IC 5063: AGN DRIVEN OUTFLOW OF WARM AND COLD GAS

The southern Seyfert galaxy IC 5063 was the first AGN where a fast outflow of neutral hydrogen was detected. Here we present new optical spectra that were taken with the ESO-NTT to compare the kinematics of the ionised gas with that of the neutral hydrogen component in order to study the mechanism that could drive this outflow. The data reveal extremely complex gas kinematics, including the presence of an outflow of ionised gas (with speeds of several hundred km/s) at the location of the brighter radio lobe. This outflow is strikingly similar to that of the HI. We consider the interaction between the radio jet and the ISM to be the most likely mechanism for the extreme kinematics and a possible scenario is described.

R. Morganti[1], T. Oosterloo[1], J. Holt[2,3], C. Tadhunter[2], J.M. van der Hulst[3]

[1]*ASTRON, Netherlands Foundation for Research in Astronomy, NL;*
[2]*Dep. of Physics and Astronomy, Sheffield University, UK;*
[3]*Kapteyn Astronomical Institute, Groningen, NL*

Huge amounts of energy are produced through the accretion of material onto the super-massive black hole situated in the centre of an Active Galactic Nucleus (AGN). This energy is released into the surrounding medium in a number of different ways, ranging from collimated radio-plasma jets to UV and X-ray emission. The regions around the AGN are, therefore, highly complex and host a wealth of physical processes. Gas in different phases (atomic, molecular and ionised) is observed in this very hostile environment and the highly energetic processes related to the presence of the AGN are likely to have a *profound influence on the physical and kinematical properties of this gas*. Thus, the study of the gas provides ideal diagnostics to trace the relative importance of the various processes and the effect that the AGN has on the surrounding medium.

The energy released from the nucleus can produce gas outflows at very high velocities (thousands of km/s) as seen in many AGN, ranging from Seyfert galaxies to quasars. Gas outflows are detected as blueshifted absorption or emission line wings in optical, UV and X-ray spectra, (see e.g. Crenshaw 2001 and refs therein).

A number of mechanisms can be considered for the origin of such outflows. In radio-loud objects, they could be driven by the interaction of the radio plasma with the (rich) gaseous medium in the direct vicinity of the active nucleus. This effect is, for example, particularly evident in young radio sources where the newly born radio jet is making its way out of the galaxy. In high-*z* radio galaxies, such jet-cloud interactions are believed to be a mechanism for triggering star formation and indirectly explaining, e.g., the alignment between the rest frame optical continuum and their associated radio sources (van Breugel 2000).

However, a complication is that fast gas outflows have also been found in radio quiet AGNs. This has led some investigators to suggest that other mechanisms are at work and that some of these outflows are more likely driven by radiation- or wind pressure from the regions near the active super-massive black hole (i.e. a quasar wind).

A very interesting and surprising aspect of these outflows is that, despite the high energies involved, they are not only seen in ionised gas but also in *neutral* gas. A few examples of this phenomenon are now known. The first case where such a fast outflow of neutral gas was detected is the Seyfert galaxy IC 5063. Using the Australia Telescope Compact Array, we detected HI absorption up to 700 km/s blueshifted with respect to the nucleus in this galaxy, indicating an outflow of neutral hydrogen with at least these velocities (see below). More recently, using the Westerbork Synthesis Radio Telescope, we have found even faster outflows of HI (up to 2000 km/s) in the radio galaxies 3C293 and 4C12.50. These observations raise the interesting question of which mechanism can drive these fast neutral outflows. Large amounts of energy are needed to push the gas out at these high velocities, but despite these high energies, some fraction of the outflowing gas remains, or becomes, neutral.

The study of the ionised gas can provide a key complement to the neutral hydrogen and help in solving this puzzle. For this reason we have made a detailed optical follow-up study of the Seyfert galaxy IC 5063 using EMMI on the NTT. In general, Seyfert galaxies are particularly interesting objects for investigating the effects described above. They have strong emission lines coming from the ionised gas. Their narrow-line regions (NLRs, regions of highly ionised gas immediately surrounding the active nucleus) can be extremely complicated kine-

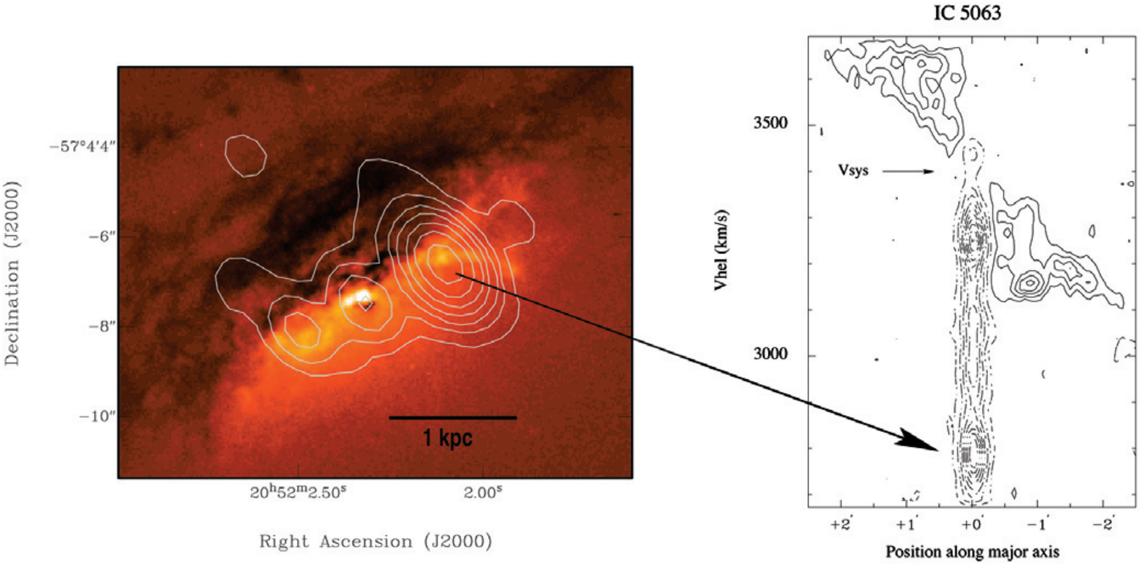

Figure 1: HST image with superimposed the radio continuum (from ATCA at 8 GHz). The radio shows three components, of which the middle one is the core. On the right is the position-velocity diagram of the HI showing the broad, blueshifted absorption (dashed). The location in the continuum image where the broad HI absorption occurs is indicated.

matically. Some of them are believed to represent the best examples of regions where interactions between the local interstellar medium (ISM) and radio plasma occur (Wilson 1997, Capetti et al. 1999). However, recent results based on HST observations (e.g. NGC 4151 and NGC 1068) have indicated that instead quasar winds may play a major role. They therefore represent ideal objects to study the importance of the impact of the AGN on its surrounding ISM. IC 5063 is, given its proximity and its characteristics, a perfect candidate for such a study. Apart from being an interesting case by itself, the results from this galaxy can shed light on what is going on in AGNs that are more distant, i.e. objects that cannot be studied in the same detail, such as radio galaxies and quasars.

The intriguing Seyfert galaxy IC 5063

The southern Seyfert galaxy IC 5063 (z = 0.0110) is classified as a Seyfert 2. According to the unified schemes for AGNs, this means that the broad-line regions (lines coming from ionised gas in close proximity to the AGN) are obscured from our direct view by the nuclear torus, but that it can be seen indirectly in scattered/polarized light. Strong and broad polarized Hα emission has indeed been observed in IC 5063.

IC 5063 is an early-type galaxy – not very common among Seyfert galaxies – that shows a complicated system of dust lanes. This is clearly seen from the HST image in Figure 1. The extended (about 15 kpc in radius) ionised gas has a very peculiar X-shaped morphology shown in Figure 2. This gas is ionised by photons from the AGN and the interesting shape is probably due to the obscuration of the AGN by the large-scale warped gas disc that is visible as the system of dust lanes.

The most intriguing characteristic of this object is seen in the radio (see Morganti et al. 1998 and Oosterloo et al. 2000 for details). IC 5063 is among the most radio-loud Seyfert galaxies known. In the radio continuum, it shows triple structure (Figure 1) of about 4 arcsec in size (about 1.3 kpc). Two very asymmetric lobes are situated at each side of the radio core. Despite being an early-type, the host galaxy is very rich in neutral hydrogen (almost 10^{10} $M_{\odot}$). A large, regularly rotating HI disc (of about 30 kpc in radius) is observed (Figure 2). Because of the strong radio continuum source, we were able to detect HI gas in absorption at very low optical depth. This absorption is indicated by the dashed contours in Figure 1, while the solid contours indicate the emission from the large HI disc. The absorption is highly blueshifted with respect to the centre of the galaxy. The systemic velocity can be accurately derived from the HI emission, and the absorption is unambiguously blueshifted. Follow-up VLBI observations showed that the broad blueshifted absorption occurs against the western and brighter radio lobe and not against the core (Oosterloo et al. 2000).

The obvious question is: what mechanism can produce such a fast outflow of gas, allowing it to remain, or become again, (partly) neutral? As mentioned above to better understand what is going on, the radio study needs to be complemented by a detailed study of the ionised gas. In particular, the kinematics and the ionisation level of the gas can shed light on whether a strong jet/cloud interaction is responsible for the outflow, or whether other processes must be invoked. This was the goal of our NTT observations.

The complex optical spectrum

IC 5063 was observed (in service mode) with EMMI on the NTT in the medium resolution spectral mode. The 0.8 arcsec-

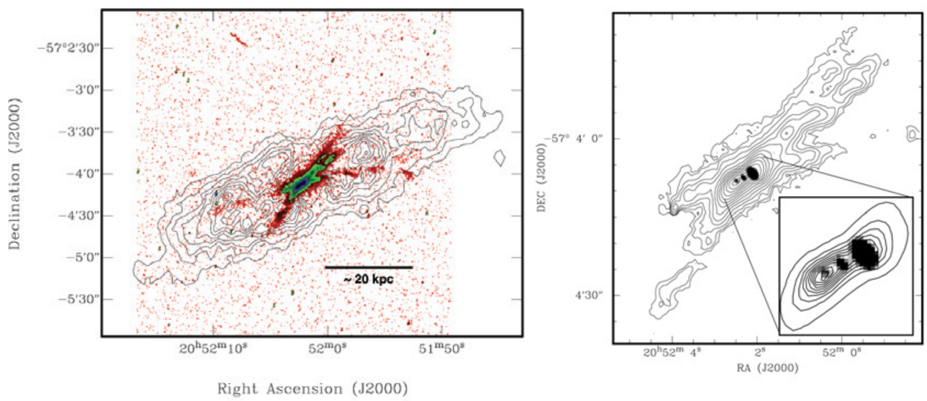

Figure 2: Left: the HI disk (contours) superimposed onto the image of the ionised gas ([OIII] 5007Å). Right: ionised gas (contours) superimposed onto the radio continuum (grey scale). In the central regions, there is an evident correspondence between the two.

wide slit was positioned along the radio axis. Spectra were taken in the blue and the red arm simultaneously. Gratings 12 and 7 were used, giving a spectral resolution of 0.92 and 0.66 Å/pix in the blue and in the red respectively. Therefore, we cover the wavelength range from [OII] 3727Å to [SII].

The spectrum shows a wealth of information with many emission lines, up to very high ionisation – in particular high ionisation Fe lines (as found by Colina et al. 1991). Most of the lines are spatially extended and because of the sub-arcsecond seeing of the observations, we can clearly separate the ionised gas at the location of the radio core from the location of the lobes, as illustrated in Figure 3. This is crucial for the success of the study. In fact, it allows us to investigate how the kinematics of the ionised gas relates with the radio structure. The extremely complex kinematics can clearly be seen in Figure 3. Different components are evident, with emission both from the disturbed gas as well as from the quieter and regularly rotating gas (i.e. the gas that follows the galaxy rotation as shown by the large scale HI emission). The region of highly disturbed kinematics extends almost 6 arcsec (almost 2 kpc), mostly in coincidence with the region where the radio emission is also present. Indeed, Figure 3 already shows an important result of this study, namely that the most extreme kinematics are detected *in the region between* the radio core and the bright radio lobe, and that, as for the neutral gas, a large blueshifted wing is clearly present near the western radio lobe. The *first order* similarity between the kinematics of the blueshifted wing of ionised gas and that of the HI is illustrated in Figure 4, where a direct comparison of the two can be made.

One interesting point to note is that the most extreme blueshifted velocities are displaced compared to the peak of the radio lobe and they appear to be located closer to the nucleus. The velocities become progressively less blueshifted as one approaches the peak of the radio lobe, producing a sort of "comma"-like shape. This can naively be interpreted as an indication of a decelerated flow: the flow gets slower as it approaches the position of the radio lobe where perhaps some "obstructing" material is present. This is, in fact, consistent with the detection of molecular gas (H_2) from NICMOS observations (Kulkarni et al. 1998) in the western region near the radio lobe.

In addition to the blueshifted wing, a very broad component is observed only in the region between the core and the western (stronger) radio lobe. This very broad component of ionised gas, however, does not appear to have a counterpart in the neutral gas. This may represent a component of highly shocked gas that is only seen as ionised.

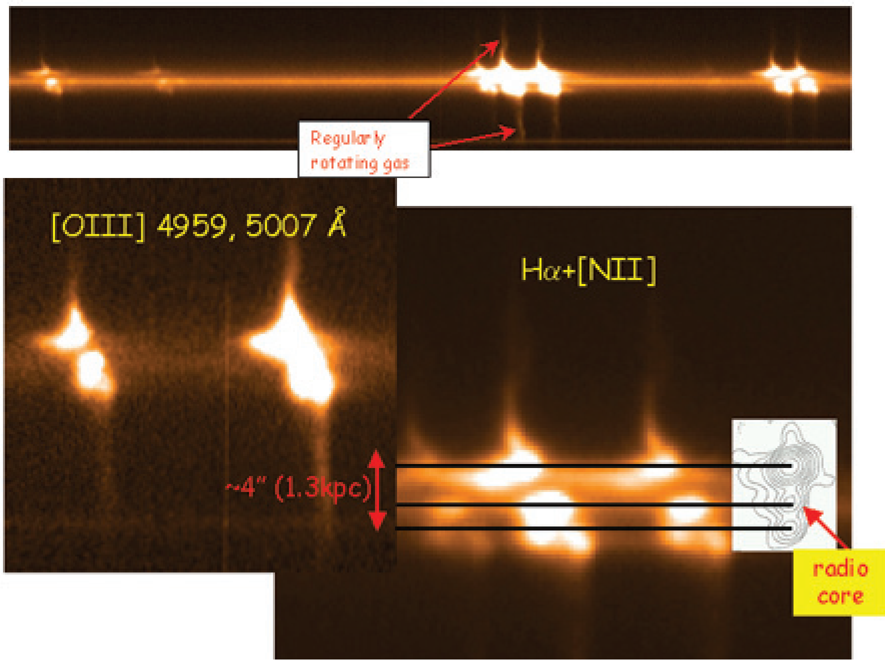

Figure 3: (Top) The spectral region from [OI] 6300Å to [SII], including the Hα+[NII] lines. With the contrast used, the different intensity of the lines allows to see different features: from the regular galaxy rotation at larger distance from the centre to the complex kinematics clearly seen especially from the [OI] lines. (Bottom) A zoom-in of the [OIII] lines. The radio image on similar scale is also shown. This allows a direct comparison between the structures observed in the radio and the kinematics of the ionised gas.

Taken all together, these properties clearly indicate that the interaction between the radio plasma with the ISM is responsible for the extreme kinematics observed both in the ionised and in the neutral gas.

Apart from the complex kinematics detected in the western region, the ionised gas in the eastern side also shows complex kinematics, in particular line splitting. Interestingly, this seems to extend *beyond* the radio emission (see below). It is clear that the gas kinematics on the two sides of the radio core are completely different, possibly reflecting some major differences in the properties of the ISM and/or that there are two different mechanisms acting.

Although it is obvious from Figure 3 that the kinematics are very complex, a quantitative analysis is required to fully identify the various kinematical components and to study their characteristics. As a starting point, we have used the strong [OIII] 4959, 5007Å doublet. A good description of each line typically requires between two and four Gaussian components. The same components were used to fit other emission lines (e.g. Hβ, [SII], Hα+[NII]) where only the relative amplitudes of the various components were allowed to change. These restricted fits gave good results in almost all cases.

Using the components found from the Gaussian fits, one can study the ionisation of the gas by, for example, looking at the ratio (for each component) of the [OIII] 5007Å and the Hβ emission lines. Although the extreme kinematics near the western lobe appear to be due to a jet/cloud interaction, that does not necessarily mean that all the gas is ionised through this mechanism. The ratio [OIII]/Hβ is found to be very high (> 10) for the narrow components close to the centre (up to a few hundred parsec from the nucleus). This component, being narrow, is likely not to be influenced at all by the interaction with the radio plasma and therefore the high ionisation is likely to be due to the UV radiation from the nucleus. In the remaining regions/components, the [OIII]/Hβ ratio is between 5 and 10, without any clear difference between the regions with extreme kinematics or the broad components. This suggests that the shocks, produced in the interaction between the radio plasma and the ISM, are not the dominant ionisation mechanism (even in the NW region).

This confirms what was derived from the energy budget argument (Morganti et al. 1998) and also what has been found from similar studies of radio galaxies, e.g. Cygnus A.

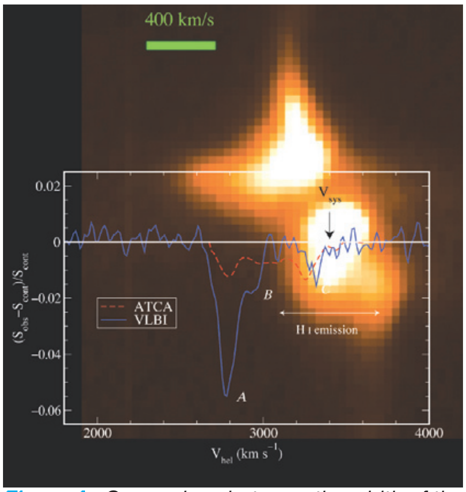

Figure 4: Comparison between the width of the HI absorption (white profile) and that of the ionised gas (from the [OIII]5007Å). The first order similarity between the amplitude of the blueshifted component is clearly seen.

Finally, the density can be measured using the ratio of the [SII] 6717/6731Å lines. The narrow component traces a decrease in the density going from almost 1000 particles cm^{-3} close to the nucleus to the low-density limit (<100 particles cm^{-3}) in the outer regions. Part of the reason for the decline of the [OIII]5007Å /Hβ can be the result of this density decrease.

A Possible Scenario

The kinematics of the ionised gas and the similarities compared to that of the neutral hydrogen, support the idea that we are observing a gas outflow in the region of the stronger radio lobe due to interaction between the radio jet and the ISM. This situation is conceivable because in IC 5063, the radio jet appears to be expanding in the galactic disc, therefore moving through a rich medium, as evidenced e.g. by the large-scale HI disc seen in emission, as well as by the presence of molecular gas from NICMOS observations (Kulkarni et al. 1998) detected in the western region near the radio lobe.

However, the question remains: *why, in such a hostile environment, is some fraction of the gas neutral?*

A possible scenario, illustrated in Figure 5, is that the radio plasma jet is interacting strongly with a molecular cloud in the ISM. Part of the gas is kinematically disturbed by the shock that is produced by the interaction. Once the shock has passed, some fraction of this gas may have the chance to recombine and become neutral, showing up as neutral gas at high velocities. To understand whether such a scenario is feasible, it is worth considering the model proposed for the evolution of clouds in radio galaxy cocoons when they are overtaken by a strong shockwave (Mellema, Kurk & Röttgering 2002). This model predicts that, as the shock runs over a cloud, a compression phase starts (as the cloud gets embedded in an over-pressured cocoon) and the shock waves start travelling *into* the cloud and the cloud fragments. By taking cooling into account, they derived that the excess of energy is radiated away on a time scale much shorter (a few hundred years) than the typical lifetime of a radio source (10^{6-7} yr). This process results in the formation of *dense, cool and fragmented structures at high velocities*. These clouds can contain neutral gas that can be seen in absorption, if located in front of the radio source. Whatever the details of the processes involved, the observations of IC 5063 show that neutral and ionised gas outflows co-exist and that the interaction between the radio plasma and the ISM is likely to produce both. This puts strong constraints on the physical processes in the centre of this galaxy.

What is the situation on the other side (i.e. the *SE* side) of the nucleus? Apart from the emission associated with the regularly rotating large-scale gas disc, a second component is seen, blueshifted compared to the quiescent gas and extending *beyond* the radio emission. It is hard to explain this component only by a jet-cloud interaction and the line split is perhaps more reminiscent of an expanding cocoon. It is worth noting that in other Seyfert galaxies radiation pressure from the nuclear emission has been proposed as the dominant acceleration mechanism. In addition to this, the clear asymmetry between the two sides of the radio source suggests that the conditions of the medium around the AGN are actually very inhomogeneous. This is likely to strongly affect the evolution of the radio plasma and its effect on the environment.

The detailed study of the nearby Seyfert IC5063 has a number of implications for other objects that cannot be studied with the same detail as IC 5063. In particular, we are now also finding broad blueshifted HI absorption in more distant *powerful radio galaxies* (the best examples so far are 3C293 and 4C12.50, Morganti et al. 2003). Moreover, in the high redshift universe, radio galaxies appear to live in very gas rich environments. Strong interaction between the radio plasma and this medium is likely to be even more common. What we learn from the study of nearby objects can therefore be of great help in interpreting what happens in their faraway cousins.

Acknowledgments

JH acknowledges a PPARC PhD studentship and a NOVA-Marie Curie Fellowship. She also wishes to thank the Kapteyn Institute, Groningen, for its hospitality where most of this work was done.

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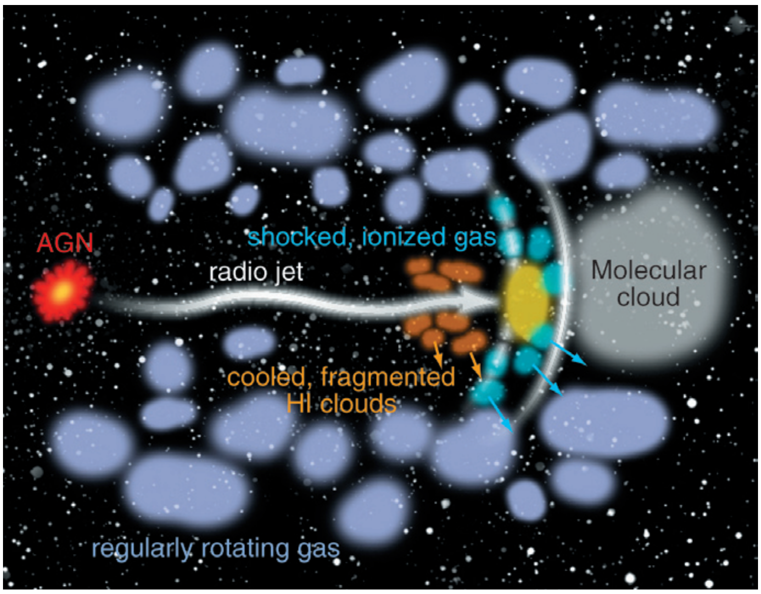

Figure 5: A schematic diagram illustrating the proposed scenario (as described in the text) and a possible geometric arrangement of the various emitting components in IC 5063.