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UNDERSTANDING NLR IN SEYFERT GALAXIES: NUMERICAL SIMULATION OF JET-CLOUD INTERACTION

A. Ferrari, S. Massaglia

Istituto di Fisica Generale, Università di Torino, Italy

and

P. Rossi, A. Capetti and G. Bodo

Osservatorio Astronomico di Torino, Italy

RESUMEN

Observaciones recientes con el *HST* sugieren que la NLR de las galaxias Seyfert puede ser el resultado de la interacción entre un chorro de plasma y un medio inhomogéneo. Con esta idea hacemos simulaciones numéricas de la colisión de un chorro radiativo con una nube densa. Se utiliza un código hidrodinámico con un tratamiento simple de los procesos radiativos, que permite estudiar los detalles de la hidrodinámica con una interpretación cualitativamente buena de los procesos de emisión. Nuestros tres objetivos principales son *(i)* reproducir en las simulaciones las condiciones observadas, *(ii)* deducir restricciones de los parámetros del chorro y *(iii)* estudiar la capacidad del chorro para fotoionizar al medio circundante.

ABSTRACT

Recent *HST* observations suggest that the NLR in Seyfert Galaxies can be the result of interaction between jet and external inhomogeneous medium; following this suggestion we perform numerical simulations considering the impact of a radiative jet on a dense cloud. We approach the problem by adopting a hydrodynamical code, that consents us to study in detail the jet hydrodynamics, while we choose a more simplified treatment of radiative processes, in order to give a qualitatively good interpretation of the emission processes. Our three main purposes are: *(i)* to reproduce in our simulations the observed physical conditions, *(ii)* to obtain physical constraints of the jet parameters and *(iii)* to study the jet capability to photoionize the surrounding medium.

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

1. INTRODUCTION

Extensive *HST* emission-line imaging of Seyfert galaxies has, for the first time, resolved details of the structure of their Narrow Line Region (NLR). These observational data provide us quite detailed information on the physical conditions of NLR clouds: typically, densities are larger than 10^3 cm^{-3}, temperatures are of the order $10^4 - 2\times10^4$ K, and velocities are in the range of $300-1000$ km s^{-1} (Caganoff et al. 1991; Kraemer, Ruiz, & Crenshaw 1998; Axon et al. 1998; Ferruit et al. 1999; Capetti et al. 1999). These are the observational constraints that we try to match in our simulations. Previous works regarding jet interactions with a uniform medium (Steffen et al. 1997; Rossi & Capetti 1998) have shown that matching the density values reported above is not possible in that situation, then we consider the case of a jet impinging on pre-existing inhomogeneities. We can identify these inhomogeneities with giant molecular clouds (GMCs), that are common in spiral galaxies. A supersonic jet, of radius ~ 10 pc, that bores its way through the interstellar medium has a good chance of impinging with a GMC, and this is the case we consider in our simulations. In any event, the head-on collision with a large cloud can be considered the most efficient case of interaction, for the compression, acceleration and heating of NLR material.

2. RESULTS

We study the evolution of a cylindrical radiative jet interacting with a cold and steady cloud, in pressure equilibrium with the external medium. The fluid-dynamics equations with optically thin radiative losses (Raymond & Smith 1977) are integrated with a PPM type code on a domain represented in Figure 1 (for details see Rossi et al. 2000).

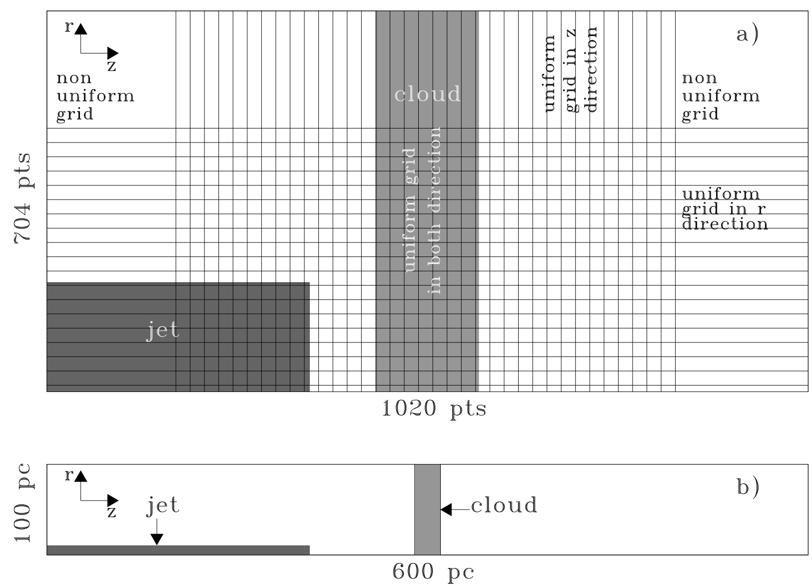

Fig. 1. *(a)* The computational domain. The grid is finer in the region of interaction, while it is coarser far from that region. *(b)* The physical domain.

The problem is complex with three different interacting and radiating media, and the number of control parameters is in principle very high. However, we can argue that some of them are not critically important and others can be constrained by observations. The external density is taken to be $\rho_{ext} = 1$ cm^{-3} (Cox & Reynolds 1987); the external temperature is not crucial, since emission depends on the shock temperature, which is fixed by the jet velocity. Observations indicate that the external medium is completely ionized, which means temperatures above 10^4 K, and we assume $T_{ext} = 10^4$ K. The jet radius is considered to be 10 pc following radio observational suggestions (Pedlar et al. 1993; Kukula et al. 1999), the jet density is taken to be equal to the external one, and from our results we will argue that it cannot be much smaller. The jet temperature is taken to be 10^6 K; however, its value is not crucial since cooling is fast and the jet temperature soon falls to 10^4 K. The parameters on which we focus our investigation are the jet velocity and the cloud density. The cloud temperature is fixed by the condition of pressure equilibrium with the external medium and the cloud thickness is taken to be 20 pc.

We begin with a short general description of the complete evolution, that can be summarized in three steps (see Fig. 2 for a visualization of the main features of the three steps for the case $\rho_{cl} = 30$ cm^{-3} and $v_{jet} = 6500$ km s^{-1}; the three columns in the figure refer to times $t = 1\ t_{\rm cc}$, $t = 2\ t_{\rm cc}$ and $t = 5\ t_{\rm cc}$, where $t_{\rm cc}$ is the cloud crossing time, defined below):

• The jet hits the cloud forming a strong shock, the hot material begins to cool down in a thin layer surrounding the jet. During this first phase, the layer is accelerated outward by the strong inside pressure and its density increases as a result of cooling (see the leftmost panels in Fig. 2).

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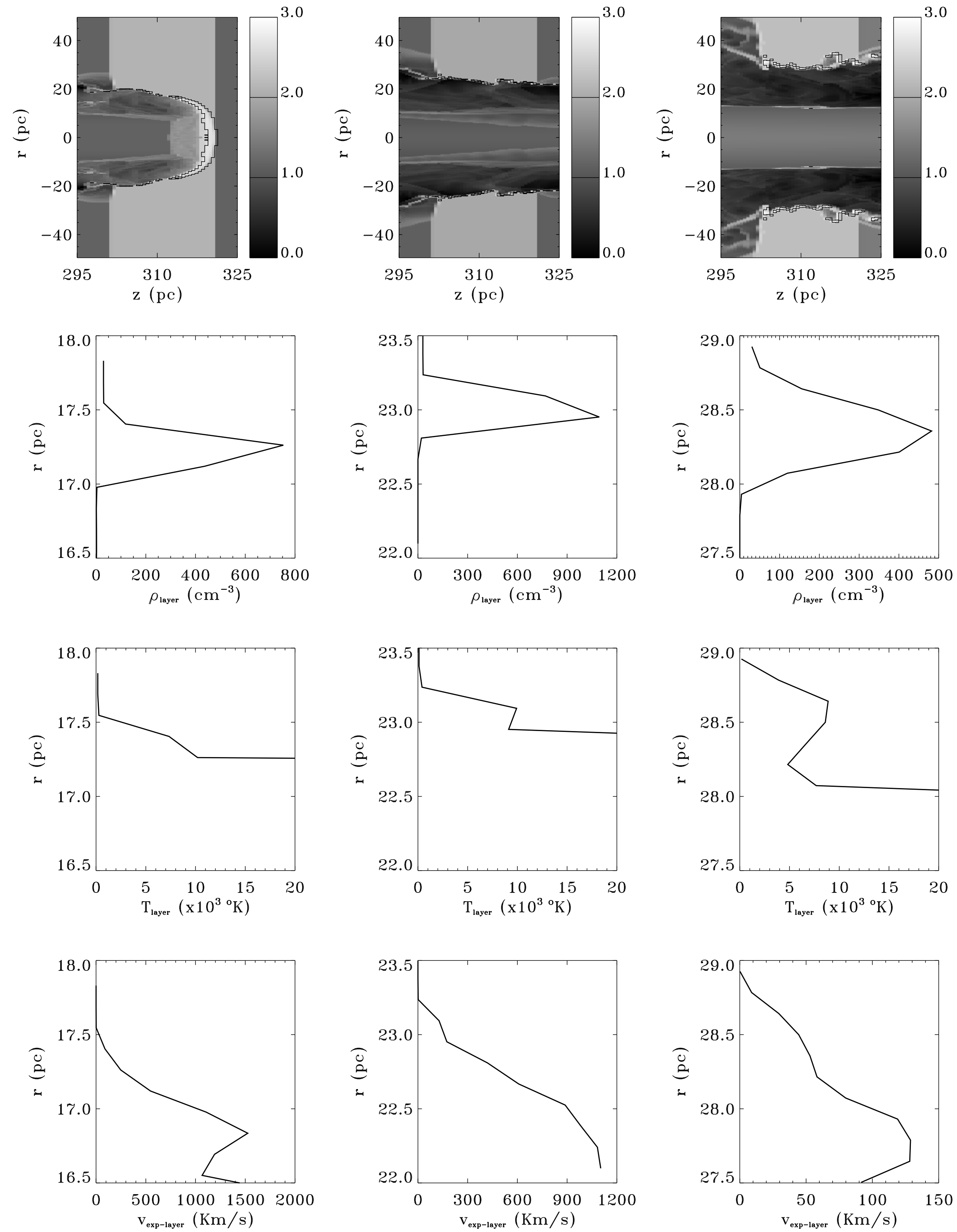

Fig. 2. Images of the density distribution showing the jet-cloud interaction and cuts of density, temperature and expansion velocity, in the middle of the cloud, across the thin layer of compressed material for the case $\rho_{\rm cl} = 30$ cm^{-3}, $v_{\rm jet} = 6500$ km s^{-1}, at different times.

TABLE 1

PARAMETERS OF THE SIMULATIONS

	$v_{jet} = 1300$ km s^{-1}	$v_{jet} = 6500$ km s^{-1}	$v_{jet} = 32500$ km s^{-1}
$\rho_{cl} = 30$ cm^{-3}	430 cm^{-3}, 23 km s^{-1}	1130 cm^{-3}, 335 km s^{-1}	31 cm^{-3}, 6 km s^{-1}
	8900 K, $\tau = 1.75$	9600 K, $\tau = 0.34$	23,500 K, $\tau = 0.06$
$\rho_{cl} = 60$ cm^{-3}		1170 cm^{-3}, 100 km s^{-1}	390 cm^{-3}, 380 km s^{-1}
	$\tau = 4.65$	8300 K, $\tau = 0.93$	21,500 K, $\tau = 0.17$
$\rho_{cl} = 120$ cm^{-3}		1360 cm^{-3}, 170 km s^{-1}	1690 cm^{-3}, 722 km s^{-1}
	$\tau = 13.2$	10,500 K, $\tau = 2.64$	11,300 K, $\tau = 0.5$

• The jet is completely out of the cloud: the compressed emitting material reaches a quasi-steady state. From Figure 2, we see that the material in the emitting layer has increased its maximum density and velocity, while its temperature decreases.

• In this decay phase the velocity and density of the emission layer decrease (see right panels in Fig. 2).

The efficient formation of the line emitting region will therefore depend on the efficiency of radiation during the jet crossing of the cloud. This efficiency depends on the ratio τ between the cooling time of the material in the layer and the crossing time. The cooling time is expressed as $t_{cool} = p/[(\gamma - 1)\mathcal{L}]$, where p is pressure, γ is the ratio of specific heats and $\mathcal{L}$ represents the energy lost per unit time and per unit volume. We estimated it by assuming for the density the cloud density and a temperature $\sim 10^7$ K, which is a typical value for the post shock material. The cloud crossing time can instead be estimated as $t_{cc} = d(1 + \sqrt{\rho_{cl}/\rho_{jet}})/v_{jet}$, where d is the cloud thickness.

We performed an exploration of the parameter space (v_{jet}, ρ_{cl}) and report in Table 1 the values of τ, densities, expansion velocities, and temperatures of the emitting material at time $t = 2\ t_{cc}$ for the cases that we have examined. We can then compare these values with the observed ones to see which cases can reproduce the observations. We see that the observed conditions can be matched only for a narrow range of parameters, and the properties of the emitting layer essentially depend only on τ. For low values of τ radiation is inefficient, and for high values the velocity of the emitting layer is too low, since the jet has not enough momentum to drive the dense cloud. Observational data can then be matched only for a narrow range of τ, $0.3 < \tau < 0.55$.

3. THE SOURCE OF IONIZATION

As mentioned above, the source of ionization for the NLR is still a matter of debate. The NLR gas is certainly illuminated by the nuclear source; however, its interaction with the jet produces high temperature regions which also radiate ionizing photons. From the results of our simulations we can estimate the ionizing radiative power produced in the interaction, and therefore derive an efficiency of conversion of the jet kinetic power into energy radiated in ionizing photons. To do that we integrate the total emission over all regions with $T > 10^5$ K, as above this temperature most of the radiative losses correspond to the production of photons with energy higher than the hydrogen ionization threshold. Our results are summarized in Table 2, where the conversion efficiency refers to the value at peak and after 2 t_{cc}. We see that even in the most favourable scenario radiation produced in the interaction can only represent a small fraction of the overall ionization budget of the NLR, but it can have important local and transient effects.

4. CONCLUSIONS

For the explored range of cloud densities, which can be considered typical of GMCs, we can match the observational constraints for jet velocities in the range from 4000 km s^{-1} to 55,000 km s^{-1}. The corresponding

TABLE 2

RADIATIVE EFFICIENCY

	$v_{jet} = 1,300$ km/s	$v_{jet} = 6,500$ km/s	$v_{jet} = 32,500$ km/s
P_{kin}	1.1×10^{40} erg s^{-1}	1.38×10^{42} erg s^{-1}	1.73×10^{44} erg s^{-1}
$\rho_{cl} =$ 30 cm^{-3}	$P_{rad}^{\max} = 0.03 \times 10^{40}$ erg s^{-1} $\eta_{max} = 2.7\%$, $\eta_{2\,t_{cc}} = 0.08\%$	$P_{rad}^{\max} = 0.02 \times 10^{42}$ erg s^{-1} $\eta_{max} = 1.6\%$, $\eta_{2\,t_{cc}} = 0.4\%$	$P_{rad}^{\max} = 0.07 \times 10^{42}$ erg s^{-1} $\eta_{max} = 0.04\%$, $\eta_{2\,t_{cc}} = 0.05\%$
$\rho_{cl} =$ 60 cm^{-3}		$P_{rad}^{\max} = 0.14 \times 10^{42}$ erg s^{-1} $\eta_{max} = 10\%$, $\eta_{2\,t_{cc}} = 0.5\%$	$P_{rad}^{\max} = 0.15 \times 10^{42}$ erg s^{-1} $\eta_{max} = 0.09\%$, $\eta_{2\,t_{cc}} = 0.04\%$
$\rho_{cl} =$ 120 cm^{-3}		$P_{rad}^{\max} = 0.02 \times 10^{42}$ erg s^{-1} $\eta_{max} = 1.4\%$, $\eta_{2\,t_{cc}} = 0.5\%$	$P_{rad}^{\max} = 0.35 \times 10^{42}$ erg s^{-1} $\eta_{max} = 0.2\%$, $\eta_{2\,t_{cc}} = 0.01\%$

jet kinetic power (for a jet density of 1 cm^{-3}) ranges from 3.2×10^{41} to 8×10^{44} erg s^{-1}, in general agreement with the estimates of Capetti et al. 1999 for Mrk 3. The jet density cannot be much lower than the assumed value, since for lower densities we would need higher velocities for matching the observations, and therefore the requirements for the kinetic power become unrealistic. We can conclude that jets in Seyfert galaxies cannot be much lighter than the external medium and are not likely to be relativistic, very different from their counterparts in radio galaxies. Another conclusion is that the radiation emitted in shocks is not sufficient for the global ionization requirement, but can be important locally.

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A. Ferrari and S. Massaglia: Istituto di Fisica Generale, Università degli Studi di Torino, Via P. Giuria,1 – 10025 Torino, Italy (ferrari, massaglia@ph.unito.it).

P. Rossi, A. Capetti and G. Bodo: Osservatorio Astronomico di Torino, Strada dell'Osservatorio, 20 – 10125 Pino T.se (To), Italy (rossi, capetti, bodo@to.astro.it).

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