Radio Continuum Study in HI Absorption Line Galaxies (Postprint)

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Abstract

We utilize VLBI archival data to study five galaxies with intrinsic HI absorption lines discovered in the 40% Arecibo extragalactic HI survey sky region (α.40 region), analyzing their radio structures and brightness temperatures (T_B) at milliarcsecond scales, calculating the galaxies' q-values (the ratio of far-infrared flux to radio flux density), and classifying the galaxies using WISE (Wide-field Infrared Survey Explorer) data. The study reveals that among the five sources, NGC 315 and NGC 5363 exhibit prominent radio jet structures; IC 860 and CGCG 049-057 possess compact cores at parsec scales, but with flux densities less than 20% of the NVSS flux density; the brightness temperatures of the nuclear regions in the aforementioned four sources all exceed 10^6 K; UGC 6081 shows no compact radio structure at milliarcsecond scales and is almost completely resolved. Based on the radio structures, brightness temperatures, and q-values, we infer that the radio continuum emission from these five sources may originate from three scenarios: radio jets, coexisting starburst activity and radio jets, and pure starburst activity, indicating that the detection of HI absorption lines may not depend on the type of continuum radiation in the central nuclear region. Classification using WISE data shows that the five sources can be divided into two categories: three are 4.6 µm-bright galaxies and two are 12 µm-bright galaxies. No dust-poor galaxies were found, suggesting that such galaxies are either rare in the α.40 region or have low HI absorption line detection rates.

Full Text

HI Absorption-line Galaxies: A Study of Radio Continuum Emission

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Abstract

Using VLBI archival data, we investigated five galaxies with intrinsic HI absorption lines discovered in the 40% Arecibo Extragalactic HI Survey (α.40 region). We analyzed their radio structure and brightness temperature (T_B) on milliarcsecond scales, calculated their q-values (the ratio of far-infrared flux to radio flux density), and performed classification using WISE (Wide-field Infrared Survey Explorer) data. Our study reveals that NGC 315 and NGC 5363 exhibit clear radio jet structures, while IC 860 and CGCG 049-057 show compact cores at parsec scales but with VLBI fluxes less than 20% of their NVSS fluxes. The brightness temperatures in the nuclear regions of these four sources all exceed 10^6 K. In contrast, UGC 6081 shows no compact radio structure at milliarcsecond scales and is almost completely resolved. Based on analyses of radio structure, brightness temperature, and q-values, we find that the radio continuum emission in these five sources originates from three distinct scenarios: radio jets, coexisting starburst and jet activity, and pure starburst activity. This suggests that HI absorption line detection may not depend on the type of central continuum emission. WISE data classification shows that the five sources can be divided into two categories: three are 4.6 m-bright galaxies and two are 12 m-bright galaxies, with no dust-poor galaxies present. This indicates that such galaxies are either rare in the α.40 region or have low HI absorption depths.

Keywords: galaxies; jets; starburst; far infrared; radio structure

1 Introduction

Hydrogen is the most important element in galaxies, and studies of the 21 cm HI line are crucial for understanding galaxy structure and evolution [**?**]. Hydrogen exists widely in galaxies from cosmic large scales to milliarcsecond scales in nuclear regions [**?**]. The 21 cm HI absorption line has been extensively applied to study the HI gas environment around high-redshift extragalactic radio-loud background sources, which can be classified as intrinsic absorption or Lyman-α analog absorption depending on the location of the absorbing gas [**?**]. Compared to HI emission lines, the detection of extragalactic HI absorption lines depends on the distribution of radio continuum emission and HI gas within galaxies, enabling investigation of HI gas properties at various resolutions. Generally, HI absorption lines can be detected at high resolutions, including VLBI observations at milliarcsecond scales, provided the radio continuum has sufficient surface brightness [**?**].

The primary sources of radio continuum emission in galaxies include radio jets, starburst activity, or a combination of both. Current methods for determining the central properties of extragalactic galaxies in the radio band mainly rely on high-resolution VLBI observations to obtain nuclear structure and brightness temperature (AGNs typically show high, compact brightness temperatures, while starburst galaxies show the opposite). Condon et al. studied the radio emission and star formation activity in the entire UGC (Uppsala Galaxy Catalog) sample, using brightness temperature T_B and q-values to distinguish whether the energy of radio emission primarily originates from AGN or starburst activity [?].

The Arecibo Legacy Fast ALFA (ALFALFA) HI 21 cm survey represents a significant improvement in sensitivity and detection depth compared to previous surveys (such as the HI Parkes All-Sky Survey), making it more suitable for finding HI absorption sources [?]. Darling et al. [?] searched for HI absorption in 7% of the ALFALFA survey data and detected only one known intrinsic HI absorption galaxy, UGC 6081. Wu et al. [?] detected ten HI absorption galaxies in 40% of the ALFALFA survey (the $\alpha.40$ region), all showing intrinsic absorption. Five of these had been previously observed and confirmed by other telescopes: NGC 315 [?], IC 860 [?], NGC 5363 [?], CGCG 049-057 [?], and UGC 6081 [?].

In this paper, we systematically study these five sources using archival VLBI and infrared data. Our primary goal is to investigate the nature of radio continuum emission in the central regions of these galaxies, analyzing their physical properties through radio brightness temperature, infrared q-values, and WISE classifications. Section 2 briefly describes the data collection and processing procedures. Section 3 presents analysis and discussion of the properties of these five sources. Section 4 summarizes our findings. We adopt the following cosmological parameters: $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$.

2 Data Collection and Processing

We collected VLBA, EVN, and infrared data for these five sources. The VLBA data were obtained from the Astrogeo VLBI Database, while the EVN data came from the EVN archive database. Both VLBA and EVN data had undergone preliminary phase and amplitude calibration. We edited the data and imported it into the DIFMAP software package for imaging and model fitting [?]. Through these procedures, we obtained parsec-scale radio continuum images of the five sources, deriving parameters including component fluxes, distances from the core, and angular diameters of model components. The fitting results and image parameters are presented in Table 2 , and the continuum images are shown in Figure 1 [Figure 1: see original paper].

To further understand the properties of these five sources, we analyzed and classified them using infrared data. The Infrared Astronomical Satellite (IRAS) data were obtained from the NASA/IPAC Extragalactic Database (NED), while

WISE data were retrieved from the Sloan Digital Sky Survey (SDSS). The infrared properties of the sample sources are listed in Table 3 .

3 Analysis and Discussion

3.1 Milliarcsecond-Scale Radio Structure

Figure 1 presents the radio continuum images of the five sources. NGC 315 and NGC 5363 show clear radio jet structures: NGC 315 displays a faint jet in the southeast direction in the 15.36 GHz VLBA data, consistent with previous high-resolution radio structure studies [?]; NGC 5363 shows jets in both northeast and southwest directions in the 8.6 GHz VLBA image, with a bent jet on larger (kpc) scales [?].

IC 860 and CGCG 049-057 are both luminous infrared galaxies [?, ?], with IC 860 also exhibiting post-starburst spectral characteristics [?]. The radio structure maps reveal compact cores at milliarcsecond scales for these sources. CGCG 049-057 contains only one component, while IC 860 has two components, with the northeastern component showing dramatic flux variation (from 0.9 mJy in 2006 to 7.1 mJy in 2019 at 5 GHz). Both sources have compact nuclear structures with brightness temperatures exceeding 10^7 K, suggesting that the radio emission likely originates from AGN radio jets. Additionally, we find that the milliarcsecond-scale fluxes (see Table 2) of these two sources do not exceed 20% of their respective NVSS total fluxes (see Table 2), indicating that most of the radio continuum flux at VLBI scales is resolved, likely arising from starburst activity.

UGC 6081 is completely resolved at parsec scales with no obvious radio structure, suggesting that the radio emission may primarily originate from starburst activity.

3.2 Jet Brightness Temperature

AGN-dominated radio sources are generally believed to exhibit distinct radio structures or brightness temperatures greater than 10^5 K at 1.4 GHz [?]. To investigate the brightness temperature properties of our sources, we obtained radio component model parameters through Gaussian fitting and calculated the brightness temperature T_B using Equation (1) [?] (results shown in Table 2):

$$T_B = 1.77 \times 10^{12} \frac{S_\nu}{\nu^2 \theta_d^2} (1 + z)$$

where S_ν is the component flux density in Jy, ν is the observing frequency in GHz, θ_d is the component angular diameter in mas, and z is the source redshift. For AGN-dominated radio sources, the brightness temperature exceeds 10^6 K at frequencies above 0.03 GHz and exceeds 10^5 K at frequencies above 1 GHz [?, ?]. Since the brightness temperatures of these sources are derived from small-scale nuclear regions, values below 10^6 K may indicate the absence of an AGN in the nuclear region.

We find that four sources have small-scale brightness temperatures greater than 10^6 K, suggesting that these galaxies likely contain AGN radio jet components. In the 1.66 GHz EVN data, UGC 6081 has a brightness temperature of $10^{4.89}$ K, indicating that it may be a starburst galaxy. As shown in Table 2, the brightness temperatures of these sources range from $10^{4.89}$ to $10^{10.1}$ K, all below the equipartition brightness temperature of 5×10^{10} K [?]. Therefore, jet beaming effects are not significant in our sample.

3.3 The q-Value

For galaxies where high-resolution continuum images show only compact cores, the origin of radio continuum emission can typically be analyzed using the ratio of far-infrared (FIR) flux to radio flux density (commonly called the q-value) [?]. Starburst galaxies exhibit far-infrared flux much greater than radio flux, caused by dust heating from young massive stars. Studies have found a strong correlation between far-infrared and non-thermal radio brightness in starburst nuclei, making far-infrared observations a suitable tool for studying star formation rates [?]. The AGN contribution is inversely proportional to the q-value; smaller q-values indicate radiation more dominated by AGN. The q-value is calculated as follows [?, ?]:

$$q = \log_{10}\left(\frac{FIR}{3.75 \times 10^{12}}\right) - \log_{10}(S_{\mathrm{NVSS}})$$

where $FIR = 1.26 \times 10^{-14}(2.58 S_{60\mu m} + S_{100\mu m})$. Here $S_{60\mu m}$ and $S_{100\mu m}$ are the flux densities from IRAS at wavelengths of 60 m and 100 m, respectively (see Table 2). Among our five sources, only NGC 315, IC 860, NGC 5363, and CGCG 049-057 have IRAS flux density measurements (see Table 2).

When most radio emission energy is provided by an AGN, the radiation is less affected by FIR, resulting in lower q-values. Therefore, AGN-dominated galaxies have q-values less than 2 [?]. Using Equation (2), we calculated q-values for four sources (see Table 2). The results show that IC 860 ($q = 2.86$) and CGCG 049-057 ($q = 2.74$) both fall between 2.2 and 3.0, indicating that the NVSS-scale radio emission in these two galaxies primarily originates from starburst components. In contrast, NGC 315 and NGC 5363 have q-values much smaller than 2.0, suggesting that their radio emission is mainly from radio jets. This is consistent with the results obtained in Section 3.1 based on radio structure and the ratio of VLBI-scale to NVSS-scale radio fluxes.

3.4 WISE Classification of the Five Sources

Using WISE infrared satellite data in four bands (W1, W2, W3, W4), galaxies can be classified into four types [?, ?]: (1) W1 - W2 > 0.5: AGN surrounded by large amounts of hot dust; (2) W1 - W2 < 0.5 and W2 - W3 < 1.6: dust-poor sources, commonly found in low-excitation radio galaxies; (3) W1 - W2 < 0.5 and 1.6 < W2 - W3 < 3.4: galaxies with mid-infrared radiation enhanced by dust continuum and polycyclic aromatic hydrocarbons (PAHs), brighter at 12 m, called 12 m-bright galaxies; (4) W1 - W2 < 0.5 and W2 - W3 > 3.4: dust-rich starburst galaxies, typically found in galaxies with high star formation rates and narrow-line radio galaxies.

We collected WISE data for all four bands for the five sources (see Table 2). We find that NGC 315 and NGC 5363 correspond to case 3, known as 12 m-bright galaxies [**?**]. UGC 6081 meets criterion 1, belonging to AGN surrounded by large amounts of hot dust. IC 860 and CGCG 049-057 meet criterion 4, belonging to dust-rich starburst galaxies, consistent with our radio analysis. Since these galaxies show brightening at 4.6 m, they are called 4.6 m-bright galaxies [**?**]. None of the five sources meet criterion 2 (dust-poor sources), indicating that such galaxies may be rare in the α.40 region or have low HI absorption depths.

4 Summary

Using multi-epoch, multi-band EVN and VLBA data, we studied the radio structure, brightness temperature T_B, and q-values of five HI absorption galaxies discovered in the α.40 region: NGC 315, IC 860, NGC 5363, CGCG 049-057, and UGC 6081, and performed classification based on WISE data. Our findings indicate that the radio emission in these five sources can be categorized into three types based on radio structure and brightness temperature: (1) Predominantly from AGN jets. NGC 315 and NGC 5363 both exhibit bidirectional jets at parsec scales with high radio brightness temperatures, indicating that radio continuum emission mainly originates from jets. (2) Primarily from starburst activity with possible jet contributions. IC 860 and CGCG 049-057 show compact radio structures at parsec scales with brightness temperatures exceeding 10^6 K, but most NVSS flux is resolved, suggesting that radio continuum emission mainly originates from starburst activity. (3) Entirely from starburst activity. UGC 6081 is almost completely resolved at parsec scales with no compact component, indicating no contribution from radio jets to the nuclear region' s radio emission.

By calculating q-values for four sources, we confirmed that NGC 315 and NGC 5363 are AGN-dominated, while IC 860 and CGCG 049-057 are starburst galaxies, consistent with results from radio structure and brightness temperature analysis. WISE infrared data classification reveals that among the five sources, two are 12 m-bright galaxies and three are 4.6 m-bright galaxies, with no dust-poor galaxies present. This suggests that dust-poor galaxies may be rare in the 40% ALFALFA region or have low HI absorption depths.

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Note: Figure translations are in progress. See original paper for figures.