Galaxy Evolution and Feedback across Different Environments
Proceedings IAU Symposium No. 359, 2020
T. Storchi-Bergmann, W. Forman, R. Overzier & R. Riffel, eds.
doi:10.1017/S1743921320002343

Excitation mechanism in the intracluster filaments surrounding the Brightest Cluster Galaxies

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Abstract. Multi-phase filamentary structures surrounding giant elliptical galaxies at the center of cool-core clusters, the Brightest Cluster Galaxies (BCGs), have been detected from optical to submillimeter wavelengths. The source of the ionisation in the filaments is still debated. Studying the excitation of these structures is key to our understanding of Active Galactic Nuclei (AGN) feedback in general, and more precisely of the impact of environmental and local effects on star formation. One possible contributor to the excitation of the filaments is the thermal radiation from the cooling of the hot plasma surrounding the BCGs, the so-called cooling flow.

Keywords. (galaxies:) cooling flows, intergalactic medium

1. Introduction

In the centers of cool-core clusters lie giant elliptical galaxies, the Brightest Cluster Galaxies (BCGs). X-ray observations revealed huge Intra-Cluster Medium cavities, which are produced by the jet of the central black hole (e.g. Boehringer *et al.* 1993). Optical observations show that the BCGs are often surrounded by a system of filaments (e.g. Heckman *et al.* 1989; Olivares *et al.* 2019), whose shapes suggest a relation between these structures and the cavities (e.g. Fabian *et al.* 2008). The filaments have been observed in a wide range of wavelengths, illustrating their multi-phase nature. Many of these filaments do not have strong on-going star formation and the photoionization by stellar emission as well as Active Galactic Nucleus (AGN) cannot reproduce their emission (e.g. Conselice *et al.* 2001). Ferland *et al.* (2009) proposed, as the main heating mechanism, collisions of the cold gas in the filaments with ionizing particles. This mechanism can reproduce the observations (optical-to-infrared), but the effect of the penetration of the radiation inside the clouds has not been explored. Combining state-of-the-art models with recent multi-wavelength observations, we investigate the contribution of the thermal radiation from the cooling of the hot plasma surrounding the BCGs, to the excitation of the filaments, and explore the outcomes due to photoionisation at different depths in the cloud.

2. Modeling

Using the spectral synthesis code Cloudy (Ferland *et al.* 2017), we model a slab of gas of extinction $A_V \leqslant 30$ mag at constant pressure, to reproduce self-consistently all of the gas phases. The ionizing source is the soft X-ray and EUV radiation emitted by the cooling gas (Polles *et al.* 2020a in prep.). Our grid of models samples different metallicities (from $0.3\,Z_\odot$ to $1\,Z_\odot$), turbulent heating rates (v_{tur} from 0 km s^{-1} to

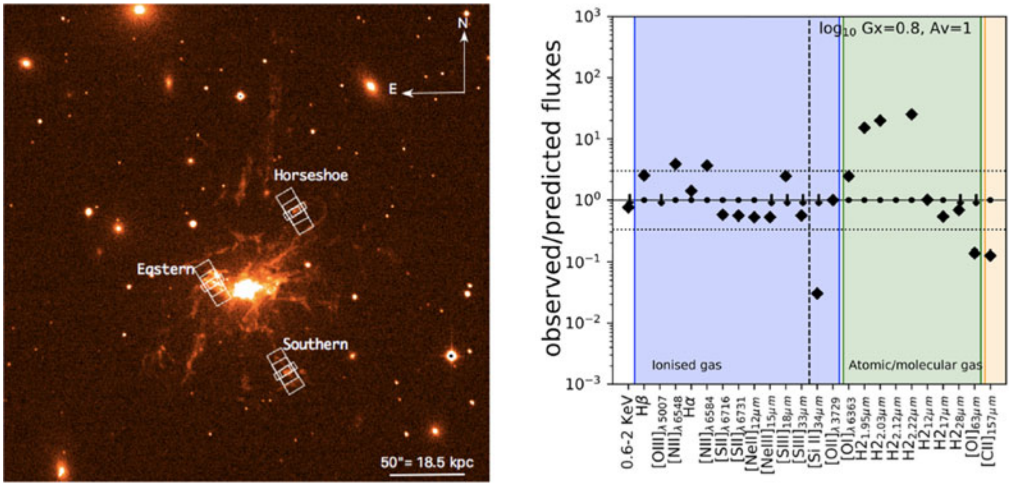

Figure 1. Left: Hα map of NGC 1275 (SITELLE/SN3). The *Spitzer*/IRS high-resolution slits are overlaid. Right: modeling results of the Horseshoe region. Comparison of the observed fluxes and the predicted fluxes from the best model: $G_X = 10^{0.8}$, $A_V = 1$ mag, $Z = Z_{\odot}$ and $v_{tur} = 2$ km s^{-1}. The points are the observed values normalised to one and the arrows indicate the upper limits. The diamonds are the observed/predicted ratios. The dashed vertical line separates the lines used as constraints, on the left, from those predicted, on the right. The dashed horizontal lines highlight an agreement within a factor of 3 between fluxes from the model and observations.

100 km s^{-1}) and X-ray intensities (G_X between 10^{-2} to 10^3; $G_X = 1$ corresponds to the integrated intensity of 1.6×10^{-3} erg cm^{-2} s^{-1} in the 0.6-2 keV band).

Constraining the model with line emission that traces different gas phases, is of fundamental importance to identify the physical properties of the filaments and to investigate the different excitation mechanisms. The multi-wavelength data set available for NGC 1275, the BCG at the center of the Perseus cluster, makes its nebula the perfect object for our modeling. We focus on three regions: Horseshoe, Southern, and Eastern (Figure 1; Polles *et al.* 2020b in prep.). The *Spitzer* observations of these regions gives us access to mid-infrared line emission. We collect all the available data from optical to far-infrared, and we combine them with our grid of models. We start using only the line emission tracing the ionised gas to constrain the models. The best model results for the Horseshoe region, as an example, is shown in Figure 1. The best model reproduces well all of the ionised gas tracers, except [Si II]λ 34 μm, which is a line that can arise from ionised gas as well as from a neutral medium. The H_2 pure rotational lines are also well reproduced, while the H_2 ro-vibrational lines as well as [C II]λ 157 μm and [O I]λ 63 μm lines are not. The overestimation of [CII] and [OI] could indicate that the filling factor of the neutral phase, which is traced by these lines, is <1 (default assumption). The underestimation of the H_2 ro-vib lines suggests that an additional heating source, e.g. shocks or cosmic rays, could be necessary to reproduce all of the line emission.

3. Conclusion

Combining the multi-phase models produced by the code Cloudy with the most recent multi-wavelength observations, we have shown that the thermal radiation from the cooling plasma can reproduce most of the observables of the filaments surrounding NGC 1275. This study is part of the LYRICS project (gas Life cYcle around galaxies : oRIgin and state of Cold accretion Streams).

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