Nuclear activity in nearby galaxies
Filho, Mercedes Esteves

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2003

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
English Summary

Twinkle twinkle little star,
How I wonder what you are.
Up above the world so high,
Like a diamond in the sky.

... When the blazing sun is gone,
When he nothing shines upon,
Then you show your little light,
Twinkle, twinkle, all the night.

... Then the traveler in the dark
Thanks you for your tiny spark;
How could he see where to go,
If you did not twinkle so?

... As your bright and tiny spark
Lights the traveler in the dark,
Though I know not what you are,
Twinkle on, please, little star.

Unknown Author
Let there be Light

The night sky is specked with small points of light. Although they do look like shining diamonds, we know they are not – they are distant objects out in space. These specks of light, however, are only a small fraction of the interesting objects that exist in outer space but that are not always observable with the naked eye.

The reason why we can see at least some objects is because they emit visible light. Light is a form of radiation, which in turn is a way of propagating energy. The best way to describe radiation is as a wave, very similar to waves seen in the ocean. The energy is then determined by the distance between each wave trough, which is called the wavelength – the smaller the wavelength, the larger the energy. In visible light, this energy is equivalent to ‘colour’ and a rainbow, for example, is made up of six such different ‘coloured’ light waves; in order of increasing energy the colours are red, orange, yellow, green, blue and violet. However, the human eye picks up only visible light, which is radiation with wavelengths in the range 4 to 7 tenths of a millionth of a millionth of a meter. Objects in space, however, may radiate at other longer or shorter wavelengths, which are therefore invisible to the human eye. In fact, visible light is but a tiny part of all the different types of radiation that constitute the electromagnetic spectrum.

The electromagnetic spectrum is made up of radiation that ranges from several hundreds of meters to less than one millionth of a millionth of a meter in wavelength (Fig. 1). Radio is the longest wavelength radiation and it is this kind of wave that radio and television stations emit. Microwaves are emitted by the well-known kitchen appliance that cooks food, whereas infrared is the type of radiation that warms the skin. Visible radiation is the kind of radiation we can pick up with the human eye. Skin burn is caused for example, by ultraviolet radiation from the sun. X-rays are used by doctors to look at bone structure and finally gamma rays are emitted by radioactive material.

**Figure 1** — The electromagnetic spectrum from radio to gamma rays, showing the relation between energy (measured in units of electron Volt), wavelength and frequency.

Besides sources emitting radiation at wavelengths not visible to the human eye, another
reason for not seeing more sources in the sky is that they may be too far away and too dim to be seen.

Using a large magnifying instrument called a telescope, we are able to solve some of these problems and observe a paraphenalia of objects. Looking down from a hill kilometers high, patches of light can be seen where towns and cities are. However, with binoculars it could be seen that in fact, those patches are made up of individual street lamps and car lights. The power to resolve out these patches of light into individual light sources is called resolution. When using a telescope, the resolution depends on the combination of wavelength and telescope diameter – the shorter the wavelength or the bigger the telescope, the better is the resolution. Detectors called CCDs mounted on telescopes function much like a photographic camera, by registering the ‘image’ of a radiative source at a certain wavelength, for example in the ultraviolet (Fig. 2). In this way, astronomers can obtain information as to the spatial distribution of the matter responsible for the ultraviolet emission.

![Ultraviolet image of the Sun](image)

**Figure 2**— Ultraviolet image of the Sun, taken with the instrument SOHO (credits: EIT, SOHO, ESA, NASA).

A source that radiates is characterized uniquely by the combination of all the different waves that it can produce – the source spectrum. Spectrographs mounted on telescopes function much like prisms refracting light. When radiation from a source incides over the spectrograph, the radiation is decomposed into the different waves that constitute it to form a spectrum. The spectrum provides information about the source and its surroundings, like, for example, its temperature and chemical composition. The wavelength or energy of the radiation is directly related to the temperature of the source that emits the radiation – the smaller the wavelength, the more energy it transports as it propagates and the higher the temperature of the source. As glass is heated for example, its colour (and therefore, the wavelength or energy of the radiation) changes as the temperature gets higher – first red, then yellow, and finally blue. So, by analysing the wavelength of the radiation, we can also measure the temperature of the source.

Furthermore, when a foreground gas cloud is cooler then the radiative source that shines on it, the matter will absorb some of the radiation and create a ‘dent’ in the spectrum. On
the other hand, if the gas cloud is viewed against a cold, dark background, the chemical elements that constitute the cloud will emit radiation that appear as spikes or ‘lines’ in the spectrum. The wavelength of the absorption or emission line is characteristic of the chemical element that produces it, like a unique fingerprint, and the width of the line is a measure of the abundance of the element. Therefore, the total spectrum of an object will be made up of the radiative source which produces a smooth ‘continuum’, on which there is superimposed the combination absorption and/or emission lines from surrounding matter (Fig. 3).

**Figure 3**— Spectra of a source and a foreground cloud of gas. Spectra are often represented by a plot of intensity per unit wavelength. Notice the underlying smooth continuum background produced by the radiative source, on which is superimposed absorption lines (top) or the emission-lines (bottom) of the chemical elements that compose the foreground cloud (credits: adapted from Nick Strobel).

**Fantastic Voyage**

Imagine for a moment that it is possible to explore outer space aboard a spaceship. Travel first away from planet Earth, millions of kilometers in the direction of the Sun, which is the nearest star. Stars are balls of hot gas that burn their own fuel and form from the collapse of individual clumps of matter in gas clouds. After leaving our Solar System, made up of the Earth and other 8 planets and the Sun, travel another 20 000 000 000 000 000 kilometers and look back. The white patch of light seen across the sky is called The Milky Way (Fig. 4).

The Milky Way is a galaxy, our Galaxy. Galaxies consist of hundreds of billions of stars and enough gas and dust to make billions more stars. The reason why the stars and gas clutter together into a galaxy is due to mutual attraction. Any particle with mass creates a field around it, which extends out in all directions and whose strength depends on the mass and the distance from the object. When this particle meets another particle with mass, they feel an attraction – gravity – due to their respective fields. By successively bringing particles close together, it is possible to build systems like stars and galaxies that are bound by gravitational
attraction.

Looking in the opposite direction of the Milky Way, into outer space, it can be seen that space is populated with many types of galaxy structures (Fig. 5). And they come in all shapes and sizes – from elliptical shaped, to spirals, to disk-like structures with central bulges.
Anatomy

In order to explore their intrinsic structure, it is necessary to travel to the center of one of these galaxies (Fig. 6).

Heart of the Matter

Extremely dense objects with the mass of a million to a billion solar masses are thought to lie at the center of most large galaxies, including our own Milky Way. Their gravitational fields are so intense that within a certain distance of it, nothing, not even light, can escape their attraction. Hence, their name – black holes.

The origin of supermassive black holes remains a controversial matter. One theory is that black holes form in the initial collapse of the gas cloud that gives rise to the galaxy that hosts it. Alternatively, it has been proposed that an individual star-like black hole forms and swallows up enormous amounts of matter over the course of millions of years to produce a supermassive black hole. Another possibility is that a cluster of star-like black holes form and eventually merges into a single, supermassive black hole.

Feeding the Monster

Although we are not able to directly see the black hole, we can infer its presence by the influence it has on the surrounding matter. A black hole in the center of a galaxy can become more and more massive as stars orbiting it are ultimately captured by gravitational attraction and add their mass to the black hole. By measuring the velocity of the stars orbiting close to the center of a galaxy, we can infer the presence of a supermassive black hole and calculate its mass.

Gas and dust near the black hole are also pulled to it by its powerful gravitational attraction. However, before being swallowed, the gas and dust takes the form of a fast rotating accretion disk – a disk of matter which has accumulated around the black hole. As the matter swirls toward the black hole, frictional forces heat the gas to increasingly higher temperatures. On the inner edge of the disk, temperatures reach millions of degrees and the gas produces X-rays. Detection of X-ray radiation from the infalling matter thus provides the evidence needed of the presence of a supermassive black hole.
Eject!

However, not all the matter in the gravitational whirlpool is doomed to fall into the black hole. Part of the gas escapes as a hot wind that is blown away from the disk. Under certain, as yet not understood conditions, the environment generated by the black hole forces ionized plasma into a collimated stream and accelerates it to speeds as high as 297 000 kilometers per second, which is 99% the speed of light. These high energy jets can be observed at radio and X-ray wavelengths as collimated beams that blast out of the galaxy and travel over 1 000 000 000 000 kilometers. As the jets plough through the intergalactic medium, often they form cocoon-like structures called lobes that are filled with hot gas glowing brightly at radio wavelengths.

A Star is Born

Another important energetic contribution in a galaxy may come from the formation and evolution of stars. Star formation in the center of the galaxy may be triggered for example, by a collision or a close encounter with another galaxy. Many of these newly formed stars are very massive and very bright, such that they use up their fuel quickly and explode as supernovae. This process produces copious amounts of infrared radiation from heated dust. However, regions of star formation and supernovae also produce plenty of radio waves, which can in some cases drown out the radio emission associated with an accreting black hole.

The AGN Family

Galaxies are said to harbour active galactic nuclei or AGN, if the supermassive black hole in their center is actively accreting matter. The power of an AGN depends mainly on the mass of its central supermassive black hole, the rate at which it swallows matter and how much matter there is available. In turn, the power of the AGN determines what kind of AGN we see. In the distant Universe, where there is a lot of available matter in young galaxies, the most common type and the most powerful AGN are quasars.

Quasars represent extreme cases where large quantities of gas are pouring into the black hole so rapidly that the energy output is equivalent to a thousand or more galaxies put together, from a region that has a diameter about one millionth of a millionth the size of that of the host galaxy. It is as if a powerhouse the size of a small flashlight produced as much light as the entire city of Lisbon. Most of the radiation from quasars is emitted in the form of optical as well as X-ray radiation.

However, since the central regions of an AGN are axisymmetric, orientation relative to the observer is also an important factor when classifying an AGN. The subpopulation of quasars that form radio jets are called radio-loud quasars. They contain a compact dust ring or torus around their black hole and accretion disk. When viewed from the plane of the ring, the bright optical nucleus is obscured and merely the faint host galaxy with its radio jets is observed. This type of AGN are called radio galaxies, of which M 87 is a nearby example (Fig. 7).

The hot accretion disk around the black hole also irradiates surrounding matter, which will produce line emission in the AGN spectrum. The chemical elements responsible for the line emission also help us to classify AGN. The stronger the power source, the more energetic are the emission lines in the spectrum. AGN called Seyferts, for example, show strong emission lines of the chemical element oxygen.
Figure 7— Image at radio wavelengths of the radio galaxy M 87. The bright nucleus, narrow jet and extended radio lobes can be seen.

Galaxies with somewhat less active supermassive black holes are more common in the nearby Universe and occur on different scales depending on the amount of available accreting matter. An example of such low luminosity AGN are LINER galaxies (acronym for Low Ionization Nuclear Emission-Line Region), which show in their spectrum characteristic emission lines for example of nitrogen and sulfur. An extreme case of a ‘starved’ black hole is for example, Sgr A*, the black hole in the center of our own Milky Way galaxy.

This Thesis

In this thesis, we have focused on the study of galaxies that are nearer than 1 000 000 000 000 kilometers from Earth, which is actually quite near. Most of these galaxies contain the nearest and also lowest luminosity AGN that can be studied. In order to detect even weak signatures of black hole activity, we have used telescopes that detect X-ray and radio waves. At these wavelengths, with large diameter telescopes and for galaxies this closeby, we can probe regions in the galaxy as small as 300 000 000 000 kilometers in diameter, which is where black hole accretion occurs. In the first instance, X-ray emission in the center of the galaxy tells us that there is very hot gas falling into the black hole and therefore that the galaxy harbours an AGN. At radio wavelengths, however, we are often plagued with star-forming radio emission besides a contribution from the black hole-related emission. Several techniques are used in order to disentangle this emission but a very crude diagnosis involves looking at the radio ‘image’ – AGN will be centrally concentrated and compact, whereas star forming regions will be more spread out.

We have applied these and other techniques to the group of galaxies called LINER and composite galaxies. Composite galaxies are cases where star-forming radio emission may drown out the AGN radio contribution, since they are thought to possess star formation very near the center of the galaxy. In these last sources low luminosity, compact emission as would be expected from an AGN, is seen in 25% of the cases. The remaining 75% may still harbour very weak AGN but the star-forming regions simply dominate the spectra (Chapter 2 and 3).
Furthermore, we have used the energy at radio and X-ray wavelengths to study how matter pours into the black hole (Chapter 4). Results show that in fact our sources accrete much less matter than quasars. Furthermore, the way the accretion proceeds is fundamentally different. In quasars accretion is made through the presence of a disk of gas. In these low luminosity, nearby AGN where the available reservoir of matter is much lower, accretion should occur almost radially, in a puffed-up torus called an ADAF. Although the way these sources accrete is different, however, we find that weak AGN also produce jets as in more powerful AGN like quasars (Chapter 4 and 6) and that this jet is energetically important.

We have also studied the distribution of low luminosity AGN in the nearby Universe and how we can relate these objects to ‘normal’ galaxies and more powerful, distant AGN like quasars (Chapter 5). Results show that the spatial distributions of nearby composite, LINER and Seyfert galaxies appear consistent with bright quasars being their progenitors.

Finally, we have carried out several detailed studies of the extended and nuclear radio emission in some interesting nearby galaxies and focused, in particular, on the way the radio emission varies (Chapter 6 and 7). Our results suggest that the spectra are consistent with ADAF-type accretion plus jet emission responsible for the radio emission characteristics (Chapter 7).

The main focus of this thesis has been the search for and study of low luminosity AGN. We have detected several low luminosity AGN in nearby galaxies, revealing that this type of activity can occur in a broad range of galaxy types and powers. Furthermore, we have been able to establish important constraints on the accretion processes in low luminosity AGN. The main repercussion of this work, however, is on how galaxies were formed and how they evolve. Quasars, for example, were very common in the distant Universe, when the Universe was young. By studying nearby low luminosity AGN, we have tried to establish a link and trace the life of powerful quasars down to nearby low luminosity AGN and then to ‘starved’ AGN like Sgr A*. Hopefully, some of the work presented in this thesis may ultimately aid in understanding how black holes are formed, how black hole fueling is triggered, how black holes grow and evolve through accretion and what role the black hole plays in galaxy formation and evolution.