A COMPLETE SAMPLE OF 12 VERY X-RAY LUMINOUS GALAXY CLUSTERS AT $z > 0.5$

H. Ebeling,¹ E. Barrett,¹ D. Donovan,¹ C.-J. Ma,¹ A. C. Edge,² and L. van Speybroeck¹

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ABSTRACT

We present the statistically complete and cosmologically most relevant subset of the 12 most distant galaxy clusters detected at $z > 0.5$ by the Massive Cluster Survey (MACS). Ten of these systems are new discoveries; only two (MACS J0018.5+1626, aka C1 0016+1609, and MACS J0454.1−0300, aka MS 0451.6−0305) were previously known. We provide fundamental cluster properties derived from our optical and X-ray follow-up observations as well as the selection function in tabulated form to facilitate cosmological studies using this sample.

Subject headings: cosmology: observations — galaxies: clusters: general — X-rays: general

Online material: color figure

1. INTRODUCTION

The Massive Cluster Survey (MACS) was launched in 1998 with the goal of compiling the first large, statistical sample of very X-ray luminous clusters at $z > 0.3$. A comparison of the flux limits and solid angles of various X-ray cluster surveys conducted previously demonstrates that the ROSAT All-Sky Survey (RASS) was then—and remains today—the only existing X-ray data set that allows these extremely rare systems to be detected in significant numbers (Fig. 1 of Ebeling et al. 2001). A detailed description of the MACS strategy is given in the same paper. In brief, the MACS cluster sample is compiled by applying limits in X-ray flux and spectral hardness to all sources listed in the RASS Bright Source Catalogue (BSC; Voges et al. 1999) that fall within the part of the extragalactic sky that is observable from Mauna Kea ($-40° > \delta > 80°$, $|b| > 20°$) and by conducting an identification program that combines searching various astronomical object catalogs with extensive optical imaging observations. Likely cluster candidates are then targeted in spectroscopic observations and added to the MACS catalog if their measured redshift exceeds $z = 0.3$. Although the required optical follow-up observations are currently complete only for the MACS Bright Sample (defined as comprising all sources with BSC detect fluxes in excess of $2 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ in the 0.1–2.4 keV band; H. Ebeling et al. 2007, in preparation), we gave priority to the most distant cluster candidates regardless of X-ray flux down to the overall MACS flux limit of $1 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$. We are thus confident that the sample presented here, the set of the 12 MACS clusters at $z > 0.5$, is complete at the nominal 90% level aimed at for the entire survey.

We assume a $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ throughout.

2. FOLLOW-UP OBSERVATIONS

As they were detected in the course of the survey, MACS clusters at $z > 0.5$ were given highest priority in our in-depth follow-up observations. Eight of the 12 clusters forming the final sample were targeted in dedicated observations at 30 GHz with the BIMA interferometer; a strong detection of the Sunyaev-Zeldovich effect was obtained for all of them (LaRoque et al. 2003). All newly discovered clusters were observed with the ACIS-I instrument aboard the Chandra X-Ray Observatory in guaranteed time made available by Chandra Telescope Scientist L. van Speybroeck. In 2006 December, we completed moderately deep observations with the SuprimeCam wide-field imager on the Subaru 8.3 m telescope on Mauna Kea in the $B$, $V$, $R$, $I$, and $z'$ passbands. In addition, $U$-band images of all systems have been obtained with the MegaCam 1° imager on the 3.6 m Canada-France-Hawaii Telescope. High-resolution imaging of the cluster cores was performed with the Advanced Camera for Surveys on the Hubble Space Telescope (program ID 09722, PI: H. Ebeling) in the F555W and F814W filters. Moreover, we conducted extensive spectroscopic observations of galaxies in the fields of all 12 clusters with multiobject spectrographs on 8 m–class telescopes on Mauna Kea (Gemini, Keck-I, Keck-II); a catalog of more than 3000 redshifts of galaxies in MACS cluster fields can be found in E. Barrett & H. Ebeling (2007, in preparation).

A wealth of science results, ranging from an in-depth study of the massive cooling-core cluster MACS J1423.8+2404, through work on galaxy evolution in clusters, to a study of the large-scale structure surrounding the most distant MACS clusters, has been obtained from these observations (LaRoque et al. 2003; Ebeling et al. 2004; Allen et al. 2004; Stott et al. 2007; G. Smith et al. 2007, in preparation; E. Barrett et al. 2007, in preparation; J. Kartaltepe et al. 2007, in preparation; H. Ebeling et al. 2007, in preparation; Edge et al. 2007), with additional major projects such as a comprehensive weak-lensing analysis of the cluster mass distribution and two complementary studies yielding strong cosmological constraints on dark matter and dark energy using MACS being well advanced (D. Donovan et al. 2007, in preparation; A. Mantz et al. 2007, in preparation; S. W. Allen et al. 2007, in preparation).

3. THE 12 MOST DISTANT MACS CLUSTERS

To facilitate the use of this statistically complete sample in studies conducted by the scientific community in general, we present here the MACS $z > 0.5$ catalog listing the clusters’ fundamental physical properties, namely, X-ray position, redshift, radial velocity dispersion, X-ray fluxes and luminosities, X-ray gas temperatures, and a simple morphological classification (Table 1). Temperatures were measured from spectral fits to the Chandra data within $r_{1000}$, whereas spatial $\beta$-models (Cavaliere
and MS 0451.6 are based on data from the RASS BSC and provide a lookup table of the MACS
and astrophysical applications, we also list the X-ray detect flux density is times the critical density at the cluster redshift,
rigorous fit of the X-ray and optical data (which may be temporarily boosted in their X-ray luminosity
indicating that the MACS sample is neither biased in favor of cool-
the adaptively segmented isodensity contours of the MACS sample. Table 2 provides a tabulated version of the MACS selection function to facilitate the use of our sample by the scientific community for a wide range of astrophysical and cosmological applications. We dedicate this Letter to the memory of our friend and colleague Leon van Speybroeck, whose advice and enthusiasm (not to mention his Guaranteed Time on Chandra) inspired all of us. We miss you, Leon. H. E. acknowledges financial support from NASA and SAO (grants NAG 5-8253 and GO2-3168X, respectively).

4. SUMMARY

We present the statistically complete sample of the 12 most distant MACS clusters, all of which feature redshifts of \( z > 0.5 \) and 10 of which are new discoveries. Extensive follow-up observations at wavelengths from the X-ray to the radio passbands have confirmed that these are indeed exceptionally massive systems and thus the high-redshift counterparts of the best studied massive clusters in the local universe. Results from several studies on individual clusters or the sample as a whole have been published; additional studies, ranging from a comprehensive weak-lensing analysis to cosmological applications of the MACS sample, are well advanced. In recognition of the legacy character of this sample, we provide in this Letter an overview of the fundamental properties of all 12 clusters as well as a tabulated version of the MACS selection function to facilitate the use of our sample by the scientific community for a wide range of astrophysical and cosmological applications.

TABLE 1

| MACS | \( \alpha \) (J2000) | \( \delta \) (J2000) | \( z \) | \( n_c \) (km s\(^{-1}\)) | \( \sigma \) | \( f_{X, \text{ACIS}} \) BSC | \( f_{X, \text{Chandra}} \) | \( kT \) (keV) | Morph. Code |
|------|----------------|----------------|-----|----------------|------|----------------|----------------|-------------|------------|
| J0018.5+1626 | 00 18 33.835 | +16 26 16.64 | 0.5456 | 55 | 1420 | 1.33 ± 0.36 | 14.2 ± 3.9 | 2.14 ± 0.03 | 19.6 ± 0.3 | 9.4 ± 1.3 | 3 |
| J0025.4-1222 | 00 25 29.381 | -12 22 37.06 | 0.5843 | 35 | 740 | 1.10 ± 0.26 | 13.7 ± 3.3 | 0.81 ± 0.02 | 8.8 ± 0.2 | 7.1 ± 0.7 | 3 |
| J0257.1-2325 | 02 57 09.151 | -23 26 05.83 | 0.5049 | 25 | 970 | 1.23 ± 0.28 | 11.3 ± 2.6 | 1.80 ± 0.03 | 13.7 ± 0.3 | 10.5 ± 1.0 | 2 |
| J0454.1-0300 | 04 54 11.125 | -03 00 53.77 | 0.5377 | 27 | 1250 | 1.55 ± 0.32 | 17.1 ± 3.5 | 1.88 ± 0.04 | 16.8 ± 0.6 | 7.5 ± 1.0 | 2 |
| J0647.7+7015 | 06 47 50.469 | +70 14 54.95 | 0.5007 | 38 | 900 | 1.34 ± 0.29 | 16.8 ± 3.6 | 1.49 ± 0.03 | 15.9 ± 0.4 | 11.5 ± 1.0 | 2 |
| J0717.5+3745 | 07 17 30.927 | +37 45 29.74 | 0.5458 | 142 | 1660 | 1.92 ± 0.32 | 20.9 ± 3.7 | 2.74 ± 0.03 | 24.6 ± 0.3 | 11.6 ± 0.5 | 4 |
| J0744.8+3927 | 07 44 52.470 | +39 27 27.34 | 0.6976 | 41 | 1110 | 1.19 ± 0.26 | 21.0 ± 4.6 | 1.44 ± 0.03 | 22.9 ± 0.6 | 8.1 ± 0.6 | 2 |
| J0911.7+1426 | 09 11 27.117 | +14 26 31.94 | 0.5049 | 26 | 1150 | 1.05 ± 0.26 | 9.8 ± 2.5 | 1.00 ± 0.02 | 7.8 ± 0.3 | 8.8 ± 0.7 | 4 |
| J1149.5+2223 | 11 49 35.093 | +22 24 10.94 | 0.5444 | 68 | 1840 | 1.20 ± 0.24 | 13.0 ± 2.6 | 1.95 ± 0.04 | 17.6 ± 0.4 | 9.1 ± 0.7 | 4 |
| J1423.8+2404 | 14 23 47.663 | +24 04 40.14 | 0.5431 | 48 | 1300 | 1.03 ± 0.23 | 11.3 ± 2.5 | 1.80 ± 0.06 | 16.5 ± 0.7 | 7.0 ± 0.8 | 1 |
| J2129.4-0741 | 21 29 26.214 | -07 41 26.22 | 0.5889 | 52 | 1400 | 1.05 ± 0.28 | 12.6 ± 3.3 | 1.45 ± 0.03 | 15.7 ± 0.4 | 8.1 ± 0.7 | 3 |
| J2214.9-1359 | 22 14 57.415 | -13 00 10.78 | 0.5027 | 68 | 1300 | 1.42 ± 0.33 | 12.6 ± 2.9 | 1.85 ± 0.03 | 14.1 ± 0.3 | 8.8 ± 0.7 | 2 |

Notes.— The listed X-ray centroids are determined from Chandra ACIS-I data; redshifts, velocity dispersions, and number of redshifts are determined within a circle of 1 Mpc radius from the X-ray centroid, using the biweight estimators provided by the ROSAT statistics package (Beers et al. 1990); X-ray fluxes (observed detect fluxes for the RASS and observed total fluxes from Chandra, both in units of \( 10^{-12} \) ergs \ s\(^{-1}\) cm\(^{-2}\)) were fitted to the full ACIS-I data sets. \( \alpha \) and \( \delta \) are from the ROSAT catalog. The listed X-ray centroids are determined from \( f_{X, \text{ACIS}} \) BSC Solid Angle within, but excluding a central region of 70 kpc radius around the listed X-ray centroid. Morphology is assessed visually based on the appearance of the X-ray contours and the goodness of the optical/X-ray alignment—the assigned codes (from apparently relaxed to extremely disturbed) are 1 (pronounced cool core, perfect alignment of X-ray peak and single cD galaxy), 2 (good optical/X-ray alignment, concentric contours), 3 (nonconcentric contours, obvious small-scale substructure), and 4 (poor optical/X-ray alignment, multiple peaks, no cD galaxy).
Fig. 1.—$VR_z'$ color images of the 12 MACS clusters at $z > 0.5$ as obtained with the Subaru SuprimeCam wide-field imager. Exposure times range from 20 to 45 minutes in the three passbands. Only the central $10 \times 10$ arcmin$^2$ region is shown. Overlaid are logarithmically spaced isodensity contours of the adaptively smoothed X-ray surface brightness in the 0.5–7 keV band as observed with Chandra's ACIS-I detector. We use the Asmooth algorithm of Ebeling et al. (2006) and require a minimal significance of 3 $\sigma$ for all features in the adaptively smoothed X-ray image. [See the electronic edition of the Journal for a color version of this figure.]
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