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The role of astrophysical jets in active galactic nuclei feedback

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The role of astrophysical jets in active galactic nuclei feedback

Abstract

This paper is a literature review of the current research on the role of jets in active galactic nulcei feedback. It looks at theories, simulations and observations to discuss the mechanism behind jet-driven star formation and its quenching. In negative feedback, jet cocoons expand and cause shocks in interstellar medium, disrupting cooling flows and expelling gas required for star formation. The paper highlights NGC2639 as a case study that provides observational data backing up the theory. Radio lobes, a signature of jet activity, is seen in NGC2639. Lower than typical star formation rates coupled with a deficiency in molecular gas and optical and ultraviolet radiation in the galaxy's central region hints at negative feedback. Simulations for jet-driven positive feedback suggest that lobes formed by jets compress the surrounding gas, inducing collapse. Bow shocks generated also lead to star formation. Multiwavelength observations of NGC5128 unveil lobes and clusters of young stars. Moreover, observations of filaments, arcs and radio as well as x-ray knots in the galaxy support the theory of a shock-driven mechanism for positive feedback. The paper also introduces jet energy composition and discusses the effectiveness of quenching star formation when the composition varies for kinetic, thermal and cosmic-ray dominated jets. It finds that simulations do not agree on the exact mechanism although cosmic-ray jets are likely to be more effective. Finally, the paper looks into future observational prospects, introducing how new telescopes such as Lynx, Athena and Cherenkov Telescope Array as well as new data from the existing Atacama Large Millimeter Array would further research. It is expected that better observational data would allow the investigation of feedback over time, cooling flows and jet properties, deepening understanding in jet-induced active galactic nuclei feedback.

(285 words)

List of abbreviations

AGN	Active Galactic Nuclei
ALMA	Atacama Large Millimeter Array
CARMA	Combined Array for Millimeter-wave Astronomy
CTA	Cherenkov Telescope Array
EVLA	Expanded Very Large Array
EDGE	Extragalactic Database for Galaxy Evolution
GALEX	Galaxy Evolution Explorer
HLLC	Harten-Lax-van Leer-Contact
HST	Hubble Space Telescope
HVS	Hypervelocity Stars
ISM	Interstellar Medium
MUSE	Multi Unit Spectroscopic Explorer
NIL	Northern Inner Lobe
NML	Northern Middle Lobe
NSR	Northern Star-forming Region
RLQ	Radio-loud quasars
RQQ	Radio-quiet quasars
SFR	Star Formation Rates
SZ	Sunyaev-Zeldovich
uGMRT	Giant Meterwave Radio Telescope
UV	Ultraviolet
UVIT	Ultra-Violet Imaging Telescope

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1 Introduction

1.1 Background

Astrophysical jets are collimated streams of ionized gas and plasma that emanate from active galactic nuclei (AGN). Research has shown that jets can quench star formation in galaxies, causing negative feedback. In more recent times, it is also noted that jets can drive positive feedback as well, leading to star formation.

Studying AGN feedback is important to understand the evolution of galaxies and produce realistic galaxy populations in cosmological simulations. Technological advancements in observational prospects and recent progress in simulations provides an opportunity to deepen understanding in jet-driven feedback.

1.2 Scope of work

This literature review explores the role of jets in AGN feedback mechanism. It discusses observational evidence in NGC2639 and NGC5128 as case studies. The paper also introduces simulations on how jet energy compositions affect feedback, focusing on negative feedback since it sees a direct impact from jet composition. (Current simulations for positive feedback do not explore this since the mechanism for jet-feedback is more indirect). Future observational prospects that would shed light on open questions in the research is highlighted.

1.3 Objectives

1. Discuss positive and negative jet-driven AGN feedback
2. Introduce jet energy composition's effect on star formation
3. Present and discuss jet activity and negative feedback in NGC2639
4. Present and discuss jet activity and positive feedback in NGC5128
5. Introduce future observational prospects on the role of jets in AGN feedback

1.4 Methodology

To obtain relevant papers, specific searches were used to retrieve information from databases such as NASA ADS, Arxiv, and Google Scholar. Citations and 'Connected Papers' were leveraged to expand on research material.

Papers were selected using PROMPT. The main ideas were from papers that were less than 3 years old, although theoretical foundation could be built on older papers. Observational data was cross-checked to ensure it was the latest and emphasis is placed on newer papers when evaluating findings.

2 Role of jets in positive and negative AGN feedback

2.1 Jet interaction with the environment

Jets channel energy away from an AGN as it propagates into the surrounding interstellar medium (ISM), transferring energy to gas upon interaction with it. Hot spots form where the jet broadens and appears to end with a collision with the ISM. These hot spots are high pressure regions which expand to form radio lobes and create a cocoon of plasma (Bourne & Sijacki, 2017). Since the radio lobes are strongly over-pressured, a shock wave is driven through the ISM and as long as the radio lobes continue to be over-pressured, they would cause a bow shock which dissipates heat into the surrounding gas. (Figure 2.1) (Krause, 2023).

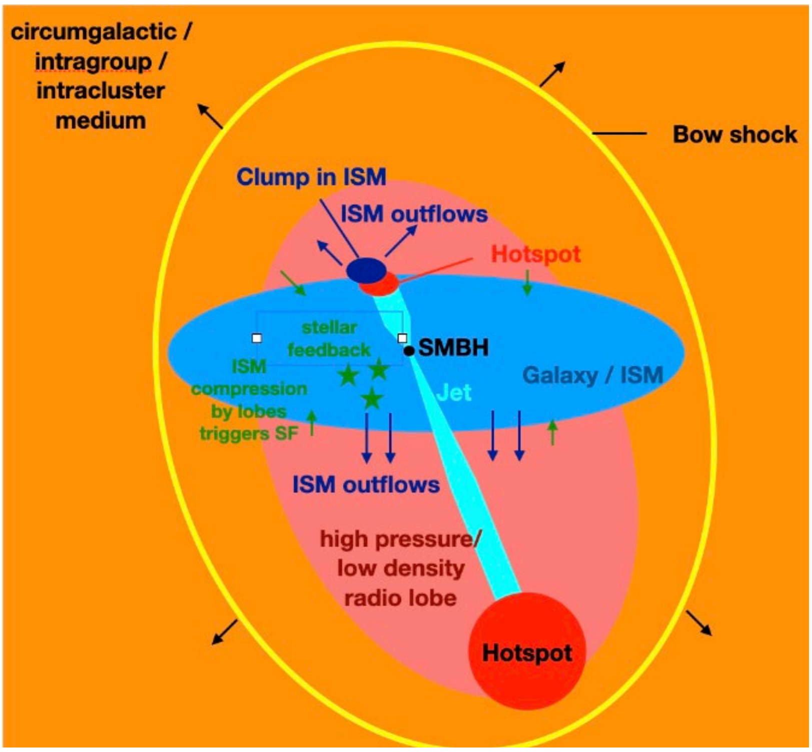

Figure 2.1 Jets produced from a supermassive black hole, impacting interstellar medium and forming radio lobes, hotspots and a bow shock. (Krause, 2023)

It is suggested that whether a jet-driven feedback is positive or negative is determined by galaxy mass, jet power threshold (Kalfountzou *et al.*, 2017) and the maximum column density of clouds the jet encounters. Small clouds are easily dispersed by the jet, leading to a lack of gas required for star formation while larger clouds are difficult to eject and prone to collapse leading to positive feedback. (Wagner *et al.*, 2016)

Moreover, both positive and negative feedback can occur in the same galaxy simultaneously. Cresci *et al.*, (2023) presents observational evidence for negative feedback along the axis of the jet outflow but positive feedback along the edges due to over-pressured radio lobes for XID2028.

2.2 Positive AGN feedback

It has been suggested by both theory (Silk *et al*. 2012) and simulations (Gaibler *et al*. 2012) that jets can trigger star formation. Jets can create high-density and low temperature cavities, creating an ideal environment for star formation (Kalfountzou *et al.*, 2017). Radio lobes compress the dense clouds and protogalactic clouds above the Bonnor-Ebert mass (the maximum mass for an isothermal gas sphere in a pressurized medium which still maintains hydrostatic equilibrium) will be induced to collapse. Thus this forms protostars and drives positive feedback. Moreover, as jet cocoons expand and compress cold gas, the bow shocks generated can also result in gas collapse, leading to star formation. (Silk and Norman, 2009).

In addition, it has been suggested that positive feedback explains several phenomenon such as the mystery of hypervelocity stars (HVS) and the alignment effect. HVSs are rare stars with extreme radial velocities that have been discovered in the Galactic halo and are believed to be launched by jets (Silk *et al.*, 2012). Simulations by Dugan *et al*. (2014) reproduces this with jet bow shocks generating high-velocity pockets of star formation. As for the alignment effect, it has been observed that radio, ultraviolet (UV) and optical emissions are aligned along the same axis and a possible reason for this is that young massive stars are formed, emitting UV and optical light, due to jets which are an expanding radio source. (Kalfountzou *et al.*, 2017)

Observational evidence also lends support to the positive AGN feedback model. Radio data shows evidence for the alignment effect (Lambert *et al.*, 2021). In Kalfountzou *et al.* (2017), far-infrared Herschel observations of quasars find an excess of star formation rates (SFRs) by a factor of 1.4 in radio-loud quasars (RLQs) compared to radio-quiet quasars (RQQs) (Figure 2.2). This is attributed to jets triggering star formation.

[redacted]

Figure 2.2. SFR excess between RLQs and RQQs as a function of bolometric luminosity (Kalfountzou *et al.*, 2017)

IMAGE REDACTED FOR COPYRIGHT REASONS

2.3 Negative AGN feedback

For negative feedback, the propagation of the jet through the ISM causes kinetic energy from the jet to thermalise through shocks. This heats up and ionizes the gas it collides with, preventing collapse under self-gravity. (Dugan *et al.,* 2014) Simulations by Li *et al.*, (2017) and Martizzi *et al*. (2019) reproduced this. Furthermore, jets can directly eject gas in the galaxy and prevent the accretion of new gas onto it, removing a key component for star formation. (Fabian, 2012). It has also been suggested that magnetic fields carried by the jet lead to additional pressure, preventing cooling flows that could otherwise create an environment for star formation (Beck *et al.,* 2012).

Negative feedback is a potential solution for the 'cooling flow problem' whereby x-ray data shows radiative cooling in galaxies and clusters (Stern *et al*. 2019) but HI and CO observations of cold gas are insufficient and SFRs are too low to account for the inferred cooling flow. Hence, a heat source is required to compensate for the cooling flow while maintaining the structure observed in the galaxies. Theoretical models suggest that jets provide the required heat source and account for the low SFR (Su *et al*., 2021).

On the observational front, x-ray images revealed space between cavities and emission from radio lobes, hinting at jets displacing the hot gas in between. (Morganti, 2017) Furthermore, Chandra images reveal shock waves and the energy flux in the waves is comparable to that required to offset cooling, showing evidence for negative feedback resolving cooling flow problems (Fabian, 2012)

2.4 Discussion

It is crucial to note that while positive feedback might explain HVSs, there are many alternative theories as well. For HVSs, this includes stellar clusters colliding, supernova explosions and triple stars having instable orbits (Tutukov, Dryomova and Dryomov, 2021). Dugan *et al*., 2014 argues that HVS orbits seem to originate from the Milky Way centre, refuting the possibility of supernovae as the cause. It is, however, possible that HVS have multiple origins and in order to prove that gas expelled from AGNs is one of them, HVSs is expected to be in discrete clumps with common velocities (Brown, 2015). Future better observational data is required to shed light on this.

When attributing higher SFRs to jet feedback, sufficient analysis needs to be made if it can be attributed to other factors. In Kalfountzou *et al*. (2017), it describes that in its sample of quasars, merger activity is common and probably explains RQQs' SFRs and could also contribute to higher SFRs in RLQs. Several papers (Joseph *et al.,* 2022; Chiaberge *et al*., 2015) mention links between AGN jets and merging events, thus, the consideration of mergers on SFRs is important to examine and differentiate from jet feedback.

For negative feedback, the cooling flow problem remains an open question and alternative solutions include Type Ia supernova injecting cosmic rays (Lacchin, Calura and Vesperini, 2021), magnetic fields in galaxies (Beck *et al*.,2012) and stellar heating (Conroy *et al*. 2015). Su *et al*., (2019) show that these processes suppress star formation but are unable to quench SFRs sufficiently to agree with observations. Hence, jet-driven negative feedback remains a promising solution given that many simulations

(Weinberger *et al*. 2023; Guo, Duan and Yuan, 2018) reproduce this easily and the discussed observational evidence lends credibility to the theory.

3 Jet energy composition affecting star formation

3.1 Criteria for negative feedback

In order to quench star formation, cooling flows in the galaxy have to be stopped so that the gas does not collapse into stars. In Su *et al*. (2021), it describes a few criteria that must be met to achieve this.

Firstly, the jet energy flux must be sufficient to overcome gas cooling flows and yet not large enough to exceed the escape velocity at the cooling radius. The cooling radius, is defined as the radius within which the cooling time is shorter than the simulation time of 1-2 Gyr. The cooling time of an optically-thin plasma is the gas enthalpy divided by the energy lost per unit volume of the plasma (Peterson & Fabian, 2006). Secondly, the cooling time within the jet cocoon has to be sufficiently long to ensure that energy from the jet remains in the cocoon until it reaches the cooling radius. Lastly, the radius of the cocoon, R_{cocoon}, has to be adequately wide to suppress cooling flows over a large volume. (Figure 3.1) (Su *et al*.,2021)

[redacted]

Figure 3.1 AGN jet suppressing cooling flows where the cocoon height , z_{cocoon} , cocoon radius, R_{cocoon} , and the cooling radius, R_{cool} , are depicted (Su et al.,2021)

IMAGE REDACTED FOR COPYRIGHT REASONS

3.2 Jet energy composition

Some of the simulations classify the energy composition of the jets as kinetic, thermal and cosmic-ray dominated depending on which type makes up the highest fraction of the energy. Su *et al.*(2021) finds that cosmic-ray dominated (CR) jets are the most efficient at inhibiting cooling flows in galaxies, followed by thermal jets and lastly kinetic jets (Figure 3.2).

.

[redacted]

Figure 3.2 The SFR as a function of time. The legend shows parameters that are varied as well as the no jet scenario. The grey areas at the bottom indicates an SFR below $\sim$ 5M yr^{-1} while darker grey is $\sim$ 1Myr^{-1} (Su *et al.,* 2021) ***IMAGE REDACTED FOR COPYRIGHT REASONS***

It also states that the opening-angle of a cocoon is related to energy flux as follows for a fixed propagation height , z_{cocoon} :

$$\frac{R_{cocoon}}{z_{cocoon}} \propto \left(\frac{\dot{E}_{tot,\mathrm{J}}}{\dot{E}_{kin}}\right)^{\frac{3}{4}}$$

where $\dot{E}_{tot,\mathrm{J}}$: total energy flux
$\dot{E}_{kin}$: kinetic energy flux
(See Figure 3.1)

Hence, the larger the kinetic energy flux, the smaller the radius to height ratio. Thus, kinetic jets tend to create narrow cocoons which are not ideal. They transfer energy far from the blackhole in a narrow solid angle since they have a high initial velocity. In comparison, thermal jets with the same energy flux would have a wider cocoon and are more effective in heating. CR jets are the most effective in fulfilling the criteria for negative feedback. CRs transfer energy to the surrounding gas, resulting in longer cooling times and a cocoon that is dominated by CR pressure. (Su *et al.*, 2021) Moreover, the CR jet cocoon also has a larger width given its larger energy density (Yang *et al.,* 2019). CR jets modify the behaviour of cooling gas as well. Instead of thermal pressure dictating its flow, pressure support from CR jets contributes to total pressure equilibrium, resulting in diffuse cooling gas that does not accrete despite being thermally-unstable. (Butsky *et al.*, 2020)

3.3 Discussion

Unlike Su *et al*. (2021), Li and Bryan (2014)'s and Meece *et al*. (2017)'s models show that varying the fraction of kinetic energy and thermal energy in a jet does not significantly affect the jet's ability to quench. This is in tension with Martizzi *et al*. (2019) which showed that a mixed jet is unable to stop cooling flows.

One difference could be due to the fact that Li and Bryan (2014)'s model has a self-regulation mechanism. Hence, jet energies are not fixed and when a jet type is inefficient at quenching, the energy flux and accretion rate would rise to drive the model towards suppressing cooling flows (Su *et al*., 2021).

Another reason suggested by Martizzi *et al*. (2019) is that the results are very sensitive to the type of Riemann solver used which can affect the jet and lobe evolution. Li & Bryan's (2014) and Meece *et al*.'s (2017) setup used the zeus solver. Martizzi *et al*. (2017) uses Harten-Lax-van Leer-Contact (HLLC) Reimann solver while Su *et al*. (2021) uses MHD solver. HLLC is better able to capture discontinuities and are less affected by inaccurate thermalization of kinetic energy (Sharma *et al*. 2012).

Martizzi *et al*. (2019) further proves the sensitivity of the results to numerical setups by showing that at low resolutions of 1.5kpc, the kinetic jet and mixed thermal and kinetic jet feedback converges to similar values but diverges at higher resolution (Figure 3.3).

[redacted]

Figure 3.3 Comparison of purely kinetic vs. mixed feedback at different resolutions. LR and HR stand for low resolution and high resolution respectively. Left: total inward mass flux at 20 kpc against time Right: deposition rate of cold gas within 20 kpc. (Martizzi *et al.,* 2019) ***IMAGE REDACTED FOR COPYRIGHT REASONS***

The exact mechanism for jet types and feedback is still uncertain and simulation results need to be viewed in light of the context of the models' parameters since the caveats are just as important as the results. Obtaining more observational data would be better able to constraint these models (Bourne and Yang, 2023).

4 NGC2639 jet activity & positive feedback

4.1 Jet episodes

NGC2639 shows evidence for multiple episodes of jet activity stopping and restarting. Radio observations from Expanded Very Large Array (EVLA) and Giant Meterwave Radio Telescope (uGMRT) reveal four pairs of lobes in the galaxy which are misaligned with each other, hinting at four separates jet episodes (Figure 4.1)(Sebastian *et al.*, 2019). Spectral ageing analysis indicates that the jet episodes were 9-22 Myr apart. (Rao *et al.*, 2023)

[redacted]

Figure 4.1. NGC2639's four jet episodes. Clockwise from left: ~9kpc radio lobes, ~1.5kpc radio jets, ~360 parsec lobes and ~3 parsec radio jets. (Rao *et al.,* 2023) ***IMAGE REDACTED FOR COPYRIGHT REASONS***

4.2 Radio observations

The Combined Array for Millimeter-wave Astronomy Extragalactic Database for Galaxy Evolution (CARMA-EDGE) survey presents radio observations of CO molecular gas measurements for 126 galaxies, one of which being NGC2639. (Bolatto *et al.* 2017) It revealed that gas fractions for the central region is typically two times lower than in star-forming areas, suggesting that the AGN consumes gas from the central area. (Ellison *et al.*, 2021).

In NGC2639, the depletion of gas is more than typical compared to the sample in the survey. Figure 4.2 shows the intensity of the CO molecular gas in the galaxy and a deficit in the central ~6kpc of the galaxy is revealed. Mapping velocity-dispersions from the CARMA-EDGE survey also reveals higher velocity-dispersion values of ~100km s^{-1} around the jet edges, hinting that the gas ring is caused by the thrust of the jet, impacting the gas around it (Rao *et al.*, 2023). Assuming that the ISM has temperature $T \sim 20K$ and density, $n > 10^3 cm^{-3}$ (Brinks, 1990), pressure can be derived using $P = nk_BT$ where k_B is the Boltzmann constant. Hence, given the gas ring radius of 3kpc, the volume of the cavity can be estimated and the work done on the gas is estimated to have a value of PV (pressure times volume) given by 3.44×10^{54} erg. Although each episode have enough power to displace the gas, to obtain the gas ring in NGC2639, multiple jet episodes in different orientations are required (Rao *et al.*, 2023). The observation of multiple lobes supports this.

[redacted]

Figure 4.2. CARMA-EDGE survey's CO molecular gas emissions and radio contours from uGMRT in NGC2639 reveals a lack of CO gas in the central ~6kpc region. (Rao *et al.*, 2023) ***IMAGE REDACTED FOR COPYRIGHT REASONS***

4.3 UV emission

The Galaxy Evolution Explorer (GALEX) observes galaxies in UV light and investigates recent star formation over the last 200 Myr. It revealed that for NGC2639, the central ~6kpc of the galaxy sees a deficiency in far-UV and near-UV emission, lending evidence to the quenching of star formation in the galaxy (Figure 4.3) (Rao *et al.*, 2023).

[redacted]

Figure 4.3 GALEX image and radio contours from uGMRT reveals that the central ~6 kpc shows a deficiency of near-UV emission (Rao *et al.,* 2023*)* ***IMAGE REDACTED FOR COPYRIGHT REASONS***

4.4 Star formation rates

The Schmidt law for star-forming galaxies shows a correlation between SFR surface density, Σ_{SFR}, and gas surface density, Σ_{gas} since stars are formed from gas collapse (Kennicutt, 1998). Using Raluy *et al.* (1998)'s Σ_{gas} data obtained from the Institute for Radio Astronomy in the Millimeter Range , Σ_{SFR} for NGC2639 is derived to be $0.0177\ \mathrm{M_{\odot}\ yr^{-1}kpc^{-1}}$. However, using different telescopes, estimates for SFR (Table 4.1) is lower than the calculated value by a factor of 5-18 , suggesting that SFR has been supressed. (Rao *et al.*, 2023)

[redacted]

Table 4.1 Estimates of SFR and Σ_{SFR} for NGC2639 (Rao *et al.,* 2023*)* ***IMAGE REDACTED FOR COPYRIGHT REASONS***

4.5 Discussion

Rao *et al.* (2023) shows strong evidence for jet-driven negative feedback in NGC2639 given that the radio observations of lobes, molecular gas analysis, UV emissions and SFR all point to star-formation quenching in the central region of the galaxy and the multiple jet episodes provide a plausible cause of the formation of the CO gas ring.

Evidence for jet activity is further supported by Sebastian *et al.* (2020) which discusses radio emission from a sample of Seyfert galaxies that includes NGC2639. The paper uses the radio and far-infrared correlation (Condon, 1991) to check for excess radio emission in starburst and Seyfert galaxies. It showed that that radio-excess is observed for Seyfert galaxies but not for starburst galaxies which do not host an AGN. Thus, radio-excess in Seyfert galaxies such as NGC2639 was attributed to radio jet activity.

Schoenmakers *et al.* (2000) states that double-double galaxies are signatures of recurrent AGN activity. A double-double galaxy is one which has a pair of lobes in both the inner and outer structure. Since NGC2639 is a double-double galaxy, this corroborates Rao *et al.* (2023)'s findings on the multiple jet episodes. Comparing NGC2639 to a similar galaxy such as J23450449 with large kpc-scale radio jets, Nesvadba *et al.* (2021) also detected a CO molecular gas ring which is very similar to that of NGC2639's, indicating that quenching in the central region due to jet feedback is not an isolated case.

5 NGC5128 jet activity & positive feedback

5.1 Features in NGC5128

At the heart of NGC5128 lies a supermassive blackhole that ejects a relativistic jet which has been capture by Tanami and the Event Horizon Telescope (EHT) (Figure 5.1) (Janssen *et al.*, 2021).

[redacted]

Figure 5.1 Distance scales of NGC5128, revealing outer lobes and the jet as captured on Tanami and EHT (Anderson N., 2021) ***IMAGE REDACTED FOR COPYRIGHT REASONS***

With reference to Figure 5.2 and 5.3, NGC5128 consists of radio lobes, namely the southern outer lobe, northern outer lobe, northern middle lobe (NML) and northern inner lobe (NIL). Since star formation occurs in the north, focus would be placed on this region often called the northern star forming region (NSR). Young star clusters are observed in UV bright filaments. The inner filament and outer filament are 8kpc and 15kpc from the galaxy center respectively. (Joseph *et al.*, 2022) X-ray knots and radio knots are observed in the NML as well as a HI cloud (McKinley *et al.*, 2022).

[redacted]

Figure 5.2 Radio features seen in NGC5128 using Murchison Widefield Array (McKinley *et al.*, 2022)
IMAGE REDACTED FOR COPYRIGHT REASONS

[redacted]

Figure 5.3 A consolidation of features seen using optical, UV, radio and x-ray frequencies for NSR of NGC5128 (McKinley *et al.*, 2022) ***IMAGE REDACTED FOR COPYRIGHT REASONS***

5.1.1 Stars & diffuse uv/optical emission

The Ultra-Violet Imaging Telescope (UVIT) shows both diffuse and point-like UV sources lying in the filaments, with most of them being in the outer filament. A double-structure is observed where a continuous distribution of UV sources is disrupted by a gap that separates it into two regions. Double-structures are often attributed to jet activity which is thought to have split the distribution of UV sources. (Joseph *et al*. 2022) Many of the point-like sources are young stars which have also been detected in the optical range by GALEX (Crockett *et al*. 2012)

In the inner filament, Joseph *et al*. (2022) identified new sites of young stars. The alignment of the sites with the NIL is seen in Figure 5.4 and hints at jet-driven positive feedback. The diffuse emission is attributed to heated gas from shocks.

[redacted]

Figure 5.4 UVIT image of diffuse emission in site A, star forming sites B and C and radio contours of the lobes of NIL (Joseph *et al.*, 2022) ***IMAGE REDACTED FOR COPYRIGHT REASONS***

At the southwestern tip of the inner filament, a dense population of blue objects are found by the Hubble Space Telescope (HST). Strong line emissions are also detected in the same region, suggesting that young star clusters exist at this site. (Crockett *et al.*, 2012)

5.1.2 Filaments and arcs

Star formation is often observed in optical filaments which are, therefore, frequently interpreted as evidence for positive feedback. Signs of jet-ISM interaction is evident in the outer filament and nearby HI cloud. Gas kinematics was studied by Santoro *et al.* (2015) using Multi Unit Spectroscopic Explorer (MUSE). It concluded that ionized gas found in the outer filament is part of the HI cloud structure that was strongly affected by the jet. Young stars detected between the ionized and neutral gas supports positive feedback.

MUSE also detected optical arcs. The arcs in the outer region resemble structures produced in simulations of expanding jet cocoons. (McKinley *et al.*, 2021). In the inner filament, MUSE reveals clumpy structures aligned with the jet axis. The width of the broad-line emission around the clumps is consistent with that expected from shocks and one of the gas in the clumps has line ratios consistent with that from star formation (Figure 5.5) (Hamer *et al.*, 2015).

[redacted]

Figure 5.5 Left: Hα flux map reveals clumpy structure of the inner filament. Centre left: Hα flux map after subtracting the clumps to reveal arcs. Centre right: Velocity map of Hα – NII complex. Right: Hα emission shows broadened linewidth at edges of clumps, suggesting gas shock. (Hamer *et al.*, 2015)

IMAGE REDACTED FOR COPYRIGHT REASONS

5.1.3 X-ray and radio knots

McKinley *et al.* (2021) also suggested that the origin of the observed x-ray knots by XMM-Newton is due to bow shocks resulting in the heating of clouds to x-ray temperatures which were later ablated. Radio knots traced out by MWA is anti-coincident with the x-ray knots and could be a result of electron interactions with magnetic fields and acceleration from the shocks. Since these knots are likely to vanish within a few Myr without a constant energy supply, it is suggested that the jet powers them (Joseph *et al.*, 2022).

5.2 Jet path

A possible jet path through the NML is proposed by Joseph *et al.* (2022) where the double-structure is split and NSR sources are absent in a 1 kpc gap (Figure 5.6) This is further supported by Atacama Large Millimeter Array (ALMA) observations which sho the region being devoid of clouds (Salomé *et al*, 2017).

[redacted]

Figure 5.6 Histogram of vector separation for star forming sources and clouds. The jet is proposed to pass through the region with a 1kpc-gap. (Joseph *et al.*, 2022) ***IMAGE REDACTED FOR COPYRIGHT REASONS***

5.3 Discussion

Many observations of NGC5128 at multi-wavelength align with each other, providing strong evidence for positive feedback. Observational features in NGC5128 such as filaments, arcs and knots prove the mechanism behind positive feedback discussed in Section 2 where jets compress ISM and induce shocks. Furthermore, the alignment effect is also clearly observed in the galaxy as first identified in Rejkuba *et al.* (2002).

General agreement on the age estimates for features in NGC5128 provide insight to its evolution. Star clusters along the SW tip have been derived by Crocket *et al*. (2012) to be 1-4Myr while Joseph *et al*. (2022) estimated 3-4Myr which falls within the same range. It also gives median age of stars in the outer region to be 64Myr. Since radio lobes are estimated to be ~1Gyr (Eilek, 2014), jet activity is older than the stars and is a plausible reason for their formation.

Although a jet is detected in NGC5128, the presence of a 'large-scale jet' which connects the inner lobes to NML is up for debate. It was observed by Morganti *et al.* (1999) and McKinley *et al.* (2018) but radio observations in Neff *et al.* (2015) does not detect it. Kraft *et al.* (2009) showed that the energy source for the knots in NML is most likely a large-scale jet. However, the latest observations by McKinley *et al.* (2022) backtracks on it previous detection, citing imaging artefacts as the issue and that new data suggests a gap in-between NIL and the first radio knot (Figure 5.3). It reasons that supersonic outflows from the AGN could power the knots in place of a jet although calculations are inconclusive. Joseph *et al.* (2022) argues that jet activity in the NML, whether previous or current, must have been the cause for the double structure in the outer region. Since jets led to double structures in Minkowski's Object, 3C385 (Salomé *et al.,*2015) and 4C41.17 (Bicknell *et al.*, 2000), its presence in the NML remains likely even if it was in the past.

6 Future observations for jet-induced AGN feedback

6.1 X-ray missions

Advancements in observational technology would allow a deeper investigation into unanswered questions on jet-induced feedback. X-ray observations are crucial because of its capability to probe environments (Hardcastle and Croston, 2020).

Lynx is a next-generation x-ray observatory with a proposed launch in 2036. Its capabilities are unprecedented, with vast improvements in capabilities compared to the existing Chandra and proposed Athena. (Fig 6.1) One of Lynx's missions is to uncover the drivers of galaxy evolution which encompasses jet-driven AGN feedback.

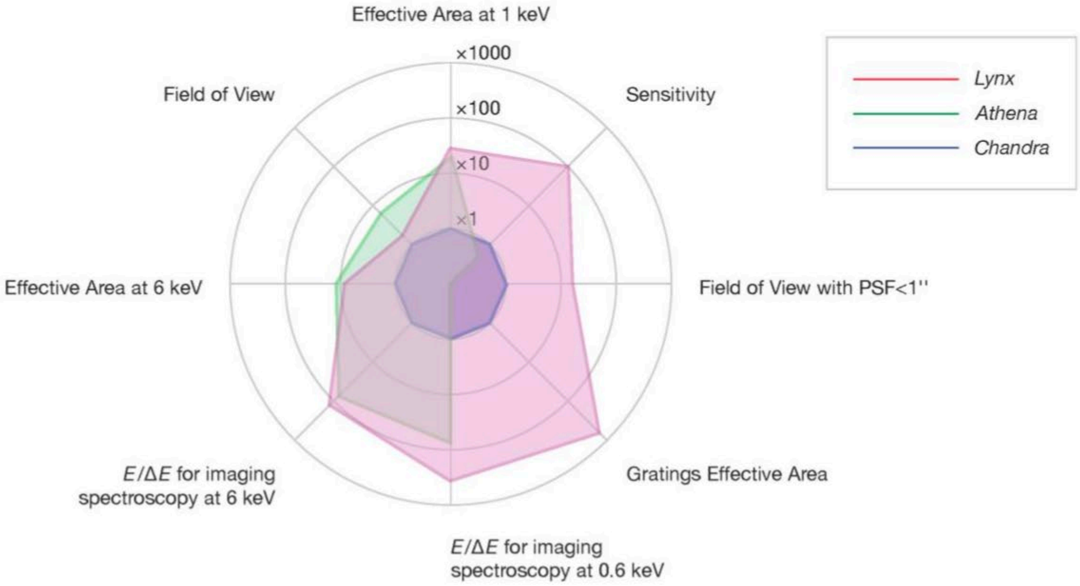

Figure 6.1 Differences in capabilities for Lynx, Athena and Chandra (The Lynx Team, 2018)

Diffuse x-ray emissions indicating heated gas is a key signature of AGN feedback and Lynx is able to map this. At the 100pc-1kpc scales, Lynx can resolve emission lines to uncover shock excitation on ISM. It is also able to observe AGN-inflated cavities in the ISM of nearby galaxies. Both capabilities are unique to Lynx and are key to understanding the feedback mechanism. (The Lynx Team, 2018). The use of machine learning to automatically detect the size of these cavities would allow for derivation of the total energy and jet power needed for inflation as well (Plšek *et al.*, 2023).

Athena, launching in 2030s, is designed for a wider field of view, larger effective area and high count rate, allowing the detection of faint objects. (Kar Chowdhury *et al.*, 2022) It is expected to survey >10,000 galaxy groups at various redshift. This would allow the tracing of AGN feedback over time including the era of peak SFR (Eckert *et al.*, 2021). Athena is able to map the energy content of the gas within the galaxy groups as it absorbs the impact of jets, determine locations of jet energy dissipation and probe cooling flows through the detection of FeXVII and OVII emission, providing invaluable insight on the impact of feedback on the cooling flow problem discussed in Section 2. (Athena White Paper, 2022)

6.2 Atacama Large Millimeter/submillimeter Array

ALMA is an interferometer of 66 radio telescopes. It allows for the investigation of the Sunyaev-Zeldovich (SZ) effect (change in apparent brightness of the Cosmic Microwave Background Radiation) at unparalled sensitivity and angular resolution, complementing x-ray data to unveil galaxy cluster evolution. (Di Mascolo, 2019). Being able to differentiate CR and thermal jet cocoons relies on the SZ effect where ALMA would show a deficiency in SZ signal, forming "SZ cavities" for the former but not the latter. This allows for the investigation of different jet compositions on ISM, possibly allowing comparison of observational data with the simulations in Section 3. (Bourne and Yang, 2023)

6.3 Cherenkov Telescope Array

Gamma-ray observatory, Cherenkov Telescope Array (CTA), launched in 2022 and is expected to study jet emission. It would identify high energy particles in lobes and probe magnetic fields, revealing the relativistic motions of the inner jet. NGC5128 emits gamma rays and is a key galaxy that would be studied by CTA. CTA would resolve its jet at TeV energies and conduct the first direct measurement of the magnetic field in a low-power jet. (Hardcastle and Croston, 2020).

7 Conclusion

Jet-induced feedback is a complex mechanism and remains an active area of research. While the general idea is somewhat agreed upon, the details are not clearly understood in the current state of the field and additional observational data is required to inform models.

Key findings in the paper are as follows:

In negative feedback, jet cocoons expand and cause shocks in ISM, disrupting cooling flows and expelling gas required for star formation. NGC2639 provides observational evidence for lower SFRs and deficit in optical and UV emissions.

Simulations for positive feedback suggest that lobes and bow shocks due to jets compress the surrounding gas, inducing collapse. Multiwavelength observations of NGC5128 unveil lobes, filaments and arcs which are signatures of this feedback.

Simulations exploring jet energy composition and its impact on feedback is inconclusive although general consensus are that they affect cocoon sizes and CR jets are the most effective at quenching.

It is expected that next generation observatories including Lynx, Athena and CTA as well as new data from the existing ALMA would provide unprecedented observations by investigating cooling flows, feedback over time and jet properties.

A proposed next research focus would be to produce mock x-ray and gamma-ray images and compare them to the actual observations, using the new data to constraint models and refine the theory on jet feedback.

(4997 words)

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