CONCORDANCE OF X-RAY CLUSTER DATA WITH BIG BANG NUCLEOSYNTHESIS IN MIXED DARK MATTER MODELS

RUSSELL W. STRICKLAND AND DAVID N. SCHRAMM
University of Chicago, Chicago, IL 60637; russell@oddjob.uchicago.edu, dns@oddjob.uchicago.edu
Received 1995 November 17; accepted 1996 July 11

ABSTRACT

If the hot, X-ray-emitting gas in rich clusters forms a fair sample of the universe as in cold dark matter (CDM) models and the universe is at the critical density $\Omega_T = 1$, then the data appear to imply a baryon fraction $\Omega_{b,X} (\Omega_{b,X} = \Omega_b$ derived from X-ray cluster data), larger that predicted by big bang nucleosynthesis (BBN). While other systematic effects such as clumping can lower $\Omega_{b,X}$, in this paper we use an elementary analysis to show that a simple admixture of hot dark matter (HDM; low-mass neutrinos) with CDM to yield mixed dark matter shifts $\Omega_{b,X}$ down so that significant overlap with $\Omega_b$ from BBN can occur for $H_0 \lesssim 73$ km s$^{-1}$ Mpc$^{-1}$, even without invoking the possible aforementioned effects. The overlap interval is slightly lower for lower mass neutrinos since fewer of them cluster on the scale of the hot X-ray gas. We illustrate this result quantitatively in terms of a simple isothermal model. More realistic velocity dispersion profiles, with less centrally peaked density profiles, imply that fewer neutrinos are trapped and thus further increase the interval of overlap.

Subject headings: cosmology: theory — dark matter — galaxies: clusters: general — nuclear reactions, nucleosynthesis, abundances — X-rays: galaxies

1. INTRODUCTION

Big bang nucleosynthesis (BBN) has repeatedly been found to be in agreement (within the tolerances of the measurements) with observed light-element abundances. Along with these observations, BBN predicts a baryon density (Copi, Schramm, & Turner 1995a, 1995b, 1995c)

$$0.007 h^{-2} \lesssim \Omega_b \lesssim 0.024 h^{-2}, \quad (1)$$

where $h \equiv H_0/(100$ km s$^{-1}$ Mpc$^{-1}$). Recent work (Bartlett et al. 1995; White et al. 1993) using the ROSAT and ASCA X-ray satellites has demonstrated that rich clusters of galaxies contain significant amounts of hot X-ray-emitting gas. If one assumes that the gas is gravitationally confined, then the temperature of the gas can be related to the gravitational potential and hence the total mass, $M_T$, of the X-ray-emitting region. The intensity of the emission is related to the density of the gas (baryons) in the emitting regions. The mass of the galaxies within the cluster is computed based upon photometric luminosities of the galaxies (e.g., Godwin & Peach 1977) and an empirical mass-luminosity relation (van der Marel 1991). If these clusters are fair samples of the universe, then the ratio of the hot gas mass plus the luminous mass in the galaxies, $M_{\text{galaxies}}$, to the total mass, $M_T$, is a measure of $\Omega_{b,X}$, the value of $\Omega_b$ derived from X-ray cluster data ($M_{b}/M_T = \Omega_{b,X}/\Omega_T$).

For reasonable values of the Hubble constant, the observed baryon mass of clusters is dominated by the gas, $M_{\text{galaxies}}/M_{\text{gas}} \lesssim 0.06$. Thus, most authors report only the gas mass. Table 1 lists the results of X-ray and optical mass determinations of $M_{b}$ (gas only) and $M_T$, respectively, for a number of clusters. The errors, when reported, do not include uncertainties in the optical observations. We have treated these errors with some skepticism. We computed a range of $M_{b}/M_T$ by taking a weighted average of the reported minimum and maximum values. Each data point was weighted by the reported error, $w_i = \sigma_i^{-2}/\sigma^{-2}$, where

$$\sigma^2 \equiv \sum \sigma_i^{-2},$$

when errors were not reported, the percent error was assumed to be of order unity for weighting purposes and negligible when determining extreme values. The final range is given by the (weighted) standard error of the sample. This weighting scheme emphasizes the relative errors as found in the literature while de-emphasizing the absolute errors. The observed range of $M_{b}/M_T$ as computed from the data in Table 1 is

$$0.035 \lesssim \frac{M_{b}}{M_T} \lesssim 0.063 \quad (2).$$

Figure 1 (adapted from Gott et al. 1974; Copi & Schramm 1996) shows the comparison of $\Omega_b$ from BBN (eq. [1]) and $\Omega_{b,X}$ from $M_{b}/M_T$ (eq. [2]), assuming that the clustered gas is representative of the baryon density in an $\Omega_T = 1$ universe. Notice that there is only overlap for $H_0 \lesssim 47$ km s$^{-1}$ Mpc$^{-1}$. Of course, if $\Omega_b < 1$ or if the clusters are not a fair sample, then there is no conflict for larger values of $H_0$. Furthermore, systematics (cf. Bird, Mushotzky, & Metzler 1995) seem to be capable of shifting $M_{b}/M_T$ primarily to lower, not higher, values. For example, density inhomogeneities in the hot gas would produce an anomalously high implied gas mass. Also, if significant magnetic fields were present in the cluster such that the magnetic pressure was nonnegligible compared to the thermal pressure, then $M_{b}/M_T$ would be larger than the value derived by considering the thermal pressure alone. Furthermore, weak lensing estimates of $M_T$ (Squires et al. 1996) seem to yield slightly larger values for $M_T$ than those from the X-ray data, which could further lower $M_{b}/M_T$. In this paper, however, we will accept the $M_{b}/M_T$ taken from the simplest “first-order” analysis of the X-ray data but will argue that a hot dark matter (HDM) component (neutrinos) can allow for a greater overlap. Obviously in a pure HDM model with structure formed by the wakes of cosmic strings (Brandenberger 1995; Stebbins 1995) clusters are unlikely to be fair samples. However, in this paper we will show that even in standard, inflation-inspired models an HDM admixture can increase the interval of overlap.
TABLE 1

| Cluster             | \( (M_b/M_T) h^{3/2} \) | \( \sigma_{M_b/M_T} \) | Reference |
|---------------------|---------------------------|-------------------------|-----------|
| Abell 644           | 0.0371                    | 0.0021                  | 1         |
| Abell 1413          | 0.0407                    | 0.0050                  | 1         |
| Abell 1650          | 0.0417                    | 0.0042                  | 1         |
| Abell 2319          | 0.0431                    | 0.0028                  | 1         |
| Abell 2029          | 0.0435                    | 0.0039                  | 1         |
| Abell 401           | 0.0460                    | 0.0025                  | 1         |
| Abell 2009          | 0.0481                    | 0.0032                  | 1         |
| Abell 1689          | 0.0484                    | 0.0035                  | 1         |
| Abell 3888          | 0.0491                    | 0.0028                  | 1         |
| Coma                | 0.0495                    | 0.0141                  | 2         |
| Abell 2142          | 0.0499                    | 0.0021                  | 1         |
| Abell 3266          | 0.0555                    | 0.0028                  | 1         |
| Abell 2163          | 0.0594                    | 0.0033                  | 1         |
| Shapley supercluster| 0.0636                    | ...                     | 3         |
| Abell 545           | 0.0640                    | 0.0085                  | 1         |
| Abell 3186          | 0.0654                    | 0.0085                  | 1         |
| Abell 85            | 0.0665                    | 0.0045                  | 1         |
| Abell 665           | 0.0700                    | 0.00745                 | 1         |
| Abell 1763          | 0.0700                    | 0.0060                  | 1         |
| Abell 1795          | 0.0728                    | 0.0053                  | 1         |
| Abell 478           | 0.0905                    | 0.0078                  | 1         |
| Coma                | 0.0955                    | ...                     | 4         |
| Abell 478           | 0.0990                    | ...                     | 5         |

Note.—These data were taken from: (1) White & Fabian 1995; (2) White et al. 1993; (3) Böhringer 1994; (4) Fusco-Femiano & Hughes 1994; (5) White et al. 1994. Note that the reported errors reflect uncertainties in \( M_b \) only.

In pure cold dark matter (CDM) models, the scale of clusters (\( R \gtrsim \text{Mpc} \)) has obtained a fair sample of the universe, and, hence,

\[
\Omega_{b,X} = \Omega_T M_b/M_T .
\]  

(3)

Since the most interesting case is \( \Omega_T = 1 \), we will focus our attention on this option. When one switches to a mixed dark matter model, with HDM as well as CDM, \( \Omega_T \) in equation (3) becomes the cosmological density of all of the matter which clumps on the scale of the cluster, \( \omega_{\text{cluster}} = b \Omega_{\text{cluster}} \), where \( \Omega_{\text{cluster}} = 0.2 \pm 0.1 \) (Faber & Gallagher 1979) and \( b \sim \text{few} \) is a bias factor which need not be the same as the galaxy formation bias factor used in some CDM models of structure formation. Thus,

\[
\omega_{\text{cluster}} = \Omega_b + \Omega_{\text{CDM}} + f \Omega_{\text{HDM}} ,
\]  

(4)

where \( f \) is the fraction of HDM which clumps within the cluster. Mixed dark matter (HDM + CDM) models (Achilli, Occhionero, & Scarmella 1985; Bonometto & Valdarnini 1985; Occhionero 1985; Schaefer & Stecker 1984; Valdarnini & Bonometto 1985) have been shown to be a viable way to enable COBE-normalized CDM-like models to fit galaxy correlation data, for \( \Omega_{\text{HDM}} = 0.2 \) with \( \Omega_T = 1 \) (Primack et al. 1995; Davis 1997).

2. LOW-MASS NEUTRINOS

Neutrinos are the best candidate for the HDM. The sum

![Figure 1](https://example.com/figure1.png)

**Fig. 1.** Values of \( \Omega_b \) allowed by BBN and implied by X-ray cluster observations for a CDM model with \( \Omega_T = 1 \). Concordance between the two methods of determining \( \Omega_b \) requires that \( H_0 \lesssim 47 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Also shown are bounds based upon the age of globular clusters (\( t_0 > 10 \text{ Gyr} \)) and Type Ia SN determinations of \( H_0 (H_0 \geq 38) \).
of the masses of all of the species of neutrinos (and antineutrinos) yields (Lee & Weinberg 1977; Cowsik & McClelland 1972; Marx & Szalay 1972)

$$\Omega_{\text{HDM}} = \frac{\sum_j m_j}{92 \times 10^3 \text{ eV}}.$$  \hspace{1cm} (5)

The fraction of neutrinos which will contribute to the cluster is $f = \frac{\varepsilon_{\text{HDM}}}{\varepsilon_{[\beta, \text{CDM}]}}$, where $\varepsilon_x$ is the ratio of the density of component $x$ within the cluster to the cosmological density of the same component. In the spirit of the Thomas–Fermi corrections used in models of degenerate electrons within a Coulomb potential (Salpeter 1961), we can write $\varepsilon_{\text{HDM}}$ for a single neutrino mass (which could be degenerate and shared by multiple neutrino species) locally as a ratio of Fermi integrals, $\varepsilon_{\text{HDM}} = I(m, \phi(r)/kT;)/I(0)$, where $\phi(r) = -GM(r)/r$, $T_v = 1.9$ K, and

$$I(z) = \int_0^\infty \frac{y^2}{e^{y^2} + 1} \ dy$$ \hspace{1cm} (6)

is the relativistic Fermi distribution function. (A relativistic distribution is employed because, owing to the low cross section for neutrino interactions, the distribution has not changed since the neutrino temperature exceeded about 1 MeV [Lee & Weinberg 1977; Tremaine & Gunn 1979].) We can generalize to neutrino species with different masses by replacing $I_{\text{HDM}}$ in equation (4) with $\sum_j I_j_{\text{HDM}}(j)$, where $f_j = f(m_j)$ and $\Omega_{\text{HDM}}(j) = m_j/(92 \times 10^3 \text{ eV})$. For the remainder of this paper we will consider only the case of a single (but possibly degenerate) neutrino mass, as this will serve to suitably illustrate the features of this model.

We defined $\varepsilon$ such that $\chi_{\text{cluster}} = \frac{\varepsilon_{[\beta, \text{CDM}]}(\Omega_b + \Omega_{\text{CDM}})}{\Omega_{\text{HDM}}}$, where $\varepsilon_{\text{cluster}} \equiv \rho_{\text{cluster}}/\rho_{\text{crit}}$ and $\varepsilon$ denotes the average value for the cluster. Thus,

$$f = (\Omega_b + \Omega_{\text{CDM}}) \frac{\varepsilon_{\text{HDM}}/\chi_{\text{cluster}}}{1 - \Omega_{\text{HDM}}(\varepsilon_{\text{HDM}}/\chi_{\text{cluster}})},$$ \hspace{1cm} (7)

where $\chi_\text{Coma} \approx 280$ (e.g., White et al. 1993). If $0 \leq \varepsilon_{\text{HDM}} \leq \chi_\text{cluster}$, as one would expect, then $0 \leq f \leq 1$. Figure 2 shows how $f$ depends on the strength of the cluster potential, $\langle v^2 \rangle$, with the cluster radius fixed at 1.5 $h^{-1}$ Mpc, the standard Abell radius. Figure 3 gives the fraction of trapped neutrinos as a function of the radius of the cluster with the potential strength fixed at (1800 km s$^{-1}$)$^2$, the value adopted by White et al. (1993). The cluster is parameterized in terms of these two quantities ($\langle v^2 \rangle$ and $R$). Notice from equation (6) that $\varepsilon_{\text{HDM}}$ is a function of $\langle v^2 \rangle = \phi \propto M/R$ but not $R$ alone and that $\chi_{\text{cluster}}$ is a function of $\langle v^2 \rangle$ and $R$; $\chi_{\text{cluster}} \propto M/R^3 \propto \langle v^2 \rangle/R^2$. Thus, Figure 2 illustrates the effects of changing $\varepsilon_{\text{HDM}}$ and $\chi_{\text{cluster}}$, since $\langle v^2 \rangle$ is an independent variable in both parameters. However, in Figure 3 only $\chi_{\text{cluster}}$ varies since $\varepsilon_{\text{HDM}}$ is not a function of $R$ alone. Figure 4 gives $f$ as a function of $m_v$. Note that $f$ increases with $m_v$ since more massive neutrinos are more likely to clump on the scale of rich clusters.

In computing $\varepsilon_{\text{HDM}}$ we adopt an isothermal velocity dispersion; therefore, $\varepsilon_{\text{HDM}}$ is constant throughout the cluster. This assumption is quite good for our purposes since even fairly large variations in the actual mass distribution of the cluster have little effect upon the derived fraction of trapped neutrinos (see Fig. 2). Furthermore, an isothermal model is the most conservative choice in that it overestimates the

![Figure 2](image-url)  

**Fig. 2.** Fraction of trapped neutrinos as a function of virial velocity dispersion (normalized to the value for the Coma cluster). We have assumed $\Omega_{\text{HDM}} = 0.2$. Thus the sum of all neutrino and antineutrino masses is approximately 18 $h^2$ eV.
Fig. 3.—Fraction of trapped neutrinos as a function of cluster radius (normalized to the radius for the Coma cluster) for a fixed $\langle \nu^2 \rangle = \langle \nu^2 \rangle_{\text{Coma}}$. See Fig. 2 for details concerning $\Omega_{\Lambda CDM}, \Omega_b$, and $m_\nu$.

Fig. 4.—Fraction of neutrinos of a given mass (in eV) which are trapped within the Coma cluster for an $\Omega_{\text{HDM}} = 0.2$ model. Note that an $\Omega_{\text{HDM}} \approx 0.2$ universe will not allow a $\nu \bar{\nu}$ pair with individual masses in excess of $\sim 5.5$ eV for $h \lesssim 0.8$. Thus, $m_\nu \gtrsim 5.5$ eV requires that $\Omega_{\Lambda CDM} + \Omega_b \lesssim 0.8$. 

574
FIG. 5.—Values of \( \Omega_b \) concordant with BBN and X-ray cluster observations. The cluster model assumes that \( \Omega_{\text{HDM}} = 0.2, \Omega_c = 1, \) and \( m_v \sim 2 \) eV, consistent with a single massive \( \nu \bar{\nu} \) pair. Values of \( \Omega_b \) consistent with both methods require \( H_0 \lesssim 73 \) km s\(^{-1}\) Mpc\(^{-1}\). See Fig. 1 for details about the other features of this plot.

FIG. 6.—Maximum values of \( h \) from concordance of BBN and “first-order” X-ray cluster observations as a function of \( \Omega_{\text{HDM}} \). Note that these curves do not represent particular values of \( m_v \) since the total mass in neutrinos is a function of \( h \) and \( \Omega_{\text{HDM}} = 1 - (\Omega_b + \Omega_{\text{CDM}}) \). The inset shows the dependence of the concordance interval upon the number of massive neutrino species. The three curves converge for larger values of \( 1 - \Omega_{\text{HDM}} \) since \( m_v \propto \Omega_{\text{HDM}} \) tends toward zero. Thus, for reasonable values of \( \Omega_{\text{HDM}} \), the number of massive neutrino species is unimportant, provided that there is at least one.
number of neutrinos bound to the cluster. In an isothermal model, \( \rho \propto r^{-2} \). Any model in which the total density profile is less centrally peaked (Bird, Mushotzky, & Metzler 1995; Girardi et al. 1996) will have \( |\phi(r)| \leq |\phi(R)| \) everywhere within the cluster. Thus, \( f \) will be smaller than in the isothermal case (see eqs. [6] and [7]).

Figure 5 shows the overlap in \( \Omega_b \) as derived from BBN (eq. [1]) and our mixed dark matter interpretation of the Coma cluster data (eqs. [2], [3], and [4]) for \( \Omega_{HDM} = 0.2 \). It is clear that this overlap increases with decreasing neutrino mass since fewer neutrinos will clump on the scale of the cluster. However, \( \Omega_x \) is fairly insensitive to \( m_\nu \) for a particular value of \( \Omega_{HDM} \). To see this, we can expand \( \Omega_{v, x} \) in powers of \( f \); from equations (3) and (4) we have

\[
\Omega_{v, x} \approx 1 + \frac{\Omega_{HDM}}{\Omega_b + \Omega_{HDM}} f + \cdots + 1 + 0.2f^2,
\]

for \( \Omega_{HDM} = 0.2 \) and \( h = 0.5 \). For this value of \( h \), equation (5) specifies a maximum neutrino mass (one \( \nu \) pair) of \( m_\nu \approx 2 \) eV. Figure 4 shows that \( f \leq 0.005 \) for this range of neutrino-masses. Thus, changing the neutrino mass, or similarly the number of massive neutrino species, will result in a change in \( \Omega_{v, x} \) on the order of several hundredths of a percent.

Although we have shown that the X-ray cluster data can be made to be consistent with the predictions of big bang nucleosynthesis for \( H_0 \lesssim 73 \) km s\(^{-1}\) Mpc\(^{-1}\), we note that this concordance depends sensitively upon the upper limit of \( \Omega_b h^2 \) derived from the observed light-element abundances. If future measurements of light-element abundances find that \( \Omega_b h^2 \) lies near the present upper limit (\( \Omega_b h^2 \approx 0.024 \)), then the consistency of X-ray cluster data and BBN will be retained. However, if \( \Omega_b h^2 \) is found to be less than the value representing the intersection of the lower \( \Omega_{v, x} \) curve and the line \( h = 0.38 (\Omega_b h^2 \approx 0.021) \), there will no longer be a range of concordance.

The maximum value of \( h \) consistent with BBN and these cluster data is given by

\[
h = \left( \frac{0.024}{0.035} \right)^2 \frac{\omega_{v, x}^2}{\omega_{\text{cluster}}}.
\]

Figure 6 illustrates the upper limit of the range of consistency for \( h \) as a function of \( 1 - \Omega_{HDM} \) for these observations for a range of \( \Omega_{HDM} \) and for various numbers of massive neutrino species. Since \( m_\nu \propto \Omega_{HDM} \), the limiting value of \( h \) becomes insensitive to the multiplicity of the mass degeneracy for larger values of \( 1 - \Omega_{HDM} \), where \( \Omega_{HDM} \) tends toward zero. This figure also illustrates this decreasing importance of the actual number of massive neutrino species with decreasing \( \Omega_{HDM} \).

3. CONCLUSIONS

Structure formation in a CDM + HDM model is initiated by perturbations in the CDM field. The neutrinos are trapped in the primordial fluctuations and thereby accrete onto the new structure. Our analytical model illustrates that neutrinos contribute to the cluster halo. Although the model is simplistic, its results are believable. We find that neutrinos are only a small component of the mass of the cluster. Since the neutrinos are such a small component of the mass of the cluster, \( \Omega_x \) is effectively represented by the (smaller) \( \omega_{\text{cluster}} \) as described in the text. Thus, we have shown that in the framework of a cold + hot dark matter model with massive neutrinos these data are consistent with BBN, \( \Omega_\nu = 1 \), and \( H_0 < 73 \) km s\(^{-1}\) Mpc\(^{-1}\). While our work was in progress, Kofman et al. (1996) carried out an extensive study of similar models including both analytical work and numerical simulations. Kofman et al. were pessimistic about their model’s ability to resolve the baryon crisis in X-ray clusters because the central, derived values of \( \Omega_b \) still disagree. However, their analysis concluded that the ratio of baryon to dark matter mass in clusters exceeds the background value by 25%, which translates to \( \omega_{\text{cluster}} \approx 0.8 + 0.2\Omega_b \) in the notation of this paper. Combining equations (1) and (2) with this criterion yields a maximum allowed value of \( h \) given by \( 6h^2 + 7h^2 + 0.041 \). Kofman et al.’s criterion can be shown to allow concordance between X-ray cluster data and observed light-element abundances for \( H_0 < 72 \) km s\(^{-1}\) Mpc\(^{-1}\), in good agreement with our result of \( h < 0.73 \). Thus, we are in good quantitative agreement with Kofman et al., but we choose to emphasize the degree of overlap rather lamenting the nonoverlapping regions of parameter space. In such mixed dark matter models the more “radical” options of Fukugita, Hogan, & Peebles (1993) for resolving this issue become unnecessary. As long as observed light-element abundances allow \( \Omega_b h^2 \geq 0.021 \) there will be a range of concordance between X-ray cluster data and BBN. This critical value of \( \Omega_b h^2 \) will increase if low values of \( H_0 \) are ruled out. However, as mentioned earlier, numerous systematic effects could shift the cluster data, lowering this critical value and increasing the range of concordance toward larger values of \( H_0 \).

We acknowledge useful discussions with David Burstein, Craig Copi, Evalyn Gates, Richard Mushotzky, and Mike Turner. This work was supported in part by NSF, NASA, and DOE at the University of Chicago and by DOE and NASA, through grant NAG5-2788, at Fermilab.

REFERENCES

Achilli, S., Occhionero, F., & Scarmiella, R. 1985, ApJ, 299, 577
Bartlett, J. G., Blanchard, A., Silk, J., & Turner, M. 1995, Science, 267, 980
Bird, C., Mushotzky, R., & Metzler, C. 1995, ApJ, 453, 40
Böhringer, H. 1994, in Cosmological Aspects of X-Ray Clusters of Galaxies, ed. W. C. Seiler (NATO ASI Ser. C, 441) (Dordrecht: Kluwer), 123
Bonometto, S., & Valdarnini, R. 1985, ApJ, 299, L71
Brandenburger, R. 1995, in CP Violation and the Limits of the Standard Model, ed. J. F. Donoghue (Singapore: World Sci.), 551
Copi, C., & Schramm, D. 1996, Comments Nucl. Part. Phys., 22, 1
Copi, C., Schramm, D., & Turner, M. 1995a, Science, 267, 192
Copi, C., Schramm, D., & Turner, M. 1995b, ApJ, 455, L95
—— 1995c, Phys. Rev. Lett., 75, 3981
Cowsik, R., & McClelland, J. 1972, Phys. Rev. Lett., 29, 669
Davis, M. 1997, in Critical Dialogues in Cosmology, ed. N. Turok (Princeton: Princeton Univ. Press), in press
(http://xxx.lanl.gov/abs/astro-ph/9610149)

Faber, S., & Gallagher, J. 1979, ARAA, 17, 135
Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1993, Nature, 366, 309
Fusco-Femiano, R., & Hughes, J. P. 1994, ApJ, 429, 545
Girardi, M., Fadda, D., Giuricin, G., Mardorissian, F., Mezzetti, M., & Biviano, A. 1996, ApJ, 457, 61
Godwin, J., & Peach, J. 1977, MNRAS, 181, 323
Gott, J., Gunn, J., Schramm, D., & Tinsley, B. 1974, ApJ, 194, 543
Kofman, L., Klypin, A., Pogosyan, D., & Henry, J. P. 1996, ApJ, 470, 102
Lee, B., & Weinberg, S. 1977, Phys. Rev. Lett., 39, 165
Mang, G., & Szalay, A. 1972, in Neutrino ’72 (Bologna: Editoria Compositori)
Occhionero, F. 1985, Cosmic Background and Fundamental Physics (Bologna: Editoria Compositori)
Primack, J., Holtzman, J., Klypin, A., & Caldwell, D. 1995, Phys. Rev. Lett., 74, 2160
Salpeter, E. 1961, ApJ, 121, 161
Schaefer, R., & Stecker, F. 1984, Phys. Rev. Lett., 53, 1292
Squires, G., Kaiser, N., Babul, A., Fahlman, G., Woods, D., Neuman, D. M., & Boehringer, H. 1996, ApJ, 461, 572
Stebbins, A. 1995, private communication
Tremaine, S., & Gunn, J. 1979, Phys. Rev. Lett., 42, 753
Valdarnini, R., & Bonometto, S. 1985, A&A, 146, 235
van der Marel, R. 1991, MNRAS, 253, 710
White, D. A., & Fabian, A. C. 1995, MNRAS, 273, 72
White, D. A., Fabian, A. C., Allen, S. W., Edge, A. C., Crawford, C. S., Johnstone, R. M., Stewart, G. C., & Vogues, W. 1994, MNRAS, 269, 589
White, S., Navarro, J., Evard, A., & Frenk, C. 1993, Nature, 366, 429