Star Formation in the Circumnuclear Ring of NGC 4736

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ABSTRACT

This research has examined the spiral galaxy NGC 4736 (M94) to determine the star formation rate and luminosity profile of the circumnuclear ring through Hydrogen Alpha observations combined with Cousins R and Johnson V photometry. A star formation rate of $0.43 \pm 0.16 M_{\odot} yr^{-1}$ was calculated within the ring. This value falls within the limits of previous research. Clear regions of high star formation density were observed characteristic of gas inflow to the core. Sérsic profiles were created to establish luminosity relations between different regions of the galaxy. An isophote analysis was also performed to discern if a barred structure is present in the core, the results of which are inconclusive. Possible limitations of, and improvements to, the methods utilized in this work is discussed.

Keywords: Starburst Galaxies, Star Formation, M94, NGC 4736, Photometry, Hydrogen Alpha, Sérsic Profile

1. INTRODUCTION

The term *starburst* was defined by Weedman (1973) to explain galaxies with higher than expected star formation rates (SFR). Many galaxies in the local universe have star formation occurring however only $\sim 1\%$ can be defined as starbursts (Bergvall & Marquart 2015).

There are multiple processes which can lead to enhanced star formation. Interactions or collisions with a neighbouring galaxy, or internal processes such as tidal disruptions or resonant rings (Pearson & Wang 2019) (Van der Laan et al. 2015) are all methods which increase star formation. Starburst galaxies in the local group, at redshifts < 0.05, are particularly interesting as localised regions can be resolved and examined in depth. There is no hard limit to the SFR required for a galaxy to be called a starburst, due to the many variables involved in star formation, including mass, density, dust, and gas content Knapen & Querejeta (2015). However, many starburst galaxies have clear processes powering star formation not present in quiescent galaxies, which notably increases star formation.

Approximately 65% of all galaxies contain a barred structure, including the Milky Way Ceverino & Klypin (2007)(Hou & Han 2014). The presence of a bar generates large tidal disruptions which can lead to the presence of a disk or ring of stars. 20% of nearby disk galaxies are thought to contain circumnuclear star forming rings which qualify as starburst events. However not all disk galaxies are known to contain bars, leading to the theory that gas inflow occurs due to tidal torques resonant rings in Lindblad regions within the disk driving high star formation (Van der Laan et al. 2015). Another theory also suggests that the star forming ring is formed by collisional outward propagating shock fronts powered by an earlier direct collision through the nuclear center of both galaxies (Arsenault 1989). Both processes result in high star forming circumnuclear disks which can provide information on the dynamics of the inner regions of these galaxies.

NGC 4736 (M94) is a Low Ionization Nuclear Emission Region (LINER) SAab circumnuclear early-type ringed spiral galaxy. Nuclear emission is thought to be characteristic of Active Galactic Nuclei (AGN) or high star forming regions near the galactic center. The source of nuclear emission in the core is still disputed [torillio?] however a ring of high star formation is present at $r \approx 45''$, within which there is evidence to suggest the presence of a central bar (Möllenhoff et al. 1995). However other evidence suggests gas and dust inflow to the core via Lindblad resonances Van der Laan et al. (2015). Due to uncertainty in the process driving the SFR, its proximity in the local universe (d = 4.38 ± 0.07 Mpc, $z \approx 0.001$), and relatively low inclination ($i \approx 35^{\circ}$) (Trujillo et al. 2009), NGC 4736 has been the source of many observations. It is widely agreed that the ring is undergoing high star formation relative to a quiescent galaxy. NGC 4736 has a stellar mass of between 3.4×10^{10} and $4 \times 10^{10} M_{\odot}$, a relatively small local galaxy when compared to our own Milky Way, at $2.3 \times 10^{11} M_{\odot}$ (Jałocha et al. 2008; Karachentsev et al. 2013). This low mass, coupled with a circumnuclear ring of high star formation and efficient star forming regions in the outer disk, classifies NGC 4736 as a starburst galaxy (Waller et al. 2001).

The method of optical photometry will be utilised in this paper to examine this region of NGC 4736. Photometry utilizes band-pass filters such as Hydrogen alpha to examine astronomical objects in particular wavelength regimes. Within hot and dense gaseous regions in starburst galaxies, large O and B stars dominate the star formation. These young, bright stars emit in the ultraviolet wavelengths, which can ionize hydrogen in the surrounding nebula. The resulting emission is the Hydrogen Alpha (H α) line. It is thus characteristic of the formation of high mass, high temperature early-type stars within galaxies (Cohen 1976). The H α line provides an accurate photometric measurement of star formation in low redshift galaxies when corrected for extinction (James 2004). A strong H α detection can also reduce the need to correct for close spectral Nitrogen emission lines (James et al. 2005).

Sérsic profiles are the primary method for fitting elliptical and early type spiral galaxies. They provide information on the distribution of luminosity in the galaxy as well as defining regions within (Pignatelli et al. 2006). As part of Sérsic profile modelling an isophote analysis can be performed. Ellipticity and primary angles can be investigated for the presence of structures within the galaxy Möllenhoff et al. (1995). The methods outlined above have been employed in exploring the goals of this research. These goals are threefold:

- Previous research has already calculated the SFR of NGC4736's circumnuclear ring (Lee 2006; Skibba et al. 2011; Calzetti et al. 2010; Van der Laan et al. 2015). This research aims to determine a value for the SFR within the ring via H α photometry to confirm the starburst classification of NGC 4736 in prior investigations. The SFR is compared with previously calculated SFRs to determine if the current method is accurate.
- A Sérsic profile model is also be carried out to define and characterise different regions within the galaxy. Parameters such as effective radius, regional luminosity, apparent magnitude, and surface brightness will be calculated to determine the limitations of the current research. To calculate the Sérsic profile an isophote analysis is performed. Effective radius, luminosity, and magnitude values are compared to the literature.
- The ellipticity and primary angles of these isophotes are used to investigate the presence, or absence, of a bar at the center of NGC 4736. The SFR density distribution is examined to attempt to provide validation for either of the leading theories for the processes driving high SFR in the ring, i.e. evidence for a barred structure or clear regions of gas inflow.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Observations and Data Reduction

Observations of NGC 4736 were made using the 1.23 meter Cassegrain reflector telescope at Calar Alto Observatory during the nights of the 11th, 13th and 14th March 2020. The CCD had a field of view (FOV) of 21.5×21.5 arcminutes and a pixel scale of 4096×4096 , corresponding to a resolution of 0.3 arcseconds per pixel ¹. The use of smaller filters reduced the FOV to 15×15 arcminutes. Observations were divided into 27 minutes of Johnson-Cousins R-band (peak: 641 nm, FWHM 159 nm), 20 minutes of Johnson-Cousins V-band (peak: 536 nm, FWHM: 90 nm), and 220 minutes using a narrowband H α filter centered at 656 nm with a FWHM of 1 nm. This totaled 267 minutes of observations. NGC $4736 \text{ was} > 50^{\circ}$ above the horizon during all observations and weather conditions were clear. The average seeing for observations was calculated to be 2.24 ± 0.87 arcseconds.

A total of 100 minutes of H α , 15 minutes of Cousins Rband and 7.5 minutes of Johnson V-band data were used for final processing and analysis due to a focusing issue affecting the remainder of the data. One H α image was affected by cloud cover. Total observation time equalled 122.5 minutes. See figure 1 for an example of the focus issues for the cross-section of a reference star.



Figure 1. Comparison of stellar cross section for in-focus and out of focus reference star data. A Gaussian distribution is fit to the in-focus data. The resulting Gaussian has a FWHM of 1.63 arcseconds, corresponding to the seeing for that image. Errors are the square root of the counts.

Data was trimmed to remove vignetting caused by the use of smaller filter sizes relative to the CCD. Images were then passed through a cosmic ray removal algorithm from the *astropy* python library (Astropy Collaboration et al. 2013). Bias and filter-specific flat removal was applied to all images, which were then aligned and stacked. Due to the low transmission rate and narrow FWHM of the filter, multiple 600 second exposures of $H\alpha$ were conducted. 150 second exposures were taken in R and V bands. This resulted in the final processed image for each filter for analysis.

2.2. Analysis

The reference stars used for apparent magnitude calibration are summarized in Appendix C. The Right Ascensions and Declinations of these stars were obtained using the *Astrometry* website ². While the H α filter used for observations had an FWHM of 1 nm, it is unlikely that emission from the neighbouring N[II] lines (654.8 nm and 658.4 nm) was entirely avoided, and as such all references to H α emission and imaging will imply H α +[NII] emission. The H α emission from NGC 4736 occurred at a wavelength of 656.94 nm due to a redshift of 0.001.

The following conversions were used to calculate the scale of regions in the galaxy: 1 pixel = 0.34 arcseconds. 1 arcsecond corresponds to 21.2 ± 0.2 parsecs assuming a distance to NGC 4736 of 4.38 ± 0.07 parsecs

2.3. Star Formation Rate Analysis

The following equation was used to determine the SFR for the circumnuclear ring in NGC4736:

$$SFR\left[M_{\odot}yr^{-1}\right] = 10^{0.4A_{H\alpha}} \frac{L(H\alpha)}{1.27 \times 10^{34}},\qquad(1)$$

where $L(H\alpha)$ is the observed luminosity from the $H\alpha$ emission line, and 1.27×10^{34} is a constant. This constant and the method used to calculate the SFR can be found in Gilbank et al. (2010). This method has the advantage of accounting for interstellar absorption. A 3-sigma cutoff was used for detection of H α regions. After R-band subtraction there remained very low traces of H α emission from the core. This was masked as the primary region of investigation was the ring, and the diffuse core emission was not significant.

2.4. Sérsic Profile Analysis

The following analysis was performed on both R and V filter images. Both images were scaled using reference star magnitudes to obtain the apparent magnitude of NGC 4736. An elliptical isophote analysis was performed using the *photutils* library (Bradley et al. 2019). From this the half light radius, 1 sigma, and 3 sigma detection regions were determined. An average of the flux

at each isophote radius was taken as the radial cross section of the galaxy. Each region was then defined from previous research and sigma detections of the outer spiral arms. A Sérsic profile was then fit to the bulge (r = 11"), inner disk(r = 11" — 23"), inner arms (r = 23" — 76"), and outer arms (r = 76" — 135"), minimising the residuals for each region. The *photutils* function *sersic1D* was used to complete the profile (Bradley et al. 2019). This function uses the Sérsic equation to determine a best fit of a radial profile. The Sérsic equation is expressed as

$$I(R) = I_e exp\left(-\left(2n - \frac{1}{3}\right)\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right), \quad (2)$$

where I(R) is the intensity at radius R, I_e is the intensity at the effective radius R_e of the region of interest, and n is the Sérsic index. The Sérsic index determines the shape of the region of interest. The bulge and inner disk were previously defined in Munoz-Tunón et al. (2004). The Sérsic profile can be used to determine the effective radius and contribution to the luminosity of each of the features of the galaxy. The ellipticity of the inner rings was also examined for the presence of a bar.

3. RESULTS

3.1. Star Formation Rate

A SFR result of $0.43 \pm 0.16 M_{\odot} yr^{-1}$ was calculated from a three-sigma signal to noise significance limit. This is also is the sum of the SFRs per unit area for the disk, as these values were calculated from the main SFR.

The colour-bar in figure 2 (a) represents SFR per unit area. Two regions directly opposite one another in the upper right and lower left of the ring in figure 2 show increased star formation compared to surrounding areas, up to a SFR per unit area of $0.055 M_{\odot} yr^{-1}[Area]^2$ in a region of approximately 50 kpc. The mean SFR per unit area is equal to approximately $0.042 M_{\odot} yr^{-1}$. The region of star formation follows the disk of NGC 4736 as shown in 2 (b). The masked area of the core is also visible in (b).

The full radius of the ring detected in H α spans 46.5 arcseconds ± 6.7 arcseconds.

3.2. Sérsic Profile

Sérsic profile plots in the R and V bands are shown in figures 3 and 4. All calculated apparent magnitudes, luminosities, effective radii, and surface brightness values are available in table 1. Luminosity errors are not displayed in the table but equal 36% of the luminosity. This

² http://nova.astrometry.net/

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0.055

0.055

0.054

area within each localised region. The scale is shown in the bottom right corner in parsecs. The dashed line represents the isophote of the circumnuclear ring in R-band images. Any low H α emission from the central nucleus has been masked to avoid excess emission in recorded SFR calculations, shown by the solid lined circle at the center of the ring. (b) H α overlay on R filter exposure to highlight star forming regions within the disk.

was determined through propagation of errors. Two regions, labelled inner and outer arms, have been defined in this paper based on 3-sigma and 1-sigma signal to noise limits. These are subdivided from the standard spiral arm region of NGC 4736, which transitions to a diffuse region not detected in the observations within this research, and do not translate to defined regions in previous research. Limiting surface brightness values of 19.5 arcsec^2 in R, and 17.4 arsec^2 in V, were determined within a 68% confidence limit. This region corresponds to an outer radius of 143 arcseconds ± 2 arcseconds or $3.2 \text{ kpc} \pm 0.1 \text{ kpc}$. The current accepted radius of NGC 4736 is 9.2 kpc (Trujillo et al. 2009). The detected region corresponds to 12.1% of the visible surface area of the galaxy. The core was determined to have an apparent magnitude in the R-band of 9.2 ± 1 . The V-band core apparent magnitude is 9.8 ± 1.3 .

The bulge to disk ratio, a weak method to determine the classification of a galaxy, is approximately 0.65. The Outer Arms region is fit by an exponential function, as Sérsic profiles best model the inner regions of a galaxy, thus a Sérsic index is not calculated.

The total R-band luminosity was determined to be approximately $1.8 \times 10^9 \pm 6 \times 10^8 L_{\odot}$ Scaling using reference stars resulted in an apparent magnitude in the bulge of 9.2 ± 1 in R, and 9.8 ± 1.2 in V. The bulge contributes 56% of the total R-band luminosity of the observed region of the galaxy, which extends to 143 arcseconds ± 2 arcseconds. In the V-band this percentage equals 57%.



1.5

Inner Arms

Radial Profile

Sérsic Residuals

2 5

Profile Mag. Erro

Zero Lin

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3.5

The disk, containing the circumnuclear ring had a luminosity of $\sim 6.5 \times 10^8 \pm 2 \times 10^7 L_{\odot}$ in the R-band and $1.7 \times 10^8 \pm 6 \times 10^7 L_{\odot}$ in the V-band. This corresponds to a ratio of 3.8. The Sérsic index for the bulge was calculated to equal 1.5 and 2 in R and V respectfully. These values are not in agreement with the Sérsic index of 4 calculated by Munoz-Tunón et al. (2004).



41°08'00



10

11

12

13

14

0.2

0.0

-0.1

0.5

۵ 0.1

Apparent Magnitude

41°08'00



Taking an average of the regions where ellipticity and PA peak gives a possible constraint to the width of a bar of 0.39 ± 0.12 kpc.

Contour profiles were also created and are available in Appendix B. The contours appear to have a weak bar like structure towards the center of the galaxy, however this is not a quantitative result.



Figure 5. PA (left y-axis) and ellipticity (right y-axis) versus distance from center for both R (bottom) and V (top). Region highlighted in red contains abrupt changes in PA and is the region of a suggested bar-like structure powering star formation in the ring.

4. DISCUSSION

4.1. Star Formation Rate

A SFR of $0.43 \pm 0.16 M_{\odot} yr^{-1}$ was determined for the circumnuclear ring. The region of star formation follows the disk observed in R and V-band images. This SFR falls within the range of previous SFRs of $0.16 M_{\odot} yr^{-1}$ (Van der Laan et al. 2015) and $0.75 \pm 0.4 M_{\odot} yr^{-1}$ (direct measurement) and $0.64 \pm 0.4 M_{\odot} yr^{-1}$ (SED model) (Trujillo et al. 2009) within error limits.

Van der Laan et al. (2015) determined that $\sim 72\%$ of the total SFR of NGC4736 is contained in the bulge. which they defined to be from 0 out to a radius of 75 arcseconds, containing the primary emission of the ring at 46 arcseconds. Other SFRs of the full surface area of the galaxy can therefore be scaled to compare to value from the current research. Calzetti et al. (2010) calculated a total SFR of $0.38 M_{\odot} yr^{-1}$ for the galaxy. When scaled to disk emission this becomes $0.27 M_{\odot} yr^{-1}$. Similarly, Lee (2006) calculated a total SFR of $0.43 M_{\odot} yr^{-1}$, giving a SFR result for the disk of $0.31 M_{\odot} yr^{-1}$. Skibba



Figure 4. Sersic profile for NGC 4736 in Johnson V. Y-axis is apparent magnitude and x-axis is distance from center in kiloparsecs. The subplot at the base of the figure is a plot of the residuals when the Sérsic profile is subtracted from the radial profile. The profile was fit to minimise the residuals, Δm .

The total luminosity of the observed region equals $2.1\times10^9\pm7\times10^8\,L_\odot$ in R and $7\times10^8\pm2\times10^7\,L_\odot$ in V.

The ring was not present in the Sérsic profile as a separate region, possibly due to averaging in the isophotes but also as the ring is not significantly brighter than surrounding regions in the disk in optical wavelengths.

3.3. Detection of SFR Processes

Sérsic Profile results has been further analysed to determine if processes behind increased SFR were detected. Results are quoted in kiloparsecs. Note again the conversion used in this research: 1 arcsecond corresponds to 21.2 ± 0.2 parsecs.

Primary angle (PA) and ellipticity versus radius from center from the isophote analysis are plotted in figure 5 for both R and V-bands. Ellipticity is the ratio of semi-major (a) and semi-minor (b) axes, calculated as (a - b)/a. Abrupt changes in both PA and ellipticity are highlighted by red bands in the figure. The PA varies between $54^o \pm 0.3^o$ to $142^o \pm 0.12^o$ between $0.26 \pm 0.01 \ kpc$ and $0.38 \pm 0.05 \ kpc$ in R-band ellipses. This PA change does not corresponding to a significant change in ellipticity within this region. At another point in the disk, the ellipticity abruptly changes from ~ 0.2 $(at \ 0.22 \pm 0.01 \ kpc)$ to ~ 0.04 (at $0.29 \pm 0.02 \ kpc$). There is no significant change in PA within this region.

In the V-band within the region $0.16 \pm 0.02 \ kpc$ to $0.51 \pm 0.05 \ kpc$ there is a significant change in PA from $29.7^{\circ} \pm 0.1$ to $155^{\circ} \pm 0.5^{\circ}$. The peak changes in PA

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Table 1. Defined regions and all major results from Sérsic profile analysis in both bands. Columns 3 and 7 are apparent magnitudes m for R-band and V-band respectively. The Sérsic index for each filter in columns 6 and 10 is denoted by n. Reference radii r_{ref} in column 3 are the measured effective radii of the bulge and disk/bar region from Munoz-Tunón et al. (2004).

Region	r_{eff}	r_{ref}	m_R	S_R	L_R	n_R	m_V	S_V	L_V	n_V
	arcsec	arcsec		$arcsec^2$	L_{\odot}			$arcsec^2$	L_{\odot}	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Core/Bulge	11.6 ± 0.9	10.82 ± 0.17	9.2 ± 1	11.3 ± 1.1	$\sim 1 \times 10^9$	1.5	9.8 ± 1.3	$13.7\pm$	4×10^8	2
Disk	22.5 ± 0.6	24.09 ± 0.32	12 ± 1.2	$14.3\pm$	$\sim 6.5\times 10^8$	0.5	$12.4\pm$	$16.2\pm$	1.7×10^8	0.5
Inner Arms	76.6 ± 2.3	-	12.9 ± 1	$17.6\pm$	$\sim 1\times 10^8$	1.2	$13.3\pm$	$17.2\pm$	7.3×10^7	1
Outer Arms	135 ± 2	-	14.2 ± 1.2	$19.5\pm$	$\sim 3.4\times 10^7$	-	$13.5\pm$	$17.4\pm$	6×10^7	-

NOTE—The missing value noted with an em-dash in column 3 is due to the separate definitions of galaxy regions in the current research. No Sérsic profile was calculated for the 'Outer Arms' region as it was fit with an exponential function.

et al. (2011) reached a value of $0.70 M_{\odot} yr^{-1}$, with disk emission contributing $0.504 M_{\odot} yr^{-1}$.

The total SFRs were compiled by Van der Laan et al. (2015). Comparing the revised SFRs for the disk to the result from this research shows close agreement. Of these methods Skibba et al. (2011), Calzetti et al. (2010), and (Van der Laan et al. 2015) are known to have used H α photometry. (Van der Laan et al. 2015) also calculated the SFR of the disk from near ultraviolet (NUV) and far ultraviolet (FUV) to minimise extinction due to the high dust content within the central 75 arcsecond region. These produced values of $0.27 M_{\odot} yr^{-1}$ and $0.25 M_{\odot} yr^{-1}$ respectively. One possible reason for the high value calculated for the SFR in the current research is the presence of N[II] emission lines near H α at 658.2 nm. The narrowband filter may still have overlapped with the N[II] emission line. It is also possible that the method used in the H α photometry overcompensates for absorption due to dust. The current research used an adjustment to the apparent magnitude of 0.8, however this is an approximation based on galaxies in the local universe (Gilbank et al. 2010)(James 2004). The star formation rate was not adjusted for N[II] based on research from James et al. (2005) which concluded that N[II] emission line did not significantly affect strong $H\alpha$ detections and that over-correction could lead to overestimations of SFRs.

The SFR of the circumnuclear ring determined from these observations agrees within limits with values found in previous research. To highlight the classification of NGC 4736 as a starburst galaxy one can compare the SFR to that of a larger quiescent galaxy, M87, and the Milky Way. M87 is a supergiant elliptical galaxy at a distance of $16.8 \pm 0.8 \ kpc$ and mass equal to $2.4 \times 10^{12} M_{\odot}$. It has a SFR of approximately $8.64 \times 10^{-3} \pm 5.4 \times 10^{-4} M_{\odot} yr^{-1}$ (Kelleher 2020). The current estimate of the SFR of the Milky Way is $0.68 - 1.45 M_{\odot} yr^{-1}$ within a stellar mass estimate of $6.43 \pm 0.63 \times 10^{10} M_{\odot}$ (Robitaille & Whitney 2010) (McMillan 2011). When compared to NGC 4736 both M87 and the Milky Way have lower SFRs per solar mass. M87 is a quiescent galaxy with no regions of high activity. While a bar is present in the Milky Way, resonant patterns do not appear to be occurring on the same scale as in NGC 4736.

4.2. Sérsic Profile

The calculated apparent magnitudes were lower than the currently accepted m in R of 8 and in V of 8.2 (Cook et al. 2014) (De Paz et al. 2007). The discrepancy may have arisen from the scaling factor calculated from the difference in apparent and instrumental magnitudes of reference stars.

One possible reason for the lower V apparent magnitude when compared to R is that NGC 4736 is classified as a LINER galaxy, with a high population of Asymptomatic Giant Branch stars with higher emission in the red and infrared region of the spectrum. Furthermore the diffuse regions of the outer arms were not detected in the current observations. These arms have higher emission in blue wavelengths due to young massive stars forming where there is an abundance of gas and dust. However, these regions are very faint due to dust absorption and do not contribute much to the V-band magnitude. When viewed in UV or IR these regions contribute significantly to the SFR of the entire galaxy out to > 600 arcseconds increasing the star formation rate of the galaxy to $1.04 \ M_{\odot} yr^{-1}$ (Trujillo et al. 2009).

The importance of Sérsic profiling cannot be understated. The effectiveness of the modelling to determining characteristics of regions in the galaxy allowed for calculations of effective radii which agreed well with previous research (Munoz-Tunón et al. 2004). A bulgeto-disk luminosity value was also calculated which falls within the range of Sab galaxies. The Sérsic index of the bulge is lower than that calculated by Graham (2001). however this may be in part due to the lower calculated apparent magnitudes in the current research. The disk was not detected however this was not detected due to the brightness of the disk in optical. The profile errors are large as each point is the average of a 360 degree isophote. Large fluctuations are likely due to the presence of dust in the ring leading to absorption of $H\alpha$ emission.

NGC 4736 is classified as an SAab galaxy with a Hubble stage value of $T \approx 2$. From this parameter the bulge to disk ratio is expected to fall between the range of 0.1 to 1.5. The ratio in this research calculated to equal ≈ 0.65 meets this criteria.

4.3. SFR Process

There is no region inside the radius of the disk where both PA and ellipticity change drastically to indicate the presence of a bar. Instead a decrease in ellipticity is observed at a shift in PA, when it would be expected that the presence of an elongated bar-like structure would increase ellipticity. Similarly no change in PA is observed at a point of slight increase in ellipticity in either band.

The plot of isophote PA and ellipticity (5) appears to show abrupt changes in angle of the semi-major axis between (0.1 - 0.6 kpc), however this alone is not evidence for the presence of a bar rotating out of phase with the spiral arms. The estimated width of a central bar is 18.4 ± 5.6 arcseconds (0.39 ± 0.12 kpc). This value lies close to that reported in Möllenhoff et al. (1995) of 15 arcseconds within the margin of error. It is important to note that this calculation is based of the change in ellipticity and PA alone and there is no direct observation of a central bar. Furthermore this value has a large error region due to the lack of alignment of abrupt increases in ellipticity and changes in PA associated with the presence of a bar. There is no result from this research which adequately supports the theory that a bar exists at the center of NGC 4736.

Areas of increased SFR per unit area were measured at opposing points in the ring to be as high as $0.05\pm0.16M_{\odot}yr^{-1}$ in a region of approximately $0.1kpc^2$. These areas are investigated in Van der Laan et al. (2015) and can possibly be attributed to gas in-flow regions from tidal disruptions. A star formation rate of $0.43 \pm 0.16 \ M_{\odot} \ yr^{-1}$ in a region as small as the circumnulear ring highlights the power of the processes thought to be occurring within. Van der Laan et al. (2015) conclude that the 'string of pearls' arrangement of the star formation can be modelled by gas inflow at the primary points of the ring (top right and bottom left in figure 2 (a). This gas inflow is estimated in their paper to be as high as $2M_{\odot} \ yr^{-1}$ at these regions. However this does not fully explain the distribution throughout, which is described as 'popcorn' star formation. As no bar-like structure was detected in the current research, and with clear high SFR density regions along pre-existing defined gas inflow points in the ring, the results from this paper appear to support that of Van der Laan et al. (2015) with a gas inflow driven model.

4.4. Points of Note

The H α filter used for these observations had an effective transmission of 20%. Future studies could make use of more efficient H α filters with larger FWHMs, and observe with N[II] filters to subtract overlapping emission. This may provide a stronger signal to noise for H α observations and thus lead to more accurate SFR calculations. This is discussed further in Appendix A. It is also important to note that while an approximation was applied to account for extinction within the ring of NGC 4736, an ideal observation would consist of UV or IR to reduce the effect of extinction.

More rigorous examination and analysis of reference stars is required to determine true apparent magnitudes for use to accurately constrain magnitudes within NGC 4736 and thus increase the accuracy of SFR calculations. Observations across multiple filters could also provide a spectral energy distribution which could give insight into the stellar composition of the circumnuclear ring and bulge of the galaxy.

5. CONCLUSIONS

NGC 4736 is an early type spiral galaxy with a circumnuclear ring in our local region of the universe. It is classified as a starburst, with the ring in particular containing regions of high star formation. This research examined the inner ring and, using H α photometry, calculated a SFR of $0.43 \pm 0.16 \ M_{\odot} \ yr^{-1}$. This value lies above the most recent estimates also determined using $H\alpha$. Overcompensation of extinction, or possible contamination from N[II] lines may have lead to the discrepancy. Two regions of high SFR density were observed in regions of gas inflow, correlating with previous research that this process powers the star formation. Sérsic profiles confirmed the high luminosity of core and disk regions relative to diffuse spiral arms, and determined effective radius the core and disk to similar radii as outlined in the literature. An elliptical isophote analysis did not conclusively detect the presence of a barlike structure, more observations of the core in NIR, UV or radio are required to definitively conclude whether a bar exists. Star formation density in H α images clearly show higher density regions which match those in previous research labelled as gas inflow regions. In conclusion, spiral starburst galaxy NGC 4735 has an incredibly complex structure, requiring far more observations to understand the processes occurring to generate high star formation rates in its circumnuclear ring.

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APPENDIX

A. FILTER EFFECTIVENESS



Figure 6. Available filters at Calar Alto Observatory. Transmission profiles are approximated to a Gaussian. The filter used for observations was 656/1, corresponding to a peak wavelength of 656 nm, and a FWHM of 1 nm.

The filter used for observations was a 656 nm Hydrogen alpha narrow-band filter with a FWHM of 1nm (red dashed line in figure 6). This gave a transmission efficiency of approximately 10%, however is more likely to have avoided nearby emission lines not related to star formation, such as N[II]. The plot above demonstrates the effectiveness of other narrow-band filters available at Calar Alto at receiving the sightly redshifted H α emission line of 656.9 nm from NGC 4736.

If further observations of NGC 4736 are made the most suitable filter to use would likely be the 657 nm filter with a FWHM of 3 nm. This filter avoids the majority of the N[II] emission and has an 80% transmission efficiency. If the redshifted H α filter with a peak wavelength of 664 nm and a FWHM of 10 nm had been used it is likely that any detected H α emission from NGC 4736 would have been masked by high emission in red wavelengths. This would have resulted in a H α image with very weak detection and less localised regions of emission after R-band subtraction.

STAR FORMATION IN NGC 4736

B. CONTOUR PROFILES AND ISOPHOTES

The contour profiles in figures 7 (a) for R-band and (b) for V-band highlight the shape of the inner region, specifically the elongated regions appearing within the central bulge equivalent to $r \approx 18$ arcseconds. These contours are not significant to determine the presence of a bar. In comparing these contour profiles it is apparent that the V-band contains sharper structures to the R-band. This could be due to the R-band observing emission from gas within the arms. The outer contours in each image are defined as the 3-sigma signal-to-noise limits for both bands.



Figure 7. Plot of contour profiles of NGC 4736 in (a) R and (b) V bands. Both appear to show a bar like structure near the center perpendicular to the main PA of the galaxy.

C. REFERENCE STARS

The brightest stars in the image were chosen as reference stars for apparent magnitude calibration. Magnitudes were obtained from the Sloan Digital Sky Survey DR16 (Blanton et al. 2017), and converted using the Sloan-to-Johnson conversion equations³. The scaling factor (difference between instrumental and apparent magnitudes of reference stars) does not appear to have been entirely accurate. One issue encountered in reference star selection was the lack of catalogues with magnitudes for stars in the field. SDSS DR16 (the most recent at time of writing) does not contain information on many of the stars in the field around NGC 4736. The reference stars used for both R and V scaling are circled in figure 8.

The equation used to convert from Sloan magnitudes to Johnson V is:

$$V = q - 0.59(q - r) - 0.01.$$
(C1)

To convert from V to R using Sloan magnitudes the following equation was used:

$$V - R = 1.09(r - i) - 0.22.$$
(C2)

³ http://www.sdss3.org/dr8/algorithms/

RIGNEY



Figure 8. Plot of final processed FOV of NGC 4736 in the R band with the reference stars used circled.

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