# SIMULATING $H_0$ DETERMINATIONS FROM GALAXY CLUSTERS

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Various simplifying assumptions are made in the determination of $H_0$ via the Sunyaev–Zel'dovich + X-ray methodology used to date. These are investigated by examining results from S–Z and X-ray simulations of intracluster gas. The most significant effect is found to be the breakdown of the assumption of isothermality. The differing dynamic states of the clusters in the sample is found, as expected, to increase the spread of best estimate; this is illustrated by S–Z, X-ray and 300 MHz radio observations of Abell 1914 which show it contains recently shocked gas.

## 1 Introduction

Combining Sunyaev–Zel'dovich (S–Z) and X-ray observations of clusters of galaxies has been used to estimate $H_0$ for a number of years — see e.g. Birkinshaw[1] and F.X. Desert[2]. However, possible systematic effects have not yet been fully characterised. Here I consider some sources of error, and then illustrate some of the challenges by reference to cluster A1914. Throughout the paper we define $h = \frac{H_0}{100 \text{ km s}^{-1} \text{ Mpc}^{-1}}$.

## 2 The simulations

Eke, Navarro and Frenk[3] have simulated the formation of a set of galaxy clusters in a $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ cosmology with CDM using AP$^3$M code. The method they used was to follow the evolution of dark matter and select the deepest potential wells when $\sigma_8$ (the density fluctuations on an 8 $h^{-1}$ Mpc scale) was equal to 1.05 (which they identify with the present). They then simulate (at a higher resolution) the growth of galaxy clusters in these potential wells with the addition of gas particles using SPH code. The present-day virial masses of the clusters generated in the simulation range from 6 to $16 \times 10^{14}$ $h^{-1}$ $M_\odot$ and bolometric luminosities of $4.8$

Table 1: Redshifts and universe ages for the simulated observations. The cosmology is CDM with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$

| redshift | 0.15 | 0.2 | 0.25 | 0.38 | 0.55 | 0.78 | 1.09 |
|---|---|---|---|---|---|---|---|
| Age of universe / $\times 10^9\ h^{-1}$ years | 8.12 | 7.74 | 7.38 | 6.56 | 5.67 | 4.73 | 3.79 |

to $108 \times 10^{44}\ h^{-2}$ erg s$^{-1}$. The SPH simulations were stopped at various redshifts and ROSAT PSPC X-ray and Ryle Telescope[4] S–Z observtions of the 10 clusters were simulated. The redshift of the observations and the ages of the universe at these redshifts are shown in table 1. As the crossing time for clusters, $\sim 10^9$ years[5], is of the same order of magnitude as the higher redshift timesteps, then there is time for significant evolution to take place between consecutive observations of each cluster. Thus we have a set of 70 S–Z and X-ray cluster observations. $H_0$ is set to 70 km s$^{-1}$ Mpc$^{-1}$ in these simulated observations.

Following the standard method of detemining $H_0$, see e.g.[6], we fit an isothermal beta model to the X-ray data. We assume that the clusters are ellipsoidal on the sky and set the core radius along the line of sight to the cluster to be the geometric mean of the other two core radii. A comparison with the "observed" S–Z effect allows an estimate of $H_0$ to be obtained for each cluster.

The geometric mean of the $H_0$ estimates that we obtain is $H_0 = 62.4^{+1.8}_{-1.7}$ km s$^{-1}$ Mpc$^{-1}$. These 1-$\sigma$ errors do *not* include either the error in the X-ray temperature or the noise on the S–Z measurement, which are currently are around 15% each for a massive $z \sim 0.15$ cluster. Taking the geometric mean gives the best estimate of $H_0$ given the lack of knowledge about the line of sight size of the cluster[7].

In an attempt to determine why this best estimate is incorrect by $4.5\sigma$, we looked for systematic links between the bulk parameters of the beta model (i.e. $\beta$, $r_c$, central density) and the value of $H_0$ for each cluster, and found none. We also looked for links with luminosity and temperature and again found none.

We looked further at the state of the gas in the cluster, in particular the lack of virialization. This was quantified by calculating the kinetic energy of the gas in the rest frame of the cluster, and divided by the gas potential energy to allow comparison between different clusters. We analysed two subsamples: one with the 15 highest values of normalised K.E. and another with the 15 lowest values of normalised K.E. The highest set of values gives a geometric mean of $H_0 = 64.3^{+7.5}_{-6.1}$ km s$^{-1}$ Mpc$^{-1}$. The lowest set gives $H_0 = 64.8^{+2.8}_{-2.6}$ km s$^{-1}$ Mpc$^{-1}$. This result clearly shows that the lack of virialization affects the spread of the values for $H_0$.

We find that the key to the discrepant best estimate of $H_0$ lies in the isothermality implicit

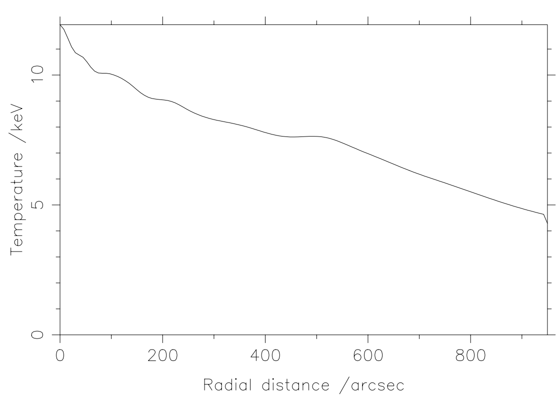


Figure 1: Temperature profile of a typical $z = 0.2$ cluster from the simulation.

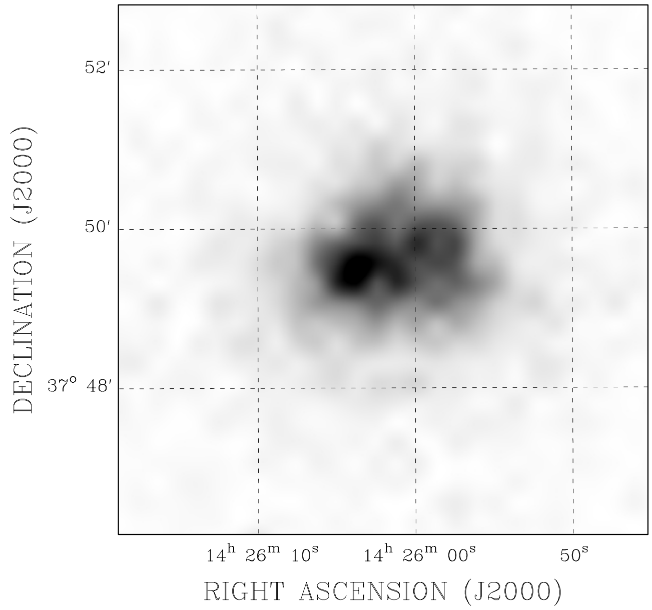


Figure 2: A 9ks observation of A1914 with ROSAT PSPC. The range of the image is 0 to 100 counts.

in using a $\beta$-model to describe the gas density distribution. Prelimary analytic work[8] indicates that this assumption, which is inconsistent with the gas being in hydrostatic equilibrium, would lead to underestimating $H_0$ by up to 15% in typical cases. The temperature profiles of the cluster gas in the simulations used here (e.g. figure 1) show a fall in termperature as the radius from the cluster centre increases, a behaviour reasonably consistent with hydrostatic equilibrium.

## 3 A1914

A1914 is a clustter of galaxies at $z = 0.171$. It has one of the highest X-ray luminosities, with $L_X = 1.84 \times 10^{38}$ W over 0.1–2.4 keV in the cluster rest frame. It has recently been observed with the Ryle Telescope, and also with the PSPC (figure 2) and ASCA. As such it seems a good candidate for $H_0$ determination.

However, the X-ray fit to a $\beta$-model is poor, and it is evident that brightest X-ray feature is not a cooling flow — it is offset from the cluster center and is not conincident with a galaxy.

There is evidence for synchrotron emission from the cluster[9]. To add to the recent NVSS observation at 1.4GHz, we have carried out Westerbork Radio Synthesis Telescope observations at 0.3 and 0.8 GHz. We find extended radio emission at low frequency (figure 3) that is offset $0.6h^{-1}$ Mpc south west from the cluster centre. The emission's extension and spectral age strongly suggest it is synchrotron emission resulting from particle acceleration due to a recent supersonic merger. This emission, the (different) offset X-ray peak and the poor fit to a $\beta$-model all point to A1914 undergoing dynamic evolution now. The formal $H_0$ estimate from A1914 is $136^{+46}_{-39}$ km s$^{-1}$ Mpc$^{-1}$. However, this cluster is not suitable for $H_0$ determination given our current models. It is far more suitable for the more interesting task of investigating how clusters work and evolve.

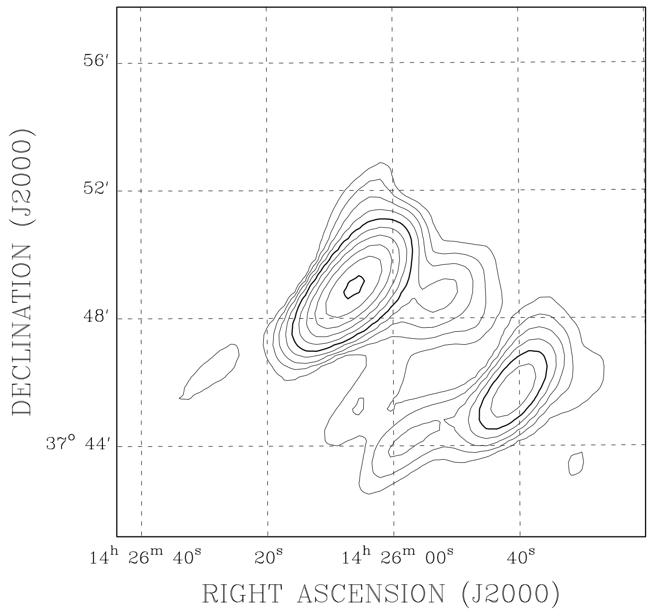


Figure 3: WRST observation of the synchrotron region (in the south) at 333MHz with a bandwidth of 24 MHz, centered on the cluster center. Contour levels are 0.01, 0.02, 0.035, 0.059, 0.097, 0.158, 0.258, 0.419, 0.68 and 1.1 Jy beam$^{-1}$. The restoring beam is a gaussian of size $143'' \times 65''$ at a position angle of 40°.

## 4 Conclusions

We have investigated the standard S–Z + X-ray method of measuring $H_0$ on sophisticated simulations of clusters. We find:

1. For large sample sizes, the method does work as long as the effect of temperature structure is included.
2. Care must be exercised when selecting samples: merging clusters are common even at low z and have very complex gas structures which are difficult to model.
3. More importantly, S–Z observations, when used in conjection with observations of radio emission, can tell us more about the state of the gas than they can about $H_0$.

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