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THE DYNAMICAL EVOLUTION OF NARROW LINE REGIONS

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RESUMEN

Revisamos los avances recientes por el equipo del RSAA para elucidar la evolución dinámica de las varias clases de regiones de líneas delgadas (RLD) en las galaxias activas.

ABSTRACT

We review recent progress by the RSAA team in elucidating the dynamical evolution of the various classes of narrow-line regions (NLR) in active galaxies.

Key Words: **GALAXIES: AGN — GALAXIES: EVOLUTION — GALAXIES: SEYFERT — ISM: HYDRODYNAMICS — ISM: JETS AND OUTFLOWS**

1. NLR ZOOLOGY

Optical spectroscopy and dynamical analysis has revealed that the so-called narrow-line regions (NLR) are an almost ubiquitous signature of the presence of an active nucleus in a galaxy (AGN). The optical diagnostic diagrams of Baldwin, Phillips, & Terlevich (1981), Veilleux & Osterbrock (1987), and Osterbrock, Tran, & Veilleux (1992) serve to classify a region as a NLR, and such regions can be further sub-divided into two general categories: Seyfert narrow-line regions (NLRs) and the low-exitation nuclear emission-line regions (LINERs), which will not be discussed here.

Homogenous sets of high-quality spectrophotometric data are now available for the NLR of most classes of AGN. Notable amongst these are complete sample of southern elliptical galaxies by Phillips et al. (1986), the similar-sized sample of nearby northern spirals by Ho, Filippenko, & Sargent (1995), the compilations of Veilleux & Osterbrock (1987) and Véron-Cetty & Véron (2000), the Seyfert galaxy study of Veilleux (1991a,b,c), the compact radio-luminous sample of Gelderman & Whittle (1994), the luminous infrared galaxy survey of Kim et al. (1995), the ultraluminous infrared galaxy survey of Kim, Veilleux, & Sanders (1998) and Veilleux, Kim, & Sanders (1999), the warm *IRAS* sample of Kewley et al. (2001), and the radio-excess *IRAS* galaxies (Drake et al. 2003). NLR are found not only in nearby galaxies, but they also appear to be a ubiquitous feature of QSOs (Francis et al. 1991), and they provide the dominant form of near-nuclear optical emission in the distant high-power radio sources (Best, Röttgering, & Longair 2000a,b; Inskip et al. 2002a,b; De Breuck 2000).

There is increasing evidence that the narrow-line regions (NLRs) associated with many classes of active galactic nuclei (AGN) have a complex dynamical and excitation evolution. Evidence for a cocoon of strong, auto-ionizing, and radiative shocks is particularly compelling for luminous classes of radio galaxies (see the theory by Dopita & Sutherland 1995; Dopita & Sutherland 1996; and Bicknell, Dopita, & O'Dea 1997, hereafter BDO). These include the steep-spectrum radio sources (CSS, Fanti et al. 1990), unbeamed gigahertz-peaked sources (GPS, see the recent review by O'Dea 1998), compact symmetric objects (CSO, Wilkinson et al. 1994), or compact double sources (CD, Phillips & Mutel 1982). Together, these represent an appreciable fraction (10 to 30%) of luminous radio sources. Not only are such sources very luminous at radio frequencies, but they also are very luminous in optical emission lines, and spectra by Gelderman & Whittle (1994) reveal intense "narrow-line" emission with line ratios similar to those of Seyfert 2 galaxies. For these objects, the line emission scales with radio power, and the continuity of properties across these different classes of sources argues strongly that the kinetic energy supplied by the radio-emitting jets may provide a substantial fraction of the power radiated at other wavelengths by shocked gas associated with the NLRs of these galaxies.

Evidence for excitation by both shocks and photons has been adduced from the powerful high-redshift radio galaxies. The study by Best et al. (2000a,b) revealed that for the 3C radio galaxies ($z \sim 1$), where the radio lobes are small they are predominantly shock-excited, but when the radio lobes have burst out into intergalactic space the ionized gas left behind is predominantly photoionized. Similar results were obtained by De Breuck (2000) for the very high-redshift radio galaxies.

The Seyfert galaxies are generally found in spiral galaxy hosts, often display lines of high-excitation, and evidence of non-gravitational motions, but are radio-quiet. Dynamical signatures of strong shocks are apparent in only 5 to 10% of cases (e.g., Whittle 1996). Many of these found amongst the more radio-luminous galaxies including Mrk 78 (Pedlar et al. 1989), NGC 2992 (Allen et al. 1999) or Mrk 1066 (Bower et al. 1995). The weakly collimated radio jets frequently seen in such objects often show close correlations between the radio and the optical morphology (Allen et al. 1999; Axon et al. 1998; Bower et al. 1995; Capetti et al. 1995; Falcke, Wilson, & Simpson 1998; Haniff, Wilson, & Ward 1988; Whittle et al. 1988). Power requirements are modest, typically 10^{41} to $10^{44}\,\mathrm{ergs\,s^{-1}}$, cf. the luminous radio sources (10^{45} to $10^{46}\,\mathrm{erg\,s^{-1}}$). The remainder of Seyfert galaxies appear to be photoionized (Evans et al. 1999).

The *Infrared Astronomical Satellite* (*IRAS*) revealed a large population of galaxies with intense circumnuclear star formation and which emit the bulk of their radiation in the infrared. Many of these have $\log(L_{\mathrm{FIR}}) > 11.0$ and are referred to as luminous infrared galaxies (LIRGs). Although it is clear that the IR luminosity derives from dust reprocessing of other sources of luminosity in the galaxy, the nature of the nuclear source is still in debate. Most of the ultraluminous sources (ULIRGS; e.g., Goldader et al. 1995) and the majority of lower luminosity galaxies (Kim et al. 1995) are star-formation dominated. Indeed, Condon, Anderson, & Helou (1991) concluded that the far-infrared luminosity and radio properties of LIRGs can be explained entirely by compact nuclear starburst events. However, Sanders et al. (1988) have argued that LIRGs contain a dust enshrouded AGN and Veilleux, Sanders, & Kim (1997) have used near-IR and optical spectroscopy to search for broad emission lines, indicative of AGN, which they found in some 25 to 30% of ULIRGs of their sample, and Lonsdale, Smith, & Lonsdale (1993) concluded that AGN are the dominant powering mechanism. It is most likely that both mechanisms contribute to the overall energy output, and where each provides a similar flux, the nuclear spectra are "composite". Such spectra are particularly common in luminous IR galaxy samples. They have been identified by Kim et al. (1995), Kim et al. (1998), and Veilleux et al. (1999), the studies of Véron, Gonçalves, & Véron-Cetty (1997), Gonçalves, Véron-Cetty, & Véron (1999), and in the extensive survey of warm IR galaxies by Kewley et al. (2001). They are also found in radio-excess *IRAS* galaxies, which are a rare but important class of radio-intermediate sources. Drake et al. (2003) have shown that 40 to 45% of such objects are compact and have steep radio spectral indices, i.e., they fit the definition of CSS or GPS radio sources.

From all of this, it should be clear that both shocks and photoionization from the central nucleus are important in exciting the NLR. In this review, we will attempt to provide observational and theoretical insight into the dynamical evolution of these various classes of NLR objects, and infer under what circumstances each of these excitation mechanisms may dominate.

2. MODELS OF THE DYNAMICAL EVOLUTION OF THE NLR

2.1. *The GPS/CSS Sources*

In their initial phases of activity the relativistic jets produced by AGN are likely to interact strongly with the interstellar medium (ISM). Thus, the early evolution of the lobe is likely to provide insight into both the nature of the circumnuclear ISM and of the jet itself. Modulo issues relating to the absolute power of the radio jet, the youngest AGN are probably also the smallest, and therefore an appropriate place to start our examination of the dynamical evolution of AGN is the gigahertz-peak sources (GPS) and the compact symmetric sources (CSS), which are likely to be triggered by the merger of a low-mass system onto a massive and evolved elliptical galaxy. In what follows we draw upon the results of Bicknell, Saxton, & Sutherland (2003).

In his early models of these sources Begelman (1996) conjectured that the mean pressure in the radio hotspot of these sources is in constant ratio to the pressure of the cocoon of hot and relativistic plasma that surrounds the jet. If the ambient ISM declines in density as a power law of the distance from the nucleus, $n(R) = n_0\,(R/R_0)^{-\delta}$, then Begelman's (1996) conjecture is valid for $\delta \sim 2$. This conjecture has been verified in detail (Carvalho & O'Dea 2002a,b). The model of BDO, which allows for the expansion losses provides the velocity of advance v_{B} of the bow-shock into a uniform medium following such a power law with radius:

$$\frac{v_{\mathrm{B}}}{c} \approx 0.056 \left[\frac{F_{46}}{n_{0.01}}\right]^{1/3} \left[\frac{R}{\mathrm{kpc}}\right]^{(\delta-2)/3}, \qquad (1)$$

where here $n_{0.01}$ is the density at $R = 1\,\mathrm{kpc}$ in units of $0.01\,\mathrm{cm}^{-3}$ and the jet power F_{46} is given in terms of $10^{46}\,\mathrm{erg\,s}^{-1}$.

The optical emission in the CSS sources shows clear signatures of shock excitation, with systematic velocity offsets of 300 to $500\,\mathrm{km\,s}^{-1}$, lines broadened and split by $\sim 500\,\mathrm{km\,s}^{-1}$, and a strong alignment between the radio jets and optical emission (de Vries et al. 1997, 1999). Whilst such effects were predicted by the BDO model, the shocks in this model were produced by radiative wall shocks, which would require relatively high ISM densities. This would permit only a low velocity of advance of the bowshock consistent with an expansion velocity of less than $1000\,\mathrm{km\,s}^{-1}$ in the walls of the cocoon, which is inconsistent with recent observations which suggest instead 0.1 to 0.3 times the speed of light. Also, the observations of de Vries et al. (1999) show that the line emission is not concentrated around the head of the radio lobe, but trails behind it in the walls.

A likely explanation is that the majority of the ISM is, in fact, characterized by a low-density medium with a strongly radially declining density gradient, but with much denser clouds embedded in it. This is entirely consistent with what we know about the structure of the ISM in galaxies, with a cold and/or molecular component embedded in a hot medium at coronal temperatures, which in elliptical galaxies has a temperature of order 1 to $2\times10^{7}\,\mathrm{K}$ and $\delta \sim 3/2$ (Irwin & Sarazin 1996). In such a cloudy medium, the overpressure in the cocoon surrounding the jets drives slower, radiative shocks into the dense clouds. For clouds lying outside the jet core itself, the ratio of the velocity of advance of the jet and the cloud shock velocity v_{S} is given in terms of the cloud density, and the intercloud density in its vicinity, by

$$\frac{v_{\mathrm{B}}}{v_{\mathrm{S}}} = \zeta^{1/2}\left(\frac{n_{\mathrm{C}}}{n_{\mathrm{IC}}}\right)^{1/2}, \qquad (2)$$

where $\zeta \sim 10$ to 100 is the ratio of the ram pressure of the jet and pressure in the cocoon of shocked gas surrounding it.

Cloud shocks will become radiative when the cooling timescale behind the shock τ_{cool} is comparable to the jet expansion dynamical timescale τ_{dyn}. The cooling timescale is given by radiative shock models (Dopita & Sutherland 1995, 1996), and in the velocity range 200 to $900\,\mathrm{km\,s}^{-1}$ can be approximated as:

$$\tau_{\mathrm{cool}} \approx 23,000\, n_{\mathrm{C}}^{-1}\left[\frac{v_{\mathrm{S}}}{300\,\mathrm{km\,s}^{-1}}\right]^{3.9}\ \mathrm{yrs.} \qquad (3)$$

The dynamical timescale is:

$$\tau_{\mathrm{dyn}} = 32,600\left[\frac{v_{\mathrm{B}}}{0.1c}\right]^{-1}\left[\frac{R}{\mathrm{kpc}}\right]\ \mathrm{yrs.} \qquad (4)$$

Approximate equality of these timescales when combined with equation (2) means that the cloud-to-intercloud density contrast has to be at least 10^{3} and possibly as large as 10^{4}, consistent with cloud temperatures of 10^{3} to $10^{4}\,\mathrm{K}$, or turbulent motions of order $10\,\mathrm{km\,s}^{-1}$.

Modeling such a large density contrast (including radiative cooling) within a hydrodynamic code is a challenging business. Sutherland, Bisset, & Bicknell (2003) have developed a code able to tackle this based on the VH-1 code of the Virginia group (see `http://wonka.physics.ncsu.edu/pub/VH-1`). This (originally adiabatic) PPM code has undergone numerous changes in its Riemann solver, and it features an "oscillation filter" designed to suppress a striping numerical instablitiy seeded by numerical noise, driven by directional splitting, and exacerbated by radiative cooling. This code has recently been ported to the MPI parallel environment.

Some results of the 2-D implementation of this code are shown in Figure 1, which shows a pair of clouds being shocked by the passage of the jet near them. When clouds are submitted to an overpressure large enough to drive non-radiative shocks into them, the clouds are rapidly ablated and torn apart, which entrains matter into the cocoon as a whole. However, when the shocks are radiative, the clouds cool and are crushed to a density which tends to put them into pressure equilibrium with the surrounding jet or cocoon environment. This makes them much more resistant to destruction on short timescales, considerably extending the cloud destruction timescale. Simulations of radio-lobe/cloud interactions are available as movies at `http://macnab.anu.edu.au/radiojets/gps`.

The evolution of the jet itself depends critically on the filling factor of the clouds. With low filling factor, the jet is bent or diverted by interaction with clouds, but is not entirely disrupted. In these cases, the evolution is like the jittering "dentist's drill" propagation envisioned by Scheuer (1982). However, above a certain critical filling factor, the jet becomes "frustrated", and is broken up into a series of channels reminiscent of a river delta (see Figure 2). In this case, the evolution of the whole cocoon is more like a cloudy stellar wind bubble. We should emphasize that jet shown in Fig. 2 is highly supersonic—its Mach number is 130. However, the jet kinetic energy is rapidly thermalized so that the pressure in the co-

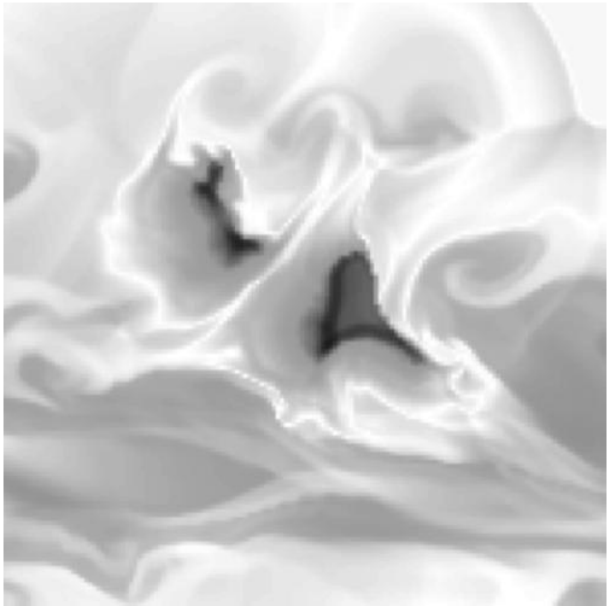

Fig. 1. Shocks induced by the passage of the jet are seen sweeping through clouds embedded in the jet cocoon. The grayscale is reversed at low levels so as to show the jet. Material which has been ablated from the clouds adds to the pressure of the cocoon.

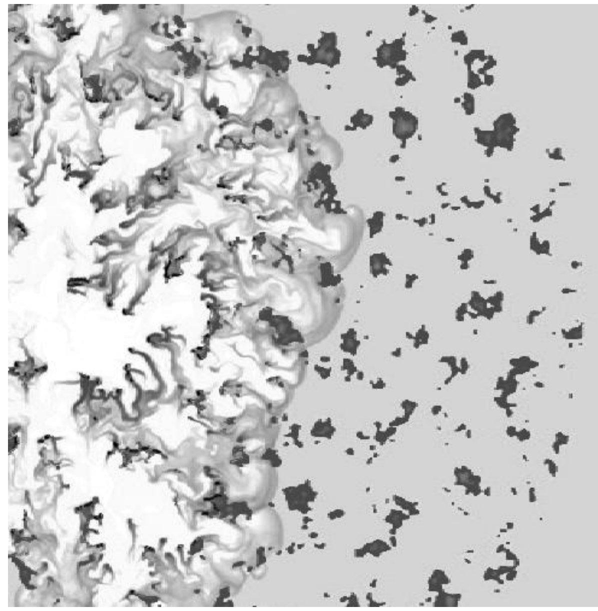

Fig. 2. The later evolution of a 2-D jet surrounded by a set of dense clouds. Above a critical filling factor, the jet is disrupted and "percolates" through the channels which it has been able to open up.

coon is very high, about M^2 times the background pressure.

2.2. *Hi-Z Radio Sources*

The theory and models discussed above suggest that, in their early phases, the jet and circumnuclear ISM interact very strongly, and that the early evolution of the NLR is characterized by the presence of strong radiative shocks. Under such circumstances the "auto-ionizing" fast shock model of Dopita & Sutherland (1995) and Dopita & Sutherland (1996) would provide the dominant source of excitation.

If this is true in the case of the GPS/CSS sources, it will apply even more strongly to the gas-rich strong radio sources which are found in abundance in the high-redshift universe. Such galaxies present us with a statistically significant sample in which to study UV line-ratio behaviour and so investigate the fraction of the NLR emission produced by shocks, and the fraction by photoionization. The study by Best et al. (2000a,b) 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 imply 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 are predominantly shock-excited, but when the lobe has burst out into intergalactic space, the ionized gas left behind is predominantly photoionized. The ratio of fluxes in the different classes of source 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 overall evolution of radio galaxies. This result, confirmed by Inskip et al. (2002a), proves that that the properties of the radio jet are intimately connected with 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.

Such sources are uniquely associated with massive gas-rich multi-L_* galaxies in the early universe ($<$ 2 to 3 Gyr). They display a strong "alignment effect", with regions of very high star-formation rate ($> 1000\,M_\odot\,\mathrm{yr}^{-1}$), and emission-line gas having the spectral characteristics of the NLR extended along the direction of the steep-spectrum radio lobes. In these objects, the radio jet appears to be driving strong shocks into the galaxian ISM (evidenced by extensive Lyα haloes; Reuland et al. 2003), which in turn triggers enormous star formation in the surrounding cocoon. A fine example of such a source is provided by the $z \sim 3.8$ radio galaxy 4C 41.17 which has recently been studied in detail by Bicknell et al. (2000). This object consists of a powerful "double-double" radio source embedded in a 190×130 kpc Lyα halo (Reuland et al. 2003) and shows strong evidence for jet-induced star formation at $3000\, M_\odot\,\mathrm{yr}^{-1}$ associated with the inner radio jet. This is apparently induced by the strong dynamical interaction of the inner jet with the shocked and compressed gas in the wall of the cocoon created by the passage of the outer jet. Shock-induced star formation in jet walls was proposed in the context of Seyfert galaxies by Steffen et al. (1997). In 4C 41.17, the outer jet also appears to have induced a large-scale outflow with velocities in excess of $500\,\mathrm{km\,s^{-1}}$ in the line-emitting gaseous halo. Thus we may be seeing the "end of the beginning" in which the central supermassive black hole has finally become large enough to drive the whole accreting envelope of gas into outflow, triggering a last and spectacular burst of star formation in the process.

2.3. *Seyferts*

Seyferts are radio-quiet, and most appear to be dominated by photoionization by the central object. The dynamical signatures of strong shocks are apparent in only 5 to 10% of Seyferts (e.g., Whittle 1996), and these tend to be more radio-luminous than the average. However, clear dynamical evidence exists for a relatively strong thermal wind arising from the central part of the accretion disk (Rodríguez-Ardila et al. 2002; Zamanov et al. 2002).

In the gas-rich and cloudy circumnuclear environments, light and low-power radio jets are readily disrupted and suffer entrainment from the surrounding material, and molecular clouds are crushed in the high-pressure environment. This is clearly demonstrated by the 2-D hydrodynamic simulations described above. However, shock velocities in Seyferts will generally be much lower than in GPS sources, and although shocks may be still important in shaping the circumnuclear medium, photoionization by the central nucleus appears to be much more important for its excitation.

Because clouds lying in the path of the jet and its surrounding high-pressure cocoon are crushed at relatively low velocity, any dust mixed with the cloud gas is likely to survive. Assuming that the central source produces UV photons with high local ionization parameter, the dusty ionized gas is compressed, raising the pressure close to the ionization front to match the radiation pressure in the EUV radiation field (Dopita et al. 2002). This regulates the apparent ionization parameter, and ensures that the density of the photoionized clouds varies as R^{-2}. Each photoablating cloud is surrounded by a coronal medium in which the local ionization parameter reflects the "true" ionization parameter delivered by the central source, and each has a dusty photo-accelerated radial tail, which may be accelerated to vey high velocities ($> 1000\,\mathrm{km\,s^{-1}}$, cf. Cecil et al. 2002).

3. CONCLUSIONS

In this paper we have presented observational and theoretical evidence to support the following model for the gross features of the temporal evolution for the NLR:

1. Early on, the radio jet (if there is one), or else a strong outflow of thermal gas from the inner accretion disk, pushes a strong shock into the surrounding galactic ISM.

2. Dense molecular clouds in the shocked region are crushed by radiative shocks, but along the jet axis such clouds may be rapidly ablated and shredded by non-radiative shocks. In this phase, the optical/UV spectral signature is one of fast radiative shocks.

3. Eventually, the jet escapes from the dense region of the galaxy, and the pressure driving the shocked cocoon drains away. The wall shocks then become first radiative, and finally, momentum conserving. Shock-induced star formation may eventually occur within them, provided they become unstable to their self-gravity. The opening angle of the shocked cocoon provides the "ionization cone". This opening angle tends to increase with time, allowing an evolution from a Seyfert II-like appearance early on, to predominantly Seyfert I-like or BLR-like spectra at late times.

4. In this phase, the crushed clouds left behind in the cocoon are photoablated by the strong UV field from the central engine, and the ablated ionized gas may be radiatively accelerated in the radial direction. In this phase the NLR presents the signatures of a photoionized plasma, and in Seyfert galaxies the coronal lines may be strong.

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