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LETTER

Letter to the Editor

Cosmology with galaxy clusters

I. Mass measurements and cosmological parameters

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Abstract. Under the assumption that the gas mass fraction of galaxy clusters estimated out to an outer hydrostatic radius is constant, it is possible to constrain the cosmological parameters by using the angular diameter distance relation with redshift. We applied this to a sample of galaxy clusters from redshifts of 0.1 to 0.94, for which published gas and total masses are available from X-ray data. After scaling the gas fraction values to the r_{500} radius (Evrard, Metzler, & Navarro 1996), we find an apparent decrease in gas fractions at high redshifts, which can be scaled back to the mean gas fraction value at z $\sim$ 0.1 to 0.2 of $(0.060 \pm 0.002)\, h^{-3/2}$, when $\Omega_m = 0.55^{+0.35}_{-0.23}$ ($\Omega_m + \Omega_\Lambda = 1$, 1-$\sigma$ statistical error). However, various sources of systematic errors can contribute to the change in gas mass fraction from one cluster to another, and we discuss such potential problems in this method.

Key words: cosmology: galaxy clusters

1. Introduction

In recent years, measurements of gas mass fraction in galaxy clusters together with the universal value for the cosmological baryon density as derived from nucleosynthesis arguments have been used to constrain the cosmological mass density of the universe. There are two basic assumptions used in such an analysis: (1) that the galaxy clusters are the largest virialized systems in the universe and based on hierarchical clustering models that clusters represent composition of the universe as whole, and (2) that the gas mass fraction when measured out to a standard (hydrostatic) radius is constant. Evrard (1997) applied this argument to a sample of galaxy clusters studied by David, Jones & Forman (1995) and White & Fabian (1995), with redshifts up to 0.2. The gas mass fraction values were scaled to the r_{500} radius first defined by Evrard, Metzler & Navarro (1996), which has shown to be a conservative estimate of the outer hydrostatic radius based on numerical simulations. When both gas and total (virial) masses are estimated out to this radius, then the assumption that all clusters should have the same gas mass fraction is well justified. The mean gas mass fraction, as derived by Evrard (1997), for the low redshift clusters is $\bar{f}^{\rm X-ray}_{\rm gas}(r_{500}) = (0.060 \pm 0.003)\, h^{-3/2}$. Recently, Myers et al. (1997) observed the Sunyaev-Zel'dovich (SZ) effect (Sunyaev & Zel'dovich 1980) in a sample of low redshift clusters, and derived a mean SZ gas mass fraction, $\bar{f}^{\rm SZ}_{\rm gas}$, that ranges from (0.061 $\pm$ 0.011) h^{-1} to (0.087 $\pm$ 0.030) h^{-1} (we refer the reader to Birkinshaw 1998 for a recent review on the SZ effect). Using the mean cluster gas fraction and the nucleosynthesis derived value for the Ω_b, both Evrard (1997) and Myers et al. (1997) put constraints on the cosmological mass density of the universe, Ω_m, with some dependence on the Hubble constant.

If cluster gas fractions are indeed constant in a sample of galaxy clusters when calculated out to the outer hydrostatic radius, then it is possible to constrain the cosmological parameters based on their dependence in the angular diameter distance relation with redshift. In Sect. 2 of this paper, we present the potential possibility of using cluster gas fraction as a *standard candle* and apply this to a sample of $\sim$ 53 clusters that range in redshifts from 0.1 to 0.94, for which published data on masses are available from literature. In Sect. 3, we discuss various systematics uncertainties and possible selection effects in this method.

2. Method and results

In general, the gas mass of a galaxy cluster is calculated by integrating the electron number density profile, $n_{\rm e}(r)$, over an assumed shape. The X-ray emission data are usually fitted to an apriori assumed distribution, and presently the β-model is used as the preferred option. The gas mass within the galaxy cluster is given by:

$$M_{\rm gas}(\leq R) = m_p \int_0^r n_{\rm e0} \left(1 + \frac{r'^2}{r_c^2}\right)^{-\frac{3}{2}\beta} d^3r', \quad (1)$$

where n_{e0} is the central number density, r_c is the core radius of the gas distribution, and β is a parameter that describes the shape of the distribution (e.g., Cavaliere & Fusco-Femiano 1976). For the purpose of this paper, when $n_{\rm e0}$ is determined through the X-ray emission:

$$M^{\rm X-ray}_{\rm gas}(\leq \theta) \propto D_{\rm A}^{5/2}, \quad (2)$$

while when the SZ decrement (or increment) towards a cluster is used to determine $n_{\rm e0}$:

$$M_{\rm gas}^{\rm SZ}(\leq\theta) \propto D_{\rm A}^2, \tag{3}$$

where $D_{\rm A}$ is the angular diameter distance to the cluster.

The total virial mass of a galaxy cluster can be known through the measurements of the intercluster electron temperature profile, $T_{\rm e}(r)$, based on the X-ray spectral data. Under the assumption of virial equilibrium and assuming an isothermal temperature distribution with electron temperature of $T_{\rm e0}$, the total mass is:

$$M_{\rm tot}(\leq R) = -\frac{k_B T_{\rm e0} r}{G\mu m_p}\frac{d\log n_{\rm e}(r)}{d\log r}, \tag{4}$$

and

$$M_{\rm tot}(\leq\theta) \propto D_{\rm A}. \tag{5}$$

Apart from X-ray temperature measurements, the total mass can be estimated using strong gravitational lensing, which allows mass measurements near the core region of the cluster where background sources are lensed to arcs, weak lensing and cluster internal velocity dispersions, which allow mass measurements to outer regions of the cluster. However, contrary to X-ray and optical virial analysis derived masses, both SZ and lensing masses measure the mass along the cylindrical line of sight across the cluster. The total masses derived from X-ray temperature and strong lensing seem to be off by factors of 2 to 3, while weak lensing, velocity dispersion, and X-ray temperature masses seem to agree with each other at very large radii. The reasons for difference between X-ray temperature and strong lensing masses have been studied based on the presence of magnetic fields (Loeb & Mao 1994; Miralda-Escudé & Babul 1995) and cluster cooling flows (Allen 1997). In the present paper, we use the X-ray temperature data as a measurement of the total (virial) mass, since most of the clusters in our sample do not have published lensing and optical virial mass measurements yet.

The two gas fraction measurements based on the X-ray total mass is:

$$f_{\rm gas}^{\rm X-ray} \propto D_{\rm A}^{3/2}, \tag{6}$$

and

$$f_{\rm gas}^{\rm SZ} \propto D_{\rm A}, \tag{7}$$

for X-ray and SZ gas masses respectively.

For Friedmann-Lemaître cosmological models, the angular diameter distance, $D_{\rm A}$, can be written as:

$$D_{\rm A} = \frac{c}{H_0(1+z)\sqrt{\kappa}}\chi\left(x\right), \tag{8}$$

where,

$$x = \sqrt{\kappa}\int_0^{\rm z}\left[(1+z')^2(1+\Omega_M z') -z'(2+z')\Omega_\Lambda\right]^{-\frac{1}{2}} dz'. \tag{9}$$

For $\Omega_M+\Omega_\Lambda=1$ (flat universe), $\chi(x)=x$ and $\kappa=1$, for $\Omega_M+\Omega_\Lambda>1$ (closed universe) $\chi(x)=\sin(x)$ and $\kappa=1-\Omega_M-\Omega_\Lambda$, and for $\Omega_M+\Omega_\Lambda<1$ (open universe), $\chi(x)=\sinh(x)$ and $\kappa=1-\Omega_M-\Omega_\Lambda$. When Ω_Λ =0, the angular diameter distance has a well known analytical closed form solution, while for more general case with a cosmological constant, the integral over redshift must be carried out (Carroll, Press & Turner 1992).

Using published data, we compiled a sample of galaxy clusters and groups with redshifts 0.008 to 0.94. Most of the low redshift cluster and group data are from White, Jones & Forman (1997) who presented results of an X-ray image analysis of 207 clusters based on *Einstein* data. These cluster range in redshift from $\sim$ 0.008 to 0.4, with few clusters between $z\sim$ 0.3 and 0.4. Our high redshift ($z>0.4$) cluster sample is derived from various published data and includes: AXJ2019+1127 ($z=0.94$, Hattori 1997), MS1054-03 ($z=0.829$, Donahue et al. 1997), MS0451-03 ($z=0.54$, Donahue 1996), and Cl0016+16 ($z=0.554$, Neumann & Böhringer 1996). In order to perform an unbiased test, we calculated both gas and total masses in a universe with $\Omega_m=\Omega_\Lambda=0$ and $H_0=100\ h^{-1}$ km s^{-1} Mpc^{-1}, and scaled them to the r_{500} radius based on relations presented by Evrard (1997):

$$r_{500}(T_{\rm e0}) = (1.24\pm0.09)\left(\frac{T_{\rm e0}}{10\,{\rm keV}}\right)^{\frac{3}{2}}\ h^{-1}\,{\rm Mpc}. \tag{10}$$

At the r_{500} radius, the gas fraction is given by:

$$f_{\rm gas}(r_{500}(T_{\rm e0})) = f_{\rm gas}(r)\left(\frac{r_{500}(T_{\rm e0})}{r}\right)^\eta \tag{11}$$

where η is a scaling parameter determined by numerical simulations and r is the radius out to which the gas fraction is first calculated using mass measurements in literature. Evrard (1997) used $\eta=0.17$, but showed that for real data it ranges from 0.13 to 0.17, based on which clusters are included. We calculated our gas fraction values at r_{500} using η values ranging from 0.13 to 0.17, but found that the final result presented here is not heavily dependent on it. This is primarily due to the fact that for massive clusters with cluster gas temperatures close to 10 keV, the ratio between r_{500} and r is within few percent of each other. From our total sample of $\sim$ 215 clusters, we removed all of the clusters with redshifts less than 0.1. This is primarily due to the fact that the low redshift sample is mainly made of group size clusters with electron temperatures less than 3 keV, and the baryonic fraction of such clusters are primarily dominated by the baryons in galaxies and stars, instead of the intergroup gas component (Fukugita et al. 1997).

The mean baryonic fraction of galaxy clusters between redshifts of 0.1 and 0.15 is (0.060 $\pm$ 0.002) $h^{-3/2}$, which is in agreement with the value derived by Evrard (1997) of (0.060 $\pm$ 0.003) $h^{-3/2}$. We normalized the cluster gas mass fractions to our low redshift mean gas fraction. In Fig. 1, we show the observed normalized cluster gas fraction with redshift. For completeness, we show the whole sample, including clusters and groups with redshifts less than 0.1. The apparent rise in the gas

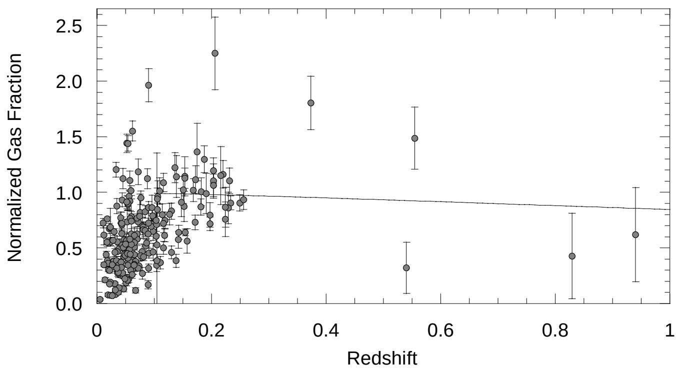

Fig. 1. The observed gas mass fraction of galaxy clusters calculated with an angular diameter distance assuming $\Omega_m = \Omega_\Lambda = 0$, and normalized the low redshift mean gas mass fraction of (0.060 ± 0.002) $h^{-3/2}$. If the universe is indeed $\Omega_m = \Omega_\Lambda = 0$ then the observed gas fraction throughout the redshift plane is expected to be constant. The apparent decrease in the gas mass fraction at high redshifts can be explained with a cosmological model where Ω_m is low. The drawn curve corresponds to $\Omega_m = 0.55$ ($\Omega_m + \Omega_\Lambda = 1$).

fraction with redshift at the low redshifts ($z \sim$ 0.008 to 0.1) is primarily due to a selection bias: as you go higher in redshift more massive clusters are selected in X-ray studies which have an increasing gas mass component.

As shown in Fig. 1, the high redshift clusters have gas fractions lower than the low redshift sample. The decrease in gas fraction at high redshift can be explained in a universe with a low Ω_m. Considering a χ^2 minimization to the observed data with the angular diameter distance, we derived a best fit Ω_m of $0.55^{+0.35}_{-0.23}$ (1-σ statistical error), with $\Omega_m + \Omega_\Lambda = 1$, at a minimum χ^2 of 62.5 for 53 clusters. The data are also consistent with $\Omega_m < 0.72$ (90% confidence interval) for an open universe with $\Omega_\Lambda = 0$.

3. Discussion

The primary assumption in constraining the cosmological parameters using the angular diameter distance is that the gas fraction at high redshift is same as the fraction at low redshift clusters. It is likely that gas fractions may vary from one cluster to another, but numerical simulations seem to strongly suggest that gas fractions measured to the outer hydrostatic radius is constant and is not significantly influenced by hydrodynamical effects (e.g., Evrard, Metzler & Navarro 1996; Evrard 1997; Lubin et al. 1996). In Shimasaku (1997), the assumption of constant gas (baryonic) fraction was used to put constrains on σ_8, the rms linear fluctuations on scales of 8 h^{-1} Mpc, and on n, the slope of the fluctuation spectrum. However, possible reasons for fluctuations in the gas fraction needs to be considered, and we discuss briefly various systematic uncertainties and biases in this method. These include gas clumping, presence of magnetic fields and magnetic pressure support, various non-gravitational processes such as heating and cooling in galaxy clusters, additional baryonic contributions, and a possible phase of gas injection from galaxies in clusters to intercluster medium.

3.1. Gas clumping and magnetic fields

Given that the gas masses are estimated from X-ray emission, which measures the $< n_e^2 >$, one needs to assume that the gas is smoothly distributed within the intercluster space. However, if gas is clumped with a clumping factor C $(=< n_e^2 >^{1/2} / < n_e >)$, then the amount of gas required to produce a fixed X-ray emission will reduce by C. The observational evidence against clumping is presented in Evrard (1997). Unlike the X-ray gas mass, the gas mass derived using the SZ effect is not subject to gas clumping as it measures $< n_e >$ directly (although the Hubble constant that could be derived by combining SZ and X-ray data is subject to gas clumping effects). Therefore, one should be able to constrain clumping in galaxy clusters based on a set of SZ and X-ray data for a cluster sample. Currently, there are 4 mass estimates from SZ effect (Myers et al. 1997), with a mean gas fraction of (0.087 ± 0.030) h^{-1} to (0.061 $\pm$ 0.011) h^{-1}. If we used the mean X-ray derived gas fraction, and under the assumption that the difference between X-ray and SZ gas fractions is due to a combination of gas clumping and the Hubble constant, an upper limit to the clumping factor C is $\sim$ 1.24 when $h = 0.65$. There is also the possibility that gas clumping is nonisothermal such that $C =< n_e^2 T_e >^{1/2} / < n_e >< T_e >$, but, constraints on such a gas clumping model will only be possible after reliable cluster gas temperature profiles are measured. In future, this should be possible with planned X-ray missions such as AXAF, XMM and Astro-E.

The presence of magnetic pressure support has been discussed as a solution to explain the difference between X-ray virial and strong gravitational lensing mass in the core regions of the cluster. Given that our method uses the fact that gas fraction out to an outer hydrostatic region is constant, it is unlikely that magnetic fields play a major role in varying the cluster gas fraction from one cluster to another. However, the difference in gas fraction near the core regions of the cluster may be explained using magnetic fields. Here again, present data do not allow reliable estimates on the amount of magnetic pressure support in galaxy clusters.

3.2. Heating and cooling in galaxy clusters

Cluster cooling flows have been observed up to $\sim$ 40% of the X-ray clusters, and it is expected that $\sim$ 10% of the observed X-ray emission in such clusters are due to cooling flows (Fabian 1994). Such cooling flows are expected to increase the gas fraction near the core region of the cluster where such effects exist. However, the apparent increase in the cluster gas fraction from high to low redshift cannot be fully explained as due to cooling flows, since the low redshift cluster sample both contains high cooling flow and low cooling flow clusters, with gas fractions that agree with each other, and that there is little evidence for cooling flows in the high redshift sample. If a heating process exists within galaxy clusters then the cluster gas fraction may be lowered.

However, no physical mechanism has yet been suggested which can lower the cluster gas fraction.

3.3. Additional baryonic contributions

The arguments used here completely ignored the presence of baryons other then gas in clusters. It is well known that the baryonic component of the massive clusters are dominated by the X-ray emitting cluster gas rather than the baryons associated with stars and galaxies in clusters. According to White et al. (1993), the mass ratio of stellar component to the X-ray emitting gas is 0.2 h^{-1} for the Coma cluster. Assuming Coma is a typical rich cluster, we can assume that all other clusters have the same ratio. However, Hattori (1997) suggested that AXJ2019+1127 at a redshift of 0.94 is a dark cluster with mass to light ratio M/L $\sim$ 1500 h $M_{\odot}/L_{\odot}$. Therefore, the stellar component may not be constant from one cluster to another, but, the effect would be to decrease the baryonic fraction at low redshifts from the high redshift values, contrary to what is observed in the present data. Also, various forms of baryonic components are expected to exist in the intercluster medium (e.g., intercluster stars, Uson et al. 1991), but, such contribution is expected to be lower than the observed variation in the gas fraction.

4. Conclusions

Under the assumption that the baryonic (gas) fraction in galaxy clusters are constant, we have constrained the cosmological parameters using the angular diameter distance relation with redshift. However, the present X-ray based data from various studies may be providing a biased result due to unknown selection effects. When the angular diameter distance dependence on the traditional Hubble constant measurements using SZ and X-ray data are included with the present method involving cluster gas mass fraction, it is likely that tighter constraints on the cosmological parameters are possible. We hope to explore this possibility in a future paper. Given the biases that may go in to the presented gas mass fraction vs. redshift diagram, we suggest that results from a well defined and random sample of galaxy clusters, such as that would be available from AXAF in X-ray and from interferometric observations in SZ, be used to constrain the cosmological parameters using the angular diameter distance relation with redshift.

5. Note

Since this work was first submitted, a paper by Danos & Pen (1998) appeared, arriving at qualitatively similar conclusions - though using cluster electron temperature, luminosity and angular size to measure the gas mass fraction of three high redshift clusters, which were compared to a global gas mass fraction value determined from numerical simulations.

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