OPTICAL–RADIO CONNECTIONS

AGN Illumination or Jet/cloud Interactions?

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1. Introduction

Many of the most important discoveries in the study of extragalactic radio sources have resulted from investigations of the relationships between optical and radio properties. The optical/radio connections include: **correlations** between optical emission line luminosity and radio power [1,2]; **alignments** between optical/UV and radio structures [1,3]; and **UV excesses** in the spectral energy distributions of radio galaxies compared with normal early-type galaxies [4].

These connections are not only important from a detailed, phenomenological point of view but are also relevant to several of the key issues concerning extragalactic radio sources, including the nature of the central engine, quasar/radio galaxy unification, and the use of radio galaxies as probes of the high redshift universe.

2. Models

Several models have been proposed to explain the connections between radio and optical properties, but the two most promising are anisotropic illumination and jet/cloud interactions.

In the **anisotropic illumination model**[5] the ambient ISM in the host galaxies is illuminated by the radiation cones of quasars hidden in the cores of the galaxies, with the emission lines resulting from photoionization of the ambient ISM by the EUV radiation in the cones, and the extended optical/UV continuum consisting of a combination of the nebular continuum[6] and scattered quasar light[7] (see Figure 1). In this case the relationship between radio and optical properties is indirect: the correlations between optical emission line luminosity and radio power require

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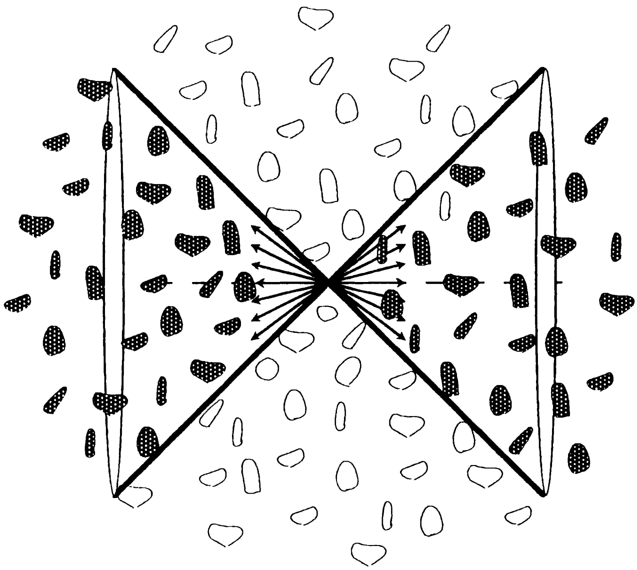

Figure 1. The anisotropic illumination model. A hidden quasar illuminates the ambient ISM in a cone pattern defined by the properties of the central obscuring torus.

that the optical/UV luminosity of the quasar is tied to the radio jet power through the physics of the central engine[8].

In the jet/cloud interaction model the relationship between the radio plasma and the optical/UV emitting components is more direct: as the radio jets plough through the ISM of the host galaxies they shock and sweep up the clouds in their path[9] (see Figure 2). The clouds involved in such jet/cloud interactions will emit both optical emission lines and optical/UV nebular continuum. It has also been proposed that the jets can trigger star formation by compressing the ambient ISM[10,11].

Each of these models is now considered in more detail.

2.1. ANISOTROPIC ILLUMINATION: ADVANTAGES

A major attraction of the anisotropic illumination model is that it is consistent with unified schemes for powerful radio galaxies, which propose that all radio galaxies have quasars hidden in their cores[12]. The putative hidden quasars will have a marked effect on the ISM in the host galaxies: typical ionizing luminosities for 3C quasars fall in the range 10^{44}–10^{46} erg s^{-1} ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$ assumed throughout), whereas the total emission line luminosities of radio galaxies are 10^{42}–10^{45} erg s^{-1} [8]. Thus, provided that covering factors of a few percent or more are possible, quasar

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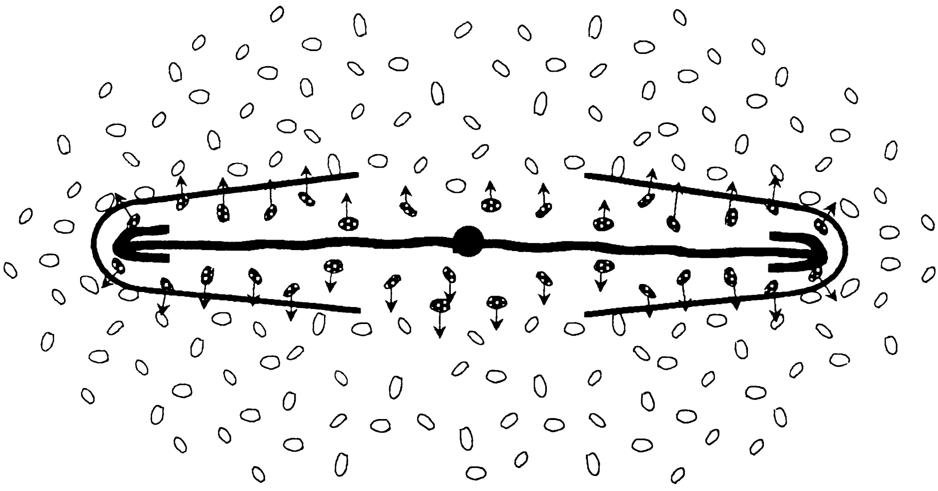

Figure 2. **The jet/cloud interaction model. Clouds entering the shocks driven through the ISM by the jets will be compressed, ionized and accelerated.**

illumination can supply a substantial fraction of the ionizing energy.

Another point in favour of quasar illumination is that the ratios of most strong emission lines measured in the spectra of low redshift extended emission line regions (EELR) are consistent with photoionization of optically thick, solar abundance clouds by a hard, power-law or hot black-body ionizing continuum [13]. Photoionization has a major advantage over other ionization mechanisms in the sense that the number of free parameters is relatively few. It is possible, for example, to explain the sequence of observed points on the emission line diagnostic diagrams by varying just one free parameter (the ionization parameter, U).

If the quasar is illuminating an undisturbed ISM/ICM, then the kinematics of the emission line gas should reflect the gravitational motions of the clouds in the haloes of the galaxies. In general, this is found to be the case in most low redshift radio galaxies ($z < 0.2$) which have velocity half-amplitudes consistent with the expected mass distributions of early-type galaxies ($\Delta V < 400$ km s^{-1}) [14]. Where larger velocity amplitudes are observed they are invariably associated with EELR along the radio axes, and jet/cloud interactions are suspected.

Perhaps the most compelling evidence for illumination is provided by polarimetry measurements which show that the UV continuum in several powerful radio galaxies is polarized at the 5 – 20% level, with the polarization E-vector aligned perpendicular to the radio/UV axis[7,15]. Recent spectropolarimetry observations also show evidence for scattered broad quasar features in a number of objects[16,17,18]. It is difficult to explain these observations in any other way than quasar illumination.

High-quality optical spectra reveal two other activity-related components which contribute to the UV excess: first, nebular continuum[6], which will make a significant contribution whenever the emission lines have large equivalent widths; second, direct AGN light from previously-unrecognised weak broad-line nuclei[19]. Both of these components are unpolarized and will act to dilute the polarization from any scattered light.

2.2. ANISOTROPIC ILLUMINATION: PROBLEMS

The most obvious problem with the illumination model is that the large-scale emission line structures do not look like cones. While emission line imaging observations have shown clear evidence for radiation cones in several Seyfert galaxies[20], there is no really convincing case of an emission line cone in a powerful radio galaxy. Part of the reason for this is that the gas distribution is sparse and inhomogeneous in the early-type host galaxies and does not provide a uniform flourescent screen against which to see the quasar polar diagram. Although individual low redshift radio galaxies ($z < 0.2$) show broad distributions of emission line gas, the emission line structures are nonetheless still consistent with the broad radiation cones predicted by the unified schemes[5]. The main problem lies with high redshift radio galaxies ($z > 0.5$) in which the linear, almost jet-like optical/UV structures are better collimated than would be expected on the basis of the broad quasar radiation cones[21].

Another problem is that, despite the good general agreement between the standard photoionization model predictions and the observed emission line spectra, some line ratios appear discrepant. A notable example is the key temperature diagnostic ratio [OIII](5007+4959)/4363, which is measured to be significantly smaller than predicted by the standard AGN photoionization models (indicating higher than predicted electron temperatures)[22].

Finally, in many of the high redshift radio galaxies the emission line kinematics are extreme, with larger velocity amplitudes ($500 < \Delta V < 1500$ km s^{-1}) and line widths ($300 < FWHM < 1500$ km s^{-1}) than can be accounted for by gravity alone[23,24]. Again, this is difficult to reconcile with the standard illumination model in which the quasars illuminate the *undisturbed* ISM of the host galaxies.

2.3. JET/CLOUD INTERACTIONS: ADVANTAGES

The jet/cloud interaction model holds the promise of being able to account for many of the features not explained by quasar illumination. Given that the bulk radio jet powers for FRII radio sources are estimated to fall in the range 10^{44}–10^{47} erg s^{-1}[8], we would require the jets to convert $1 - 10\%$ of their power into emission lines in order to explain the total emission line luminosities by jet/cloud interactions alone.

Although the interaction between the warm clouds and the radio jets is likely to be complex, in general we expect the clouds to be compressed, ionized and accelerated as they enter the shocks driven through the ISM/ICM by the jets. Strong evidence for all of these effects has recently been found in detailed studies of low redshift jet/cloud interaction candidates[25,26]. The evidence includes: pressures in the emission line clouds which are orders of magnitude greater than those expected in the hot confining ISM at similar radii; complex emission line profiles with split narrow components ($\Delta V \sim \pm 500$ km s^{-1}), and underlying broad components ($FWHM \sim 1000$ km s^{-1}); [OIII](5007+4959)/4363 and HeII(4686)/Hβ diagnostic line ratios which are more consistent with shocks than with quasar photoionzation; and anticorrelations between line width and ionization state in the EELR.

We do not yet have such compelling evidence for shocks at high redshifts ($z > 0.5$), but it is clear that the high-z radio galaxies are at least qualitatively similar to the low-z jet/cloud interaction candidates, and jet-induced shocks are a promising way of explaining both their highly collimated emission line structures and extreme emission line kinematics.

2.4. JET/CLOUD INTERACTIONS: PROBLEMS

A major problem with the jet/cloud interaction model is that, at low redshifts at least, many of the EELR lie well away from the radio axes, and so it is unlikely that these EELR are directly energized by the jets.

But the most controversial issue concerns the continuum: can jet/cloud interactions explain the UV excess and continuum alignment effect? The possibilities for optical/UV continuum emission in jet/cloud interactions include jet-induced star formation[10,11] and the nebular continuum emitted by the warm, shocked clouds. The nebular continuum will certainly be significant[6], but more careful work is required to determine whether this component *dominates* the continuum in the extended structures aligned along the radio axes. The main evidence for the alternative, jet-induced star formation mechanism comprises the detection of starbursts along the radio axes of a few low redshift radio sources[27,28], but there is currently a lack of direct observational evidence for this mechanism in high redshift radio galaxies.

3. Conclusions

It is clear that no single model can explain all of the properties of radio galaxies across the whole range of radio power and redshift.

At low redshifts ($z < 0.2$) the distribution, ionization and kinematics of the EELR in most radio galaxies are consistent with illumination of the ambient ISM by the anisotropic radiation field of a hidden quasar. It is only in a minority of EELR — invariably those along the radio axis — that we see evidence for something different going on.

The situation is different at high redshifts ($z > 0.5$) where we require *both* quasar illumination and jet-induced shocks: the quasar illumination to explain the polarization properties, and the jet-induced shocks to account for the highly collimated EELR and extreme emission line kinematics observed in many of the high-z objects.

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