WHERE TO LOOK FOR RADIATIVELY INEFFICIENT ACCRETION FLOWS (AND FIND THEM)

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Submitted to ApJL

ABSTRACT

We have studied the nuclear emission detected in high-resolution radio and optical data of carefully selected samples of low luminosity AGN (LLAGN) in the local universe. When the Eddington ratio is plotted against the nuclear “radio-loudness” parameter, sources divide according to their physical properties. It is thus possible to disentangle between nuclear jets and accretion disks of different radiative efficiencies. If this simple interpretation is correct, we now have a powerful tool to investigate the nature of the nuclear radiation, and identify radiatively inefficient accretion flows (RIAF) candidates. Our results show that the best chance of investigating RIAF processes in the IR-to-UV spectral region is to observe (at the resolution provided by HST) the nuclei of unobscured Seyferts of the lowest luminosity, as well as a sub-class of LINERs. In all other objects other radiation processes dominate. In a sample of 132 LLAGN we identify 8 objects in which we predict the radiation from a RIAF can be directly detected.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: jets — accretion, accretion disks

1. INTRODUCTION

Models of radiatively inefficient accretion flows (RIAF) were originally developed to reproduce the low state of activity observed in Cyg X-1 (Ichimaru 1977). They were later discussed in relation to AGN (Rees et al. 1982, Fabian & Rees 1995) in order to account for the lack of activity not even at the levels predicted by Bondi accretion (Bondi 1952). The models are based on the possibility that at low accretion rates a physical solution for the accreting flow involves low density, hot, optically thin gas, which is also radiatively inefficient. This regime would occur instead of that of optically thick, geometrically thin gas, which is radiatively inefficient. This region would occur instead of that of optically thick, geometrically thin disk accretion (“Shakura–Sunyaev disks”). While the theoretical effort to characterize accretion at very low rates has been impressive (Narayan & Yi 1995 and many papers since then), direct observations of RIAFs still lack behind.

Low luminosity AGN (LLAGN) are the class of extragalactic objects in which RIAFs are most likely to be at work. They show some level of activity (compact radio emission with high brightness temperatures, line emission, nuclear X-ray emission) which in the majority of the objects cannot be explained in terms of processes other than a faint active nucleus powered by the central supermassive black hole. However, because of their intrinsic low luminosities, it is extremely difficult to study the emission from RIAFs in LLAGN. This holds in particular for the wavelengths at which the spectral differences between RIAFs and “standard” accretion disk models are expected to differ the most, i.e. the IR-to-UV spectral region. RIAFs should lack both the “big blue-bump” and the IR (reprocessed) bump, which instead characterize optically thick, geometrically thin accretion disk emission and the surrounding heated dust (e.g. Elvis et al. 1994).

While it is now possible to routinely disentangle the nuclear emission from that of the host thanks to HST (e.g. Ho & Peng 2001, Chiaberge et al. 1999, 2003, Capetti & Balmaverde 2005), the RIAF emission cannot be seen when it is swamped by other nuclear radiation processes, or obscured by dust. M 87 (Di Matteo et al. 2003) is a clear example of that, where the nuclear emission at all wavelengths is dominated by non-thermal synchrotron radiation. Maoz et al. (2005) have shown that among a sample of 17 LLAGN, 15 of them show variability over a timescale of a few months, which demonstrate their non-stellar origin. However, it was still unclear from their work whether the nuclear radiation is from a jet or from the accretion flow.

Recently, among LLAGN which show very low Eddington ratios $L_{bol}/L_{Edd} << 10^{-3}$, Chiaberge et al. (2005) have found that a class of LLAGN, mainly composed by LINERs and low-luminosity Seyfert 1 galaxies, show faint unresolved optical nuclei in HST images that may be interpreted as direct radiation from a very low efficiency accretion flow. In fact, that work shows that when the radio-optical properties of LLAGN are considered, Seyfert, LINERs and low luminosity (FR I) radio galaxies separate into different regions of diagnostic planes, according to the properties of their nuclei. If this interpretation is correct, we now have a powerful tool to identify the nature of the nuclear radiation (i.e. jet-dominated or accretion-dominated). This picture appears to be confirmed by the nuclear SED of the low luminosity Seyfert galaxy NGC 4565, which shows very low obscuration and lacks the typical signature of standard accretion (Chiaberge et al. 2006).

In this Letter, by expanding the sample of LLAGN, we discuss what is, in our view, the most efficient way of identifying a sample of objects that are most likely to host a RIAF and in which IR-to-UV radiation from the accretion process can be directly studied.

2. IS THE ‘‘FUNDAMENTAL PLANE OF BLACK HOLE ACTIVITY?’’ A DIAGNOSTIC PLANE?
LLAGN have been found to lie on the so-called “fundamental plane of black hole activity” (Merloni et al. 2003; Falcke et al. 2004), which has the great merit of attempting a unification of all sources associated to black holes, over a large range of masses and luminosities, from Galactic sources to powerful quasars. But the origin of such a “fundamental plane” and its relationship with the physical properties of the source is still a matter of debate (e.g. Bregman 2003; Koerding et al. 2003). Here we want to test whether such a plane can be easily used for discriminating between different radiation processes associated to inflows and/or outflows around black holes, with the aim of finding RIAF candidates.

We perform a simple test, to check whether objects with different emission processes and of different physical origin are located in distinct regions. The “fundamental plane” is based on the radio and X-ray luminosity, combined with the black hole mass, which is the ultimate “energy source” for the radiation we observe in the form of inflows (accretion) or outflows (jets). However, if we check where other sources of radio and X-rays that are not associated to black holes are located in this plane, we find something intriguing. We take the radio and X-ray fluxes of solar system objects, together with their masses, and we over plot them onto the “fundamental plane of black hole activity”. Unexpectedly, the Sun, the Moon, Jupiter and Saturn do fall on the same plane, although they are tens of orders of magnitudes fainter and less massive than all “black hole” sources (Fig. 1). In fact, the radiation processes that originate the emission from the solar system objects are varied. While it is well known that we observe thermal radio emission from the quiet Sun, Saturn, the Moon and Jupiter (below 3cm), scattered solar radiation is the origin for the X-ray emission of the Moon and probably Saturn, high ionization emission lines dominate in the X-ray Sun and Jupiter (see e.g. Manson 1977; Kraus 1986; Schmitt et al. 1991; Ness et al. 2004; Branduardi-Raymont et al. 2000).

This implies that such a “fundamental plane” might be telling us something profound associated with the emitting power of all sources of radio and X-ray radiation, but cannot be easily used as a diagnostic to discriminate between different radiation processes. On the other hand, the apparent correlation might only be a result of mere plotting luminosity vs. luminosity, and “artificially” rescale the quantities with the mass (Bregman 2005). We speculate that a closer look at the scatter of the “correlation” might lead to more physical information than just trying to reproduce it assuming “a priori” different models. However, as we show in the following section, in order to discriminate different radiation processes (and eventually find RIAF candidates) we should use diagnostics that enhance the differences.

3. HOW TO FIND RIAFS: NUCLEAR RADIO LOUDNESS AND EDDINGTON RATIO

In order to explore the nuclear properties of all kinds of LLAGN in the local universe with the aim of searching for RIAF candidates, we consider the following samples:

1) 33 FR I Radio Galaxies (i.e. low luminosity radio galaxies) from the 3CR catalog (radio selected) (Chiaberge et al. 1999).

2) 25 Seyferts from the Palomar Survey of nearby galaxies and from the CFA sample, clearly limiting ourselves to those belonging to Type 1, i.e. unobscured, (optically selected Ho & Peng 2001).

3) a complete sample of 21 LINERs from the Palomar Survey of nearby galaxies (optically selected Ho et al. 1997).

4) 51 nearby early-type galaxies (E+S0) with radio emission $> 1$ mJy at 5 GHz (optical + radio selection) (Capetti & Balmaverde 2003, and references therein). The large majority of the galaxies in the sample are spectrally classified as either LINER or Seyfert.

5) the 12 broad-line radio galaxies with $z < 0.3$ included the 3CR catalog (Chiaberge et al. 2002, and references therein).

Samples 1, 2 and 3 have been examined in detail in (Chiaberge et al. 2003). Note that being selected according to different criteria, these objects do not constitute a complete sample. However, they perfectly represent the overall properties of low power active nuclei in the local universe, where RIAFs are most likely to be found. The sample of nearby ellipticals partially overlaps with samples 1) 2) and 3). However, there are only 10 objects in common, so the total number of objects considered is 132.

In (Chiaberge et al. 2003) we showed that the nuclear properties of LLAGN are best understood when the ratio between optical luminosity and Eddington luminosity $L_o/L_{Edd}$ is plotted against the “nuclear radio-loudness parameter” $R$, defined as the ratio between the nuclear radio (core) luminosity at 5GHz ($F_{5GHz}$) as measured from high-resolution (VLA or higher resolution) data and the nuclear optical luminosity $L_o$ as measured from HST images. The power of this diagnostic plane resides in the fact that we only need two measured quantities, plus an estimate of the black hole mass, to clearly separate sources of different physical origin. This allows us to discriminate between jets and accretion disks of different
radiative efficiency (and/or different accretion rates).

Since here we are looking for object harboring RIAF candidates, in Fig. 2 we plot galaxies for which the “active nucleus” has been detected both in the radio and the optical (or near IR) bands. The lack of detection of compact radio emission is considered as lack of evidence for AGN activity. On the other hand, the lack of detection of the optical nucleus would set a double upper limit in the plot and, most importantly, the location of the data point along the radio loudness axis would remain undetermined. Therefore, we discard such objects. We also only plot the objects for which a black hole mass estimate is available, either through gas dynamics or by using the relation with the stellar velocity dispersion.

Sources separate into 4 quadrants: Seyfert 1s occupy the top-left quadrant, FR I radio galaxies are in the bottom-right quadrant. These two classes define the regions characterized by “radio-quiet” high radiative efficiency accretion and “radio-loud” jet emission, associated to low radiative efficient accretion, respectively. LINERs split into two sub-samples: both are in the region of low $L_o/L_{\text{Edd}}$, some of them being radio quiet and some radio loud. Nuclei of ellipticals separate according to the properties of the radial brightness profile of the host (Capetti & Balmaverde 2006), and behave as the LINERs: core-galaxies are radio-loud, power-law galaxies are radio-quiet (for a definition of core and power-law galaxies, see e.g. Faber et al. 1997). Broad line radio galaxies, instead, are found at the top of the plot, at high values of $L_o/L_{\text{Edd}}$, while their location on the radio loudness axis most likely depends on the relative importance of the jet and disk emission in the optical band (the radio core being dominated by radiation from the jet). Although it is not easy to identify any “bi-modality” when plotting all the samples together as done in Fig. 2 we draw dashed lines just to guide the eye in discriminating between physical processes that are clearly different. Clearly, there is a bit of ambiguity for the nuclei that fall close to those “dividing lines”.

Let us now focus on the right hand side of the panel. Here we find jet-dominated nuclei (LLRG and a subsample of LINERs). In these objects, both the radio and the optical radiation is most likely synchrotron emission from the base of the jet, as it has been established for low luminosity radio galaxies (e.g. Chiaberge et al. 1999, Verdoes Kleijn et al. 2002). The radiation from the accretion flow is swamped by the jet emission, and cannot be studied directly (at least in the observing bands considered here). We should point out that in this case we have an “upper limit” to the Eddington ratio. Nevertheless, for several objects, this upper limit is as low as $L_o/L_{\text{Edd}} \sim 10^{-8}$. On the other hand, none of the detected objects on the left side of the plot reaches such low values. On the other hand, these extremely low efficient accreting black holes are still capable of producing a “jet”. This means that although RIAFs (or whatever these objects are!) are inefficient from the point of view of producing radiation, under certain circumstances (i.e. for the “radio-loud” nuclei) they can be very efficient in producing outflows or even (relativistic) jets, as in the case of LLRG (see e.g. Rees et al. 1982). In Chiaberge et al. (2005) we pointed out that “radio-loud” (i.e. jet dominated) nuclei tend to be associated with the most massive black holes. Thus it is tempting to speculate that the enhanced efficiency in producing powerful jets is somehow related to the higher black hole mass. An alternative picture is that it is the black hole spin that efficiently powers the jets (Blandford et al. 1990, Sikora et al. 2000), or possibly a combination of the two proposed scenarios.

Let us now focus on the left side of the plot, which is central for the purposes of this Letter. As discussed in detail in Chiaberge et al. (2005), in that region we find nuclei that show a low value of $L_o/L_{\text{Edd}}$, i.e. an optical excess with respect to the optical counterpart of the radio (synchrotron) radiation. For Seyfert 1s, such an optical excess is readily interpreted as emission from the accretion disk. A few bright Seyferts for which the nuclear SED has been derived support this interpretation (see e.g. Alonso-Herrero et al. 2003; Chiaberge et al. 2006). For the brightest nuclei, the limits on the Eddington ratio are still compatible with radiatively efficient accretion. Furthermore, we should stress that for those objects a bolometric correction of a factor $10^{-6}$ (Elvis et al. 1994, Marconi et al. 2004) should be performed, because we know their SED and we know that the optical $R$ or $V$ band do not correspond to the peak of radiatively efficient accretion energy output. On the other hand, for objects of the lowest Eddington ratios, we don’t know what the bolometric correction should be, but a factor of 10 (or even slightly higher) would not change our conclusions. Objects with Eddington ratios as low as $10^{-6}$ cannot be anyhow reconciled with “standard” accretion disk models. Therefore, they are the best candidates to host radiatively inefficient accretion disks.

In fact, we have shown in Chiaberge et al. (2006) that...
NGC 4565, a low luminosity Seyfert (not included in the sample considered in this Letter) that resides in the lower-left region of the diagnostic plane, shows an unusual SED which does not display the typical signatures of radiatively efficient accretion disks (i.e. lacks both the UV and the IR bumps). This strongly supports our prediction that objects in that part of the plot are not “standard” disks.

Since we want to identify the objects in which radiation from a RIAF can be detected and studied in the IR-to-UV spectral region, in order to derive the SED and set constraints to the models, our best RIAF candidates are those in which a nuclear source has been detected in archival HST images. This reduces the number of objects to eight candidates, plus NGC 4565 which has been already studied elsewhere. Summarizing, we predict that RIAFs can be detected and studied in the following objects: M 81, NGC 3245, NGC 3414, NGC 3718, NGC 3998, NGC 4143, NGC 4203, NGC 4565 and NGC 4736.

4. SUMMARY AND CONCLUSIONS

By combining the Eddington ratio as measured from detected unresolved nuclei in HST images and the nuclear “radio-loudness” parameter, we have found a straightforward way of distinguishing radiation emitted by the accretion process from jets in LLAGN and find RIAF candidates. At the end of the selection process, which started from a large sample of 132 AGN in the local universe, we are left with eight RIAF candidates for which the nuclear source is detected in archival HST images. These are the best targets for follow-up studies, not only in the IR-to-UV spectral region, but also in other bands such as far-IR, mm, and X-rays. Studying those objects in more detail is the best chance to provide constraints for RIAF models associated with supermassive black holes.

The method to find RIAF candidates outlined in this Letter is based on the radio and optical emission. However, it is possible to extend our ability of discovering new candidates using other bands in which the nuclear luminosity can be estimated. For example, nuclear IR radiation between ∼ 10 and ∼ 20 µm can be isolated in nearby objects using 8m class telescopes, as done by Whysong & Antonucci (2001). Another possible way of estimating the nuclear flux is to use the emission line strength, assuming a correlation between these two quantities, as Capetti & Balmanverde (e.g. 2006) pointed out that when the [OIII] luminosity is used instead of the optical nuclear luminosity from HST images, similar results are achieved. However, in all these alternative methods we are not sure that the optical source can be detected in order to derive the SED and constrain the models.

We should also stress that the diagnostic plane discussed here holds for LLAGN in the local universe. When high-z more powerful AGN are over-plotted, cosmic evolution may play a role in determining the position of the nuclei in the plane. For example, since it is not clear whether the local relations between properties of the host galaxy and the supermassive black hole mass can be easily extended to high-redshift galaxies, the estimate of the black hole mass may change substantially with cosmic time. Furthermore, the overall spectral properties of jets and disks, and their relative importance in the SED may change as well, and all this should be carefully investigated before including “all known AGNs” in the plane and draw conclusions. However, RIAFs are so faint and so difficult to detect, that at this stage it is best to look for them in local objects.

M.C. wishes to thank A. Capetti, A. Celotti, D. Macchetto, R. Gilli and W.B. Sparks for useful discussions and insightful comments.

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