Face-on dust disks in galaxies with optical jets$^1$

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ABSTRACT

The presence of optical synchrotron jets in radio galaxies is relatively rare. Here, we show that of the nearest five FR-I 3CR radio galaxies showing optical jets, four show evidence for almost circular, presumably face-on, dust disks. This is strong support for the two-fold idea that (i) jets emerge close to perpendicular to inner gas disks and (ii) optical non-thermal synchrotron emission is seen only when the jet points towards the observer. The implied critical angle to the line-of-sight is approximately 30 — 40°, i.e. if the angle of the jet to the line-of-sight is less than about 40° we see an optical jet. The corresponding relativistic $\gamma$ factor is $\approx 1.5$ which is consistent with current observations of jet proper motion that show a range up to $\gamma \sim 6$ for M87. The relatively low speeds implied by $\gamma \approx 1.5$ may be due to a global deceleration of the jet as in unified theories, or else to stratification within the jet. Unresolved nuclei are common in the optical. Their luminosities are also consistent with the beaming concept when compared to inclination inferred from the dust lanes. The disk sizes are typically several hundred parsecs, to kiloparsec size. The galaxy with an optical jet that does not show a face-on disk, M87, instead has more complex radial dust and ionized gas filaments.

Subject headings: galaxies:active, galaxies:jets, galaxies:nuclei, radio continuum: galaxies

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1. Introduction

The reasons why radio galaxies project high energy jets of relativistic plasma over vast, galactic and even extragalactic, distances from a tiny volume at the nucleus of the host galaxy remain unknown. Essentially all radio galaxies seem to display jets when observed with sufficient sensitivity and resolution, suggesting this is a fundamental characteristic of radio galaxies and energy transport. A small fraction of these jets are seen in the optical. This represents a potentially profound insight into the nature of jets since the presence of optical synchrotron radiation demands relativistic particles of high energy and short lifetime, unlike the radio, and in-situ acceleration processes are probably required.

It is widely believed that a rotating black hole at the nucleus, coupled to an inner accretion disk is somehow responsible for the onset of a jet. The extraordinary collimation is likely to occur at the very nucleus, though galactic influences at larger distances may play a role in collimating the jet, Junor, Biretta & Livio 1999. It is also generally accepted that both orientation (the angle of the emerging jet and of the inner accretion disk to the line of sight) and relativistic beaming, play roles in the appearance of any particular source to the observer. By such means, FR-I (or low power) radio galaxies may, when viewed from the appropriate direction, appear as luminous, variable BL Lac objects, Urry & Padovani 1995.

Optical emission from jets, in the beaming scenario in which the jet moves relativistically towards the observer, isfavoured because both the typical synchrotron spectral break is blueshifted closer to the optical window, and also because the intrinsic intensity “beam pattern” is strongly forward projected, with an opening angle of order $1/\gamma$ where $\gamma$ is the relativistic factor, $\gamma = \sqrt{1/(1 - v^2/c^2)}$.

Other physical processes may play a role, however. The high-pressure environment close to a galaxy nucleus could quench the progression of the jet and the high pressure may translate to high synchrotron losses and a greater tendency for optical radiation. The case of 3C 264 offers evidence of such an influence, as there the optical jet terminates at the very edge of an inner dust lane, Baum et al. 1997. Age, or rather youth, may also play an important role. Best, Longair & Röttgering 1996 show the evolution of optical morphology of radio galaxies with increasing radio source size, for example, and discuss this in the context of jet-induced star formation and the alignment effect.

Here, we make a very simple observation that we believe strongly supports the beaming and orientation paradigm, which is that the majority of nearby radio galaxies showing optical jets have compact well-ordered dust disks that are almost circular and are hence likely to be face-on. This implies that jets emerge close to perpendicular to such disks and that they are pointing almost towards us. We also note that the nuclear point source luminosities are consistent with this general behaviour. In § 2 we describe the data, in § 3 we discuss and conclude.
2. HST imaging observations of 3CR galaxies

In a series of proposals, we acquired multiwavelength images of 3CR radio galaxies and quasars using the Wide Field and Planetary Camera 2 (WFPC2) on-board the Hubble Space Telescope (HST). The observations utilised the efficient snapshot mode of observing, whereby short exposures are used to fill scheduling gaps. The data and observations are described in de Koff et al. 1996, McCarthy et al. 1997, Martel et al. 1998(b), Lehnert et al. 1999, Martel et al. 1999. An early goal of our observations was to use the high sensitivity and spatial resolution of HST to locate new optical synchrotron jets in radio galaxies and hence understand the systematics relating high energy synchrotron emission with the host properties. That effort has been successful, and is ongoing. New optical jets were found in 3C 78, Sparks et al. 1995, 3C 15, Martel et al. 1998(a) and elsewhere, Sparks et al. 1996. To date, there are about 12 extragalactic radio sources with known optical jets, and a similar number of candidate optical jets.

The majority of nearby confirmed optical jets are in FR-I galaxies and for the purposes of this paper we define a sample of nearby FR-I galaxies by restricting attention to 3CR radio galaxies from Bennett 1962 whose redshift $z < 0.1$ and $|b| > 10^\circ$, Spinrad et al 1985. Galaxies classified as either FR-I or FR-I/II in Zirbel and Baum 1995 were selected, resulting in a sample of 25 radio sources, counting 3C 75 as two, as listed in Table 1. Five have known optical jets: 3C 15, 3C 66B, 3C 78, 3C 264, and 3C 274 (M87).

Nuclear point sources are common in our high resolution images of radio galaxies, and may provide additional insight into the beaming hypothesis. We also therefore measured the nuclear core brightness where there was an obvious point source using aperture photometry and the magnitude zeropoint from the HST Data Handbook. The magnitudes are on the Vega system and are presented in Table 1.

3. Dust lanes in nearby 3CR FR-I radio galaxies

de Koff et al. 2000 investigated the systematics of dust lanes in 3CR galaxies from the snapshot observations and show that in FR-I galaxies, dust lanes tend to be regular and compact and that in such sources there is a strong tendency for the radio axis to be perpendicular to the dust disk. Typical scale lengths for the dust disks are hundreds of parsecs. Martel et al. 2000 present an in-depth analysis of the dust-lanes in several of these nearby radio galaxies.

Baum et al. 1997 presented a detailed study of 3C 264 and showed its remarkable circular dust disk, with the bright optical jet apparently terminating at the edge of the disk, Fig. 2. The morphology of this dust lane was quite unique, with no other dust lanes of the de Koff et al. 2000 sample having such a circular appearance. However, detection of round, low optical depth dust features can be difficult since they can be significantly harder to see than edge-on features that cut into the galaxy isophotes.
Motivated by the appearance of the 3C 264 disk, and a similar one in 3C 66B, Sparks et al. 2000, we inspected all the remaining low-$z$ FR-I optical jet galaxies to search for the presence of subtle dust features, and in addition those of the well-defined sample of 25 (above) which had not already been investigated. This was done in case, by looking harder at the jet galaxies than the others, we were biasing our result. However, of the 25 galaxies, 24 have clearly detectable dust. Even the remaining one, the Southern component of 3C 75, shows a hint of a very faint feature in an archival HST image. The dust detection rate is 96% and we conclude therefore that we are not witnessing the effects of missing subtle dust features in galaxies: our dust detection rate is essentially complete. Fig. 1 shows dust images of those galaxies not shown in the references above.

Fig. 2 shows the dust in the optical jet galaxies shown in a variety of ways. All five of the optical jet objects have multicolor HST images available. For 3C 264 and 3C 66B no special processing is needed, and we simply show a single direct image for each. For the others, we fitted isophotes to the red F702W galaxy images with iterative sigma clipping to reject isophotal outliers (i.e. the jets). The isophotal profiles were then used to make a smooth, perfectly elliptical model of the red light in the galaxy (where the effects of dust are minimized), and the bluer data is divided by this red model as in Sparks et al. 1985 to generate an image of the dust. These are the $(V-R_{\text{model}})$ images, or “dust images” referred to elsewhere in the text.

The center row of Fig. 2 shows the galaxy hosting 3C 15. To the left is a direct image, whose irregularities are attributable to dust. In the center is a pure $(V-R)$ image, and on the right is the $(V-R_{\text{model}})$ image. The large scale circular features in the $(V-R_{\text{model}})$ image are most likely artifacts from the modelling, unlike the more compact feature towards the center which also shows in the $(V-R)$ data image (i.e. the ratio of the $V$ image to the $R$ image, as opposed to the ratio of the $V$ image to a smooth, elliptical model of the $R$ image). The dust optical depth is low (as might be expected if the dust lane is close to face-on), but by comparing the different images, and perhaps most easily seen in the center one, there is a faint, almost complete, ring of absorption and reddening, rather deeper to the West. The jet is on a much larger scale than the dust, as it is in 3C 66B.

The lowest row of Fig. 2 shows the dust in 3C 78. To the left is a direct $V$ image, in the center is a direct $R$ image and on the right, the $V$ image divided by a smooth model of the $R$ image. Again, by comparing amongst the images, the absorption can be seen in the color image and in the direct $V$. It is almost absent in the $R$ image. Once more, absorption can be traced entirely around the nucleus in a compact ring.

Hence, remarkably, four of the five optical jet galaxies show circular dust lanes. The other one is M87 whose dust shows a more chaotic morphology, with distinct, roughly radial filaments that coincide with line-emitting gas, Sparks, Ford & Kinney 1993, Sparks 1999. None of the other 25 galaxies show similar circular dust lanes.

To obtain a better estimate of the axial ratios of each of the “round” dust lanes, four cuts were made at 45$^\circ$ angles to one another across the clearest images. The diameters were marked
by eye, and these measurements were then used to determine the parameters of the least-squares best-fit ellipse. The resulting measurements are given in Table 1. Note that uncertainties tend to bias the measurements to smaller $b/a$ values if the disk is truly circular. The remaining dust lane axial ratios were taken either from the literature as cited, or measured from the direct images referenced using a major and minor axis cut.

Fig. 3 shows the axial ratio distributions of the dust lanes in radio galaxies for the 15 galaxies with reasonably well-defined dust disks, and it is clear that the optical-jet objects have a significantly rounder distribution. Formally, the difference is significant at the 0.1% level (i.e. a probability of chance occurrence of less than 0.001), based on the plotted axial ratio distributions and using the Fisher exact probability test. The diameters of the dust disks (or rings) are approximately 1300, 350, 430 and 620 pc for 3C 15, 66B, 78 and 264 respectively, assuming $H_0 = 75$ km/s/Mpc.

4. Discussion

4.1. Dust and jet properties

The simplest way to understand this result is that a round dust disk is a dust disk seen close to face-on. Since we have shown in de Koff et al. 2000, that radio jets tend to lie perpendicular to dust disks, especially in the settled FR-I objects, the natural inference therefore is that we are also seeing the optical jets almost pole on, that is pointing directly towards us. de Koff et al. 2000 found that for FR-I sources with dust disks of size $< 2.5$ kpc, the radio jet lies within less than or about 15 degrees of the disk (perpendicular) axis (but with a small number of exceptions such as 3C31). The roundest disk in the sample without jets would imply an inclination $\phi$ of order 40 degrees to the line-of-sight if it is intrinsically circular. Similarly, the flattest disk in the jet sample would require an angle $\phi$ to the line of sight of $\phi \approx 30$ degrees, taken at face value. This suggests that the dispersion in angles $\phi$ is dominated by the projection of the assembly of dust disk plus jet, rather than by an intrinsic scatter of jet angles to dust disk angles. It also implies that there is a critical angle, $\phi_c$, such that if jets point within that angle we see optical emission. From these numbers we expect $\phi_c$ to lie in the range 30—40 degrees.

There are some small asymmetries and irregularities apparent in the circular dust lanes, and these may be due to the effects of what inclination there is to the plane of the sky, or else to intrinsic irregularities within the disk. Detailed analysis of the optical depth around the disk becomes highly model dependent as there is nowhere to obtain the unobscured light profile.

Why jets and dust lanes are close to perpendicular remains a mystery. Since these are relaxed, orderly systems, perhaps the disk, galaxy and black hole spin axes have had time to co-align, Natarajan & Pringle 1998. Alternatively, the jet ejection process itself may react back on the disk and force it into a perpendicular orientation, Quillen and Bower 1999. Also, in these round
dust disks, the outer edge of the disk is remarkably sharp. Perhaps this is an indication of a more settled and evolved disk than the irregular morphologies often seen, de Koff et al. 2000, which would in turn suggest that evolutionary processes within the jets are not responsible for the optical emission. One would expect galaxy dynamical timescales to be much longer than the evolutionary timescale for a radio jet (given its high speed and short synchrotron loss lifetime).

If the sample is a set of randomly oriented linear jets, we expect the distribution of $\phi$ to be $\sin(\phi)$ for $\phi$ in the range 0 to 90 degrees. Hence, statistically we would expect a fraction $1 - \cos(\phi_c)$ to have an angle to the line of sight $\phi$ less than a critical angle $\phi_c$. If $\phi_c \approx 40$ degrees, then the fraction is 23% which for a sample size of 25 means six objects (three if $\phi_c = 30$ degrees). This is obviously consistent with the five that we find, if the optical jet galaxies represent those whose jets point within 30—40 degrees to the line of sight.

It is possible that more face-on disks tend to appear more irregular and hence are excluded from the statistical comparison. There are no compelling reasons to think that this is actually the case, however. One of the 10 galaxies with “irregular” dust has an optical jet; by chance we would expect 1.8 galaxies to be oriented with $\phi < 35$ degrees so there is nothing inconsistent in the statistics to suggest a large fraction of the irregular dust disks are actually face-on.

Hence, we are led to a picture where optical jets “appear” when they point to within (of order) $\phi < \phi_c \approx 35 \pm 5$ degrees to our line-of-sight, based on the apparent axial ratios of their associated dust lanes.

This is reasonable qualitatively, given expected relativistic beaming and Doppler boosting of the underlying synchrotron break frequency. $\gamma$ values of order ‘a few’ are typically thought to occur jets in radio galaxies, and indeed superluminal proper motion is observed in the jet of M87 which is very direct evidence for $\gamma \sim 6$, Biretta, Sparks & Macchetto 1999. If the beam angular width is $\sim 1/\gamma$, a critical angle of $\approx 40$ degrees implies a rather lower value, $\gamma \approx 1.4$ or $v \approx 0.7c$. If $\phi_c = 30$ degrees, the corresponding $\gamma = 2$ and $v = 0.85c$. Such numbers should be taken as illustrative: clearly, in principle, beams are observable outside the primary beam width, at much lower surface brightness. Much deeper observations with fainter surface brightness limits may help to disentangle the effects of multiple velocity components and intrinsic beam pattern.

Laing et al. 1999 discuss the case for relativistic beaming in FR-I radio galaxies in detail. Based on comparison with radio data, primarily, they develop a consistent model in which jets are intrinsically symmetric, initially relativistic but decelerating, and faster on-axis than at the edges. This is quite consistent with our inference of jet $\gamma > 1.4$ provided that either optical emission becomes unobservable at lower values of $\gamma$ (where the beam is broad enough for many more jets to be included within it) or else the jets never have velocity less than $v = 0.7c$. Laing et al. 1999 finds a best fitting velocity for single-velocity models, of $v_0 = 0.72c$, but they also achieve good fits with lower minimum velocities when a range of velocities is allowed. It seems more plausible that the optical emission becomes undetectable (with current observations) at lower velocity.
4.2. Nuclear core sources

Nuclear point sources are common in radio galaxies, and are often apparently bright in galaxies with optical jets, Martel et al. 1998(a). Chiaberge, Capetti & Celotti 1999 and Hardcastle & Worrall 2000 showed that the optical core source luminosity is very well correlated with the radio core flux, and hence is most likely also synchrotron emission arising from the base of the jet. In a pilot study of five objects Capetti & Celotti 1999 showed that there are indications of a correlation between gas disk inclination and core prominence, consistent with the expectations of the proposed unification of BL Lac and FR-I radio galaxies. To take this a step further, we plot the nuclear magnitude where there was obviously a point source against the axial ratio of the dust lanes, Fig. 4. There is a trend, with the brightest cores in the most face-on disks, and a correlation coefficient of $-0.83$ yielding a formal significance level of better than 1%. However, many targets do not appear on the plot. Either they have cores but irregular dust, including two of the brightest, or else they do not have well-defined cores in our data. We consider the plot therefore primarily indicative and intriguing for future study.

To examine the FR-I/BL Lac unification idea, we include on Fig. 4 the average of the BL Lac objects from the comparison sample of Capetti & Celotti 1999, showing the $\pm 1\sigma$ dispersion in their magnitudes. We assume this representative BL Lac object is viewed directly along the line-of-sight. If the average spectral index is $\alpha \approx 1$ in the optical, the relativistic boosting for continuous outflow is $\propto (1 - \beta \cos \theta)^{-2 - \alpha}$, where $\beta = v/c$ and $b/a = \cos \theta$. For illustration, the best-fit value for $\gamma \approx 5.6$ is shown, with the zeropoint of the proportionality chosen so that the curve passes through the BL Lac point and assuming that all nuclei have the same intrinsic brightness. The derived $\gamma$ is sensitive to $\alpha$, with lower $\alpha$ yielding higher $\gamma$. While there are major uncertainties and selection effects (we only see the most luminous cores; there is no expectation that all cores have identical intrinsic flux) it is interesting to note that there is a good consistency with conventional beaming models and relativistic factors between 1 and 10. A more detailed investigation into these issues would be useful.

4.3. Caveats

Perhaps the most worrisome objection to the scenario described in § 4.1 is that in the case of 3C 264, the optical jet flares and essentially ends right at the edge of the dust disk. This leads one to suppose either (i) a causal connection, as discussed by Baum et al. 1997, or (ii) a coincidence. None of the other optical jets show any sign of interaction with the host disks: for the most part they are on a much larger spatial scale. In the scenario where the disk is face-on and the jet almost perpendicular to it, the coincidence of the jet flaring out at the edge of the disk must be accepted. In the contrary situation, where the jet ends at the edge of the disk due to a physical interaction with the disk, the alternate coincidence that of all galaxies, this one has the most face-on disk must be accepted. More exotic options, such as dust spheres in the centers of optical-jet galaxies
rather than disks, can be excluded from detailed analysis of the color distribution in the case of 3C 264, Martel et al. 2000.

It may be possible to resolve this issue, either with increased sample sizes for the optical jet cases, although that seems unlikely given our 100% detection rate for nearby FR-I dust lanes, while more distant objects are much harder to resolve, or else by demonstrating perhaps through spectroscopic observations, that there is a genuine interaction between the 3C 264 dust lane and the outward propagating jet. In the latter case, we would favour a scenario in which more than one physical process can be relevant, however it would remain very curious as to why that one disk, of all disks, is so close to circular!

5. Conclusions

We have derived a simple but appealing result: those galaxies with optical jets that are sufficiently nearby to allow a detailed view of the nuclear environments and whose nuclei are not so luminous as to swamp that view, show in 4 out of 5 cases evidence for a circular dust disk. None of the other 21 galaxies in the sample show such a feature. We interpret this as support for a two-fold model in which jets emerge perpendicular to dust lanes and optical emission arises when those jets are pointing towards us, specifically within a critical angle of $\phi_c \approx 30-40$ degrees. Nuclear core luminosities show a trend with more luminous cores in the face-on disks, as expected from the beaming scenario.

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Fig. 1.— Dust lanes in galaxies not shown in previous references. Top row 3C 29, 3C 75 (North) and 3C 76.1 from left to right respectively; Bottom row, from left to right, 3C 317 (Abell 2052), 3C 386, and 3C 442. Each of images on the top row is 2.3 arcsec on a side, and on the bottom row, 13.8, 6.9 and 6.9 arcsec respectively, left to right. 3C 75 and 3C 76.1 are simple, direct images, while the remainder are $(V-R_{\text{model}})$ images. 3C 29 shows a remarkable X-shape; 3C 317 a chaotic extensive dust distribution (the giant elliptical galaxy would be centered); 3C 386 (which has a very bright point source) faint patches to the West and North-East, and 3C 442 an irregular fan to the North West.

Fig. 2.— Montage of dust disks in nearby radio galaxies with optical jets. Top row, from left to right, 3C 264 (3.3 arcsec on a side) F547M direct image; 3C 66B (3.4 arcsec) FOC F430W direct image, and 3C 274 (11.9 arcsec) from Sparks 1999. Center row shows 3C 15, 2.9 arcsec on a side, from left to right direct $V$, $(V-R)$ and $(V-R_{\text{model}})$ respectively. Bottom row shows 3C 78, 2.3 arcsec on a side, from left to right direct $V$, direct $R$ and $(V-R_{\text{model}})$ respectively.

Fig. 3.— Dust axial ratio distributions for dust lanes with disk-like morphology, data from Table 1. The shaded region indicates those sources with optical jets.

Fig. 4.— Core source luminosity versus dust axial ratio. The galaxies with optical jets are shown as ‘+’ signs, the other radio galaxies as open symbols, and for comparison, we include the average point for the BL Lac comparison sample of Capetti & Celotti 1999 (the cross). The curve is a beaming model assuming fixed total core luminosity and $\gamma = 5.6$. 