The Orientation of Jets Relative to Dust Disks in Radio Galaxies[1]

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ABSTRACT

We use HST broad band images, VLA and VLBI continuum data to study the three dimensional orientation of jets relative to dust disks in 20 radio galaxies. Contrary to what have been claimed by most previous studies, we find that there is no correlation between the orientation of the jets and their host galaxies dust disks axes, with the observed values being consistent with a homogeneous distribution of jets. We discuss several explanations for this effect, and argue that it is most likely not due to misaligned inflow of gas from outside the galaxy, or warping of the accretion disk by self-irradiation instability or by the Bardeen-Petterson effect. We propose that warping of the accretion disk by a misaligned gravitational potential, or even kinematically distinct cores could explain the random orientation of the jets.

Subject headings: accretion – accretion disks – galaxies:active – galaxies:jets – galaxies:structure – galaxies:nuclei

1. Introduction

The orientation of a black hole rotation axis relative to its host galaxy rotation axis is an important diagnostic for the structure of the accretion disk and the nuclear region of the galaxy. In the case of spiral galaxies, the simplest picture suggests that they should be aligned, since the gas which fuels the nucleus is expected to originate in the galaxy disk, or if new gas is added to the galaxy, it will end up in the disk. However, Clarke, Kinney & Pringle (1998), Kinney et al. (2000, hereafter K00) and references therein, showed that this assumption is wrong. By comparing the orientation of radio jets, which are believed to be perpendicular to accretion disks and aligned with the black hole axis, with that of host galaxy major axis of Seyfert galaxies, they showed that these jets have random orientations.

In the case of Radio galaxies the situation is a little different from that of Seyfert's. Most of their hosts are ellipticals, which are triaxial systems (Binney 1982) and have very little gas to feed the nucleus, meaning that the gas is likely to have an external origin, probably from mergers. Birkinshaw & Davies (1985) and Sansom et al. (1987) presented the comparison between the position angle of jets and radio galaxy major axis for this class of objects. They found that there is very little or no correlation between the two, a result similar to the one found for Seyfert galaxies. This result is contradicted by the one obtained by Kotanyi & Ekers (1979), who approached the problem using a different technique. They used dust lanes to trace the orientation of the gas in these galaxies, and found that their radio galaxies have jets aligned nearly perpendicular to these dust lanes, implying a close connection between the gas in these structures and the accretion disk. A similar result was obtained by Möllenhoff, Hummel & Bender (1992) also based on ground based data. More recently, van Dokkum & Franx (1995) and de Koff et al. (2000) used HST images to detect dust lanes in radio galaxies. Their results show that there is a large range for the angle between the jets and dust lanes. However, according to them, the majority of the jets are still aligned nearly perpendicular to the dust lanes (see de Ruiter et al. (2001) for a different interpretation).

Although the previous studies of the orientation of jets in radio galaxies presented interesting results, they faced several problems. One of the problems is the fact that the intrinsic major and minor axes of triaxial systems do not necessarily correspond to the projected ones (Franx, Illingworth & de Zeeuw 1991; Ryden 1992). As a consequence of this fact the results obtained by Sansom et al. (1987) and Birkinshaw & Davies (1985), which show no correlation between the jets and host galaxies major axes, do not necessarily contradict the ones obtained based on dust lanes, they could simply be due to orientation effects. In the case of papers which used the orientation of jets relative to dust lanes, it is assumed that the gas and dust follow one of the allowed orbits in the galaxy, defining a preferential plane and eliminating the uncertainties of projection (Kotanyi & Ekers 1979; van Albada, Kotanyi & Schwarzschild 1982). However, the inspection of the HST images presented by De Koff et al. (2000) and Capetti et al. (2000) shows that most of the dust lanes in radio galaxies are patchy and not very well organized, suggesting that they may not be dynamically relaxed systems, and consequently may not be directly related to the feeding of the nucleus. It is extremely difficult, and even impossible in some of the cases, to determine the orientation and measure a position angle of the dust in most of these galaxies.

In this letter we address the question of the orientation of jets relative to dust structures in radio galaxies using a new approach. Instead of using all radio galaxies with dust lanes, we use only those with dust disks in their nuclei. We also improve relative to previous papers by using the statistical techniques devised by K00.

2. Data and Measurements

In order to avoid the uncertainties faced by previous works, we decided to use only radio galaxies which present clear dust disks. These disks are relaxed structures, settled in the gravitational potential of the galaxy, for which we can determine their major axis position angles, as well as their inclinations relative to the line of sight, under the assumption that they are circular. Another advantage of using only dust disks is the fact that it allow us to use the same technique developed by K00 for Seyfert galaxies. This technique determines, in a statistical way, which distribution of angles β, the angle between the jet and disk rotation axis in 3 dimensions, is the best represention to the data. Previous studies relied only on the difference between the position angles of dust lanes and jets, which are 2-dimensional projections on the plane of the sky.

Our sample was selected from a list of all radio galaxies with z$\leq$ 0.1, obtained from NED. This list was cross correlated with the HST archive and the galaxies for which we could find broad band images were inspected for dust disks. We found a total of 20 galaxies with dust disks, 13 of which already had measurements of major axis position angles and inclinations published by other authors. For the remaining galaxies we did these measurements by overploting different ellipses on top of the images, centered at the nucleus, and determined by eye which one was the best reproduction to the observed dust disk. The radio measurements for these galaxies were obtained from the literature, or measured directly on published radio images. We excluded cases like 3C 40 from the sample, because, eventhough we could see a dust disk, the galaxy does not present a jet, only the hotspots far away from the nucleus, making it impossible to obtain a robust estimate of the position angle of the extended radio emission. Similarly, cases like 3C 264, which show a face-on disk (Sparks et al. 2000), also had to be eliminated from the sample, since in these cases it is impossible to constrain the position of the jet relative to the disk.

The sample is presented in Table 1, where we give the names of the galaxies, the position angles of the dust disks major axes (PA$_d$) and host galaxies major axes (PA$_h$), the position angles of the jets on VLBI (PA$_{VLBI}$) and VLA scales (PA$_{VLA}$), the diference between the position angle of the dust disks major axes and that of jets on VLA scales (δ), the inclination of the dust disks relative to the line of sight (i), the smallest value of the angle β can have (β_{min}), described below, and the references from which the data were obtained.

3. Results and Discussion

We first compare the orientation of the dust disks relative to their host galaxies, to check if they are relaxed systems. Figure 1 presents the difference between the position angles of host galaxy major axes and dust disk major axes for our sample. In most of the cases the dust disk major axis is closely aligned with the host galaxy major axis, but in some of the cases they are aligned with the minor axis. According to Schwarzschild (1979), in a triaxial system, only orbits around the major and minor axis are stable. This result indicates that the dust disks are relaxed structures, following orbits around one of the symmetry axis of the galaxy. The fact that the alignment between dust and stars is not perfect is due to the fact that the projected position angle of the major and minor axes do not necessary coincide with the intrinsic ones in a triaxial system.

The distribution of angles β is studied using KOO techniques, where we can also find a detailed description of the geometry of the problem. An important feature about the geometry we are dealing with is the fact that, for a given pair of angles (i,δ), the jet is determined to lie on a pair of great circles drawn on a sphere centered at the nucleus. These great circles are mirror reflections of each other. It can also be shown that all points in this great circle lie at angles $\beta \geq \beta_{min}$, meaning that for a given pair (i,δ), the jet will never be at an angle closer than $\beta_{min} = \sin^{-1}(\sin i \cos \delta)$ relative to the disk rotation axis. The values of β_{min} for our sample are presented in Table 1 and the cumulative distribution of these angles is presented in Figure 2. This distribution varies smootly and shows a large range of values. In the case of some radio galaxies, like NGC 315, the jet can be very well aligned with the dust disk rotation axis, with $\beta_{min} = 1°$. However, in most of the cases the jet has to be misaligned by at least 20°, with the largest value corresponding to 53° for UGC 12064.

Besides obtaining the β_{min} distribution, we also used the method described by K00 to test whether a homogeneous distribution of jets in the range $0° \leq \beta \leq 90°$ can represent the observed δ distribution. This technique assumes a homogeneous distribution of β's and uses, for each one of the galaxies, the information about the dust disk inclination relative to the line of sight (i), and the angle between the jet and the dust disk major axis (δ) to obtain the corresponding P($\delta|i$) probability distribution. This distribution is integrated between $0 \leq \delta \leq \delta_k$, where δ_k is the observed value of δ for the galaxy, to obtain the centile point c_k. The final distribution of c_k's is then compared with a homogeneous distribution in the interval [0,1] using the Kolmogorov-Smirnov test (see K00 for a detailed explanation of the technique). We find that the observed distribution of angles δ can be represented by a homogeneous distribution of angles β. The KS test shows that on 29% of the time a random distribution of β's would produce a distribution of δ's which is as discrepant from the predicted distribution as the observed data.

The above results clearly show that, contrary to what most of the previous papers have found, jets are not closely aligned perpendicular to dust disks, being well represented by a random distribution. As for the case of Seyfert galaxies, this result contradicts the simplest expectations that the black hole should have its angular momentum vector aligned to that of the host galaxy. In their study of Seyfert galaxies, K00 presented a series of mechanisms to explain how the observed misalignment could happen. Here we analyze the viability of these mechanisms in the case of radio galaxies.

Misaligned inflow of gas towards the nucleus of the galaxy could explain the observed misalignment of the jets. Since we are dealing with elliptical galaxies, the origin of gas to feed the nucleus is probably external from the galaxy, where mergers with gas rich galaxies can provide the necessary gas. Under this scenario, the observed jet would be the result of a previous merger, while the observed dust disk is the result of a more recent one, which had a different geometry, and will produce jets oriented in a different direction. There are several evidence which point against this scenario. We showed that the dust lanes are closely aligned with the host galaxy major and minor axes, meaning that they are not the result of recent mergers. These structures had enough time to settle into the gravitational potential of the galaxy. The comparison between the orietation of jets on small (VLBI) and large (VLA) scales also indicates that their directions are not regulated by mergers. For 8 of the galaxies in Table 1 we found high resolution VLBI continuum data, which show an alignment better than 10° with the VLA scale jets, showing their long stability over time.

Another possibility to explain the misalignment between the jets and dust disk axes is the warping of the accretion disk. In the case of Seyfert galaxies K00 pointed out that this could be due by self-irradiation instability (Pringle 1996, 1997), by the Bardeen-Petterson effect in the case the galaxy has a rapidly rotating black hole, or by a misaligned gravitational potential in the nuclear region of the galaxy. However, some of these mechanisms present some problems in the case of radio galaxies. Since, the black holes of radio galaxies are believed to be rotating rapidly (Blandford 1990; Wilson & Colbert 1995), and the jets are belived to be aligned with the black hole spin axis. According to Pingle (1997), a rapidly rotating black hole stabilize the inner region of the accretion disk and can inhibit the self-irradiation instability. However, this result could change once more elaborate modeling of this effect is performed.

Warping of the accretion disk by the Bardeen-Petterson effect could in principle explain misaligned dust disks and jet axes if the black hole has a rotation axis different from that of the galaxy and the dust disk. In this case, even if the accretion disk is aligned with the galaxy disk, the black hole spin would force it to precess and get warped, resulting in their alignment. However, it was pointed out by Ress (1978) and more recently by Natajan & Pringle (1998), that due to Newton's third law, the black hole exerts a torque on the disk, which will exert a torque on the black hole, making the alignment between the two occur very fast, in a time scale of $\sim 10^5$ years. This would result in bent jets, which contradicts the fact that we found that the jets are relatively well aligned from the VLBI to the VLA scales.

The observed misalignment can also be explained if the accretion disk is warped by a misaligned gravitational potential around the nucleus, like an axisymmetric globular cluster (Gebhardt et al. 1996), or if the whole nuclear region is misaligned relative to the rest of the galaxy. If the elliptical galaxies which host these radio galaxies are formed by the merger of spirals, as suggested by observations (Kormendy & Djorgovski 1989), the merger of the black holes of the two spiral galaxies will result in a more massive and rapidly spinning black hole (Wilson & Colbert 1995), with a rotation axis which does not necessarily coincide with the major or minor axis of the resulting elliptical. A case like this could result in nucleus with an angular momentum different from the rest of the galaxy. It was shown by Sridhar & Touma (1999) and Poon & Merritt (2001) that the orbits of stars inside the radius of influence of a black hole can be strongly affected by it, which could result in kinematically distinct nuclei. This was observed in several elliptical galaxies (Forbes et al. 1996), and can also be test in our galaxies.

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Table 1. Properties of dust disks, host galaxies and radio jets

Name	PA_d (°)	PA_h (°)	PA_{VLBI} (°)	PA_{VLA} (°)	δ (°)	i (°)	β_{min} (°)	References
NGC 315	40	39	-50	-49	89	77	1	1,3
NGC 383	140	145	-15	-21	19	39	37	4
NGC 2329	174	171	-30	-29	24	47	42	1,3,15,10
NGC 3557	31	34	—	78	47	60	36	12,14
NGC 4261	165	158	-93	-96	81	65	8	3,4
NGC 4335	158	156	—	79	79	66	10	1,3,5,10
NGC 4869	-9	-11	—	-90	81	78	9	12,17
NGC 5127	48	68	—	118	70	76	19	1,3,10,16
NGC 5141	88	65	190	192	76	76	14	1,2,3,10
NGC 5532	155	146	—	35	60	72	28	4
NGC 6251	4	21	297	294	70	76	19	8,9
NGC 7052	65	64	203	202	43	70	43	1,2,3
NGC 7720	10	28	-49	-56	66	43	16	4
IC 4296	79	60	—	130	51	72	37	12,14
MCG -02-36-02	55	53	—	-60	65	66	23	12,18
UGC 367	158	150	—	-87	65	71	24	2,11,12
UGC 12064	160	176	—	189	29	66	53	4
3 C 402 N	55	150	—	175	60	68	28	5,6,7
4 C -03.43	73	-25	—	13	60	67	27	12,18
B 2 0915+32	109	123	—	30	79	28	5	12,13

Column 1: galaxy name; Column 2: position angle of the dust disk major axis; Column 3: position angle of the host galaxy major axis; Column 4: position angle of the VLBI scale jet; Column 5: position angle of the jet on VLA scales; Column 6: the difference between the position angle of the dust disk major axis and jet axis; Column 7: dust disk inclination; Column 8: minimum value of the β angle; Column 9: references from which the data was obtained: 1-) Verdoes Kleijn et al. (1999), 2-) Fanti et al. (1986), 3-) Xu et al. (2000), 4-) Martel et al. (2000), 5-) Condon & Broderick (1988), 6-) de Juan, Colina, & Golombek (1996), 7-) de Juan, Colina & Pérez-Fournon (1994), 8-) Ferrarese & Ford (1999), 9-) Jones et al. (1986), 10-) RC3, 11-) Capetti et al. (2000), 12-) Our measurements from HST data, 13-) Fanti et al. (1987), 14-) Birkinshaw & Davies (1985), 15-) Wrobel & Heeschen (1984), 16-) Fanti et al. (2000), 17-) measured from Feretti et al. (1990), 18-) measured from Owen, White & Burns (1992).

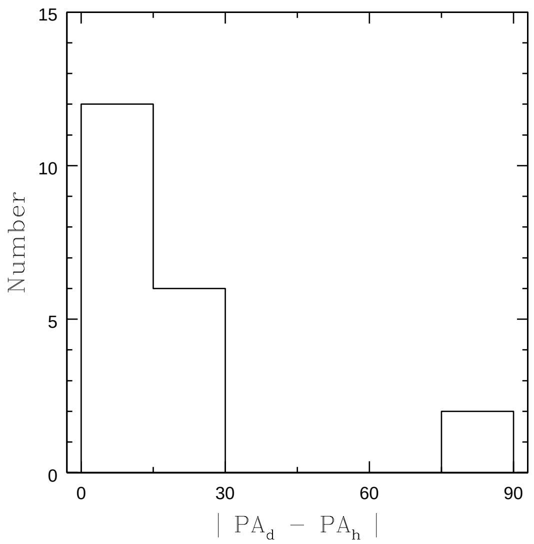

Fig. 1.— The histogram of the difference between the position angle of the dust disk major axes and host galaxy major axes.

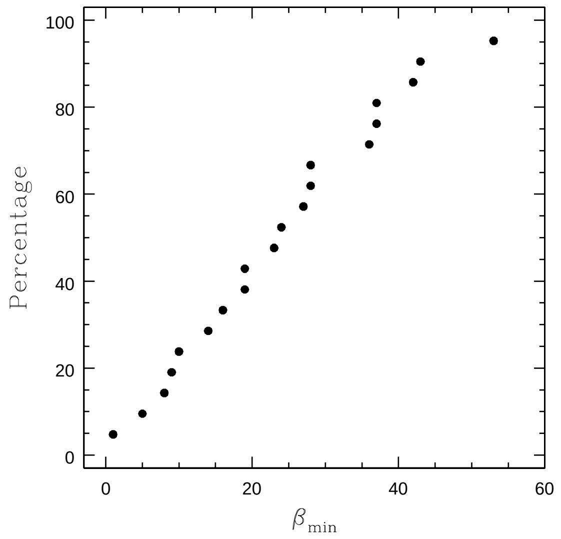

Fig. 2.— The cumulative distribution of β_{min} angles, the minimum angle the radio jet can have relative to the dust disk rotation axis, calculated using the i and δ values in Table 1.