Boletim da Sociedade Astronômica Brasileira, **34**, no. 1, 126-127

The evolution of the mass - X-ray luminosity in the CODEX galaxy cluster sample

I. Pederneiras[1], E. Cypriano[1], A. Finoguenov[2]

[1] Instituto de Astronomia, Geofisica e Ciências Atmosféricas, USP, SP
e-mail: `isabelpederneiras@usp.br`
[2] Department of Physics, University of Helsinki, Helsinki, Finland

Abstract. Galaxy clusters occupy a privileged position for studies of cosmology and astrophysics, and their formation and evolution can be unveiled by the study of scaling relations between cluster properties. The work presented here analyses the temporal evolution of the correlation between the X-ray luminosity and the total mass of the clusters, obtained by weak gravitational lensing, for a sample in the CODEX Catalog of galaxy clusters. A Bayesian statistical model is also presented, seeking a more consistent study by taking into account factors that can bias the results. We present a preliminary result with slope of $\beta = 1.37 \pm 0.55$ and no evidence for evolution, both in agreement with the self-similar model ($\beta = 4/3$).

Resumo. Aglomerados de galáxias ocupam uma posição privilegiada para estudos de cosmologia e astrofísica, e sua formação e evolução podem ser desvendadas pelo estudo das relações de escala entre propriedades dos aglomerados. Apresentamos uma análise da evolução temporal da correlação entre a luminosidade em raios-X e a massa total dos aglomerados, obtida por lentes gravitacionais fracas, para uma amostra do Catálogo CODEX de aglomerados de galáxias. Também é considerado um modelo estatístico Bayesiano, buscando um estudo mais consistente ao considerar fatores que podem enviesar os resultados. Obteve-se um resultado preliminar com parâmetro de inclinação $\beta = 1.37 \pm 0.55$ e sem evidência de evolução, ambos de acordo com o modelo auto-similar ($\beta = 4/3$).

Keywords. Galaxies: clusters: general – Gravitational lensing: weak – Methods: statistical

1. Introduction

The established theory for structure formation is the hierarchical model, in which the first structures would be small, and tend to increase their mass during the evolution of the Universe, giving rise to bigger objects. Within this scenario, the largest structures that have already reached a certain degree of dynamic maturity are galaxy clusters. Due to the general complexity of these systems, their formation is usually approximated by non-dissipative models, which are very successful in predicting the existence and functional form of correlations between cluster properties, the so-called scaling relations (Kravtsov & Borgani 2012). The self-similar model (Kaiser 1986) is commonly adopted, which predicts that the main physical properties of a cluster (e.g. L_X, T_X, velocity dispersion) can be described by power laws. In particular, for the relationship between total mass and X-ray luminosity - emitted by the ionized gas in the inter cluster medium - in log space, we have

$$log[L_X E(z)] = \alpha + \beta \, log[M E(z)^{-1}] + \gamma \, (1 + z) \, , \qquad (1)$$

where we expect $\beta = 4/3$ and $\gamma = 0$ for the self-similar model. Deviations from such a model are meanly due to recent mergers, radiative cooling, and stellar and AGN feedback (Sereno et al. 2019).

When dealing with astronomical data, even a simple linear regression must be worked with caution, since we need to consider many effects to uncover the properties we really want (Sereno 2016). Measurement errors, for example, can affect both independent and dependent variables, and are usually heteroscedastic (i.e. they differ and possibly correlate). Moreover, the independent variable may be hidden, when we cannot actually measure the quantity, but only scattered proxies of it (e.g. the gravitationally lensed mass of a cluster rather than the true mass). Selection effects can cause the sample to be non-representative of the population we intend to work with, and last but not least, the physical effects that determine the scaling parameters can be time depending. In order to address these aspects, a Bayesian statistical model and fitting method will be discussed in Sec. 3.

2. The CODEX sample

The CODEX catalog was thoroughly constructed adopting an X-ray and optical selection of clusters in the overlapping area of the Rosat All Sky Survey (RASS) and Sloan Digital Sky Survey (SDSS, York et al. 2000) (Finoguenov et al. 2020). The total halo mass data for our sample of clusters were obtained by weak gravitational lensing (Kiiveri et al. 2021). The latter is a distinction of this project since this method is sensitive to the entire matter of the cluster with no assumptions needed for the system dynamics, which contributes to a more unbiased analysis. Due to the need for high-quality observational data, such measurements were performed for a subsample of the catalog that has complementary observations with the CFHT (Canada-France-Hawaii Telescope), providing a full probability distribution function (PDF) for the mass of each of these clusters. We are using a CODEX-CFHT sample of 32 galaxy clusters with a redshift range of $0.26 < z < 0.62$, where we implemented a richness cut of $\lambda > 60$. Figure 1 shows one of these clusters.

3. Statistical modeling

In view of the statistical factors discussed in Sec. 1, it was decided to use the LIRA package - *LInear Regression in Astronomy* - in the R language, which performs linear regression from a Bayesian analysis, whose posterior distribution of the parameters is sampled by Monte Carlo via Markov Networks (MCMC).

Figure 1. XMM-CFHT image of galaxy cluster CODEX 24981 of our subsample. The X-ray emission by the intracluster medium in the 0.5 - 2 keV band is represented by the contours.

Modeling the intrinsic distribution of the independent variable - in this case, the total mass of the clusters - is extremely important to correct for the Eddington bias, since this occurs when the mean value of an observed sample differs from the true intrinsic mean of the objects. Since very massive objects are rarer, but also generally strong emitters - and therefore easier to detect at very large distances - LIRA models the shape of the distribution as unimodal and can be approximated by a time-evolving normalized n_{mix} Gaussian mixture (Sereno 2016):

$$P(M) = \sum_{k=1}^{n_{mix}} \pi_k N(\mu_{M,k}(z), \sigma^2_{M,k}(z)) \; ; \qquad \sum_{k=1} \pi_k = 1 \qquad (2)$$

The Eddington bias correction is done by considering the presence of an intrinsic scatter between the mass proxy - in this case, the weak gravitational lensing mass - and the cluster's true mass. It is also considered the intrinsic scatter of the response variable - the X-ray luminosity L_X - given a fixed true mass. For this, LIRA adopts the model where observables have a lognormal scatter (Sereno 2016).

To consider heteroscedastic errors in both variables, the connection between the intrinsically scattered proxies - discussed above - and the actually observed values with measurement uncertainties are also modeled by a lognormal distribution.

As a follow-up to this work, we also intend to correct for the Malmquist bias, in which a sample made only by objects above an observational cutoff value is non-representative. To address this bias, the relations between true values and spread proxies, and between the latter and measured values, must be modified. This can be done by truncating the probability distributions by a threshold $U(L_{X_{th}})$, modeled as a uniform distribution, null for $L_X < L_{X_{th}}$. The threshold will be implemented by the CODEX selection function and the sampling function - that accounts for the construction of our subsample - both currently in preparation.

4. Results

As a preliminary analysis, we consider the modeling of the mass PDF, and its evolution with redshift, as in Eq. 2 with $n_{mix} = 1$. The intrinsic scatter and measurement errors in both variables are also taken into account, with priors defined as in (Sereno 2016). Figure 2, shows the linear regression resulting from this analysis, for which we found $\beta = 1.37 \pm 0.55$, $\alpha = 24.0 \pm 8.2$ and $\gamma = -0.2 \pm 1.5$. We also compare with previous works that analyze the $M_{lens} - L_x$ relationship, based on different catalogs and surveys. All of them presented results in agreement with the self-similar purely gravitational model.

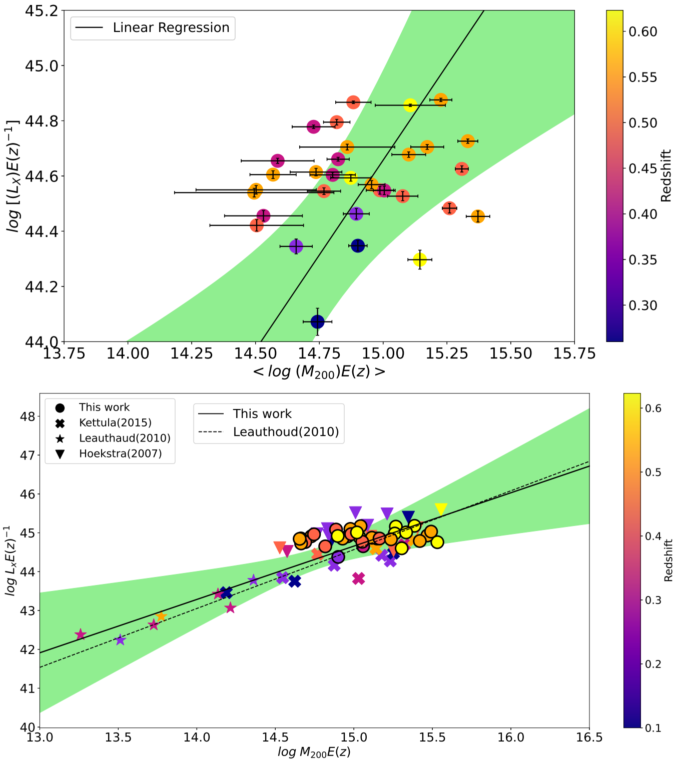

Figure 2. *Top*: Masses and X-ray luminosities of galaxy clusters in our CODEX-CFHT sample. The colors correspond to the redshift of the clusters. The 1σ confidence interval is highlighted in green and the regression in black. *Bottom*: Comparison of our sample with three previous works. The solid and dashed lines corresponds to the results of this work and (Leauthaud et al. 2010), respectively.

5. Conclusions

We presented a preliminary analysis of the mass - X-ray luminosity relation in a subsample of galaxy clusters in the CODEX catalog, accounting for proper modeling of the intrinsic distribution of halo mass, and the relation's temporal evolution. It was also possible to address the Eddington bias and measurement errors in both variables, using LIRA package. We found both the slope and evolution to be consistent with the self-similar model, and in expanding the mass and luminosity range by adding similar data from previous studies, we observe an agreement with our results. A more robust analysis and unbiased results are expected by implementing the full selection function in the future.

Acknowledgements. This study was financed in part by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil* (CAPES) - Finance Code 001. ESC acknowledges the support of the funding agencies CNPq (309850/2021-5) and FAPESP (2019/19687-2).

References

Finoguenov, A. et al. 2020.
Hoekstra, H. 2007,MNRAS, 379, 317
Kaiser, N. 1986, MNRAS, 222, 323
Kettula, K., Giodini, S., van Uitert, E., et al. 2015, MNRAS, 451, 1460
Kiiveri et al. 2021.
Kravtsov A. & Borgani S., 2012. Annu. Rev. Astron. Astrophys.
Leauthaud A., et al., 2010, ApJ, 709, 97–114.
Sereno M. 2016, MNRAS, 455, 2149–216
Sereno M. et al. 2019, MNRAS 492, 4528-4545