The Interactions of AGN Jets with the Intracluster Medium

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I. Introduction

Chandra revealed that many clusters of galaxies exhibit an interaction of AGN jets with intracluster medium (ICM). Therefore, the AGN jets are thought to supply a large amount of heat energy to the ICM so that the cooling flow is restricted.

We observed and analyzed nearby bright clusters, 2A0335+096 and A2199 which associate with radio robes, and found only a weak disturbance of the ICM around the radio jets. These results indicate that radio jets observed presently could take place only local heating and/or cooling, but they do not sufficiently reduce the overall radiative cooling. Then, we concluded that much more violent jets, whose emission has now decayed, heated up the cooling gas > 10^9 years ago.

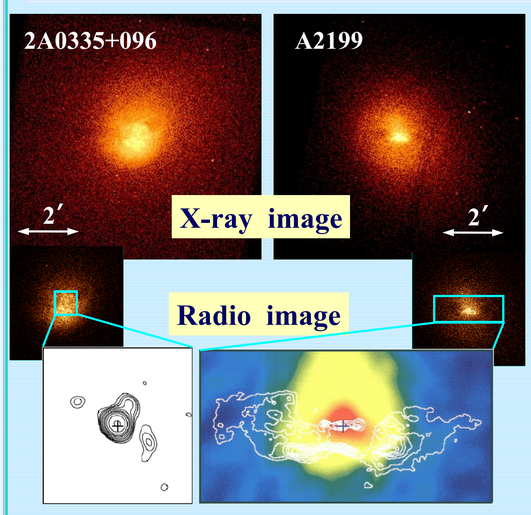
The elliptical galaxies are suitable to study the interactions between hot gas and radio jets or outbursts, because of their proximity and a smaller amount of hot gas than that of clusters of galaxies. We studied the hot gas cavities of NGC4636, and found significant increase of temperature and column density around cavities. However, the energy of gas disturbance is not so large in comparison with the clusters of galaxies.

These results indicate that the activity of most of the radio galaxies has now faded, and thus cannot supply a significant heat energy to the ICM.

II. ICM of the Galaxy Clusters, 2A 0335+0956 and A 2199

2A0335+096 and A2199 are nearby bright clusters of galaxies which are thought to be typical cooling flow clusters.

Because of efficient radiation in the central high density region, the pressure gradient arises between the inner cool gas and the outer hot one. Then, the outer gas flows into the center.



	z	Lx (erg/s)	cooling rate ($M_\odot$/yr)
2A0335	0.035	3.3×10^{41}	181
A2199	0.030	2.7×10^{44}	204

Chandra revealed that the X-ray morphology of them is not symmetric as same as other galaxy clusters.

For example, the X-ray emission of A 2199 is fainter in the W-E direction from the center than other direction.

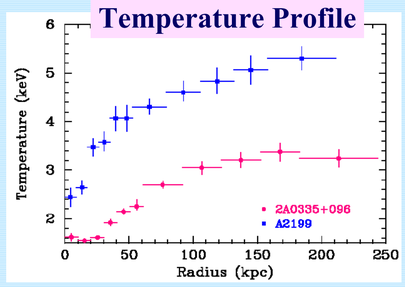
Comparing with the radio image, we can notice a weak correlation between the X-ray emission and the radio jet.

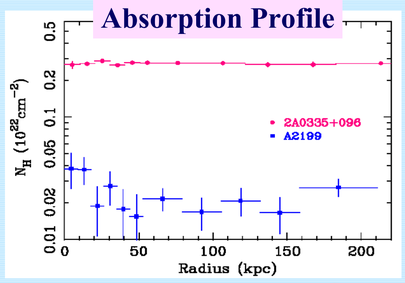
The ICM temperature decline toward the center, and the central temperature is 1.5~2.1 keV.
⇒ higher than that predicted from cooling flow (< 1 keV) !

The column density profile is monotonous (almost constant).
⇒There is no a large amount of cool gas in the central region.

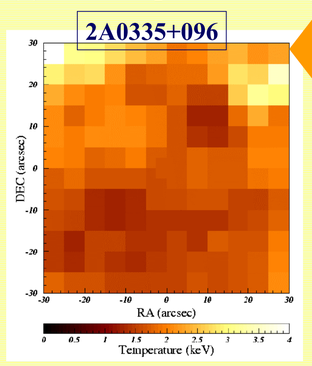
Since the radiative cooling is likely to take place under the condition of the ICM in the cluster center, it is expected that there is some heating mechanism against cooling.
jet heating ?

Then, we studied the correlation of the structure of the ICM temperature and the radio jet distribution.



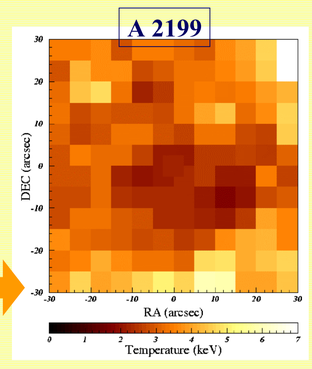


(1) The temperature map in the central region of clusters

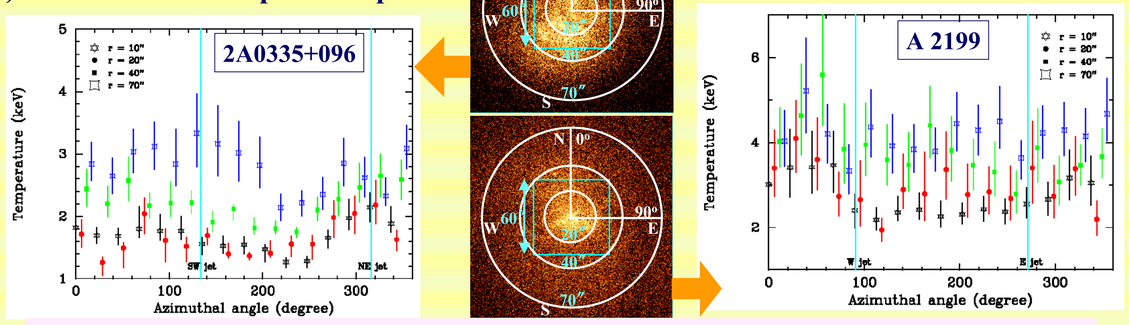


There are two hot regions of 5-10 arcsec size along the jet direction at 15 arcsec from the center, where the temperature is higher by 0.3-0.5 keV.

A remarkable cool region exists at the southern region of the center, and there is a weak hint of a higher temperature along E-W jet direction.

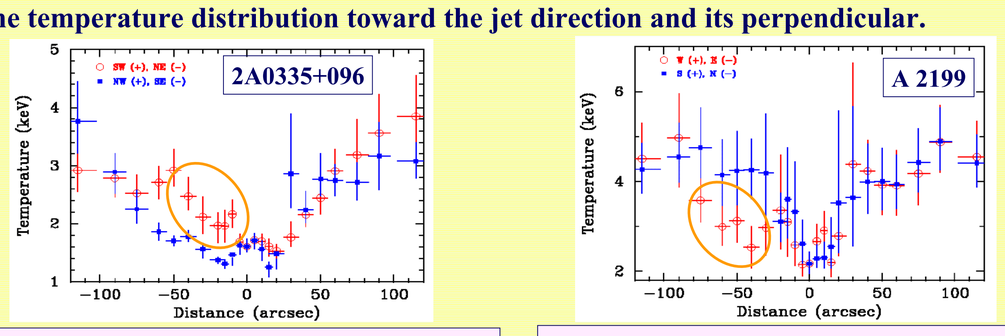


(2) The azimuthal temperature profile



Both clusters exhibit some correlation between temperature variation and radio jets.

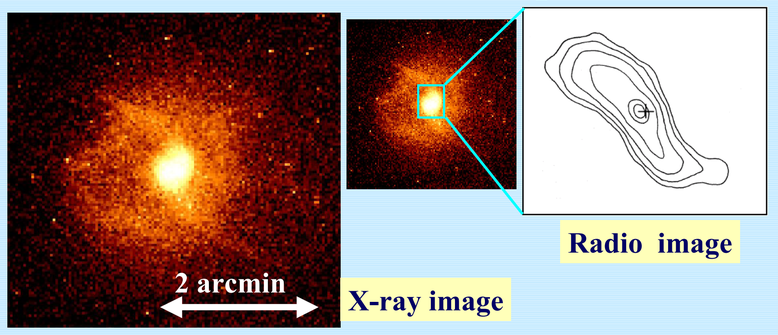
(3) The temperature distribution toward the jet direction and its perpendicular.

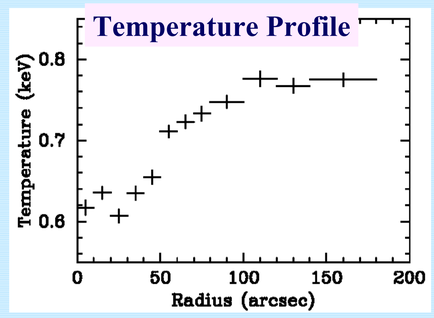


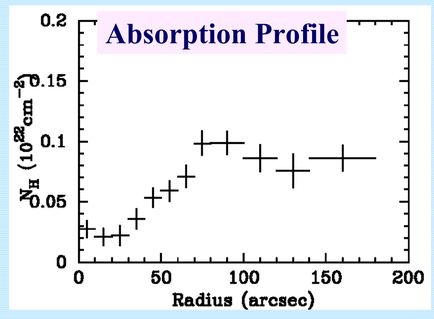
The NE jet shows a remarkably higher temperature region than that of the SW jet.

We can see the region of rather lower temperature along the W jet.

III. ISM of the Elliptical Galaxy NGC4636







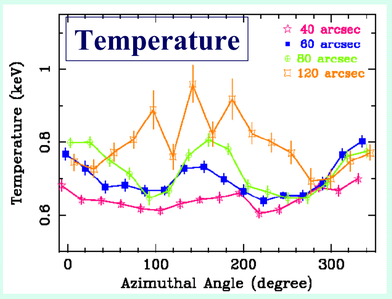
NGC4636 is a nearby (15 Mpc) bright elliptical galaxy which is located at the south outskirts of Virgo cluster.

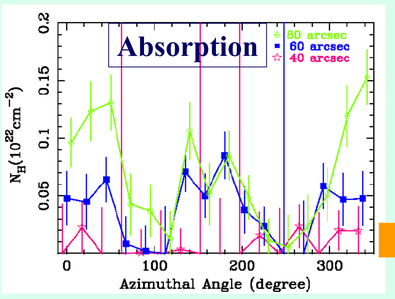
X-ray distribution of NGC4636 is so complex and shows two outstanding arm-like structure in the NE and SW direction. There are strong correlation between the X-ray and radio emission. Then, it is expected that interactions between ISM and radio jets or outbursts take place.

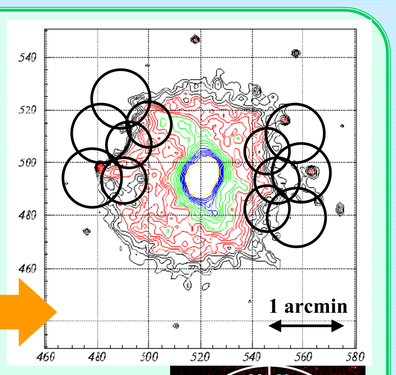
The temperature of ISM increases toward the outside.
And the profile of the absorption column density exhibits the maximum at 80-100 arcsec from the galaxy center at the radius where the temperature rises suddenly.

Then, we analyzed the properties between ISM structure and the temperature or absorption.

(1) The azimutahal profile

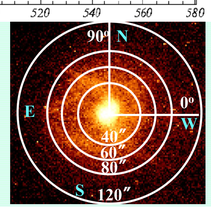






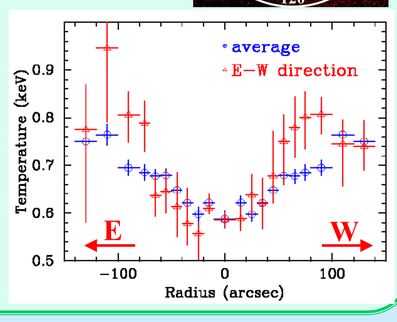
The profile of temperature and absorption significantly varies along the azimuthal direction, and the tendency of the variation is similar for both temperature and absorption.

The high temperature and absorption regions, which is designated as solid circle in right figure, are associated with the inner part of the arm structure.



(2) The directional property of the ISM temperature

At the radius of 80-100 arcsec in the east and 60-100 arcsec in the west, the temperature is clearly higher than the average. This shows that the hot regions have a scale of few tens of aecsec.



IV. Discussion

2A0335+096 and A2199

From the disturbance of temperature, the energy injected by the jets into the ICM is as follows.

- The temperature gradient dt ~ 1 keV
- The scale of hot region dL ~ a few tens of kpc
- The density in the central region n ~ 0.01 cm^{-3}

⇒ corresponds to the work of 10^{57} erg.

On the other hand, the heat conduction or sound wave reduce the temperature and density variation. The heat conduction flux for dt ~ 1 keV and dL ~ 10 kpc is calculated to be ~ 10^{42} erg/s, which indicates that the the heated-up regions found in both clusters are vanish within 10^7 years. (The crossing time of the sound wave is also the same order.)

In the cluster center, the gas lose the energy at the rate 10^{44} erg/s. Then, to reduce the radiative cooling, it is necessary to be injected the energy of 10^{59} erg by radio jets over the past 10^7 yr, which is 100 times larger than that inferred from the present ICM disturbance.

A few clusters is reported to have such a powerful radio jet at a redshift of z < 0.1, which implies that the radio jet inject a large amount of heat energy into the ICM in the past and such an active phase might have ended 10^9 years ago.

NGC 4636

The thermal energy to make the cavities under the condition that n ~ 0.015, kT ~ 0.67 and dL ~ 60 arcsec is calculated to be 10^{55} erg.

The disturbance can be smoothed by the heat conduction and sound wave in 10^7 yr. The total amount of thermal energy associated with the hot gas is ~ 10^{57} erg, which implies that nuclear outburst with 10^{55} erg take place in the time interval of 10^8 yr. However, such phenomenon is not known in other elliptical galaxies.

The similar cavities are found in many clusters of galaxies, and an energy of 10^{58} erg is necessary to make a cavity of dt ~0.5 keV and dL ~30 kpc. Thus, the disturbance energy in NGC4636 is much smaller than that of clusters of galaxies.

V. Summary

- We analyzed 2A 0335+096, A 2199 and NGC 4636 to investigate the correlation between the AGN jet and the ICM or ISM.
- As a result, the structure of the gas temperature exhibit weak correlations with the distribution of the AGN jets.
- Then, we estimate the energy injected by the jets into the ICM, and considering the effect of the heat conduction and sound wave, it is founded that the disturbance by the AGN jet vanish in a time scale of 10^7yr.
  Therefore, we can conclude that the radio jets do not have sufficient power to reduce the large scale radiative cooling.
- These results implies that the powerful activity of most of the AGN jets has finished in the past, and thus cannot supply a significant heat energy to the ICM.