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Gas turbulent motions in galaxy clusters

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Abstract. We discuss various possibilities to constrain ICM turbulence in galaxy clusters using bright X-ray lines. Numerical simulations are used to find the most appropriate description of the 3D velocity field power spectrum (PS) and to calibrate the relation of observables to this PS. The impact of the velocity field on the surface brightness distribution and on the spectral shape of strong X-ray lines, modified by the resonant scattering (RS), is evaluated via radiative transfer calculations. We investigate the sensitivity of RS not only to amplitudes of motions, but also to anisotropy and spatial scales. In particular, we show that the amplitude of radial motions is most important for RS, while tangential motions only weakly affect the scattering.

Key words. X-rays: galaxies: clusters – Galaxies: clusters: intracluster medium – Line: profiles – Radiative transfer – Polarization – Methods: numerical

1. Introduction

The dynamical state of the hot gas in galaxy clusters is still poorly known. It is believed that as clusters merge or as matter accretes along filaments, turbulence should develop in the ICM, energy of which should cascade down to the small scales and dissipate. However, resolution of numerical simulations is not yet sufficient to fully resolve this process.

Current observations give us only upper limits on turbulence in clusters by means of direct measurements of line width (Sanders, Fabian & Smith 2002) or by resonant scattering (RS) measurements (Churazov et al. 2004; Werner et al. 2009). In the near future, the *Astro-H* observatory with its high-energy resolution will allow us to measure shifts and width of lines with high accuracy.

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Here we discuss a way to relate observables, such as the line-of-sight velocity and dispersion, with full 3D velocity PS. First we consider the PS from simulated galaxy clusters, then we illustrate how to implement the calibration and in the end we consider RS as one of the ways to measure and study velocities of gas motions.

2. 3D velocity power spectrum and observables

Hydrodynamical simulations provide us information about the full 3D velocity field in galaxy clusters. Using results of SPH simulations (Dolag et al. 2009) we calculated the PS (Fig. 1) for the cluster g676, which has the highest resolution, through the method described by Arévalo et al. (2010) which avoids a problem of non-periodic boundaries in data boxes. One can see (i) a significant deviation of

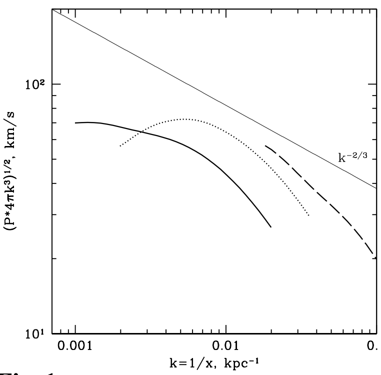

Fig. 1. Power spectrum (PS) of the 3D velocity field in a galaxy cluster from SPH simulations. the PS are calculated in cubes of 1 Mpc (solid curves), 0.5 Mpc (dotted curves) and 55 kpc (dashed curves) on a side through the variance method described in Arévalo et al. (2010). The Kolmogorov PS is shown with the thin solid line.

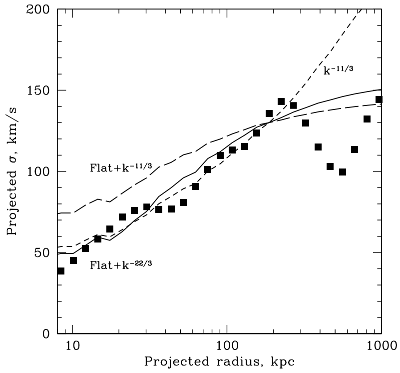

Fig. 2. Profile of projected velocity dispersion for simulated galaxy cluster (dots). Long-dashed, short-dashed and solid curves show velosity dispersion calculated from eq. (2) assuming three different PS of velocity field. Notice that measured projected velocity dispersion (emission measure weighted mean) can be considered as a structure function since the interval with size $\sim R$ mostly contribute to the dispersion measured at the projected distance R.

the PS shape from the canonical Kolmogorov PS, (ii) that both shape and amplitude of PS depend on the size of the cube used for the calculation. To some extent this behavior could be attributed to insufficient (and distance dependent) resolution of the SPH simulation and to the artificial viscosity.

Since gas motions are predominantly subsonic, the centroid shift and the width of lines, measured with X-ray observatories, contain most essential information on the ICM velocity field (Inogamov & Sunyaev 2003). I.e. we have information about emission measure weighted mean velocity and dispersion along the line of sight. Relations between these observables and the 3D velocity PS are the following:

$$P_{2D}(k) = \int P_{3D}(\sqrt{k^2 + k_z^2}) W^2(k_z) dk_z, \qquad (1)$$

$$\sigma^2 = \int P_{3D}(1 - W^2(k_z)) dk_z dk_y dk_x, \qquad (2)$$

where $P_{2D}(k)$ is a PS of observed mean velocity, σ is observed velocity dispersion, P_{3D} is a 3D PS and W is a Fourier transform of $n_e^2(z)$. In Fig. 2 we illustrate the relation (2) for simulated galaxy cluster, PS of which is shown in Fig. 1. One can see that velocity dispersion from "flat+$k^{-22/3}$" PS model (flat at low k and twice steeper than Kolmogorov PS at higher k) fits the observed velocity dispersion very well, which is in agreement with the PS shown in Fig. 1.

3. Resonant scattering as a way to measure gas motions

RS in the brightest X-ray emission lines can cause distortions in the surface brightness distribution, changes in line spectral shapes, variations in the abundance of heavy elements and polarization in lines. The magnitude of these effects is also sensitive to the characteristics of the gas velocity field (Gilfanov, Sunyaev & Churazov (1987), see also review Churazov et al. (2010)).

If one accurately measures the line ratios of (optically thick) resonant and (optically thin) non-resonant lines, the velocity amplitudes of gas motions can be found. Werner et al. (2009) obtained high-resolution spectra of the elliptical galaxy NGC 4636 using the RGS on the XMM-Newton satellite. The Fe XVII line at 15.01 Å is suppressed (Fig. 3) only in the dense

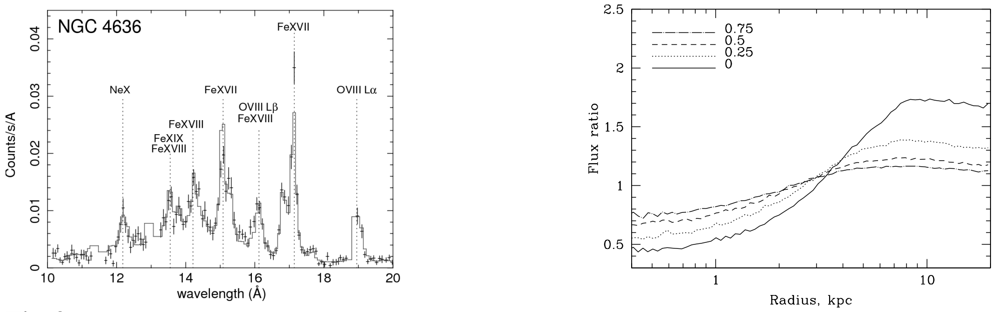

Fig. 3. *Left: XMM-Newton* RGS spectra extracted from a 0.5′ wide region centered on the core of NGC 4636. *Right:* Simulated radial profiles of the ratio of the 15.01 Å line intensities calculated with and without the effects of resonant scattering, for isotropic turbulent velocities corresponding to Mach numbers 0.0, 0.25, 0.5, and 0.75 and a flat abundance profile. Adapted from Werner et al. (2009).

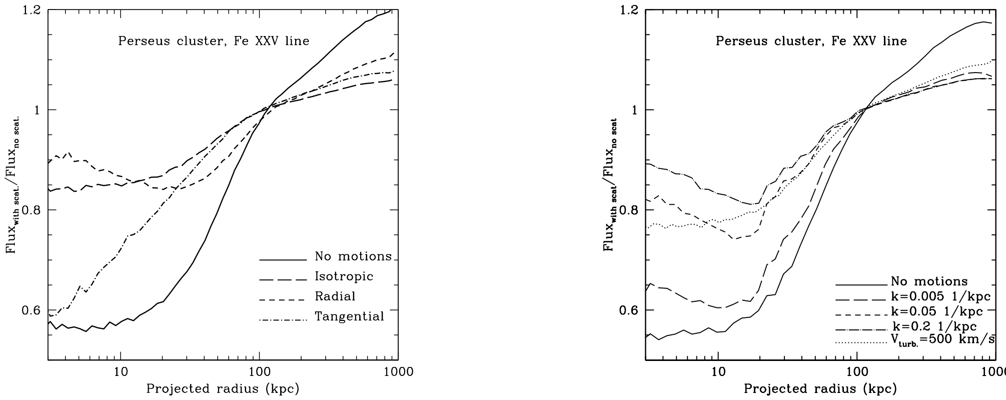

Fig. 4. *Left:* Impact of the anisotropy of stochastic gas motions on the ratio of the fluxes in the Fe XXV line at 6.7 keV in the Perseus cluster calculated with and without RS effect. *Right:* Impact of the spatial scales of gas motions on RS. Two cases of small scale motions are shown with dot-dashed and short-dashed curves. Case of large scale motions is shown with long-dashed curve. Adapted from Zhuravleva et al. (2010b).

core and not in the surrounding regions, while the line of Fe XVII at 17.05 Å is optically thin and is not suppressed. Werner et al. (2009) modeled the radial intensity profiles of the optically thick line, accounting for the effect of RS for different values of the characteristic turbulent velocity. Comparing the model to the data, it was found that the isotropic turbulent velocities on spatial scales smaller than ≈ 1 kpc are less than 100 km/s and the turbulent pressure support in the galaxy core is smaller than 5 per cent of the thermal pressure at the 90 per cent confidence level (taking into account only statistical errors).

The relation between the RS effects and the velocity field can be used to test anisotropy and spatial scales of gas motions. Zhuravleva et al. (2010b) showed that RS is most sensitive to radial small-scale motions (Fig. 4).

RS also gives us a unique opportunity to put constraints on transverse gas motions in galaxy clusters by means of polarization in lines (see Sazonov, Churazov & Sunyaev (2002); Zhuravleva et al. (2010a)). The calculated degree of polarization is shown in Fig. 5 (Zhuravleva et al. 2010a) with and without account for gas motions. For one of the most massive simulated clusters (g8 in the sample

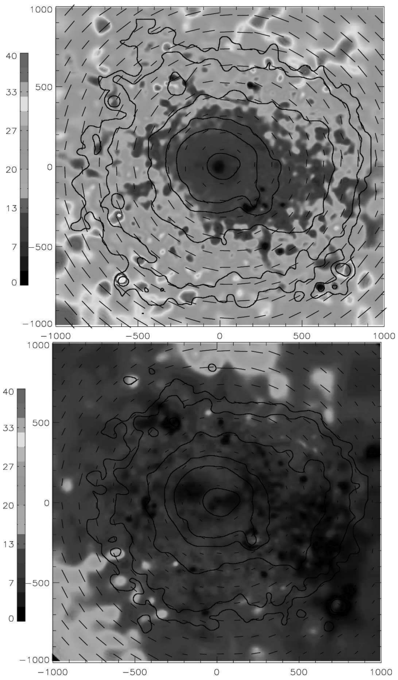

Fig. 5. Polarization degree of the simulated massive cluster g8 (Dolag et al. 2009) in the line of Fe XXV at 6.7 keV. The colors denote the polarization degree in per cent. The short dashed lines show the orientation of the electric vector. Contours of the X-ray surface brightness in the chosen line are superposed. The size of each picture is 2×2 Mpc. The top panel shows the case of gas being at rest. The bottom panel shows the case of the gas velocities obtained in the simulations. Adapted from Zhuravleva et al. (2010a)

of Dolag et al. (2009)) the polarization degree in the 6.7 keV He-like iron line reaches ~ 25 per cent at a distance of ~ 500 kpc from the center if no turbulent motions are present (top panel). Inclusion of gas motions substantially decreases the polarization down to ~ 10 per cent (bottom panel) within the same region.

4. Conclusions and future prospects

We presented a convenient way to put constraints on the amplitude and shape of 3D PS using only observables, i.e. mean velocity and dispersion along the line-of-sight. SPH simulations show that the 3D velocity PS (i) is distance-dependent, (ii) deviates significantly from the canonical Kolmogorov PS. This results should be verified with AMR simulations and simulations with higher resolution.

Line-of-sight velocity and dispersion measurements will be available in the nearest future with *Astro-H* mission. We discussed RS as one of the ways to study gas motions with *Astro-H* data, showing that RS is most sensitive to radial small-scale gas motions. Moreover, future polarimetric mission (e.g. onboard *IXO*) will fully exploit RS and allow us to constrain transverse gas motions.

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