The multi-phase ISM of radio galaxies

Santoro, Francesco

Publication date:
2018

Chapter 8

Conclusions and future prospects

8.1 Conclusions chapter by chapter

In this thesis I have addressed some of the open questions related to the interaction between the energy released by the active galactic nucleus (AGN) and the host galaxy's interstellar medium (ISM). This has been done by studying radio AGN spanning different evolutionary stages, and by using various techniques to observe the different phases of the gas, in particular the warm ionized and warm molecular.

In what follows I summarize the main results obtained in each chapter.

- **Chapter 2 - The jet-ISM interaction in the outer filament of Centaurus A**

  By using integral field VIMOS observations of the outer filament of Centaurus A, I find that the kinematics of the ionized gas matches the kinematics of the nearby H I cloud, where signs of a jet-cloud interaction have previously been reported to be present. Both the regularly rotating H I structure, as well as that part of the H I which appears disturbed by the jet, have a counterpart in the ionized gas.

  The new kinematical information suggest that the ionized and neutral components are part of the same gas structure, likely originating form the merger that shaped Centaurus A. The geometry is such that this structure, rotating around the galaxy, has entered the zone of influence of the jet from the back, moving towards us.

  The uniformity of the [O III]λ5007/Hβ line ratios throughout the observed region suggests the existence of a spatially extended ionization mechanism. Photoionization by starlight and pure shock ionization can be excluded, also taking into account the narrow width of the ionized gas emission lines. The most likely mechanism ionizing the gas is photoionization by the radiation field of the central AGN.

  The kinematics of the H I and of the ionized gas affected by the AGN can be explained by the lateral motions, away from the observer, of the jet's cocoon. Considering also the fairly diffuse nature of the radio jet near the outer filament and the narrow width of the ionized gas emission lines, a jet-cloud interaction, in the form of entrainment by a cocoon, is to be expected.

- **Chapter 3 - The outer filament of Centaurus A as seen by MUSE**

I expand the results presented in Chapter 2 by using new MUSE integral field observations of a larger region of the outer filament of Centaurus A. Thanks to these observations I could uncover, at high spatial resolution, the velocity structure of the ionized gas. I find that the two kinematical components previously detected by the VIMOS observations cover a much larger area and, furthermore, I identify a new low-velocity component. This supports the results and interpretation from the VIMOS data that the gas is affected by the interaction with the radio jet, and in particular, that this is the case for a much larger area and, by implication, probably for the entire outer filament.

I find that the different kinematical components show different gas morphologies (i.e. linear, arc-like, and diffuse). I propose that the diffuse and the low-velocity components are directly affected by the passage of a slow-moving jet. A smooth, head-on, interaction between the large-scale jet of Centaurus A and dense gas clouds would, indeed, explain the arc-like clumps embedded within these components. On the other hand, the kinematical component with linear morphology is characterized by velocities similar to the anomalous velocities of the nearby H I cloud. This component represents the part of the H I cloud that, through its rotation about the galaxy, has entered the zone of influence of the large-scale radio jet. This, together with the well-defined elongation of the linear component along the same direction as the radio jet, indicates that it is the result of the jet's lateral expansion.

The ionization level of the gas, as traced by the [O III]λ5007/Hβ line ratio, decreases from the more collimated, linear, component to the more diffuse components. This might reflect a change in the ionized gas density or in the number of ionizing photons across the outer filament. Apart from the low-velocity component, for which the typical full-width-at-half-maximum (FWHM) of the emission lines is $\sim$205 km s^{-1}, the narrow velocity width of the other kinematical components (FWHM$\sim$140 km s^{-1}) indicates that the jet does not drive strong shocks across the whole observed region.

By finding signs of a jet-ISM interaction across all the identified gas components, my results clearly show that, although poorly collimated, the large-scale and low-power radio jet of Centaurus A is still active and affects the surrounding gas.

- **Chapter 4 - Embedded star formation in the extended narrow line region of Centaurus A: extreme mixing observed by MUSE**

  Thanks to the MUSE data presented in Chapter 3 I could study with high spatial resolution the ionization structure of a small cloud ($\sim$ 250 pc) located in the outer filament of Centaurus A, where jet-induced star formation has been suggested to occur by different studies. Within this cloud I find two H II regions where star formation is occurring and another location where star formation must have ceased very recently. One of the H II regions represents an early evolutionary stage of star formation where young stars are still heavily embedded in the dusty natal cocoon. On the other hand, the other H II region is hosting less young/embedded star formation. In addition, I find a young stellar source in the vicinity which is not associated with a knot of ionized gas, likely representing a former H II region that has already dispersed/ionized its birth gas.

  The line ratios of the star forming region clearly show that, close to the continuum source, stellar radiation dominates the gas ionization, while ionization due to the central AGN light takes over at larger distances. In particular, the region around the youngest stars shows a narrow 'mixing line' in the diagnostic diagram which also correlates with the observed Balmer decrement, and, thus, with the dust distribution.

  I could reproduce the mixing line associated with the region that is actively forming stars using the plasma modeling code MAPPINGS III, by mixing stellar and AGN photoionization. This confirms that photoionization by young stars and by the central AGN are the sources driving the gas ionization across this region. It is likely that dust shields the gas from the external radiation field of the AGN, favoring a smooth transition between stellar and AGN photoionization and increases the chance to detect the mixing line in the diagnostic diagram.

  The results I present in this chapter and in Chapter 2 and Chapter 3 emphasize the complexity of the processes occurring under the influence of radio jets and AGN radiation. In particular, in this chapter I show that, even though star formation influences the gas over a limited region, it can coexist with the radiation field of the AGN and it can possibly be triggered by the transit of a jet.

- **Chapter 5 - The warm molecular hydrogen of PKS B1718-649: feeding a newly born radio AGN.**

  By taking advantage of integral field SINFONI observations, we could reveal the presence of warm molecular H_2 gas in the central regions (<2.5 kpc) of the young radio galaxy PKS B1718-649. We find that the H_2 gas is distributed in two disks with orthogonal orientations.

  The outer disk (on scales >650 pc) is aligned with the stellar body of the galaxy and its kinematics connects smoothly to the one of the H I disk extending to larger-scales. On the other hand, we find that in the inner regions (on scales <650 pc) the H_2 gas is part of a circum-nuclear disk oriented in the orthogonal direction with respect to the outer disk. The inner disk has a mass of warm molecular H_2 gas of about 1×10^4 $M_\odot$ which may indicate a mass of cold molecular hydrogen of about 2×10^9 $M_\odot$.

  The rotational velocities of the inner disk can be explained by the gravitational force of the stars and of the central super-massive black hole (SMBH), however part of the H_2 (~ 130 $M_\odot$), in the innermost 75 pc, deviates from regular rotation. We find that this gas has redshifted velocities with respect to the systemic velocity of the galaxy, matching the velocities of previously observed H I clouds. This suggests the presence of gas falling onto the SMBH and possibly fueling the AGN activity.

  The distribution of the H I and the H_2 gas can be caused by stellar torques aligning the gas in a stable configuration and creating the small clouds with unsettled kinematics. In this view, the inner H_2 disk might be the gas reservoir from which the central SMBH accretes via small infalling clouds.

- **Chapter 6 - Probing multi-phase outflows and AGN feedback in compact radio galaxies: the case of PKS B1934-63**

  By studying the warm ionized gas in the young and compact radio source PKS B1934-63 with X-Shooter, I find emission lines which are double peaked and have broad wings indicating complex gas kinematics. By modeling the [O III]λ5007Å line it is possible to recognize four different kinematical components, namely two narrow components (width of about 100 $\mathrm{km\,s^{-1}}$), one intermediate component (width of about 700 $\mathrm{km\,s^{-1}}$) and one very broad component (width of about 2000 $\mathrm{km\,s^{-1}}$).

The entire reservoir of warm ionized gas is concentrated in the inner 1 kpc of the host galaxy and has a total mass of about $M_{\mathrm{gas}} \sim 6.8 \times 10^6$ $\mathrm{M_\odot}$. Thanks to a spectro-astrometry technique, I find that the gas of the two narrow kinematical components is part of a structure which is possibly a circum-nuclear disk with a radius of about 200 pc, and includes most of the warm ionized gas. Only a very small fraction of the warm ionized gas, namely the gas of the intermediate and very broad kinematical components, shows kinematical signs of interaction with the energy released by the AGN.

I estimate the gas electron density with a recently developed technique, using transauroral [O II] and [S II] lines, which is sensitive to the high density regime. I find that the warm ionized gas has densities ranging from about 10^3 $\mathrm{cm^{-3}}$ (for the narrow components) up to $10^{5.5}$ $\mathrm{cm^{-3}}$ (for the very broad component). There is a correlation between the FWHM of a component and its electron density. By attributing the broadening of the spectral lines to the interaction of the AGN with the ISM, I argue that this FWHM-density relation is mainly driven by the ability of the AGN-ISM interaction to compress, at different levels, the gas, increasing its density.

The excitation of the warm ionized gas indicates that the AGN-ISM interaction is driving shocks within the ISM. In particular, the [S II]$\lambda\lambda$6717,31/Hα and the [O I]λ6300/Hα line ratios of the intermediate component can be reproduced by shocks with velocities v_{s}=400-500 $\mathrm{km\,s^{-1}}$. In addition, taking into account the trend of models, the high value of the [O I]λ6300/Hα ratio of the very broad component can only be reached in the presence of fast shocks (possibly with $v_{\mathrm{s}} \gtrsim$1000 $\mathrm{km\,s^{-1}}$)

By using the properties of the intermediate and the very broad components, I obtain low mass outflow rates (i.e. 10^{-3}-10^{-1} $\mathrm{M_\odot\ yr^{-1}}$) and I find that only a small fraction of the available accretion power of the AGN is used to drive the outflow (i.e. maximum efficiency

$F_{\rm kin}$ ~10^{-5}). This is in contrast with feedback cosmological models which require higher outflow efficiency.

I investigate gas with a low ionization state (via Mg II absorption lines) and warm molecular gas (via H_2 emission lines) and I do not find signs of outflowing or kinematically disturbed gas. By combining these results with information from the literature, I find that this is possibly due to the fact that the AGN-ISM interaction in PKS B1934-63 is very recent and the gas involved in this interaction did not have enough time to cool down and accumulate in a colder phase.

- **Chapter 7 - The relation between atomic and ionized gas in a sample of 248 nearby radio galaxies.**

  Using SDSS spectroscopic data, I study the ionized gas in a sample of 248 radio galaxies for which information on the presence and kinematics of the H I is available from previous studies. I find that, in general, the presence of ionized gas, traced via the [O III]λ5007Å emission line, is not strongly connected to the presence of H I gas. However, the ionized gas detection rate, as well as the H I detection rate, is higher for sources with compact radio morphology, extended on sub-galactic scales. These sources are likely young radio galaxies which are, thus, still embedded in a gas-rich and multi-phase ISM.

  I find indication for a relation between the kinematics of both the H I and the ionized gas and the galaxy radio power, suggesting that the mechanical energy injected into the ISM by the radio source might be the main driver of the gas outflows.

  There is no general trend between the kinematics of the ionized and of the H I gas. Compared to the H I, the ionized gas seems to be more sensitive to the effect of the AGN-ISM interaction and shows broader lines. In fact, most of the radio galaxies of the sample show H I in a regularly rotating configuration (circum-nuclear or large-scale disk) while the ionized gas is kinematically disturbed ([O III]λ5007Å line width $\gtrsim$430 km s^{-1}).

  The galaxies with disturbed H I kinematics (H I line width $\gtrsim$430 km s^{-1}) show a correlation between the kinematics of the ionized and the H I gas. Most of these sources are compact and young radio galaxies with high radio powers (log$P_{1.4\rm GHz}$ $\gtrsim$24 W Hz^{-1}). This confirms the ability of radio sources to drive galaxy-scale and multi-phase gas outflows during their first evolutionary stages.

I find that the sources showing, from an optical perspective, signs of a more effective AGN-ISM interaction ([O III]λ5007Å line width $\gtrsim$700 km s^{-1}) are lacking H I. This is likely indicating that a strong coupling between the energy release by the AGN and the ISM can result in the ionization of a significant fraction of the H I.

8.2 General conclusions

The work of this thesis clearly shows the complexity involved in the study of the ISM in relation to the AGN feeding and feedback processes in radio galaxies. Compact and young radio galaxies are hosted by galaxies with a gas rich and multi-phase ISM (Chapter 7) and are an ideal class of sources that I extensively investigate to study both these processes. In this section I summarize and address the main open topics outlined in Chapter 1 (Sec. 1.4) by combining the results obtained in the different chapters of this thesis.

- **The relevance of radio sources in driving gas outflows at galactic scales**

  My study of compact and young radio galaxies confirms the crucial role of the AGN mechanical feedback on galactic scales, especially in the firs evolutionary phases of a radio galaxy. In fact, I find that compact and young radio galaxies with high radio powers show the clearest cases of multi-phase (ionized and H I gas) outflows extended below kpc scales (Chapter 7). In addition, there are hints of a relation between the radio power and the ISM kinematics suggesting that gas outflows are mainly driven by the mechanical energy injected into the ISM by the radio source (Chapter 7). The case of Centaurus A shows how also the jets of low-power radio galaxies are clearly able to influence the ISM kinematics. Thanks to the high spatial resolution of our data, I find that both the head-on and the lateral expansion of the jet/cocoon can ablate, and likely compress, the gas, influencing both its excitation and kinematics (Chapter 2 and Chapter 3).

- **The physical processes involved in the feeding of the AGN activity**

By studying compact and young radio galaxies, whose AGN activity recently switched on, I show that a potential reservoir of gas that can be used to trigger the AGN activity are circum-nuclear disks of H_2 and ionized gas, extended on scales of few hundred pc (Chapter 5 and Chapter 6). In addition, the detection of cold gas whose velocity deviates from regular rotation within these disks suggests that one of the way to actually feed the SMBH might be via infalling clouds of cold material (Chapter 5).

- **The efficiency of the AGN negative feedback**

  Thanks to a new diagnostic method, I find that outflowing warm ionized gas can reach high densities. This contributes to give indications that only a small amount of the AGN accretion energy is used to drive warm ionized gas outflows, meaning that the efficiency of AGN negative feedback is low. This is in contrast with cosmological simulations, which predict a higher outflow efficiency, and with some of the current observations. However, the classical method or the assumptions that are usually used to estimate the warm ionized gas electron density are not sensitive to the high density regime and might be not suitable to determine the physical condition of the outflowing gas. I argue that this might have biased the results of past studies, which have reported higher outflows efficiencies, to be more in line with the predictions by the models (Chapter 6).

- **The relation between different gas phases within an outflow**

  Young radio sources can be used as a clock to monitor the evolution of AGN-driven outflows and have the potential to help us understanding the still debated origin of cold outflowing gas. I find that the multi-phase properties of their gaseous outflows suggest that cold gas originates within the outflowing material, when shock-ionized gas cools down (Chapter 6). This implies that ionized gas outflows characterize especially the first phases of the AGN-ISM interaction while cold gas outflows represent a more evolved stage of such interaction. The relation between different phases of outflowing gas in radio galaxies is, thus, subtle to understand and might be dictated by the timescales of the gas cooling and by the time the radio source switched on and the AGN-ISM started.

- **The occurrence and efficiency of jet-induced star formation**

AGN positive feedback is a challenging phenomenon to observe and is getting increasing attention thanks to the higher spatial resolution of new observational facilities. By studying the case of the outer filament of Centaurus A, I show how star formation can happen under the influence of the AGN radiative and mechanical energy, possibly triggered by the radio jet. Single star forming clumps have low star formation efficiency and their ionization effect on the surrounding gas is only local. However, depending on the overall efficiency of this process within the entire zone of influence of the jet/AGN ionization cone, this might be an important way to form stars, which has to be included in models of (negative and positive) AGN feedback (Chapter 4).

- **The relevance of shocks in AGN-driven outflows**

  Although observationally poorly constrained, AGN-driven shocks are potentially a key phenomenon that can drive the excitation and the kinematics of gas within outflows. My results show that fast shocks (with velocities ranging from $\sim$500 km s^{-1} up to thousands km s^{-1}) can be driven by the expansion of radio jets/lobes across the ISM of a radio galaxy and are actually affecting the gas excitation and kinematics. These results show the importance of further developing shock models to test their effect under different physical condition of the gas and, more in general, in the framework of the AGN feedback (Chapter 6).

- **The different phases of the ISM in radio galaxies**

  Understanding the link between the different gas phases in AGN is a challenging task, also taking into account that gas is involved in both the AGN feeding and feedback processes. I find indications that while the ionized gas seems to be more sensitive to the effects of AGN negative feedback in radio galaxies, the H I gas is usually found in stable configurations such as regularly rotating circum-nuclear/large-scale disks, which are possibly related to the SMBH feeding. This might suggest that within an outflow the H I gas phase is a short transitional phase, thus more difficult to detect, between the ionized and the molecular phase. The radio galaxies whose ionized gas shows the clearest signs of an AGN-ISM interaction are poor in H I gas indicating that, when the coupling between the AGN output energy and the ISM is more efficient, it is able to ionized a significant amount of the neutral ISM (Chapter 7).

8.3 Future prospects

The results shown in this thesis give some new insights in the processes at play in AGN feeding and feedback in relation to the different gas phases of the ISM. There are still many open questions on the exact physics underlying these phenomena and on their ability to reshape the ISM of a galaxy. In the future, spatially resolved observations of the different ISM phases, using the existing and upcoming instruments, will allow to expand our investigations and answer some of these open questions.

In particular, observations of the CO performed with the Atacama Large Millimeter Array (ALMA) and Northern Extended Millimeter Array (NOEMA) will be able to probe the distribution and kinematics of the cold molecular gas in the very inner regions of AGN. Thanks to the narrow field mode (NFM) of the Multi-Unit Spectroscopic Explorer (MUSE) and the new adaptive optics system (GALACSI) mounted on the Very Large Telescope (VLT) it will be possible to complement these studies with spatially resolved information on the warm ionized gas phase and have a comprehensive/multi-wavelength view on the physical processes that fuel SMBH and trigger the AGN activity.

Our understanding of AGN-driven outflows is limited, and likely biased, by the current observations which often probe specific classes of AGN, and have spatial resolutions for the different gas phases that are not comparable. Recent findings seem to indicate that a significant fraction of the gas mass in outflows resides in the molecular phase and, thus, is in the form of H_2, the most abundant molecular species. However, the detection of H_2 outflows is observationally challenging due to the fact that its emission lines are faint and hard to detect. The advent of the James Webb Space Telescope (JWST) will allow us to increase the statistics on H_2 outflows by exploring more rotational and ro-vibrational transitions of the H_2 in the mid-infrared band. By probing the H_2 excitation state, these observations have also the potential to test the occurrence and relevance of shocks within AGN-driven outflows. At the same time, JWST will allow to extend the investigation of warm ionized gas outflows to high redshifts.

Nowadays, to study molecular gas we mainly rely on CO observations which are only detecting the most powerful and fast outflows. Increasing the integration times of future observations performed with the currently available mm/sub-mm interferometers, such as ALMA and NOEMA, will allow us to detect the less massive and slower cases of CO outflows and extend our investigation to a broader range of AGN classes. In addition, short baseline observations performed with these interferometers will provide new information about the diffuse and extended component of cold molecular gas in outflows which so far remained almost unexplored.

Furthermore, recent results are showing that with high sensitivity ALMA observations we can detect the mm/sub-mm emission from cold dust within AGN-driven outflows. Dust is a fundamental catalyst for the formation of H_2 and these observations will shed light on how it can survive/reform in such a harsh environment.

In the optical band, observations exploiting the adaptive optics capabilities of MUSE will help to better characterize warm ionized gas outflows in the local Universe and give stronger constraints on their spatial extent and geometry. This will allow a more robust estimate of the typical mass outflow rate and outflow efficiency of warm ionized gas outflows which still suffer from high uncertainties.

By combining the spatially resolved and multi-wavelength information from the aforementioned observations it will be finally possible to give more reliable constraints on the global efficiency of the AGN negative feedback and, in addition, have new hints on the occurrence and the physics underlying AGN positive feedback.