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1WGA J1226.9+3332: A HIGH-REDSHIFT CLUSTER DISCOVERED BY *CHANDRA*

I. CAGNONI,[1,2] M. ELVIS,[2] D.-W. KIM,[2] P. MAZZOTTA,[2,3] J.-S. HUANG,[2] AND A. CELOTTI[1]

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ABSTRACT

We report the detection of 1WGA J1226.9+3332 as an arcminute-scale extended X-ray source with the *Chandra X-Ray Observatory*. The *Chandra* observation and *R*- and *K*-band imaging strongly support the identification of 1WGA 1226.9+3332 as a high-redshift cluster of galaxies, most probably at $z = 0.85 \pm 0.15$, with an inferred temperature $kT = 10^{+4}_{-3}$ keV, and an unabsorbed luminosity (in a $r = 120''$ aperture) of $1.3^{+0.16}_{-0.14} \times 10^{45}$ ergs s^{-1} (0.5–10 keV). This indication of redshift is also supported by the *K*- and *R*-band imaging and is in agreement with the spectroscopic redshift of 0.89 found by Ebeling and coworkers. The surface brightness profile is consistent with a β model with $\beta = 0.770 \pm 0.025$, $r_c = 18.''1 \pm 0.''9$ (corresponding to 101 ± 5 kpc at $z = 0.89$), and $S(0) = 1.02 \pm 0.08$ counts arcsec^{-2}. 1WGA J1226.9+3332 was selected as an extreme X-ray–loud source with $F_X/F_V > 60$; this selection method, thanks to the large area sampled, seems to be a highly efficient method for finding luminous, high-*z* clusters of galaxies.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (1WGA J1226.9+3332) — galaxies: high-redshift — X-rays: galaxies: clusters — X-rays: individual (1WGA J1226.9+3332)

On-line material: color figure

1. INTRODUCTION

Clusters of galaxies are good tracers of the large-scale structure of the matter distribution in the universe. The standard models of structure formation predict that cluster distribution and evolution are fully determined by the spectrum of primordial perturbations and cosmological parameters Ω_0 and Λ (e.g., Press & Schechter 1974, and later works); thus, observations of high-redshift clusters constrain these parameters (e.g., Oukbir & Blanchard 1992). Moreover, X-ray measurements of high-redshift clusters of galaxies can place strong constraints on the thermodynamic evolution of the intracluster medium (ICM). For example, the luminosity-temperature (L_X-T) relation at different redshifts probes the interrelated evolution of the cluster baryon mass and the total mass (e.g., Kaiser 1991; Evrard & Henry 1991, and later works). Furthermore, X-ray and Sunyaev-Zeldovich effect observations of a sample of objects at different *z* can be used to obtain an independent estimate of H_0 (for a review see, e.g., Birkinshaw 1999).

Given this potential wealth of information, in the past few years a great effort has been made to search for high-redshift clusters of galaxies (e.g., Rosati et al. 1998; Vikhlinin et al. 1998). Among the different methods, X-ray surveys have played the most important role, but no method has allowed the identification of more than a handful of clusters at $z > 0.8$.

The finding of clusters from X-ray data was complicated mainly by the low spatial and/or spectral resolution of the previous X-ray missions. *Einstein* and *ROSAT* marked an important step in the study of clusters, but thanks to *Chandra*'s subarcsecond spatial resolution, it is now possible to distinguish easily between point sources and the more diffuse X-ray emission from clusters at any redshift.

We present the *Chandra* observation of 1WGA J1226.9+3332. This source is one of 16 peculiar *ROSAT* PSPC sources selected for their extremely high X-ray–to–optical flux ratio (Cagnoni et al. 2001; I. Cagnoni et al., in preparation). 1WGA J1226.9+3332 is a bright ($F_{0.1-2.4\mathrm{keV}} > 10^{-13}$ ergs cm^{-2} s^{-1}) WGA Catalog (WGACAT; White, Giommi, & Angelini 1994) source with blank fields, i.e., no optical counterparts on the Palomar Observatory Sky Survey up to $O = 21.5$. The extreme F_X/F_V ratio that follows from this is incompatible with all major and common classes of extragalactic sources, including normal quasars, active galactic nuclei (AGNs), normal galaxies, and nearby clusters of galaxies (Maccacaro et al. 1988). Possibilities for the nature of these "blanks" (I. Cagnoni et al., in preparation) include (1) type 2 quasars, i.e., high-luminosity, high-redshift, heavily obscured quasars, the bright analogs of Seyfert 2 galaxies; (2) low-mass Seyfert 2 galaxies, that is, AGNs powered by a low-mass obscured black hole (i.e., an obscured, narrow-line Seyfert 1 galaxy); (3) AGNs with no big blue bump, e.g., advection-dominated accretion flows (ADAFs); (4) isolated neutron stars undergoing Bondi accretion from the ISM (Madau & Blaes 1994); (5) γ-ray burst X-ray afterglows; (6) failed clusters, in which a large overdensity of matter has collapsed but has not formed galaxies (Tucker, Tananbaum, & Remillard 1995); and, most relevant to this paper, (7) high-redshift clusters of galaxies. Here we present strong evidence that 1WGA J1226.9+3332 is indeed a high-redshift cluster. We use $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$; errors in the paper represent 1 σ confidence levels, unless explicitly stated otherwise.

2. *CHANDRA* OBSERVATIONS

1WGA J1226.9+3332 was one of two blanks for which we obtained cycle 1 *Chandra* (Weisskopf, O'Dell, & van Speybroeck 1996) observing time. It was observed in the

[1] International School for Advanced Studies, Via Beirut 4 -34138, Trieste, Italy; icagnoni@cfa.harvard.edu (or ilale@sissa.it), celotti@sissa.it.

[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; melvis@cfa.harvard.edu, dkim@cfa.harvard.edu, jhuang@cfa.harvard.edu.

[3] ESA fellow; pmazzotta@cfa.harvard.edu.

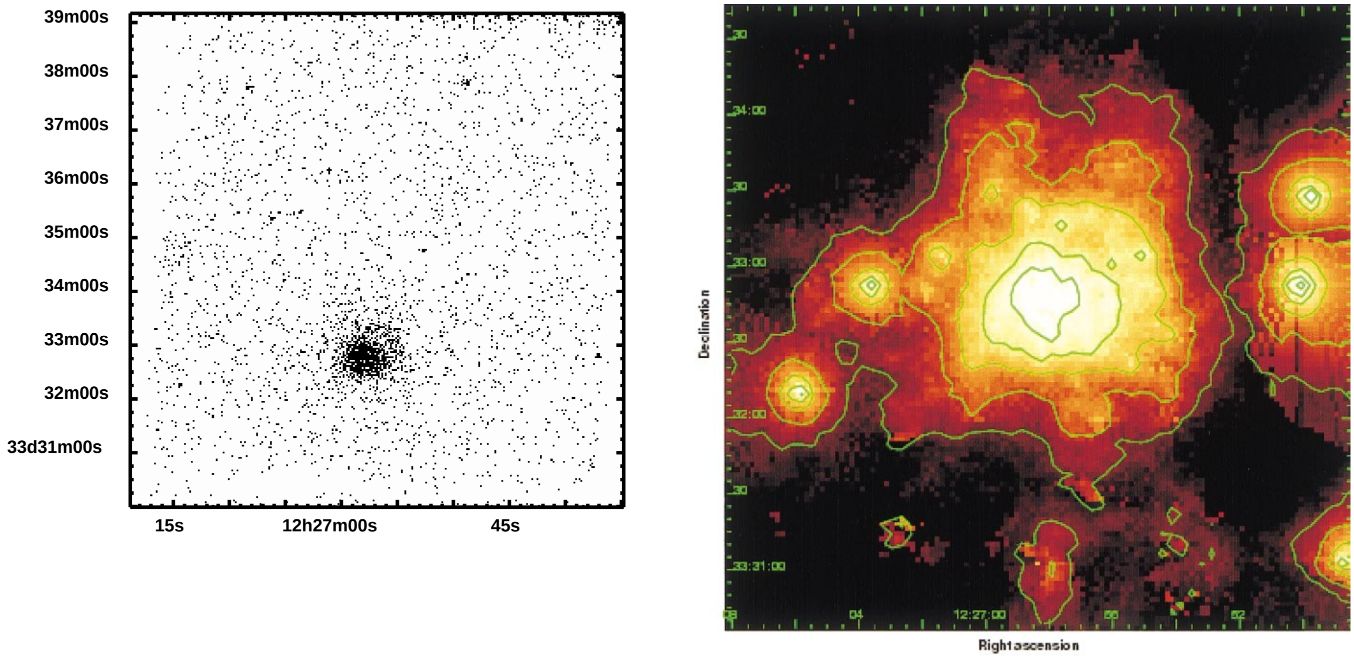

FIG. 1.—*Chandra* view of 1WGA J1226.9+3332. *Left*: Cleaned data (see text) from the whole S3 chip. *Right*: Zoom of the cluster (smoothed and background-subtracted).

ACIS-S configuration (G. P. Garmire et al., in preparation) with the backside-illuminated S3 chip for a total useful exposure time of 9832.3 s. The data were cleaned as described in Markevitch et al. (2000), and for the spectral and image analysis we used the latest available ACIS background data set.[4]

2.1. *Spatial Analysis*

To maximize the signal-to-noise ratio, we extracted the image in the 0.5–5 keV band (Figs. 1*a* and 1*b*). Along with a number of faint pointlike sources, 1WGA J1226.9+3332 is clearly seen as an extended source on an arcminute scale. It shows azimuthal symmetry, except for a possible excess to the northwest, $\sim 40''$ from the cluster center.

After subtracting the background from the same regions in a normalized ACIS background map, we extracted the X-ray surface brightness profile (Fig. 2) in concentric annular regions centered on the X-ray emission peak and chosen in order to have 20 counts per annulus. The profile appears to be smooth, without any obvious central excess related to a cooling flow (Figs. 1 and 2). We fitted the surface brightness profile with a standard β model[5] (Cavaliere & Fusco-Femiano 1976) using the SHERPA (A. Siemiginowska et al., in preparation) modeling and fitting tool from the *Chandra* X-Ray Center (CXC) analysis package CIAO 2.0 (M. Elvis et al., in preparation). We obtained best-fit values of $\beta = 0.770 \pm 0.025$, $r_c = 18''.1 \pm 0''.9$ (corresponding to 101 ± 5 kpc at $z = 0.89$), and $S(0) = 1.02 \pm 0.08$ counts arcsec^{-2} with a χ^2 of 27.5 for 26 degrees of freedom (dof). The excess to the northwest of the cluster is also visible in the radial profile; a drop in the surface brightness at $\sim 40''$ is present in the radial profile for the northwest sector. Similar features in the surface brightness radial profiles were detected by *Chandra* in nearby clusters (e.g., Markevitch et al. 1999, 2000; Vikhlinin, Markevitch, & Murray 2001; Mazzotta et al. 2001) and were interpreted as signs of subclump motion.

2.2. *Spectral Analysis*

We extracted an overall spectrum in a circle with $r = 120''$ in the 0.5–10 keV band in PI (pulse-height invariant) channels, corrected for the gain difference between the different regions of the CCD. The spectrum (Fig. 3) contained ~ 1100 net counts, and we binned it in order to have 100 counts per bin.[6] Both the effective area file (ARF) and the redistribution matrix (RMF) were computed by weighting each of the position-dependent ARFs and RMFs by their X-ray brightness. We fitted the spectrum in the 0.5–10 keV range with an absorbed Raymond-Smith model (Raymond & Smith 1977) using SHERPA. The source redshift was treated as unknown, and because of the low statistics, no iron line or other line complex features were expected to be visible.

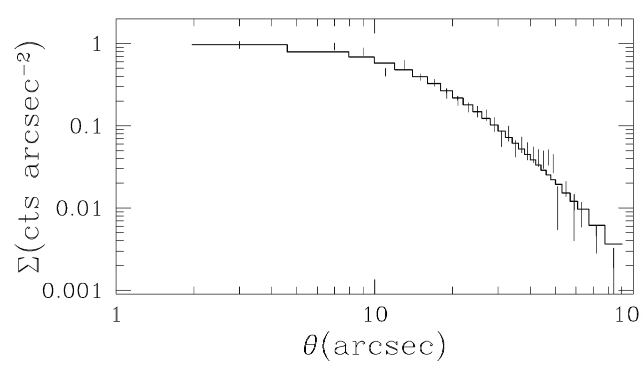

FIG. 2.—Background-subtracted surface brightness radial profile of 1WGA J1226.9+3332 (*error bars*), together with the best-fit β model (see text).

[4] This information is under "ACIS Background" at http://asc.harvard.edu/cal/Links/Acis/acis/WWWacis_cal.html.

[5] $S(r) = S(0)[1 + (r/r_c)^2]^{-3\beta+1/2}$.

[6] A smaller binning, e.g., as in Fig. 3, leads to similar results.

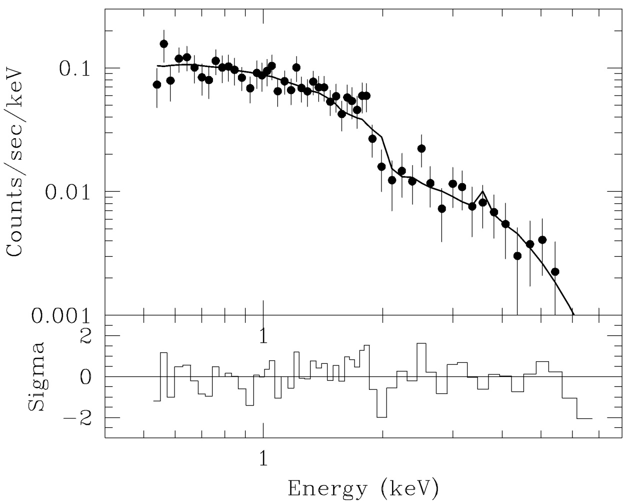

FIG. 3.—*Chandra* ACIS spectrum and residuals for a Raymond-Smith model with $kT = 10.23$ keV and $z = 0.89$. The spectrum was binned, for display purposes, to obtain a minimum of 30 counts per bin. [*See the electronic edition of the Journal for a color version of this figure.*]

In order to get an estimate of the temperature, we fix the equivalent hydrogen column density to the Galactic value ($N_H = 1.38 \times 10^{20}$ cm^{-2}; Stark et al. 1992) and the metal abundance to 0.3 times the solar value, and we draw confidence levels for T and z (Fig. 4). We find a best-fit value of $kT = 10.24$ keV and $z = 0.85$ (χ^2 is 18.68 for 20 dof)[7]. However, as shown in Figure 4, these values are not well constrained.

While submitting this paper we found that the same object had been independently identified as a cluster of galaxies in the WARPS survey (Ebeling et al. 2001) and observed for a Sunyaev-Zeldovich effect measurement by Joy et al. (2001). The cluster spectroscopic redshift measured by Ebeling et al. (2001) was $z = 0.89$, which is within the errors of our estimate based on *Chandra* and optical/IR constraints (see § 4). Fixing the redshift to this value, we obtain a temperature of $kT = 10.47^{+4}_{-3}$ keV ($kT = 12.07$ keV using a normalized background), which is in good agreement with that obtained from the Sunyaev-Zeldovich measurement by Joy et al. (2001; $kT = 10.0^{+2.0}_{-1.5}$ keV). The absorbed 0.5–2.0 keV flux[8] in an $r = 120''$ aperture is $(3.0 \pm 0.3) \times 10^{-13}$ ergs cm^{-2} s^{-1}, consistent with the Ebeling et al. (2001) PSPC measurement; the 0.5–10.0 keV absorbed flux in the same aperture (Table 1) is $(8.03^{+0.96}_{-0.88}) \times 10^{-13}$ ergs cm^{-2} s^{-1}. For $z = 0.89$, the unabsorbed bolometric and 0.5–2.0 keV band luminosities are $L = (2.2 \pm 0.2) \times 10^{45}$ ergs s^{-1} and $L_{X(0.5-2.0)} = (4.4 \pm 0.5) \times 10^{44}$ ergs s^{-1}, respectively.

3. OPTICAL, INFRARED, AND RADIO OBSERVATIONS

We obtained an R band image of the 1WGA J1226.9+3332 field on 1997 February 2, using the Smithsonian Astrophysical Observatory (SAO) 1.2 m telescope on Mount Hopkins. An $R = 20.4 \pm 0.2$ galaxy is detected less than 1″ from the X-ray centroid (Table 1).

A K-band image of the field was obtained using NSFCam at the NASA Infrared Telescope Facility (IRTF) on 2000 January 31. The same galaxy is also seen, but is much brighter, at a $K = 15.5$ (Fig. 5) isophotal magnitude. The K-band magnitude within the core radius of the X-ray source is $K = 15.4$, implying that little large-scale IR emission is present. The $R-K$ color of this object is 5.1, with an estimated uncertainty of 0.3 mag due to the poor image quality in both the K and R bands.

Comparing the R- and K-band images, it is clear that there are many more objects detected in the K than in the R band. We detect 23 objects with $K < 19.5$ mag in the 1′.5 × 1′.5 image, using source extractor software (SExtractor; Bertin & Arnouts 1996), versus only 4 at R. The star/galaxy classification was carried out morphologically using the Kron radius (Bertin & Arnouts 1996), and three objects are classified as pointlike. These objects are also detected in the R band and have bluer colors ($R - K < 4.2$) than the extended objects; we argue that they are stars. We should not have to worry about star contamination of the sample, since there are very few stars with $K > 16$ (e.g., Glazebrook et al. 1994). The rest of the morphologically extended objects are galaxies. These, including the bright one located at the X-ray centroid, have very similar red colors ($4.5 < R - K < 6.5$), implying that they likely have similar redshifts and belong to a cluster. A high-z cluster, CIG J0848+4453 at $z = 1.27$, was detected in a near-IR field

[7] By normalizing the background map using an area of 1WGA J1226.9+3332 observation without sources (7.56% lower background), consistent results are obtained: $kT = 11.94$ keV and $z = 0.87$.

[8] The main component in the flux error is the uncertainty of the cluster temperature (quoted in the text); using the $\pm 1\ \sigma$ values of T, we derive an error of $^{+11\%}_{-12\%}$ for the flux. Other contributions come from the normalization chosen for the background (±9%), from the fraction of counts lost using the $r = 120''$ aperture assuming a β profile (±5%), and from the Poisson error of the counts (±3%).

TABLE 1

1WGA J1226.9+3332 OBSERVATIONS

Energy Band	Instrument	Date	Exposure (ks)	R.A. (J2000)	decl. (J2000)	Offset[a] (arcsec)	Count Rate (counts s^{-1})	Flux (units)
X-ray	*Chandra*	2000 Jul 31	9832.3	12 26 58.2	+33 32 48.28	0.0	0.107 ± 0.006[b]	8.03×10^{-13} (ergs cm^{-2} s^{-1})[b]
R band	SAO 48 in	1997 Feb 2	900	12 26 58.2	+33 32 48.7	0.87	...	20.4 ± 0.2 (Mag)
K band	IRTF	2000 Jan 31	1200	12 26 58[c]	+33 32 48[c]	2.0	...	15.5 (Mag)
Radio	FIRST	...	...	12 26 58.19	+33 32 48.61	0.79	...	3.61 ± 0.18 (mJy at 1.4 GHz)

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] Offset from *Chandra* position.
[b] [0.5–10 keV] in a circle with $r = 120''$, computed from the spectral model within SHERPA.
[c] Because of the lack of bright stars in the K-band image, we obtained an estimate of the position using the objects in common with the R-band image.

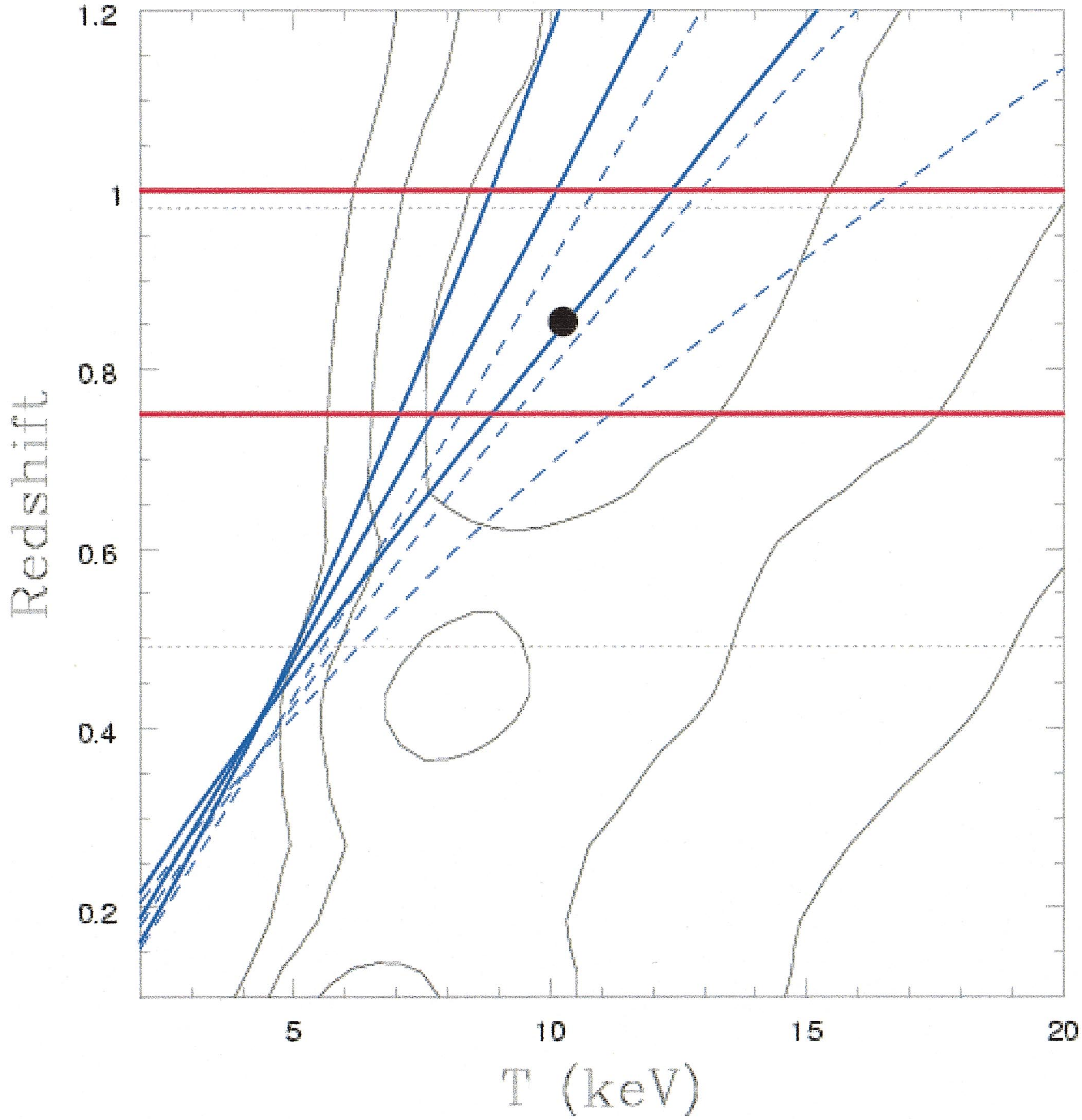

FIG. 4.—Contours of the fit with a Raymond-Smith plasma at 1, 2, and 3 σ. The three blue solid lines represent the luminosity-temperature relation (Markevitch 1998) for $q_0 = 0.5$, and the three blue dashed lines show $q_0 = 0$. The red lines represent the limits on the redshift obtained from the *R*-*K* color of the brightest object, assuming it is a first-ranked elliptical (Coleman et al. 1980), while the dotted lines show the limits of the magnitude of the first-ranked elliptical (see text). The filled circle corresponds to the best fit to the *Chandra* spectrum.

survey using similar color criteria in an overdense region (Stanford et al. 1997). The apparent asymmetry of the galaxy distribution may be an artifact of the longer exposure time at the center of the *K*-band mosaic image, which is offset from the X-ray centroid.

The galaxy surface density in the *K*-band image is clearly high (Fig. 5). We generate *K*-band galaxy number counts in our field in the range $15 < K < 19.5$, and compare them with those obtained from the near-IR field survey in this range (Gardner, Cowie, & Wainscoat 1993; Saracco et al. 1999; Huang et al. 1997, 2001; Minezaki et al. 1998), with their coverage ranging from 200 arcmin^2 to 10 deg^2. The number counts obtained from our image are substantially higher (greater than 10 σ, a factor of 100 at $K = 19$) than those from the field surveys. Such a large excess cannot be due to Poisson statistics or magnitude errors.

Both the high density and the similar (extremely red) colors for these galaxies thus imply that they are likely to be members of a cluster.

The Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey detected a faint 3.61 ± 0.18 mJy source at 1.4 GHz (Becker, White, & Helfand 1995) close to the center of the X-ray emission (Table 1). The radio source is pointlike (FWHM $\leq 0\farcs91$, ≤ 16 kpc at $z = 0.85$) and has a luminosity $L_R(z = 0.85) \sim 6.6 \times 10^{24}$ W Hz^{-1}, compatible with low-luminosity radio-loud AGNs (e.g., Zirbel & Baum 1995).

4. DISCUSSION AND CONCLUSION

Chandra has shown that 1WGA J1226.9+3332 is an extended X-ray source, with a hard, high-temperature thermal spectrum. Optical and IR imaging has shown that

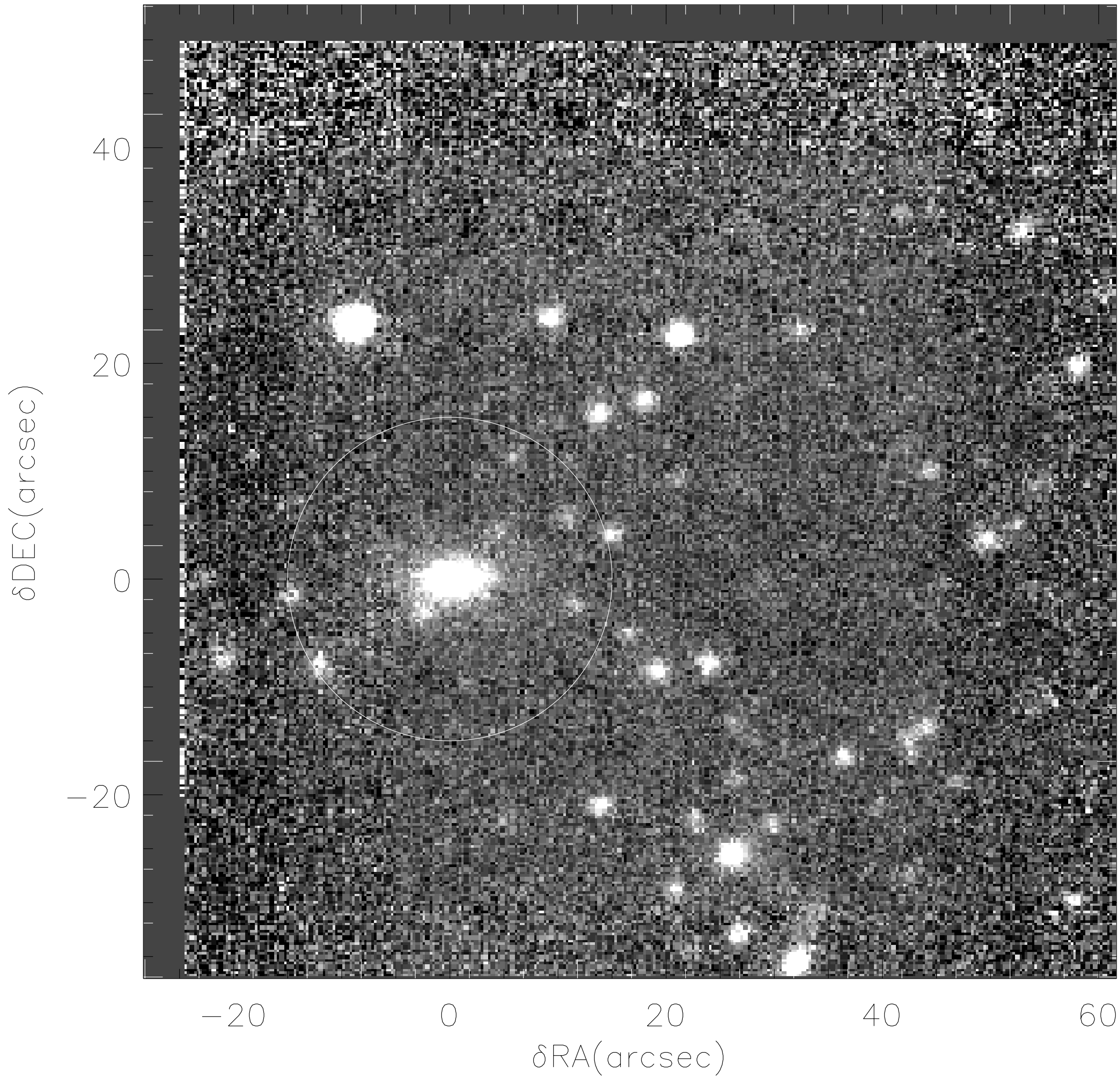

FIG. 5.—*K*-band image of 1WGA J1226.9+3332. The circle shows the *Chandra* X-ray core radius of 18″.

1WGA J1226.9+3332 has faint optical/IR counterparts. A cluster of galaxies is the only known type of object that could fit such a description. Moreover, the *K*-band image shows a strong excess of galaxies compared with field counts at $K > 17$ (Fig. 5) around 1WGA J1226.9+3332. Physical clustering is the only possible explanation. Several lines of argument go on to suggest that it is a high-redshift cluster of galaxies. Below, we list these arguments and try to constrain the temperature and redshift of 1WGA J1226.9+3332. These results are summarized in Figure 4.

(1) The *Chandra* X-ray profile is well fitted by a β model with $\beta = 0.77$, a value in agreement with a typical relaxed cluster (e.g., Jones & Forman 1999, and references therein). Moreover, if the cluster redshift is $0.7 < z < 1.2$, then the observed angular core radius, $r_c = 18\farcs1 \pm 0\farcs9$ (101 ± 5 kpc at $z = 0.89$, with the assumed cosmology), corresponds to a linear size of $90 < r < 150$ kpc for any value of Ω ($130 < r < 220$ kpc for any value of Ω for $H_0 = 50$ km s^{-1} Mpc^{-1}), which are values consistent with a typical relaxed cluster.

(2) It is well known that clusters of galaxies follow a well-defined luminosity-temperature relation (e.g., Markevitch 1998, and references therein). Recently, it has been shown that the local L_X-T relation does not evolve (or is consistent with little evolution) with redshifts up to $z \approx 0.8$ (see, e.g., Wu, Xue, & Fang 1999; Della Ceca et al. 2000; Fairley et al. 2000, and references therein). Figure 4 shows that the L_X-T relation [$L = AT_6^{\alpha}$, where $T_6 = T/6$ keV, $\alpha = 2.02 \pm 0.40$, and $A = (1.71 \pm 0.21) \times 10^{44}$ h^{-2} ergs s^{-1}] from Markevitch (1998) requires a 3 σ lower limit of $T > 4$ keV and $z > 0.4$, while the 1 σ limits require $T > 7.5$ keV and $z > 0.65$ if no evolution is assumed. The best-fit value of 0.85 obtained from the *Chandra* spectrum (Fig. 4, *filled circle*) is consistent with the unevolving L_X-T relation.

(3) *K*-band imaging has shown that 1WGA J1226.9+3332 has a galaxy at $K = 15.5$. If this source is a

first-ranked elliptical cluster with $M_K = -26.7 \pm 0.5$ (Collins & Mann 1998), then assuming negligible K-band correction ($q_0 = 0.5$ and $H_0 = 50$ km s^{-1} Mpc^{-1}, as in Collins & Mann 1998), it has $z = 0.68^{+0.30}_{-0.19}$ (Fig. 4, *dotted lines*).

(4) The color of the K band galaxies is extremely red, with none bluer than $R - K \sim 4.5$ and a maximum of $R - K = 6.5$. Only an unevolving elliptical galaxy at $0.7 < z < 1.5$ or an Sbc galaxy at $z > 1.1$ can have such a red color (Coleman, Woo, & Weedman 1980). Using the more accurate R-$K \sim 5.1 \pm 0.3$ of the first-ranked elliptical, we can restrict the redshift range to $0.75 < z < 1.0$ (Fig. 4, *red lines*).

Using all these constraints, we conclude that 1WGA J1226.9+3332 is a distant cluster of galaxies with a most probable redshift of 0.85 ± 0.15 and not smaller than $z = 0.65$.

This gives $kT = 10^{+4}_{-3}$ keV and implies an X-ray luminosity, determined in an $r = 120''$ aperture, of $L_{X(0.5-10\,keV)} = 1.3^{+0.16}_{-0.14} \times 10^{45}$ ergs s^{-1}, corresponding, for $z = 0.85$, to a bolometric $L = (2 \pm 0.2) \times 10^{45}$ ergs s^{-1}. Our estimated redshift is similar to the spectroscopic $z = 0.89$ found by Ebeling et al. (2001).

The blank-field X-ray source 1WGA J1226.9+3332 is thus a highly luminous and massive high-redshift cluster and a useful source for determining the evolution of the cluster X-ray luminosity function (e.g., Rosati et al. 1998). Since models in the direction of a low-Ω universe (with or without cosmological constant, e.g., Henry 2000; Borgani & Guzzo 2001) predict a higher density of high-redshift clusters compared to high-Ω models, finding hot, high-redshift clusters has a strong impact on cosmological models.

Since such high-luminosity, high-redshift clusters should be rare, the relative ease with which this discovery was made is potentially of great significance. The search for high F_X/F_V sources (blanks), sampling a large area of the sky, is an efficient method for finding very luminous high-redshift clusters; typical serendipitous flux-limited surveys can find (and have found) $z > 0.6$ clusters, but they are inefficient at finding rare luminous clusters, since they cover relatively small areas (~ 100 deg^2). This methodology is a useful complement to serendipitous flux-limited surveys.

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