On the Origin of Correlated Radio–Optical Asymmetries in Double Radio Sources

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ABSTRACT

A new explanation is proposed for the striking correlation that in powerful radio galaxies the brighter [O II]λ3727 line emission is nearly always found on the side of the (shorter) radio lobe which is closer to the nucleus. As an alternative to the conventional interpretation where the above result is understood by postulating a large-scale density asymmetry about the parent elliptical galaxy, we propose that the side of the longer lobe is marked by a greater accumulation of dust, which leads to an increased attenuation of blue/UV photons in that region. This dust enrichment is caused by the motion of the galaxy, which not only stretches the downstream radio lobe, but also results in a net displacement of the (dusty) ISM of the galaxy towards that lobe; the galaxy motion further supplements this dust accumulation towards the longer lobe by causing a ram-pressure stripping of the dusty disk of the galaxy. The many advantages of this asymmetric obscuration model over the conventional explanation invoking an environmental density asymmetry are pointed out, and observational tests for distinguishing between the two possibilities are outlined.

Subject headings: galaxies: active — galaxies: clustering — galaxies: elliptical — galaxies: jets — ISM: dust, extinction — radio continuum: galaxies

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1. Introduction

Although the first indication for a bi-polar ejection of energy from active galactic nuclei (AGN) came from the observed general symmetry of powerful double-lobed radio sources, subsequent radio imaging has revealed that the hot-spots located near the outer edges of the lobes are rarely seen at equal separations from the galactic nucleus. The ratio of their separations (or asymmetry parameter) defined as $Q \equiv D_1/D_2 \geq 1$, has proved to be particularly useful observable for probing the nature of radio sources. In the case of powerful radio galaxies, Q has been shown to correlate with the percentage optical polarization of the extended emission line region (EELR) associated with the parent galaxy (Cimatti et al. 1993), radio depolarization asymmetry (e.g., Tribble 1993), and with the radio spectral curvature (Mangalam & Gopal-Krishna 1995). Most strikingly, the lobe length asymmetry is mirrored in the asymmetries of the peak optical emission line intensity (McCarthy & van Breugel 1989; McCarthy, van Breugel, & Kapahi 1991; hereafter MvBK).

Moreover, since the departure of Q from unity can arise from light travel time differences between the approaching and receding hot-spots, the statistics of Q has also been used extensively to constrain the velocities of advance of the hot-spots (V_h) (Ryle & Longair 1967; Longair & Riley 1979; Banhatti 1979). A recent analysis performed for radio galaxies (RGs) and quasars (QSRs) separately has yielded $V_h \approx 0.2c$ (Best et al. 1995). When the additional constraint that the lobe exhibiting a jet must be the approaching one is applied, then a separation velocity of $V_h \approx 0.05c$ is deduced for even very powerful radio sources (Scheuer 1995). Such velocities are on the lower side of the ones estimated from the observed spectral index gradients across the radio lobes (Myers & Spangler 1985; Alexander & Leahy 1987; Liu, Pooley, & Riley 1992). This discrepancy could be partly explained by allowing for a substantial backflow speed within the lobes (Leahy & Williams 1984; Scheuer 1995). Regardless of these considerations, it is clear that the velocity inferred from the Q-distribution would be too high if a part of the observed asymmetry is intrinsic to the double radio structure. Within beam propagation models (Scheuer 1974; Gopal-Krishna & Wiita 1987, 1991), such asymmetries can arise from various factors, such as different powers and/or opening angles of the twin jets, or an asymmetric environment about the parent galaxy.

An unequally dense environment on the two sides of the galaxy could also result in an asymmetric efficiency of conversion of the beam power into radio emission (Eilek & Shore 1989; Gopal-Krishna & Wiita 1991; Saikia et al. 1995, 1996), thereby leading to an asymmetry in the flux density. Another potential cause for flux density asymmetries, $R \equiv S_1/S_2$, is the light travel time differences between the two lobes, combined with the temporal evolution of the lobe flux densities (Mackay 1973; Swarup & Banhatti 1981). Although it is usually assumed that the lobes radiate isotropically, at least at low frequencies, the possibility that jet and even hot-spot emission could contribute a substantial relativistically boosted anisotropic component has been discussed (e.g., Scheuer 1987; Tribble 1993). This, however, would not affect the statistics of the Q parameter, which is the focus of this paper.

A potentially important evidence for the environmental factor in the creation of asymmetries has come from a study by MvBK of the extended optical emission line regions (EELR) associated with powerful 3CR radio galaxies (RGs). For a large unbiased set of FR II RGs, these authors found strong evidence for the peak surface brightness of the optical line emission to occur on the side of the radio lobe which extends out to a *smaller* distance from the active nucleus. Also, the optical brightness contrast was found to be particularly large for higher redshift sources ($z > 0.3$; McCarthy & van Breugel 1989) for which the optical asymmetry was quantified in terms of the blue emission line [O II]λ3727. McCarthy et al. (1991) proposed that the causal link for these tightly correlated radio and optical asymmetries is a large-scale density asymmetry of the circumgalactic medium (CGM) about the radio-loud elliptical, which slows the radio lobe propagation more effectively on the denser side (e.g., Swarup & Banhatti 1981) while simultaneously enhancing the optical output of the thermal filaments in the EELR on that same side (via better confinement).

Although appealing for its simplicity, this hypothesis of environmental asymmetry is unlikely to be a complete explanation for the *nearly universal* (37 of 39 cases; see MvBK) correlation which is found to hold even when the lobe distance asymmetry, (defined such that D_1 and D_2 are respectively the distances to the farther and closer hot-spots) is minute ($\approx 1\%$ level), particularly as the physical separations of the radio and optical emission peaks from the nucleus usually differ by roughly an order of magnitude. On the other hand, should the spatial scale of the environmental density asymmetry be large enough to encompass the entire radio lobes, the putative excess ambient pressure enhancing the optical emission from the shorter radio lobe through a more effective confinement on that side, should also render that lobe more luminous in the radio; however, significant evidence for such behavior is not found (MvBK; Macklin 1981). Moreover, it remains unclear why the optical asymmetry is more pronounced for higher z sources whose EELRs were imaged in the (blue) [O II]λ3727 line, as compared to the lower z RGs imaged in the Hα line (see, MvBK). Note also that if the trajectories of the two jets are not precisely anti-parallel, or linear (which is likely, given the "dentist drill" behavior of the advancing hot-spots; Scheuer 1982; Clarke 1996; Norman 1996), then the value of Q could easily depart mildly from unity without there being any systematic difference in the two lobes' environments. Thus we conclude that the explanation invoking a nearly universal environmental density asymmetry is too simplistic to account for the remarkably robust radio–optical correlation, and a more foolproof mechanism seems to be at work.

We argue here that the bulk of the tight radio-optical correlation can be explained quite naturally without invoking an *ab initio* density asymmetry in the circumgalactic medium (CGM). In our picture, the motion of the parent galaxy with respect to an intracluster medium (ICM) will generate a ram pressure, leading to an asymmetric disposition of its (dusty) ISM. As a result, the dust obscuration of the nuclear UV photons and of the light emitted by the EELR filaments will become stronger and more widespread on the downstream side of the galactic center. At the same time, the radio lobe on that side would be automatically identified as the more distant or longer one, due to the ongoing motion of the galaxy in the opposite direction. Not only would this naturally engender the observed correlated radio–optical asymmetry, but also the strong tendency for the RGs at higher z to show a greater asymmetry of EELR emission can be readily understood since the observed optical window would then sample shorter rest-frame wavelengths, where dust obscuration is expected to be more effective.

Aside from the well-known X-ray emitting halos (e.g., Forman, Jones, & Tucker 1985), robust evidence for the ISM in the elliptical parents of powerful radio sources comes from the fairly sharp-edged emission gaps observed between the radio lobe pairs, which probably arise from the backflowing cocoon radio plasma impinging on the denser ISM of the host galaxy (Leahy & Williams 1984; Black et al. 1992; Wiita, Rosen & Norman 1990; Wiita & Gopal-Krishna 1990). The postulated ISM asymmetry arising from the galaxy motion should then be reflected in an asymmetry of the radio emission gap about the active nucleus, which is indeed observed on the high quality radio maps of many double radio sources (cf §4). The presence of substantial quantities of dust in the kpc-scale ISM of powerful AGN has been established by recent *Hubble Space Telescope* observations of radio quasars, where no narrow emission lines were detected in their UV spectra (Wills et al. 1993).

In §2 we discuss the radio–optical correlation effect and the motion of RGs in clusters. Section 3 examines the natures of the dusty ISM and the CGM. We then consider the effect of ICM ram-pressure and illustrate how this might explain most of the correlated optical–radio asymmetries (§4). A discussion and predictions of our model comprise §5.

2. The Radio–Optical Correlation and the Galaxy Environment

Narrow-band optical imaging of powerful RGs has revealed EELRs on typical scales of 10 kpc which show a strong tendency to be aligned with the radio axis for $z > 0.3$ (McCarthy 1993; Baum & Heckman 1989). Quite plausibly, these line emitting filaments are produced by strong compression and shock heating of gaseous clumps of the CGM by the passage of advancing hot-spots and/or expanding radio lobes (van Breugel et al. 1985; Pedlar, Dyson, & Unger 1985; Rees 1989; Wilson 1989; Meisenheimer & Hippelein 1992). An important means of sustained excitation of this filamentary nebulosity is the photoionization by the UV flux emerging from the active nucleus through the bi-conical funnels of the nuclear torus, so that the brighter emission usually occurs within a few kpc of the AGN (McCarthy 1993 and references therein). At larger redshifts the size of the EELR often exceeds 10 kpc, presumably because of the higher UV output of the nuclei of distant sources and/or a greater abundance of gaseous clumps (McCarthy 1993).

Further, although powerful RGs at $z < 0.5$ tend to avoid rich clusters of galaxies, it is now clear that at higher z they frequently occur in clusters (Yee & Green 1987; Hill & Lilly 1991; Bahcall & Chokshi 1992; Yee & Ellingson 1993). Thus we expect the presence of a significant ICM (of poorly constrained temperature; cf. Castander et al. 1995) around high redshift RGs, and that such galaxies at higher z would be moving at substantial speeds relative to the ICM, as these clusters are still in the process of virialization. The evidence for virialization lasting to the present epoch comes from the steep cosmological evolution of soft X-ray emission from clusters (Edge, Stewart & Fabian 1992; Castander et al. 1995). Considering this, a random velocity of at least $\sim$500 km s^{-1} may be taken as the typical value for the radio luminous ellipticals at higher z, as discussed below.

Thus, within the typical lifetime of nuclear activity of a few tens of millions of years, the parent galaxy would have moved a distance $D = 5\tau_7 V_{500}$ kpc from the origin, marked by the point of symmetry of the two hot-spots, where the active lifetime, τ_7, is in units of 10^7yr and the velocity, V_g, is given in units of 500 km s^{-1} (see below). Our simple picture assumes that both the jets and the ICM density profile are symmetric about the nucleus and, moreover, that the jet flow speed on all scales vastly exceeds V_g; the evidence that the FR II jets remain relativistic all the way to the hot-spots is accumulating (e.g., Dreher 1984; Scheuer 1987; Bridle 1992; Laing et al. 1994). Therefore, within an average age of (3–5) $\times$ 10^7 yr, a typical FR II RG or QSR can develop a structural asymmetry of $\approx$ 50%, i.e., $Q \approx 1.5$, given that the typical size of a powerful RG for $z > 0.5$ is $\sim 100 - 150$kpc (taking $H_0 = 75$km s^{-1} Mpc^{-1} and $q_0 = 0.5$).

We now turn from the velocities of the radio hot-spots to the velocities of the galaxies producing them. In the CDM simulations of Katz & White (1993), the typical velocities for test particles increase with cosmic time, quasi-monotonically from $v_{circ} = 500$ km s^{-1} at $z = 1.75$ to $v_{circ} = 900$ km s^{-1} at $z = 0.13$, but throughout this interval the velocities of the galaxies, while hard to determine, since there were not that many of them in their simulations, were somewhat smaller; however at high $z > 0.5$ the bias factor $b_v = V_g/v_{circ} \approx 1.0$, while it falls to $\approx 0.5 (z = 0.13)$. They also find significant gas densities to be present in a hot extended gas that evolves to fairly closely mimic the situation in the Virgo cluster. This type of moderate velocity bias was shown to hold for a wide range of galaxy formation scenarios by Carlberg (1994).

The growth of first-rank galaxies in poor clusters has recently been investigated via N-body simulations (Bode et al. 1994). It was found that dynamical friction leads to orbital decay and enhances the encounter rate so that the dominant galaxy accretes many smaller ones. While this first rank galaxy tends to have a velocity less than half the average dispersion velocity, a goodly fraction of them retain higher speeds, in agreement with the observations of the rich Abell clusters studied by Zabludoff et al. (1993). Thus we feel justified in taking a typical value of V_g to be around 500 km s^{-1}.

3. The Dusty ISM of Elliptical Galaxies

The densities of hot gaseous coronae of massive ellipticals at low z can be estimated from their thermal X-ray profiles, and while central densities of $10^{-2} - 10^{-1}$ cm^{-3} are obtained for nearby galaxies (e.g., Forman, Jones & Tucker 1985; Trinchieri, Fabbiano & Canizares 1986; Canizares, Fabbiano & Trinchieri 1987), the average densities in the hot halo are significantly lower, falling approximately as $(r/r_c)^{-1.5}$ outside the core radius $r_c \leq 2$kpc. Nonetheless, enormous masses of hot gas ($\sim 10^{11} M_\odot$), comparable to that of the stars, are detected. The presence of significant amounts of obscuring dust distributed over the ISM of massive ellipticals has been established recently from multi-color imaging and IRAS observations (Goudfrooij & de Jong 1995).

Independent evidence for a dusty ISM comes from UV spectroscopy performed by Wills et al. (1993); they have shown that the narrow line emission in each of a set of seven quasars is seriously affected by dust distributed on kpc scales. Furthermore, the gap between the broad line and narrow line regions (BLR; NRL), as well as the apparently much lower covering factor for narrow line clouds in Seyfert galaxies can be naturally explained if a significant quantity of dust is spread throughout the NLR, but is sublimated in the BLR (Netzer & Laor 1993). Therefore, by analogy, and accepting that QSRs and RGs have basically identical host galaxies (e.g., Kukula et al. 1996), then we also expect plenty of dusty ISM within the hosts of FR II RGs.

In that our model ascribes much of the observed asymmetry to dust obscuration, we note that evidence for dust lanes in radio-loud ellipticals is growing rapidly; Cen A is the well-known prototype (Junkes et al. 1993, and references therein). Quite clear evidence for a dust lane has recently been obtained for the distant radio galaxy 0852+124 (z = 2.468) from the suppression of Lyα halo emission on the far side of the galaxy (Gopal-Krishna et al. 1995). Distant radio galaxies where the striking weakness of the Lyα line has been attributed to dust attenuation are TX 0211−122 (z = 2.34; van Ojik et al. 1994) and MG 1019+0535 (z = 2.76; Dey, Spinrad, & Dickinson 1995). At extremely high redshifts, $z > 3$, the evidence for dust lanes coming from Lyα asymmetry (Gopal-Krishna et al. 1995) is bolstered by the detection of such galaxies in the mm continuum emission (Dunlop et al. 1994; Chini & Krügel 1994). Similar evidence exists for high z quasars (Andreani, LaFranca, & Cristiani 1993; Heckman et al. 1991). A highly plausible scenario for the formation of dust lanes in the hosts of radio powerful AGN is the accretion of a gas rich galaxy, which could also trigger nuclear activity (e.g., Colina & de Juan 1995; Sparks, Macchetto, & Golombek 1989). As discussed in §4, a dusty disk can act as a rich reservoir of dust which is gradually released into the diffuse ISM due to the motion of the galaxy. Recalling that only a small amount of dust is needed to block the blue light substantially, it is significant that for RGs at higher z where the optical asymmetry is found by MvBK to be more pronounced, the imaging data refers to the blue emission line [O II]λ3727.

4. The Role of Ram-Pressure

In order to detect the inner edges of the radio lobes bounded by the ISM one requires not only radio maps of both high sensitivity and large dynamic range, but also that the lobes themselves are oriented appropriately, i.e., close to the plane of the sky. Despite these difficult demands, clear examples of lobes with rather sharp inner boundaries have been found in a number of double radio sources. A few examples of such radio emission gaps are: 3C227 (Black et al. 1992); 0828+32 and 1833+23A, (Capetti et al. 1993); 3C34 (Johnson, Leahy & Garrington 1995); and Cen A (Junkes et al. 1993). Good possibilities include 0247+39 (Bondi et al. 1993) and 3C265 (Alexander & Leahy 1987). Interestingly, the radio nucleus is often not found to be coincident with the mid-point of the emission gap. The offset provides an indication of the galaxy moving with a significant component of its velocity directed towards one of the lobes which, consequently, typically appears nearer (i.e., shorter). Of the seven sources listed above, five are consistent with this expectation, having the radio nucleus closer to the shorter lobe (with separation ratios between 1.08 and 1.50), while the distances to lobe peaks are the same in 1833+23A, and slightly the opposite way (ratio 0.95) in 3C34. In a few other cases the nuclear offset is largely normal to the line joining the two hotspots (e.g. 3C234, Alexander 1987; 3C285, Alexander & Leahy 1987). In such cases the radio contours near the galaxy are seen to bend in the direction opposite the nuclear offset. A simple interpretation would be that in these cases too, the ISM of the moving galaxy is being swept downstream, due to the ram-pressure of the ICM, and the cocoon backflow is deflected along this trailing ISM.

Specifically, the ram-pressure generated by the galaxy's motion can give rise to an asymmetric disposition of the ISM about the galactic nucleus. The condition for a significant displacement of the ISM relative to the galactic center is $\rho_{ICM} V_g^2 > \rho_{ISM} \sigma^2$, where ρ is the density and σ the velocity dispersion within the galaxy (Gunn & Gott 1972). The timescale for complete stripping of the ISM is roughly given by: $t_{\rm strip} \sim (4/3)(r/V_g)(\rho_{ISM}/\rho_{ICM})$, with r the radius of the galactic ISM (Forman et al. 1979). For the situation of interest here, the stripping is not likely to be complete, nor is it required to be so. During the radio source lifetime, the typical distance traveled by the host galaxy is comparable to the typical radius of the galaxy ($\sim 10 - 20$kpc), and significant ISM asymmetries can thus arise. The galaxy velocities can be reasonably set in the range $V_{500} \sim 1 - 2$ (e.g., Katz & White 1993; see §2). Internal velocity dispersions within even massive ellipticals rarely exceed 250 km s^{-1} and are typically less than 200 km s^{-1} (Mihalas & Binney 1981). Therefore, as long as the mean gas density in the ICM exceeds roughly one-sixth of the ISM density, a substantial displacement of the ISM by $\approx$10 kpc relative to the stellar body of the galaxy can be expected over a typical active lifetime of a few $\times 10^7$ yr (§2). Even if the core of the galaxy produces a deep potential that tightly binds the inner $\sim$1 kpc of gas, so that ram-pressure sweeping is less effective, partial stripping, coupled with accretion from the downstream side, is likely (Balsara, Livio & O'Dea 1994) and will serve to relocate the dusty gas towards the radio lobe on the downstream side which is, obviously, also becoming longer, compared to the other lobe. At low redshifts ($z \approx 0.1$) substructures within rich clusters seem to have fairly large relative motions (Pickney et al. 1993). Recent numerical simulations of colliding sub-clusters show large-scale high-velocity flows which easily affect radio jet morphologies on scales well outside an ordinary galactic radius and may be very important for the formation of Wide-Angle Tailed radio sources (Loken et al. 1995). However, such mergers are unlikely to be frequent enough to distort the most powerful RGs and QSRs. Beyond $z \approx 0.5$, there is little direct evidence for hot gas bound to individual sub-clusters, though such condensations are probably present but fall below current X-ray detection thresholds, and may have quite large relative velocities.

An obvious consequence of the displacement of the ISM would be to enhance the degree and domain of obscuration on the downstream side of the galaxy, *vis á vis* the upstream side, which coincides with the shorter lobe. If, as argued above, the ISM is substantially displaced relative to the galactic center the resulting obscuration asymmetry would be commensurate with the absorption associated with the original ISM. For the latter, a rough estimate can be taken from recent studies of the ISM in nearby ellipticals, which yield an optical depth of $\tau_V \approx 0.4$, corresponding to $A_B \geq 0.5$ (Goudfrooij & de Jong 1995). Thus, a substantial attenuation of the [O II]λ3727 emission can be expected on the downstream side of the galaxy, even if the ISM dust is co-extensive with the EELR.

The obscuration asymmetry resulting from the offset ISM will be further exacerbated by the dusty material being stripped from the disk component, again due to the motion of the galaxy. The efficiency of the stripping process will depend upon the details of the multi-phase density structure of the disk medium, and is essentially impossible to evaluate at present. But let us assume that a small fraction (~ 0.1) of the total dust content (which is estimated to be $\sim 10^9 M_\odot$ for some high z RGs; Chini & Krügel 1994) is swept out of the disk and is spread over a region of about 10 kpc in diameter, roughly coincident with the main body of the galaxy on the downstream side. This material would contribute an extra obscuration of $\Delta A_B \approx 0.1$, extrapolating from typical values of $A_B \simeq 0.3 - 0.4$ for the dust lanes in nearby ellipticals (Goudfrooij 1994). This extra contribution of dust from the disk could also enhance the scattering of the incident photons, thereby providing a possible explanation for the observed positive correlation between the radio structural asymmetry and the degree of optical/UV polarization of the EELR associated with the parent galaxy (Cimatti et al. 1993).

5. Discussion and Conclusions

In the canonical picture the extended emission line regions (EELR) of radio galaxies are believed to arise from shock compression of preexisting gaseous clumps by the passage of the jets (e.g., McCarthy 1993). The compressed gas is probably concentrated within several kpc of the nucleus and also around the surface of the expanding radio lobes. An important source of continued excitation of the EELR is the UV photon flux emanating from the nucleus, which is partially collimated in two opposite directions by the surrounding torus (e.g., Baum & Heckman 1989; Antonucci 1993).

In our scenario, there is no preexisting asymmetry in the clumpy ISM/CGM about the galactic center, nor is the motion of the galaxy with respect to the ICM likely to displace this dense material appreciably (unlike the volume-filling light component of the ISM). A symmetrically extended EELR is also permitted in the scheme of MvBK, except that the EELR is required to be more compressed, and hence brighter, on the side of the shorter lobe where the global ambient density is postulated to be higher. Instead, in our model, where no such asymmetry is assumed, the apparent weakness of the EELR on the side of the longer radio lobe is explained as an artifact arising from a stronger dust obscuration on that side (§4). This effectively attenuates firstly, the nuclear photoionizing radiation incident on the EELR and, secondly, the optical (blue) emission of the EELR towards the observer. As long as the radio nucleus has a non-trivial velocity component along one of the jets, the lobe on that side will necessarily become shorter compared to the other lobe unless the source is viewed at a very young stage. For this velocity driven asymmetry to work, we basically only need $V_g/V_h > 0.05$; this can then easily lead to an observed $Q > 1.1$ and a fairly large emission line brightness contrast between the two lobes. Clearly, this contrast would be more pronounced for higher z sources, for which the optical observations correspond to bluer wavelengths in the rest-frame, and hence the dust attenuation is more effective. Indeed, the optical emission asymmetry found by MvBK is prominent only for the blue [O II] λ3727 emission line, and the effect is much less conspicuous for lower z sources, which were imaged in Hα λ6563. Such a difference is not readily understood in the scenario proposed by MvBK.

The EELR emission on the largest scales, which is associated with the radio lobe surface, is probably too far from the nucleus to be obscured from us by the offset ISM. Nonetheless, it is likely to exhibit the same sense of asymmetry as the smaller scale EELR, since the ISM offset towards the longer lobe will preferentially attenuate the cone of ionizing photons emerging from the nucleus in that direction, leading to a relative paucity of ionized material even in the outer regions of the longer lobe. In particular, the dust swept from the disk would be more effective in this regard as it would be concentrated in the proximity of the nucleus. The asymmetry in escaping ionizing photons from the nucleus could also be the reason behind the reported trend for the longer radio lobe to show a weaker depolarization, though this trend was derived from a small sample of sources (Pedelty et al. 1989), and needs to be confirmed.

As noted in §1, if the EELR asymmetry were to arise from a large scale density asymmetry in the CGM/ICM of the parent galaxy, one would also expect the shorter radio lobe to emit a larger radio flux. Since MvBK find this to hold for only 65% of the RGs in their sample (also, Macklin 1981), the statistical significance of this result is quite low. Although simple theoretical models predict a stronger dependence of the lobe length ratio Q on the density asymmetry than that of the lobe flux ratio, R (Swarup & Banhatti 1981), slightly more sophisticated analytical models favor an even stronger dependence of R than Q on the ambient density asymmetry (cf. Gopal-Krishna & Wiita 1991; Saikia et al. 1996). So the remarkably robust correlation of the EELR brightness asymmetry with the lobe asymmetry, despite the weak observed correlation of R with Q is puzzling, if the fundamental driver is indeed the large-scale density asymmetry of the ICM/IGM. In contrast, these observed trends follow quite naturally from our asymmetric obscuration scenario. Note that any relativistic beaming of the hot-spot emission, which could greatly confuse these matters, is expected to be a minor effect for the 3CR RGs, which were selected at 178 MHz, and should be oriented relatively close to the sky plane (cf. Barthel 1989).

Note that our assumption that the galaxy could be moving at a random angle from the jet direction may, in fact, be too conservative for estimating the resultant lobe length asymmetry. Recently, West (1993) has presented evidence that massive ellipticals hosting powerful double radio sources are dynamically confined to large-scale filamentary structures dotted by clusters and superclusters of galaxies. West argues that the radio jets are ejected preferentially along the filament containing the active galaxy. An expectation for such a model would be that any gravity-induced motion of the active galaxy would be directed roughly along the filament and would thus have a large component along its jet, particularly at higher redshifts, where galaxy mergers are believed to be more common.

It needs to be recalled that aside from the orientation effects which are most important for any relativistically moving components, the origins of asymmetries could also be related to initial conditions. The possibility that jet ejection could alternate from side-to-side under some circumstances was suggested (Wiita & Siah 1981) and a group of radio sources that seemed to evince this "flip-flop" behavior was pointed out by Rudnick & Edgar (1984); analysis of a large sample of radio quasars appeared to support the alternating side ejection picture (Hutchings, Price & Gower 1988). While the great majority of theoretical models tend to launch a pair of equally powerful jets from the central engine of the active galactic nucleus (AGN) there are some magnetically dominated models that can produce jets of arbitrary initial asymmetry (e.g. Wiita 1991; Wang, Sulkanen & Lovelace 1992), and very extended jets may even break up, leaving hot-spots well behind the extended emission (Hooda, Mangalam & Wiita 1994). Nonetheless, Tribble (1993) has argued that neither of these mechanisms is likely to dominate for radio galaxies.

It should be stressed that we are not claiming to exclude the occurrence of environmental asymmetries in RGs. Indeed, they might well be a dominant effect in a small minority of RGs showing $Q > 2$. However, we have endeavored to demonstrate that an environmental density asymmetry as a general feature of powerful radio galaxies is not demanded by the currently available observations.

While the lack of quantitative details in the present stage of our phenomenological model is a shortcoming, this is an inevitable outcome of the currently poor knowledge of the properties of dust in elliptical galaxies and of the ICM at higher redshift. Nonetheless, the physical basis of the model appears to be quite well defined and seems capable of qualitatively accounting for the available observations in a fairly natural way. Moreover, our model makes some specific predictions: firstly, the correlation with the radio lobe asymmetry should be much less pronounced when near IR images of the EELR are employed (instead of blue images), as the former are much less susceptible to dust attenuation; such a wavelength dependent behavior would not be expected in the MvBK picture. Another test of our scenario may soon become feasible through deep, high-resolution imaging in the far IR. We predict that the far IR emission, reradiated by the dust, should be brighter on the side of the longer radio lobe where more dust is present; this is opposite to the expectation from the MvBK explanation of the correlated radio–optical asymmetry.

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