THE EFFECTS OF X-RAYS FROM ACTIVE GALACTIC NUCLEI ON THE INTERSTELLAR MEDIUM OF THE SURROUNDING GALAXY

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ABSTRACT

I will outline some of the important unsolved problems concerning active galaxies, and then specialize to a discussion of some of the effects that an active nucleus can have on the large-scale properties of the host galaxy. In particular, I will discuss the effects of X-ray heating on the interstellar medium of the host galaxy.

1. OVERVIEW OF ACTIVE GALACTIC NUCLEI

There are many unsolved problems in the field of active galactic nuclei (AGNs). To tackle these problems we must first develop some idea of what the active galactic phenomenon is, that is, what makes a galaxy active. The following seem to me to be the four key properties that are shared by active galactic nuclei.

1. There must be some kind of very compact source of energy right at the center of galaxy. The evidence for compactness is primarily from variability.

2. There are often (but not always) extremely large rates of energy output. Optically, the most luminous AGNs are quasars. Although we still do not know for certain that a quasar is the nucleus of a galaxy, it seems extremely likely that it is. The quasars are distinguished by extremely large rates of energy output that can exceed the
output of all the other observable sources of energy inside the galaxy. The same is true for another powerful class of active galaxies, the radio galaxies. The energy output during the lifetime of a radio galaxy can be equivalent in some cases to the conversion of hundreds of millions of stars entirely into energy through mass-energy equivalence. So these engines at the centers of active galaxies can sometimes produce energy at tremendous rates and produce tremendous amounts of energy over their lifetimes. But that is not a necessary feature of an active galaxy. Very weak AGNs (such as may exist at the center of our galaxy) have also been observed.

3. There is evidence for rapidly moving gas. Quasars typically have broad emission lines. We believe that they are due to bulk motions of gas. The velocities are typically thousands to tens of thousands of kilometers per second. There are even more dramatic rapid motions in the form of jets. From indirect evidence, one can make the case that the velocities of jets are often very close to the speed of light.

4. The energy emerging from an active nucleus seems almost certainly not to arise in normal stellar processes. For one thing, the spectrum is not entirely dominated by thermal features, although there are what appear to be thermal features in some cases. Often there are comparable radiation fluxes in the infrared, optical, ultraviolet and X-ray bands, suggesting nonthermal radiation mechanisms. Also, much of the energy seems to emerge in jets, in many sources.

To the list above, one might add two changes in perspective which have been brought about by increasingly sensitive observations over a wide range of frequencies, during the past few years.

1. Until the widespread discovery and study of jets in radio galaxies, and of the connections between jets and quasar-like activity in the center of galaxies, it was not really appreciated that radio galaxies, Seyfert galaxies, quasars and several other classes of objects were actually different manifestations of the same AGN phenomenon.

2. The weak forms of activity, such as weak radio galaxies and LINERS, seem to be the most common forms of activity in galactic nuclei. Thus, the forms which were discovered first were simply the high luminosity tail of this phenomenon. It appears likely that activity at some level occurs in the nuclei of most or all galaxies, during some period of the galaxy’s life. Therefore, we want to address two important questions.

1. Why does activity occur so commonly? How does it arise naturally during the evolution of the galaxy.

2. Since activity in some cases can release tremendous amounts of energy, what are the effects of this energy on the evolution of galaxies to their presently observed states? We may need to understand the interaction of AGNs with their host galaxies before we can really understand the evolution of what we call typical normal galaxies. In other words, a normal galaxy may be active. Table 1 is the classification of AGNs, summarizing major radiative properties and correlations with galaxy type.

Figure 1 is a very crude picture to set the stage for what we think some of the structural elements in AGNs may be. (The scale on the left is logarithmic in parsecs. -5 is about 1 AU.)
Most people believe that the central engine is probably a black hole (B.H.) surrounded by some kind of accretion flow which interacts with the B.H. For convenience I call the accretion flow a "torus", but the geometric configuration is actually quite uncertain.

From variability, one guesses that the X-ray, UV and optical radiation is produced in a region very close to the central B.H. But the evidence is much less clear for the lower frequencies. The infrared may be produced by a combination of non-thermal processes very close to the central engine and reradiation by dust further out. We must consider optical depth effects in our calculations of AGN spectra. It is a particular problem in the case of Seyfert galaxies where we have some additional direct evidence that there is dust. The radio emission is produced further out. In most cases, with the exception of blazars, the radio and infrared do seem to vary somewhat more slowly than the high frequencies. Unfortunately, it is difficult for us to get a direct picture of AGNs on scales smaller than about a parsec. Perhaps improvements in very-long-baseline radio astronomy can reduce the observable scale by another order of magnitude, within the next decade. If current ideas are correct, however, it is very likely that opacity effects will prevent us ever making direct observations of the structure of AGNs in the radio on much smaller scales than about a tenth of a parsec. Observations on comparable scales in the IR, optical or UV will have to await the development of imaging interferometers operating at those wavelengths.

At least for the luminous examples of radio-bright AGNs, we know that on the scale of a parsec, there appear to be jets, and the jets usually appear to be one-sided. This is also the scale on which superluminal motion appears to occur, which is usually interpreted as evidence for relativistic bulk flow. We can diagnose some of the properties of the thermal gas because the emission lines with Doppler width greater than a few thousands km/s are also produced on this scale. Unfortunately, we cannot easily probe the properties of gas on much smaller scales simply because the radiation density becomes so high that the gas is heated to high temperatures and ionized to levels where it is unlikely to produce any observable emission lines. Of course, we
should continue to look for possible diagnostics that we can use on the gas.

It is very hard to say where the AGN ends and where the rest of the galaxy begins. It is not even clear what the question means. So, in fact, one might regard the narrow-line region (NLR) as the outer reaches of the nucleus, ranging from perhaps tens to hundreds of parsecs, where narrow emission lines appear to be produced. And there is evidence that there is a continuous distribution of gas between the broad-line region (BLR) and the NLR.

It is not clear to what distance from the B.H. the gravitational potential of the B.H. or central object dominates. It is likely to be a few parsecs. But even outside the place where the central potential dominates, it may well be that the radiation and other forms of energy released by the AGN dominate the properties of the gas. This is what I will start to talk about in a few minutes. Finally, we also know that active galaxies interact with their environment on a large scale, because we see the extended radio sources, extending with jets in many cases out to distances which may be as large as several megaparsecs.

Thus the active galactic phenomenon is one that not only involves some small self-contained engine or furnace at the center of the galaxy, but also emerges into the interstellar medium (ISM) of the galaxy itself. And an active nucleus may be important in the evolution of the galaxy as a whole because of the interaction between the AGN and its environment. To finish my introduction, I list some key problems in the study of AGNs.

1) Prime mover -- B.H. or other?
People have been building up a more and more complicated theory of how a B.H. would interact with its surroundings. But there are only very weak observational tests that have been suggested so far.

2) Central engine -- How to get the observed variety of energy output? What is the source of energy?
It is possible that much of the energy can come from the rotation of the B.H., but this still requires that a large amount of matter surround the B.H. Because the energy extraction from rotation of the B.H. relies on the interaction between the B.H. and its surroundings, we expect that at least some of the energy must come from accretion, and we must ask:

3) Where does the accreted gas (fuel) come from?
There is still some debate over whether the source of material flowing into the AGNs is local, in the sense that a B.H. may be embedded in some star cluster or very dense relic disk of gas which is slowly feeding the B.H. In that case we might treat an AGN as a self-contained machine, to place in a galaxy, turn the crank, and operate. Even if this picture has some truth to it, I think the material from time to time must be supplied by falling in from large distances. So, I think AGNs can not only have an important effect on the galaxy, but their operation depends crucially on the inflow of material from the galaxy or even from outside the galaxy. Several observational trends appear to favor this view. There seem to be correlations between activity and encounters of galaxies, which might trigger gravitational disturbances. Such disturbances might cause gas to lose angular momentum and fall toward the nucleus. A large fraction of Seyfert galaxies appear to possess stellar bars or ovals, which may produce similar dynamical effects. In a number of active galaxies, abnormally large quantities of molecular gas have been detected in the inner few kiloparsecs.

4) Finally, some more general considerations of the interactions between AGNs and their environment:
• What is the link of the active nucleus to the ISM? Is the NLR simply the ISM which is disturbed and perhaps illuminated by the AGN or is it a more direct participant in an accretion flow?
• What are the effects of energy from AGNs on host galaxies?
• What triggers activity?
• Is there any relation between the forms of (non-stellar) activity I have talked about and starbursts?
• What is the significance of activity in the context of the formation and evolution of a galaxy? Is the B.H. a central ingredient, for example, in forming a galaxy of the type that we see or is it a byproduct of galaxy formation? (Something that formed from the leftover
material? Are there any long-term observable effects of activity that persist long after the activity itself has subsided?

2. X-RAY HEATED WINDS AND CORONAE

I want to turn now to a more specific topic which is the effect of X-rays from an AGN on the ISM of the surrounding galaxy. I think there are very few theoretical problems in the study of AGNs which can be easily motivated and for which there are good reasons other than trying different things to find out what works. I think there are some good reasons for studying the X-ray heating problem. We know from direct observations that quasars and the nuclei of Seyfert galaxies are powerful X-ray sources. Their spectral index is approximately 1, which means that there are similar amounts of energy in every decade of frequency. If the radiation is incident on an ionized gas with no other strong cooling mechanism present, the temperature will tend to increase to a point where the inverse Compton cooling balances Compton heating. In the case of AGNs, where we have been able to estimate the spectrum over many decades, the inverse Compton temperature is given by

$$T_{IC} = \frac{1}{\frac{\hbar}{4k}} \int \frac{L_{hv}dv}{L_{v}} = 10^{8} \text{ K}.$$

In some cases, $T_{IC}$ may be slightly lower, but it is certainly very hot. That is a good reason to guess that X-rays will have some effect.

We now have evidence that some of the phenomena connected with X-ray heating are partially responsible for observed properties of type 2 Seyfert galaxies. This evidence concerns the gas on a scale of a few parsecs; I will describe it later. First, I will discuss the effects of X-ray heating on the ISM of a galaxy at large distances (kiloparsecs) from the nucleus.

We understand X-ray heating. Figure 2 is a diagram which illustrates the effect of X-rays on gas as a function of temperature and pressure, for a fixed X-ray flux.

Fig. 2. UV/X-ray heating vs. (two-body) cooling (heating = cooling curve)

The main thing that prevents gas from heating up to the inverse Compton temperature is cooling due to two-body collisions between the gas particles. Therefore, the cooling rate per particle increases linearly with the density of the gas at a fixed temperature. Because the heating results from the interaction between photons and gas particles, the heating rate per particle is proportional to the flux of radiation. If you solve the equation of thermal equilibrium (heating equals cooling) at $T \ll T_{IC}$ (so that Compton cooling is unimportant), you will find that the equilibrium temperature simply depends on the ratio of radiation flux to the density of the gas. A convenient way to describe the thermal equilibrium curve in Fig. 2 is to regard temperature (y-axis) as a function of the ratio of local radiation pressure to gas pressure (x-axis). When the ratio is very small, then the two-body interaction wins, and the gas can remain cool. But if you increase this ratio, eventually you reach a point where the cooling processes can no longer keep up with the heating and the gas suddenly heats. On Fig. 2, the lower flat line is the region in which the main cooling processes are atomic processes, i.e., line excitation due to collisions. At
higher temperatures, especially in the presence of X-rays, so many electrons are removed from the ions in the gas that there are no longer enough accessible transitions to give line cooling. Then, the main cooling mechanism becomes bremsstrahlung. The temperature as a function of the ratio in Fig. 2 is the line with negative slope. Because it has negative slope, bremsstrahlung is not efficient enough at keeping the gas cool as you increase the temperature, so, when the gas reaches the temperature in the line with negative slope it is thermally unstable. Once the gas starts to heat, it just continues heating up to the point where you reach the equilibrium between Compton heating and inverse Compton cooling (upper flat line in Fig. 2). It is like a phase transition. The details of this thermal instability are very important in the study of broad line regions. I will simply use the fact that once you get to this point, you have a situation of runaway heating, i.e., you are in a place where heating exceeds cooling, and the temperature starts to increase.

What happens when the X-rays from an AGN shine on cool gas in a galaxy? A related problem was studied several years ago. In compact binary X-ray sources in our own galaxy, we believe that there is an accretion disk in which the material is confined to the equatorial plane by the vertical component of the gravitational field, and supported radially by rotation. Generally, you would expect the gas in the accretion disk to be quite opaque. In other words, if you shine X-rays onto this gas from the outside, it will not be able to penetrate to the central plane of the disk. Furthermore, if the disk is very flat, then X-rays from the central region may not be able to reach even the surface layers of the disk. However, there is an argument that suggests that this disk may have a tendency to flare, as I show in Fig. 3. Suppose you are on the surface of the disk, where the gas density becomes very low. (Density is highest on the equatorial plane, and decreases as you go above or below the plane.) Then, you may be able to see the X-ray heating effect.

The heating of gas depends on the radiation spectrum and the ratio $\Xi = P_{\text{rad}} / P_{\text{gas}}$ mentioned in Fig. 2. The very high energy X-rays are most important when the gas is already hot. When gas on the surface of the disk starts heating, it is primarily heating up not because it is absorbing very high energy X-rays, but because it is absorbing far UV radiation that tends to heat up and ionize the species which are responsible for cooling. By ionizing it destroys the transitions which are able to cool the gas.

The gas in the disk has a certain pressure, which is highest on the equator because of the force of the gas pressing down under the influence of gravity. As you move above or below the central plane, the pressure decreases. At the same time, more and more of the radiation at a wider range of frequencies can penetrate the gas, because the optical depth is also decreasing. Although the gas inside the disk does not see radiation that can heat it to high temperature, we must reach a point near the surface of the disk where $\Xi$ comes to a critical point and the gas starts to heat up. This results in the presence of hot gas that is evaporated from the disk. I should point out that this heating does not always lead to a wind because there is an upper limit on the temperature that the gas can reach under the influence of X-rays. That is the inverse Compton temperature, about $10^8$ K. Instead, there will be a corona at radii where the virial temperature is greater than $10^8$ K, that is, out to $-10^4 - 10^5$ Schwarzschild radii. The corona, illustrated in Fig. 3, is an atmosphere of hot gas, sitting on the top of the disk. At larger distances, the gas will heat to a point where it can escape the gravitational pull of the B.H., and therefore you get a wind.
I am going to argue that it is this wind which has an important effect on the ISM of the host galaxy. In both AGNs and compact binaries, this type of wind can have a number of interesting effects, including dynamical effects - the wind can carry away a large amount of angular momentum, therefore can be important in determining the outer boundary of an accretion disk. If you insert some material into orbit around a compact object at a particular radius, and there are viscous forces which transport angular momentum, then angular momentum tends to be transported outward. In the inner part of the disk, matter flows inward, but some matter must flow outward in order to carry away the excess angular momentum. Now mass loss due to the X-ray heated wind increases outward. Therefore it is possible to evaporate material from the outer part of the disk, and to get rid of all the extra angular momentum in this way. Another interesting effect occurs because the mass loss rate may be larger than the accretion rate. It is possible that this type of wind may cause the accretion to become intermittent.

Below are some typical quantities characterizing a Compton-heated wind from an accretion disk surrounding a $10^8 M_\odot$ solar mass black hole in an AGN. $L_E$ is the Eddington limit ($\sim 1.3 \times 10^{46} M_\odot$ ergs s$^{-1}$) and $L_{46}$ is the luminosity in units of $10^{46}$ ergs s$^{-1}$.

Compton Temperature $T_{IC} = 10^8 K$

Corona exists where $T_{IC} < 0.15 T_{virial}$

$R_{corona} = 1.5 \times 10^{17} M_\odot$ cm

Total Mass Loss Rate $\dot{M} = (6.45) \times \frac{L_{46}}{TICB(L/L_E)^{1/3}} \left(\frac{R}{R_{cor}}\right)^{1/3} M_\odot$ yr$^{-1}$

Scattering Optical Depth $\tau_{max} = L/L_E$

Relation to Accretion Rate $\frac{\dot{M}}{\dot{M}_{accretion}} = \frac{(3-20)}{TICB(L/L_E)^{1/3}} \left(\frac{R}{R_{cor}}\right)^{1/3} > 1$

If the source is very luminous, then the gas will be able to heat all the way to the inverse Compton temperature before it escapes from the vicinity of where it starts. In that case, it goes through a sonic point near the disk. It escapes with a speed similar to the sound speed at the inverse Compton temperature.

If the heating is slightly weaker, then it will heat up to escape temperature in less time than the free fall time. Again, gravity is unimportant in preventing or slowing the escape. This is a free escape of hot gas, but the gas does not have to heat all the way to the inverse Compton temperature. It escapes at some lower temperature, but still not hindered by gravity.

In the third case, when the heating is very weak, it takes longer than the free fall time to heat up to escape temperature. Here gravity must be important; the gas is confined by gravity as it is being heated. However, that does not stop the escape because if you wait long enough, the gas will always heat eventually to the inverse Compton temperature and will be able to escape. In this case, the time scale for heating that is important is the time scale for heating to the escape (virial) temperature, and the characteristic speed is the radius (distance from the center) divided by the heating time scale. This is the regime of heating that is most important for X-ray heating of the ISM in AGNs. This is very weak heating. In fact, it is so weak that the gas probably does not go through a sonic point. It is really slow evaporation of gas from the system. Nevertheless, because the pressure is fixed and the heating time is very long, there can be a large mass loss.

It turns out that the optical depth in the wind is quite low, so we know something about the flux of radiation if we know the luminosity of the central source. Thus we know the radiation pressure. We can calculate the pressure at the base of the wind by looking at the heating and cooling diagram (Fig. 2) to determine the crucial ratio at which the heating starts. It turns out that the ratio corresponds roughly to radiation pressure equal to a few times the gas pressure for a typical AGN spectrum.

In this theory, the pressure at the base of the wind is fixed by the atomic physics and heating and cooling processes. The pressure in the wind which emerges and escapes the gravitational potential deter-
The momentum flux in the wind. So, in this type of wind, it is not primarily the mass flow that is most directly determined by the parameters of the system. There is no fixed amount of mass flow and there is no fixed amount of energy in the wind. It is the momentum per unit area which is fixed. This is the crucial physical result that comes out of the heating and cooling theory. Thus, we have

\[
\text{MOMENTUM OF WIND: } P_0 = P_0 (\text{fixed by L_R})
\]

\[
\text{MASS LOSS: } \dot{m} = \frac{P_0}{V_{\text{char}}}
\]

\[
\text{ENERGY USED: } \dot{E} = P_0 \cdot V_{\text{char}}
\]

where \(V_{\text{char}}\) is the characteristic flow speed. If the wind goes through a sonic point, the speed will be some constant times the speed at the sonic point. Because Compton heating is basically a very inefficient heating process, it is difficult to absorb a large fraction of energy in heating the gas. But if you have inefficient heating, and low characteristic speed, that has the effect of giving you a very large mass loss rate. So, very little energy needs to be absorbed in order for a large amount of gas to be evaporated from the disk.

If the mass loss rate is much larger than the accretion rate, the outer part of the disk can be evaporated and completely blown away by the heating. The inner part does not get evaporated, because the inverse Compton temperature is not high enough. Therefore, when the inner part finishes accreting, there is nothing left, and the X-rays turn off. The cycle starts again with the material building up in the disk. This intermittency occurs because of the time delay involved in gas traveling between the place where the wind starts and the inner part of the disk, where the X-rays are produced. There is some observational evidence that this type of wind may be responsible for partial eclipses in X-ray binaries. We cannot yet measure polarization in the X-ray, but this will be an important test of the theory. Broadening of emission lines from the disk may also result from scattering by the wind. There is some additional observational evidence connected with type 2 Seyfert galaxies, which I will discuss later.

3. X-RAY HEATING AND THE ISM

The ISM is not a quiet place, it is a very dynamic system. It has the structure that we observe because there is a continual supply of energy from stellar evolutionary processes, as well as continual recycling of gas.

In the inner ten kiloparsecs of the Milky Way, the energy supply to the ISM is a few times \(10^{41}\) ergs s\(^{-1}\). How does that compare with the energy that can be supplied by X-ray heating? X-ray heating is not a very efficient source of energy, but it can be significant, because the total luminosity of an AGN can be several orders of magnitude higher than the total energy budget of the ISM. The amount of energy that is absorbed is smaller by a factor of order the optical depth, which may be only \(10^{-3}\) for a large-scale X-ray heated wind in a galaxy, and another factor of order \(kT_{\text{IG}}/mc^2\), where \(m\) is the electron mass.

The first factor arises because the luminosity is a small fraction of the Eddington limit, when we consider the mass of the whole galaxy, not just that of the B.H. The second factor comes from the fact that the photons behave like very light particles hitting heavy particles unless their energies are comparable to the rest mass energies of electron, i.e., the collisions are nearly elastic.

There are two effects which help X-ray heating to be more effective, compared with other forms of energy which might also heat the ISM.

1) X-ray heating is uniformly spread in the sense that anywhere the X-rays go, the gas will get heated to a certain extent. Heating by Supernovae and stellar winds is much less uniform, and much of the energy may be lost to the galactic halo through hot exhausts.

2) X-ray heating destroys important coolants, stripping electrons from atoms and thus decreasing the number of transitions that can be used to cool the gas. So gas exposed to X-rays can be heated by other means more effectively, because it is less able to cool by collisions.

Under typical conditions in the ISM, where will the X-rays from an AGN cause runaway heating? If the pressure in the ISM is large
enough, compared to the radiation pressure, then the gas will not
necessarily heat. Unfortunately, we know very little about the ISM in
most galaxies other than our own, and perhaps several very nearby
galaxies. In fact, we do not know whether the ISM in Seyfert galaxies
or in the galaxies which we assume surround quasars is at all similar to
our own. It is possible that it may be quite different. But right now,
the best we can do is to assume that the host galaxy starts out with an
ISM similar to our own and try to calculate what would happen if the
quasar or Seyfert nucleus were to turn on in the center. I will
describe a model based on that assumption.

For a typical spiral galaxy with a flat rotation curve, $v_{\text{rot}}$,
-250 km s$^{-1}$, the temperature at which the gas is no longer effective
held by the galaxy (by the local part of the galaxy potential) is a few
million degrees. But the X-rays are trying to heat the gas to a
temperature that is much larger than that. So if you wait long enough,
the gas that starts heating will continue to heat until it can escape
the galaxy. To be more precise, we must use the correct gravitational
potential of the galaxy. We have very good evidence that galaxies have
large halos which are approximately like isothermal spheres. Therefore,
the potential at the center of the galaxy may contain a logarithmic
factor which would make it more difficult for gas to escape. As the gas
is heated and tries to escape from the gravity of the central part of
the galaxy, it finds that it encounters gravity of more and more mass.
This is counterbalanced by the fact that X-ray heating continually heats
the gas, so there is a continual source of energy into the gas. The
difference between considering the escape from a point mass and escape
from a logarithmic potential is only a factor of a few in mass loss
rate.

What, then, is the pressure in the ISM; is it sufficient to
avoid heating, or not? The answer for the typical ISM in our galaxy
with a pressure of somewhat less than $10^{-12}$ dynes cm$^{-2}$, is that the gas
will undergo runaway heating out to distances as large as 20 kpc for a
typical quasar luminosity. So X-ray heating will certainly be important
in the inner few kpc for most of the luminous Seyferts and virtually all
quasars if the ISM has a pressure close to the typical value.

If you assume that the ISM is a disk and apply the simple X-ray
heated wind theory for a flaring disk, you get a huge rate of mass loss
of over 100 solar masses per year. It is not clear that this is
realistic. You may not be able to maintain such a mass loss rate for
very long. If you carry the analysis of an ISM like our own one step
further, you might want to include the fact that material is continually
replaced by the evolution of stars. And if you adopt a typical
replacement rate for Population II stars from the literature, and try to
balance that against the mass loss rate, then you find that in the inner
few kpc, you can prevent any cool gas from persisting in the ISM in a
steady state. Somewhat further out, you may be able to replenish the
gas rapidly enough to maintain some cool ISM, but you still can't stop a
steady wind coming from the ISM. It is only at large distances that the
ISM may begin to have a fairly normal structure, although if the X-rays
get out that far, then much of the ISM may still be photoionized. In
fact, there is enough hard radiation to photoionize a large region (tens
of kpc) around the AGN.

If you assume that the mass injection rate follows the light in
the stellar disk, and the surface brightness of the disk has an
exponential structure, then there is a threshold luminosity, such that
once the ISM is cleared out beyond the place where the exponential turns
over, then the entire cool ISM will evaporate. This is true only if the
system has enough time to reach a steady state. The thing that lessens
the effect of X-rays on a real ISM is that the luminous phase of an AGN
may only last for a certain period of time. Unfortunately, we don't
know how long an episode of activity lasts. X-ray heating is a rather
slow process: it takes some time to create the outflow, and to actually
evaporate the material of the disk. Here is an estimate of the time
scale for heating the gas of the disk up to a temperature at which it
can escape:

$$t_{\text{heat}} \approx 7 \times 10^6 \left( \frac{v^2}{250} \right) \left( \frac{T}{10^8} \right) \left( \frac{R}{10^4 \text{ kpc}} \right) \text{ yr}$$

This time scale can be quite short for distances of 1 or 2 kpc,
but for several kpc or a low luminosity AGN the time scale is quite
large, and easily exceeds $10^8$ or $10^9$ years. If it exceeds $10^9$ years, it becomes very doubtful that there is enough time to establish a steady state. Instead, we need to study the time dependent solution to this problem. What happens if you have a "normal" ISM (like the one in our galaxy), and an AGN suddenly turns on? To answer this question, we must consider the fact that there are some important differences between the structure of the ISM and that of an accretion disk.

Figure 4 is my simplified model of the ISM in our galaxy and, presumably, in most spiral galaxies. Seyfert galaxies are known to be spirals. For my purposes, all of the violent phenomena that normally affect the ISM are not important because I assume that heating by the AGN will dominate over them. But at the next level of approximation, they can be important.

I simply assume that there is a thin layer of giant molecular clouds and a thicker layer of neutral hydrogen. In this case, it is not clear that the disk will flare so that all parts can see the center; maybe that will be true in the outer regions. In fact, the precise geometry of the disk doesn't matter, since I argue that the X-rays will always be able to eat away at the inner edge of the ISM, provided there is no inner disk that can prevent the X-rays from reaching the ISM. Thus, the radius at which material is being heated gradually increases with time. There are some Seyfert galaxies in which the gas in the inner few kpc appears to be disturbed. I think there is a chance that the disturbances are due to some of the effects that I am describing.

The ISM, particularly the giant molecular cloud (GMC) component, is extremely opaque to much of the hard radiation. Certainly, the UV and the soft X-rays cannot penetrate to large distances. Therefore, the heating will tend to occur on a surface layer as in the case of an accretion disk. Heating will probably not occur beyond a relatively narrow surface layer for two reasons:

1) The opacity is wavelength-dependent. Even if the hard X-rays penetrate the ISM, the onset of runaway heating will not occur without UV and soft X-ray radiation.

2) Most of the photons are absorbed in the surface layer, so gas in the surface will tend to compress the gas behind it to a pressure which is comparable to that of the radiation. If you remember my early comments on the necessary conditions for runaway heating, the result is that you only get heating if the radiation pressure is larger than gas pressure. Therefore, you would not get heating beyond the surface layer, even if a fraction of the UV and soft X-rays managed to get through.

We can calculate, from the theory of the wind, how fast the material is blown away. In the HI layer, the material is blown away at a rate so that the hole in the center will grow to a radius of order kiloparsecs if the source is a luminous quasar which remains on for $10^7 - 10^8$ years. In a low luminosity source, such as a Seyfert, the hole may not be nearly as large. Thus, one evidence for quasar activity in a galaxy's past might be a hole that is larger than one might expect from the present activity of a Seyfert.

Once such a hole is formed it is not clear how long it takes to erase it. If you have to rely on direct replenishment of gas by stellar evolution, it will probably take an extremely long time, more than $10^9$ years. If there are gravitational effects which can transport material into the center very effectively, it may take much less time. Central holes which have been observed in the ISM of some spiral galaxies may be scars of past activity.

One can carry this simple model of X-ray heating somewhat further to study, e.g., the influence of X-ray heating on GMCs, which are much denser and have a small cross section to the X-rays. They tend
to be left behind when the HI gas is evaporated. The HI layer is removed first out to a large radius, then you are left with exposed GMCs. Eventually, the GMCs will also be evaporated. An additional side effect of the evaporation will be the development of noncircular velocities in the GMCs, which may be as large as 500 km s⁻¹. The radial acceleration is driven by a combination of direct radiation pressure and the back pressure of the evaporating gas (rocket effect), both of which act on one side of the cloud only.

There is some evidence for X-ray heated winds in some Seyfert galaxies. I will summarize some of the observational features that may result from this kind of process. Unfortunately, most of these observational features provide somewhat indirect evidence for the processes described above. They do not immediately tell you that they are associated with X-ray heating, and there are other processes that one can imagine that can produce similar effects. It would be more convincing if several of these features are observed together in a particular source rather than any one of them. I have mentioned some of these signatures already.

1) The photoionization of a large fraction of the ISM in a galaxy is seen in some cases. But that does not necessarily mean that there is a wind. There should be a large amount of shadowing, because the ISM is highly inhomogeneous and the optical depth is large. Therefore, you would expect the line emission not to be spread uniformly, but rather to be quite patchy. You might see shadows of individual molecular cloud complexes.

2) The evaporation of GMCs and HI clouds would produce an unusual velocity field.

3) The onset of the wind at a particular pressure means that any clouds you see should be at the characteristic pressure corresponding to the onset of heating. This is perhaps the clearest diagnostic test of X-ray heating. If you have some way of measuring pressure, e.g., from forbidden lines, then, the pressure decreases as the inverse square of distance from the nucleus. There is a claim in the literature that in some Seyfert galaxies this sort of scaling is observed.

4) One might associate this type of process with the creation of a hole in the inner region of the ISM. I do not want to claim that the holes that are observed in the molecular and atomic gas in our ISM and that of other nearby spirals are associated with the same process. I think there may be other processes that can create this type of structure, e.g., processes associated with gravitational dynamics.

5) X-ray heating should also create a low column density in cool gas, hence there should be a very weak soft X-ray cutoff. I believe that there is essentially no detectable EUV/soft X-ray absorption along the line of sight to 3C273.

More direct evidence for a wind would be provided by measurement of the velocity field of the wind itself (as opposed to the noncircular velocities of clouds induced by the rocket effect). I think that it will be very difficult to make such a measurement, because the X-ray heated wind speed is very slow, slower than the escape speed from the galaxy. The more feasible observation would be to look for either scattering by the wind or some evidence of X-ray lines. The difficulty with this is that the optical depth on a galactic scale would tend to be very small. However, on a smaller scale I believe that we have already seen direct evidence of X-ray heated winds. This is in the case of type 2 Seyfert galaxies.

4. X-RAY HEATED WINDS IN TYPE 2 SEYFERTS

In the usual classification scheme, type 2 Seyfert galaxies differ from type 1 Seyferts (and quasars) primarily in that they do not show very broad emission lines. One might think that perhaps there is a different structure in this object, and there is no gas present emitting broad emission lines. Other features which distinguish type 2 Seyferts from type 1 Seyferts have become known over recent years. The most important are that type 2's tend to be weaker X-ray sources than type 1's, and the ratio of their radio emission to their optical emission is larger.

About 2 years ago, in NGC 1068 (a typical type 2 Seyfert), Antonucci and Miller found a result which I think is one of the most
interesting observations of AGNs in recent years. When you look at the total line emission of a type 2 Seyfert, you see the typical spectrum with just narrow lines, which are unpolarized (or very weakly polarized). But when we restrict our observation to polarized flux, then NGC 1068 and some other observed Seyfert 2's look like type 1 Seyferts. In other words, the polarized spectrum of NGC 1068 contains broad emission lines with roughly the same profiles and ratios as in a normal type 1 Seyfert galaxy. The degree of polarization of the continuum (about 15% in the case of NGC 1068) is independent of wavelength. Furthermore, the equivalent widths of the narrow lines in type 2 Seyferts are larger by about a factor 10 than the equivalent widths of narrow lines in type 1 Seyferts, and the ratio of narrow lines to X-rays in type 2 is higher than in type 1.

If we suppose that the narrow lines are the same in Seyfert 1's and Seyfert 2's, then the observations of Seyfert 2's imply that the optical continuum and X-rays are depressed by a factor of 10. But when you look at the broad lines in polarization, the ratios of broad lines to X-rays and broad lines to optical continuum are the same as in type 1's. There is a very simple geometric interpretation for this: we are observing Seyfert 2's, NGC 1068 in particular, along a line of sight from which we cannot see the central source of optical continuum, the X-rays, or the broad lines directly. Rather, we can only see them indirectly in scattered light.

The NLR is further from the nucleus than the BLR. So, if we have a sheath of some obscuring dust with a hole in it, perhaps in the form of a torus, it is quite possible that the NLR could be above the hole in the torus (shown in Fig. 5). We could then see the unpolarized line radiation from the NLR directly. But we only see the fraction of the light from the BLR, the X-rays and the optical continuum which is scattered into our line of sight, presumably by electron scattering. Electron scattering is the most common form of scattering mechanism which doesn't introduce frequency dependence. The polarized part looks the same as in a type 1 Seyfert, where we presumably see everything directly, and where there is very weak polarization.

Fig. 5. The molecular torus in NGC 1068

Thus, there is quite good evidence that a picture like this could be correct. Recently, with the analysis of IRAS data, it seems that type 2 Seyferts are particularly luminous in the infrared, which is exactly what you would expect if much of the primary radiation is being absorbed by dust in an opaque torus. The dust in the ring of gas would re-radiate a large fraction of the optical, UV and X-ray radiation in the form of IR. Thus, there is observational support for this picture over a wide range of wavelengths.

Now, it seems that this torus of gas is not aligned with the disk of the spiral galaxy. Thus, the angular momentum of this gas is not the result of material flowing in from the large-scale galactic disk. This poses a very interesting puzzle: What determines the axis of this disk? There are several examples of this phenomenon now. Miller et al. have observed radiation from inside the torus scattered or reprocessed on the ISM in the disk of the galaxy, indicating directly that the hole in the torus is not aligned with the rotation axis of the galaxy.

In order for electron scattering to occur, there must be warm electrons situated as shown in Fig. 5, with an optical depth of about 0.1. They cannot be warmer than about $10^6$ K because otherwise they would broaden the broad lines too much. So, from the width of the scattered broad lines, we can put an upper limit on the temperature. That is a very interesting conclusion, because it is difficult to understand how that many electrons covering such a large volume could
remain at a temperature of $10^6$ K. If you look at the heating and cooling curve (Fig. 2), $10^6$ degrees is not a temperature where gas likes to remain. It is a very unstable temperature. Such gas is probably either in the process of cooling down, or in the process of heating up.

Krolik and I have tried to understand how this configuration might have come to exist. The density and temperature of the electrons fit very well with the theory of X-ray heated winds. We predicted, according to this idea, that the amount of matter flowing out in the wind is about 1 solar mass per year, which is about 20 times the rate at which material needs to be accreted in order to power the central source.

We can get an idea of the orientation of the torus projected on the sky, because of the direction of polarization. This object has a jet, and the polarization vector is exactly perpendicular to the jet on the sky. This suggests that whatever determines the orientation of the torus also determines the orientation of the jet.

5. **A SUMMARY OF SOME OF THE EFFECTS OF X-RAY HEATING**

- AGNs may be wasteful of their fuel. You may have to supply much more mass than what you would estimate from the luminosity of the AGN.

- The existence of the wind may make it difficult for a steady accretion flow to be self-consistent in some cases. Some kind of self-shielding may be necessary, or at least the degree of self-shielding may be important in determining the observed properties of an AGN.

- When the X-rays do reach a large radius and hit the ISM of the galaxy, there may be a very large effect. I think the physics of this problem is better determined than the physics in most AGN problems. I think this is a particularly interesting area because the X-rays and UV hitting the ISM and NLR make them light up. When we have a good telescope for observing the UV on small scales, then we can really study the ISM of active galaxies. The Hubble Space Telescope is good for this study.

- My final message is that X-rays from an AGN may be hazardous to the gas in the galaxy which hosts the AGN.

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