The characteristics of galaxies with powerful radio jets
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Radio AGNs launch extremely powerful jets consisting of charged particles moving at relativistic velocities. These jets can extend to Mpc scales and interact with intergalactic medium (IGM). This can produce cavities or bubble structures in X-ray emitting gas of galaxy clusters and groups. In this way, radio AGNs inject a massive amount of energy into the IGM and heat up the associated gas. Because the prevalence of radio AGNs increases with the stellar mass of galaxies, the heating of radio jets was proposed to explain the low star formation rate in massive galaxies and the low number of massive galaxies compared with predictions of the first models of the formation of galaxies.

However, it is still not fully understood how and when a galaxy can launch a radio jet. Theoretical studies suggested that black hole spin, magnetic field and accretion rate could be important ingredients in the jet launching process. With the development of the new generation of radio telescopes such as LOFAR and SKA, a large number of radio AGNs with radio luminosity $L_{150\text{MHz}}$ down to $\sim 10^{21}$ W Hz$^{-1}$ will be found in the nearby universe. This makes it possible to investigate the triggering mechanism of radio AGNs statistically. An important part of this is linking the prevalence and properties of radio AGNs with the morphological parameters of the host galaxies, such as the axis ratio, the concentration, and the presence of tidal features.

The morphology of massive galaxies reflects their assembly history and divides the galaxies into two populations, the first of which, with weak or no disc features, has a merger dominated history and the second, with prominent stellar discs, has an evolutionary path dominated by secular processes (e.g. disc instability or bar-related processes). It is
therefore suggested that the two populations contain SMBHs with different properties due to the different importance of black hole mergers in their growth process. The SMBHs resulting from black hole mergers would have different spins compared to SMBHs growing mainly by accretion. Hence the two populations would exhibit different radio properties. Recent studies of the relation between morphology and radio AGNs suggested that powerful radio AGNs tend to reside in galaxies with a merger dominated history.

This thesis

This thesis mainly discusses the relation between radio AGNs and the evolutionary path of galaxies based on the data from new radio surveys especially the LOFAR Two-metre Sky Survey (LoTSS) combined with optical surveys. It consists of statistical studies as follows.

1. The link between radio AGNs and the axis ratio of galaxies

   In Chapter 2, we investigate the optical projected axis ratio (the ratio of the minor axis to the major axis) of the galaxies hosting radio AGNs in the LoTSS data release one (DR1). Thanks to the high sensitivity and large area coverage of LOFAR, for the first time we observed a difference between the axis ratio distributions of radio AGNs with $L_{150\text{MHz}} > 10^{23}\text{ W Hz}^{-1}$ and $L_{150\text{MHz}} \leq 10^{23}\text{ W Hz}^{-1}$ in the nearby universe ($z < 0.3$). The host galaxies of high-power radio AGNs are typically rounder than other galaxies with similar stellar mass while the galaxies hosting low-power radio AGNs do not have a preference in shape. This supports the idea that high-power radio AGNs are triggered in galaxies with a merger dominated assembly history while the low-power radio AGNs can be triggered in galaxies less affected by mergers.

   In Chapter 3, we extend this study to higher redshifts ($0.3 < z \leq 1$) with the radio AGNs in the Karl G. Jansky Very Large Array Cosmic Evolution Survey (VLA-COSMOS) 3 GHz Large project. The high-power radio AGNs do not tend to be in round galaxies at redshift 0.6 to 1. A possible reason for this is that the universe at higher redshifts is denser, therefore radio AGNs in elongated galaxies could have more fuel and also be more luminous than their low redshift counterparts. Thus high-power jets could be found in elongated
Figure B.1: The radio luminosity vs. axis ratio diagram for nearby LoTSS DR1 radio AGNs (z < 0.3) with optical counterparts in the SDSS and $M_* = 10^{11} - 10^{11.5} M_\odot$. The SDSS $r$-band images of some selected sources are also shown, with LoTSS images overlayed as contours. The contour levels are selected for display. The 6″ × 6″ beam of LoTSS is shown in the bottom left of each panel. The dashed lines denote the ellipses enclosing 90% of the optical flux.
English Summary

2. The kinematics of galaxies hosting radio AGNs

Chapter 4 presents the angular momentum of galaxies hosting radio AGNs in the LoTSS data release two (DR2) from the Mapping Nearby Galaxies at Apache Point Observatory survey (MaNGA). The angular momentum estimated from the velocity maps of the MaNGA are important to understand the evolutionary path of galaxies. We find that high-power radio AGNs are more likely to be slow rotators with low angular momentum. As slow rotators are typically round, this trend can explain the higher fractions of radio AGNs in rounder galaxies revealed in previous studies. The results confirmed that galaxies with a merger dominated history are better breeding grounds for high-power radio AGNs.

3. Jet-galaxy alignments

In Chapter 5, we investigate the positional angle differences (dPA) between the radio and optical images of radio AGNs in the LoTSS DR2. The dPA distribution of radio AGNs peaks at $90^\circ$, indicating that the radio jets are typically aligned with the projected minor axis of the host galaxies. A two-Gaussian intrinsic jet-galaxy alignment model fits the projected dPA distribution well. The fitting results showed a significantly larger fraction of minor-axis aligned sources for radio AGNs with lower luminosity. This is in line with the scenario that lower luminosity radio AGNs are less affected by BH-BH mergers and chaotic accretion.

This thesis shows the importance of mergers in the jet launching processes. From Chapter 2 to 4, the morphology and the kinematics of the galaxies hosting radio AGNs reveal that powerful radio AGNs have a preference to be hosted by post-merger galaxies. In Chapter 5, the jet-galaxy alignment reflecting the direction of the black hole spin further implies that radio properties are related to the spin of black holes. The black hole spin would change significantly during BH-BH mergers and chaotic accretion processes, which are important for massive galaxies. Moreover, Chapter 2 discusses the heating of radio jets in oblate galaxies, indicating that the heating of radio jets can be responsible for quenching
the star formation in massive oblate galaxies as well as in massive triaxial galaxies.