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Jets and emission-line regions

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Summary. We propose that the low excitation broad line regions in active galaxies are closely associated with the jets reponsible for compact radio sources. Various consequences of this hypothesis are considered for emission line structure, including broad and narrow line regions, radio morphology and active galaxy type.

Key words: active galaxies – jets of galaxies – line formations

1. Introduction

There are compelling reasons for considering possible interactions between jets and the broad emission line regions of active galactic nuclei. Jets certainly interact with clouds to produce emission line structures on larger scales and there is considerable evidence for a link between larger scale line emission and the broad line regions.

On the larger scale in Coma A, for example, there is a continuum and emission-line knot at ~5 kpc from the nucleus (Miley et al., 1981; van Breugel and Heckman, 1983). There is a strong evidence that here a jet has interacted with a cloud producing local particle acceleration and a local source of photoionization as well as significant bending and decollimation of the jet itself. The recent studies of NGC 4151 by Heckman and Balick (1983) have shown that the narrow emission-line region (NLR) is a linear extended structure and that the photoionization source is probably generated in the jet itself. Kiloparsec scale jet-like structures have also been seen in several more distant Seyferts (Ulvestad and Wilson, 1983) and the asymmetries in their line profile indicate that the line emitting gas is moving predominantly radially outwards. Further evidence for interaction of jets with matter on the kiloparsec scales comes from the sharp bends in the radio emission of two quasars with steep spectrum cores, which are postulated to be due to collision with a dense molecular cloud (Barthel and Lonsdale, 1983; Barthel et al., 1983). In both cases the bent jet leads to a compact hot spot. Again, powerful radio quasars exhibit one-sided jets far more frequently than radio galaxies and this has a natural interpretation in terms of more environmental interaction for quasars.

Recently the distinction between the NLR and BLR has become unclear. For example, sometimes broad wings extending for several thousand km s^{-1} are seen in the "narrow" forbidden lines. Excellent examples of this are the broad [O III] wings observed in Mkn 435 by Van Groningen and de Bruyn (1984) whose profiles are modelled rather well by jet calculations. A kinematic connection between the BLR and NLR has been demonstrated by the work of Heckman et al., (1983) who find a correlation between the widths of the Hα and [O III] λ 5007 lines. It is therefore reasonable to argue that, just as in the radio emission, there is a continuum of properties between the kiloparsec scale NLR and the parsec scale BLR.

Since the characteristic sizes and energetics of (jet-like) flat spectrum VLBI radio components are similar to those of the BLRs we have been motivated to examine various aspects of the hypothesis that a substantial component of the BLR is connected with a jet. Outlined in this paper are a number of aspects of this hypothesis that we consider important and that deserve further detailed consideration. This essentially new idea for models of the BLR may, however, already prove useful when considered as a specific alternative concept to the standard photoionization work in this area. The structure of this study is as follows. We commence by describing relevant characteristics of the BLR including correlations of BLR properties with jet properties (Sect. II). Then we present an idealized jet model that can explain some essential features of the BLR (Sect. III). We consider how the Jet's radio properties will be influenced by the BLR and emission-line regions on larger scales (~10 pc) (Sect. IV) and discuss correlations and predictions. Finally we suggest that the properties of the nuclear environment is as important as the collimation, energetics and beaming of the jet in determining the form in which activity manifests itself and determining the type of active galaxy that develops (Sect. V).

II. Relevant broad-line region characteristics

The most important correlations between the broad emission lines and other properties of active galaxies, are as follows. Broad-line radio galaxies (BLRG's) have weaker Fe II/Hβ than Seyfert I's (Osterbrock 1977). Radio loud quasars have weaker Fe II/Hβ than radio quiet QSO's. These seem quite consistent with the first group being lower luminosity versions of the second (Osterbrock, 1982). Possibly the most illuminating correlation is that found amongst the class of radio quasars. Radio loud quasars with extended jets tend to have broader Hβ lines and relatively weak or virtually no detectable Fe II/Hβ compared with the

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compact, "core-dominated" radio quasars (Miley and Miller 1979, see also Bergeron and Kunth, 1983). A plausible way to look at this is to reason that if a jet is stopped, its energy may dissipate and excite the low ionization Fe II in dense regions of the BLR. If a jet propagates it will not energize the above region.

The extensive work on Fe II excitation mechanisms by Collin-Souffrin and colleagues (Collin-Souffrin et al., 1980) strongly suggested that there are two distinct *ionization* systems: (I) a standard photoionisation region containing Lyα, C III, He I, He II, *some* Balmer ($\lesssim$20%), Paschen, Mg II, Fe II (UV); and (II) a collisionally excited partially ionized region containing most of the Balmer and Paschen lines, the optical Fe II, Mg II and O I. This conclusion is independent of how region II is energized. Mechanical heating and X-ray heating (Kwan and Krolik, 1981; Weisheit et al., 1981) seem the most plausible possibilities. The correlations mentioned previously imply that for active galaxies possessing extended $\lesssim$100 kpc radio sources (broad-line radio galaxies and most steep spectrum quasars) the Fe II in region II is not excited.

The very high spectral resolution investigation of quasars by Wilkes and Carswell (1982) implies that two *kinematic* systems exist within an individual quasar: (I) Symmetric profiles for the high ionization species such as Lyα and (II) for the low ionization species particularly O I the kinematic system is redshifted by $\sim 10^3\,\mathrm{km\,s^{-1}}$ with respect to (I). Radial flow combined with obscuration seems the most probably explanation here. We find it most plausible to associate the two regions found independently in both the excitation models and the kinematic data. This would be consistent with the work of Gaskell (1983) which showed a clear redshifting of O I, Mg II and Balmer lines with respect to C IV, N V, C III] and possibly Lyα in his sample. Shifts of $\gtrsim 10^3\,\mathrm{km\,s^{-1}}$ are seen. More interesting perhaps is the strong evidence for equally probable red- and blue-shifts of $\sim 10^4\,\mathrm{km\,s^{-1}}$ for the low ionization broad-line region with respect to the narrow line region which is assumed to be at the time redshift. The effect seems more pronounced in extended radio sources where collimated energy flow is known to be occurring throughout the broad line region. In this jet model the line-widths can be much larger than the systemic velocity shift of the line since the former are related to the jet velocity via the entraining and backflowing cocoon and the latter to the slower mean motion of, for example, the jet hot-spot as it ploughs through the dense nuclear environment. Line shifts of $\sim 10^4\,\mathrm{km\,s^{-1}}$ could occur if emission from one jet dominates at a given time.

The correlation of Lyα/Hα with the continuum can be explained in terms of the above model, if the optically thin Lyα responds to the continuum but the Balmer lines formed in the dense high optical depth region II do not (Allen et al., 1982). The strongest argument for optically thin Lyα comes from the symmetric profile of Wilkes and Carswell (1982). Calculation of optically thick Lyα in centrally illuminated photoionization model give very asymmetric profiles.

We therefore assume that the low ionization system II is produced by interaction with a jet which is also responsible for the global properties of the excitation and kinematics. This would imply that in the absence of jet dissipation no observable Fe II lines would be produced.

III. Jet model: influence of the jet on the BLR

The basic model is shown schematically in Fig. 1 as a jet propagating through and interacting with its environment via internal shocks and its unstable boundary layer cocoon. Broad line region clouds can be made in these interaction regions and sprayed off the jet into the general BLR. Cocoon turbulent velocities are of similar order of magnitude to their directed flow velocities, i.e. there is considerable shear across the turbulent jet. The essence of the model is that the jet can, in principle, both create and energize much of the broad line region and create a continuum of properties out through the narrow line region and beyond.

The typical pressure exerted by a jet on the BLR can be estimated as

$$P_J = 10^{-2}\left(\frac{L}{10^{44}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{10^{-2}}{\Omega/4\pi}\right)\times\left(\frac{1\,\mathrm{pc}}{R}\right)^2\left(\frac{10^5\,\mathrm{km\,s^{-1}}}{V_J}\right)\,\mathrm{dyne\,cm^{-2}} \tag{1}$$

for a jet power L, opening angle $\Omega/4\pi$, velocity V_J, all calculated at a distance R from the jet origin. Assuming that the clouds can cool and reach pressure equilibrium in the cocoon of the jet with a temperature $\sim 10^4$ K typical of the low ionization BLR,

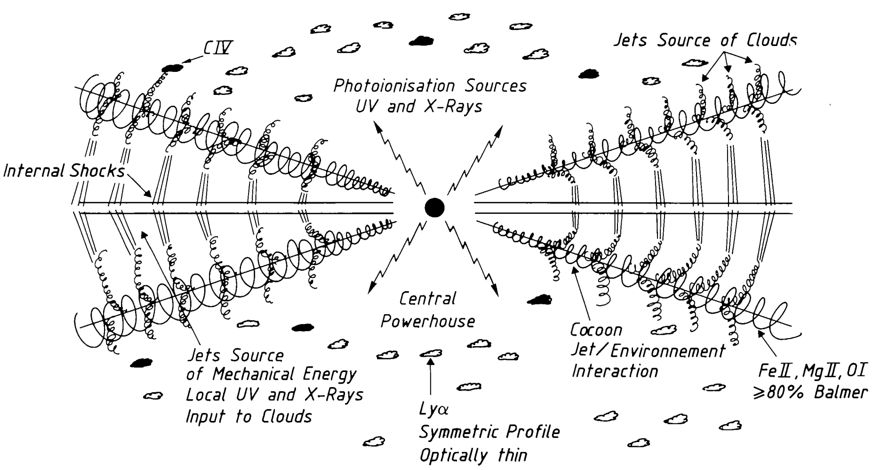

Fig. 1. Turbulent jet and environment interaction creates the BLR clouds and energizes to low ionization species

we use $P_J \sim nkT$ and obtain a filament density

$$n = 10^{10}\left(\frac{10^4\,\mathrm{K}}{T}\right)\left(\frac{L}{10^{44}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{10^{-2}}{\Omega/4\pi}\right)\left(\frac{1\,\mathrm{pc}}{R}\right)^2 \times\left(\frac{10^5\,\mathrm{km\,s^{-1}}}{V_J}\right)\mathrm{cm^{-3}}\,. \qquad (2)$$

This simple calculation shows that the density needed for the Fe II formation in the BLR is quite plausibly obtained for the above jet parameters. We expect dense filamentary structures to form in the jet cocoon as is illustrated in the numerical simulations of Norman et al. (1982). The initially dominated bremstrahlung-cooling column density in the jet is $N \sim 10^{23}\left(\frac{V_J}{10^5\,\mathrm{km\,s^{-1}}}\right)^2\mathrm{cm}^2$, and the transfer calculations of Collin-Souffrin et al. (1980) require such column densities to obtain the correct line ratios $N \sim 10^{25}\left(\frac{V_T}{10^3\,\mathrm{kms^{-1}}}\right)\left(\frac{\tau UV3}{10^5}\right)\mathrm{cm}^2$, where V_T is the turbulent velocity in the coccoon and τ_{UV3} is an estimate of the optical depth in the Fe II lines. It is remarkable these independent estimates agree so well. In fact it is only at $V_J \sim 10^5\,\mathrm{km\,s^{-1}}$ that the cocoon gas can cool. This offers an explanation of the relation between filament formation and cocoon velocities $\sim 10^4\,\mathrm{km\,s^{-1}}$ as seen in the BLR.

The covering factor of the BLR in this jet geometry is the opening angle of the jet $\frac{\Omega}{4\pi} \sim 10^{-1}$–$10^{-2}$. The filling factor of $\sim 10^{-3}$ is a natural consequence of a relatively thin cocoon region forming around the jet. It is interesting to note here that for the emission-line regions definitely associated with jets in lobes the emission lines do, in fact, come from the jet perimenter (Miley, 1983, van Breugel and Heckman, 1982).

The mass of the BLR gas is typically $\sim 30\left(\frac{\mathrm{L(H}\beta)}{10^{45}\,\mathrm{erg\,s^{-1}}}\right)\cdot\left(\frac{10^{10}\,\mathrm{cm^{-3}}}{n}\right)M_\odot$ which could be either outflowing jet gas $\sim 1\,M_\odot\,\mathrm{yr}^{-1}$ or entraining gas or, more plausibly, both. The central energy flow in the jet is most likely to be at least marginally relativistic (Rees et al., 1983). However, it is the cocoon that provides the BLR component. The head of the jet may be moving significantly slower as it ploughs through the dense medium and with the incorporation of backflow (Norman et al., 1982, 1983) systematic velocities of $\sim 10^3\,\mathrm{km\,s^{-1}}$ with larger turbulent velocities can be envisaged.

There is, at present, some uncertainty about whether the heating input to the low ionization BLR is mechanical energy input via, say, turbulence cascading or the effect of X-ray heating. Either mechanism could work here. A prodigious *local* source of both X-rays, via shock cooling, and wave energy, from the turbulent cocoon will be generated as the jet dissipates. The results of detailed heating calculations will clarify our model. An additional source of photoionization in the BLR may arise in the low frequency variables where the Compton scattering of the electrons on the low-frequency photons gives a local source in the optical and UV (Marscher, 1983). The advantage of local photoionization is that optically thick clouds could still give symmetric Lyα.

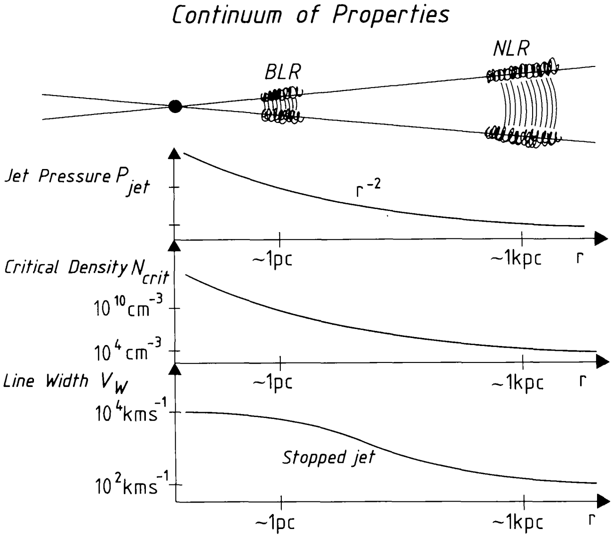

Fig. 2. Collimated energy flow continues from BLR to NLR. A smooth continuum of properties is indicated. The critical density when collisional and radiative de-excitation are equal is n_{crit}, v_w is the apparent line width decreasing from BLR to NLR, and p_{jet} is the pressure the jet applies to the emission line clouds

The covering factor of the BLR is a decreasing function of luminosity in both the optical and X-ray (Lawrence and Elvis, 1982). Wide turbulent cocoons are associated with low power, low Mach number jets and the cocoon opening angle will decrease as the jet power increases, thus qualitatively giving the observed correlation. Broad absorption line troughs are observed in 1–10% of quasars (Turnschek et al., 1982). This could be due to absorption in turbulent jet cocoon structures that cover the BLR with a typical opening angle $\Omega/4\pi \sim 10^{-1}$. The P Cygni profile with detached emission and absorption strongly suggest collimated flow. Further study of correlation of this phenomena with C III] and other species will prove most useful.

The variability studies of NGC 4151 (Perola et al., 1982) show that the UV and X-ray emitting regions must be spatially distinct, the X-rays coming from a smaller region such as an accretion disk. We tentatively suggest that the UV may come from the jet cocoon. Infrared variability is unclear at present as is the presence of dust in the BLR although it has been suggested that $A_V \sim 1$ in this region (Gaskell, 1981; Hyland and Allen, 1982). The cocoon could have dust at $\sim 10^3$ K with an associated infrared emission at $\sim 10\left(\frac{T}{10^3\,\mathrm{K}}\right)\mu\mathrm{m}$. Such $\sim 10\,\mu$m emission could then vary on time scales of order years and could radiate most of a jet's dissipated energy.

Our model is easily extended to the narrow line region, as shown in Fig. 2, whose properties show a smooth transition with the BLR (Heckman et al., 1983). With constant opening angle, typical densities at 1 kpc are $\sim 10^4\,\mathrm{cm^{-3}}$ or lower if the opening angle of the jet widens as it propagates radially. These inferred densities would be consistent with the NLR filaments. In addition to the previously mentioned work of van Groningen and de Bruyn (1983) broad [O III] has been seen along the radio jet of NGC 1068 and is closely associated with it (Wilson and Ulvestad, 1983). In the study of the NLR of NGC 7213, Filipenko (1984) has found a remarkably tight positive correlation between line width and critical density of a given ionic species. With filament densities given by (2) and a slowing, dissipating jet such a correlation would seem qualitatively in agreement with our jet hypothesis for the NLR as well.

IV. Radio emission characteristics: influence of the emission line region on the jet

It has been proposed by Blandford and Konigl (1979) that BLR clouds moving into the relativistic jet, with bulk Lorentz factor γ_b, can be accelerated in the jet direction and produce the superluminal effect. This ballistic type of model is one of the plausible ways to produce superluminal velocities. However the effect is only seen within an angle $\sim 1/\gamma_b$ to the direction of motion. Screen effects have also been invoked (Blandford et al., 1977; Morrison and Sartori, 1968; Lynden-Bell, 1977; Miley, 1983). The cocoon of the jet which we postulate to be the low ionization BLR or similar cocoon at ~ 10 pc would be a natural screen. The detailed structure of a screen model is very dependent on the exact geometry but the basic features involve a cocoon–jet interaction via intersecting relativistic shocks within the jet propagating with respect to one another or view the jet producing shocks as it propagates into the emission-line clouds in the cocoon. Specific examples of the shock structures that can develop both due to internal instabilities and cocoon generated effects are given in Norman et al. (1983) The superluminally moving hot spot is at the intersection between the shocks. Within such a model it is possible to envisage situations where only superluminal expansion is seen (Miley, 1983) although, quite generally, screens will give the possibility of superluminal contraction. The relativistic shock intersections can produce a moving hot *spot* rather than a trail or other diffuse structure. Such screen models can also apply to low frequency variables although the contraction problem is as yet absent due to the substantially lower resolution.

For the above models to be plausible, bulk velocities close to the velocity of light would probably be required anyway for the energizing signal. The X-ray variability limits support this view but given the strong dependence of this result on the angular size estimates one can infer that $\gamma_b \sim 3$ would be sufficient in all cases studied (Marscher, 1983).

There are ~ 9 known superluminals compared to 2 known subluminals but a well defined complete sample has not been observed and analysed as yet. Of order $\sim 50\%$ of all compact sources are low frequency variables. Screen type models can give the necessary widening of the viewing angle of these effects particularly if there are many screens with different orientation in the jet and its cocoon. Rees' (cf. Rees et al., 1984) ballistic spray model was proposed for the same reason. Points that await resolution for viable screen models concern the (non) existence of superluminal contractions, the constancy of the superluminal velocity per outburst and the correlation of the outburst direction with that of the large scale energy flow. The latter two points could be resolved by interaction with jet cocoon screens although screens are less efficient.

We have previously argued that bulk velocities of the emitting electrons in extended jets are non-relativistic (van Groningen et al., 1981) and may be caused by the slowing influence of the BLR and NLR acting on an initially relativistic jet. The emission line regions are the energy dump and the strongest evidence at present is the correlation of "core-dominated" sources with Fe II/Hβ. In this model one-sidedness of jets is *not* due to Doppler favouritism but to one-sided jet blocking in the core. In a nucleus with massive molecular clouds the blocking time would be of the order of a fraction of the dynamical time $\sim 10^5$–10^6 yr. We identify core jet sources with dissipative blocking of one side of the jet. Here asymmetry and shifts in line profiles should be observed as in Gaskell's (1983) study. We note here that compact and extended one-sided jets are always observed on the same side and this is to be interpreted here as a strong asymmetry in the jet and environment interaction across the galaxy from one jet to the other down to subparsec scales.

V. Active galaxy types

In attempting to explain the presence of Fe II in compact radio quasars and its absence in extended ones we asserted that the jet is dissipated in or near the BLR and does indeed produce the BLR. Obviously this process is a function of the stopping power of the nuclear environment. This is clearly an important additional parameter to include when discussing active galaxy type.

An elegant hypotheis for a unified scheme of compact versus extended radio sources and radio quiet QSOs versus radio loud quasars has been developed by Scheuer and Readhead (1979) and Orr and Browne (1982). In this scheme radio sources are observed to be compact (core dominated) or extended merely as a consequence of the geometrical configuration. When we are looking down a relativistic jet the core appears to be Doppler boosted.

Evidence in favour of the Doppler boost model of compact sources was provided by observations of superluminal expansion as well as the one-sidedness and bent nature of compact sources. However in recent years several observations have been made which cast doubt on the validity of this model in its simplest form. To summarize some of these points

(i) the presence of extended, low surface brightness jets associated with core-dominated sources constraining their aspect angles (Schilizzi and de Bruyn, 1983) unless these jets swing through large angles.

(ii) the similarities of the structure and sizes of high luminosity extended radio sources associated with galaxies and with quasars coupled with a difference in core-strengths by ~ 20 (e.g. Miley, 1981) imply that non-aspect effects are responsible for at least a part of the differences in radio core strengths.

(iii) the few core dominated sources that are close enough to study in detail (3C 120, NGC 1275) have very peculiar underlying galaxies suggesting that the strong nuclear radio sources are an intrinsic property of these galaxies.

(iv) the most powerful nearby quasar 3C 273 appears in the unified scheme to be pointing towards us.

(v) one-sidedness is also no longer confined to compact sources but one-sided jets are seen extending for several hundred kiloparsecs.

(vi) no further superluminals or velocities comparable to *c*, have been found in a sample of fainter core dominated sources (Readhead et al., 1983).

(vii) emission-line properties of extended and core-dominated sources are significantly different (Heckman, 1983).

If, as argued in Sect. III, jet blocking is a function of nuclear density we propose that the nuclear density is higher in spirals than ellipticals so that spirals jets do not propagate to form extended radio lobes. The increased jet dissipation gives an increased Fe II/Hβ in Seyferts and QSOs, which we associate with spirals, with respect to BLRGs and quasars which we associate with ellipticals as summarized in Table 1.

Because we have made the extreme assumption that the low ionization BLR is the jet, then this component of the emission-line region will switch off rapidly on a time scale of order years when

Table 1. Nuclear activity and environment

Environment		Sparse ————	————	———— Dense
Galaxy type		Elliptical	Intermediate	Spiral
Jet propagation		Jet penetrates and energizes lobes	Most dissipation in inner parsec	Blocked or inhibited
Radio type		Lobe dominated	Core dominated	Quiet
Active nucleus type (Power index)	↑ Increasing jet power		← *Bl Lac* (1, –, –, –)	→
		Lobe-dominated quasar (3C 47) (–, 1, 1, –)	*Core-dominated quasar* (3C 345) (–, 1, 2, 3)	*Radio quiet Quasar* (PHL 5200) (–, 1, 1, –)
		Broad-line radio galaxy (3C 390.3) (–, 2, 2, 2)	*Core-dominated radio galaxy* (NGC 1275) (–, 2, 3, 3)	*Seyfert* 1 (NGC 4151) (–, 2, 2, –)
		Narrow-line radio galaxy (Cygnus A) (4, 4, 2, 2)		*Seyfert 2* (NGC 1068) (4, 4, 2, –)
				Liner (4, 4, 3, –)
		Weak-line radio galaxy (NGC 6251) (4, 4, 3, 2)		*Starburst* (M82) (4, 4, 4, 2)
		Quiescent elliptical (4, 4, 4, 4)	*Quiescent intermediate type* (4, 4, 4, 4)	*Quiescent spiral* (4, 4, 4, 4)

Footnote to Table 1. The "Power index" is a measure of the luminosity emitted from size scales ($\ll 1$ pc, ~ 1 pc, ~ 1 kpc, ~ 100 kpc) respectively for the various types of active nuclei. The (subjective) power scale extends from 1 = very powerful to 4 = very weak. The type of active galaxy would then be determined by a combination of environment and the power input to the jet integrated over the corresponding jet propagation time scale

the jet turns off. Seyferts Is will then change to Seyfert IIs and BLRGs to NLRGs the latter retaining their extended jet structure while the inner jet is temporarily off.

Similarly, Seyfert IIs can still have extended jets on ~kpc scale over a timescale of $\sim 10^6$ years if the jets have velocities $\sim 10\,\mathrm{km\,s^{-1}}$. This is consistent with the number of Seyfert IIs being roughly equal to the number of Seyfert Is in Wilson's (1983) sample. The inferred on-off duty cycle is therefore of order one to one.

Table 1 is a possible description of the relation of the various types of nuclear activity to the associated environment. The relative strengths of the individual building blocks can be viewed as determined by a combination of environment and jet powerflow integrated over the jet propagation time scales appropriate to the various building blocks.

There are two types of active galaxies whose place within this scheme is uncertain, namely, BL Lacs and starburst nuclei. It is possible that the BL Lac phase of activity which corresponds to nuclear flaring on time scales of ~ 1 yr. can occur in both sparse and dense environments. The weak-line radio galaxies constitute an interesting class. These are associated with ellipticals. The powerful radio lobes indicate that they have undergone strong nuclear activity during the last 10^8–10^9 yr but there is little evidence for this in their observed nuclear properties. An important question concerns the signature that such past nuclear activity might leave behind if it occurred in the dense spiral environment and whether, in fact, it could be detected. An intriguing possibility is that starburst nuclei are such objects. In that case, the direct effects of the jet dissipation and its high ionization would no longer be present and the only remnant of nuclear activity would be the previously triggered starbursts.

In summary, although Doppler boosting may play a role in explaining differences between types of active galaxies, the nuclear environment is likely to be a much more important factor. Specifically, a dense nuclear environment could cause one-sided or two-sided blocking of the emerging jets with significant production of line-emission and infra-red radiation by dust. The jet cocoons are relevant to batch screen models of superluminal expansion and low frequency variability.

If the environment does indeed play the dominant role one might expect to find correlations between the variability of lines due to species such as [O I] and both low frequency variability and superluminal outbursts.

The more basic prediction here is that the 1–10 pc scale radio structures now easily obtained with VLBI arrays should have fairly well defined correlations in the line profiles of the low ionization species of the BLR. In our own Galaxy, if there is a low luminosity jet present in the Galactic Centre with a mildly relativistic core then variability of continuum structure and emission lines may occur on time scales of years.

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