IDCS J1426.5+3508: THE MOST MASSIVE GALAXY CLUSTER AT $z > 1.5$

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ABSTRACT

We present a deep (100 ks) $Chandra$ observation of IDCS J1426.5+3508, a spectroscopically confirmed, infrared-selected galaxy cluster at $z = 1.75$. This cluster is the most massive galaxy cluster currently known at $z > 1.5$, based on existing Sunyaev–Zel’dovich (SZ) and gravitational lensing detections. We confirm this high mass via a variety of X-ray scaling relations, including $T_X-M$, $f_{\text{gas}}-M$, $Y_X-M$, and $L_X-M$, finding a tight distribution of masses from these different methods, spanning $M_{500} = 2.3-3.3 \times 10^{14} M_\odot$, with the low-scatter $Y_X$-based mass $M_{500,Y_X} = 2.6^{+1.5}_{-0.5} \times 10^{14} M_\odot$. IDCS J1426.5+3508 is currently the only cluster at $z > 1.5$ for which X-ray, SZ, and gravitational lensing mass estimates exist, and these are in remarkably good agreement. We find a relatively tight distribution of the gas-to-total mass ratio, employing total masses from all of the aforementioned indicators, with values ranging from $f_{\text{gas,500}} = 0.087-0.12$. We do not detect metals in the intracluster medium (ICM) of this system, placing a $2\sigma$ upper limit of $Z(r < R_{500}) < 0.18 Z_\odot$. This upper limit on the metallicity suggests that this system may still be in the process of enriching its ICM. The cluster has a dense, low-entropy core, offset by $\sim 30$ kpc from the X-ray centroid, which makes it one of the few “cool core” clusters discovered at $z > 1$, and the first known cool core cluster at $z > 1.2$. The offset of this core from the large-scale centroid suggests that this cluster has had a relatively recent ($\lesssim 500$ Myr) merger/interaction with another massive system.

Key words: galaxies: clusters: individual (IDCS J1426.5+3508) – galaxies: clusters: intracluster medium – galaxies: high-redshift – large-scale structure of universe – X-rays: galaxies: clusters

1. INTRODUCTION

In recent years the study of galaxy clusters has meaningfully entered the $z > 1$ regime, with several surveys identifying large samples via X-ray (Fassbender et al. 2011; Mehrtens et al. 2012), Sunyaev–Zel’dovich (SZ, Hasselfield et al. 2013; Bleem et al. 2015; Planck Collaboration et al. 2015), infrared (IR, Eisenhardt 2008; Muzzin et al. 2009; Papovich et al. 2010; Rettura et al. 2014), and radio (Wylezalek et al. 2013; Galametz et al. 2013; Blanton et al. 2014; R. Paterno-Mahler et al. 2015, in preparation) selections. These surveys have extended the reach of cluster cosmology (e.g., Benson et al. 2013), scaling relations (e.g., Andersson et al. 2011), and galaxy formation and evolution in the richest environments (e.g., Hilton et al. 2010; Tran et al. 2010; Brodwin et al. 2013) to $z \sim 1.5$.

It is crucial to identify the earliest massive progenitors of these $1 \lesssim z \lesssim 1.5$ cluster samples, and the present-day massive clusters into which they evolve, in order to quantify the build-up of the intracluster medium (ICM) and the establishment of self-similarity. In particular, the scaling relations between different cluster mass observables—e.g., ICM temperature, SZ signal, weak lensing—are calibrated to better than $\sim 20\%$ at $z < 0.5$ (e.g., Kravtsov et al. 2006; Vikhlinin et al. 2009b; Andersson et al. 2011), but are currently poorly constrained at high redshifts ($z > 1$) where clusters provide the greatest leverage as probes of the growth of structure.

Very massive, high-redshift galaxy clusters also provide a natural testing ground to confirm or refute the predictions stemming from recent galaxy evolution studies in clusters at $1 \lesssim z \lesssim 1.5$. While little star formation activity is seen in the most massive ($M \sim 10^{15} M_\odot$) South Pole Telescope (SPT) clusters in this regime (e.g., Brodwin et al. 2010; Foley et al. 2011; Stalder et al. 2013), the case is notably different for clusters with masses in the range $M \sim (1-4) \times 10^{14} M_\odot$. Indeed, Brodwin et al. (2013) reported the discovery of a major epoch of star formation at $z \gtrsim 1.4$ for IRAC Shallow Cluster Survey (ISCS, Eisenhardt 2008) clusters in this mass range. They attributed it in part to a high merging rate of gas-rich cluster members, as suggested by Mancone et al. (2010). A consequence of this model is that the epoch at which the merging (and hence merger-induced star formation) ceases should be a function of cluster mass. While the SPT clusters at $z \lesssim 1.3$ are generally too massive to permit efficient merging, their lower-mass progenitors at higher redshifts should have the high star formation rates seen in the ISCS. Indeed, in the most distant SPT cluster, SPT-CL J2040–4451, with a mass of $M_{500,SZ} \sim 3.2 \times 10^{14} M_\odot$ at $z = 1.48$, residual star formation activity still persists after its earlier bursting phase (Bayliss et al. 2014).

To extend the infrared cluster search to $z > 1.5$, we repeated the methodology of the ISCS using the $Spitzer$ Deep, Wide-Field Survey (Ashby et al. 2009), which quadrupled the $Spitzer$/IRAC exposure time over the 9 deg$^2$ IRAC Shallow Survey (Eisenhardt et al. 2004). The resulting survey, the IRAC Distant Cluster Survey (IDCS, Brodwin et al. 2012; Gonzalez et al. 2012; Stanford et al. 2012), has identified two of the most distant clusters to date: IDCS J1426.5+3508 at $z = 1.75$...
Stanford et al. (2012) and IDCS J1433.2+3306 at $z = 1.89$ (Zeimann et al. 2012). The latter appears to be a moderate mass cluster still in the process of formation, whereas IDCS J1426.5+3508 at $z = 1.75$, the subject of this paper, is a very massive cluster.

Stanford et al. (2012) reported a detection in only 8.3 ks of archival Chandra X-ray Observatory data, resulting in an $L_X$-based mass estimate of $M_{500, L_X} = (3.3 \pm 1.0) \times 10^{14} M_\odot$. IDCS J1426.5+3508 was also observed with the Sunyaev–Zel’dovich Array, a subarray of the Combined Array for Research in Millimeter-wave Astronomy (CARMA). An $SZ$-based mass of $M_{500, SZ} = (2.6 \pm 0.7) \times 10^{14} M_\odot$ was measured from the strong (5.3 $\sigma$) decrement (Brodwin et al. 2012). Finally, IDCS J1426.5+3508 has a giant gravitational arc, from which a minimum mass of $M_{500, arc} \geq 2.0 \times 10^{14} M_\odot$ was estimated (Gonzalez et al. 2012). Although these independent mass measurements are all in good agreement, indicating that IDCS J1426.5+3508 is a very massive, relaxed cluster at $z = 1.75$, the $L_X$-based X-ray mass was based on only 53 counts and is highly uncertain.

In this paper we present deep new Chandra observations from which we measure the ICM properties of IDCS J1426.5+3508. In Section 2 we describe the data used in this analysis. In Section 3 we present the flux, energy spectrum and gas density profile of IDCS J1426.5+3508, along with the quantities we derive from these direct measurements, including the luminosity, temperature, gas mass and metallicity. Using standard scaling relations from the literature, we estimate $M_{500}$ for IDCS J1426.5+3508 from four different X-ray estimators in Section 4, and compare these to complementary SZ- and lensing-based mass estimates. We also compute gas fractions for each of these halo mass estimates and compare these with the value predicted from low-redshift clusters. In Section 5 we present IDCS J1426.5+3508 in the context of the known $z > 1.5$ galaxy cluster population and discuss the evolutionary state of its ICM. Finally, we present our conclusions in Section 6. We use $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ throughout.

2. DATA

The X-ray data used in this work were acquired via Chandra proposal 148000534 (PI: Brodwin). A total exposure of 100 ks was acquired over two pointings (OBSIDs 15168 and 16321). A total exposure of 100 ks was also observed with the Sunyaev–Zel’dovich Array, a subarray of the Combined Array for Research in Millimeter-wave Astronomy (CARMA). An $SZ$-based mass of $M_{500, SZ} = (2.6 \pm 0.7) \times 10^{14} M_\odot$ was measured from the strong (5.3 $\sigma$) decrement (Brodwin et al. 2012).

3. X-RAY PROPERTIES OF IDCS J1426.5+3508

3.1. Images, Centroid and Peak

Chandra and Hubble Space Telescope (HST) images of IDCS J1426.5+3508 are shown in Figure 1. The first column shows Chandra images and contours for Gaussian-smoothed (FWHM = 3″, upper panel) and adaptively smoothed (lower panel) 0.5–2.0 keV X-ray images, respectively. The second column shows these contours overlaid on color optical/IR $HST$ images, a full description of which are given in (Mo et al. 2015). The upper right panel is zoomed in to the cluster core to better show the brightest cluster galaxy (BCG) and the giant gravitational arc. We use the centroid measured within a 250–500 kpc annulus as the cluster center, which tends to provide less biased estimates of the global properties for unrelaxed clusters. This choice of center, $(\alpha_X, \delta_X) = (14:26:32.6, +35:08:25)$, is within 4″ of the X-ray peak, within 5″ of the BCG position (Stanford et al. 2012) and within 28″ of the SZ centroid (Brodwin et al. 2012). Given the uncertainty in the SZ centroid ($\approx$35″), this positional offset is not statistically significant.

3.2. Point Sources

The incidence of AGN in clusters has been shown to increase rapidly with redshift (Eastman et al. 2007; Galametz et al. 2009; Martini et al. 2013; Alberts et al. 2015). This is a natural consequence of the Brodwin et al. (2013) merger model discussed above, where the mergers that induce starbursts also fuel the AGN that provide the eventual quenching.

Point sources were identified and masked using an automated routine following the wavelet decomposition technique described in Vikhlinin et al. (1998). There are two bright X-ray point sources near the cluster core, previously discussed in Stanford et al. (2012). The northern one is a QSO in the cluster, with a flux of $S_{0.5–2.0} = (1.85^{+0.33}_{-0.37}) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. The southern one is a bright radio source listed in both the NVSS (Condon et al. 1998) and FIRST (Becker et al. 1995) catalogs. It has a flux of $\approx$95 mJy at 1.4 GHz, and was found to have a 31 GHz flux of $5.3 \pm 0.3$ mJy in the SZ analysis of Brodwin et al. (2012).

3.3. Counts, Flux and Luminosity

We measure 401 net counts (0.5–6 keV) from IDCS J1426.5+3508, after point source masking and background subtraction. The flux in the soft band is $S_{0.5–2.0} = (2.2 \pm 0.6) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, corresponding to a luminosity of $L_{0.5–2.0} = (3.6 \pm 0.5) \times 10^{44}$ erg s$^{-1}$. The bolometric luminosity over the 0.01–100 keV energy range is measured from the best-fit model described below (Section 3.4) to be $L_{X, bol} = (12.8 \pm 1.1) \times 10^{44}$ erg s$^{-1}$. These quantities are all measured within $r_{2500, KS} = 530 \pm 10$ kpc, as determined from the core-excised $Y_X$ measurement described below (Section 3.6). Pratt et al. (2009) showed the bolometric luminosity to be a lower scatter mass proxy than $L_{0.5–2.0}$. Using their scaling relation, we find $M_{500, L_X, bol} = (2.8 \pm 0.3) \times 10^{14} M_\odot$.

3.4. Temperature

The 0.5–6.0 keV ACIS-I spectra within $r_{500} (=0.45 r_{2500, KS}$; Vikhlinin et al. 2006) for each OBSID are shown in Figure 2. This aperture was chosen to maximize signal to noise, although we also consider a core-excised (0.15–1)r$_{500}$ annulus below. The spectroscopic temperature was measured by modeling the X-ray spectrum using a combination of an absorbed, optically thin plasma (PHABS X APEC), an absorbed hard background component (PHABS X BREGN) and a soft,
Galactic background component (APEC; \(kT = 0.15\) keV). Foreground and background models were constrained by fitting simultaneously to an off-source region within the same field of view and to the on-source region. The Galactic hydrogen column density, \(N_H\), was set to the weighted average from the Leiden–Argentine–Bonn survey (Kalberla et al. 2005). The source redshift was fixed to \(z = 1.75\) (Stanford et al. 2012). The reduced \(\chi^2\) of this fit is 0.95, demonstrating that the data are very well described by the simple, single-temperature plasma model. While the goodness-of-fit is excellent, the individual parameters (e.g., \(kT, Z\)) are not well constrained, as discussed below.

The average temperature within \(r_{500}\) is \(kT_{500} = 6.2^{+1.9}_{-1.0}\) keV. This global (not core-excised) temperature, while not optimal as a mass observable due to inclusion of the cluster core, is useful for comparison to lower resolution measurements from other facilities or low signal-to-noise ratio Chandra observations for which all the counts are required to measure the temperature. For completeness we also report a core temperature, within \(r < 0.15 r_{500}\), of \(kT_{\text{core}} = 7.3^{+2.7}_{-1.3}\) keV.

We measured the core-excised spectroscopic temperature over (0.15–1) \(r_{500}\) using the \(T_{X} - M_{500}\) scaling relation from Vikhlinin et al. (2009a) to estimate \(M_{500}\), iteratively updating the radius (\(r_{500}\)) until it converged. We used the pipeline described in B. Benson et al. (2016, in preparation) and McDonald et al. (2013), which closely follows the procedures described in Andersson et al. (2011). We find \(kT_{500} = 7.6^{+8.7}_{-1.9}\) keV, in good agreement with the global value.
given above. This temperature corresponds to a mass of 
\( M_{500,t} = 3.3_{-1.2}^{+5.7} \times 10^{14} \, M_\odot \) and \( r_{500,t} = 560 \pm 20 \, \text{kpc} \), where the subscript refers to the scaling relation from which the physical quantity was derived. The error on the core-excised \( kT_{500} \) is larger than that on \( kT_{2500} \) as roughly a third of the signal is removed with the core, and the noise is significantly increased by moving from \( r_{2500} \) to \( r_{500} \). Nevertheless, temperature measurements and confidence level determinations remain unbiased down to core levels well below those in this work (e.g., Churazov et al. 1996).

### 3.5. Gas Mass

Similarly, \( M_{g,500} \) was derived via the \( f_g-M_{500} \) scaling relation from Vikhlinin et al. (2009a). The derivation of the gas density profile, described in detail in McDonald et al. (2013), involves measuring the X-ray surface brightness in the rest-frame energy 0.7–2.0 keV as a function of radius. The resulting surface brightness profile, shown in Figure 3 (upper panel), is fit with a projected double-beta model, following Vikhlinin et al. (2006). In converting from electron density to gas density, we assume \( n_e = n_H A Z \), where \( A = 1.397 \) is the average nuclear charge and \( Z = 1.199 \) is the average nuclear mass. We integrate the deprojected gas density profile within an initial radius of \( r_{500,t} \), estimate the total enclosed gas mass, and then use this to derive \( M_{500} \) via the \( f_g-M_{500} \) relation. This process is iterated until convergence, leading to a revised estimate of \( r_{500,M} = 500 \pm 10 \, \text{kpc} \) and \( M_{500,M} = 2.3_{-0.5}^{+1.0} \times 10^{14} \, M_\odot \), consistent with values inferred from the \( T_X-M \) scaling relation. The gas mass is \( M_{g,500} = 2.5_{-0.6}^{+0.8} \times 10^{13} \, M_\odot \).

### 3.6. \( Y_X \)

The product of the core-excised temperature and gas mass, referred to as \( Y_X \), approximates the total thermal energy in the cluster. It has been shown in simulations to be a low-scatter mass proxy that is independent of the dynamical state of the cluster (Kravtsov et al. 2006). Following the same approach as for \( kT_{500} \) and \( M_{g,500} \), we estimate \( Y_{X,500} \) iteratively, adjusting \( r_{500} \) to satisfy the \( Y_X-M_{500} \) relation. We find \( r_{500,Y_X} = 530 \pm 10 \, \text{kpc} \) and \( M_{500,Y_X} = 2.6_{-0.5}^{+1.5} \times 10^{14} \, M_\odot \). Within \( r_{500,Y_X} \), we measure \( Y_{500} = 1.9_{-0.6}^{+1.9} \times 10^{14} \, M_\odot \, \text{keV} \).

### 3.7. Metallicity

Interior to \( r_{2500} \) and \( r_{500} \) (non core-excised), we measure 1σ \((2\sigma)\) upper limits on the metallicity of \( Z_{2500} < 0.33 \, Z_\odot \) \((0.47 \, Z_\odot)\) and \( Z_{500} < 0.10 \, Z_\odot \) \((0.18 \, Z_\odot)\), respectively. As Figure 2 illustrates, there is no obvious detection of the Fe Kα emission line, such that, within \( r_{2500} \), these data are consistent with anywhere from “typical” to a complete absence of metals. Over larger radii we may be observing a marked lack of metals, with the typical average metallicity of low-redshift clusters being \( Z_{500} \sim 0.3 \pm 0.1 \, Z_\odot \) (De Grandi & Molendi 2001), a level of enrichment also seen in some \( z > 1 \) clusters (Rosati et al. 2009; Santos et al. 2012; De Grandi et al. 2014). However, deeper
data are needed to properly constrain the metallicity in this system, and determine whether it is, indeed, metal-poor.

4. TOTAL MASSES FOR IDCS J1426.5+3508

4.1. $M_{500}$ from X-Ray Scaling Relations

Using the measured luminosity, temperature, gas mass and $Y_{500}$, we reported in the previous section several complementary estimates of the total mass within $r_{500}$. These masses, along with a host of physical parameters, are listed in Table 1. Had we assumed no evolution rather than a self-similar evolution, our $Y_{X}$-based mass would be ~50% higher.

These masses all show a high level of consistency, indicating IDCS J1426.5+3508 is relaxed, and offering good support for the hydrostatic approximation that is underlying all these scaling relations. A more stringent test is provided by comparisons with complementary, independent mass probes.

4.2. $M_{500}$ from Complementary Measurements

IDCS J1426.5+3508 is unique in that it is the highest redshift cluster, by far, for which independent mass measurements are available in the X-ray, SZ, and from strong gravitational lensing analyses. This rare confluence is only possible due to its extreme mass—it is the most massive cluster known at $z > 1.5$—and the fortuitous (and surprising) presence of a background galaxy for strong lensing (Gonzalez et al. 2012).

Brodwin et al. (2012) reported a strong ($>5\sigma$) SZ detection at 31 GHz with CARMA. The resulting mass measurement, $M_{500,SZ} = (2.6 \pm 0.7) \times 10^{14} M_\odot$, is in excellent agreement with all of the X-ray mass measures presented above. Relative to the $Y_{SZ}-M$ scaling relation from Andersson et al. (2011) that was used in Brodwin et al. (2012), the normalization is expected to increase by ~25% in $Y_{SZ}$, corresponding to a ~15% increase in mass (B. Benson et al. 2016, in preparation). The increase is primarily due to two factors—a statistical shift resulting from a much (~5×) larger SZ and X-ray cluster sample, and updated mass normalization from more recent weak-lensing observations (Hoekstra et al. 2015). The close agreement of the SZ mass for IDCS J1426.5+3508 with the X-ray mass measures will not be affected by this modest change.

Gonzalez et al. (2012) reported the discovery of a giant gravitational arc, visible in Figure 1, about 15″ N of the BCG at a clustercentric radius of ~125 kpc. Attempts to secure a spectroscopic redshift for the source galaxy were unsuccessful, though from the available photometry Gonzalez et al. (2012) constrained the source redshift to the range $2 < z < 6$. With a non-detection in subsequent deep (AB ~ 28, 10σ) HST/ACS F606W imaging, new data described in Mo et al. (2015), the redshift constraint is now refined to $4.5 < z < 6$. The strong lensing mass directly measured within the arc radius ranges from $(6.9 \pm 0.3) \times 10^{13} M_\odot$ for $z_e = 6.0$ to $(8.5 \pm 0.3) \times 10^{13} M_\odot$ for $z_e = 4.5$. Extrapolating to $r_{500}$ using the Duffy et al. (2008) mass–concentration relation, this corresponds to a mass range between $M_{500,arc} = 1.9_{-0.5}^{+0.7} \times 10^{14} M_\odot$ and $M_{500,arc} = 2.6_{-0.7}^{+1.8} \times 10^{14} M_\odot$, in good agreement with all the ICM-based masses.

A weak lensing analysis of IDCS J1426.5+3508 is underway (Mo et al. 2015). A shear signal is detected in Cycle 20 HST images, consistent with expectations for a cluster this massive, even at $z = 1.75$.

Figure 4 (upper panel) compares all of the mass measures described in this paper, and shows the uniformly excellent agreement among them. This confirms that, despite its extreme redshift, IDCS J1426.5+3508 is by all measures a relatively evolved, relaxed cluster. We take the low-scatter $Y_{X}$-based mass as our best estimate of the halo mass of IDCS J1426.5+3508, $M_{500,YX} = 2.6_{-0.7}^{+12} \times 10^{14} M_\odot$.

4.3. $f_{\text{gas}}$

As massive galaxy clusters assemble, they are expected to retain baryon fractions ($f_b$) close to (but slightly lower than) the universal value, with relatively low scatter (e.g., Kravtsov & Borgani 2012). Observationally, the gas mass fraction ($f_{\text{gas}}$) is highest in the most massive clusters, with a weakly decreasing fraction to lower masses (e.g., Vikhlinin et al. 2009a; Andersson et al. 2011).

We calculate $f_{\text{gas}}$ using each of the masses derived above, integrating the gas mass out to the $r_{500}$ value appropriate to each mass proxy. These are plotted in Figure 4 (lower panel). The $f_{\text{gas}}$ measurements for which the $M_{500}$ and halo mass measurements are independent are shown as filled symbols, while those affected by covariances between the gas and total mass have open symbols. We compare the measured $f_{\text{gas}}$ values with the value predicted from the redshift-independent

| Table 1 |
|---------|
| Properties | Value | Unit |
| $z$ | 1.75 | ... |
| X-ray Centroid | (14:26:32.6, +35:08:25) | ... |
| X-ray Peak Position | (14:26:32.9, +35:08:26) | ... |
| SZ Centroid | (14:26:34.0, +35:08:03) | ... |
| BCG Position | (14:26:32.95, +35:08:23.6) | ... |
| $r_{500,T_c}$ | 560 ± 20 | kpc |
| $r_{500,M_0}$ | 500 ± 10 | kpc |
| $r_{500,YX}$ | 530 ± 10 | kpc |
| Counts | 420 | ... |
| Count Rate | $4.14 \times 10^{-3}$ | s$^{-1}$ |
| $S_{0.5-2}$ | $(2.2 \pm 0.6) \times 10^{44}$ | erg s$^{-1}$ cm$^{-2}$ |
| $L_{0.5-2}$ | $(3.6 \pm 0.5) \times 10^{44}$ | erg s$^{-1}$ |
| $L_{X,\text{bol}}$ | $(12.8 \pm 1.1) \times 10^{44}$ | erg s$^{-1}$ |
| $kT_{\text{core}}$ | $7.3^{+1.1}_{-1}$ | keV |
| $kT_{500}$ | $6.2^{+1.9}_{-1.9}$ | keV |
| $kT_{500}$ | $7.6^{+1.9}_{-1.9}$ | keV |
| $M_{500}$ | $2.5_{-0.8}^{+0.8} \times 10^{14}$ | $M_\odot$ |
| $Y_{500}$ | $1.9_{-0.5}^{+0.5} \times 10^{14}$ | $M_\odot$ keV |
| $Z_{2500}$ | <0.33 (1σ) | $Z_\odot$ |
| $Z_{500}$ | <0.10 (1σ) | $Z_\odot$ |
| $M_{500,YX}$ | $2.6^{+1.3}_{-0.8} \times 10^{14}$ | $M_\odot$ |
| $M_{500,XY}$ | $3.3^{+1.2}_{-1.2} \times 10^{14}$ | $M_\odot$ |
| $M_{500,M_0}$ | $2.3^{+0.8}_{-0.8} \times 10^{14}$ | $M_\odot$ |
| $M_{500,SZ}$ | $(2.8 \pm 0.3) \times 10^{14}$ | $M_\odot$ |
| $M_{500,arc}$ | $(2.6 \pm 0.7) \times 10^{14}$ | $M_\odot$ |
| $M_{500,arc}$ | $(1.9-2.6,0.7) \times 10^{14}$ | $M_\odot$ |

Notes:

a. The core temperature is measured within $r < 0.15 r_{500}$.

b. This mass range accounts for possible source redshifts between 4.5 < $z$ < 6, as described in the text.
Andersson et al. (2011) relation. This is shown as the solid red line, where the error range includes the errors from $f_{\text{gas}}$-$M_{500}$ fit parameters in Andersson et al. (2011), as well as the mass error in $M_{500,Y}$, which we took as the value of $M_{500}$ for this relation.

The observed value of $f_{\text{gas}}$ from every available mass proxy is completely consistent with the expected value for a cluster with the mass of IDCS $J1426.5+3508$. This provides additional evidence of the maturity of IDCS $J1426.5+3508$ and bolsters our confidence in our use of scaling relations at this extreme redshift to estimate its mass. The recent measurement of the gas fraction in XDCP J0044.0–2033 at $z = 1.58$ (Tozzi et al. 2015), $f_{\text{gas}} = 0.08 \pm 0.02$, is slightly lower than the mean of the present measurements, though in agreement within 1σ.

5. DISCUSSION

5.1. Comparison With Other Distant, Massive Clusters

IDCS $J1426.5+3508$ was the first relaxed, massive galaxy cluster to be confirmed at $z > 1.5$ (Stanford et al. 2012). The present analysis of its X-ray properties confirms the SZ and lensing masses reported in Brodwin et al. (2012) and Gonzalez et al. (2012), respectively. The former paper also demonstrated that IDCS $J1426.5+3508$ is an evolutionary precursor to the most massive known clusters at all redshifts. Several new $z > 1.5$ clusters have subsequently been reported, but none are as massive, and hence as rare, as IDCS $J1426.5+3508$. Although the probability of detecting a cluster this massive in the 9 deg$^2$ IDCS area is very small (<1%), Brodwin et al. (2012) demonstrated that its existence poses no threat to ΛCDM. That paper also estimated that the SPT should expect ~2.4 such clusters over their entire 2500 deg$^2$ survey. In the final SPT catalog paper, Bleem et al. (2015) reported three clusters with strong decrements that do not yet have optical/IR confirmations. Though not confirmed to date, current photometric limits suggest that these three clusters lie at $z = 1.7 \pm 0.2$.

Tozzi et al. (2015) described deep Chandra observations of XDCP J0044.0–2033 at $z = 1.58$, from which they measured a total mass of $M_{500,Y} = 2.2_{-0.4}^{+0.5} \times 10^{14} M_\odot$, using the same Vikhlinin et al. (2009a) $Y_X-M$ scaling relation employed above. This is slightly below the identical mass measure for IDCS $J1426.5+3508$, $M_{500,Y} = 2.6_{-0.5}^{+1.5} \times 10^{14} M_\odot$, as well as all the other ICM-based (i.e., X-ray and SZ) mass measures in Table 1.

A direct comparison of temperatures is not straightforward, as Tozzi et al. (2015) do not quote a value for $T_{2500}$ or $T_{500}$. They instead measure a spectroscopic temperature of

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**Figure 4.** Upper panel: masses for IDCS $J1426.5+3508$ from the X-ray measurements described herein (filled circles), along with complementary SZ (Brodwin et al. 2012) and strong lensing (Gonzalez et al. 2012) masses (filled squares). For the latter we plot the two masses corresponding to the extreme source redshift values, as described in the text. We take the $Y_X$-based mass our best estimate (green horizontal line and error range), as it has the lowest intrinsic scatter (Kravtsov et al. 2006). The remarkable agreement among these independent methods demonstrates that IDCS $J1426.5+3508$ is a remarkably mature, evolved cluster even at $z = 1.75$. Lower panel: $f_{\text{gas}}$ measurements for IDCS $J1426.5+3508$ using each of these halo mass measurements. $f_{\text{gas}}$ measurements with independent $M_{500}$ and halo mass measurements have filled symbols; those affected by covariances between the gas and total mass are shown with open symbols. The expected $f_{\text{gas}}$ value for IDCS $J1426.5+3508$, shown as the red line with 1σ errors, is taken from the $f_{\text{gas}}$-$M_{500}$ relation of Andersson et al. (2011). The observed value of $f_{\text{gas}}$ is in good agreement with the predicted value for all mass probes.
$kT = 6.7^{+1.3}_{-0.9}$ keV at a radius of 375 kpc. As the $r_{500}$ values for both clusters are quite similar, we measure the temperature at this metric radius in IDCS J1426.5+3508 in order to make a meaningful comparison. We find $kT_{75\text{kpc}} = 7.3^{+3.3}_{-2.0}$ keV, confirming that IDCS J1426.5+3508 is likely the hotter and more massive cluster.

Newman et al. (2014) presented the spectroscopic confirmation of JKCS 041 at $z = 1.80$, for which Andreon et al. (2014) report a mass, based on its X-ray and optical properties, in the range $M_{500} \sim (1-2) \times 10^{14} M_{\odot}$. Given the non-detection in deep SZ imaging (Culverhouse et al. 2010), the mass is likely at or below the lower end of that range and thus less massive than IDCS J1426.5+3508.

Finally, cluster candidates reported at $1.6 \lesssim z \lesssim 2$ by Papovich et al. (2010), Zeimann et al. (2012), Gobat et al. (2011, 2013) and Mantz et al. (2014), are all considerably less massive than IDCS J1426.5+3508. Mantz et al. (2014) describe the most massive of these, XLSSJ J021744.1+034536 with $M_{500} \sim 1-2 \times 10^{14} M_{\odot}$, at a photometric redshift of $z_{\text{phot}} \sim 1.9$. Despite this redshift uncertainty, which strongly affects mass proxies in the X-ray, we can say with certainty that this cluster has a lower mass than IDCS J1426.5+3508. This assertion is based on a comparison of the spherically averaged dimensionless Comptonization, $Y_{\text{sph,500}}$, measured with CARMA for both clusters. The SZ mass proxy, $M \propto (Y_{\text{sph,500}} D_A/k)^2/E(z)^{2/3}k^{1/2}$ (e.g., Marrone et al. 2012), where $D_A$ is the angular diameter distance and $E(z)$ is evolution of the Hubble parameter, is weakly dependent on redshift. With $Y_{\text{sph,500}}$ being a factor of 2.6 higher in IDCS J1426.5+3508, we find its mass is larger by a factor of $\sim 1.9$.

### 5.2. Dynamical and Cooling State of the ICM

In Figure 3 we show the projected surface brightness profile for two different choices of center: the large-scale (250–500 kpc) centroid of the X-ray emission and the X-ray peak. Using the former definition, we fit a projected beta model to the data, finding no evidence for a central surface brightness excess. However, we show in the lower panel of Figure 3 that the peak of the X-ray emission—which lies $\sim 30$ kpc from the centroid—represents a significant overdensity. Following Vikhlinin et al. (2007), we measure the cuspiness of the peak-centered surface brightness profile, finding $\alpha \equiv (d \log \rho/[d \log r]|_{0.05 \text{r}_{\text{proj}}} = 0.82 \pm 0.09$. Such a high cuspiness at high redshift is rare. Indeed, Vikhlinin et al. (2007) found no such systems at $z > 0.5$ in their 400 deg$^2$ survey. Two similar systems, albeit at much lower redshift ($z \sim 1.1$), have been identified—one by McDonald et al. (2013) in a sample of 83 SPT clusters and one by Santos et al. (2012) in the WARPS survey.

The offset of $\sim 30$ kpc between the X-ray centroid and the dense core suggests that this cluster has undergone a recent interaction, and that the cluster core is sloshing about the potential minimum. Such an offset ought to remain visible for $\lesssim 500$ Myr after any interaction (Ascasibar & Markevitch 2006; ZuHone et al. 2010). Considering that this system is being observed when the universe was only 3.8 Gyr old, and that it had to assemble rapidly to achieve such a high mass at such early times, it is unsurprising that it retains an imprint of this hurried growth in its core.

Following McDonald et al. (2013), we calculate a pseudo-deprojected entropy, using the deprojected gas density profile (Section 3.5), an aperture temperature, and assuming the X-ray peak as the center. We find $K_0 \sim 20$ keV cm$^2$, corresponding to a cooling time of $\sim 160$ Myr. These properties are typical of cool core clusters (Hudson et al. 2010; McDonald et al. 2013), suggesting that such systems can form very early in the cluster lifetime.

The fact that the dense core appears elongated (Figure 1) suggests that, rather than a traditional cool core, we may be observing a dense infalling group. This is consistent with many of the observed qualities, including the low entropy, the offset from the potential minimum and the non-symmetric morphology. Conversely, the nearly coincident BCG and X-ray peak (within $\sim 3''$; Figure 1) suggests that this may be an offset core rather than an infalling group. Distinguishing between these two scenarios requires a deeper X-ray follow-up observation.

### 6. CONCLUSIONS

We have presented a deep 100 ks Chandra observation of IDCS J1426.5+3508 at $z = 1.75$, the most massive cluster discovered at $z > 1.5$ from any method. We measured the luminosity, temperature and gas mass, from which we derived halo mass estimates from the $T_X-M$, $L_X-M$, $Y_X-M$, and $L_X-M$ scaling relations. These all show excellent consistency and are in remarkable agreement with independent SZ and strong lensing masses. Similarly, the gas mass fractions for all these mass proxies were found to be in good agreement with each other and with the value predicted from low redshift clusters.

The bolometric luminosity is $L_{X,\text{bol}} = (12.8 \pm 1.1) \times 10^{43}$ erg s$^{-1}$, from which we estimate a mass of $M_{500,500,\text{bol}} = (2.8 \pm 0.3) \times 10^{14} M_{\odot}$. We measure a central temperature within $r_{2500}$ of $kT_{2500} = 6.2^{+1.9}_{-1.0}$ keV and a coreexcised temperature within $r_{500,T} = 560 \pm 20$ kepc, used in mass scaling relations, of $kT_{500} = 7.6^{+8.7}_{-1.9}$ keV. This results in a mass of $M_{500,500} = 3.3^{+5.2}_{-1.3} \times 10^{14} M_{\odot}$. We find no evidence for metals in the ICM of this system, placing a 2$\sigma$ upper limit of $Z_{500} < 0.18 Z_{\odot}$, suggesting that this system may still be in the process of enriching its ICM.

We measure a gas mass of $M_{g,500} = 2.5^{+0.8}_{-0.6} \times 10^{13} M_{\odot}$, from which we infer an $M_{g}$-based halo mass of $M_{500,M_g} = 2.3^{+0.7}_{-0.5} \times 10^{14} M_{\odot}$. From the gas mass and coreexcised temperature, we find $Y_{500} = 19^{+1.9}_{-0.6} \times 10^{14}$ keV, from which we derive our lowest-scatter estimate of the mass of IDCS J1426.5+3508, $M_{500,Y} = 2.6^{+1.5}_{-0.5} \times 10^{14} M_{\odot}$. All the X-ray masses for IDCS J1426.5+3508 are in agreement, as are the SZ- and lensing-based mass from previous analyses.

The cluster has a dense, low-entropy core, offset by $\sim 30$ kpc from the X-ray centroid, which makes it one of the few “cool core” clusters discovered at $z > 1$, and the first known cool core cluster at $z > 1.2$. The offset of this core from the large-scale centroid suggests that this cluster has had a relatively recent ($\lesssim 500$ Myr) merger/interaction with another massive system. We measure a central entropy of $K_0 \sim 20$ keV cm$^2$, indicating the cool core may have a very rapid cooling time of $\sim 160$ Myr.

IDCS J1426.5+3508 is the first cluster at $z > 1.5$ to have all these independent mass measurements. In addition to being the most massive known cluster in this redshift regime, IDCS J1426.5+3508 also has a remarkably relaxed ICM suggesting a very early and rapid formation. Deeper follow-up X-ray observations are essential to permit a meaningful constraint on its metalliclicity and to measure the entropy profile.
to better understand how and when such cores can form and when the cooling/feedback loop is established.

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