Atmospheric Gas Dynamics in the Perseus Cluster Observed with Hitomi

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Gas motions in galaxy clusters

- clusters of galaxies
  - grow by merger and/or accretion
  - often host an AGN in the center

- gas motions in clusters
  - merger-driven shocks, bulk shear and turbulence
  - AGNs inject mechanical energy into the ICM and drive its motions
  - significant gas motions are expected in galaxy clusters

Markevitch+06

(c) NASA
Measuring ICM motions (bulk motion)

- line centroid: Doppler effect — LOS bulk motions

- LOS velocity with CCD (e.g. Dupke+06, Ota+07, Tamura+11)
  - higher significance measurements only in a few merging systems (e.g. Abell 2256)

- has been difficult
  - 500 km/s bulk velocity ~ 11 eV @ 6.7 keV
  - CCD: ΔE~150 eV
  - mostly upper limits or low significance detections
Measuring ICM motions (LOS velocity dispersion)

- Doppler broadening with grating spectrometers (e.g. Sanders+10, Pinto+15)
  - spatial extent of ICM also affects line widths
  - only bright cluster cores
  - upper limits
Hitomi SXS

- **Hitomi (ひとみ) — “Eye” to the Universe**
  - successful launch on February 17, 2016
  - observed several targets before the communication loss on March 26, 2016

- **Soft X-ray Spectrometer (SXS)**
  - one of the four main instruments
  - first non-dispersive X-ray spectrometer in orbit
  - $\Delta E \sim 5$ eV ($\times 30$ better than CCD)
  - large effective area at Fe K-band
Hitomi SXS observation of the Perseus cluster

- First light observation of the Perseus cluster core
  - Perseus cluster: brightest cluster in X-ray
  - one of the most extensively studied clusters
  - 320 ksec observation of the Perseus cluster
  - 230 ksec used in H16
- very narrow spectral lines
Hitomi SXS observation of the Perseus cluster

- LOS velocity dispersion
  - Outer: 164±10 km/s
  - Center: 187±13 km/s
- Bulk velocity map
  - bulk shear of ~150 km/s
- “quiescent” ICM
- hint of RS/non-Gaussian line shape
What’s new?

- updated velocity maps
  - full dataset (320 ksec) including remaining two offset pointings -> probing out to ~100 kpc
  - scientifically motivated region selection -> investigating associations with interesting structures
- careful treatment of PSF mixing effect
- more detailed treatment of gain calibration and systematic uncertainties
- updated redshift of NGC 1275

- other probes into ICM motions
  - line shape of emission lines
  - ion temperature

Reg0: AGN & cluster core
Reg3: Hα filament
Reg4: NW ghost cavity
Figure 6. Left: PSF corrected bulk velocity ($v_{\text{bulk}}$) map with respect to $z=0$. Right: PSF corrected LOS velocity dispersion ($\sigma_v$) map. The unit of the values is km s$^{-1}$. The Chandra X-ray contours are overlaid.

Figure 7. Same as figure 6, but PSF correction is not applied.

After determining the self-consistent parameter set of the continuum as mentioned above, we again fitted all the spectra simultaneously to obtain the parameters associated with spectral lines. This time, the temperatures and normalizations were fixed to the above obtained values, and the Fe abundance, the LOS velocity dispersion and the redshift were allowed to vary. The fitting was done using a narrow energy range of 6.4–6.7 keV, excluding the energy band corresponding to the resonance line in the observer-frame (6.575–6.6 keV). The obtained C-statistic/d.o.f. in the velocity fitting is 2822.38/2896.

Figure 6 shows the obtained velocity maps with PSF correction. The corresponding velocity maps without PSF correction are shown in figure 7 for comparison. The best-fitting values are listed in Table 1.

- bulk shear of ~100 km/s
- zero point is consistent with NGC1275
- low $\sigma_v$
  - ~200 km/s around AGN and NW cavity
  - ~100 km/s everywhere else
Search for non-Gaussian line shapes

- line center -> bulk velocity
- line width -> LOS velocity dispersion

- line shapes also reflect ICM motions
  - projected bulk motions, non-Maxwellian electron PDF
  - motion of the sizes comparable to the spectral extraction region causes deviation from Gaussian
Search for non-Gaussian line shapes

- Line shapes of less contaminated Fe transitions
- Stacked residual in velocity space
- Hint of non-Gaussianity?
  - Narrower than LSF (~230 km/s)
- Voigt function made little difference
- Skewness, kurtosis = 0
- No evidence of non-Gaussianity
First $T_{\text{ion}}$ measurement

- line center -> bulk velocity
- line width -> LOS velocity dispersion
- line shape -> projected motion, PDF

**Ion temperature also ($T_{\text{ion}}$) reflects ion motions**
- $T_{\text{ion}}$ can be probed by measuring line widths for various elements
  - thermal widths are different among species
  - velocity dispersions due to fluid motions are same

\[
\sigma_{\text{th}} = \sqrt{kT_{\text{ion}}/m_{\text{ion}}} \quad \sigma_{v+\text{th}} = (\sigma_v^2 + \sigma_{\text{th}}^2)^{\frac{1}{2}}
\]
First $T_{\text{ion}}$ measurement

- $T_{\text{ion}}$ can be probed by measuring line widths for various elements (assuming $\sigma_v=$ const for all the ions)
- line width measurement of each element to estimate $T_{\text{ion}}$ using empirical model (continuum+Gaussian)

\[
\sigma_{v+th} = \left(\sigma_v^2 + \sigma_{th}^2\right)^{1/2}
\]

\[
\sigma_{th} = \sqrt{kT_{\text{ion}}/m_{\text{ion}}}
\]

\[
\sigma_v = 129+32-45 \text{ km/s}
\]

\[
kT_{\text{ion}} = 7.3+5.3-5.0 \text{ keV}
\]

- $T_{\text{ion}}$ is consistent with $T_{\text{elec}}$ determined by continuum
Implications (dynamics)

- origin of gas motions
  - Both current AGN inflated bubbles and buoyantly rising ghost bubbles (<100 kpc) are important $\sigma_v$ sources
  - superposed streaming motions or turbulence

- if turbulence
  - if driving scale $>\sim 100$ kpc, $\sigma_v$ would radially increase (Zhuravleva+12)
    - $\sigma_v$ not radially increasing
  - emission lines are Gaussian (collected over $\sim 100$ kpc) -> driving scale is not comparable to $\sim 100$ kpc
  - driving scale is mostly smaller than 100 kpc (consistent with cavity sizes)
Implications (thermodynamics)

- Kinetic pressure support
  - \( \sigma_v \sim 100-200 \text{ km/s}, V_{\text{bulk}} \sim 100 \text{ km/s} \)
  - \( \varepsilon_{\text{kin}}/\varepsilon_{\text{therm}} = \mu m_p (3 \sigma_v^2 + V_{\text{bulk}}^2) / 3kT \) \( \sim 0.1 \)
  - HSE valid in the core

- Thermal equilibrium between electrons and ions
  - equilibration time scale is \( t_{\text{ie}} \sim 1800 t_{\text{ee}} \sim 43 t_{\text{ii}} \)
  - put lower limit on elapsed time after last major heat injection at

\[
 t_{\text{eq}} \sim 6 \times 10^6 \text{ yr} \left( \frac{n_e}{10^{-2} \text{ cm}^{-3}} \right)^{-1} \left( \frac{kT}{4 \text{ keV}} \right)^{3/2}
\]
Summary

• LOS velocity dispersion is low and mostly uniform within ~100 kpc
  • ~200 km/s around the AGN and NW ghost cavity
  • ~100 km/s everywhere else

• bulk shear of ~100 km/s
  • the zero point is consistent with the redshift of NGC1275

• no evidence of non-Gaussianity
• $T_{\text{ion}}$ is consistent with $T_{\text{elec}}$

• implications
  • both currently AGN inflated bubbles and buoyantly rising ghost bubbles seem to be important
  • turbulent driving scale < 100 kpc
  • HSE assumption is valid within the core
  • at least ~6x10^6 yr is elapsed from the last major heat injection

See also Hitomi Collaboration 2017, PASJ, in press
(https://arxiv.org/abs/1711.00240)