Baryon Crisis and Cluster Mass Estimates

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Abstract. I report the current status on the determinations of the baryon fractions and dynamical/lensing masses of galaxy clusters as well as the $\sigma - T$ relationship, making use of all the published data in literature which include 304 measurements for baryon fractions, 320/21 data points for masses of intracluster gas/cluster galaxies, (152+228)/72 data points for cluster masses derived from X-ray emitting gas/optical galaxies based on the hydrostatic equilibrium hypothesis, 46/33 measurements for the projected cluster masses obtained from strong/weak lensing. A straightforward statistical analysis yields the following features: (1) The cluster baryon fraction indeed shows an increasing tendency to reach a value of $\sim 30\%$ at large cluster radius. (2) The dynamical cluster masses are in fairly good agreement with the masses determined by weak lensing technique; (3) The cluster masses provided by strong lensing and other methods are essentially consistent within a factor of $\sim 2$. (4) The cluster $\sigma - T$ relationship is in concordance with the scenario that overall galaxy clusters are the well relaxed dynamical systems. These results are strongly suggestive of a low-mass density universe ($\Omega_m < 0.3$), in which the fraction of baryonic matter ($\sim 30\%$) is not very small!

1. Introduction

The standard Big Bang Nucleosynthesis (BBN) has set rather a tight limit on the baryonic matter density of the universe (Walker et al. 1991; Schramm & Turner 1997): $0.028 < \Omega_b < 0.08$ (I adopt $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ throughout). The recent measurements of various baryonic matter components in the nearby universe indeed yield a good agreement with the BBN prediction (Fukugita et al. 1997), indicative of a relatively small fraction of baryonic matter if the total mass density of the universe is $\Omega_m > 0.1$, i.e., a significant fraction of the mass in the universe is invisible. With the progress in X-ray technique over the past decade, a considerably large amount of hot X-ray emitting gas has been detected in groups and clusters of galaxies, which gives rise to a baryon fraction of up to $f_b \sim 30\%$ (see Figure 1). If clusters are a fair sample of matter composition of the universe and if a flat cosmological model of $\Omega_0 = 1$ is acceptable, we are inevitably faced with the difficulty of the so-called baryon crisis (White et al. 1993). The most prevailing solution to the puzzle today is to work with an open universe with matter density $\Omega_m < 0.3$, which is,
nevertheless, consistent with the result obtained by a number of recent studies on the abundances and evolution of galaxy clusters, in particular the mass-to-light ratio \( M/L \) measurements (e.g. Bahcall & Cen 1993; Bahcall et al. 1995; Carlberg et al. 1997; Bahcall et al. 1997).

The key issue of either confirming or resolving the baryon crisis is closely connected to the question of how accurately one can determine the masses of galaxy clusters. Recall that the traditional cluster estimators strongly rely upon the assumption of hydrostatic equilibrium: both optical galaxies and intracluster diffuse gas trace the underlying gravitational potential of the whole cluster. An independent method of estimating cluster mass, which has been available only for decade, is to employ the gravitational lensing technique. It gives rise to cluster masses regardless of the cluster matter components and their dynamical states. A series of work has thus been made on a statistical comparison of the cluster masses derived from the traditional dynamical method and the gravitational lensing based on the published data in literature (Wu 1994; Wu & Fang 1996, 1997; Wu et al. 1998a). In this talk, I summarize the most recent finding of such series. The purpose is to demonstrate how large the uncertainties could be among the present various cluster mass estimates. Such a statistical comparison may eventually help towards confirming or resolving the baryon crisis and the \( \Omega_0 \) discrepancy, if a flat universe is preferred by the standard inflationary model, and a better understanding of the dynamical evolution of galaxy clusters.

2. Sample

In order to avoid prejudices that may have arisen from our selection criteria, we adopt only the published data sets in literature and make no attempt to extrapolate the original work. For example, we will not make additional computation of the X-ray cluster masses that were not provided by the authors, even if we have known the gas density and temperature distributions. Based on this strategy, an extensive search for literature yields 21 measurements for galaxy masses in clusters, 320 data for mass of intracluster gas, 79 data for virial cluster masses derived from optical galaxies, 152+226 data for X-ray cluster masses derived from X-ray emitting gas, 8 data for X-ray group masses, and 46/33 data for the projected cluster masses derived from strong/weak lensing. Compared to the cluster sample of White, Jones and Forman (1997 and hereafter WJF), the present sample extends the data of baryon fractions from 176 to 304, the X-ray cluster masses from 226 to 378, the gas masses from 226 to 320. Note, however, that the data points are apparently larger than the actual cluster population because in many cases several measurements have been carried out toward a single cluster. We have simply added the observed/derived data that are not among the WJF sample. Our data sets and references will be reported elsewhere (also available upon request).

3. Baryon fraction

Figure 1 displays the 304 measurements of cluster baryon (gas) fractions \( f_b \) for 238 clusters obtained at different radii. With the data being properly binned according to radius, an increasing tendency of \( f_b \) along cluster radius is clearly
Figure 1. (a) The baryon fractions in clusters of galaxies obtained from X-ray observations under the assumption of isothermal and hydrostatic equilibrium. A total of 304 data points for 238 clusters in literature are shown. (b) The same as (a) but the data sets are binned such that each bin contains 19 measurements. The observed baryon fractions in galaxies and groups of galaxies are also illustrated. The dashed lines show the BBN prediction for a flat universe of $\Omega_0 = 1$, for which we have already accounted for the uncertainty in the recent determination of the primordial Deuterium abundance.

presented. Such a variation was actually noticed two decades ago and has been confirmed by a number of recent observations (e.g. White & Fabian 1995; Ettori et al. 1997; David 1997; WJF). Two conclusions can be drawn immediately: (1) Because the cluster baryon fraction is representative of the universal value, the measurements of the baryon fractions over an ensemble of clusters shown in Figure 1 thus imply a cosmological value of $f_b = \Omega_b/\Omega_m \approx 30\%$. This leads to $\Omega_m < 0.3$ combined with the BBN prediction of $\Omega_b < 0.08$. (2) The increase of baryon fraction with radius indicates that a greater fraction of dark matter is distributed at small scales than at large scales, in contradiction with the conventional point of view.

4. Statistical comparison of mass estimates

The original data of the observationally determined cluster masses versus cluster radii are shown in Figure 2, in which we have also displayed the projected mean
Figure 2. Different mass estimates versus radii for galaxy clusters. All the data points are taken from literature. Note that the cluster masses derived from gravitational lensing are the projected ones.

cluster mass required to produce the quasar-cluster associations detected at the smallest cluster radius \( r = 1.5 \) Mpc among the four measurements (Wu & Fang 1996a), and the recent result based on the red galaxy counts behind A1689 (Taylor et al. 1998).

The X-ray/optical selected clusters exhibit a large dispersion in their dynamical masses due to the difference of richness. On the other hand, the lensing clusters are usually the most massive ones at intermediate redshifts, which enables them to act as lenses for distant galaxies. This requires that our comparison of different cluster mass estimates can only be made among the hot and massive clusters. Examination of the lensing cluster sample (see also Wu & Fang 1997) shows that the mean X-ray temperature and galaxy velocity dispersion of lensing clusters are approximately \( T = 7.5 \) keV and \( \sigma = 1200 \) km s\(^{-1}\), respectively. We slightly relax these limits and use the criteria of \( T \geq 7 \) keV or \( \sigma \geq 1100 \) km s\(^{-1}\) to select the X-ray/optical clusters for comparison. This leaves us 49/56 measurements from the WJF/other samples and 18 data for the virial cluster masses \( M_{\text{vir}} \). Furthermore, in order to facilitate a statistical comparison among different cluster mass estimates, the selected data sets are properly binned and shown in Figure 3. We fit the X-ray cluster mass \( M_{\text{xray}} \) using an isothermal \( \beta \) model with core radius \( r_c \) for the distributions of hot X-ray emitting gas based on hydrostatic equilibrium hypothesis (Figure 3). Our best-fit of the X-ray data (WJF + others) for \( \beta = 2/3 \) to \( M_{\text{xray}} = 2(kT/G\mu m_p)r^3/(r^2 + r_c^2) \) gives \( r_c = 0.25 \) Mpc and \( T = 9.5 \) keV. Apparently, no significant difference between the mean values of \( M_{\text{xray}} \) and \( M_{\text{vir}} \) is detected. Since the gravitational lensing always provides a projected gravitating cluster mass \( m_{\text{lens}} \), we need to transform the best-fitted mass profiles \( M_{\text{xray}} \) into the corresponding 2-D masses \( m_{\text{xray}} \) for the purpose of comparison. Alternatively, it should be noted that the current weak lensing technique only sets a lower bound on \( m_{\text{lens}}(r) \) within cluster radius \( r \) (e.g. Fahlman et al. 1994): \( m_{\text{lens}}(r) > \pi r^2 \Sigma_{\text{crit}} \int_r^{r_{\text{max}}} \langle \gamma T \rangle (1 - r^2/r_{\text{max}}^2)^{-1} d\ln r \).
Figure 3. (a) Statistical comparison of cluster masses inside radii \( r \) derived from dynamical analysis and gravitational lensing. We only select the massive X-ray/optical clusters in Figure 2 that satisfy \( T \geq 7 \) keV or \( \sigma \geq 1000 \) km s\(^{-1}\). The dynamical masses for these selected clusters are properly binned for illustration and fitting. The dashed/solid lines are the best-fit of the 3-D/2-D X-ray cluster masses to the theoretically expected results under the hydrostatic equilibrium hypothesis for an isothermal \( \beta \) gas distribution with \( r_c = 0.25 \) and \( T = 9.5 \). Multiplying the best-fitted 2-D X-ray cluster mass (solid line) by a factor of 2 gives the result shown by dotted line. The binned gas mass distribution of all the measurements (320) is also shown.

where \( \Sigma_{\text{crit}} = \frac{c^2}{4\pi G}(D_d/D_sD_{ds}) \) is the critical mass density, with \( D_d \), \( D_s \) and \( D_{ds} \) being the angular diameter distances to the cluster, to the background galaxies, and from the cluster to the galaxies, respectively, \( \langle \gamma_T \rangle \) denotes the shear effect on the image configuration of background galaxies introduced by the intervening cluster gravitational potential, and \( r_{\text{max}} \) is the maximum radius of a control annulus.

It turns out that the dynamical masses of clusters given by the traditional methods, namely X-ray analysis and virial theorem, are in good agreement with the gravitating cluster masses revealed by weak lensing. While we cannot exclude the possibility that dynamical analysis may systematically underestimate the true cluster masses as compared with strong lensing, the mass discrepancy, if any, is well within a factor of \( \sim 2 \). When the measurements errors are included and the uncertainties in our selection criteria of \( T \geq 7 \) keV or \( \sigma \geq 1000 \) km s\(^{-1}\) are taken into account, we conclude that there is no significant mass discrepancy among the various cluster mass estimators. This is compatible with the previous
5. The $\sigma$-$T$ relationship

The consistency between the different mass estimates indicates that as a whole, galaxy clusters can be regarded as the well relaxed dynamical systems, though substructures and complex temperature patterns have been observed at small scales. A simple and robust way to test this scenario is to employ the velocity dispersion - temperature relationship: If both the galaxies and gas are the tracers of the depth and shape of a common gravitational potential, we would expect $\sigma \sim T^{0.5}$ (Cavaliere & Fusco-Femiano 1976). In Figure 4 we show the updated $\sigma$-$T$ relationship based on 141 clusters selected from our largest cluster sample, for which both $\sigma$ and $T$ are observationally determined, where we exclude those clusters whose $\sigma$ and/or $T$ are obtained by indirect methods such as the $L_x$ - $\sigma$ and $L_x$ - $T$ correlations. Our best-fitted result reads $\sigma = 10^{2.57\pm0.03} T^{0.53\pm0.04}$ (unweighted) and $\sigma = 10^{2.53\pm0.02} T^{0.60\pm0.04}$ (weighted), which are fully consistent with previous similar work but with a reduced s.d. of the residuals (see Wu et al. 1998b and references therein). Therefore, at 3$\sigma$ confidence level the $\sigma$-$T$ relationship also supports for cluster of galaxies being a virialized system.

6. Discussion and conclusions

The overall observed baryon fraction of galaxy clusters is $\sim 30\%$. This value has been justified by our statistical comparison of various mass estimates of clusters published so far in literature, which shows a consistency between the cluster masses obtained by traditional dynamical methods and gravitational lensing,
while the latter is independent of dynamical state and matter content. Therefore, such a cosmological baryon fraction can be used for the determination of the mean mass density of the universe. In combination with the BBN prediction an open universe of $\Omega_m < 0.3$ is thus preferred. It turns out that the solution to the so-called baryon crisis is either to modify the standard BBN model or inflationary model, or to introduce a nonzero cosmological constant into physics/astrophysics.

The increasing tendency of the observed cluster baryon fraction to $\sim 30\%$ with scales (Figure 1) has brought about not only the baryon crisis, if we live in a flat universe and if we do not intend to accept a nonzero cosmological constant, but also a mystery that a greater fraction of dark matter exists at small scales than at large scales. Future cosmological study of structure formation should take this fact into account. Meanwhile, we should be aware that the fraction of baryonic matter in the universe is not small at all: $\sim 30\%$ of the matter of the universe is actually visible!

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