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Optical and UV Spectral Diagnostics for GPS and CSS Sources

Michael A. Dopita

Research School of Astronomy and Astrophysics, Australian National University,
Cotter Rd, Weston, ACT 2611, Australia
Michael.Dopita@anu.edu.au

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Abstract: In this paper I examine the use of optical and UV spectral diagnostic ratios to distinguish between gas which is locally shock-excited by the interaction with a jet and that which is photoionised by the central engine. In many cases key UV lines remain unobserved except in the case of high redshift radio galaxies. However, in one case, the nearby GPS galaxy NGC1052, UV data was obtained with the FOS. This object shows LINER characteristics at optical wavelengths, but has a rich coronal-line spectrum in the UV. We conclude that jet-driven shocks tend to evolve from shock-excited to photoionised later in their evolution.

Keywords: galaxies: radio sources — ISM: shocks, photoionisation

1 Introduction

The spectral characteristics of the gas in GPS (Snellen et al. 1999) and CSS (Gelderman & Whittle 1994) galaxies and in the ultra-steep spectrum high-redshift galaxies (e.g. De Breuck 2000) are remarkably similar to the narrow-line regions (NLRs) of Seyfert galaxies. This strongly suggests that all these classes of object are excited by a common mechanism. However, the GPS quasars are distinctly different in character, and from their optical characteristics alone seem to be related to the flat-spectrum quasars (Snellen et al. 1999). This difference is supported by many other lines of evidence presented at this conference, and these objects will not be discussed further.

For many years NLR emission was assumed to result from photoionisation by the central engine (see e.g. Koski 1978; Ferland & Osterbrock 1986). However, such models cannot explain non-gravitational motions or high-velocity outflows ($\sim$1000 km s^{-1}, e.g. Pedlar et al. 1989). 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 1978) or line width (Wilson & Willis 1980). This led Wilson & Willis (1980) to suggest that the nucleus ejects radio components that interact with ambient gas and replenish the high kinetic energy and ionisation of the NLR. Such correlations exist not only for Seyfert galaxies, but persist (see review by O'Dea 1998) up to much more luminous classes of radio galaxies which include the steep-spectrum radio sources (CSS), the gigahertz-peaked sources (GPS), and the compact symmetric objects (CSO). 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 luminous radio sources require far more energy: 10^{45}–10^{46} erg s^{-1}.

2 Shocks or Photoionisation?

The theory of Dopita & Sutherland (1995, 1996) shows that the fast shocks needed to account for Seyfert-like NLR spectra generate hot gas which produces copious soft X-rays and EUV photons as it cools. These pass (in almost equal numbers) upstream into the pre-shock plasma, where they photoionise the pre-shock plasma, and downstream, where they produce photoionisations in the recombination zone of the shock. The two regions have quite different ionisation parameters, thanks to the compression of gas through the shock which is controlled by the Alvén Mach number $\rho_1/\rho_0 = 2^{1/2}\mathcal{M}_A$.

There are 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 characterises regions with a dense and extensive ISM surrounding the shocked region. In the first case the low-ionisation parameter recombination and photoionisation region dominates the optical spectrum in the optical, providing a LINER-like spectrum. In the UV, the high-temperature cooling region is more evident, and temperature-diagnostic line ratios indicate temperatures of $(1.5–3.0) \times 10^4$ K. In the second case, the photoionised precursor provides a high-ionisation zone as well, with strong emission lines of high-ionisation species. These

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limiting cases are only two limits of a continuum of potential spectra which depend on the geometry of the absorbing ISM around the shocked region. For the GPS/CSS model of Bicknell, Dopita, & O'Dea (1997) the optical emission was assumed to arise in a radiative shocked cocoon of gas around the radio jets, which is optically thick to free–free emission at lower frequencies. In this conference data supporting this hypothesis has been presented by Inoue & Kameno, but other evidence suggests that synchrotron self-absorption may be more important in the radio lobes themselves. The presence (or otherwise) of a shocked radiative cocoon 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 $\tau_{\rm dyn} > \tau_{\rm cool} \sim 200\, v_{100}^{4.4}/Zn_0$ yr, 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 ($\sim$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 velocities $\sim$1500 km s^{-1}, and sizes $\sim$1000 kpc, the dynamical timescale is $\sim 10^6$ yr, and densities would have to exceed about 50 cm^{-3} to keep the gas radiative, and to ensure that free–free absorption is the dominant opacity at radio frequencies.

A major problem of these shock models, pointed out in our original papers, is that fast shocks are thermally unstable. This was first considered by Innes, Giddings, & Falle (1987a,b). The condition for thermal stability is given by the Field (1965) criterion: $[\partial \dot{Q}/\partial T_e]_P > 0$. If the cooling is represented by a local power-law in temperature $\dot{Q} = \Lambda_0 T_e^p n^2$, it is clear that the medium is thermally stable in isobaric cooling if $p > +1$. However (Sutherland & Dopita 1993), p is rarely as large as unity, and is greater than zero only below $\sim 10^5$ K or $\geq 10^7$ K. Fully three-dimensional hydrodynamic models are required to model such shocks, but these do not yet exist.

Shocks provide a wide variety of distinct observational signatures such as particular spectral line ratios, spatial correlations between radio bubbles and the optical emission, correlations between the radio or X-ray power and optical line luminosity, or line width versus excitation correlations. Here we concentrate on NLR line ratios. Optical diagnostic diagrams (Veilleux & Osterbrock 1987) distinguish between AGN and HII regions, because the location of the observed point is sensitive to the hardness of the ionising spectrum. Both shock and photoionisation models can reproduce the correct line ratios because both have similar 'hardness' of the EUV photoionising spectrum. However, these diagrams cannot effectively distinguish between the excitation mechanisms. A curious feature of the observations 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 the [O III] λ 5007 Å/Hβ, [N II] λ 6583 Å/Hα, or [O I] λ 6300 Å/Hα ratio, according to the extensive homogeneous observations in the review of Véron & Véron-Cetty (2000). Within individual galaxies, spatial variations in these line ratios are even tighter (Allen et al. 1999). Whilst this is a natural consequence of shock models, it is harder to understand using standard photoionisation modelling. In principle, the disposition of the ionised gas with respect to the central engine is arbitrary, and the ionisation parameter in each NLR cloud could vary widely. In practice observations constrain the dimensionless ionisation parameter U in the low-ionisation gas to the range $-3 < \log U < -2$. This suggests a self-regulatory process is coupling the density of the photoionised clouds to the local radiation field. This is precisely what is predicted on the new class of radiation pressure-dominated dusty photoionisation models advocated by Dopita et al. (2002). These also explain the presence of coronal species such as Si VII or Fe X which require very high values of U for their production.

The best, and most unambiguous diagnostics to distinguish between shocks and photoionisation are in the UV. For Seyfert galaxies and high-redshift radio galaxies, 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. LINERS are particularly interesting. Their optical spectra fit with either a photoionisation model of low ionisation parameter, $\log U \sim -4$, or high velocity shocks without precursors. In the UV, however, the model spectra are quite different; photoionised 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 ionisation 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 or NGC1052 do not give such unambiguous results, because the LINER spectrum arises in a high-density circumnuclear medium with strong radial density gradients. NGC1052 is a very nearby GPS LINER galaxy (see Vermeulen and Kameno, this conference). In its UV spectrum (Figure 1) a rich coronal-line spectrum is revealed. This requires an intense, high ionisation parameter radiation field. The model suggested is one in which a number of shock-excited clouds are being dynamically shredded but also photoablated by the EUV photon field.

3 Clues from the Hi-z Universe

The high redshift radio galaxies present us with a sample in which we can already study UV line ratio behaviour. The study of Best, Röttgering, & Longair (2000a,b) revealed an extraordinary result for powerful 3C radio galaxies with $z \sim 1.0$. Both the UV line profiles and 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 are shock-excited, but when the lobe has burst out into intergalactic space, the ionised gas left behind is predominantly photoionised. The ratio of

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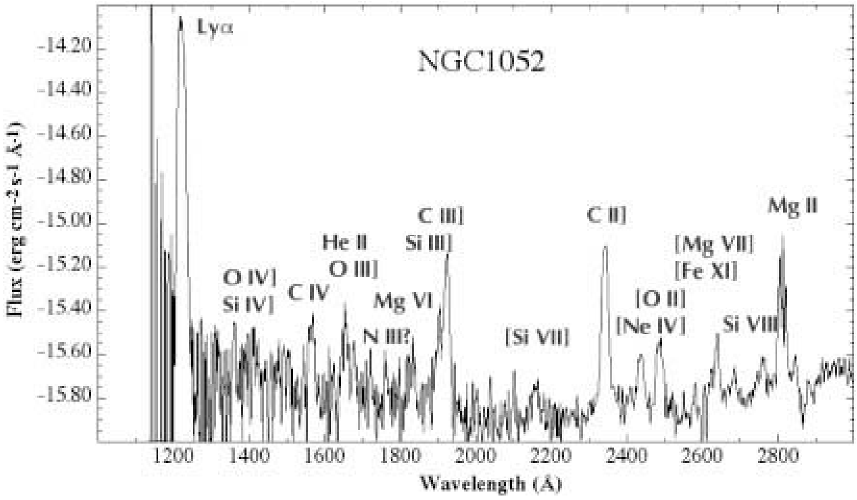

Figure 1 The HST FOS UV spectrum of NGC1052. In the optical this is a LINER, but the UV it displays a rich spectrum of coronal emission lines, which demand an intense EUV radiation field.

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 photoionisation are important in the evolution of radio galaxies. Similar results have been obtained for the distant radio galaxies studied by De Breuck (2000). For diagnostic diagrams involving C IV, He II and C III] the fit to the pure photoionisation models is good, but the observed C II]/C III] requires there to be a high-velocity shock present. Composite models are required to give a self-consistent description of all the line ratios, and these may also require a mix of different physical conditions.

The radio galaxy 4C 41.17 ($z \sim 3.8$) has been intensively studied. This is a powerful 'double–double' radio source with $\sim$3000 $M_\odot$ of jet-induced star formation along the inner radio jet. Bicknell et al. (2000) have constructed a detailed model which required a high-powered jet with an energy flux of $\sim 10^{46}$ ergs s^{-1} interacting with a dense cloud to both produce shock-excited emission-line nebulosity through a $\sim$1000 km s^{-1} shock and to induce star formation. The line ratio diagnostics require that the gas involved in the interaction is of relatively low metallicity. Recently Reuland et al. (2002) have shown that the inner jet is shocking a dense cocoon of gas produced by the outer radio lobes located 50–80 kpc from the nucleus. These are embedded in an enormous Lyα halo, and are characterised by a very steep radio spectral index ~ -2.2. [O II] spectroscopy, and the earlier optical Lyα spectroscopy (Dey et al. 1997), show that both emission lines exhibit blue-shifted gas at a velocity $\sim$1000 km s^{-1} in the vicinity of the south–west radio lobe. Furthermore, the gas is very disturbed along the filament out to this distance, with Lyα velocity widths ranging up to $\Delta v \sim 2000$ km s^{-1}. Beyond the radio hot spot, the Lyα line width decreases abruptly to $<$500 km s^{-1}. The filamentary structure, kinematics, and the chemical enrichment of the gas all strongly suggest that gas is shocked and entrained by the radio jet.

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 10–30 kpc, the interactions with the surrounding medium are strong, and the NLR is predominantly shock-excited. The radio jets bore out 'ionisation cones' which are responsible for the alignment effect of the NLR. At late phases, though, the ionised gas is either photoionised by the central source, or through the shock-induced star formation that, for a dense galaxian medium, must inevitably take place along the boundaries of the old shocked cocoon.

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