TITLE
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Evolution of Cluster Scaling Relations

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Abstract. I look at the evolution of scaling relations in a simulation of clusters that includes radiative cooling of the intracluster medium. The temperature-mass relation for the brightest clusters approximately follows the self-similar theoretical prediction, but that for the luminosity-temperature relation does not. Individual clusters show mainly temperature evolution but with occasional large excursions in both temperature and luminosity during merging events.

1. Introduction

Predictions of the evolution of cluster properties often make use of the theoretical scaling relations for self-similar systems. However, these do not apply to systems in which there is non-gravitational heating and/or cooling, as is required to reproduce the present-day luminosity-temperature relation. In this paper I look at the evolution of the X-ray properties of clusters in a cosmological simulation that includes radiative cooling.

The simulation is described in Muanwong et al. (2001; see also her contribution in this volume). It has 160^3 particles each of gas and dark matter in a box of comoving size $100\,h^{-1}$ Mpc, and the cosmology is ΛCDM. By the end of the simulation approximately 20 percent of the baryons have cooled and formed stars in the box as a whole, but much more than this in clusters. Despite this overcooling, the clusters reproduce the observed luminosity-temperature relation rather well.

2. Temperature-mass evolution

The theoretical scaling relation between temperature and mass is

$$T \propto \frac{M}{R} \propto M^{\frac{2}{3}}\rho^{\frac{1}{3}} \propto M_{200}^{\frac{2}{3}}(1+z), \tag{1}$$

where M_{200} is measured within a fixed overdensity relative to the critical density.

As a population, the lower-mass clusters are more affected by radiative cooling and this makes them hotter (by removal of low-entropy core gas) and raises the constant of proportionality in Equation 1. However, this effect is small compared to the change in temperature over a cluster's lifetime and, as Figure 1 shows, the emission-weighted temperatures of clusters as they age do approximately follow the self-similar prediction.

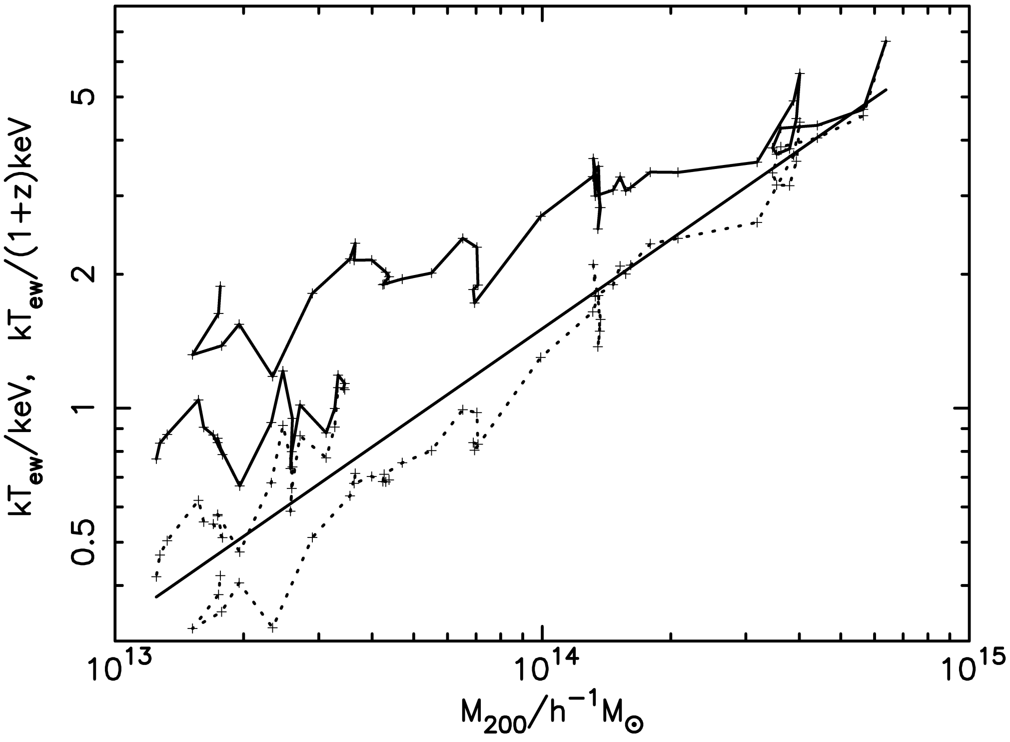

Figure 1. The solid curves show the evolution in the $T_{\rm ew}$-M_{200} plane of two example clusters. The dotted curves show the temperature multiplied by the scale factor of the Universe; for self-similar evolution this should lie parallel to the straight solid line.

3. Luminosity-temperature evolution

Assuming isothermal, self-similar clusters radiating via bremsstrahlung ($kT \gtrsim 1\,$keV) then the luminosity scales as

$$L \propto \int \rho^2 T^{\frac{1}{2}} \mathrm{d}V \propto M\rho T^{\frac{1}{2}} \propto (1+z)^{\frac{3}{2}} T^2. \tag{2}$$

However, the observed relation is steeper than this self-similar prediction (see e.g. Xue & Wu 2000) because the luminosity is dominated by the core emission that is strongly affected by heating and cooling; nor is there much evidence for redshift evolution below $z = 1$ (Borgani et al. 2001). For this reason, the results from simulations may be regarded as an empirical prediction.

As Figure 2 shows, individual clusters evolve mainly in temperature. The high-mass clusters maintain a roughly constant luminosity over time, whereas lower-mass clusters show a gradual decline in luminosity. Overall, the evolution is stronger than is seen in observations but less than predicted by the self-similar theory.

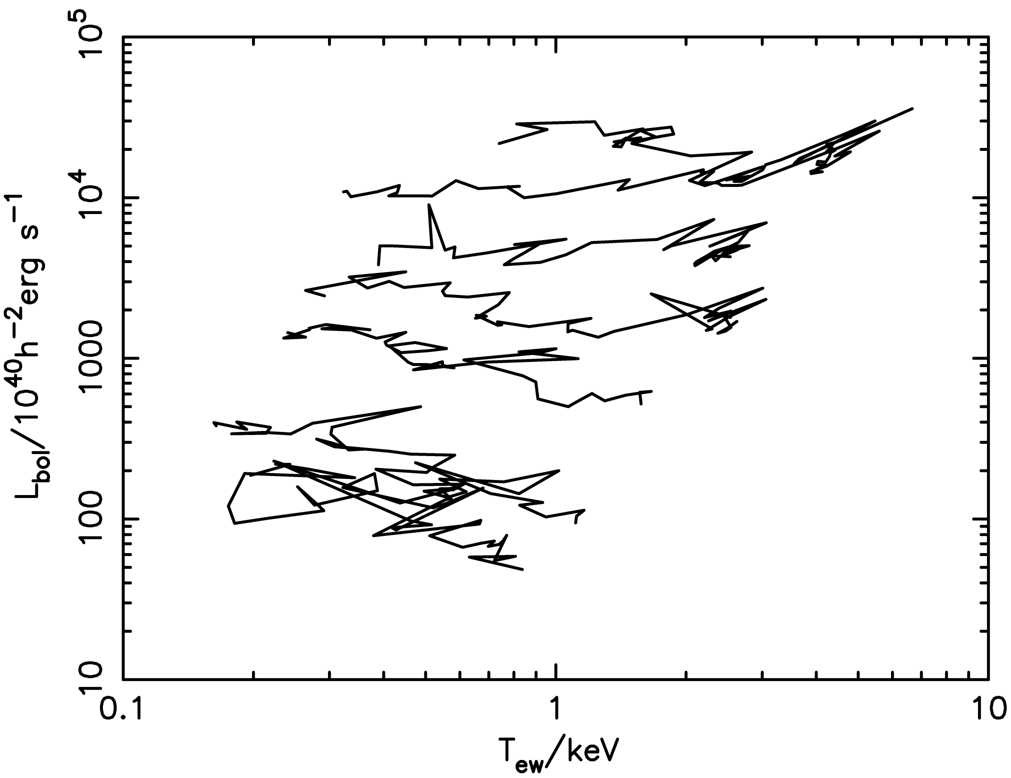

Figure 2. Evolution in the $L_{\rm bol}$-$T_{\rm ew}$ plane of a selection of clusters.

4. Mergers

Many of the trajectories in Figure 2 show large excursions in temperature and luminosity which are associated with merger events. High-resolution simulations of mergers of pairs of clusters (for a detailed description see Ritchie & Thomas 2001) show that the temperature and luminosity of merging systems can temporarily increase by factors of 3 and 10 or more, respectively. However, as shown in Figure 3, these fluctuations are roughly parallel to the observed L-T relation and so do not add considerable scatter.

5. Conclusions

Cluster simulations show that cooling breaks the expected self-similarity between temperature and mass: in low-mass clusters $T_{\rm ew} > T_{\rm vir}$, but in high-mass clusters $T_{\rm ew} \sim T_{\rm vir}$ and shows the correct redshift scaling.

Both observations and simulations give a steeper $L_{\rm bol}$-$T_{\rm ew}$ relation than is predicted by self-similar theory. However the simulated clusters show more evolution in $L_{\rm bol}$-$T_{\rm ew}$ than is observed.

Individual clusters maintain an almost constant luminosity while their temperature changes by a factor of 10, however large excursions in temperature and

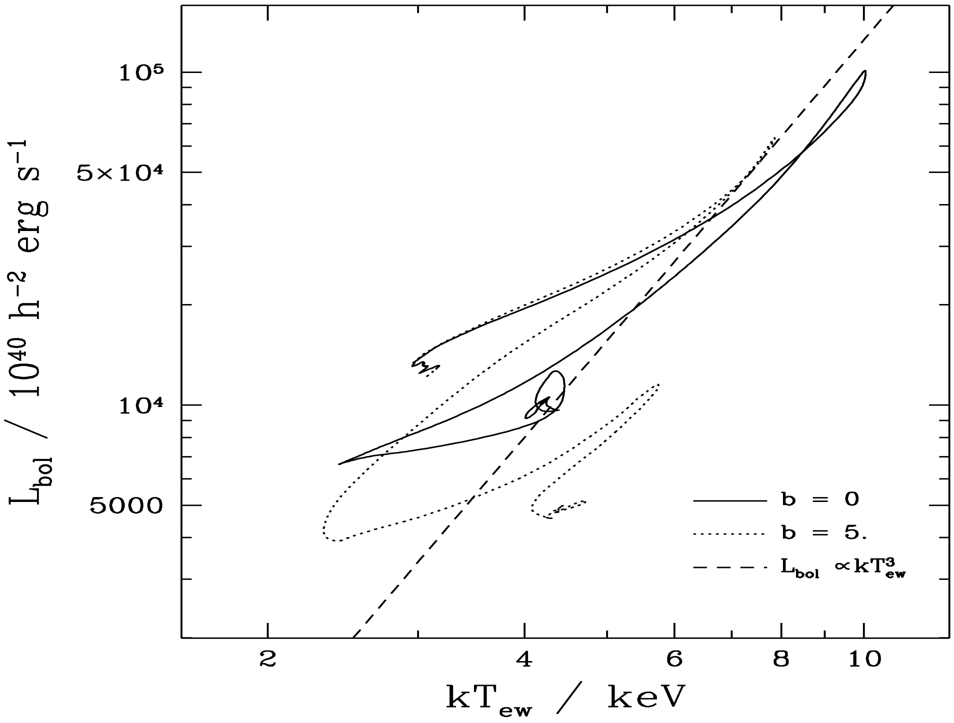

Figure 3. Evolution in the $L_{\rm bol}$-$T_{\rm ew}$ plane of two merging systems: one head-on, one with an impact parameter of 5 core radii.

luminosity are seen during merger events. This adds scatter to the $T_{\rm ew}$-M relation, but the excursions are roughly parallel to the observed $L_{\rm bol}$-$T_{\rm ew}$ relation.

For a copy of the transcripts of the conference talk, including many more results than presented in this paper, see
http://astronomy.sussex.ac.uk/~petert/public_html/index.html

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