Boletim da Sociedade Astronômica Brasileira, **33**, no. 1, 49-50

Methods for determining the trail vectors of jellyfish galaxies

Rubens E. G. Machado[1], Elvis A. Mello-Terencio[2], Caroline A. F. Oliveira[1], Ana L. Chies-Santos[3], & Fabricio Ferrari[4]

[1] Departamento Acadêmico de Física, Universidade Tecnológica Federal do Paraná, Curitiba, Brazil
e-mail: `rubensmachado@utfpr.edu.br`
[2] Departamento de Física, Universidade Federal do Paraná, Curitiba, Brazil
[3] Departamento de Astronomia, Instituto de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil
[4] Instituto de Matematica Estatistica e Fisica, Universidade Federal do Rio Grande, Rio Grande, RS, Brazil

Abstract. Jellyfish galaxies are an extreme case of ram pressure stripping, when gas is removed as the galaxy moves through the intracluster medium. Identifying the direction of motion is not trivial. We aim to compare four different methods to estimate the direction of trail vectors, namely: (i) visual inspection, (iii) the Radon transform and (iii) neural networks. In order to study these methods in a controlled environment, we use the output from hydrodynamical simulations. In these simulations, a disc galaxy composed of stars, gas and a dark matter halo moves thorough the gas of the intracluster medium along a radial orbit, falling face-on (or edge-on) towards the cluster core. We produce maps of projected gas mass, which will serve as proxies for observed images. The snapshot is rotated randomly to produce a sample of images. The task of the four methods is to treat these simulated images as observations and estimate the directions of the velocity vectors, which can then be compared to the true vectors. Preliminary results indicated that visual inspection by humans produced relatively large errors, strongly dependent on morphology. The Radon transform was suitable if the galactic discs were seen nearly edge-on, but produced large errors otherwise. The neural networks seemed promising, because they were able to recover the orientations with quite good accuracy for a broader diversity of morphologies. They were able to extrapolate to some snapshots for which they had not been trained. Further simulations with different morphologies should provide a clearer picture of the performance of each method under various regimes, giving an indication of their expected reliability when applied to real observations.

Resumo. Galáxias jellyfish são um caso extremo de pressão de arraste, onde o gás é removido conforme a galáxia se move através do meio intra-aglomerado. Identificar a direção do movimento não é trivial. Pretendemos comparar quatro métodos diferentes para estimar a direção dos vetores velocidade, a saber: (i) inspeção visual, (iii) a transformada de Radon e (iii) redes neurais. Para estudar esses métodos em um ambiente controlado, usamos os resultados de simulações hidrodinâmicas. Nessas simulações, uma galáxia composta de estrelas, gás e um halo de matéria escura se move através do gás do meio intracluster ao longo de uma órbita radial, caindo de face (ou de perfil) em direção ao centro do aglomerado. Produzimos mapas projetados de massa de gás, que servirão como proxies de observações. Cada snapshot é rotacionado aleatoriamente para produzir uma amostra de imagens. A tarefa dos quatro métodos é tratar essas imagens simuladas como observações e estimar as direções dos vetores de velocidade, que podem então ser comparados aos vetores verdadeiros. Os resultados preliminares indicaram que a inspeção visual por humanos produziu erros relativamente grandes, fortemente dependentes da morfologia. A transformada de Radon se mostrou adequada se os discos galácticos forem vistos quase de lado, mas produz grandes erros de outra forma. As redes neurais parecem promissoras, pois foram capazes de recuperar as orientações com bastante boa precisão para uma diversidade mais ampla de morfologias. Elas foram capazes de extrapolar para alguns snapshots para os quais não foram treinadas. Futuras simulações com diferentes morfologias deverão fornecer um panoama mais clara do desempenho de cada método sob vários regimes, dando uma indicação de sua confiabilidade esperada quando aplicados a observações reais.

Keywords. Galaxies: clusters: intracluster medium – Galaxies: spiral – Galaxies: evolution

1. Introduction

As a galaxy moves through the intracluster medium, part of its gas may be stripped by ram pressure. A jellyfish galaxy is an extreme case of this phenomenon, in which the galaxy exhibits a long tail in the direction opposite to its motion. However, if the asymmetry is only mild or if the velocity vector is inclined with respect to the plane of the sky, the identification of the direction of motion is not straightforward (Ebeling, Stephenson, & Edge 2014; Roman-Oliveira, et al. 2019). Simulations may help disentangle projected morphology from intrinsic features (Yun et al. 2019).

2. Simulation setup

In order to study the methods in a controlled environment, we use the output from 2 hydrodynamical N-body simulations, performed with Gadget-3 including star formation. The initial conditions are composed of a cluster with total mass 10^{14} M$_\odot$, and a galaxy with stellar mass 5×10^{10} M$_\odot$ and 25% gas fraction in the disc. In these simulations, the galaxy moves thorough the gas of the intracluster medium along a radial orbit, falling face-on (or edge-on) towards the cluster core. The galaxy starts at $r = 1$ Mpc with a relative velocity of 1000 km/s, and the central passage occurs at 0.8 Gyr. We take 5 snapshots at the times of interest, from each simulation (Figs. 1 and 2). From each snapshot, we produce maps of projected *gas* mass, which will serve as proxies for observed images. Each snapshot is rotated randomly to produce a samples of 100 projected images. The task of the different methods is to treat these simulated images as observations and attempt to recover the directions of the velocity vectors, which can then be compared to the true vectors.

3. Methods and results

The first method is visual inspection. Two humans separately inspected the randomly projected images, estimating the direction

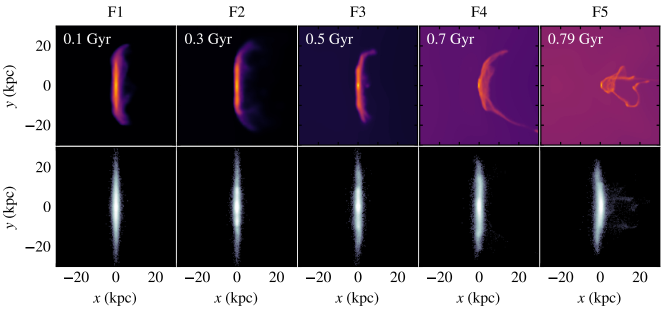

Figure 1. Projected gas mass (top) and projected stellar mass (bottom). Galaxy 'F' moves face-on into the cluster.

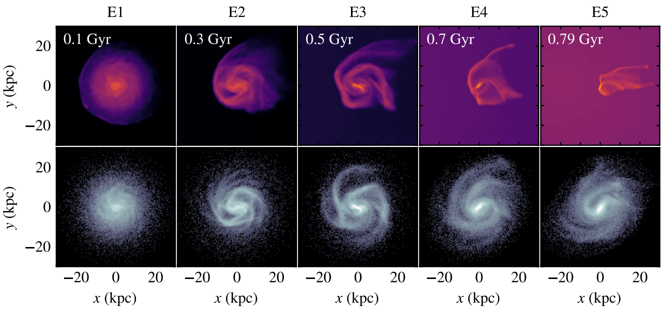

Figure 2. Projected gas mass (top) and projected stellar mass (bottom). Galaxy 'E' moves edge-on into the cluster.

of motion by eye; averages are shown. This was done only for the snapshots F2 and E2. Compared to the true orientations, the median errors were 25° and 38°, respectively. In the case of E2, the systematic shift towards ~45° can be understood by considering the misleading non-axisymmetry of E2 in Fig. 2. In any case, both dispersions are rather large and preliminary analysis had indicated that the accuracy is strongly dependent on the morphology of the particular snapshot.

The second method is the Radon transform, a tool not widely used in astronomy (but see footnotes in Krone-Martins et al. 2013). The Radon transform of an image results in a 'sinogram' (Fig. 3) whose peak gives the preferred direction. To decide the sign of the perpendicular vector, we count number of occupied pixels above a certain threshold on both sides of the yellow line. The side with the least occupied pixels is the one the velocity vector is headed towards. This method is accurate for some images, but produces large systematic errors (90° and 180°) for others. The systematic errors of 45° can be understood considering the morphology of E3, for example. For galaxy F, the method gives better results if the galaxy is *seen* edge-on; likewise for galaxy E. Thus, this method gives poor results when the galaxy is seen nearly face-on, regardless of the intrinsic tail direction.

The third method is neural networks. The architecture used was simple, being composed of two convolutional layers followed by a sequence of 3 fully connected layers, utilizing ReLU as activation function. The training set for the neural networks consisted of a total of 2000 random images produced from F2 and E2 together. The trained model was applied to the random images in each sample. We wished to find whether it would be able to distinguish between the F and E cases and to extrapolate to other morphologies. The first and last snapshots are not recovered. This method succeded in extrapolating for the morphologies of E3 and E4 with good accuracy (Fig. 4).

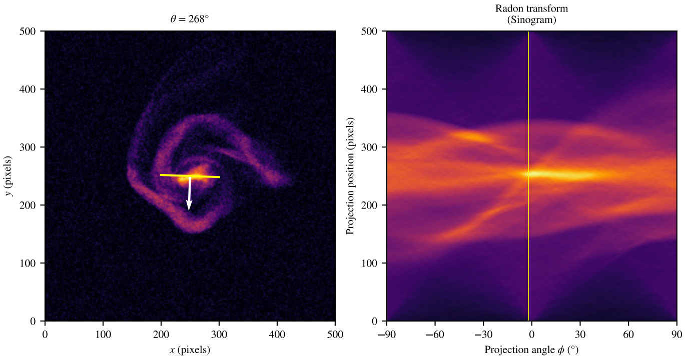

Figure 3. An example of a sinogram from the Radon transform.

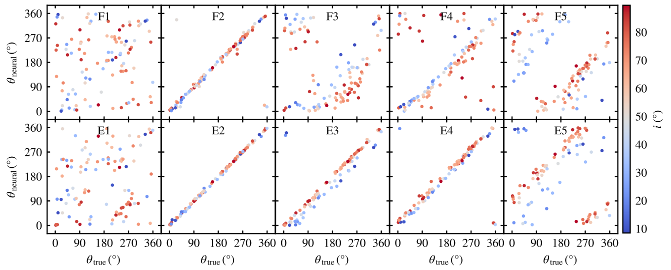

Figure 4. Estimates from the neural network, compared to the true orientations.

4. Summary

- **Visual inspection** by humans tended to produce relatively large errors, but the accuracy overall is strongly morphology-dependent. Larger samples would be needed to draw more general conclusions.
- The **Radon transform** proved suitable only when the galactic disc is seen nearly edge-on, regardless of tail inclination. Towards galaxies seen face-on, large systematic erros were obtained.
- The **neural networks** were able to accurately recover the orientations for a relatively broader diversity of morphologies. In all cases, the orientations at the beggining and at the end of the simulation were not recovered, because the morphologies were too dissimilar from those of the training set. These shortcomings might be ameliorated by the future application of larger and more diverse training sets.
- Overall all methods explored were sensitive to the particular morphology of the galaxy at a given time in the simulation – either intrinsic or in projection.

Acknowledgements. The authors acknowledge the National Laboratory for Scientific Computing (LNCC/MCTI, Brazil) for providing HPC resources of the SDumont supercomputer, which have contributed to the research results reported within this paper. REGM acknowledges support from the Brazilian agency *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq) through grants 303426/2018-7 and 406908/2018-4. This study was financed in part by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil* (CAPES) - Finance Code 001. The authors thank Alberto Krone-Martins for useful suggestions.

References

Ebeling H., Stephenson L. N., Edge A. C., 2014, ApJL, 781, L40

Krone-Martins A., Ducourant C., Teixeira R., Galluccio L., Gavras P., dos Anjos S., de Souza R. E., et al., 2013, A&A, 556, A102

Roman-Oliveira F. V., Chies-Santos A. L., Rodríguez del Pino B., Aragón-Salamanca A., Gray M. E., Bamford S. P., 2019, MNRAS, 484, 892

Yun K., Pillepich A., Zinger E., Nelson D., Donnari M., Joshi G., Rodriguez-Gomez V., et al., 2019, MNRAS, 483, 1042