows near-IR colours compatible with stellar emission, although the CO index is inconsistent with an old stellar population (Alonso-Herrero et al. 2001). To explain this, Alonso-Herrero et al. (2001) suggested that the nuclear SF is more evolved than that of the star-forming ring.

Based on *ASCA* X-ray observations, Risaliti et al. (2000) suggested that NGC 1614 may host a Compton-thick AGN. However, the Fe K 6.4 keV line, which usually has a high EW in Compton-thick AGNs (although it depends on the obscuring matter geometry; see e.g. Fabian, Wilman & Crawford 2002), is not detected in more sensitive *XMM-Newton* observations (Pereira-Santaella et al. 2011). More recently, the non-detection of CO(6–5) emission and 435 μm continuum in the nucleus in high-resolution Atacama Large Millimeter/submillimeter Array (ALMA) observations implies that the amount of dust and molecular gas is much lower than that expected for a Compton-thick AGN (Xu et al. 2015). Similarly, interferometric radio continuum observations reveal that the nuclear emission is mostly thermal and relatively weak, which also supports the non-AGN nuclear activity (Herrero-Illana et al. 2014). Consequently, SF, as traced by the nuclear Pa α emission, would be the dominant energy source of the nucleus of NGC 1614.

Our new mid-IR data challenge these previous results. The nuclear spectrum shows a strong 12 μm mid-IR continuum (and a low EW of the 11.3 μm PAH feature), and the nuclear 24 μm continuum is weak in comparison with the SF ring emission. Therefore, the nucleus of NGC 1614 presents some characteristics (weak X-ray and far-IR emissions, lacking molecular gas, strong 12 μm mid-IR continuum, and Pa α emission) that cannot be explained in a

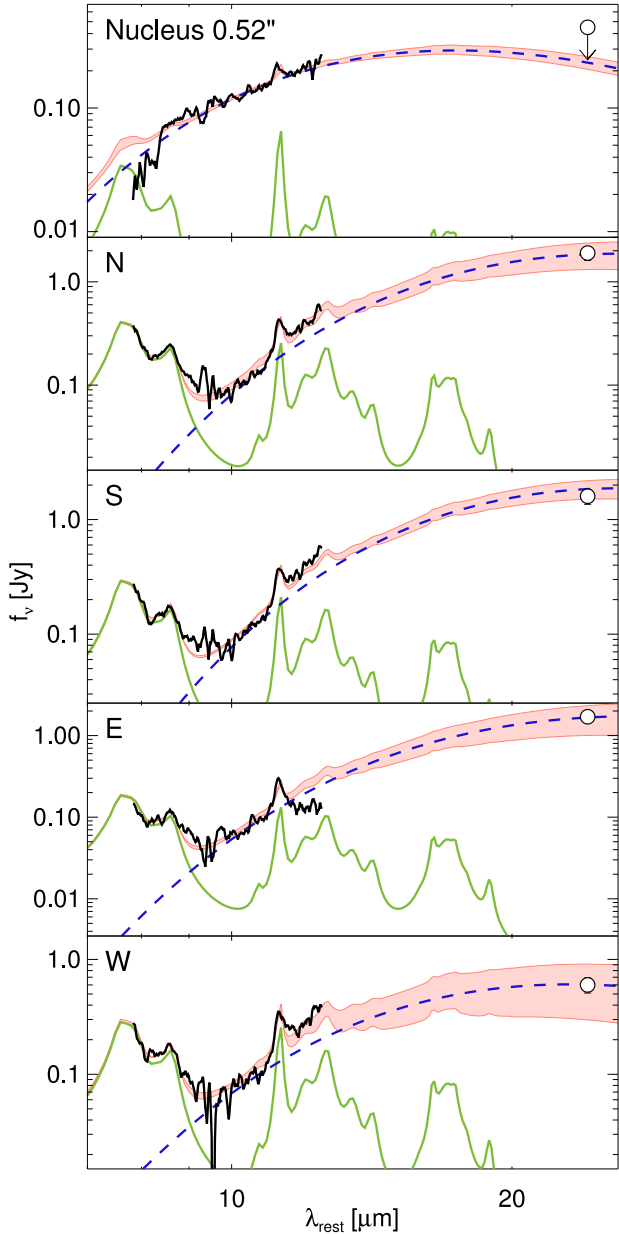


Figure 4. Best fit of the modified blackbody+PAH template models to the CC spectroscopy (solid black line) and 24.5 μm photometry (white circle) of the different regions of NGC 1614. The 1σ range of the best-fitting model is indicated by the red shaded area. The solid green line and the dashed blue line represent the PAH template and the modified blackbody continuum, respectively.

standard AGN or SF context. In the following, we discuss possible modifications to the AGN and SF scenarios to explain the observations available so far.

4.1 X-ray weak AGN?

4.1.1 Mid-IR AGN evidences

The CC spectrum of the nucleus is remarkably different from the spectra of the star-forming regions in the ring of SF. It shows a strong mid-IR continuum relative to the PAH emission, a dust temperature higher than in the SF regions of the ring (Table 3), and a continuum peak at around $\sim 20 \mu\text{m}$ (Fig. 4).

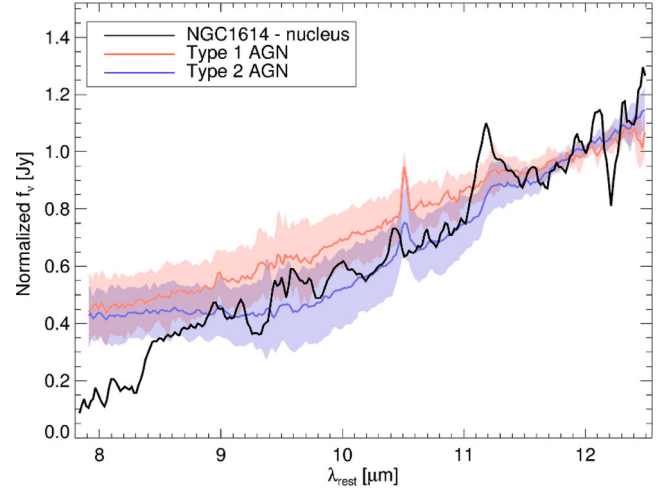


Figure 5. Comparison of the nuclear NGC 1614 mid-IR spectrum (black) and the average spectra of type 1 (red) and type 2 (blue) Seyfert galaxies from Alonso-Herrero et al. (2014) normalized at 12 μm . The shaded regions represent the 1σ dispersion of the averaged spectra.

Differences in the dust continuum emission are also evident if we consider the 24 μm to 10 μm flux ratio which is $\sim 10\text{--}30$ in the ring and < 5 in the nucleus (see Table 2 and Fig. 1). Low 24 $\mu\text{m}/10 \mu\text{m}$ ratios are predicted by AGN torus models because of the high dust temperatures reached in the torus (150–1500 K; Nenkova et al. 2008). Moreover, mid-IR *Spitzer*/IRS spectroscopy of active galaxies shows that for ~ 30 per cent of them (including type 1 and 2 Seyfert objects) the mid-IR spectra peaks at $\sim 20 \mu\text{m}$ indicating that a warm dust component ($T \sim 150\text{--}170 \text{ K}$) dominates the mid-IR emission (Buchanan et al. 2006; Wu et al. 2009). This trend is also observed in ground-based sub-arcsecond mid-IR spectroscopic surveys of Seyfert galaxies (e.g. Ramos Almeida et al. 2009, 2011; Alonso-Herrero et al. 2011). In Fig. 5, we compare the average type 1 and type 2 AGN spectra obtained by Alonso-Herrero et al. (2014) for nearby Seyfert galaxies. It shows that they all have similar continuum slopes. This suggests that the warm dust conditions in the nucleus of NGC 1614 are similar to those found in Seyfert galaxies. Although, the emission of hotter dust (at $\sim 8 \mu\text{m}$) is weaker in NGC 1614.

The minimum 11.3 μm PAH EW is located at the nucleus $(79 \pm 8) \times 10^{-3} \mu\text{m}$ (Table 2). This behaviour is also observed in local Seyfert galaxies, and it is explained in these objects by the increased AGN continuum contribution in the nucleus (Alonso-Herrero et al. 2014; Esquej et al. 2014; Ramos Almeida et al. 2014; García-Bernete et al. 2015). In addition, in the nucleus of NGC 1614, the 11.3 μm PAH feature is enhanced by a factor of ~ 2 with respect to the 7.7 μm PAH feature (Table 3). Similar enhancements of the 11.3 μm PAH feature are observed in active galaxies although on kpc scales (Diamond-Stanic & Rieke 2010).

4.1.2 Weak X-ray emission

A correlation between the 12 μm and the 2–10 keV luminosities is observed for Seyfert galaxies (Horst et al. 2008; Gandhi et al. 2009; Levenson et al. 2009; Asmus et al. 2011). For the nuclear 12 μm luminosity measured from the spectrum of NGC 1614 ($\nu L_\nu = 2.6 \times 10^{43} \text{ erg s}^{-1}$) the expected hard X-ray luminosity would be $1.6 \times 10^{43} \text{ erg s}^{-1}$ according to the Gandhi et al. (2009) relation. Therefore, both the nuclear 12 μm and expected 2–10 keV

Table 4. 2–10 keV X-ray observations of NGC 1614.

Date	Telescope	Flux (10^{-13} erg cm $^{-2}$ s $^{-1}$)	Ref.
1994-02-16	ASCA	5.6	1
2003-02-13	XMM-Newton	2.7±0.4	2
2012-04-10	Swift	2.5±0.4	3

References: (1) Risaliti et al. 2000; (2) Pereira-Santaella et al. 2011; (3) Evans et al. 2014.

luminosities are comparable to that of an average local Seyfert galaxy (see fig. 1 of Gandhi et al. 2009). However, the observed integrated hard X-ray luminosity of this galaxy is just 1.4×10^{41} erg s $^{-1}$, almost a factor of 200 lower than expected for an AGN, and most of it can be explained by the hard X-ray emission from star formation (i.e. high-mass X-ray binaries; Pereira-Santaella et al. 2011). Similarly, the soft X-ray emission is also better explained by star formation (Pereira-Santaella et al. 2011; Herrero-Illana et al. 2014).

If an AGN is present in the nucleus of NGC 1614, three possibilities may explain the weakness of the X-ray emission: it may be a strongly variable source observed during its low state; it may be a Compton-thick AGN so the 2–10 keV emission is absorbed; or it may be an intrinsically X-ray weak AGN. There are three hard X-ray observations of NGC 1614 during 18 yr (Table 4) which show that the variability is less than a factor of 2. So it is not likely that X-ray variability is the reason for the X-ray weakness. The Compton-thick AGN possibility was rejected by Xu et al. (2015) based on the low amount of molecular gas and cold dust in the nucleus. Moreover, NGC 1614 is not detected in the 14–195 keV Swift/BAT 70-Month Hard X-ray Survey (Baumgartner et al. 2013). If NGC 1614 would be a Compton-thick AGN with an intrinsic 2–10 keV luminosity of 1.6×10^{43} erg s $^{-1}$ (see above), its 14–195 keV flux would be 6×10^{-11} erg cm $^{-2}$ s $^{-1}$, which is ~ 4 times the 5σ sensitivity of the Swift/BAT survey. Finally, it is also possible that the X-ray emission of the NGC 1614 AGN is intrinsically weak. The ULIRG Mrk 231 (Teng et al. 2014), as well as several quasars (Leighly et al. 2007; Miniutti et al. 2012; Luo et al. 2014), have X-ray luminosities 30–100 times weaker than those predicted by the α_{OX}^2 versus $L_{2500\text{\AA}}$ correlation, probably due to a distortion of the accretion disc corona (Miniutti et al. 2012; Luo et al. 2013). In the case of NGC 1614, the nuclear UV emission is completely obscured (see Petty et al. 2014), so a direct comparison with the results for these X-ray weak AGNs is not possible. However, using the 12 μm emission we obtain that the observed 2–10 keV emission is more than two orders of magnitude lower than the expected value, similar to the X-ray weakness observed on those objects.

4.2 Or nuclear star formation?

Alternatively, it is possible to explain the nuclear observations assuming only star formation (SF). However, the nuclear SF and the SF taking place in the ring surrounding the nucleus must have very different characteristics. In particular, the nuclear mid-IR spectrum shows a strong 8–12 μm continuum that is not present in the ring spectra (Fig. 4), and the nucleus remains undetected in the 435 μm

¹ Using XSPEC (Arnaud 1996) and assuming a power-law spectrum with $\Gamma = 1.9$ (Marconi et al. 2004) and $N_{\text{H}} = 3 \times 10^{24}$ cm $^{-2}$. Increasing the N_{H} up to 10^{26} cm $^{-2}$ the flux would be reduced by a factor of 2.

² $\alpha_{\text{OX}} = -0.384 \log(L(2\text{ keV})/L(2500\text{\AA}))$.

Table 5. SFR from different IR tracers.

Region	A_{k} ^a	Pa α ^b	SFR (M_{\odot} yr $^{-1}$)	
			11.3 μm PAH ^c	24 μm ^d
Nucleus ^e	0.3	1.5	0.9	<6
N	0.7	9.3	4.1	22
S	0.8	11.2	3.1	21
E	0.6	7.8	4.1	26
W	1.0	16.4	5.2	7

Notes: ^aK-band extinction in magnitudes derived from the stellar colours (Alonso-Herrero et al. 2001). ^bExtinction corrected Pa α SFR using the Kennicutt & Evans (2012) calibration assuming $H\alpha/\text{Pa}\alpha = 8.51$. ^cSFR obtained from the 11.3 μm PAH luminosities (Table 2) based on the Diamond-Stanic & Rieke (2012) calibration. We multiplied by 2 our 11.3 μm PAH luminosities to account for the different method used to measure the PAH features (local continuum versus full decomposition, see Smith et al. 2007). ^dSFR derived from the monochromatic 24 μm luminosities (Table 2) using the Rieke et al. (2009) calibration. ^eNuclear SFR derived assuming that all the nuclear emission is produced by SFR (i.e. no AGN).

far-IR continuum and CO(3-2) maps (Xu et al. 2015; Usero in preparation) while the ring is clearly detected.

In our nuclear mid-IR spectrum, we detect the 11.3 μm PAH feature which is usually associated with SF (mostly B stars; see Peeters, Spoon & Tielens 2004). Using the $L_{11.3\mu\text{mPAH}}$ SFR calibration of Diamond-Stanic & Rieke (2012), we estimate a nuclear SFR of $\sim 0.9 M_{\odot}$ yr $^{-1}$ (Table 5 and see Section 5). We also used the nuclear Pa α flux (Díaz-Santos et al. 2008) to derive an SFR $\sim 1.5 M_{\odot}$ yr $^{-1}$ (assuming $A_{\text{k}} = 0.3$ mag; Alonso-Herrero et al. 2001), so both SFR tracers are in agreement within a factor of 2. Finally, we used the IR continuum upper limits at 24 and 432 μm to derive an upper limit for the nuclear IR (4–1000 μm) luminosity of $< 6 \times 10^{43}$ erg s $^{-1}$. This upper limit is compatible with the expected IR luminosity for an SFR $\sim 1.5 M_{\odot}$ yr $^{-1}$ ($\sim 4 \times 10^{43}$ erg s $^{-1}$; Kennicutt & Evans 2012). Therefore, all these IR SFR tracers are compatible and they indicate that the nuclear SFR is $\leq 1.5 M_{\odot}$ yr $^{-1}$, that is, less than < 2 per cent of the total SFR of NGC 1614 ($\sim 100 M_{\odot}$ yr $^{-1}$; Pereira-Santaella et al. 2015).

However, the nuclear and the integrated IR (8–500 μm) spectral energy distributions are very different. The ring is detected at 435 μm (Xu et al. 2015) and 24 μm (Fig. 1), but the nucleus is not. Therefore, this implies that the dust temperature is much higher in the nucleus, as already suggested by our mid-IR data. This higher nuclear dust temperature (Table 3) can be explained by the enhanced radiation field density, which is expected to increase the dust temperature (see Draine & Li 2007), due to an increased density of young stars in the nucleus (or an AGN, see Section 4.1.2).

Molecular gas is not detected in the nucleus of NGC 1614. From the 0.5 arcsec resolution CO(3-2) ALMA observations of NGC 1614, Usero (in preparation) estimate an upper limit to the nuclear molecular gas mass of $3 \times 10^6 M_{\odot}$.³ This low molecular gas mass puts the nucleus of NGC 1614 well above the Kennicutt–Schmidt relation (see fig. 8 of Xu et al. 2015). Consequently, the molecular gas depletion time is < 3 Myr, much lower than in normal galaxies at 100 pc scales (1–3 Gyr; e.g. Leroy et al. 2013), and also lower than in local ULIRGs (70–100 Myr; e.g. Combes et al. 2013). A short depletion time might indicate that the ignition of the nuclear SF occurred earlier than in the ring (see Alonso-Herrero

³ Assuming a CO(3-2) to CO(1-0) ratio of ~ 1 and the Galactic CO-to- H_2 conversion factor (Bolatto, Wolfire & Leroy 2013). Using the conversion factor for ULIRGs it would be a factor of ~ 4 lower.

et al. 2001). Therefore, the nuclear starburst would have consumed a larger fraction of the original cold molecular gas than the younger starburst of the ring. Actually, the evolutionary state of the SF regions is commonly used to explain the dispersion of individual SF regions in the Kennicutt–Schmidt relation (e.g. Onodera et al. 2010; Schruha et al. 2010; Kruijssen & Longmore 2014). However, the integrated (including nucleus and SF ring) dense molecular gas depletion time in NGC 1614 is also shorter (~ 10 Myr) than in other LIRGs (~ 50 Myr; García-Burillo et al. 2012), so it is not obvious to associate the particularly short nuclear depletion time with older SF. Alternatively, a massive molecular outflow, produced by an AGN or supernovae (SN) explosions (see García-Burillo et al. 2015), could have swept most of the molecular gas away from the nucleus.

On the other hand, the hard X-ray luminosity of this object is also compatible with an SF origin (Pereira-Santaella et al. 2011), although most of the emission would be produced in the ring. Unfortunately, the angular resolution of the *Chandra* X-ray data is not sufficient to separate the nucleus and the ring (Herrero-Illana et al. 2014).

Note that, in principle, a combination of SF and a normal AGN would be also possible. However, this assumption suffers the same problems explaining the observations than the SF and AGN individually. For these reasons, we do not discuss this AGN+SF composite possibility.

5 SFR TRACERS AT ~ 150 PC SCALES

Using the new CC mid-IR data (11.3 μm PAH and 24 μm continuum) in combination with the NICMOS Pa α image, we can test several SFR calibrations at 150 pc scales in this galaxy.

In Table 5, we show a summary of the SFR derived using these tracers for the five regions we defined in NGC 1614. We used the calibrations of Kennicutt & Evans (2012), Diamond-Stanic & Rieke (2012), and Rieke et al. (2009) for the Pa α , 11.3 μm PAH, and 24 μm tracers, respectively. The Pa α emission was corrected for extinction using the near-IR continuum colours (see Alonso-Herrero et al. 2001). Since the extinction corrected Pa α calibration is a direct measurement of the number of ionizing photons produced by young stars, we consider it as the reference SFR tracer.

The 24 μm luminosity gives the highest SFR values (2–3 and 5–7 times higher than those derived from the Pa α and 11.3 μm PAH luminosities, respectively), except in the W region of the ring. The modelling of the radio emission of the W region indicates the presence of SN (Herrero-Illana et al. 2014), so it could be more evolved than the rest of the ring. Therefore, a lower amount of young stars would be dust embedded in this region reducing the warm dust emission.

The disagreement between the extinction corrected Pa α and the 24 μm SFR values is ~ 0.4 dex, which is higher than the calibration uncertainty (0.2 dex). Although, in principle, both tracers should produce similar SFR estimates (see equations 5 and 8 of Rieke et al. 2009). There are two possibilities to explain this. First, it is possible that even the extinction corrected Pa α emission underestimates the SFR. In extremely obscured regions (e.g. $A_v > 15$ –20 mag), dust might absorb the Pa α emission completely, as well as part of the ionizing photons, and therefore, rendering any extinction correction ineffective. Alternatively, an increase of the dust temperature at high SFR densities, like in the SF ring of NGC 1614, can produce enhanced 24 μm emission that might not be taken into account by the 24 μm SFR calibration which is valid for integrated emission of galaxies (e.g. Calzetti et al. 2010). The stellar A_k measured in the SF ring of NGC 1614 is 0.6–1.0 mag ($A_v = 5$ –10 mag; Alonso-Herrero

et al. 2001), so the obscuration level is not as extreme as observed in some ULIRGs ($A_v = 8$ –80 mag; Armus et al. 2007). In addition, the 9.7 μm silicate absorption in the SF ring spectra is not very deep (Fig. 4). Therefore, this favours the second possibility. That is, an increased 24 μm emission in the SF ring of NGC 1614 due to a warmer dust emission.

According to Table 5, the SFR derived from the 11.3 μm PAH luminosity is 2–4 times lower than that derived from Pa α . The 11.3 μm PAH SFR calibration is based on $\sim\text{kpc}$ integrated measurements (Diamond-Stanic & Rieke 2012). However, it is known that the PAH emission, and in particular the 11.3 μm PAH emission, is more extended than the warm dust continuum and other ionized gas tracers (e.g. [Ne II] 12.81 μm ; Díaz-Santos et al. 2011). Actually, ~ 30 –40 per cent of the total PAH emission is not related to recent SF (Crocker et al. 2013). Therefore, this SFR calibration possibly includes a considerable amount of PAH emission not produced by young stars. In addition, using templates of SF galaxies, Rieke et al. (2009) showed that the 11.3 μm PAH contribution to the total IR luminosity drops by a factor of ~ 2.5 for galaxies with $L_{\text{IR}} > 10^{11} L_{\odot}$. A similar result was found by Alonso-Herrero et al. (2013) for a sample of local LIRGs. A combination of these reasons might explain why we obtain these relatively low SFR estimates from the 11.3 μm PAH luminosities for the ~ 150 pc SF regions in the ring of NGC 1614.

6 CONCLUSIONS

We analysed new GTC/CC high angular resolution (~ 0.5 arcsec) mid-IR observations of the local LIRG NGC 1614. The new *N*-band spectroscopy and *Q*-band imaging are combined with existing *HST*/NICMOS Pa α and T-ReCS 8.7 μm images to study the properties of the bright circumnuclear SF ring and the nucleus of this object. The main results are the following.

(i) We extracted mid-IR spectra from four different regions in the circumnuclear SF ring and from the nuclear region (central 0.5 arcsec ~ 150 pc). The spectra from the SF ring are typical of an SF region with strong PAH emission and a shallow 9.7 μm silicate absorption. By contrast, the nuclear spectrum has a strong mid-IR continuum, which dominates its mid-IR emission, and weak PAH emission ($\text{EW}_{11.3 \mu\text{m}} = 80 \times 10^{-3} \mu\text{m}$). Similarly, the SF ring is clearly detected in the 24.5 μm image, as expected for an SF region, while the nucleus is weaker at this wavelength.

(ii) A two-component model, consisting of a modified blackbody with $\beta = 2$ and a PAH emission template, reproduces the observed *N* spectra and *Q* photometry well. The main differences between the nuclear and the SF ring observations are: the higher dust temperature in the nucleus (160 K in the nucleus versus ~ 110 K in the ring); the lower PAH EW; and the lower nuclear 7.7 μm /11.3 μm PAH ratio.

(iii) The above results based on the mid-IR data, suggest that an AGN might be present in the nucleus. However, this is at odds with the low X-ray luminosity of NGC 1614 (~ 200 times lower than that expected for an AGN with the observed 12 μm continuum luminosity). Since the hard (2–10 keV) X-ray emission shows no variability, and likely it is not a Compton-thick AGN, if an AGN is present in NGC 1614, it must be an intrinsically X-ray weak AGN. We also calculated an upper limit to the IR luminosity of the nucleus, $< 6 \times 10^{43} \text{ erg s}^{-1}$.

(iv) Alternatively, SF can explain the observations of the nucleus too. However, we need to invoke extremely short molecular gas depletion times (< 3 Myr for a nuclear SFR of ~ 1 –1.5 $M_{\odot} \text{ yr}^{-1}$),

and an increased radiation field density to explain the observed hot dust in the nucleus.

(v) Finally, we compared three SFR tracers at 150 pc scales in the circumnuclear ring: extinction corrected Pa α , 11.3 μm PAH, and 24 μm continuum. Since the extinction is not extremely high ($A_V < 10$ mag), we take as reference the Pa α derived SFR. In general, the 24 μm SFR overestimates the SFR by a factor of 2–3, while the 11.3 μm PAH underestimates the SFR by a factor of 2–4. The former might be explained if the dust temperature is higher in the SF regions of NGC 1614, while the latter could be because we do not include diffuse PAH emission in our measurements as well as because the PAH contribution to the total IR luminosity might be reduced in LIRGs.

(vi) In the west region of the ring, the 24 μm emission is ~ 5 times weaker than expected based on the observed Pa α /24 μm ratio in this galaxy. We propose that this is because this is a more evolved SF region (SN are present; Herrero-Illana et al. 2014) where a larger fraction of the young stars are not dust embedded.

In summary, our mid-IR data suggest that an intrinsically X-ray weak AGN ($L_{\text{bol}}^{\text{AGN}} \sim 10^{43}$ erg s $^{-1}$, < 5 per cent of the NGC 1614 bolometric luminosity) might be present in the nucleus of NGC 1614. However, SF with a short molecular gas depletion time and increased dust temperatures can explain the observations as well. In order to further investigate the nature of the nucleus of this galaxy, IR and sub-mm high angular resolution observations are needed.

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