Imaging the Origins of Gas Outflows in Red Geysers Galaxies

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Abstract

The origin of the atomic gas emissions in Red Geysers, which maintains their quiescent state, likely involves complex processes deriving from the AGN. To understand the exact mechanism, radio emissions on the parsec (pc) scale from the AGN are observed. Whatever produces these emissions is likely also involved in powering the atomic gas outflows. Three possible origins of emissions are explored - coronas, winds, and jets. Four Red Geyser galaxies are examined by analyzing Very Long Baseline Array data at 1.4 GHz (L Band) and 4.8 GHz (C Band) to pinpoint emission origins and understand mechanism responsible for driving the pc-scale outflows in each galaxy. The results reveal that the Red Geyser outflows have different driving mechanisms. MaNGA 1-26878 shows the likely presence of a corona and a jet-like structure. MaNGA 1-27393 emissions imply presence of a corona, with very large wind possibly also being present. MaNGA 1-19818 suggests presence of a deflected wind and a corona, while MaNGA 1-43718 suggests emissions coming from a large deflected wind. Thus, AGN activity can manifest in different ways. The processes keeping the Red Geysers quiescent do not follow a singular model – they can vary depending on the specific Red Geyser galaxy.

1. Introduction

Galaxies can be categorized on the color-magnitude diagram, which plots them by color versus the stellar mass (Figure 1). Within this framework, galaxies cluster into three distinct groups: the blue cloud, the red sequence, and the green valley. The blue cloud (lower left corner) is primarily composed of star-forming galaxies, green valley (middle) houses the galaxies that are in a transitional phase between the blue cloud and the red sequence, while the red sequence (upper right corner) contains galaxies that are non-star forming or have low star formation rates. Red sequence galaxies typically contain older stellar populations (resulting in a redder color), are often more massive, and have less gas and dust available for star formation [1].

Particularly interesting subset of red sequence galaxies are Red Geysers. They are a type of early, non-star forming (quiescent) galaxies and constitute 5-10% of red sequence galaxies by stellar mass. What makes them unique is the presence of atomic gas (NaD), which is unusual for quiescent galaxies [6]. Some studies even suggest that the atomic gas moving away from the center of the galaxy could possibly be a result of the Active Galactic Nuclei (AGN) activity (as there is no star formation).

AGN is the central region (nucleus/core) of its host galaxy that emits significant amount of energy and (non-stellar) luminosity. It is likely powered by energy released as matter accretes onto the supermassive black hole (SMBH) [2]. AGN feedback that suppresses star formation is mainly described in two ways:

- “Quasar” / “Radiative” Mode – AGN luminosity is very high, which transfers energy to the surrounding gas. The gas heats up and inhibits star formation.
- ”Maintenance” / ”Radio” Mode – AGN luminosity is low and produces insufficient light for the above method to work. Thus, there is some other mechanism that keeps the gas hot (or expelled) and shuts down star formation.

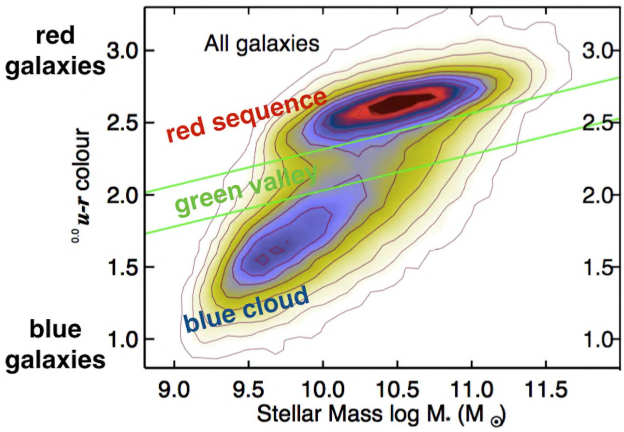

Figure 1: Example of a Color-Magnitude Diagram [8]

Red Geysers are mainly associated with the ”Maintenance” / ”Radio” mode of AGNs [7].

Heated gas is often responsible for suppressing down star formation. But at some point the hot gas should become cool and restart star formation - which does not happen in Red Geysers. This is because of the atomic gas outflows being produced, which keep Red Geysers quiescent. As this gas is likely produced by an AGN, it is interesting to look at what exact mechanism produces the gas outflows and keeps Red Geysers in the quiescence state. While previous literature often assumes that jets that inject heat into the surrounding gas (heat it) are responsible for ceasing star formation [3], his study aims to delve deeper into the exact mechanisms responsible for quiescence in

Red Geysers. Exploring how ”Maintenance” / ”Radio” mode AGNs work is key to understanding what keeps Red Geysers quiescent - particularly if Red Geysers have an active AGN, and how the AGN generates the atomic gas outflows.

2. Approach

2.1. Sample

The study analyses four distinct Red Geyser galaxies. All four of them were previously unresolved in arc-second resolution, 1.4 GHz (VLA) observations. This means that they produce radio emissions (in fact, Red Geysers have higher than average radio detection rates). However, the emission scales are much smaller than kilo-parsec (kpc), which already makes presence of strong jets less likely. As the scales are smaller than kpc, some of the emissions could be on the parsec (pc) scale, especially if they are a result of the AGN activity.

The four sample galaxies are presented in Figure 2. The optical and radio images underline that the sample consists of regular galaxies (i.e. simple detection - no extraordinary structures such as mergers). The BPT diagrams, which are used to classify the ionization state of emission-line galaxies, show that all four galaxies are LI(N)ERs. LI(N)ER is an ionization class associated with either a weak AGN or post-AGB (asymptotic giant branch) stars (indicative of a very old stellar population).

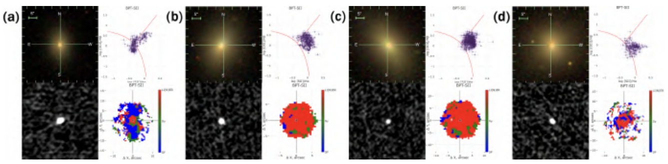

Figure 2: Optical and Radio images, and BPT diagrams for each galaxy: (a) MaNGA-ID 1-268789, (b) MaNGA-ID 1-273933, (c) MaNGA-ID 1-198182, (d) MaNGA-ID 1-43718 [4]

2.2. Methodology

The origin of the atomic gas observed in Red Geysers likely involves complex processes deriving from the AGN. As mentioned, some of the sub-kpc emissions could come on the pc-scale. To understand the exact mechanism, we observed parsec-scale radio emissions, and whatever produces these emissions is likely also involved in powering the atomic gas outflows. Some of the possible origins of the pc-scale outflows (as outlined in Figure 3) are:

- Coronas — hot, ionized plasma around the accretion disk (center of the galaxy);
- Winds — fast, large-angle material coming off of the disk (yellow conical emissions emerging from the galaxy);
- Jets — highly collimated, highly relativistic material (similar to a very powerful laser beam, like the arrow emerging from the galaxy center).

By analyzing the radio data from each galaxy, one of the above candidates could be identified as the primary driver of the observed pc-scale outflows.

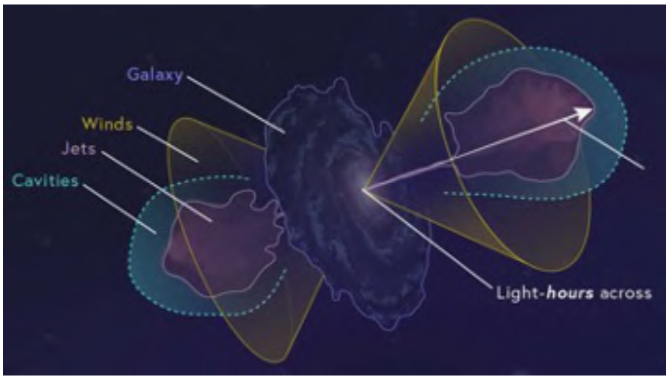

Figure 3: Supermassive Black Hole/AGN Flows [5]

2.3. Radio Analysis

Analysis consisted of reducing Very Long Baseline Array (VLBA) radio data at frequencies of 1.4 GHz (L Band) and 4.8 GHz (C Band) by hand in Astronomical Image Processing System (AIPS). VLBA’s high angular resolution makes it possible to investigate the detailed structure and morphology of the emissions. The radio data was taken by 9 telescopes (Figure 4) across the United States. Initially, reference telescope (red marker, Hawaii) was chosen, and bad readings/channels were removed (black marker, U.S. Virgin Islands). Then, the data was flagged baseline by baseline for all four channels. This means removing certain portions of data that may be corrupted or contain errors due to factors such as instrumental issues, radio frequency interference, or atmospheric effects. After flagging, the observations were calibrated to correct for instrumental variations and ensure consistent readings across the entire dataset. Calibration typically involves adjusting for changes in amplitude, atmospheric conditions, instrumental responses, time delay, and any discrepancies caused by telescope-specific factors. Fringe fittings and solutions were also applied, meaning that the program solved for how the atmosphere adjusted the phase of radio waves as well as the delay due to geographical locations. These steps resulted in clean and reliable data that was imaged to generate radio maps.

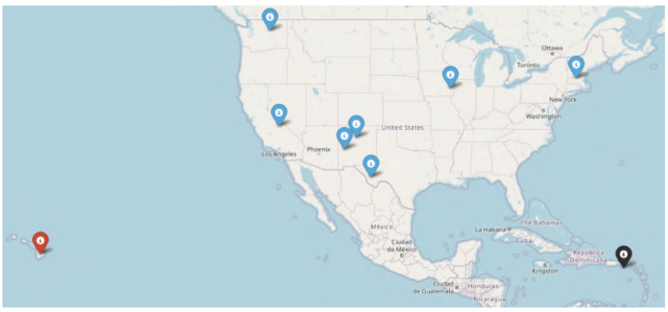

Figure 4: Radio data antenna locations

2.4. Size of Radio Emissions

If the observed radio detections are resolved (extended) with a narrow angle (collimated emissions), this indicates that jets are responsible for the parsec-scale outflows. To determine whether these outflows are from winds or coronas, properties of interferometry can be used to assess the angular size of the emissions. Interferometry involves selectively removing shorter baselines from the data and analyzing the impact on the flux. Shorter baselines correspond to larger emission regions, while longer baselines correspond to smaller regions. Consequently,

- If the source is small (a corona), the flux remains the same as the minimum baseline increases;
- If the source is big (winds), the flux decreases as the minimum baseline increases.

To examine this, the data for each galaxy was imaged again by increasing the minimum baseline incrementally while keeping the maximum baseline constant. Each flux reading (for each minimum baseline) was taken to observe the flux change trend.

3. Results & Discussion

The detection for MaNGA 1-268789 in 4.8 GHz was more complex. The radio map (Figure 5) shows a two-component detection - the North-East, and the South-West lobe - which were analyzed separately. The map contains the 4.8 GHz radio image, overlayed with contours of the 1.4 GHz detection (each corresponding to a specific sigma value).

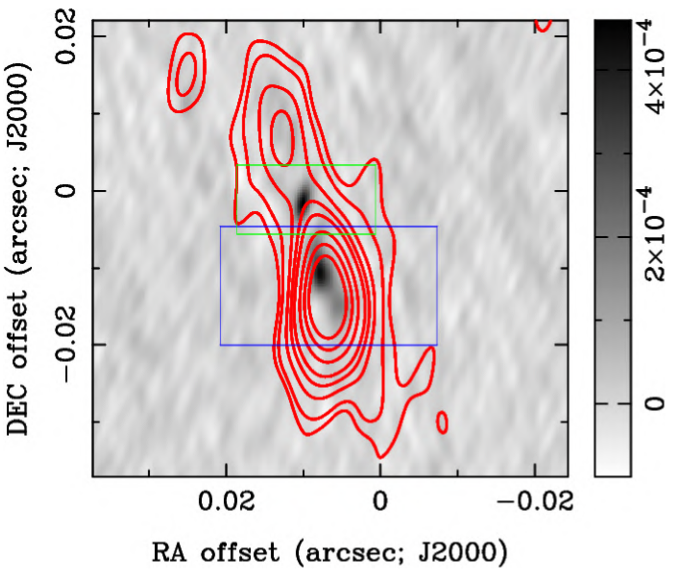

Figure 5: MaNGA 1-268789 Radio Map: Contours (1.4 GHz): 3, 5, 10, 15, 20, 30, 40, 50 sigma; Grey scale (4.8 GHz)

The resulting flux changes were analyzed for the regions indicated by the colored boxes, and are displayed in Figure 6. For the North-East lobe (the green box), change of flux as the minimum baseline increases was analyzed for 4.8 GHz reading (green line). It appears to be fully unresolved with a flat spectrum - the flux remains relatively constant as minimum baseline increases, meaning a very compact detection. According to the criteria established (in section 2.4), this suggests presence of a **corona**, and the **supermassive black hole** is also likely located in the North-East lobe. For the South-West lobe (the blue box), both 1.4 and 4.8 GHz fluxes decrease as minimum baseline increases - following a Gaussian fit, a diffuse emission. The corresponding spectrum is also steep (spectral indexes were calculated for the common minimum baselines between 1.4 GHz and 4.8 GHz readings within the South-West lobe). Therefore, this suggests presence of a wind or a jet.

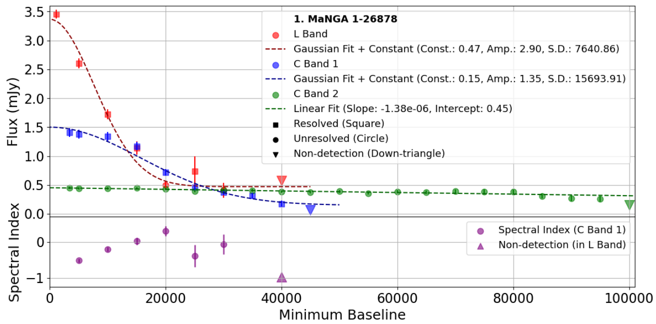

Figure 6: MaNGA 1-268789 Flux Change and Spectral Index

The position change graph plots the detection centers for each minimum baseline (as the distance from the image center), with approximate shapes of the resolved detections drawn as ellipses (Figure 7). The position change appears to be in the South-West direction - aligning with the ellipses' major axes (of lower minimum baseline detections). This indicates a narrow opening angle along the position change, which is associated with jets (ruling out winds). Therefore, the South-East lobe likely contains a **jet-like structure**. The position change, or the initial emission direction, also matches the extended emission direction (towards North-East and South-West, as inferred from the contour directions).

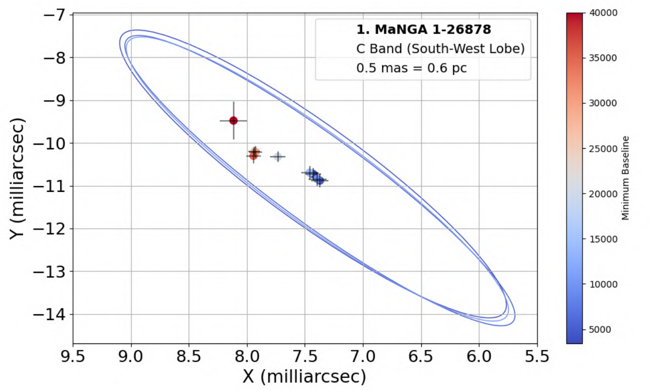

Figure 7: MaNGA 1-268789 Position Change (4.8 GHz, the South-West lobe, blue box) with approximate sizes drawn as ellipses for resolved detections

MaNGA 1-273933 did not have any visible detections in 1.4 GHz radio image. Therefore, its Radio Map (Figure 8) presents 4.8 GHz radio image overlayed with contours of itself. The flux does not decrease with increasing minimum baseline (Figure 9). The spectrum appears to be very flat, more than 0.66 (estimated using the RMS value of 1.4 GHz radio data). Thus, this compact detection suggests presence of a **corona**, where the **supermassive black hole** is also located. However, the galaxy had a 1.4GHz VLA detection but no visible 1.4 GHz VLBA detec-

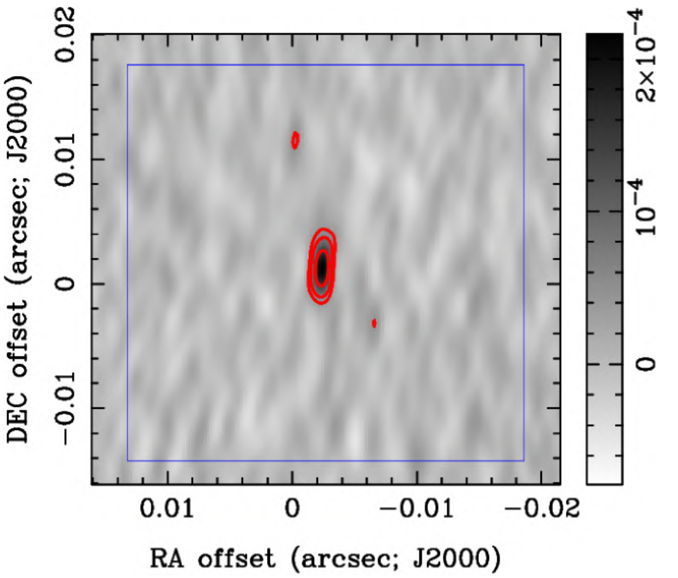

Figure 8: MaNGA 1-273933 Radio Map: Contours (4.8 GHz): 3, 5, 10 sigma; Grey scale (4.8 GHz)

tion. This means that majority of the 1.4 GHz flux is generated at scales much higher than the pc-scale of this analysis. Therefore, there is still a possibility of a **very big wind** being present (which cannot be fully identified in this analysis).

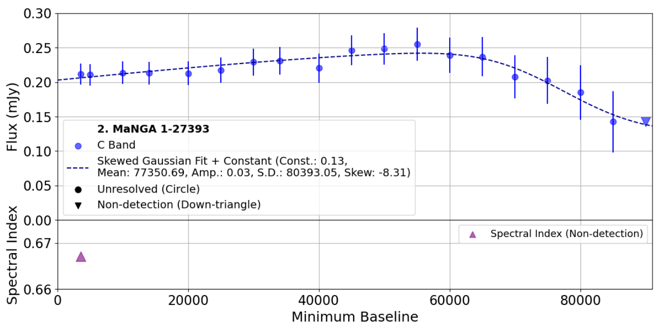

Figure 9: MaNGA 1-273933 Flux Change and Spectral Index

MaNGA 1-198182's 4.8 GHz flux change appears to be constant as minimum baseline increases (Figure 10), suggesting presence of a corona near the galaxy center (and the SMBH). The 1.4 GHz flux is diffuse, and the spectrum is steep for smaller minimum baselines (it gets flatter as the baselines increase).

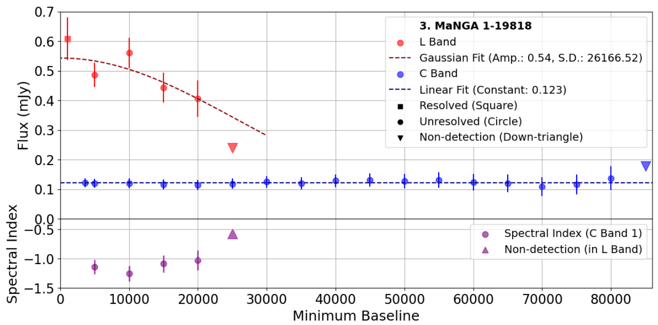

Figure 10: MaNGA 1-198182 Flux Change and Spectral Index

The flat spectrum corresponds to positions of higher-baseline detections (redder color), where the **corona** and the **SMBH** are located (Figure 11). The position changes South-East (towards smaller minimum baselines) - likely, there is a wind generated in that direction (corresponding to the steep spectrum).

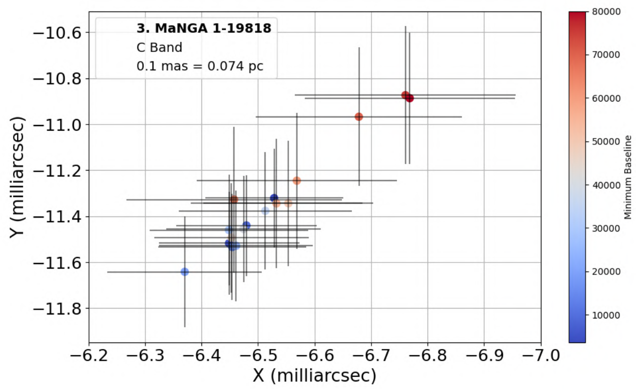

Figure 11: MaNGA 1-198182 Position Change (4.8 GHz)

However, the 1.4 GHz contours (Figure 12) suggest that the extended emissions are directed North-West (final wind direction). So, there is a change in direction - from the initial South-East towards final North-West. This could be because of the presence of dense material (resulting from the AGN) - the material could be swept into the wind, resulting in a **deflected wind**.

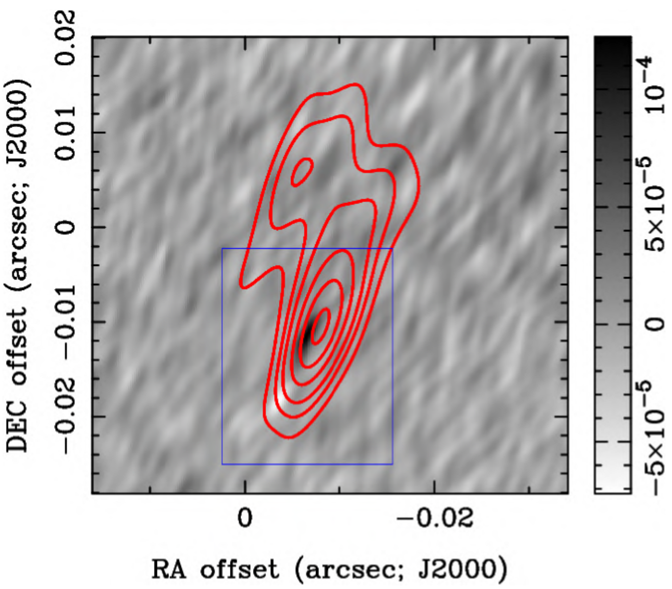

Figure 12: MaNGA 1-198182 Radio Map: Contours (1.4 GHz): 3, 5, 10, 13, 16 sigma; Grey scale (4.8 GHz)

MaNGA 1-43718 flux analysis seems to be more complex - both flux changes as the minimum baseline increases follow a bimodal Gaussian fit (Figure 13). The 4.8 GHz flux initially decreases as the minimum baselines increase, but later becomes constant (for higher minimum baselines). The 1.4 GHz flux, on the other hand, appears to be diffuse, decreasing with the increasing minimum baselines. The spectral index is also steep for smaller minimum baselines, and later becomes flatter (for higher minimum baselines).

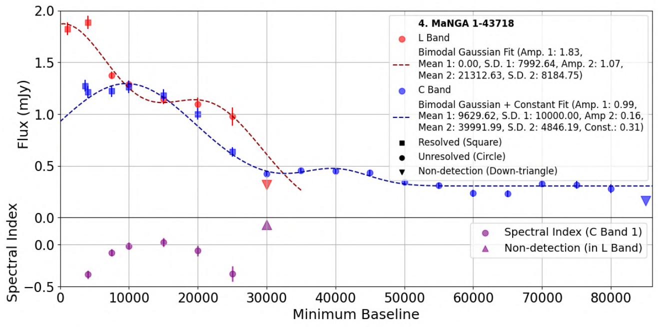

Figure 13: MaNGA 1-43718 Flux Change and Spectral Index

The flat spectrum could be resulting from the **supermassive black hole**, corresponding to the higher minimum baseline detection positions (Figure 14). The position change appears to be in the South-East direction. However, the change has a large/wide opening angle (between the high minimum baseline position and the major axis of the resolved/small minimum baseline detection ellipses). This suggests presence of a very large wind in the galaxy.

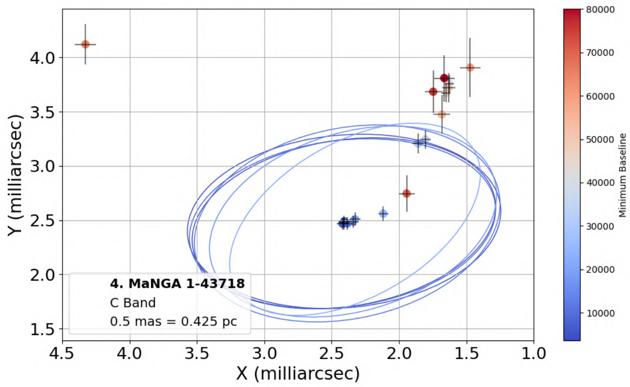

Figure 14: MaNGA 1-43718 Position Change (4.8 GHz) with approximate sizes drawn as ellipses for resolved detections

However, the extended emissions (1.4 GHz contours) are directed towards the West (the final wind direction) (Figure 15). Thus, the wind changes direction again, probably from the dense material present in the surroundings mentioned above. Likely, there is a **deflected wind**.

4. Conclusion

Examining the four galaxies using Very Long Baseline Array data at 1.4 GHz (L Band) and 4.8 GHz (C Band) reveals that the outflows in Red Geysers can have different driving mechanisms — not simply jets, as often assumed in much of the literature [3, 7]. AGN activity can manifest in various forms depending on the specific conditions within each galaxy. MaNGA 1-26878 shows the likely presence of a corona and a jet-like structure. MaNGA 1-27393 emissions imply presence of a corona, with very large wind possibly also being present. MaNGA 1-19818 suggests presence of a deflected wind and a corona, while MaNGA 1-43718 suggests emissions coming from a large deflected wind.

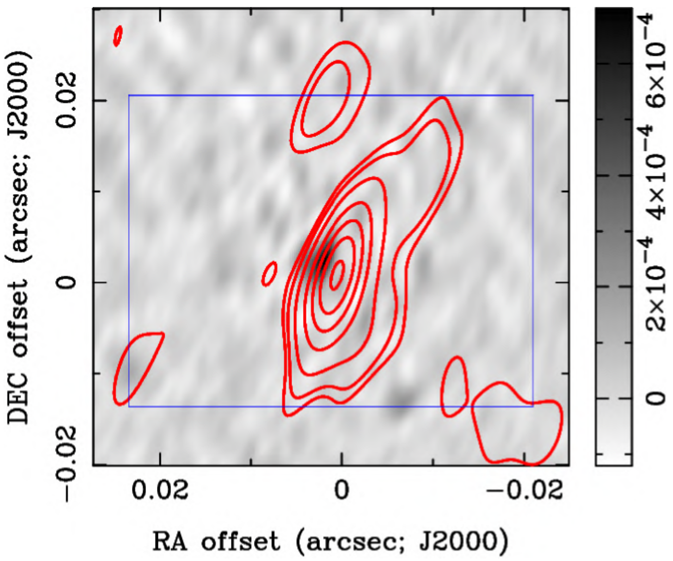

Figure 15: MaNGA 1-43718 Radio Map: Contours (1.4 GHz): 3, 5, 10, 20, 30, 40, 50 sigma; Grey scale (4.8 GHz)

The processes responsible for maintaining the quiescence of Red Geysers do not follow a singular model. The presence of three different emission sources across these four galaxies underscores the need for a nuanced understanding of the interplay between AGN activity and quiescence. Therefore, future studies should further explore the specific conditions that correlate with different emission origins observed across these galaxies. Refined theoretical models that better cover the observed complex and diverse behaviors could help explain the different mechanisms affecting the galaxies. This would lead to a more comprehensive (and possibly unified) understanding of the factor that keeps the Red Geysers quiescent.

5. Acknowledgements

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