Insights on bar quenching from a multi-wavelength analysis: The case of Messier 95

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ABSTRACT

The physical processes related to the effect of bar in the quenching of star formation in the region between the nuclear/central sub-kpc region and the ends of the bar (bar-region) of spiral galaxies is not fully understood. It is hypothesized that the bar can either stabilize the gas against collapse, inhibiting star formation or efficiently consume all the available gas, with no fuel for further star formation. We present a multi-wavelength study using the archival data of an early-type barred spiral galaxy, Messier 95, which shows signatures of suppressed star formation in the bar-region. Using the optical, ultraviolet, infrared, CO and HI imaging data we study the pattern of star formation progression, stellar/gas distribution and try to provide insights on the process responsible for the observed pattern. The FUV–NUV pixel colour map reveals a cavity devoid of UV flux in the bar-region that interestingly matches with the length of the bar (∼ 4.2 kpc). The central nuclear region of the galaxy is showing a blue color clump and along the major-axis of the stellar bar the colour progressively becomes redder. Based on a comparison to single stellar population models, we show that the region of galaxy along the major-axis of the bar (unlike the region outside the bar) is comprised of stellar populations with ages ≥ 350 Myr, with a star-forming clump in the center of younger ages (∼ 150 Myr). Interestingly the bar-region is also devoid of neutral and molecular hydrogen but with an abundant molecular hydrogen present at the nuclear region of the galaxy. Our results are consistent with a picture in which the stellar bar in Messier 95 is redistributing the gas by funnelling gas inflows to nuclear region, thus making the bar-region devoid of fuel for star formation.

Key words. galaxies: star formation – galaxies: evolution – galaxies: formation – ultraviolet: galaxies – galaxies: nuclei

1. Introduction

Galaxies in the local Universe follow a bimodal distribution in the optical broad band colors with the blue region mostly populated by star forming spiral galaxies and the red region dominated by elliptical/S0 galaxies with little or no ongoing star formation (Strateva et al. 2001; Baldry et al. 2004). However there exists a fraction of elliptical galaxies in the blue region (Schawinski et al. 2009) and spiral galaxies in the red region (Masters et al. 2010). The number density of red galaxies are observed to increase from z ∼ 1 which is now understood to be at the expense of blue galaxies (Bell et al. 2004; Faber et al. 2007). Several internal (AGN/stellar feedback, action of stellar bar) and external process (ram pressure stripping, major mergers, harassment, starvation, strangulation) have been proposed as responsible for the suppression of star formation (a process known as “quenching”) that often involve morphological transformation of spiral galaxies (see Peng et al. 2010; Man & Belli 2018 and references therein). The existence of a population of passive red spiral galaxies (van den Berg et al. 2016; Couch et al. 1998; Dressler et al. 1999; Poggianti et al. 1999; Lee et al. 2008; Cortese & Hughes 2009; Peng et al. 2010; Masters et al. 2010 and references therein) imply galaxies can transform from star forming to non star forming phase without invoking morphological transformation (Fraser-McKelvie et al. 2016). Red spiral galaxies are found to have a higher optical bar fraction than blue spiral galaxies, which highlight the importance of stellar bars in quenching star formation (Masters et al. 2010; 2011).

Stellar bars redistribute the disk content of galaxies via torques and can drive the secular evolution in spiral galaxies (Combes & Sanders 1981; Combes et al. 1990; Debattista et al. 2004; Kormendy & Kennicutt 2004 and references therein). This is possible through the inflow of gas from the outer disk to the central region which results in an enhanced nuclear/central star formation observed in barred spiral galaxies (Athanassoula 1992; Ho et al. 1997; Sheth et al. 2015; Coelho & Gadotti 2011; Ellison et al. 2011; Oh et al. 2012). However, apart from the enhancement of star formation at the central regions the stellar bars can also suppress star formation (bar quenching) and is discussed in recent literature based on simulations as well as observations (Masters et al. 2010; 2012; Cheung et al. 2013; Gavazzi et al. 2015; James & Percival 2016; Spinoso et al. 2017; Khoperskov et al. 2018; James & Percival 2018). The stellar bar in massive star forming galaxies is understood to play a dominant role in regulating the red-shift evolution of specific star formation rates and mass dependent star formation quenching in field galaxies (Gavazzi et al. 2015). The likelihood for disk galaxies hosting a bar is observed to be anti-correlated with specific star formation rate regardless of stellar mass and the prominence of bulge (Cheung et al. 2013). Barred galaxies are also shown to have lower star formation activity relative to unbarred galaxies (Consolandi et al. 2017; Kim et al. 2017). They are found to be devoid of Hα flux in the radial range covered by the bar suggesting no ongoing or recent star formation. Based on a multi-wavelength analysis of the archival data of a barred spiral galaxy Messier 95, which highlights the importance of the bar in quenching star formation.

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LETTER TO THE EDITOR
However the physical processes responsible for bar quenching are not well understood. There are primarily two mechanisms suggested for the quenching of star formation due to the effect of bars. During its formation the bar collects most of the gas inside the co-rotation radius. Then the bar induced shocks and shear can stabilize the gas against collapse by increasing turbulence and hence inhibit star formation (Tubbs 1982; Reynaud & Downes 1998; Verley et al. 2007; Haywood et al. 2016; Khoperskov et al. 2018). Alternate mechanism is that, the bar induced torque drives gas inflows which enhance the nuclear star formation and making the region close to the bar devoid of fuel for further star formation (Combes & Gérin 1985; Spinoso et al. 2017). It is not certain which of these processes or a different unknown mechanism is responsible for star formation quenching in the region between the nuclear/central sub-kpc region and the ends of the bar (bar-region) of barred spiral galaxies. In the scenario of suppression of star formation by the stabilization of disk due to the bar induced torques, the gas from the bar-region of the galaxy need not be re-distributed/depleted. Thus the presence/absence of gas in the bar-region can put strong constraints on identifying the mechanism responsible for bar quenching in this galaxy. In this context here we present a multi-wavelength study based on the archival data of a barred spiral galaxy, Messier 95 (M95).

M95[1] (also known as NGC 3351) is a nearby (10 ± 0.4 Mpc, Freedman et al. 2001) early-type barred spiral galaxy (Morphology: SBb). The angular scale of 1" corresponds to 48 pc at the distance of the galaxy. M95 has stellar mass, HI mass, H$_2$ mass and integrated star formation rate of $\sim 10^{10.4}$ $M_\odot$, $\sim 10^{9.2}$ $M_\odot$, and $\sim 0.940$ $M_\odot$/yr respectively (Leroy et al. 2008). The gas phase metallicity (12 + Log O/H) of M95 is 8.60 (Remy-Ruyer et al. 2014). It is a nearly face-on galaxy (inclination=41\(^\circ\), position angle=192\(^\circ\)) with a prominent bar (See Figure 1). High quality multi-wavelength data of M95, ranging from radio to Ultraviolet (UV), are available. It shows nuclear star formation and hosts a star forming circumnuclear ring with a diameter of $\sim 0.7$ kpc. This sub-kpc scale star formation is well studied in X-rays (Swartz et al. 2006), UV (Ma et al. 2018; Colina et al. 1997, Hr (Planesas et al. 1997); Bresolin & Kennicutt 2002) and near infrared (Elmegreen et al. 1997). In a multi-wavelength study, from Ultraviolet to mid-infrared, of the nuclear ring of M95, Ma et al. 2018 presented the integrated properties of the ring and their correlation with bar strength. Muzzalay et al. (2013) presented the properties of molecular gas within $\sim 300$ pc of this galaxy using near infrared integral field spectrograph, SINFONI in Very Large Telescope and suggested that the nuclear region host a stellar population of a few Myr. H$_z$ imaging of larger area of M95 shows that the bar-region is devoid of emission (James et al. 2009). The stellar population studies of this region indicate that they host an old population (James & Percival 2016). Long-slit spectroscopy of the bar-region showed a diffused emission which are not found to be associated with star formation. They attribute this emission to be due to post Asymptotic Giant Branch (p-AGB) stars (James & Percival 2015). These studies suggest that the observed nuclear star burst and suppression of recent star formation ($\sim 10$ Myr) in the bar-region is due to the effect of bar. However, the physical mechanism responsible for this observation is not understood. All the above points make this galaxy an excellent candidate to study the effect of bar on quenching star formation. Throughout this paper, we adopt a flat Universe cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$ (Komatsu et al. 2011).

2. Data and analysis

In this study we exploit the archival data of M95 observed from ultraviolet to radio wavelengths as part of different campaigns. We used the SDSS $urz$ DR9 (Ahn et al. 2012) optical imaging data of M95 to construct a colour composite image which is shown in Figure 1 and demonstrate the presence of a prominent stellar bar. The choice of blue ($u$) and red ($z$) pass band images helps in better visualizing the spatial variation of the relative contribution of young and evolved population of stars in the galaxy. The $u$ band flux is negligible in the bar-region, which instead is dominant in the region outside the stellar bar and could be hosting intense star formation which we address in detail using UV data.

M95 was observed in FUV ($\lambda_{eff}=1538.6$ Å, Integration time=1692.2s) and NUV ($\lambda_{eff}=2315.7$ Å, Integration time=1692.2s) wavelengths using the NASA GALEX mission (Martin et al. 2005). The GALEX FUV channel imaging is at $\sim 4.2$' and the NUV channel imaging is at 5.3" resolution (Morrissey et al. 2007). The FUV image is degraded to NUV resolution by running a Gaussian 2D kernel of width 0.57". The GALEX GR6/GR7 data of M95 field observed as part of Nearby Galaxy Survey (NGS) is pipeline reduced (with good photometric quality) and astrometry calibrated. We study the UV properties of this galaxy to probe recent star formation (past a few 100 Myr, Kennicutt & Evans 2012) over scales of $\sim 288$ pc. The HI map of M95 from The HI Nearby Galaxy Survey (THINGS; Walter et al. 2008) and the CO map (J$_{1-1}$

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1 $\alpha(2000) = 10:43:57.7$ and $\delta(2000) = +11:42:14$ according to NASA/IPAC Extragalactic Database (NED).
transition) from CO measured by HERA CO-Line Extragalactic Survey and Berkeley-Illinois-Maryland Association Survey of Nearby Galaxies (HERACLES; Leroy et al. 2009) are used to understand the gas distribution. We used the infrared image from Spitzer IRAC 3.6 μ channel observed as part of S^G (Sheth et al. 2010) to understand the distribution of evolved stellar population in the bar-region of the galaxy.

The foreground extinction from the Milky Way galaxy in the direction of M95 is \( A_V = 0.076 \) (Schlegel et al. 1998) which we scaled to the FUV and NUV \( \lambda_{mean} \) values using the Cardelli et al. (1989) extinction law and corrected the magnitudes. The region of the FUV and NUV images that correspond to M95 was isolated using the threshold set by the background counts from the whole image. Pixels with values above the 3σ of the threshold were selected to isolate the galaxy. The counts in the selected pixels were background subtracted, integration time weighted, and converted to magnitude units using the zeropoints of Morrissey et al. (2007). Magnitudes for each pixel are used to compute the FUV–NUV colour map of the galaxy (see Figure 2). The pixels are colour coded in units of FUV–NUV colour. The image is of size \( \sim 8' \times 8' \) and corresponds to a physical size of \( \sim 24\text{kpc} \) on each side at the rest-frame of the galaxy. The FUV–NUV colour map of M95 displays a redder region at the centre (with an embedded small blue clump) which is separated from the rest of the galaxy by a region with negligible UV flux. The redder region in Figure 2 coincides with the major-axis of the bar of M95. It is interesting to note that the bar-region has negligible UV flux. This region also coincides with the region identified to be devoid of emission in Hα (James et al. 2009).

The FUV–NUV colour map can be used to understand the star formation history of M95 and can, in particular, offer insights into the last burst of star formation. We used the Starburst99 stellar synthesis code to characterise the age of the underlying stellar population in M95 (Leitherer et al. 1999). We selected 19 single stellar population (SSP) models over an age range of 1 to 900 Myr assuming a Kroupa IMF (Kroupa 2001) and solar metallicity (\( Z = 0.02 \)). The synthetic SED for a given age was then convolved with the effective area of the FUV and NUV pass-bands to compute the expected fluxes. The estimated values were then used to calculate the SSP ages corresponding to the observed FUV–NUV colours. We performed a linear interpolation for the observed colour value and estimated the corresponding ages in all pixels in the FUV–NUV colour map. The ages for the FUV–NUV colour is shown in the colour bar in Figure 3. This exercise shows that the region along the major-axis of the bar hosts stellar populations of age \( \geq 350 \) Myr and the nuclear/central sub-kpc region shows embedded bluer, younger clump of star formation (\( \sim 150-250 \) Myr). Figure 3 shows an azimuthally averaged colour profile of M95. The FUV–NUV pixel colour maps and the derived ages can therefore be considered as the upper limits of the actual values.

The Spitzer IRAC 3.6 μ image of a galaxy can be used as a extinction free tracer for the evolved stellar population which dominate the underlying stellar mass (Meidt et al. 2014). The Spitzer IRAC 3.6 μ image of M95 is shown in Figure 4 with appropriate scaling to enhance the appearance of the stellar bar. We note that the stellar bar is prominent in infrared image and could be hosting evolved stellar population. The length of the stellar bar from the infrared image is \( \sim 87' (\sim 4.2 \text{kpc}) \). The HI contours (black colour) and the CO contours (yellow colour) are overlaid over the Spitzer image. Comparing Figure 2 and Figure 3, it is interesting to see that the 4.2 kpc diameter circular region (interesting the length covered by stellar bar), avoiding the central nuclear region, lacks molecular/neutral hydrogen and star formation. The central sub-kpc nuclear region of the galaxy is hosting significant molecular gas content, star formation and some amount of neutral hydrogen.

3. Discussion

The stellar bar can channel the gas inwards of the central regions of the galaxy within which star formation can happen and is proposed to be responsible for the formation of pseudo bulge (Sanders & Huntley 1976; Roberts et al. 1979; Athanassoula 1992; Ho et al. 1997; Kormendy & Kennicutt 2004; Jogee et al. 2005; Lin et al. 2017; Spinoso et al. 2017). On the other hand the bar can also suppress recent star formation in galaxy disks (James & Percival 2016; Spinoso et al. 2017; James & Percival 2018). The recent simulations demonstrate that the stellar bar to efficient in quenching star formation in galaxy disks (James & Percival 2016; Spinoso et al. 2017; James & Percival 2018). Simulations also predict stellar bars as long lived features in isolated disc galaxies with life time up to \( \sim 1000 \text{Myr} \).
stellar bar feature is prominently seen in the IRAC 3.6 \( \mu m \) center of the galaxy. The color scale is adjusted such that the redshift. It is therefore necessary to make a detailed understand-

There is an offset between the HI and CO emission peak at the center of the galaxy. The color scale is adjusted such that the stellar bar feature is prominently seen in the IRAC 3.6 \( \mu m \) image.

**Fig. 3:** Azimuthally averaged FUV–NUV colour profile of M95. The 2\(^{\prime}\) (\( \sim 6 \) kpc) region of the galaxy been averaged in colour in concentric annuli of width 6\(^{\prime}\). The profile shows an inner blue region gradually changing to redder colors, followed by a change to blue colours. The FUV–NUV colour values and the corresponding age estimates are shown on the left and right axes, respectively.

(Athanassoula et al. 2013). This imply that stellar bars can keep the galaxy quenched for at least 10\(^9\) yr and could be a dominant mechanism in shutting down star formation in galaxies over all redshift. It is therefore necessary to make a detailed understand-

The multi-wavelength study of M95 based on the archival data ranging from ultraviolet, optical, infrared, neutral hydrogen and molecular hydrogen, as traced by CO, paint a picture of star formation quenching happening in the bar-region. There is no star formation in the last 100-200 Myr as evident from the FUV–NUV colour map. The lack of molecular and neutral hydrogen in this region implies that the stellar bar might have re-distributed the gas. The stellar bar can funnel the gas to the center and can be the reason for significant molecular gas content and recent star formation observed in the central sub-kpc nuclear/central region. This can lead to nuclear star bursts and formation of substructures (such as circumnuclear rings). M95 is known to have such features (Colina et al. 1997; Ma et al. 2018). We note here that the barred galaxies are demonstrated to have an enhanced star formation at the center (Ellison et al. 2011) and in the case of M95 also it is observed to have younger age clumps (\( \sim 150-250 \) Myr). This funneling of gas to the central sub-kpc region would have depleted gas in the bar-region. Hence suppressed star formation due to lack of fuel. On the other hand, there is significant neutral hydrogen present outside the length of bar along with presence of young stellar population.

The absence of CO and HI in the bar-region of M95 can be considered as a support to the scenario of gas re-distribution. The scenario of gas heating due to the stabilization of disk by bar induced torques can prevent gas cooling which in turn can inhibit star formation. However we expect to see the signature of such a gas heating in the form of significant H\( \alpha \) emission which is lacking along the stellar bar (within the detection limits) in the case of M95 as demonstrated by the H\( \alpha \) imaging observations of James et al. (2009) (see also James & Percival 2015 where a di-ffulte or in other words bar quenching is a dominant star formation the processes operating during the bar quenching in galax-

There are primarily two mechanisms suggested for the quenching of star formation due to the effect of bars. The stellar bar in the galaxy can either stabilize the disk against collapse, inhibiting star formation (Tubbs 1982; Reynaud & Downes 1998; Veldt et al. 2007; Haywood et al. 2016; Khoperskov et al. 2018), or efficiently consume all the available gas, with no fuel for further star formation (Combes & Gérin 1985; Spinoso et al. 2017). The turbulence set by the bar prevents the fragmentation of molecular gas within the co-rotation radius and thus suppresses star formation in the bar-region of the galaxy. In such a scenario the gas in the bar-region of the galaxy need not be depleted nor re-distributed to quench star formation. The presence or alternatively the absence of the neutral and molecular hydrogen in the quenched barred galaxies can provide insights regarding the mechanisms responsible for bar quenching. We note that in the scenario where the suppression of star formation due to bar induced turbulence, it is not clear whether all the gas will be shock heated. Signatures of shock heating should be seen in H\( \alpha \) observations.

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We present here evidence for gas re-distribution due to the stellar bar and subsequent star formation quenching within the bar co-rotation radius in M95. The main result of our analysis is a region, between the nuclear region and the ends of the bar, devoid of gas and star formation in the past a few 100 Myr. Star formation is quenched in this region and the absence of molecular/neutral hydrogen gas imply no further star formation is possi-

**Fig. 4:** The Spitzer IRAC 3.6 \( \mu m \) image (flux unit (MJy/sr)) of Messier 95 with the black contour demarcate stellar bar detected with a length (\( \sim 4.2 \) kpc). The HI contour (black colour) from THINGS (levels -0.66,20,22,41.10,61.99,82.87 in flux unit (Jy/beam/s)) and the CO contour (yellow colour) from HERA-CLES (levels -1.65, 2.27 in flux unit (K km/s)) are overlaid. There is an offset between the HI and CO emission peak at the center of the galaxy. The color scale is adjusted such that the stellar bar feature is prominently seen in the IRAC 3.6 \( \mu m \) image.
suppression mechanism in M95. In the absence of an external supply of gas, the star formation in the center will deplete the molecular hydrogen completely and the galaxy will be eventually devoid of star formation in the bar and the central nuclear region. It is not clear whether bar quenching is the dominant process responsible for star formation suppression in barred spiral galaxies in general and the redistribution of the gas due to stellar bar the main governing process. The pilot study reported here demonstrate the capability of multi-wavelength analysis in understanding the role of stellar bar in star formation progression and gas distribution in spiral galaxies. The results presented here calls for a detailed analysis of a statistically large sample of face-on barred galaxies with multi-wavelength observations which will be reported in a forthcoming paper. The stellar and gaseous kinematics (ionized gas) along the region of bar can be understood in more detail from the observations based on ongoing optical IFU surveys.

4. Summary

We present here observational evidence for star formation quenching due to the presence of a stellar bar and the mechanism responsible for quenching in galaxy Messier 95 based on a multi-wavelength analysis using the archival data. Based on the FUV–NUV pixel colour map we demonstrate that the central 4.2 kpc diameter region along the stellar bar of galaxy is composed of stellar population with equivalent ages ≥ 350 Myr. This imply that currently there is no ongoing star formation along the region covered by the bar. The central sub-kpc region of the galaxy is hosting abundant supply of molecular hydrogen with the region along the bar devoid of neutral and molecular hydrogen, but is present outside the stellar-bar-region. This is a direct evidence along the bar devoid of neutral and molecular hydrogen, but is present outside the stellar-bar-region. This is a direct evidence along the bar devoid of fuel for star formation. A similar analysis along with a spatially resolved study of the gaseous and stellar kinematics on a statistically significant number of barred galaxies can give more insights on bar quenching in spiral galaxies.

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