Jet cocoons and the formation of narrow-line clouds in Seyfert galaxies

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ABSTRACT

We present non-adiabatic hydrodynamic simulations of a supersonic light jet propagating into a fully ionized medium of uniform density on a scale representative of the narrow-line region (NLR) in Seyfert galaxies with associated radio jets. In this regime the cooling distance of the swept-up gas in the bowshock of the jet is of the same order as the transverse extent of the jet bowshock, as opposed to the more extreme regimes found for more powerful adiabatic large-scale jets or the slow galactic jets which have previously been simulated. We calculate the emissivity for the Hα line and for radio synchrotron emission. We find that the structure of the line-emitting cold envelope of the jet cocoon is strongly dependent on the non-stationary dynamics of the jet head as it propagates through the ambient medium. We observe the formation of cloud-like high density regions which we associate with NLR clouds and filaments. We find that some of these clouds might be partially neutral and represent sites of jet-induced star formation. The calculated Hα flux and the spectral line width are consistent with NLR observations. The simulation of the radio-optical emission with radiative cooling confirms the basic result of the geometric bowshock model developed by Taylor et al., i.e. that the start of noticeable optical line emission can be significantly offset from the hotspot of the radio emission. However, the time-dependent nature of the jet dynamics implies significant differences from Taylor et al.'s geometric bowshock model.

Key words: methods: numerical – galaxies: active – galaxies: individual: Mrk 1066 – galaxies: jets – galaxies: kinematics and dynamics – galaxies: Seyfert.

1 INTRODUCTION

The study of the narrow-line region (NLR) in Seyfert galaxies is contributing substantially to the understanding of the central engine of active galaxies. Of particular interest is the apparent close association between radio continuum and optical line emission in this region, which has a typical extent of 0.1–1 kpc. The link between optical and radio emission in the NLR manifests itself most prominently in a positional association between linear radio structure and optical line emission, as well as in a correlation between line width and radio power (Wilson & Willis 1980; Whittle 1985). It is widely accepted that the radio emission is related to the outflow of relativistic plasma from the core of the galaxy. As is found in higher power radio galaxies and quasars, this outflow appears to be highly collimated into jets. The radio–optical association suggests that the interaction of the jets with the interstellar medium (ISM) strongly influences the dynamics of the ionized gas in the NLR. It can be hoped that the study of this interaction will reveal important information on the physical conditions of the gas in the NLR and in the plasma jets.

The expansion of the cocoons of large-scale extragalactic jets in radio galaxies has been examined analytically by Scheuer (1974) and Begelman & Cioffi (1989) and numerically by Cioffi & Blondin (1992). Blandford & Königl (1979) first suggested that the interaction of jets with broad-line region (BLR) clouds could cause the radio emission and the associated kinematics of the BLR. The observation of symmetric double or triple radio sources associated with emission-line gas in the NLR of a number of Seyfert galaxies (in particular in NGC 5929, Haniff, Wilson & Ward...
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with the local ISM. Pedlar, Dyson & Unger (1985) proposed an expanding plasmon model for the NLR. They suggested that a high-pressure relativistic plasma bubble expands and drives a shock wave sweeping up the surrounding ISM.

Whittle et al. (1986) found a spatial separation of 0.95 ± 0.11 arcsec between the peaks of the [O III] 5007-A components in high-dispersion spectroscopic observations. This separation is significantly smaller than the measured distance between the radio components. Based on these observations, Pedlar et al. (1987) proposed a variant of the plasmon model similar to the radiative bowshock model suggested earlier by Wilson & Ulvestad (1987) for the radio structure observed in NGC 1068. This model explains the difference in the spatial separation between the peaks of the radio and the optical components. It invokes a supersonic motion of a jet or plasmon inducing a bowshock in the ambient medium. In the frame of the head of the bowshock, the shocked ISM gas then moves along its surface. All the basic properties of an expanding plasmon model are still applicable, but, in addition, the cooling time of the gas behind the bowshock allows the gas to flow a significant distance from the vertex before cooling to a temperature sufficiently low (∼ 10⁴ K) for optical lines to be emitted. Since the radio emission is expected to peak at the vertex, there will be a difference in the peak positions of the optical and the radio emission. This model was further developed by Taylor et al. (1989), Taylor, Dyson & Axon (1992) and Ferruit et al. (1997).

Recent Hubble Space Telescope (e.g. Capetti et al. 1995a,b; Bower, Wilson & Mulchaey 1994; Bower et al. 1995) and MERLIN observations (Pedlar et al. 1993; Kukula et al. 1996) revealed overwhelming new structure in the NLR of several Seyfert galaxies with radio jets. Discrete clouds and diffuse line emission are found to be closely aligned with highly structured and sometimes distorted radio jets. These observations clearly show that the idea of a radio jet interacting with the NLR can account for the basic features of these jets. However, the phenomena are far more complicated than can be accounted for by the simple geometric bowshock model. The full non-stationary character of the interaction between a jet and its environment has to be taken into account to explain the newly observed features.

In this paper, we therefore apply high-resolution axisymmetric hydrodynamic simulations to explore the time-dependent interaction of Seyfert jets with the NLR. We demonstrate that the association between the radio and the optical emission can be explained as a natural consequence of the expansion of a hot jet cocoon into the interstellar medium, creating an envelope of dense cool gas and discrete emission-line knots which can be associated with the narrow-line clouds themselves. We compare our model with observations of the NLR Hα emission in Mrk 1066, which has a similar linear extension (Bower et al. 1995).

In Section 2 we estimate the properties of our cocoon shock model analytically. The numerical procedure of the simulations is briefly described in Section 3. Section 4 contains the results and their discussion. We summarize our conclusions in Section 5.

2 ANALYTICAL ESTIMATES

We consider the dense optically emitting envelope of swept-up ISM gas around the cocoon of a supersonic jet propagating into a uniform, ionized medium. The ionization is assumed to be the result of photoionization from a UV source at the active nucleus of the galaxy. For a UV photon rate $S \sim 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ similar to the one in NGC 5929 (Bower et al. 1995) and an ambient density of $1 \text{ cm}^{-3}$ the radius of the Strömgren sphere is 700 pc, which is well beyond the distances we consider in this paper. For an estimate of the initial conditions in a simulation which can be compared with typical observations, we assume that the envelope is a thin cylindrical shell of radius $r_\odot \sim 20 \text{ pc}$, length $l_\odot = 150 \text{ pc}$, Hz luminosity $L_{\text{Hz}} = 10^{37} - 10^{39} \text{ erg s}^{-1}$, and a thickness $d_\odot \ll r_\odot$. Within our model the spectral line width in the NLR will be similar to twice the cocoon expansion speed, if observed from a direction perpendicular to the jet axis. We therefore have typical shock velocities of 100–200 km s⁻¹ (e.g. Mrk 1066, Bower et al. 1995). In the following, we estimate some characteristic quantities, such as the density $n_\odot$ of the ambient ISM and the density $n$, and thickness $d$, of the dense cool envelope, using this range of observed sizes and luminosities.

2.1 Non-magnetic case

We first assume that there is no magnetic field in the environment which could limit the compression at the shock, which is driven perpendicularly to the jet axis into the ISM by the over-pressured cocoon. We further assume that the shock is isothermal, at the temperature $T_s = 10^4 \text{ K}$ of the pre-shock gas. This assumption is justified by estimating the cooling distance $\delta$ behind a shock of speed $v_s = 150 \text{ km s}^{-1}$ in typical environmental gas with a hydrogen density of $n_0 = 1 \text{ cm}^{-3}$, using the adiabatic compression factor of 4. We then have (Taylor et al. 1992)

$$\delta = \frac{\tilde{m}_v k T_s^{(1-z)}}{4 \mu m_\odot \Lambda_0},$$

where we use a power-law cooling function of the form

$$\Lambda(T) = \Lambda_0 T^z,$$

with $\Lambda_0 = 4.6 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^3$ and $z = -0.76$ at $T > 1.5 \times 10^3 \text{ K}$. The temperature $T_s$ immediately behind the shock is given by

$$T_s = -\frac{3}{16} \frac{\tilde{m}}{k} v_s^2,$$

where $\tilde{m}$ is the mean molecular weight and $k$ is the Boltzmann constant (we assume $\tilde{m} = 0.5 m_\odot$, where $m_\odot$ is the proton mass). The cooling distance perpendicular to the shock is then $\delta = 1.8 \times 10^{17} \text{ cm}$ or 0.06 pc with a corresponding post-shock temperature of $T_s = 2.5 \times 10^3 \text{ K}$. For $v_s = 100 \text{ (200) km s}^{-1}$ the cooling distance will be 2.2 (3.7) times smaller (larger) than for $v_s = 150 \text{ km s}^{-1}$. All these values are much smaller than the radius $r_\odot \sim 20 \text{ pc}$ of the cocoon,
justifying the assumption of an isothermal shock for the estimates.

We now calculate the density $n_e$ and thickness $d_e$ of the compressed post-shock layer of gas and the density of the environmental gas $n_0$. We start with the compression ratio of the isothermal shock, which is

$$f = \frac{n_e}{n_0} = \frac{\dot{m} v_s^2}{k T_0} = \frac{120 \dot{m}}{m_p} \left( \frac{T_0}{10^4 \text{K}} \right)^{-1} \left( \frac{v_s}{100 \text{ km s}^{-1}} \right)^2.$$

(4)

In terms of the volumes of the cylindrical cocoon $V_c$ and the cylindrical shell of swept-up gas around the cocoon $V_e$ we also have

$$f = \frac{V_e}{V_c} = \frac{\pi r_e^2 l_e}{2 \pi r_e d_e} = \frac{r_e}{2 d_e}.$$

(5)

Combining equations (4) and (5) we find the thickness of the layer of swept-up gas to be

$$d_e = \frac{r_e}{2} \frac{k T_0}{2 \dot{m} v_s^2} = 0.083 \text{ pc} \left( \frac{\dot{m}}{m_p} \right) \left( \frac{r_e}{20 \text{ pc}} \right) \left( \frac{T_0}{10^4 \text{ K}} \right) \left( \frac{v_s}{100 \text{ km s}^{-1}} \right)^{-2}.$$

(6)

Assuming pure hydrogen gas of uniform density, the Ha luminosity of this layer will be

$$L_{\text{H}_\alpha} = n_e^2 \varepsilon V_c = 3.7 \times 10^{38} \text{ erg s}^{-1} \left( \frac{n_e}{100 \text{ cm}^{-3}} \right)^2 \left( \frac{V_c}{10^{39} \text{ cm}^3} \right),$$

(7)

where $\varepsilon = 3.8 \times 10^{-25} \text{ erg cm}^{-3} \text{ s}^{-1}$ is the Ha emission coefficient at $T_0$ (see Section 3.4.1).

The total mass swept up from the environment into the shell is

$$M = n_e m_p V_c = 8300 M_\odot \left( \frac{n_e}{100 \text{ cm}^{-3}} \right) \left( \frac{V_c}{10^{39} \text{ cm}^3} \right).$$

(8)

We assume full ionization of the gas in the NLR. A column of swept-up hydrogen gas of density $n_e$ at a distance $l_e$ from the ionizing photon source with a photon flux $S$ will stay fully ionized up to a thickness

$$d_i = 1.1 \text{ pc} \left( \frac{n_e}{100 \text{ cm}^{-3}} \right)^{-2} \left( \frac{l_e}{100 \text{ pc}} \right)^{-2} \left( \frac{S}{10^{52} \text{ s}^{-1}} \right),$$

(9)

assuming that no photons are intercepted on their way to the cloud.

In Section 4 we compare these analytic estimates with the results from our simulation.

### 2.2 Magnetic case

We now consider the case in which the undisturbed environment is threaded by a random magnetic field, assuming the components in the plane of the shock will be compressed with the field lines frozen into the gas. The effect of the magnetic field will be to limit the compression of the shocked gas when the magnetic pressure equals the thermal pressure. The compression factor $f_m$ is then given by (e.g. Dopita and Sutherland 1995):

$$f_m = \frac{n_{cm}}{n_{0m}} = \frac{(8 \pi \dot{m})^{1/2} v_s}{B_0 n_{0m}^{1/2}} = 64 \left( \frac{\dot{m}}{m_p} \right)^{1/2} \left( \frac{v_s}{100 \text{ km s}^{-1}} \right) \left( \frac{B_0 n_{0m}^{1/2}}{\mu \text{G} \text{ cm}^{-3/2}} \right)^{-1}.$$

(10)

The thickness of the shocked gas layer is then

$$d_{cm} = \frac{r_e B_0 n_{0m}^{-1/2}}{2 v_s (8 \pi \dot{m})^{1/2}} = 0.15 \text{ pc} \left( \frac{r_e}{20 \text{ pc}} \right) \left( \frac{v_s}{100 \text{ km s}^{-1}} \right)^{-1} \left( \frac{B_0 n_{0m}^{-1/2}}{\mu \text{G} \text{ cm}^{-3/2}} \right).$$

(11)

Values of the magnetic parameter $(B_0 n_{0m}^{-1/2})(\mu \text{G cm}^{-3/2})$ are of order 1, in the range 1–10 (Dopita & Sutherland 1995).

As a result of the additional magnetic pressure, the thickness of the cold envelope will be larger and the density lower than in the non-magnetic case. Since the optical line emission depends on the square of the density, the emission received from a strongly magnetized envelope will be considerably lower than that coming from a non-magnetic envelope.

### 3 NUMERICAL SIMULATION

#### 3.1 Initial conditions

The determination of jet parameters like plasma speed and density is a classical and basically unsolved problem in extragalactic astrophysics. For the purpose of simulating the expanding envelope, the exact values of the jet speed and density input parameters are not important. The expansion of the cocoon shock is principally determined by the cocoon pressure, and a given pressure can be obtained from a range of jet parameters. For practical purposes this range of parameters is also somewhat restricted by the available computing resources. We therefore performed a small series of test runs, varying the particle density in the ISM around 1 cm$^{-3}$, jet velocities around $10^4$ km s$^{-1}$ (Bicknell et al. 1990) and Mach numbers around $10$. A Mach number higher than 5 is required for a jet with a noticeable cocoon (Norman, Smarr & Winkler 1985). From these tests we chose a set of parameters which compares well with the observations of Seyfert galaxies given in Section 2 (in particular Mrk 1066) and which illustrates best the qualitative features of the formation and structure of the dense cocoon envelope. A more detailed account of the influence of varying the parameters will be given in a forthcoming paper (Steffen et al., in preparation).

The chosen parameters are:

- $n_0 = 1.5 \text{ cm}^{-3}$
- $T_0 = 10^4 \text{ K}$
n_j = 0.18 cm\(^{-3}\)

\(M_j = 8.3\)

\(v_j = 6.8 \times 10^6\) cm s\(^{-1}\)

\(r_j = 5.3 \times 10^{18}\) cm.

This yields a jet mechanical luminosity of \(L_j = 2 \times 10^{39}\) erg s\(^{-1}\).

### 3.2 Scaling and similarity

In the absence of cooling, the jet will evolve in a self-similar fashion,

\[ l_e = \left( \frac{L_j}{n e} \right)^{1/5}, \]

with \(\alpha = 1\), once \(l_e \gg (n_e/n_r)^{1/2}r_j = 2 \times 10^{18}\) cm (Falle 1991).

Cooling will begin to have an effect when the advance speed of the outer shock at the base of the jet is roughly 100 km s\(^{-1}\) (Dyson 1984), i.e. roughly when \(l_j = l_{\text{cool}} = 6 \times 10^{19}\) cm, if the aspect ratio of the jet is \(\delta = l_e/l_r = 5\). Thus, for our typical parameters, the jet will be self-similar before cooling becomes important (neglecting the effects of turbulence in the jet).

Once cooling becomes non-negligible, self-similarity no longer holds, but the evolution of jets with different parameters will be similar to each other, if times are scaled to the time at which the gas begins to cool, and distances are scaled to the length of the jet at this time. For the cooling law, equation (2), the lengths will scale as

\[ l_{\text{cool}} \approx 6 \times 10^{19} \left( \frac{L_j}{2 \times 10^{39}} \right)^{(3 - 2\alpha)/(9 - 4\alpha)} \left( \frac{n_0}{1.5 \text{ cm}^3} \right)^{-(6 - 2\alpha)/(9 - 4\alpha)}, \]

and the times as

\[ t_{\text{cool}} \approx 6 \times 10^{19} \left( \frac{L_j}{2 \times 10^{39}} \right)^{(2 - 2\alpha)/(9 - 4\alpha)} \left( \frac{n_0}{1.5 \text{ cm}^3} \right)^{-(7 - 2\alpha)/(9 - 4\alpha)}. \]

If the jet power is doubled, the time-scale will increase by 22 per cent and the length-scales by 30 per cent, while if the ambient density is doubled the length-scales will decrease by 35 per cent and the time-scales by nearly 40 per cent.

Once the cooling becomes rapid at the head of the jet, when \(l_j \approx \alpha^{1/2}l_{\text{cool}}\) the global evolution of the jet will enter a second self-similar regime with its evolution varying according to equation (12), only with a rather smaller constant of proportionality.

### 3.3 The hydrodynamic code

We used the adaptive grid hydrodynamic code described by Biro et al. (1995) in axisymmetric mode. It solves the equations of mass, momentum and energy conservation using a flux-vector splitting scheme. The computation was carried out in a five-level, binary adaptive grid. In our simulations we assume full ionization of the jet and the ambient medium as a result of photoionization from the central UV source. We have the non-equilibrium cooling function described by Biro et al. (1995) with an additional term taking into account bremsstrahlung losses, \(L_{\text{me}}\), given by

\[ L_b = 2.29 \times 10^{-27} n_e n_p T_e^{3/2} \text{ erg s}^{-1} \text{ cm}^{-3}, \]

where \(n_e\) and \(n_p\) are the electron and proton densities in particles per cm\(^3\), respectively, and \(T_e\) is the electron temperature in Kelvin (Cox & Tucker 1969). We do not allow the gas temperature to drop below 10\(^{4}\) K, where we assume it is maintained by the thermostatic effect of \([\text{O III}]\) 5007-Å emission.

The computational domain was set to be 513 \times 1025 computational cells and 5 \times 1.25 times 10\(^{39}\) cm. The grid cells are smaller in the radial direction than in the axial direction for better resolution of the small distance-scales of the radially expanding envelope. The initial jet radius was covered by 27 cells in the axisymmetric simulation. The cooling distance \(\delta\) was marginally resolved for \(v_j = 150\) km s\(^{-1}\). The thickness \(\delta_{\text{w}}\) of the cold envelope of swept-up gas was near the resolution limit and was smeared out artificially over 2–3 cells at shock speeds higher than 150 km s\(^{-1}\). This artificially limits the compression with effects similar to those that would be expected if magnetic fields were present in the ISM (with a magnetic parameter of the order of 5, although magnetic fields were not taken into account explicitly). However, increasing the resolution further would lead to prohibitively large computing times for these initial studies. Quantitative results will therefore be only order-of-magnitude estimates, but the qualitative results, as discussed in this paper, will not therefore be significantly altered. The boundary conditions are reflective on the axis and on the left side of the computational domain (except for the inflow condition where the jet is injected, see Fig. 1 below). The top and right boundary have outflow conditions.

### 3.4 Emission maps

#### 3.4.1 Optical emission

We calculate the H\(\alpha\) emissivity \(\epsilon\) using radiative recombination (Case B) following Aller (1984). In the temperature regime of our simulations \((T > 10^4\) K), only recombination contributes considerably to the emissivity. We assume full ionization of the hydrogen, which would mainly be the result of photoionization from the UV source at the centre of the galaxy and, to some extent, from shock ionization in the bowshock region.

\[ \epsilon = 4.16 \times 10^{-25} \text{ erg cm}^{-3} (T_e^{9.83} 10^{0.042/T_e})^{-1}, \]

where \(T_e\) is the temperature in units of 10\(^{4}\) K.

#### 3.4.2 Radio emission

Only relativistic electrons (and perhaps positrons) contribute significantly to the radio emission of jets. Since it is still unclear how these high energy electrons are generated (most probably through re-acceleration in shocks), we...
assume that this population of fast electrons shares the same hydrodynamics as the non-relativistic fluid of electrons and protons. A more detailed description would require the consideration of two jet populations to account for the non-relativistic gas (electrons and protons) with a ratio of specific heats of 5/3, and the ultrarelativistic electrons with a ratio of 4/3. Duncan, Hughes & Opperman (1996) have performed preliminary simulations of highly relativistic jets using a variable adiabatic index and found that the rest frame variables vary more smoothly along the jet axis, with smaller amplitude maxima at the bowshock and in the vicinity of the contact surface. We ignore these effects in the present simulations.

In order to calculate the synchrotron emission from the jet whose hydrodynamics is modelled as above, we need to establish how the internal energy is distributed among the relativistic electrons. Observations suggest that this distribution follows the usual power law \( N(E)dE = N_0E^{-\gamma}dE \), with spectral index \( \gamma \), and energies above a minimum value \( E_{\text{min}} \). Assuming that the relativistic electron energy density \( U_e \), and number density \( N_e \) are proportional to their corresponding thermal quantities calculated by the hydrodynamical code as a function of position in the jet, the previous power law is determined by the equations (Gómez et al. 1995)

\[
N_e = \left[ \frac{U}{(p - 2)} \right]^{-\gamma/2} \left[ N_e (p - 1) \right]^{\gamma - 2}
\]

and

\[
E_{\text{min}} = \frac{U}{(p - 2)} \frac{p - 2}{N_e p - 1}.
\]

The synchrotron emission is also determined by the magnetic field, and since we are neglecting its influence on the fluid dynamics, we assume that the magnetic energy density remains a fixed fraction of the particle energy density, which leads to a field of magnitude proportional to \( U_e^{1/2} \). We refer the reader to Gómez, Alberdi &Marcaide (1993) and Gómez et al. (1995) for a detailed discussion of the radio emission calculations.

### 4 RESULTS AND DISCUSSION

#### 4.1 Structure

We show the results of our simulation at a time when the jet has reached a distance of approximately 150 pc from the injection point. This is 127 000 yr after the jet switched on.

Fig. 1 (opposite p. 1036) shows the density (top) and the pressure (bottom) distribution on a logarithmic scale. We can identify several characteristic features which are marked in the schematic view shown in Fig. 2. The jet itself shows several recollimation shocks on the axis, best seen in the pressure image. At the tip of the jet, the termination shock generates high-pressure and high-temperature jet plasma. This plasma flows back into the hot jet cocoon, which surrounds the high-speed jet. The jet cocoon is surrounded by a thick layer of hot gas from the interstellar medium which has passed through the bowshock. Near the head of the jet we find a thin layer of hot shocked gas from the ISM which, further back, turns into an even thinner, but cold and very dense, envelope of the jet cocoon. This enve-

![Figure 2](https://example.com/figure2.png)

**Figure 2.** A schematic summary of the features seen in our hydrodynamic simulations. It includes the jet with recollimation shocks, the jet shock, the cocoon of jet plasma, the hot bowshock and the cold-layer of shocked ISM.
Figure 1. Density (top panel) and pressure (bottom panel) distribution on a logarithmic scale after 127 kyr. Note the high-density cocoon envelope after the swept-up ISM material has cooled to the equilibrium temperature of $10^4$ K. The recollimation shocks and the very high pressure near the jet shock can clearly be seen in the pressure image.

Figure 3. The bowshock structure (using the Hz emissivity) is shown at three different times with the same separation between them. While the head of the jet has advanced considerably between the first and second panels, the point where the cold envelope starts has not advanced appreciably. After a further time-step, a full arc has collapsed and cooled and has become very bright.
lope is what distinguishes the NLR jet from adiabatic high-power extragalactic jets. The fact that this envelope starts at a significant distance from the front of the bowshock distinguishes NLR jets from the regime of strongly cooling galactic jets (e.g. Blondin, Fryxell & Königl 1990).

We find that the radius of the cold envelope in the simulation is approximately 7.8 × 10^6 cm and the expansion speed of the cocoon is somewhat above 100 km s^-1. The peak density in the envelope varies from values between 30 to 40 cm^-3 over most of its extent, up to 100 cm^-3 in the dense clouds. These values correspond to compression factors of 30 and 70, respectively. This is factors of 2 too low when compared to equation (4), which is probably the result of numerical smearing. This effect mimics a magnetic parameter of the order of 5 (see equation 11), which corresponds to an ambient magnetic field near 5 μG. The integrated Hz luminosity at this time-step is 5.8 × 10^37 erg s^-1 and the envelope has a thickness of d_e ~ 1 – 2× 10^14 cm and volume of V_e ~ 2 × 10^59 cm^3. These values are in good agreement with our analytical estimates and the results from optical observations of Seyfert galaxies with associated NLR radio jets.

We find that the non-stationary dynamics of jet propagation through interstellar medium have a strong influence on the structure of the cold shell. The quasi-periodic recollimations of the jet cause the advance speed of the jet head to oscillate, thereby accumulating jet material in a restricted region for some period of time. It is then released into the cocoon almost explosively, when the jet expands and slows down again. This imposes a characteristic arc structure on to the bowshock and the cold shell of swept-up gas. These arcs cool almost as a unity once catastrophic cooling sets in. This can be seen in Fig. 3 (opposite p. 1036), where the density is shown at three different times with the same separation between them. While the head of the jet has advanced considerably between the first and second panels, the point where the cold dense envelope starts has not advanced appreciably. However, later, after the same time-step, the full arc has cooled. Therefore, a cooling distance for the bowshock measured from the head of the jet, as discussed by Taylor et al. (1989, 1992), can at best be only an average property.

At the positions at which neighbouring arcs meet, the two shock waves cross at an angle near 90°. This interaction will produce a Mach shock at the vertex with an effective speed of √2 times the speeds of the incident shocks (assuming that they are the same). Correspondingly, the compression and the emissivity of the gas increase by factors of ~2 and ~4, respectively. As a result of the radiative nature of the crossing shocks, they merge to form short high-density filaments and clouds, marked as 'high-density spots' and 'intruding dense filaments' in Fig. 2. In the simulation these spots have peak densities between 80 and 100 cm^-3, consistent with the previously estimated additional compression by factors of around 2. We suggest that these spots could be identified with the brightest discrete clouds in the NLR of some Seyfert galaxies. Note that the spacing between these spots is directly related to the time-dependent quasi-periodic recollimation of the jet and therefore contains information about the history of the interaction between the jet and its environment. Several Seyfert galaxies show a knotty NLR structure, and the distances between the strongest emission-line clouds are indeed similar to, but rather smaller than, the distances between the radio knots (e.g. Mrk 3, Capetti et al. 1995a; Mrk 6, Capetti et al. 1995b; NGC 4151, Boksenberg et al. 1995).

At some distances from the jet head, the arc structure in the envelope is lost and it becomes roughly cylindrical, justifying the approximations of Section 2 (Fig. 1). However, the high-density clouds and filaments created at the intersection points of these arcs are retained. When the envelope fragments (as can be expected in a full three-dimensional simulation), these regions will be seen as discrete NLR clouds and filaments. Since the creation of these arcs and clouds is related to the recollimations of the jet, we have found a direct relation between the optical structure of the NLR and the internal non-stationary shock structure of the jet.

The expansion of the over-pressured jet cocoon into the undisturbed interstellar medium is similar to a supernova explosion. Some theoretical aspects can therefore be treated in an analogous fashion. This applies in particular to the stability of the shock and the post-shock layer of swept-up gas. The stability of a radiative shock wave has been considered by a number of authors with varying emphases (e.g. Vishniac 1983; Bertschinger 1986). The radiative shock instabilities discussed by Bertschinger (1986) are present in our simulations and produce the pressure variations near the cold envelope. These are likely to be disruptive and thus contribute to the formation of NLR clouds and filaments. From the results presented by Jun, Norman & Stone (1985) one might expect to find that the shock region in our simulation is also Rayleigh–Taylor (R–T) unstable, with the fastest growth of features on the scale of the thickness of the cold layer of swept-up gas. The onset of these instabilities can be observed as pressure variations and small ripples in some sections of the cold envelope (Fig. 1). As these instabilities grow, they might contribute to the fragmentation process of the envelope and form further NLR clouds, in addition to the high-density clouds produced at the intersection of the arcs (discussed in the previous section). However, magnetic fields have a stabilizing effect and therefore different combinations of ambient magnetic parameters and jet powers might lead to two categories with fewer small clouds, and R–T unstable ones with a higher number of small NLR clouds with separations of a few times the thickness of the cold layer (i.e. ~1 pc). More detailed investigations of this process will have to be carried out to quantify this prediction over a range of parameters in order to compare it with recent and future high-resolution observations of the NLR in Seyfert galaxies.

The Strömgren column given by equation (9) is similar to the thickness of the cocoon envelope and the size of the clouds. It may well be that the highest density clouds can develop neutral cloud cores. As a result, NLR clouds could be sites of jet-induced star formation (Van Breugel & Dey 1993; Tresch-Fienberg et al. 1987).

4.2 Emission

In Fig. 4 the Hz emissivity distribution is displayed on a logarithmic scale, along with the radio emission superimposed as contours in the lower panel. As expected, most of
the optical line emission comes from the thin envelope of cold post-shock material. The Hα luminosity obtained from this axisymmetric simulations is $5.8 \times 10^{37}$ erg s$^{-1}$. This is well within our expectations, considering the simplicity of our analytical estimates. The length of the NLR jet in Mrk 1066 is similar to that in our simulation, although the transverse extent could be 2–3 times smaller. From observations by Bower et al. (1995) we determined the Hα flux coming from the area covered by the north-eastern jet in Mrk 1066 to be $3.3 \times 10^{37}$ erg s$^{-1}$, which is in excellent agreement with our simulation, taking into account the simplifications of the model and the smaller radius of the cocoon in Mrk 1066.

From our model one might expect that higher power radio jets would yield faster cocoon shocks, producing broader emission lines. This would result in a correlation between line width and radio power, which is consistent with the observed correlation between these quantities (Wilson & Willis 1980; Whittle 1985). Our initial study, however, does not allow a more quantitative conclusion about the correlation. An extensive survey of the parameter space and other factors which influence the line width, like galaxy rotation, is needed for a detailed theoretical study of this correlation in terms of our model.

The calculated line spectrum is shown in Fig. 5 for three different viewing angles. In the spectrum, emission from the background has not been included in order to focus on the expanding envelope. Inclusion of the background would produce a narrow peak at zero velocity. Within the volume of this simulation the background emission amounts to $4.8 \times 10^{36}$ erg s$^{-1}$, an order of magnitude less than is contained in the envelope. The strength of this central peak, compared to the broader contribution from the envelope, is a measure of the ratio of disturbed and undisturbed gas. Because of the cylindrical shape of the expanding envelope and the small velocity of the gas along the shell, the line shape of the envelope is double peaked for viewing angles far from the axis but becomes almost rectangular if the line of sight is near the jet axis. The line width of the expanding cylindrical shell is, of course, not only a function of the expansion speed (which is approximately the same as the shock speed), but depends also on the angle between the symmetry axis and the line of sight. This is in apparent disagreement with results from Whittle (1985), which suggest that there is no strong correlation between the orientation of the galaxy and the NLR line width, assuming that the jet follows the rotation axis of the galaxy. However, observations of radiation cones (e.g. Wilson & Tsvetanov 1994), which at least can be expected to have a closer link to the radio jets, and point-symmetric bending of jets in Seyferts (presumably as a result of the interaction with the rotating environment: Wilson & Ulvestad 1982; Steffen, Holloway & Pedlar 1996) suggest that the jets often are not aligned with the rotational axis of the galaxies. This would strongly weaken any correlation between line width and galaxy orientation.
The contours in Fig. 4 show the radio emission at 10 GHz as calculated from our model described in Section 3.4.2. A spectral index in the power-law energy distribution of the electrons of 2.4, and magnetic field strength at the jet inlet of 100 µG, have been used. A total flux for the jet of 4 mJy is obtained. As expected, most of the radio emission comes from the hotspot region near the head of the jet, with some low brightness emission from the recollimation shocks.

There are a number of Seyfert jets in which the head of the jet is dominant at radio wavelength. However, in most cases there are a number of strong radio knots along the jet, especially in the case of NGC 1066, which has rather continuous emission along the jet (at the resolution of the VLA) and no hotspot near the head. This highlights the problem of the nature of the knots seen along radio jets in general. Internal shocks can produce this kind of knot. In our simulations we find two different types of internal shocks: the recollimation shocks and the shocks produced by the interaction with the turbulent cocoon near the head of the jet. From our simulations and our model for the synchrotron emission, we find that these are not strong enough to explain the radio emission knots seen in most of the Seyfert jets. One possible solution is time variations in the ejection parameters at the base of the jet. Gómez et al. (1996), Hughes, Duncan & Mioduszewski (1996) and Komissarov & Falle (1996) have shown that variations of the ejection velocity can produce strong internal working surfaces which are visible as strong radio knots in the jet. Such variations in the jet properties may possibly have some influence on the structure of the cold cocoon envelope and thus on the NLR.

In a forthcoming paper we will investigate the effects of variable jet properties on the NLR in more detail (Steffen et al., in preparation).

5 CONCLUSIONS

Using hydrodynamic simulations with radiative cooling we confirm the basic structure of the interaction between a jet and the NLR in Seyfert galaxies as obtained in a geometric model by Taylor et al. (1989). However, we find new features of the interaction, like the formation of NLR clouds and a larger extent of the cold cocoon envelope. As a result of the time-dependent propagation speed of the jet into the ISM, the cooling distance of the bowshock material as measured from the head of the jet varies episodically with time. Our simulations show that there might be a link between the time-dependent internal recollimation structure of the radio jets and the narrow-line clouds. We expect that the distances between particularly bright knots along the symmetry axis are similar to the separation between the radio knots behind the main hotspot (assuming that the latter are the result of internal recollimation shocks). Estimates of the Strömgren column show that the dense clouds produced in this simulation could be partially neutral. They might represent cores for jet-induced star formation in the NLR of Seyfert galaxies.

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