Boletim da Sociedade Astronômica Brasileira, **37**, no. 1, 155-156

X-ray surface brightness substructures in galaxy clusters

Isabelle G. Martimiano[1] & Gastão B. Lima Neto[1]

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo (IAG/USP)
e-mail: `isabelle.martimiano@usp.br, gastao@astro.iag.usp.br`

Abstract. We investigated the presence of substructures in 40 galaxy clusters ($0.03 \leq z \leq 0.40$) using X-ray data from Chandra telescope. The surface brightness was fitted with the two-dimensional β-model and quantified through the χ^2 statistic applied to elliptical rings. Two representative cases, Abell 2029 and Abell 2744, illustrate a relaxed system and a merging system, respectively. No significant correlations were found between substructure and geometric or physical parameters. The broad band proved to be the most effective for detecting substructures, while the soft and hard bands highlight distinct thermal components of the intracluster gas.

Resumo. Investigamos a presença de subestruturas em 40 aglomerados de galáxias ($0.03 \leq z \leq 0.40$) usando dados em raios-X do telescópio *Chandra*. O brilho superficial foi ajustado com o modelo bidimensional β e quantificado por meio da estatística do χ^2 em anéis elípticos. Dois casos representativos, Abell 2029 e Abell 2744, ilustram um sistema relaxado e um sistema em fusão, respectivamente. Não foram encontradas correlações significativas entre subestrutura e parâmetros geométricos ou físicos. A banda *broad* mostrou-se a mais eficiente para detectar subestruturas, enquanto as bandas *soft* e *hard* ressaltam componentes térmicas distintas do gás intra-aglomerado.

Keywords. large-scale structure of Universe – X-rays: galaxies: clusters

1. Introduction

Galaxy clusters hold a crucial role in understanding the formation and evolution of the Universe, representing the largest collapsed structures that have reached a state of dynamical equilibrium, at least marginally (Andrade-Santos, Lima Neto & Laganá 2012). The formation and growth of these clusters involve a complex interplay of phenomena, such as major mergers, the accretion of galaxy groups, and interactions of galaxies with the intracluster medium as well as with other galaxies.

In galaxy clusters, most of the baryonic matter is found in a diffuse and highly ionized phase that fills the space between galaxies, known as the intracluster gas. Owing to its high temperature, 10^7–10^8 K, and its relatively low density, typically $\sim 10^{-2}$ – 10^{-3} cm^{-3}, this gas emits strongly in the X-ray band, primarily through a process known as thermal bremsstrahlung (Sarazin 1986). Its chemical composition also affects the emission: the intracluster gas typically has a metallicity of $\sim 0.3\,Z_\odot$, reflecting enrichment from supernovae and the long-term evolution of cluster galaxies.

The degree of substructure is closely linked to the dynamical state of galaxy clusters: systems with more substructures tend to be dynamically young, indicating that they have not yet reached full hydrostatic equilibrium, whereas clusters with more regular morphologies are considered relaxed (Richstone, Loeb & Turner 1992; Suwa et al. 2003). These substructures are manifested through local variations in gas density, thermal shocks, and cold fronts, often associated with merger processes and perturbations in the gravitational potential.

In this work, we investigated the presence of substructures in nearby galaxy clusters ($0.03 \leq z \leq 0.40$), using X-ray data obtained by the Chandra telescope. Surface-brightness fits of the intracluster gas were also presented for the clusters Abell 2029 and Abell 2744, along with an investigation of the correlation between the degree of substructures and physical and geometrical parameters, as well as an analysis of data in different energy bands: broad [0,5–7 keV], soft [0,5–1,2 keV] and hard [2,0–7 keV].

2. Materials and Methods

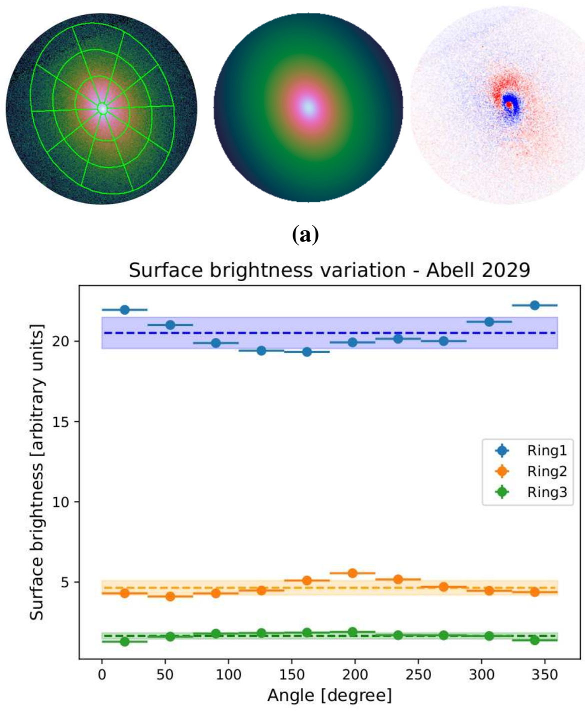
We selected 40 galaxy clusters observed by Chandra with exposure times above 30 ks, retrieving the data from the public archive and processing them with the FTOOLS, XSPEC, CIAO, and SHERPA packages to generate exposure-corrected images in multiple energy bands. To model the surface brightness profile, a diffuse image was constructed by removing point sources.

For each image, the two-dimensional β-model with elliptical symmetry was fitted to the central region of the cluster to determine the X-ray emission peak (Cavaliere & Fusco-Femiano 1976). From this fit, the core radius, mean ellipticity, and position angle were obtained. Based on these parameters, the region around the cluster was divided into three concentric elliptical rings that sample its inner, intermediate, and outer parts. The outer boundary of the ring system was scaled according to the core radius, while the inner boundaries were defined by partitioning this radial range into layers of equal width. Each ring was then subdivided into 10 azimuthal sectors. The cluster center was excluded from the analysis, within a radius of approximately $18''$, as it may be affected by phenomena such as AGN activity or cooling-flow processes (Fabian 1994, 2012).

The main objective is to investigate how the surface brightness varies across the sectors as a function of angle within each ring. To do so, the surface brightness is measured in each sector, and the mean and variance for each ring are computed, adopting a 1σ statistical measure, corresponding to a 68% confidence interval. For the quantitative analysis, the chi-squared statistic is applied, and higher values of χ^2 are expected to indicate a greater degree of substructure in the cluster.

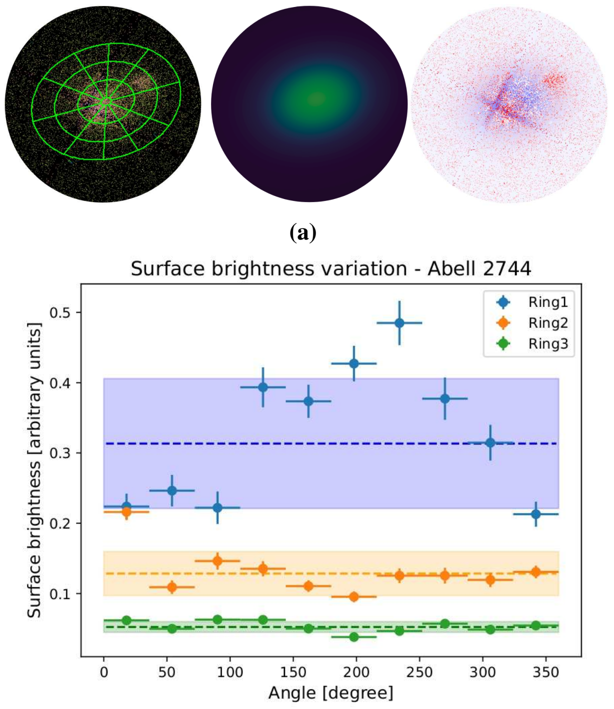
3. Results

Two illustrative cases were analyzed in greater detail: Abell 2029 and Abell 2744. Abell 2029 has a well-defined core and is well fitted by the two-dimensional β-model, as shown in the central panel of Fig. 1a. Its diffuse X-ray image reveals a clear spiral feature, seen in the left panel, which indicates internal substructure



(b)

Figure 1: a) Abell 2029: X-ray image (left), fitted two-dimensional β-model (center) and residuals (right). The first two panels use a logarithmic color scale and the residuals a linear scale; all images share the same pixel scale of approximately $2''$/pixel. b) Surface brightness as a function of position angle.



(b)

Figure 2: a) Abell 2744: X-ray image (left), fitted two-dimensional β-model (center) and residuals (right). The first two panels use a logarithmic color scale and the residuals a linear scale; all images share the same pixel scale of approximately $2''$/pixel. b) Surface brightness as a function of position angle.

driven by dynamical perturbations that impart angular momentum to the intracluster gas (Clarke, Blanton & Sarazin 2004). The residual image on the right strengthens this interpretation by enhancing the same spiral pattern. This behavior is consistent with gas sloshing in the cluster core (Laganá, Andrade-Santos & Lima Neto 2010), further supported by the surface-brightness variations measured in the innermost ring in Fig. 1b.

In contrast, the β-model applied to Abell 2744, shown in the central panel of Fig. 2a, does not reproduce the complex X-ray morphology seen in the left panel, failing to capture its multiple emission peaks and asymmetries. The residual image, shown in the right panel, highlights significant excesses and deficits in surface brightness, consistent with a highly disturbed, merging system far from hydrostatic equilibrium (Owers et al. 2011). This interpretation is further supported by the strong surface-brightness fluctuations in the innermost ring, shown in Fig. 2b.

The χ^2 analysis for the 40 clusters did not reveal a significant correlation with ellipticity, position angle, redshift, or core radius, indicating that these parameters are not directly associated with the degree of substructure within the redshift range $0.03 \leq z \leq 0.40$. The absence of correlation with the position angle was expected, since it merely reflects the cluster's orientation; the lack of correlation with ellipticity reinforces the robustness of using elliptical rings in the two-dimensional β-model; and the absence of correlation with the core radius suggests that the model is robust to different central structures of clusters. However, since the redshift range analyzed is relatively narrow, it is not possible to probe significant cosmological evolution. The comparison between energy bands showed that the broad band, which captures the full thermal emission, is the most effective for detecting local variations and substructures, producing the highest χ^2 values. In contrast, the soft and hard bands, each sensitive to different thermal regimes, exhibit weaker variations and lower χ^2 values. These narrower ranges thus provide a complementary view of the intracluster gas.

4. Conclusion

The methodology based on surface brightness analysis, combined with the two-dimensional β-model and the use of χ^2 statistics, proved to be effective in identifying and characterizing substructures and the dynamical state of galaxy clusters. Future analyses could explore correlations between χ^2 and physical properties such as the temperature and mass of the clusters.

Acknowledgements. We thank FAPESP for the financial suppport under grants 2024/01585-7 and 2024/06400-5.

References

Andrade-Santos, F., Lima Neto, G. B. & Laganá, T. F. 2012, ApJ, 746, 139
Cavaliere, A. & Fusco-Femiano, R. 1976, A&A, 49, 137
Clarke, T. E., Blanton, E. L. & Sarazin, C. L. 2004, ApJ, 616, 178
Fabian, A. C. 1994, ARA&A, 32, 277
Fabian, A. C. 2012, ARA&A, 50, 455
Laganá, T. F., Andrade-Santos, F. & Lima Neto, G. B. 2010, A&A, 511, A15
Owers, M. S., Randall, S. W., Nulsen, P. E. J., Couch, W. J., David, L. P. & Kempner, J. C. 2011, ApJ, 728, 27
Richstone, D., Loeb, A. & Turner, E. L. 1992, ApJ, 393, 477
Sarazin, C. L. 1986, Reviews of Modern Physics, 58, 1
Schneider, P. 2014, in Extragalactic Astronomy and Cosmology: An Introduction, (Berlin: Springer), 242
Suwa, T., Habe, A., Yoshikawa, K. & Okamoto, T. 2003, ApJ, 588, 7