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SPECTRAL SIGNATURES OF JET-DRIVEN SHOCKS IN ACTIVE GALACTIC NUCLEI

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RESUMEN

Está ahora claro que las ondas de choque impulsadas por jets en galaxias activas son las responsables de una importante fracción de la emisión de las regiones extendidas de líneas angostas (en todas las longitudes de onda). La fracción restante resulta de la fotoionización por fotones UV con origen en el núcleo activo mismo. Esta revisión examina las signaturas espectrales y dinámicas de choques impulsados por jets en estos ambientes y demuestra cómo éstas pueden ser utilizadas para obtener límites para las velocidades de choques, los parámetros del jet, el medio galáctico y circungaláctico y la naturaleza del motor central.

ABSTRACT

It is now clear that jet-driven shocks in active galaxies are responsible for an important fraction of the emission of the extended narrow-line regions (at all wavelengths). The remainder arises from photoionisation by UV photons originating at the active nucleus itself. This review examines the spectral and dynamical signatures of jet-driven shocks in these environments, and shows how these can be used to constrain the shock velocities, the parameters of the jet, the galactic or circumgalactic medium and the nature of the central engine.

Key Words: **GALAXIES: ACTIVE — GALAXIES: SEYFERTS — HYDRODYNAMICS — ISM: JETS AND OUTFLOWS**

1. INTRODUCTION

The spectral characteristics of the gas in the narrow-line regions (NLRs) of Seyfert galaxies strongly suggest that it is predominantly photoionized by a hard EUV spectrum. For many years the dominant paradigm was that the ionizing photons originate in a compact nuclear source (see, e.g., Koski 1978; Ferland & Osterbrock 1986; Osterbrock 1989), and that the EUV spectrum was therefore a smooth. featureless power-law, or broken power-law. However, these models cannot explain the dynamics of NLRs, which often show clear evidence of non-gravitational motion, and evidence for outflow at velocities up to (or even in excess of 1000 km s^{-1}) (e.g., Pedlar et al. 1989; Allen et al. 1999). In addition, where the NLRs are spatially resolved, there often are found to be strong correlations between radio power and either line luminosity (de Bruyn & Wilson 1987) or line width (Wilson & Willis 1980). These results led Wilson & Willis (1980) to suggest that the nucleus ejects radio components that interact with ambient gas and replenish the high kinetic energy and ionization of the NLR. Such correlations exist not only for Seyfert galaxies, but persist up to much more luminous classes of radio galaxies which include the steep-spectrum radio sources (CSS, Fanti et al. 1990), the Gigahertz-peaked sources (GPS, O'Dea et al. 1990, and references therein), the compact symmetric objects (CSO, Wilkinson et al. 1994, and references therein) or the compact double sources (CD, Phillips & Mutel 1982). Together, these represent an appreciable fraction (10–30%) of the luminous radio sources. Not only are these sources very luminous at radio frequencies, but they also are very luminous in optical emission lines. The spectra of Gelderman & Whittle (1994) reveal the broad emission lines of the AGN itself as well as intense "narrow line" emission reminiscent of Seyfert 2 galaxies. These connections with radio power, and the continuity of properties across these different classes of sources argues strongly that the same physical processes are at work in all of them, and that the kinetic energy supplied by the radio-emitting jets may provide a substantial fraction of the power radiated in the NLRs of these galaxies. The power requirements for Seyfert 2 galaxies are relatively modest, typically between 10^{41} and 10^{44} ergs s^{-1}, while the luminous radio sources require far more energy; 10^{45}–10^{46} erg s^{-1}.

The means whereby the kinetic energy of radio jets or thermal outflows from galactic nuclei can be converted into ionizing photons is by radiative shocks. Fast radiative shocks generate a very strong EUV and soft X-ray spectrum which can escape either upstream to create photoionized precursors or

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downstream to profoundly influence the ionization structure of the cooling and recombination region of the shock flow. This idea was first advocated by Daltabuit & Cox (1972) in the context of the broad-line regions of QSOs, but was developed and applied to NLR by Binette, Dopita, & Tuohy (1985), Dopita & Sutherland (1995; 1996) and Morse, Raymond, & Wilson (1996).

2. THE SPECTRA OF STRONG SHOCKS

The theory of Dopita & Sutherland (1995;1996) shows that fast shocks with velocities of 300–1000 km s^{-1}, which are required to account for the emission-line spectra of Seyfert galaxies (Dopita & Sutherland 1995), generate gas with post-shock temperatures 10^6–10^7 K. This gas produces copious soft X-rays and EUV photons as it cools (cf. Laor 1998). The photons are emitted in almost equal numbers upstream into the pre-shock plasma, where they photoionize the pre-shock plasma in a thick zone of high ionization parameter, and downstream, where they produce photoionizations in the recombination zone of the shock. This region has a much lower ionization parameter, thanks to the compression of gas through the shock. Apart from their shock velocity, v_{s} , these shocks are characterized by their Alfvén Mach Number, $\mathcal{M}_{\mathrm{A}} = v_{\mathrm{s}}/v_{\mathrm{A}}$ where v_{A} is the Alvén velocity in the transverse component of the pre-shock magnetic field, $v_{\mathrm{A}}^2 = B^2/4\pi\rho_0$. The Alvén Mach Number controls the emergent spectrum by moderating the compression in the post shock plasma:

$$\frac{\rho_1}{\rho_0} = 2^{1/2}\mathcal{M}_{\mathrm{A}}.$$

Dopita & Sutherland distinguish two limiting cases; *shock only* in which the precursor gas is optically thin to the upstream EUV photons, and *shock plus precursor*, in which there is enough gas around to completely absorb these upstream photons. The first case is encountered in gas-poor environments, such as in the shocked disk of M87 (Dopita et al. 1997), while the second case characterizes regions with a dense and extensive ISM surrounding the shocked region. In the first case the low-ionization parameter recombination/photoionization region dominates the optical spectrum, providing a LINER-like spectrum. In the UV, the high-temperature cooling region is more dominant, and temperature-diagnostic line ratios indicate temperatures of (1.5–3.0) × 10^4 K. In the second case, the photoionized precursor provides a high-ionization zone as well, with strong emission lines of high-ionization species. This 'Seyfert 2'-like spectrum is similar to that produced by the older pure photoionization models.

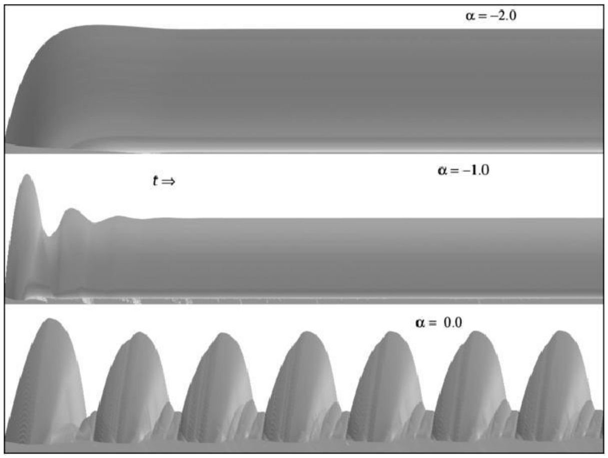

Fig. 1. One-dimensional shock models by Sutherland (2002, in preparation) with a power-law cooling function of various exponents to show the nature of thermal instabilities. In more than one dimension, the thermal cycles of thermally unstable shocks become less well-defined, and the cooling zone of the shock breaks up into a set of fractal filaments

It should be recognized that the shock only models, and the shock plus precursor models, are only two limits of a continuum of potential spectra which depend on the disposition of the absorbing ISM around the shocked region. On line diagnostic plots such as those by Veilleux & Osterbrock (1987) or Osterbrock et al. (1992), this continuum of models can be represented by mixing lines joining shock only, and shock plus precursor models having the same values of shock velocity and Alvén velocity.

A major problem of these shock models, pointed out in the orginal papers, but ignored by observers, is that fast shocks are thermally unstable. This was first considered by Innes, Giddings & Falle (1987a,b). The condition for thermal stability in a cooling isobaric plasma is given by the Field (1965) criterion:

$$\left[\frac{\partial \dot{Q}}{\partial T_{\mathrm{e}}}\right]_P > 0. \qquad (1)$$

If the cooling is represented by a local power-law in temperature; $\dot{Q} = \Lambda_0 T_{\mathrm{e}}^p n^2$, it is clear that the medium is thermally stable in isobaric cooling if $p > +1$. However, the form of the cooling function out of the collisional ionization equilibrium, given by Sutherland & Dopita (1993), shows that p is rarely as large as unity, and is greater than zero only below (roughly) 10^5K or above 10^7K.

Figure 1 illustrates the effect of the thermal instability in the case of a one-dimensional flow with

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Editors: W. J. Henney, W. Steffen, A. C. Raga, & L. Binette

such a power-law cooling function, as calculated by Sutherland (2002, in preparation). When the plasma goes unstable, the shock enters into a series of regular pulsations in which a fast shock is launched, the gas behind it cools catastrophically, and the cooled layer collapses onto the shock piston before another fast shock is re-launched. In higher dimensions, the situation is much more complex, and detailed spectral predictions for thermally unstable shocks must await the supercomputer calculations of Sutherland, currently underway.

3. SPECTRAL SIGNATURES OF FAST SHOCKS

If NLRs are shock-excited, then what specific observational signatures might we expect to see which would enable shocks to be distinguished from regions photoionized by the central nucleus? In brief, these are:

- Spatial correlations between radio bubbles and the optical emission; in general, we might expect to see the optical emission surrounding the radio jets or bubbles
- Correlations between the radio power (or the X-ray power in the case of thermally-dominated bubbles) and the optical line luminosity. Bicknell, Dopita, & O'Dea (1997) showed that the radio power is related to the jet energy flux, while the optical emission is related to the PdV work done on the surrounding ISM, which is also proportional to the jet energy flux.
- Similar pressures in the X-ray plus non-thermal plasma and the post-shock optically emitting gas.
- Emission line widths correlated with inferred shock velocities, after these have been corrected for the effect of galactic rotation.
- Line width-excitation correlations, and finally, but most importantly,
- Line ratio diagnostics which are unique to shocks.

In the case of Seyferts, strong associations between the narrow emission line and radio continuum properties have been found. The correlation between radio power and both line luminosity and line width has already been discussed. In the detailed study of NGC 2992 by Allen et al. (1999), all these correlations were confirmed in spatially-resolved observations. Recent imaging and spectroscopic observations (Axon et al. 1998; Bower et al. 1995; Capetti et al. 1995; Falcke, Wilson, & Simpson 1998; Haniff, Wilson, & Ward 1988; Whittle et al. 1988) have confirmed that the structure of the NLR in many Seyfert galaxies is dominated by compression of interstellar gas by the bubbles of partly relativistic gas ejected from the nucleus. Theoretical models for these interactions have involved expanding radiolobes (Pedlar, Dyson, & Unger 1985; Bicknell et al. 1997), bow shocks driven by the radio jets (Taylor, Dyson, & Axon 1992; Ferruit et al. 1997; 2000), shocks caused by interactions with dense clouds in the jet (Bicknell et al. 1997) or driven into the jet cocoon (Steffen et al. 1997).

For the GPS, CSS and CSO radio sources the sizes of the optically-emitting regions are too small to be resolved from the ground. However, Bicknell et al. (1997) predicted that the optical emission arises in a shocked cocoon of gas around the radio jets, which is optically thick to free-free emission at lower frequencies. This results in spatially-dependent depolarisation and Faraday rotation of the synchrotron emission from the jet, which has recently been confirmed by observation (Kameno et al. 2000).

The spatial correlations between radio emission and optical emission, although strong in many cases, are not universal. Whether we see such a correlation depends critically upon whether the local cooling timescale, $\tau_{\rm cool}$, is short enough that the shock can become radiative within a dynamical expansion timescale, $\tau_{\rm dyn}$:

$$\tau_{\rm dyn} > \tau_{\rm cool} \sim 200 \frac{v_{100}^{4.4}}{Z n_0} {\rm yr}, \qquad (2)$$

where Z is the chemical abundance of the gas in solar units, v_{100} is the shock velocity in units of 100 km s^{-1}, and n_0 is the number density of the gas (cm^{-3}). Thus, in Seyfert 2s, the observed velocities (~ 500 km s^{-1}) imply dynamical timescales of ($10^5 - 10^6$ yr). Thus, provided the densities exceed a few cm^{-3}, the shocks are radiative. In CSO sources, with shock velocites ~ 1500 km s^{-1}, and sizes ~ 1000 kpc, the dynamical timescale is $\sim 10^6$ yr, and densities must exceed about 50 cm^{-3} to keep the gas radiative.

In radio-loud objects, the correlation between radio luminosity and NLR luminosity is good (Bicknell et al. 1997), and can be explained quantitatively by a combination of synchrotron theory for the jets, and shock theory for the cocoons around the jets. However, for radio-quiet objects, including Seyfert galaxies, the ratio of radio luminosity to NLR luminosity is about three orders of magnitude lower. This implies that the ratio of the radio power to relativistic jet energy flux is much smaller than is usually assumed for radio galaxies. This can be partially attributed to the smaller ages (10^6 yr) of Seyferts compared to radio galaxies, but one also requires that either the magnetic energy density is more than 1 order of mag-

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nitude below the equipartition value or, more likely, that the internal energy densities of Seyfert jets are dominated by thermal plasma, as distinct from the situation in radio galaxy jets where the jet plasma is generally taken to be nonthermally dominated.

This thermal component, if present, might be reasonably searched for in its X-ray emission, provided that it is not too hot. Soft X-ray emission from the NLR has been detected in NGC 1068 (Wilson et al. 1992), NGC 2110 (Weaver et al. 1995), and NGC 4151 (Morse et al. 1995). In general, the observed *Einstein* IPC soft X-ray flux (from the entire galaxy) and the [O III] 5007 flux (from the NLR) are similar. Wilson & Raymond (1999) show this to be consistent with photoionizing shocks—about 4% (of the kinetic power of a 300 km s^{-1} radiative shock is radiated in the Einstein band (0.24 keV) while 2% is radiated as [O III] 5007 according to the models of Dopita & Sutherland (1996). These observations suggest that this X-ray emission is associated with the cocoon shocks, rather than with entrained thermal matter in the jet. However, evidence for MHD thermal winds from the vicinity of the central nucleus have been found by UV and soft X-ray absorption components in the Seyfert 1 galaxy NGC 5548, (Bottorf, Korista, & Shlosman 2000). They find that the clumpy warm absorbing gas exists in the outer part of the wind and is not a continuation of the flow in the broad emission-line region; and that the warm absorber extends both in radial and polar directions and is ionization stratified. The X-ray absorption is found at smaller radii, while the UV absorption originates at larger distances from the central continuum source.

Clear dynamical correlations attributable to shocks have been found in only a few galaxies (e.g., Whittle 1996). Many of these, as pointed out by Whittle (this conference) are amongst the most radio-bright of the Seyfert galaxies. Examples include, Mrk 78 (Pedlar et al. 1989), NGC 2992 (Allen et al. 1999) and Mrk 1066 (Bower et al. 1995). In these cases, excitation is correlated with local dynamics, as expected in the cocoon shock model. However, in other cases, often showing lines of high excitation, a substantial component seems to be due to material in outflow from the nucleus. Examples include NGC1068 (Cecil, Ferruit, & Veilleux 2002, this conference), NGC 7319 (Aoki et al. 1996). The simple cocoon shock model has no place for this type of dynamics, which must be fairly common given the frequency of blue asymmetries on Seyfert 2 line profiles. However, globally, few Seyfert galaxies show clear evidence of non-gravitational motions in the NLR gas. Indeed Véron & Véron-Cetty (1986) found that the line width of the NLR correlates with the Hubble type, suggesting that the width is set by the mass of the bulge. This was confirmed by Nelson & Whittle (1996). The conclusion to be drawn from all of this is that shocks are certainly present, and dominant in exciting the NLR in a few objects, but that in many others, photoionization from the central AGN is probably dominant.

Turning now to line ratio diagnostics. The optical diagnostic diagrams of Veilleux & Osterbrock (1987) are useful in distinguishing between AGN and H II regions, because the location of the observed point is sensitive to the hardness of the ionizing spectrum. The fact that both the shock models and the photoionization models can provide a description of the observations merely reflects the fact that both shock models with velocities between 300 and 500 km s^{-1} and photoionization models with photon spectral indices of between -1 and -2 have about the right "hardness" of the photoionizing spectrum. These diagrams do not therefore effectively distinguish between the two excitation mechanisms. A curious feature of the observations, which has not yet had an adequate theoretical explanation is the tight grouping of the observational points for the Seyfert 2 galaxies. Nearly all Seyfert galaxies are located in a region with less than 0.8 dex variation in [O III] $\lambda\,5007\,\mathrm{Å}/\mathrm{H}\beta$, [N II] $\lambda\,6583\mathrm{Å}/\mathrm{H}\alpha$ or [O I] $\lambda\,6300\,\mathrm{Å}/\mathrm{H}\alpha$ ratio, according to the extensive homogeneous observations of Véron & Véron-Cetty (2000). Within individual galaxies, spatial variations in these line ratios are even tighter (Allen 1998; Allen et al. 1999). While this tight grouping is a natural consequence of shock models, it is harder to understand in terms of standard photoionization modelling. In principle, the disposition of the ionized gas with respect to the central engine could be anything one could imagine. One would therefore expect that the ionization parameter characterizing the NLR clouds could vary widely between different parts of the same object, or between different objects. In practice the observations constrain the dimensionless ionization parameter to lie in the range $-3 < \log U < -2$. This (unnaturally restrictive) range suggests that, if these regions are photoionized, then some other self-regulatory process such as pressure balance between different phases is at work to ensure that the density of the photoionized clouds falls of roughly as the inverse square of the distance from the central engine.

The best, and most unambiguous diagnostics that enable us to distinguish between shocks and

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photoionization from an AGN are to be found in the UV. In this regard, objects with a LINER-like spectrum are particularly tractable, since, in the optical, their spectra are either fit with a photoionization model of low ionization parameter ($\log U \sim -4$), or by high velocity shocks without precursors. In the UV the spectra resulting from these two kinds of excitation are quite different; photoionized regions have low electron temperatures, and the UV spectra are weak, and of low excitation, while shock-excited regions show a rich collisionally-excited UV spectrum, lines of high ionization potential, and temperature-sensitive diagnostics give high values of electron temperature. This is exactly what Dopita et al. (1997) found in the case of HST FOS spectra of M87. Other LINERs such as M81, for example do not give such unambiguous results, because the LINER spectrum arises in a high-density circumnuclear medium with strong radial density gradients, and in this case both multi-component shock models, or photoionization models can give a fair description of the spectrum.

Seyfert galaxies present a more difficult problem, since the shock+precursor models are photionization dominated. However, a few cases have been studied. Allen, Dopita, & Tsvetanov (1998) gave a set of UV line ratio diagnostics that will find general utility when the Cosmic Origins Spectrograph (COS) is installed in the *HST*. Evans et al. (1999) studied the UV/Optical spectra of the Seyfert galaxies NGC 5643 and NGC 5728. These objects have ionization cones, radio and soft X-ray emission, and evidence of nuclear outflows and winds, suggesting that shocks may be associated with the emission-line gas. Comparison of the UV/optical data with grids of both photoionization and shock+precursor models suggests that an unambiguous shock+precursor signature is not present, and that mechanical energy input may not play the same dominant role in exciting these objects with weak radio jets as appears to be the case in strong radio jet sources such as M87.

The high redshift radio galaxies present us with a statistically significant sample in which to study UV line ratio behaviour. The pivotal study by Best, Röttgering,& Longair (2000a,b; see also Best et al. 2002, this conference) has revealed an extraordinary result for powerful 3C radio galaxies with $z \sim 1$. They find that both the UV line profiles and the UV line ratio diagnostics show that, when the scale of the radio lobes is such that they are still able to interact with the gas in the vicinity of the galaxy, they appear to be predominantly shock-excited, but that when the lobe has burst out into intergalactic space, the ionized gas left behind is predominantly photoionized. The ratio of fluxes suggests that the energy flux in the UV radiation field is about 1/3 of the energy flux in the jets. Thus, both shocks and photoionization are important in the evolution of radio galaxies. This result, if confirmed for radio sources in general, would prove that the properties of the radio jet are intimately connected with the properties of the central engine.

Very distant radio galaxies have been recently studied by De Breuck (2000). He finds that diagnostic diagrams involving C IV, He II, and C III] fit to the pure photoionization models, but that the observed C II]/C III] requires there to be a high-velocity shock present. He argues that composite models would be required to give a self-consistent description of all the line ratios, and that these may require a mix of different physical conditions as well.

On the basis of such observations, we can propose a simple scenario. First, the accretion onto the central engine drives a radio jet. This might first be visible as a GPS source, but later as a powerful 3C-like double lobe radio source. During the time that the scale of the radio lobes is less than 10–30kpc, the interactions with the surrounding medium are strong, and the NLR is predominantly shock-excited. The radio jets bore out "ionization cones" which are responsible for the alignment effect of the NLR. At late phases, though, the ionized gas is either photoionized by the central source, or through the shock-induced star formation that must inevitably take place along the boundaries of the old shocked cocoon.

At much higher redshift, ($z \sim 3.8$) the radio galaxy 4C 41.17 has recently been studied in detail by Bicknell et al. (2000). This object consists of a powerful radio source with strong evidence for jet-induced star formation along the radio axis. Bicknell et al. (2000) constructed a detailed model to explain the data. This required a high-powered jet with and energy flux of $\sim 10^{46}$erg s^{-1} interacting with a dense cloud to produce shock-excited emission-line nebulosity through $\sim$ 1000 km s^{-1} shock, which in turn induce star formation. The line ratio diagnostics require that the gas involved in the interaction is of relatively low metallicity, and both the shocked and the photoionized precursor gas could be distinguished as separate components in the C IV line profile.

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