Kinematics of Filaments in Cooling Flow Clusters and Heating by Mixing

Shlomi Hillel¹ and Noam Soker¹,²

¹ Department of Physics, Technion—Israel Institute of Technology, Haifa 3200003, Israel
² Guangdong Technion Israel Institute of Technology, Guangdong Province, Shantou 515069, People’s Republic of China; soker@physics.technion.ac.il

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Abstract

We compare a recent study of the kinematics of optical filaments in three cooling flow clusters of galaxies with previous numerical simulations of jet-inflated hot bubbles, and conclude that the velocity structure functions (VSFs) of the filaments better fit direct excitation by the jets than by turbulent cascade from the largest turbulent eddies. The observed VSFs of the optical filaments in the three clusters are steeper than that expected from a classical cascade in turbulent dissipation. Our three-dimensional hydrodynamical simulations show that as the jets inflate bubbles in the intracluster medium (ICM), they form vortexes in a large range of scales. These vortexes might drive the ICM turbulence with eddies of over more than an order of magnitude in size. A direct excitation of turbulence by the vortexes that the jets form and the slow turbulent dissipation imply that heating the ICM by mixing with hot bubbles is more efficient than heating by turbulent dissipation.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Cooling flows (2028); Galaxy jets (601); Circumgalactic medium (1879)

1. Introduction

In the cooling flow process in clusters of galaxies, in galaxies, and during galaxy formation, the gas radiative cooling time is shorter than the age of the system. The thermal state of the intracluster medium (ICM; or the interstellar medium, ISM) is determined by radiative cooling and by heating, both operate together in a negative feedback cycle (for reviews see, e.g., Fabian 2012; McNamara & Nulsen 2012; Soker 2016; Werner et al. 2019). In one direction of the feedback cycle the gas suffers radiative cooling and feeds the active galactic nucleus (AGN), while in the other direction jets that the central AGN launch heat the gas (e.g., Farage et al. 2012; Gaspari et al. 2013a; Pfrommer 2013; Barai et al. 2016; Soker 2016; Birzan et al. 2017; Igbal et al. 2017; Wang et al. 2019).

Many studies in recent years support the cold feedback mechanism (Pizzolato & Soker 2005; Gaspari et al. 2013b; Voit et al. 2015) by which cold clumps that radiatively cool from the hot ICM (or from the hot ISM) feed the AGN (e.g., a small sample of papers from past 3 years; David et al. 2017; Donahue et al. 2017; Fujita & Nagai 2017; Gaspari et al. 2017; Hogan et al. 2017; Prasad et al. 2017; Babyk et al. 2018; Gaspari et al. 2018; Ji et al. 2018; Prasad et al. 2018; Pulido et al. 2018; Voit 2018, 2019; Yang et al. 2018; Choudhury et al. 2019; Iani et al. 2019; Qiu et al. 2019; Rose et al. 2019; Russell et al. 2019; Stern et al. 2019; Storchi-Bergmann & Schnorr-Müller 2019; Vantyghem et al. 2019).

On the other hand, there is an ongoing dispute on the main heating processes of the ICM. We list the several different heating processes as follows. (1) Cosmic rays that are accelerated within the jet-inflated bubbles stream into the ICM and heat it (e.g., Fujita & Ohira 2013; Pfrommer 2013; Ehlert et al. 2018; Ruszkowski et al. 2018). However, it seems that even in the case where the jet-inflated bubbles are filled with cosmic rays, mixing of the bubble content with the ICM (the heating by mixing process; see below) is more efficient than streaming of cosmic rays along magnetic field lines (Soker 2019). (2) Excitation of sound waves in the ICM (e.g., Fabian et al. 2006; Tang & Churazov 2018). (3) Driving shocks in to the ICM (e.g., Randall et al. 2015; Guo et al. 2018). (4) Powering turbulence (e.g., de Young 2010; Banerjee & Sharma 2014; Gaspari et al. 2014; Zhuravleva et al. 2018). (5) Uplifting gas from inner regions (e.g., Gendron-Marsolais et al. 2017). (6) Generation of internal waves in the ICM by buoyantly rising bubbles (e.g., Zhang et al. 2018). (7) Heating by mixing that operates through the many vortexes that the jets form as they interact with the ICM and inflate the bubbles. These vortexes mix the ICM with the energetic content of the bubbles (whether cosmic rays or thermal hot gas), and by that heat the ICM (e.g., Brüggen & Kaiser 2002; Brüggen et al. 2009; Gilkis & Soker 2012; Hillel & Soker 2014; Yang & Reynolds 2016). The changing of the jets’ axis direction with time allows efficient mixing of the entire inner ICM volume (e.g., Cielo et al. 2018; Soker 2018).

Our past simulations show that it is possible that only part of the hot bubble gas mixes with the ICM and heats it. The other part of the hot bubble, mainly the inner part, continues to buoy out through the cluster and forms a rising bubble that is no longer powered by a jet. Such outer bubbles (outer X-ray cavities) are observed in a number of clusters (e.g., Fabian et al. 2011; Randall et al. 2015). Gilkis & Soker (2012) conduct a hydrodynamical simulation of jet-inflated bubbles and find that mixing is the main heating mechanism. Although the jet (they simulate only one half of the space) was active for only the first 20 Myr of the simulation, a well-defined bubble is still rising through the ICM at t = 80 Myr, when the bubble is at about 30 kpc from the center (their Figure 5). In Hillel & Soker (2017a) we further analyzed our simulations of heating by mixing (Hillel & Soker 2016), and found that alongside with the heating by mixing the bubbles maintain their identity with unmixed hot gas, up to tens of kpc from the center (our grid was up to 50 kpc). We can see a hot low-density bubble at a distance of about 40 kpc from the center at t = 80 Myr (see Figure 2 in Hillel and Soker (2016); the jet was periodically active, therefore, other bubbles trail the first bubble).

There are several recent studies of the turbulent motion in the ICM, observationally (e.g., Hitomi Collaboration 2016; Hitomi Collaboration et al. 2018; Simionescu et al. 2019; Sanders et al.
2020) and numerically (e.g., Miniati & Beresnyak 2015; Vazza et al. 2017, 2018; Yang et al. 2019). In a recent study Fujita et al. (2020) suggested that the heating by mixing works, but that most mixing is by ICM turbulence that is formed by continuous accretion of gas onto the cluster. Our simulations (e.g., Gillikis & Soker 2012; Hillel & Soker 2016) show that jet-excited turbulence is sufficient to induce the required mixing.

In another recent paper, Li et al. (2020) studied the kinematics of optical filaments in the cooling flow clusters Perseus, A2597, and Virgo, and find the motion of filaments to be turbulent (Section 2). They further conclude that their result is consistent with turbulence as an important heating mechanism, supporting earlier claims from the results of Hitomi (Hitomi Collaboration 2016). In this paper we present an opposite view. Despite turbulence being present in the ICM (e.g., Zhuravleva et al. 2014; Anderson & Sunyaev 2016; Arévalo et al. 2016; Hofmann et al. 2016; Zhuravleva et al. 2019), and it maybe playing a role in the evolution of condensations in the cold feedback mechanism (e.g., Voit 2018), some studies find heating by turbulence to have limited efficiency (e.g., Falceta-Gonçalves et al. 2010; Reynolds et al. 2015; Hitomi Collaboration 2016; Bambic et al. 2018; Mohapatra & Sharma 2019; Valdarmini 2019). However, many of these do not recover the directly-measured velocity with Hitomi, or have other inconsistencies with observations. Reynolds et al. (2015) simulate violent feedback rather than a gentle feedback as observations suggest (Hogan et al. 2017), Bambic et al. (2018) assume that turbulence is generated in the cluster center rather than by bubbles in a large volume of the core, and Mohapatra & Sharma (2019) ignore the effects of stratification in the ICM. In that respect we note that we have shown that the simulations we performed in 2016 (Hillel & Soker 2016) and that we further analyze in this study, can account for the observations of Hitomi (Hillel & Soker 2017b), and yield a gentle heating (Hillel & Soker 2017a).

In the present study we present our view (Sections 2, 4, and 5) that the heating by mixing process better fits the new findings of Li et al. (2020). We summarize in Section 6.

### 2. Filament Kinematics

Li et al. (2020) analyze optical observations of filaments in three cooling flow clusters. They pair many different regions and record the velocity difference within each pair $\delta v$, and bin the different pairs by the distance $L$ between the two regions of each pair. They calculate the average absolute value of the velocity differences within each distance bin, $V_f(L) = \langle |\delta v| \rangle$. The function $V_f(L)$ is the velocity structure function (VSF) of the optical filaments.

Li et al. (2020) conclude that on small scales $L < L_m$, where $L_m$ is the scale of the driving force, which they calculate from the typical size of the jet-inflated bubbles in each cluster, the VSF is steeper than the classical Kolmogorov expectation. They infer that the turbulent driving scales of the three clusters are $L_m$(Perseus) $\approx 10$ kpc, $L_m$(A2597) $\approx 4$ kpc, and $L_m$(Virgo) $\approx 1–2$ kpc.

From Figure 2 of Li et al. (2020) we approximate the VSF for $L < L_m$ by a power law, $V_p \propto L^\alpha$. These approximate VSFs for small scales in the three clusters are

$$V_p(\text{Perseus}) \propto L_p^{0.8}, \quad 0.3 \text{ kpc} \lesssim L \lesssim 4 \text{ kpc}, \quad (2)$$

and

$$V_p(\text{Virgo}) \propto L_p^{0.9}, \quad 0.2 \text{ kpc} \lesssim L \lesssim 3 \text{ kpc}. \quad (3)$$

These functions teach us two important things. The first, as Li et al. (2020) noticed, is that if there is no dissipation on all scales, these steeper-than-Kolmogorov VSFs imply that the energy dissipation of the turbulence is much below the value that the large scale gives $Q_m \approx \rho v^3_\text{f}/(L_m/L_m)$. We note that $Q_m$ is already short of explaining heating in Perseus (Hitomi Collaboration 2016). While in the Kolmogorov VSF the contribution of each scale is the same down to the dissipation length, for the three VSFs above the contribution to heating, $Q(L) \propto L^{3\kappa-1}$, rapidly decreases for shorter scales since $3\kappa - 1 = 0.5, 1.4, \text{ and } 1.7$, for the three clusters, respectively.

The second property that these VSFs reveal is that the dissipation time is longer than the time between consecutive jet-launching episodes in these clusters. The dissipation time is a few times the turnover time $t_t \approx L/V_p(L)$. Li et al. (2020) noticed this for the largest scale, and here we emphasize this also for the smaller scales. For example, in Perseus they take $V_p(L_m) \approx 140$ km s$^{-1}$, which gives $t_t(10 \text{ kpc}) \approx 70$ Myr and a dissipation time of $t_{\text{diss}}(10 \text{ kpc}) > 100$ Myr. The period of AGN activity in Perseus is highly uncertain (Li et al. 2020) $t_{\text{AGN}} \approx 10$ Myr $< t_{\text{diss}}$. Even for the smallest scale in Perseus the turnover time is longer than the jet activity cycle, $t_m(0.2 \text{ kpc}) \approx 13$ Myr, implying a dissipation time of $t_{\text{diss}}(0.2 \text{ kpc}) > 20$ Myr. The inequality $t_{\text{AGN}} < t_{\text{diss}}$ implies that over a limited span of time that is not much longer than $t_{\text{diss}}$, the turbulence can transfer only a small fraction of the AGN power to heat the ICM. Since in many clusters the power of AGN activity is about equal or not much larger than what is required to heat the ICM (e.g., Birzan et al. 2004), we conclude that under these assumptions turbulence cannot supply enough power to heat the ICM against radiative cooling. However, we note that the timescale of $t_{\text{AGN}} \approx 10$ Myr is highly uncertain, and that over a very long time that is much longer than $t_{\text{diss}}$, turbulent dissipation and AGN heating might balance, such that turbulent dissipation can contribute to ICM heating. Overall the dissipation time is too long to account for pure turbulent heating.

We conclude from this short discussion that the turbulence cannot be an important heating process in these clusters. The present conclusion is opposite to the conclusion of Li et al. (2020). As we claimed in earlier papers (e.g., Hillel & Soker 2017b, 2018), the interaction of the jets and the bubbles they inflate with the ICM does drive turbulence, but it is a byproduct of many vortexes that this interaction forms, and not the major heating process. To better illustrate this, we turn to analyze our earlier three-dimensional (3D) hydrodynamical simulations.

### 3. The Numerical Scheme

We present the flow structure of a 3D hydrodynamical simulation from Hillel & Soker (2016), which we also analyzed in Hillel & Soker (2017b). We describe here only the essential details of the numerical scheme (more information is in these two papers).

We used the code PLUTO (Mignone et al. 2007) and simulated the octant, $x > 0$, $y > 0$ and $z > 0$, where we take the $z$-axis along the jet’s axis. The highest resolution of this
The simulation includes a gravity field that maintains the gas at hydrostatic equilibrium before we inject the jets, and radiative cooling.

4. Numerical Flow Structure

4.1. Vortex Scales

The vortices that the jet–ICM interaction forms play a significant role by mixing hot bubble content with the ICM (Section 1). First we present the flow structure that reveals vortexes in one case from Hillel & Soker (2016), that we also analyzed in Hillel & Soker (2017b) as tracer A. Tracer A is frozen in to the gas that at \( t = 0 \) was inside a torus with a circular cross section having a radius of \( r_0 = 2.5 \) kpc and centered at \((x_c, z_c)_{t=0} = (10, 5)\) kpc, where \( x = (x^2 + y^2)^{1/2} \) (a yellow circle in Figure 1). Namely, the torus is parallel to the \( x - y \) symmetry plane and its axis is the \( z \)-axis. Figure 1 presents the flow structure in the \( y = 0 \) meridional plane at \( t = 80 \) Myr. The color coding depicts the concentration of a tracer A. A tracer is an artificial flow quantity that is frozen in to the flow, and therefore it represents the spreading and mixing with time of the original parcel of gas. The initial value of the tracer inside the original volume is \( \xi(0) = 1 \), and it is \( \xi(0) = 0 \) outside that volume. When the traced gas mixes with the ICM that started outside the original volume of the tracer or with the jets’ material, its value drops to \( 0 < \xi(t) < 1 \).

Figure 1 demonstrates the following flow properties. (1) A complicated flow structure that the vortexes form. (2) The vortexes spread the tracer-gas over a large volume. (3) The vortexes span a large size range.

With the resolution we have it is impossible to resolve vortexes with diameters much less than about 1 kpc. The bubble size that the jet inflates (about the diameter of a sphere of the same volume as the bubble) is \( D_{\text{bubble}} \approx 20 \) kpc (Hillel & Soker 2016). We get here vortexes that are an order of magnitude smaller. One might imagine that the still narrow jet near the center might form small vortexes. Nonetheless, there are small vortexes far from the center.

To further analyze the flow structure we examine the temperature of the different flow zones in the ICM and in the bubble. In Figure 2 we present the temperature and the velocity at \( t = 44 \) Myr. The length of each arrow is proportional to the velocity up to \( v = 150 \) km s\(^{-1}\). Any velocity of \( v > 150 \) km s\(^{-1}\) is represented by an arrow with the same length as for \( v = 150 \) km s\(^{-1}\). This way we emphasize the slow gas that is the focus of this study. Most of the gas that moves at higher velocity is in the pre-shocked jets (in Hillel & Soker 2016 we present more detailed velocity maps). This figure shows that turbulence of different scales develops in the post-shock region of the jet, in particular in the mixing zones with the ICM.

In Figure 3 we present the flow structure only of gas that has a temperature of \( T < 6 \times 10^7 \) K = 2\( T_{\text{ICM}} \), so that we avoid hot bubble gas. Due to its adiabatic cooling, the velocity of the pre-shock jets is also in that map (near the center). In this figure we also present the distribution of tracer C, a tracer that is frozen to the gas that at \( t = 0 \) was inside a sphere of radius 15 kpc centered on the center of the grid (one octant). The tracer reveals a very complicated structure, with many small vortexes in the hot regions (where there are no arrows). The cooler regions also have a very complicated flow structure, with vortexes with sizes that span an order of magnitude.

The conclusion from the results of this subsection is that the jet–ICM interaction can directly excite small-scale turbulence. Namely, the cascade from large scales to small scales accounts for only a fraction of the turbulent power at small scales in the ICM. We further show this in the next subsection.

4.2. No Time to Dissipate the Large Eddies

The small vortexes (eddies) cannot come from the large vortexes by dissipation as there is no time for that. To show that, we use Figure 4 that we took from Hillel & Soker (2017b). In that earlier study we used this figure to show that the velocity dispersion of the ICM is similar in values to what observations with Hitomi show for the Perseus cluster (Hitomi Collaboration 2016).

The velocity that Figure 4 presents is the line-of-sight rms velocity, which we termed numerical velocity dispersion, of all cells that contain even a little tracer A and also have a temperature of \( T < 4.5 \times 10^7 \) K. This velocity is

\[
\sigma_n = \frac{\sqrt{\langle v^2 \rangle}}{\sqrt{3}} = \frac{1}{\sqrt{3}} \frac{2E_{k,n}}{M_{t,n}} \quad \text{for} \quad T < 4.5 \times 10^7 \text{ K},
\]

where \( E_{k,n} \) and \( M_{t,n} \) are the kinetic energy and mass, respectively.

Figure 4 shows two relevant properties to the present study. First it shows the dispersion velocity, that most of the time is \( \sigma_n \lesssim 250 \) km s\(^{-1}\). The turnover time of a vortex of size \( L_{\text{max}} = 10 \) kpc is then \( t_n \approx L_{\text{max}} / \sigma_n \gtrsim 40 \) Myr. The dissipation time is a few times the turnover time, which is longer than the \( t = 80 \) Myr time of Figure 1 and the \( t = 44 \) Myr time of Figures 2 and 3.

As well, Figure 4 shows that the general dispersion velocity increases with each jet-launching episode. This shows that the energy has no time to dissipate, and that a different heating process is responsible for most of the ICM in cooling flows.

From this numerical simulation and others, Hillel & Soker (2016) found that only \( \approx 20\% \) of the jet’s kinetic energy is channeled to shock waves, sound waves, and a global flow. This is compatible with the calculation of Forman et al. (2017) that in the Virgo cluster the shock carries \( \approx 22\% \) of the AGN energy. Namely, heating by mixing, Hillel & Soker (2016) concluded, is the main heating process as about 80% of the
jet’s energy is channeled to heating the ICM by mixing. Hillel & Soker (2017b) used this simulation to find that the numerical velocity dispersion is \(\sigma \approx 100-250 \, \text{km s}^{-1}\), similar to the line-of-sight velocity dispersion of \(\sigma_{los} \approx 164 \pm 10 \, \text{km s}^{-1}\) found by Hitomi in Perseus (Hitomi Collaboration 2016).

5. The Numerical VSF

We now examine the numerical VSF before the large vortexes have time to cascade down. We proceed as follows.

1. We take the flow at \(t = 44 \, \text{Myr}\), a time that ensures no significant cascade of the large turbulent eddies, since a typical cascade time is \(t_{\text{cascade}} \approx 10 \, \text{kpc}/100 \, \text{km s}^{-1} = 100 \, \text{Myr}\).

2. We interpolate the numerical AMR grid (where cells have different sizes) to a grid of 64 \(\times\) 64 \(\times\) 64 cells, where all cells have the same size.

3. We mirror the octant grid about the planes \(x = 0\), \(y = 0\), and \(z = 0\), so that we have a grid that covers all space around the center.

4. To avoid outer regions that the jets did not influence yet because of the short simulation time of 44 Myr, we limit the volume we analyze to the ICM inside the ellipsoid \((x^2 + y^2)/(33 \, \text{kpc})^2 + z^2/(39 \, \text{kpc})^2 = 1\). We term this the large-volume structure function. To examine the sensitivity to the volume we use, we also calculate the numerical VSF for a smaller region that includes only regions close to the edge of the bubble. We take for the outer boundary of the regions of the small-volume structure function the surface \((x^2 + y^2)/(28 \, \text{kpc})^2 + z^2/(35 \, \text{kpc})^2 = 1\), which has its outer boundary at about half the distance from the bubble edge compared with that of the large volume above.

5. To avoid the hot bubble gas we consider only gas with a temperature at or below the initial ICM temperature, i.e., we consider only ICM gas with \(T < T_{\text{ICM}}(0) = 3 \times 10^7 \, \text{K}\). We exclude the fast pre-shock jet gas (it is cold because of adiabatic cooling) by avoiding gas with velocities of \(v > 10^3 \, \text{km s}^{-1}\).

6. For each pair of two cells that obey the above criteria, we record the distance \(d_i\) and velocity difference \(\delta v_i\) between the two cells.

7. We divide the pairs according to the distances \(L_i\) and velocity difference \(\delta v_i\) in bins of \(\Delta L = 0.1 \, \text{kpc}\), and calculate the average velocity within each distance bin and obtain the VSF \(V(L) = \langle |\delta v| \rangle\) as function of \(L\). For comparison, the largest cell size in the region we analyze is 0.2 kpc, which is twice as large as the smallest cell size in the entire numerical grid.

We present the numerical VSF in Figure 5. The differences between the large-volume structure function (blue dots) and the small-volume structure function (green-“+” symbols) are very small, in particular in the relevant range. We are not sensitive to...
the choice of the region when calculating the numerical VSF. From this figure we learn that the process of bubble inflation excites turbulence over more than an order of magnitude in scale, much before the large eddies, \( L \approx 10-20 \) kpc, have time to cascade and form small eddies, \( L \lesssim \text{few} \times \) kpc. This strengthens the results of Section 4. We see that some parts are steeper, \( L \lesssim 45 \) kpc, and some are shallower, \( 5 \lesssim L \lesssim 45 \) kpc, than the classical Kolmogorov expectation (a slope of 1/3).

We do not take the VSF that we obtain here to be universal. We only claim that as jets inflate bubbles they excite turbulence with eddies with sizes over more than an order of magnitude. The VSF depends on the properties of the jets and the preexisting weak turbulence in the ICM. It might well be that jets can induce a turbulence where at all scales the VSF is steeper than 1/3, as Li et al. (2020) infer for three clusters.

6. Summary

The conclusion of this short study is that the jet–ICM interaction drives vortexes (turbulent eddies) in a large range of scales (Figures 1–3), that in turn drive the turbulence in the ICM with eddies of over more than an order of magnitude in...
size (Figure 5). We argue, therefore, that the dissipation of the large turbulent eddies is not the main process that determines the VSF of the optical filaments that Li et al. (2020) find, but rather the excitation of the turbulence by the jet–ICM interaction. Indeed, the turbulent properties do not allow for an efficient heating of the ICM in these three cooling flow clusters (Section 2).

We did not build our earlier 3D hydrodynamical simulations (Hillel & Soker 2016) to study the VSF of cold filaments. We encourage the study of VSFs in 3D hydrodynamical simulations of jets that inflate bubbles in the ICM. For that, the simulations should replace the simple tracer by a volume that has a gas with a somewhat lower temperature than that of the ICM. After a long time the gas will cool and form filaments. The VSF of these numerical filaments can be compared with the VSFs that Li et al. (2020) deduce from observations, in cases with strong viscosity, where cascade down is rapid, and in cases with very small viscosity where cascade down is negligible. Our prediction is that the jet–ICM interaction by itself can explain most (but not all) of the properties of the VSFs.

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ORCID iDs

Noam Soker https://orcid.org/0000-0003-0375-8987

References

Anderson, M. E., & Sunyaev, R. 2016, MNRAS, 459, 2806
Arav, N., Borguet, B., Chamberlain, C., Edmonds, D., & Danforth, C. 2013, MNRAS, 436, 3286
Arévalo, P., Churazov, E., Zhuravleva, I., Forman, W. R., & Jones, C. 2016, ApJ, 818, 14
Babyk, I. V., McNamara, B. R., Nulsen, P. E. J., et al. 2018, ApJ, 862, 39
Bambic, C. J., Morsony, B., & Reynolds, C. S. 2018, ApJ, 857, 84
Banerjee, N., & Sharma, P. 2014, MNRAS, 443, 687
Barai, P., Murante, G., Borgani, S., et al. 2016, MNRAS, 461, 1548
Birzua, L., Raftery, D. A., Brüggen, M., & Intema, H. T. 2017, MNRAS, 471, 1766
Farage, C. L., McGregor, P. J., & Doppia, M. A. 2012, ApJ, 747, 28
Forman, W., Churazov, E., Jones, C., et al. 2017, ApJ, 844, 122
Fujita, Y., Cen, R., & Zhuravleva, I. 2020, MNRAS, 494, 5507
Fujita, Y., & Nagai, H. 2016, MNRAS, 465, L94
Fujita, Y., & Ohira, Y. 2013, MNRAS, 428, 599
Gaspari, M., Brighenti, F., & Ruszkowski, M. 2013a, AN, 334, 394
Gaspari, M., Churazov, E., Nagai, D., Lau, E. T., & Zhuravleva, I. 2014, A&A, 569, A67
Gaspari, M., McDonald, M., Hamer, S. L., et al. 2018, ApJ, 854, 167
Gaspari, M., Ruszkowski, M., & Oh, S. P. 2013b, MNRAS, 432, 3401
Gaspari, M., Temi, P., & Brighenti, F. 2017, MNRAS, 466, 677
Gendron-Marsolais, M., Kraft, R. P., Bogdan, A., et al. 2017, ApJ, 848, 26
Gilks, A., & Soker, N. 2012, MNRAS, 427, 1482
Guo, F., Duan, X., & Yuan, Y.-F. 2018, MNRAS, 473, 1332
Hillel, S., & Soker, N. 2014, MNRAS, 445, 4161
Hillel, S., & Soker, N. 2016, MNRAS, 455, 2139
Hillel, S., & Soker, N. 2017a, ApJ, 845, 91
Hillel, S., & Soker, N. 2017b, MNRAS, 466, L39
Hillel, S., & Soker, N. 2018, RAA, 18, 081
Hiroti Collaboration 2016, Natur, 535, 117
Hitomi Collaboration, Aharonian, F., Akamatsu, H., et al. 2018, PASJ, 70, 9
Hofmann, F., Sanders, J. S., Nandra, K., Clerc, N., & Gaspari, M. 2016, A&A, 585, A130
Hogan, M. T., McNamara, B. R., Pulido, F., et al. 2017, ApJ, 851, 66
Iani, E., Rodighiero, G., Fritz, J., et al. 2019, MNRAS, 487, 5593
Iqbal, A., Kale, R., Majumdar, S., et al. 2017, JApA, 38, 68
Ji, S., Oh, S. P., & McCourt, M. 2018, MNRAS, 476, 852
Li, Y., Gendron-Marsolais, M.-L., Zhuravleva, I., et al. 2020, ApJL, 889, L1
McNamara, B. R., & Nulsen, P. E. J. 2012, MNRAS, 423, 3401
Mignone, A., Bodo, G., Massaglia, S., et al. 2007, ApJS, 170, 228
Minniti, F., & Beresnyak, A. 2015, Natur, 523, 59
Mohapatra, R., & Sharma, P. 2019, MNRAS, 484, 4881
Pfrommner, C. 2013, ApJ, 779, 10
Pizzolato, F., & Soker, N. 2005, ApJ, 632, 821
Prasad, D., Sharma, P., & Babul, A. 2017, MNRAS, 471, 1531
Prasad, D., Sharma, P., & Babul, A. 2018, ApJ, 863, 62
Pulido, F. A., McNamara, B. R., Edge, A. C., et al. 2018, ApJ, 853, 177
Qiu, Y., Bogdanovic, T., Li, Y., et al. 2019, ApJL, 877, 47
Randall, S. W., Nulsen, P. E. J., Jones, C., et al. 2015, ApJ, 805, 112
Reynolds, C. S., Balbus, S. A., & Schekochihin, A. A. 2015, ApJ, 815, 41
Rose, T., Edge, A. C., Combes, F., et al. 2019, MNRAS, 489, 349
Ruszkowski, M., Bahramian, R., Fabian, A. C., et al. 2019, MNRAS, 490, 3025
Soker, N. 2018, RAAAS, 2, 48
Soker, N. 2019, MNRAS, 482, 1883
Stern, J., Fielding, D., Faucher-Giguère, C.-A., & Quataert, E. 2019, MNRAS, 488, 2549
Storch-Bergmann, T., & Schnorr-Müller, A. 2019, NatAs, 3, 48
Tadros, Y. J., & Churazov, E. 2018, MNRAS, 477, 3672
Valdarnini, R. 2019, ApJ, 874, 42
Vantyghem, A. N., McNamara, B. R., Russell, H. R., et al. 2019, ApJ, 858, 64
Voit, G. M. 2018, ApJ, 868, 102
Wang, C., Li, Y., & Ruszkowski, M. 2019, MNRAS, 482, 3576
Werner, N., McNamara, B. R., Churazov, E., & Scannapieco, E. 2019, SSRv, 215, 5
Yang, H.-Y. K., & Reynolds, C. S. 2018, ApJ, 858, 64
Zhuravleva, I., Churazov, E., Schekochihin, A. A., & Vernaleo, J. C., Reynolds, C. S. 2006, ApJ, 645, 83
Zhuravleva, I., Churazov, E., & Schekochihin, A. A. 2014, NatAs, 3, 896:104
Zhuravleva, I., Churazov, E., Schekochihin, A. A., & Vernaleo, J. C., Reynolds, C. S. 2006, ApJ, 645, 2549
Zhuravleva, I., Allen, S. W., Mantz, A. B., & Werner, N. 2018, ApJ, 865, 53
Zhuravleva, I., Churazov, E., Schekochihin, A. A., et al. 2014, Natur, 515, 85
Zhuravleva, I., Churazov, E., Schekochihin, A. A., et al. 2019, NatAs, 3, 832

Noam Soker https://orcid.org/0000-0003-0375-8987