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Jet-driven outflows in Seyfert galaxies

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Abstract. Growing evidence over the past decade has indicated that low-luminosity active galaxies are often associated with outflows from their nuclei. In particular, a small but important fraction of Seyfert galaxies have extended collimated radio emission on the scales of the narrow-line region (NLR). In most of these cases, the emission-line gas displays morphological and kinematic signatures of disturbance or acceleration by the nuclear jet. Using the STIS spectrograph on the *HST*, we have obtained high spatial resolution long-slit spectra of six Seyfert galaxies which show clear signs of jet-gas interactions. Combined with *HST* and ground-based optical and archival radio imaging, we are able to explore these interactions in considerable detail. We have isolated the signatures of a number of key dynamical processes such as cloud shocks and acceleration, ablation, jet bending and drag forces. Other elements of the circumnuclear environment, such as gaseous disks, AGN winds and star-forming regions are also shown to play an important role in our view and interpretation of jet interaction and Seyfert ionization. Finally, a detailed dynamical study of jet-interaction archetype Mkn 78 provides strong evidence for a thermally-dominated, slow and dense Seyfert jet, quite unlike the powerful jets thought to be present in classical Radio Galaxies. Our results provide new insights into the nature of nuclear outflows in low-luminosity and radio-quiet AGN.

Key words. galaxies: Seyfert, nuclei, jets – techniques: spectroscopic

1. Introduction

Seyfert galaxies and other low-to-intermediate luminosity AGN account for the most common form of supermassive black hole accretion activity in the nearby universe. Frequently, Seyferts are associated with extended radio structures on 10-1000 pc scales (Nagar et al. 1999). While there is good evidence that these radio jets have a dynamical impact on the gaseous environment of the AGN (Capetti et al. 1995; Ferruit et al. 2004; Whittle & Wilson 2004, Fig. 1), their compostion and properties are not well established. What is clear is that these jets differ quite significantly from those in powerful radio galaxies, in terms of extent, synchrotron popula-

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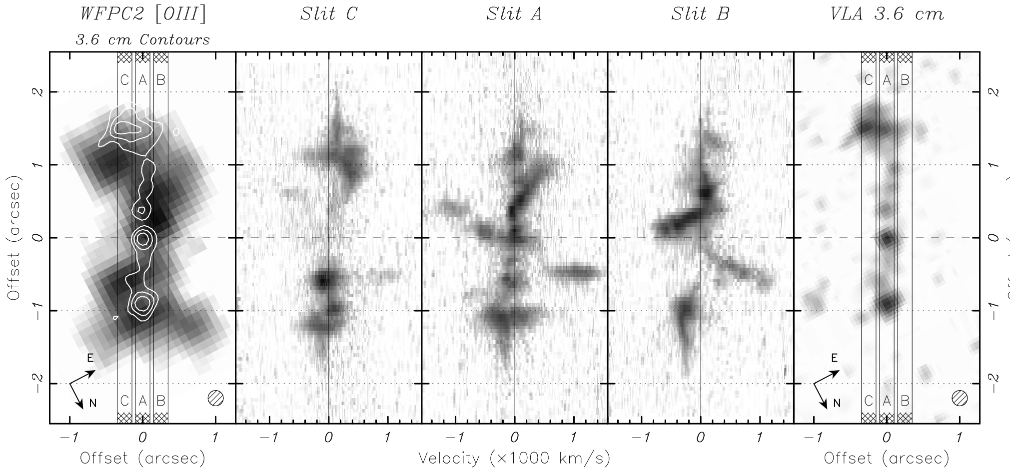

Fig. 1. The jet interaction in Mkn 34 as seen by *HST* and the VLA. The middle three panels are STIS G430M long-slit spectra in the [OIII]λ5007 line. The wavelength axis has been plotted as velocity with respect to the galaxy systemic. A 3.6 cm VLA radio map is shown in the righthand panel. In the lefthand panel, we have plotted an *HST*/WFPC2 emission line image in [OIII] with radio contours overlayed in white. The positions of the three slits and the VLA beam size are shown on both images.

tions and initial jet speeds (Ulvestad & Wilson 1989; Bicknell et al. 1998; Nagar et al. 1999; Middelberg et al 2004) We describe here a program of *HST*/STIS spectroscopy and multiwavelength imaging of six Seyferts with extended radio structures aimed at understanding the degree of radio-jet driven motion in these objects, as well as the impact of the circumnuclear environment on narrow-line region (NLR) appearance and kinematics. The final aim of this study is the establishment of useful constraints on the nature and dynamics of radio outflows in Seyferts and the degree to which these outflows can serve as agents of kinetic feedback to the host galaxy.

Our program objects have all been extensively studied by many previous works. Some principal references which serve as sources of data and interpretive context are listed here. The Seyferts in our sample are: Mkn 78 (Whittle & Wilson 2004; Whittle et al. 2005), Mkn 34 (Falcke, Wilson & Simpson 1998), NGC 2110 (Nagar et al. 1999; Ferruit et al. 2004), Mkn 1066 (Bower et al. 1995; Knop et al. 2001), Mkn 348 (Capetti et al. 1996; Peck et al. 2003), NGC 5929 (Bower et al. 1994; Su et al. 1996).

2. The influence of the circumnuclear environment - gas disks

We see clear evidence for dusty disks in NGC 2110 and Mkn 1066. In both cases, and less clearly in Mkn 34, the gas in the disk appears to be dynamically connected to the jet-accelerated material, indicating that the disk may serve as a reservoir of gas which interacts and is entrained into the jet. In addition, the appearance and dynamics of the jet in NGC 2110 implies that it is likely being bent by the pressure gradient perpendicular to the disk. The presence of a circumnuclear disk, as well as inhomogeneous dust on the scale of the NLR, is an ubiquitous characteristic of Seyfert galaxies (Martini et al. 2003). Anisotropic gaseous structures can have a significant impact on the direction and capacity of jet-driven feedback in Seyferts.

3. Physical processes

3.1. Acceleration of emission-line gas

What can provide the forces needed to drive the momentum measured in the emission line gas? We consider three plausible sources:

1. Radiation pressure: The ionization state of the gas allows an estimate of a lower-limit to the radiation pressure which may drive the gas motion. In most cases, the radiation pressure is more than capable of driving the observed outflow. However, results of this study, (no correlation between emission line kinematics and ionization properties) as well as known properties of radio-jetted Seyferts (the tendency of this class of objects to be associated with disturbed NLR kinematics; Wilson & Willis 1980), implies that radiation pressure is not a principal player. Better models of the action of radiation pressure on multiphase ionized gas are needed to understand this effect better.
2. Radio source pressure: We examine the relationship between the momentum of the gas and the pressure of the most proximate radio source. We find that in all of our objects, except for Mkn 34, the radio jet pressure cannot drive the gas motions that are seen. In the particular case of Mkn 348, the radio jet pressure is two orders of magnitude too low to accelerate the jet-driven gas.
3. Jet ram pressure: By virtue of its internal momentum, the jet material can accelerate material that it intercepts or entrains, such as the gas forming the emission line clouds. Based on our exploration of acceleration mechanisms in Mkn 78 (Whittle et al. 2006), we affirm that jet ram pressure plays the major role in driving the kinetics of the interacting gas. This has important consequences for the composition of the jet.

3.2. Shocks

Shocks are expected to be widespread in the interacting NLR, given the high velocities of the emission line material. In most of our galaxies, the emission line power of photoionized gas far outweighs that expected from shock-ionized emission (Dopita & Sutherland 1995). However, in NGC 5929, the weakest Seyfert in our sample, we find a good case for shock-ionized material in the form of broad wings to the Hβ line ($FWHM$ ~ 300 kms^{-1}), which are not observed in [OIII]λ5007 (Fig. 2). The broad emission comes from shocked gas, while the narrow [OIII] is dominated by an undisturbed precursor ionized by the shock. Shock velocities similar to the width of the broad component nicely match the estimates from emission line modelling (Ferruit et al. 1999). However, NGC 5929 has a jet structure that is very different from typical Seyfert jets and may not be a representative case of this class.

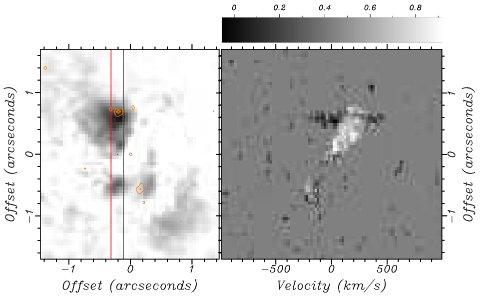

Fig. 2. NLR ionization gradients in NGC 5929. In the right panel, we present a map of the [OIII]λ5007/Hβ ratio obtained from the STIS G430M dataset of this object. In the left panel, a *HST*/WFPC1 emission line image in [OIII] is shown with 6 cm MERLIN radio contours overplotted in orange and the position of the STIS slit plotted in red. In the region of the galaxy coincident with the southwest radio knot, a broad, low-ionization wing is clearly noticeable, which we interpret to be a direct detection of shocked gas.

3.3. Jet-gas interpenetration

A characteristic feature of all jet-gas interactions in our sample is the lack of significant interpenetration between jet and emission-line material. We take this to imply that the jet percolates through the network of gas clouds which form the NLR. However, in all cases, the jet still maintains its structure and relative collimation across the interaction region. Based on simulations of jet cloud interactions (Higgins et al. 1999; Wang et al. 2000; Saxton et al. 2005), this behaviour implies that the jet/cloud density ratio is quite high (~ 0.1) and that the internal Mach number of the jet is low ($\leq$ 1). Unfortunately, most simulations in the literature assume jet properties akin to powerful jets in Radio Galaxies. The time is ripe for hydrodynamic jet simulations exploring the parameter space of slower, wind-like outflows.

4. A slow, heavy jet?

The Mkn 78 spectroscopic and imaging dataset allows one of the most complete dynamical studies of a Seyfert with a widespread jet-driven interaction. From emission line fluxes and kinematic measurements, we estimate ionized gas masses, momenta and kinetic energies. From the geometry of the NLR, we can constrain gas covering factors and interaction region sizes. From a 3.6 cm VLA radio map, we estimate radio source properties such as energy content, pressures and magnetic field strengths from synchrotron equipartition arguments. Finally, the sizes of the regions and the gas kinematics allow us to estimate plausible timescales for the jet interaction (which work out to be around 10^6 yrs). In this analysis, it is assumed that radiation pressure and shocks have negligible effects on the energetics of the gas, which is not a stringent condition. However, we choose to explore the consequences of these assumptions in developing a reasonable model for the jet dynamics.

We use the radio lobe in Mkn 78 as a jet calorimeter, which enables us to work out the total energy and momentum *fluxes* of the jet over the course of its lifetime, after applying corrections for the filling factor of the radio plasma (which is assumed to be a tracer of the jet pressure), the effect of energy-driven processes on the jet dynamics, and adiabatic expansion of the lobe. A significant result of this analysis is that the jet is dominated by a thermal component which has sufficient ram-pressure to accelerate the emission line gas to its current kinetic state. Such a jet is quite dense ($n_{\rm jet} \sim 1$ cm^{-3}) and slow-moving ($V_{\rm jet} = 300 - 3000$ kms^{-1}) compared to those in radio galaxies. This is consistent with the general observation that the jet bends and percolates through the NLR. In addition, the thermal component of the jet seems to match the total quantity of gas intercepted by the jet in the course of its lifetime as it propagates out into the NLR. Entrainment is therefore expected to be an significant determinant of the physics of Seyfert jets.

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