The Interplay among Black Holes, Stars and ISM in Galactic Nuclei
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Seyfert jets: Weak, slow and heavy

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Abstract. We make use of extensive HST optical and VLA radio observations of the Seyfert galaxy Markarian 78 to analyse the properties of the jet flow. Our starting assumption is that the jet's power can be inferred from the energy stored in the radio lobe, and the jet's momentum flux can be inferred from the momentum of the ionized gas. Using the properties of three regions, we derive a jet flow power of $\sim 10^{40.5}$ erg s^{-1} and momentum flux of $\sim 10^{33.5}$ dyne. Assuming the jet contains both thermal and relativistic material, we find that the thermal component dominates both the jet's luminosity and its momentum flux. We find the jet to be mildly transonic, with speed only a few times that of the [OIII] velocities. The jet is, however, quite dense, with sufficient ram pressure to accelerate the ionized gas to the observed velocities. Over the region lifetime, the jet can provide the thermal component of the lobes, and likely does this by entraining ISM material en route. These jet properties seem, at least to us, to be eminently plausible, suggesting an approach of this kind may be appropriate for other radio quiet objects.

1. Introduction

This contribution is part of the same project introduced by Rosario et al (these proceedings). Briefly, our aim is to study the nature of Seyfert galaxy jets and jet-gas interactions using Markarian 78 as an archetype. We have gathered an extensive dataset, comprising HST emission line and continuum images, HST STIS spectra at four slit locations, and a deep VLA 3.6cm radio continuum map. In Rosario's contribution, we showed conclusively that the emission line regions were ionized by the radiation field of the central source and not by shock or shock-related processes. Here our aim is to use the physical constraints provided by the emission line and radio data to understand the nature of the jet-gas interaction in more detail, and thereby gain access to the properties of the jet flow itself. The whole project is reported in a series of three papers: Whittle & Wilson 2004, Whittle et al. 2004a, and Whittle et al. 2004b.

2. Overall Region Properties

Figure 1 shows the [OIII]λ5007 emission line image, with radio contours and four STIS slits superposed, while figure 2 shows the spectroscopic data for just the [OIII]λ5007 line. The STIS spectra yield emission line velocities and line strengths which in turn provide ionized gas covering and filling factors, densities, pressures, masses, momenta, and kinetic energies. The VLA map gives, following the usual equipartition assumption, radio source pressures and energies in the various components. For present purposes, we identify three distinct regions: "W-knot", "E-fan", "W-lobe". For each region, we find $\sim 10^6$ M$_\odot$ of ionized gas with low ($\sim 10^{-4}$) filling factor, and high ($\sim 50\%$) covering factor. We estimate the region ages using their size and [OIII] velocities, finding ~ 0.4, ~ 4, ~ 8 Myr, respectively, confirming our expectations, based on morphological appearance alone, that

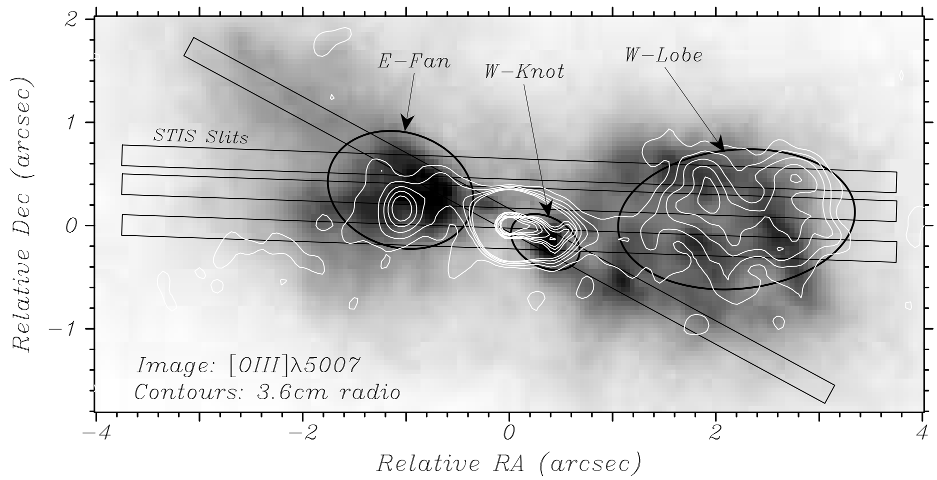

Figure 1. Mkn 78. Image: HST [OIII]λ5007. Contours: VLA 3.6cm natural weight map, with deconvolved uniform weight map of the core region superposed. HST STIS slit positions are shown, as well as the three regions discussed in the text

the regions represent the early, intermediate, and late stages of a time sequence in the interaction and destruction of a cloud by a jet.

2.1. *Pressures and Energies*

For the relativistic and line emitting components, we find $P_{\rm rel} \approx P_{\rm em} \approx 1 - {\rm few} \times 10^{-10}$ dyne cm^{-2}, with evidence for both falling roughly as r^{-1}. This nicely shows rough pressure balance between the relativistic and emission line components, as well as with the general ISM found in the bulge regions of massive galaxies. While these fairly high pressures can drive the lobe expansion into the ISM at roughly the [OIII] speed, we find they are barely capable of accelerating the ionized gas, which requires yet higher, probably dynamical, pressure from the jet flow itself.

We are also able to compare a number of energies and luminosities pertaining to the regions. First, the emission line output from the regions and the UV input to the regions is roughly similar: $L_{em} \approx L_{UV} \approx 10^{43}$ erg s^{-1}, consistent with our prior conclusion that it is the central source UV radiation field which ionizes the gas. Using the region lifetimes to convert the kinetic energy of the ionized gas and the internal energy of the radio source into luminosities, we find $L_{mec} \approx L_{rel} \approx 10^{40}$ erg s^{-1}. This supports the notion that the ionized gas acceleration is intimately related to the radio source growth, but neither seem closely tied to the much more powerful central UV radiation field.

3. The Jet's Energy and Momentum

While these region properties help define the overall relation between the various components, we ultimately want to zero in on the jet flow itself, and derive its properties. To this end, we have found the work of Bicknell et al. (1998) very useful, and we follow their analysis quite closely. We do, however, make two significantly different starting assumptions, and these lead to a very different kind of jet to the one derived in their work.

The critical starting point is to estimate the jet's luminosity and momentum flux. While Bicknell et al. (1998) assume jet-driven shocks power the emission lines and accelerate the

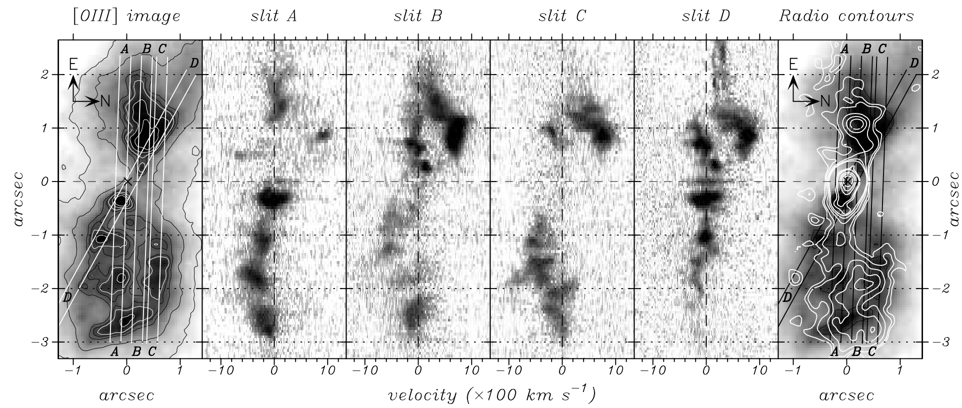

Figure 2. High dispersion STIS spectra of [OIII]λ5007 for the four slits shown in Figure 1. Slit locations are shown overlaying the [OIII] image (left) and the radio image (right).

ionized gas, we cannot make that assumption, having just shown that the emission lines are *not*, in fact, powered by shocks. Instead, we assume that over the region's lifetime, the jet has deposited its energy into the radio source lobe (modulo adiabatic expansion losses). Using the lobe as jet bolometer, we find $L_j \sim 10^{40.5}$ erg s^{-1}. Similarly, we assume that over the region lifetime, the jet's momentum flux has been roughly shared with the ionized gas (since its covering factor is high), giving $F_j \sim 10^{33.5}$ dyne. Notice that these values are *significantly* lower than those derived by Bicknell et al.'s method (by factors $\sim 10^3$ and $\sim 10^2$ respectively).

Hence, making the reasonable assumption that the jet ultimately inflates the radio souce, we find the Seyfert jet to be quite weak, at least compared to earlier estimates.

4. Detailed Jet Properties

To proceed, we assume that on the $100 - 1000$ pc scale, the jet contains two distinct components in pressure balance: a relativistic component (which we observe via its synchrotron emission) and a thermal component (which we do not observe), their ratio defined by a filling factor, ff_{rel}. Under these circumstances, the jet's total luminosity and force are shared between these two components, and by using our estimates of each, we can solve for the separate components.

We find that the jet's total energy and momentum flux are *both* dominated by the thermal component. The ratio of the jet's bulk kinetic energy to its internal energy is $\sim 10/2/1$ for the three regions, consistent with the bulk energy being converted to internal energy as the jet continues to traverse the region and interact with the ISM. The jet's ram pressure is significantly greater than its internal pressure, with $P_{ram} \sim 30/7/4 \times P_{rel}$ for the three regions. Although this ram pressure, acting over the region lifetime, can nicely accelerate the ionized gas to its observed velocity, note that it is significantly smaller than the ram pressure of Bicknell et al.'s jet (by factors $10^2 - 10^3$). This is easily seen, since they require the jet's ram pressure to *impulsively* shock accelerate the emission line clouds — contrast accelerating a golf ball by (a) hitting it with a club, or (b) gradually blowing it along a frictionless fairway.

The ratio of the jet's energy and momentum fluxes gives its velocity, which we find to be $0.3 - 3 \times 10^3$ km s^{-1}, or $\sim$ 1−few× the [OIII] speed. This jet is *slow* compared to Bicknell et al.'s jets, which have velocities $15 - 90 \times 10^3$ km s^{-1}.

The jet's force, velocity and area allow us to derive its density and mass transport rate: $\rho_j \sim 0.1 - 5$ cm^{-3} and $\dot{M}_j \sim 0.5 M_\odot$ yr^{-1}. The jet is therefore quite *heavy*, indeed comparable to a typical ISM density, suggesting the jet's thermal component may have arisen by entrainment. Integrating over the region's lifetime, we find the total mass transported is similar to the low density thermal content of the lobes, again consistent with the jet flow filling the lobe and driving its expansion into the ISM.

Going a little further, the jet's internal pressure and density yield its temperature: $T_j \sim 10^6 - 10^7$K. This is somewhat lower than a fully virialized jet flow, as expected from the fact that $P_{ram} > P_{rel}$. The associated internal sound speed implies the jet is mildly transonic, with Mach numbers $\sim 5/2.5/1.5$ for the three regions. This is, superficially at least, consistent with the importance of entrainment, since transonic jets are thought to yield boundary layers which entrain efficiently.

Finally, we find a net synchrotron efficiency $R_{syn} = L_{radio}/L_j \sim 1$−few%. This is similar to estimates for extragalactic radio sources, such as CSS, FR-I and FR-II radio galaxies. While initially gratifying to find this agreement, it is nevertheless surprising, since the jets in the radio loud AGN are thought to be dominated by a relativistic component, whereas our analysis suggests a thermally dominated jet in which the relativistic material is dynamically unimportant.

5. Conclusions

We have combined optical and radio data to measure a number of basic properties across the kpc-scale regions in Mkn 78, an archetypal Seyfert exhibiting a strong interaction between its radio jet source and its emission line region. By assuming that the jet's kinetic luminosity can be inferred from the energy stored in the radio lobes, and the jet's momentum flux can be inferred from the momentum of the emission line region, we are able to derive a number of properties for the jet flow. Compared to earlier studies (which used fast shocks to infer jet properties) we find a jet flow that is significantly weaker, slower, and denser, with its energy and momentum fluxes dominated by a thermal (as opposed to a relativistic) component. We find the jet to be mildly transonic; move at roughly the [OIII] velocity; have a density similar to the ISM; drive only weak shocks into the emission line clouds; have normal synchrotron efficiency; and possibly supply the low density thermal material filling the emission regions. Since we feel this object is representative of its class, these jet properties may be typical of Seyferts, and other radio quiet AGN, in general.

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