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Hydrodynamic simulations of the kiloparsec-scale jet of 3C 338

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Abstract. Located in the central region of the cluster Abell 2199, the cD galaxy NGC 6166 harbors a radio source known as 3C 338. Despite the features frequently seen in radio galaxies, there is an unusual structure in 3C 338 labelled as ridge that has led to the proposition of different hypotheses about its physical origin in the literature. One of the proposed physical scenarios considers the orbital motion of the source 3C 338 either around the barycenter of NGC 6166 and NGC 6166B, one of the galaxies optically identified in the vicinity of 3C 338 or around the dark matter gravitational potential well of Abell 2199. In this work we adopted a simplified model with Keplerian orbits that respect observational constraints to study the feasibility of these two scenarios from the point of view of three-dimensional hydrodynamic simulations. The physical characteristics of the intra-cluster medium in which the jet propagates was constrained by observations in the vicinity of NGC 6166. From these hydrodynamic simulations, we generated maps of temperature, density, pressure and velocity in order to study the jet's behavior as it propagates through the intra-cluster medium. Our preliminar results suggest that the two orbital-motion scenarios explored in this work are able to produce the main structures seen in the interferometric radio images of 3C 338.

Resumo. Localizada na região central do aglomerado Abell 2199, a galáxia cD NGC 6166 abriga uma fonte rádio conhecida como 3C 338. Apesar das características frequentemente observada em rádio galáxias, há uma estrutura incomum em 3C 338 rotulada como Ridge que levou ao proposição de diferentes hipóteses sobre sua origem física na literatura. Um dos cenários físicos propostos considera o movimento orbital da fonte 3C 338 em torno do baricentro de NGC 6166 e NGC 6166B, uma das galáxias oticamente identificadas nas proximidades de 3C 338 ou em torno do poço de potencial gravitacional de matéria escura de Abell 2199. Neste trabalho adotamos um modelo simplificado com órbitas Keplerianas que respeitam restrições observacionais para estudar a viabilidade desses dois cenários do ponto de vista de simulações hidrodinâmicas tridimensionais. As características físicas do meio intragrupo no qual o jato se propaga foram restringidas por observações nas proximidades do NGC 6166. A partir dessas simulações hidrodinâmicas, geramos mapas de temperatura, densidade, pressão e velocidade para estudar o comportamento do jato enquanto ele se propaga através do meio intra-aglomerado. Nossos resultados preliminares sugerem que os dois cenários de movimento orbital explorados neste trabalho são capazes de produzir as principais estruturas vistas nas imagens de rádio interferométricas do 3C 338.

Keywords. Galaxies: active – Radio continuum: galaxies – Hydrodynamics

1. Introduction

NGC 6166 is a cD galaxy with an active core located in the central region of Abell 2199. The radio source 3C 338 (associated with NGC 6166) exhibits a jet and counter jet, besides an unusual structure displaced south from the nowadays location of the radio core (e.g., Burns et al. 1983).

High-resolution interferometric maps on 3C 338 at radio wavelengths reveal a compact core from which jet and counter-jet emanate, reaching symmetrically an approximate distance of 10 pc. (Gentile et al. 2007).

Although the relatively compact and symmetrical structure seen on parsec scales, interferometric maps with lower angular resolutions reveal a very complex morphology at kiloparsec scales, apparently revealing structures of diffuse jets and lobes, it is also possible that this radio galaxy may be active intermittently, in that case the outermost structures would be fossil radio plasma left over from an earlier phase of activity, while newly restarted core and jets are visible as well.

In fact, the classical theory of synchrotron radiation predicts that the observed radiation spectrum produced by relativistic electrons in magnetized regions will decrease in intensity at higher temperatures frequencies as the higher energy electrons lose energy by radiation, if synchrotron radiation is the dominant process, the synchrotron lifetime will be a good estimate of the lifetime of the structures. If there is a offset between the cD galaxy and the center of the cluster and consequently a dissipative movement, the observed structures associated with lifetime estimates can provide indications of how the movement takes place. Burns et al. (1983) estimated the approximate age of the detected structures based on the synchrotron losses: an age gradient among different structures is noted (outer radio lobes older than 30 Myr and a nowadays active jet from the nucleus of NGC 6166).

Considering the morphology and the lifetime of the structures, it is possible that NGC 6166 is moving in an orbit in the central region of Abell 2199 and the jet emission is intermittent (e.g., Burns et al. 1983).

2. Method

We adopted two possible scenarios that respect observational constraints presented in Table 1 for a ΛCDM cosmological model with $H_0 = 71 \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.730$ and $\Omega_M = 0.270$: NGC 6166 in a circular orbit around a barycenter with neighboring galaxy NGC 6166B; NGC 6166 in a dissipative orbit around the center of the Abell 2199 cluster.

We used the numerical code PLUTO (Mignone et al. 2007) to solve the hydrodynamic (HD) differential equations for a gas with mass density, thermal pressure and velocity. Mass profiles were adopted according to previous works such as Burns et al. (1983), Main et al. (2017) and Johnstone et al. (2002). We simulated a cubic region of 160 kpc × 160 kpc × 160 kpc, using a grid

Table 1. Observational links

Observacional link	Value	Reference
Redshift	0.030	Vaucouleurs et al. (1991)
Parsec-scale jet speed	$(0.22 \pm 0.04)c$	Gentile et al. (2007)
Parsec-scale jet viewing angle	$(50^\circ \pm 11^\circ)c$	Gentile et al. (2007)
Jet power	4.7×10^{43} ergs s^{-1}	Gentile et al. (2007)
Jet position angle	80°	Observation
NGC 6166 velocity in relation to te average velocity of the Abell 2199	(206 ± 39) km s^{-1}	Bender et al. (2015)
Jet intermittency timescale	3 Myr	Burns et al. (1983)

with 200 points in each Cartesian direction (spatial resolution of 0.8 kpc per cell).

3. Results

For the first scenario, a circular orbit was defined as shown in FIGURE 1, with an orbital radius of 6.5 kpc and an orbital period of 41 Myr. NGC 6166 rotates around the center of mass in a counterclockwise direction, compatible with the model proposed by Burns et al. (1983).

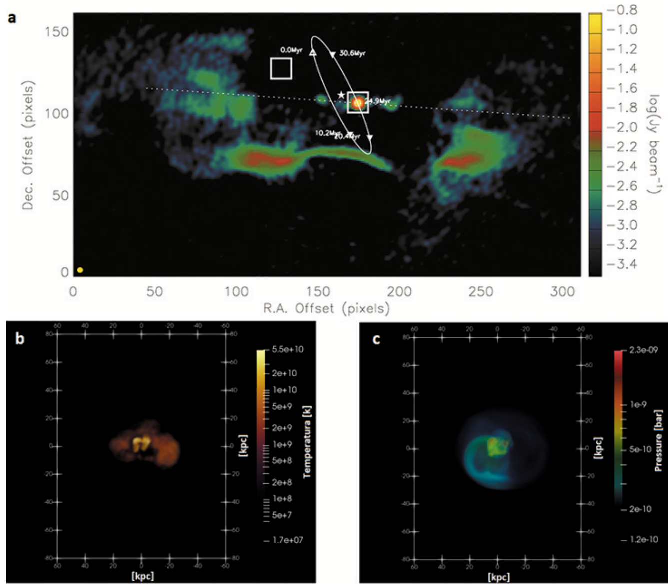

Figure 1. Initial (a) Circular orbit with a radius of 6.5 kpc superimposed on the image at 1.67 GHz (in colored gradient) obtained by Giovanni et al. (1983). The white star marks the position of the center of mass between NGC 6166 and NGC 6166B. Rendering-volume maps of (b) temperature and (c) pressure obtained from our HD simulation after 41 Myr of evolution.

For the second scenario, a counterclockwise orbit was obtained with an approximate eccentricity of 0.94 and an orbital period of 33.6 Myr. This model predicts an elapsed time of 5.0 Myr between the ridge and the current position of NGC 6166. The temperature, density, pressure, and velocity maps are shown in FIGURE 2

4. Final remarks

Temperature maps for both kinematic scenarios exhibit similarities with the main structures (lobes, ridge, jet) seen in the arcsecond radio images. Density maps show jet-induced cavities, similar to those seen at X-ray images of Abell 2199. The relatively complex morphology of 3C 338 at kiloparsec scales seems to be compatible with a dynamic scenario where there is jet intermittency of the 3C 338 , as well as an orbital motion of NGC 6166, which is supported by the results of our hydrodynamic simulations. Such movement can be described through a dissipative orbit with high eccentricity around the center of the cluster. Additional scenarios with different orbital parameters and/or jet power will be studied from HD numerical simulations. A more detailed exploration of the parameter space is necessary to better constrain the evolution of 3C 338 in the last few tens of Myr.

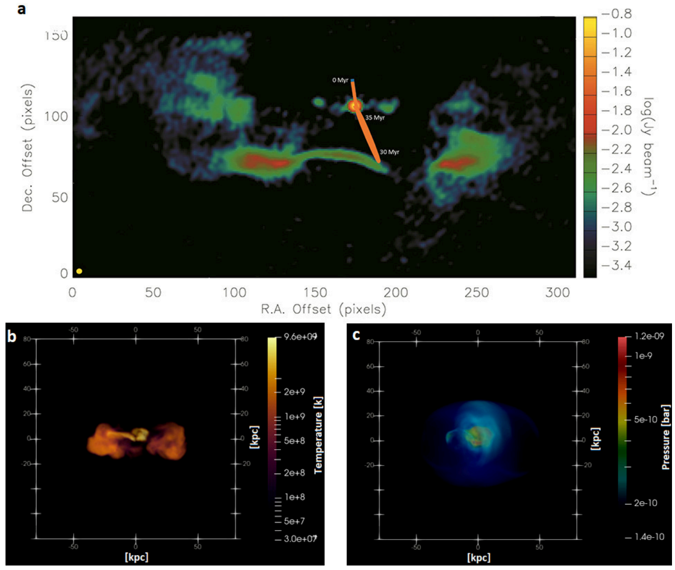

Figure 2. (a) Orbit around the center of Abell 2199 superimposed on the 1.67 GHz image (in colored gradient) obtained by Giovanni et al. (1983). Rendering-volume maps of (b) temperature and (c) pressure obtained from our HD simulation after 33.6 Myr of evolution.

References

Bender, Ralf, John Kormendy, Mark E. Cornell e David B. Fisher: Structure and Formation of cD Galaxies: NGC 6166 in Abell 2199. ApJ, 807(1):56, 2015.
Burns, J. O., E. Schwendeman e R. A. White: CD galaxy dynamics and an aged ridge (jet) in 3C 338. ApJ, 271:575–585, 1983.
Gentile, G., Rodríguez, C., Taylor, G. B., et al: Monitoring the Bidirectional Relativistic Jets of the Radio Galaxy 3C 338. ApJ, 659, 225. 2007.
Giovannini, G., Cotton, W. D., Feretti, L., Lara, L., & Venturi: VLBI Observations of a Complete Sample of Radio Galaxies. VIII - Proper Motion in 3C338. ApJ, 493, 632, 1998.
Johnstone, Roderick, S. Allen, A. Fabian e J. Sanders: Chandra observations of Abell 2199. MNRAS, 336, 2002