Tuning in to the feedback bassline: revealing the operation of AGNs in galaxy clusters with high-resolution radio observations

Timmerman, R.

English summary

Those who stare at a clear night sky will be able to admire a few bright stars. The idea that stars are objects like the Sun, but then very far away, was suggested some two thousand years ago by the Greek philosopher Anaxagoras. However, it cost humanity a long time (and some their life) before this idea was generally accepted. This realization forms one of the first moments in which our horizon was broadened and we saw that the Universe was larger than our solar system. We were able to map the distribution of stars thanks to the development of telescopes. This taught us that our Sun is part of a larger collection of stars: the Milky Way. Only in 1918 did the work of Harlow Shapley using variable stars reveal the true scale of our Milky Way, as well as the position of our solar system within the Milky Way. Then, the next big question arose: is the Milky Way all there is in the Universe? In the Great Debate, Harlow argued that the spiral-shaped nebulae that had recently been observed were located at the edges of the Milky Way. Meanwhile, Heber Curtis saw these nebulae as independent galaxies. The conclusive proof was delivered by Edwin Hubble, who using variable stars was able to demonstrate that the distance to the Andromeda nebula was much larger than the scale of our Milky Way: approximately a million lightyears from the Earth. Suddenly it was clear that our Universe was much bigger than just the Milky Way.

A second fundamental discovery was that our Universe is not only much larger than previously thought, but also that it is dynamic. Edwin Hubble's most famous scientific result is the discovery of a correlation between the distance to a distant galaxy and the speed with which this object recedes from us. This confirmed the suspicion of the Belgian priest Georges Lemaître that the Universe could be expanding. This provided humanity with the first insight into the past of our Universe. If everything moves away from each other, then these objects would have been closer together in the past. Even more so, if you project all motions back in time, you will find that all galaxies come together at the same point in time: approximately 13.7 billion years ago. This is the foundation of the current cosmological model of the Big Bang.

Thanks to modern instruments, we can look even deeper into the Universe and carefully study the objects we see. Currently, the number of galaxies is estimated to be in the hundreds of billions. The limited speed of light is very valuable to research into the history of our Universe. In a vacuum, light travels a distance of 299,792,458 meters per second. This high, but limited, speed causes us to see everything at great distances with a significant time delay. Our Moon is just over a second away, the Sun at around 8 minutes, the planet Neptune is at

approximately 4 hours, and the Voyager 1 probe at the time of writing at almost a day. The nearest star (Proxima Centauri) is at a distance of over 4 lightyears and the diameter of our galaxy is approximately 100,000 lightyears. Thanks to the enormous distances in our Universe, we can see what the Universe looked like in the past by observing very distant objects. With modern telescopes, we can see and study galaxies billions of lightyears away, and therefore also look billions of lightyears into the past. With sub-millimeter observations we have even mapped the edge of our observable Universe: the afterglow of the Big Bang.

Thanks to deep observations and detailed simulations, we currently know that our Universe began as an extremely hot and dense medium. In the beginning, this medium was too hot for the formation of most particles we are made of. As the Universe expanded, the temperature also decreased, and the first protons, neutrons, electrons, nuclei, and atoms formed. After a long time, the temperature decreased enough for this matter to clump together through gravity. This led to the formation of the first stars, galaxies, and even galaxy clusters. These galaxy clusters are currently the most massive objects we find in our Universe. They do not only contain hundreds to thousands of galaxies but also a hot gas named the intracluster medium. As this gas cools down, it accretes onto the galaxies in the cluster and initiates the formation of new stars.

In addition to the formation of stars, the intracluster medium feeds something else: the supermassive black holes in the core of galaxies. In particular, in the central galaxies, we often find a black hole with a mass of a billion times the mass of our Sun. While devouring this gas from their environment, they release a large amount of energy. This happens in two different ways. First, the surrounding gas is generally heated so much that it produces intense radiation. Secondly, a part of this heated gas is channeled by magnetic fields into two jets which escape the gravitational pull of the black hole with almost the speed of light along the rotation axis of the black hole. This process causes a feedback cycle that reheats the intracluster medium and slows down the cooling of this gas.

To study this process, different types of observations are used. First of all, there are optical observations. These allow us to map distant galaxies and study both the existing stellar population and the formation of new stars. Because the atmosphere is largely transparent to optical light, many observations are performed from the ground. Although, for the best image quality, optical telescopes are commonly placed on top of high mountains, or even in space like the Hubble Space Telescope. In addition to optical observations, we also use X-ray observations. Because the intracluster medium has an extremely high temperature, it is primarily visible with X-ray observations. Because our atmosphere is not transparent for X-ray photons, we can only perform such observations using satellites like Chandra and XMM-Newton.

Finally, we commonly use radio observations such as those taken with the European LOw Frequency ARray (LOFAR) or the American Very Large Array. Contrary to optical and X-ray observations, where a single telescope can produce a detailed image, the radio observations used in this thesis were taken using interferometry. The angular resolution of a telescope is proportional to the ratio between the wavelength of the light that is being observed and the size of the telescope. For radio wavelengths, which are very long, you would also need a very big telescope. Because this is technically near impossible, we employ a trick. By placing different radio antennas at a distance from each other, we can simulate a single telescope the size of the distance between these antennas. This makes it possible to build a virtual telescope with a size of a few thousand kilometers, which provides a high angular resolution.

Many questions remain about how the Universe as it is today came to be. How did galaxies form? What is the influence of the feedback process between black holes and the intracluster medium on the formation of new stars, and how did all of this work not just now, but also in the distant past? In this dissertation we study the feedback process in galaxy clusters, primarily using new high-resolution radio observations at low frequencies. With this, we intend to obtain a better view of what precisely happens near the black hole, how the intracluster medium is heated, and how this all relates to the formation of stars in the cluster.

In Chapter 2, we study the feedback process and the diffuse radio emission (also known as a “mini halo”) in the Phoenix cluster using radio observations taken with the Very Large Array at frequencies between 1 and 12 GHz. Previous observations demonstrated that the intracluster medium in this cluster cools rapidly without being inhibited by the black hole at the center. We find that the mini halo was most likely formed due to turbulence in the intracluster medium after the merging of galaxy clusters in the past. In addition, we observe that the black hole undergoes varying periods of activity instead of being active at a constant level and that this black hole is likely underweight for a cluster of such a mass.

In Chapter 3, we focus on the famous radio source Hercules A. By combining Very Large Array observations with LOFAR observations, we can study the spectrum of this radio source over a much wider range than before. This offers insight into the electron population in the radio lobes of Hercules A. We find that the bright ring structures that were previously detected feature an increasingly steep spectrum as the distance to the central black hole increases. This measurement supports the hypothesis that these rings were not formed by shock waves but rather by inner lobes forming within the larger radio lobe. This also immediately provides insight into the time scale between outbursts of the central black hole.

In Chapter 4, we take LOFAR observations of a sample of 14 galaxy clusters. Using these observations, we test a method to measure the amount of energy being emitted by the environment of the black hole. This method requires that our low-frequency observations are sensitive enough to detect the complete radio lobes. By comparing the measured volume of the radio lobes with the volume of the imprint of these radio lobes in the intracluster medium, we can confirm that this method is indeed reliable.

In Chapter 5, we apply this method for the first time on a sample of distant galaxy clusters using LOFAR observations. Thanks to LOFAR’s sensitivity and high angular resolution, we are able to measure the amount of energy injected by the black hole into its environment for the first time at such distances. This demonstrates that this method can also realistically be employed to measure the impact of the feedback process between the central black hole and the intracluster medium in the early Universe.