AGN feedback in NGC 3982

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ABSTRACT

The energetic feedback from supermassive black holes can influence star formation at the centres of galaxies. Observational evidence for AGN impact on star formation can be searched in galaxies by combining ultraviolet imaging and optical integral field unit data. The ultraviolet flux directly traces recent star formation, and the integral field unit data can reveal dust attenuation, gas ionisation mechanisms, and gas/stellar kinematics from the central regions of the galaxy disk. A pilot study on NGC 3982 shows star formation suppression in the central regions of the galaxy, likely due to negative AGN feedback, and enhanced star formation in the outer regions. The case of NGC 3982 could be observational evidence of AGN feedback operating in a Seyfert galaxy.

Key words. ultraviolet: galaxies – galaxies: individual: NGC 3982 – galaxies: active – galaxies: star formation

1. Introduction

Galaxies in the local universe host supermassive black holes (SMBH) with mass \( > 10^6 \, M_\odot \) at their centres which can accrete large amounts of gas from the immediate vicinity (Kormendy & Ho 2013). The accretion changes the SMBH and the host galaxy to an active galactic nucleus (AGN) phase with a net effect of energy release in the form of radiation, jets and outflows. The energy output can heat the cold molecular gas and increase the turbulence, suppressing star formation and regulating the gas accretion onto the SMBH. This self-regulating process is termed AGN feedback. It is believed to be an important aspect of galaxy formation and evolution, with various observational evidences supporting this as a star formation quenching pathway for galaxies (see Fabian 2012 and Morganti 2017 for reviews). AGN feedback is included in galaxy simulations to match observed galaxy properties (Springel et al. 2005, Di Matteo et al. 2005, Somerville et al. 2008, Beckmann et al. 2017). While it may be anticipated that this feedback results in the suppression of star formation (negative AGN feedback) due to the copious amount of energy released by the AGN, there also exists the inverse case of positive feedback where star formation is triggered due to AGN activity (Zinn et al. 2013).

Although the evidence for AGN feedback is available, direct observations of its influence on star formation in the local universe remain limited. One reason for the scarcity of direct observations could be that AGN luminosities vary considerably during a typical star-forming episode, and the effect of feedback on star formation may not be readily apparent (Hickox et al. 2014). Such variability can give rise to situations where even if a galaxy’s star formation was affected by AGN activity, the corresponding signatures of a strong AGN could have become undetectable. Similarities in star formation efficiencies between Seyfert and inactive local galaxies have been found by Rosario et al. (2018); while this observation may suggest that the AGN activity does not affect star formation efficiencies in the AGN host galaxies, it is also possible that the AGN could have been active in the past in the inactive galaxies. In studies where the sample of galaxies is selected by AGN activity, it may be challenging to obtain a correlation between the highly variable activity of AGN feedback and star formation that takes place on a relatively long timescale.

However, there may exist galaxies which hosted AGN in the recent past, where we can directly probe the evidences of AGN activity affecting star formation. If we can find such galaxies and study the recent star formation in the central regions and its connection to any recent AGN activity, it may lead to a better understanding of the complex relationship of AGN feedback with star formation. Such studies might make it possible to find relatively smoothly time-variable parameters connected to the AGN feedback and explore their relationship with the star formation as a proxy to unravel how AGN feedback transforms the galaxy.

The observations of AGN feedback affecting star formation in nearby galaxies have cases of both positive and negative feedback. The AGN jet-induced positive feedback is found in Centaurus A, NGC 1275 and Minkowski’s Object (Mould et al. 2000, Canning et al. 2010, Van Breugel et al. 1985). Outflow-induced star formation exists near the nuclear region of NGC 5643 (Cresci et al. 2015). In NGC 7252 observed by George et al. (2018), AGN activity is proposed to have suppressed the star formation in the central region. Both positive and negative feedback has been observed in NGC 5728 (Shin et al. 2019). It will be interesting to increase the statistics of galaxies with evidence of AGN feedback on star formation present in the local universe.

A comprehensive search for observational signatures of AGN feedback on star formation in nearby galaxies could help unravel the complex spatial and temporal relationship of AGN interaction with its host galaxy environment. Since the AGN is known to impart energy through radiative (sometimes called quasar or wind) and mechanical (also known as radio, kinetic or jet) modes (Harrison 2017), they leave behind observational sig-
natures that could be identified. The gas around AGN will get ionised by the large energy throughput and produce excitation lines that can be spatially mapped. Similarly, star formation can get suppressed or triggered in the galaxy, which can be observed using the absence/presence of emitted ultraviolet (UV) flux associated with star formation activity.

The integral field unit (IFU) based spectroscopy of galaxy disk allows us to resolve the excitation mechanisms present in the galaxy spatially; this is particularly useful in identifying the extent of AGN-excited regions. The ultraviolet imaging data directly probe the recent star formation (< 200 Myr, Kennicutt Jr & Evans 2012), and any effect of AGN feedback on the galaxy should be revealed in the UV images as reduced flux due to suppressed star formation. IFU observations of nearby galaxies from Mapping Nearby Galaxies at APO (MaNGA) and UV data from GALEX can be used to check for possible spatial evidence of AGN feedback (Martin et al. 2005; Bundy et al. 2014; Gunn et al. 2006; Drory et al. 2015; Smeee et al. 2013).

Our objective is to study the impact of AGN activity on star formation using MaNGA and GALEX data. We created a sample of galaxies with SDSS optical spectral classification of "AGN" or "BROADLINE". We removed edge-on galaxies from our sample following a visual check of SDSS urz imaging data and selected only those galaxies with both MaNGA and GALEX data. There are 86 galaxies in the thus created sample. NGC 3982 is the nearest face-on galaxy in the sample and was selected for our pilot study, where we demonstrate the feasibility of our project in identifying the effect of AGN activity on star formation. NGC 3982 (UGC 6918), is a late-type galaxy at $z = 0.00371$. NGC 3982 is classified as a Seyfert 1.9 type galaxy based on optical spectra (Véron-Cetty & Véron 2010). Very-long-baseline interferometry (VLBI) observations of NGC 3982 in 1.7 and 5 GHz reveal that there could be jet/outflow structures in milliarcsecond scales (Bontempi et al. 2012). González-Delgado & Pérez (1993) noted the presence of circum-nuclear star formation in the galaxy. We note that 1 arcsecond in the sky corresponds to 0.076 kpc at 15.6 Mpc distance of the galaxy (Wright 2006).

The paper is organised as follows. Section 2 describes the MaNGA, GALEX, and supporting radio (VLLAS) data used for the study and the associated analysis. We discuss the possibility of AGN feedback in NGC 3982 and summarise in section 3.

We adopt a flat Universe cosmology with $H_0 = 71 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$ (Komatsu et al. 2009).

### 2. Data and analysis

MaNGA survey observed galaxies up to redshift $z \sim 0.03$. There are 10010 unique galaxies in the final MaNGA data release DR17 (Accetta et al. 2022). The reduced MaNGA data has a median angular resolution of 2.54 arcseconds (Law et al. 2016). A detailed description of the MaNGA sample design can be found in (Wake et al. 2017). NGC 3982 was observed with 127 fibre IFU with a size of 32 arcseconds diameter as part of the MaNGA survey (Manga-ID: 1-189584). A summary of a few observed and derived properties of the galaxy is given in Table 1. The SDSS urz colour image cutout of NGC 3982 with MaNGA IFU hexagonal aperture is shown in Fig. 1.

GALEX was a UV survey mission that had NUV (5.3 arcseconds FWHM) and FUV (4.2 arcseconds FWHM) channels (Morrissey et al. 2007). GALEX observed NGC 3982 in the NUV channel for an effective exposure time of $\sim 2200$ seconds (GALEX tile: GI6_012039_HRS74_75). We accessed the NUV imaging data from the MAST GALEX archive (no FUV data was available). The MaNGA resolution corresponds to 0.193 kpc, and the GALEX NUV resolution is 0.403 kpc at the galaxy’s distance.

We checked the nature and extent of AGN ionisation in the central region of NGC 3982 as described below. The MaNGA data-analysis pipeline (MaNGA DAP) generates secondary data products derived from MaNGA spectroscopy (Westfall et al. 2019). The stellar and emission-line kinematics are derived using Penalized Pixel-Fitting (PPXF) software by simultaneously fitting a modified MILES stellar library and Gaussian emission-line templates to the MaNGA spectra (the PPXF software employs a maximum penalized likelihood approach to fit templates to spectra) (Cappellari 2017; Westfall et al. 2019; Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011). MaNGA DAP products are accessible through Marvin software (Cherinka et al. 2019). MaNGA DAP generated maps of $H_b$, $H_\alpha$, [OIII] $\lambda5007$, [OII] $\lambda3727$, [NII] $\lambda6584$, and [SII] $\lambda6717, 31$ emission line intensities are used in our subsequent analysis. To
We used the GALEX NUV band image to find the spatial distribution of recent star formation. The GALEX NUV image pixels units are in counts per second (CPS), which we converted to flux using the Unit Conversion factor given in Morrissey et al. (2007):

$$F_{\text{NUV}} = 2.06 \times 10^{-16} \times \text{CPS}$$  \hspace{1cm} (1)

where $F_{\text{NUV}}$ is the NUV flux in erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The image in the CPS unit was subtracted for background before flux conversion. The NUV flux was corrected for Galactic extinction by adopting a Cardelli et al. (1989) law with $A_V = 0.0437$ (Schlegel et al. 1998) and $R_V = 3.1$. The dust present in NGC 3982 can attenuate the observed NUV band fluxes, leading to inaccurate interpretation. Therefore, we need to understand the spatial variation of dust attenuation levels, especially in the galaxy’s central regions.

We used the Balmer decrement, the ratio between two Hα and Hβ emission line flux values, to estimate the dust attenuation. We created the observed Balmer decrement map by calculating the ratio between observed Hα and Hβ emission line maps, $(H_\alpha/H_\beta)_{\text{obs}}$. Equation 4 from Domínguez et al. (2013) was then used to convert the Balmer decrement to a color excess map:

$$E(B-V) = 1.97 \log_{10} \left( \frac{(H_\alpha/H_\beta)_{\text{obs}}}{(H_\alpha/H_\beta)_{\text{int}}} \right)$$ \hspace{1cm} (2)

where $E(B-V)$ is the color excess map and $(H_\alpha/H_\beta)_{\text{int}}$ is the expected Balmer decrement map without dust attenuation. We used $(H_\alpha/H_\beta)_{\text{int}} = 3.1$ for spaxels falling inside the AGN region of Fig. 2  and 2.86 for the remaining (Groves et al. 2012). Finally, we converted the color excess map to an $A_{\text{NUV}}$ map (NUV band attenuation in magnitude) using a Calzetti attenuation law (Calzetti et al. 2000):

$$A_{\text{NUV}} = k_{\text{NUV}} \times E(B-V)$$ \hspace{1cm} (3)

where $k_{\text{NUV}}$ is the value on the Calzetti reddening curve evaluated at NUV effective wavelength (2315.7 Å). We found from the $A_{\text{NUV}}$ map (see Fig. 4) that both outer and central regions have comparable attenuation levels, with a median $A_{\text{NUV}}$ value of 2.04 in the central AGN ionised regions and 2.15 in the galaxy disk.

To correct attenuation by dust in NGC 3982, we used the $A_{\text{NUV}}$ map. The extinction and attenuation corrected NUV flux was calculated using:

$$F_{\text{NUV, corrected}} = F_{\text{NUV}} \times 10^{0.4(A_{\text{NUV, Galactic}} + A_{\text{NUV}})}$$ \hspace{1cm} (4)

where $F_{\text{NUV}}$ is the NUV flux, $A_{\text{NUV, Galactic}}$ is the Galactic extinction in the NUV band, and $F_{\text{NUV, corrected}}$ is the extinction and attenuation corrected NUV flux. The $A_{\text{NUV}}$ map created from the MANGA data only covers the footprint shown in Fig. 1 which we need to extrapolate to the full galaxy to get the integrated extinction. Therefore, we used the median value of the $A_{\text{NUV}}$ map for the full extent of the NUV image of the galaxy. We note that this estimate should be considered a lower limit and suggests that the flux could be attenuated at least by a factor of 7.2.

The NUV band luminosity, $L_{\text{NUV}}$, was calculated using:

$$L_{\text{NUV}} = 4\pi D^2 F_{\text{NUV, corrected}}$$ \hspace{1cm} (5)

where $D$ is the distance (see Table 1) and $F_{\text{NUV, corrected}}$ is the attenuation corrected flux. $L_{\text{NUV}}$ is in erg s$^{-1}$. The NUV luminosity is converted to star formation rate (SFR), assuming a constant star formation for 10$^8$ yr. Equation 4 from Cortese et al. (2008) was used to derive the SFR from $L_{\text{NUV}}$:

$$\text{SFR (M}_\odot\text{yr}^{-1}) = \frac{L_{\text{NUV}}}{3.83 \times 10^{33}} \times 10^{-9.33}$$ \hspace{1cm} (6)

Fig. 2. BPT diagram for NGC 3982 showing [O III]/H$_\beta$ vs [N II]/H$_\beta$, vs [S II]/H$_\beta$, vs [O I]/H$_\beta$, plots. Left: MaNGA spaxels have been classified into star-forming (SF), AGN, Composite (AGN + SF), and Ambiguous categories. Middle & Right: MaNGA spaxels categorised as SF, Seyfert, and LINER.

Fig. 3. Spaxel BPT diagram classification of Fig. 2. The figure origin coincides with the galaxy centre. North is up and East is towards the left. The angular offsets from the origin are given in the top and right axes. The angular offsets have been converted to kpc scale at the bottom and left axes. Star-forming (cyan), Composite (green), Ambiguous (grey), and AGN (red) categories are shown.

make a spaxel map of the gas excitation mechanisms present, we created a Baldwin, Phillips & Terlevich (BPT) diagram for NGC 3982 using the get_bpt function of Marvin (Baldwin et al. 1981). Marvin uses the classification system of Kewley et al. (2006) and uses all three diagnostic criteria from [O III]/H$_\beta$ vs [N II]/H$_\beta$, vs [S II]/H$_\beta$, vs [O I]/H$_\beta$, plots. It labels MaNGA spaxels as star-forming (SF), AGN, and Composite (AGN + SF). The function marks spaxels as ambiguous when it fails to classify them into previously mentioned categories. Seyfert galaxy (Seyfert) and low-ionisation narrow emission-line region (LINER) classification are also carried out. A detailed explanation of the function can be found on the Marvin documentation website. The generated BPT diagram is shown in Fig. 2 and the on-sky map of spaxel classification in Fig. 3.

https://sdss-marvin.readthedocs.io/en/latest/tools/bpt.html
Fig. [5] shows the NUV-derived SFR surface map of the galaxy. A boundary contour encompassing Composite and AGN regions from Fig. [3] is overlaid over the figure. Also shown in the figure is the hexagonal aperture footprint of MaNGA IFU. The cavity region in the centre matches the composite and AGN photoionised region. We estimated the median SFR density observed in the cavity and the ring-shaped region; there is a factor of ∼2 reduction in SFR density of the cavity region compared to the ring-shaped region.

To check whether the lack of a full disk attenuation map of the galaxy affects our interpretation of the observed cavity region in the centre, we created an azimuthally averaged flux profile of the galaxy using the NUV image as follows. The axis ratio and position angle of NGC 3982 were found on the NED website. Multiple elliptical apertures were defined centred on NGC 3982 with an axis ratio of 0.901 and a position angle of 14.5°, each separated by 1.5 arcseconds along the minor axis. The apertures were placed up to ∼0.4 arcminutes (2 kpc), and NUV fluxes were estimated. Then the differences between the aperture fluxes were found to get the annuli fluxes. Finally, annuli average fluxes were used by dividing by the annuli area. Annuli average flux is plotted as a function of distance from the centre of NGC 3982 (see Fig. 5). Similarly, elliptical apertures were used on the A_NUV map to estimate the annuli average attenuation levels. The annuli average attenuation levels were used to correct the annular average flux values. Attenuation corrected annuli average fluxes are also plotted in Fig. 6. Note that the A_NUV map only covers the central region of the NUV image. Therefore, we can correct NUV fluxes for attenuation up to ∼0.2 arcminutes. We stress that attenuation does not affect the NUV profile of the galaxy’s central region, as demonstrated in Fig. 6.

We used the Very Large Array Sky Survey (VLASS) radio sky survey data with an angular resolution of ∼2.5 arcseconds (Lacy et al. 2020) to probe AGN activity in NGC 3982. We accessed the Quick Look images from the VLASS archive. The VLASS contours are overlaid on the NUV image in Fig. 5. The contours show an elongated structure directed Southeast to Northwest. Interestingly, VLBI observations of NGC 3982 in 1.7 and 5 GHz using the European VLBI Network (EVN) reveal that there could be jet/outflow structures in milliarcsecond scales (Bontempi et al. 2012). The VLBI detected features are also oriented in a Southeast-northwest direction.

[O III] is a forbidden optical emission line highly excited by strong ionising sources like AGN than star-forming regions. Spatially resolved [O III] flux and kinematics maps have been used in AGN feedback studies to trace ionised gas outflows (for example: Shin et al. 2019; Ruschel-Dutra et al. 2021) The [O III] velocity dispersion in AGN host galaxies is mostly due to AGN activity (Kashit & Woolf 2018; Woo et al. 2016). The MaNGA DAP maps of the [O III] flux and [O III] ionised gas velocity dispersion are shown in Fig. 6. The velocity dispersion has been corrected for instrumental dispersion.

3. Discussion and Summary
The NUV band directly traces stars formed over the last 200 Myr and, therefore, probes recent star formation (Kennicutt Jr & Evans 2012). The GALEX NUV derived profile of SFR surface density shows recent star formation in a ring-like region around the centre of NGC 3982 (see Fig. 5). We also created an interactive 3D visualisation of the SFR surface density profile. A snapshot from the interactive plot is shown in Fig. 7. It appears that star formation is suppressed in the central region of NGC 3982.

The intrinsic UV flux from star-forming regions can be modified due to dust attenuation. Even if the central region has the same levels of intrinsic NUV emission as the ring-like region, a large attenuation in the central region can produce the presently observed NUV profile. However, the A_NUV map shown in Fig. 6 has comparable dust attenuation levels in the central and outer regions, with a median A_NUV value of 2.04 in the central AGN ionised regions and 2.15 in the galaxy disk. We do not see large attenuation levels in the central region. Also, the F_NUV profile of the galaxy closely matches the F_NUV profile (see Fig. 6). Therefore, dust attenuation of NUV flux in the galaxy cannot explain the cavity.

The observed suppression of star formation should be a real feature, not an artefact of attenuation. This suggests that processes in the central region prevent star formation in the last 200 Myr. The observed NUV cavity is approximately shaped like an elongated ellipse. We estimated that it has major and minor axes lengths of ∼17 and ∼8 arcseconds, respectively (∼1.3/0.6 kpc). The two distinct observational features that require explanation are the ring-like star-forming and star formation suppressed central regions.

The first possible explanation we consider is the presence of a bar. Bars are observed to induce star formation along the co-rotation radius and suppress star formation inside it (George et al. 2020). If present, a bar may produce the observed NUV profile in the galaxy. However, Regan & Mulchaey (1999) studied the central region of NGC 3982 using HST and ruled out the presence of a bar.

The visualisation is hosted at https://prajwel.github.io/NGC3982/
The presence of even a weak bar. NGC 3982 hosts an AGN, and the cavity region is covered by composite and AGN emissions. The boundary contour encompassing Composite and AGN regions overlaid in Fig. [5] shows the extent of AGN ionisation in the galaxy estimated using a BPT diagram. AGNs are known to suppress star formation and can also be associated with positive feedback. Therefore, the likely mechanism for star formation suppression in NGC 3982 is a jet/outflow associated with the AGN activity.

The radio observations and [O III] flux and velocity dispersion maps provide clues regarding the AGN activity. The VLASS2.1 observations reveal an extended structure with elongation along the Southeast-Northwest direction (see Fig. [5]). While the [O III] flux map shows a symmetrically distributed high emission at the central region, the velocity dispersion map shows signs of perturbations in the gas (see Fig. [5]). The perturbations are most prominently observed in the Southeast (~130 km s^{-1}) and Northeast (~120 km s^{-1}) regions. The Southeast perturbed gas is aligned to the elongated VLASS radio structure, and the Northeast perturbed gas runs parallel. These observations clearly show that the ionised gas is perturbed in the AGN-dominated region and that such perturbation may be driven by an AGN jet/outflow. Brum et al. (2017) also noted that a mild nuclear outflow could be present in the galaxy by analysing the ionised gas kinematics. But compared to other local galaxies hosting outflows, ionised gas outflow signatures in NGC 3982 are not prominent (Ruschel-Dutra et al. 2021).

The AGN hosted in NGC 3982 is classified as Seyfert 1.9 and likely belongs to the radiative-mode AGN population. Therefore, the galaxy may have an outflow driven by radiation. Note that the AGN X-ray luminosity is ~5 orders of magnitude more than the radio luminosity (see Table 1). Nevertheless, the AGN luminosities in different bands may vary within a short time span (for example, 3C 273; Soldi et al. 2008). A jet may produce outflows with features similar to that generated by radiation (Cielo et al. 2018). Regardless of the nature of the AGN activity, NGC 3982 is perhaps one of the best examples of a nearby low-mass AGN affecting star formation in the disk.

It is interesting to compare the NGC 3982 case with other observations of AGN feedback. Although the activity is presently not detectable, the AGN in NGC 7252 could have been active until recently (Schweizer et al. 2013) and suppressed star formation in the central region of the galaxy (George et al. 2018). In NGC 5728, a ~1 kpc radius star-forming ring with a cavity is observed, and AGN outflow is found to be responsible (Shin et al. 2019). Surprisingly, ring-like star formation is also observed in NGC 7252 and NGC 3982 at a radius of ~1 kpc from the centre. While all three galaxies may host a ~1 kpc radius ring-like star-forming region attributed to AGN feedback, they differ in galaxy morphology and AGN activity.

Based on a multi-wavelength analysis, we present evidence for star formation suppression in the central region of the Seyfert galaxy NGC 3982. As revealed from line diagnostic analysis, the galaxy’s central region with reduced star formation is dominated by AGN-composite emission. This is further supported by the indications of AGN jet/outflow revealed from radio and gas velocity dispersion map analysis. The most plausible explanation for the observed scenario presented here is suppression of star formation in the central regions due to feedback from a recent AGN activity.

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Fig. 7. A snapshot from the interactive 3D visualisation of SFR surface density profile of NGC 3982. The visualisation is hosted at https://prajwel.github.io/NGC3982/.

Fig. 8. MaNGA derived maps of [O III] emission line intensity and [O III] traced ionised gas velocity dispersion. VLASS2.1 radio contours with contour levels 0.0007, 0.0012, 0.0018, 0.0024 Jy/beam and a beamwidth of $\sim$2.5 arcseconds are overlaid on the second panel in black dashed lines.
