A dark cluster of galaxies at redshift $z = 1$

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The abundance of metals in the hot, gaseous X-ray haloes of galaxy clusters depends crucially on the evolution of the constituent galaxies and their associated stellar populations. The metal abundances in X-ray clusters at high redshifts should therefore provide important insights into the nature and epoch of galaxy formation. Here we report the detection of an extended X-ray source in the direction of the lensed quasi-stellar object MG2016 + 112 (refs 1, 2). Although deep optical searches have failed to reveal a galaxy cluster at the lens position^{3,4}, the X-ray emission is consistent with thermal bremsstrahlung radiation from a hot metal-rich, diffuse gaseous halo, as observed in nearby galaxy clusters. This is the most distant galaxy cluster discovered in X-rays so far. Furthermore, the mass of the cluster derived from this emission is consistent with that implied by lensing models of the system⁵. Given that the cluster apparently comprises few galaxies, yet contains a large amount of iron, a new type of astronomical object is implied by our results. A revision of theoretical models of the metal enrichment process in galaxy clusters may therefore be required.

A deep observation of MG2016 + 112 with the ASCA satellite X-ray observatory was performed from 24 to 26 October 1994, with an effective exposure time of 85 ks. A new X-ray source (referred to as AX J2019 + 1127) was discovered in the direction of the lens system with a significance of 10σ . The position of the source is coincident with the location of all components of MG2016 + 112 taking into

account the positional accuracy of 1 arcmin for both telescopes equipped with Gas Imaging Spectrometers (GISs).

The source could originate from either the high-redshift quasar at redshift 3.27 or from a cluster centred on a giant elliptical galaxy, named galaxy D, at redshift 1.01 which is producing the lensing effect^{3,5,6}. A clue to resolving this question comes from X-ray spectroscopy. Figure 1 shows the X-ray spectrum of AX J2019 + 1127 obtained by ASCA. A single continuum model—that is, a bremsstrahlung with three free parameters (temperature, strength and absorption column density)—gives a statistically acceptable fit to the GIS and SIS (solid imaging spectrometer) spectrum simultaneously ($\chi^2 = 56.66$ with 54 degrees of freedom d.o.f.); however, an emission line feature is clearly seen at 3.5 keV. Inclusion of an emission line in a bremsstrahlung model reduces χ^2 by 9.4 which, for two additional free parameters (line energy and strength), is significant at the 99.1% level. This shows that the existence of the emission line is statistically significant. The best-fit line energy is $3.49^{+0.11(+0.15)}_{-0.09(-0.13)}$ keV where the first errors are the 90% confidence level statistical errors and the errors in parentheses represent the $\pm 1\%$ systematic error in the ASCA energy scale calibration. (The statistical errors are estimated by treating all the parameters as free except the one of interest, in this case, the line energy.) This implies a redshift of $z = 0.92^{+0.05(+0.07)}_{-0.06(-0.08)}$ if the line is due to Fe XXV or $z = 1.00^{+0.05(+0.07)}_{-0.06(-0.08)}$ if due to Fe XXVI. If the source is a cluster of galaxies, the line is a combination of Fe XXVI and Fe XXV. Thus the line matches well with the redshift of galaxy D. Assuming that the source is a cluster, the spectrum can be fitted with a Raymond–Smith plasma model⁷. The inclusion of a non-zero abundance reduces χ^2 by 10.01 and is significant at the 99.9% level (3σ). The fitted redshift is $z = 0.94^{+0.05(+0.07)}_{-0.06(-0.08)}$. The fitted intra-cluster gas temperature is $kT = 8.6^{+4.2}_{-3.0}$ keV (errors are 1σ statistical errors). We find an X-ray luminosity of $L_X = (8.4^{+2.4}_{-1.7}) \times 10^{44} h_{50}^{-2} \text{ erg s}^{-1}$ (2–10 keV; we assume in this Letter that $H_0 = 50 h_{50} \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$) and an iron abundance of $Z = 1.7^{+1.25}_{-0.74} Z_\odot$ (where $Z_\odot$ is the solar value) with an acceptable fit yielding χ^2 with 52 degrees of freedom where the solar iron abundance is 4.67×10^{-5} (ref. 8). The best-fit absorption hydrogen column density of $N_H = (0.18^{+0.15}_{-0.10}) \times 10^{22} \text{ cm}^{-2}$ is consistent with the Galactic value of $N_H = 0.15 \times 10^{22} \text{ cm}^{-2}$ (ref. 9). The correlation of X-ray gas temperature and X-ray luminosity for nearby clusters^{10,11} and the observed X-ray luminosity of AX J2019 + 1127 gives a temperature of ~ 7.5 keV, in good agreement with the observed value. These results are consistent with the idea that there is a cluster of galaxies including the galaxy D as a member galaxy. A single power-law model also gives an acceptable fit to the continuum ($\chi^2/\text{d.o.f.} = 58.11/54 = 1.08$) with a fitted

Figure 1 X-ray spectrum of AX J2019 + 1127 obtained by ASCA. The ASCA observatory has four identical telescopes covering the energy range 0.3–10 keV (ref. 22). They are equipped with two gas imaging spectrometers (GIS 2 and 3) and two solid-state imaging spectrometers (SIS 0 and 1) at the focal plane. The background-subtracted source spectrum obtained by two GISs (top panel) and by two SISs (bottom panel) with 1σ Poisson errors are shown. The solid lines are the best-fit Raymond–Smith models obtained by simultaneous fitting of the GIS and SIS spectra. The background is taken from blank field observations during the test phase of the ASCA mission. The SIS data were taken with two CCD bright mode observations with an effective exposure time of 22 ks.

photon index of 1.8 ± 0.2 . The derived slope is consistent with that found for active galaxies¹². If the object is an active galaxy, the detected iron line should be fluorescent Fe and this implies a redshift of $z = 0.83^{+0.03(+0.05)}_{-0.03(-0.05)}$. However, this is clearly inconsistent with the redshift of the quasi-stellar object (QSO) and there is no known object, at this redshift, inside the error circle.

Another crucial test for the cluster origin of the X-ray emission would be to resolve the source extent. This was performed with a deep observation with the High Resolution Imager (HRI) on the Rosat satellite. We find a diffuse source with 76 ± 24 source counts, $(1.4 \pm 0.4) \times 10^{-3}$ counts s^{-1} within a circle of radius 1 arcmin. Figure 2 shows the source image. The peak detection significance of the source is 4.2σ . The maximum of the X-ray emission is consistent with the position of the cD galaxy D within the HRI pointing accuracy. The HRI count rate is consistent with, but slightly less than, that expected from the ASCA observation, that is, $\sim 2.5 \times 10^{-3}$ counts s^{-1} . We confirm that there is no other source above the 3σ significance detection limit in the circle of radius 3 arcmin centred on MG2016 + 112 by applying a standard maximum-likelihood analysis of the source content of the HRI field. We therefore conclude that the source detected by the Rosat HRI is identical to AX J2019 + 1127. Figure 3 shows that the X-ray surface brightness distribution of the source deviates significantly from the profile of the Rosat HRI point-spread function and is more extended. The significance of the deviation is estimated to be $\sim 4\sigma$. From this we conclude that the source is extended. As the source counts within a concentric circle increases monotonically up to 1 arcmin, the source radius is estimated to be 1 arcmin ($500h_{50}^{-1}$ kpc for $z = 1$). The optical quasar consists of two almost equally bright images separated by 3.4 arcsec. For the point-spread function of the HRI with full-width at half-maximum of 5 arcsec, the X-ray surface brightness for two X-ray images at 3.4-arcsec separation would not be significantly different from the point

source result. Therefore, the extent of AX J2019 + 1127 cannot be explained if the quasar is the source. The low central surface brightness implies that the possible X-ray flux of the QSO contributes at most 10% to the observed value. This is consistent with the flux of the two bright QSO images as expected from their optical luminosity¹, based on an optical to X-ray correlation¹³, that is, 1.2×10^{-14} erg $cm^{-2} s^{-1}$ in the band 2–10 keV and an HRI count rate of 0.16×10^{-3} counts s^{-1} .

The above results imply that AX J2019 + 1127 is a galaxy cluster in which galaxy D is the central dominant galaxy. This is the most distant galaxy cluster discovered in X-rays so far. Because the X-ray emission provides the best evidence that clusters are gravitationally bound entities (unless a large number of measured galaxy redshifts are available), this is also the most distant clearly confirmed galaxy cluster. The redshift of the next furthest known X-ray cluster is MS1054.5 – 0321 at $z = 0.826$ (refs 14, 15). We can now further test if the observations are consistent with the mass distribution model needed for the lensing effect (for example, model II in ref. 5). Assuming that the cluster is isothermal and in hydrostatic equilibrium, one can obtain a rough estimate of the cluster mass. The best-fit results yields a central electron density of $1.7 \times 10^{-2} h_{50}^{0.5} cm^{-3}$, a gas mass of $2.4 \times 10^{13} h_{50}^{-2.5} M_{\odot}$ and a gravitational mass of $3.6 \times 10^{14} (kT/8.6 \text{ keV}) h_{50}^{-1} M_{\odot}$ within a sphere of radius of $500h_{50}^{-1}$ kpc in the cluster (here $M_{\odot}$ is the solar mass). The gas mass fraction of $\sim 7h_{50}^{-1.5}\%$ of the total mass is typical for the central regions of nearby clusters¹⁶ within the measurement errors.

These results are consistent with the mass model for the lens proposed by ref. 5. It implies that we have indeed discovered the object responsible for the lensing effect. Another important result of this discovery is the high iron abundance detected in the intra-cluster medium of AX J2019 + 1127. Although the errors on the abundance are quite large, the lower limit on the iron content in this cluster is at least as high as that for nearby clusters of galaxies¹⁷.

Figure 2 X-ray image of AX J2019 + 1127 obtained by the Rosat HRI. A deep Rosat HRI²³ observation was performed to resolve the possible extent of the source (right ascension and declination are equinox 2000.0). The lens system was observed from 15 to 20 November 1995, from 19 to 28 April 1996 and from 22 October to 13 November 1996 with a total exposure time of 79 ks, yielding an effective exposure of 53.7 ks after removal of observing times with high background flux. The accuracy of the HRI pointing is calibrated with two point sources coincident with stars in the Palomar Sky Survey observed in the field. The accuracy of the HRI pointing is better than 9 arcsec. The contours show the significance levels with a linear spacing of 0.5σ from the minimum level of 1.5σ . The peak significance is 4.2σ . The image is smoothed with a gaussian filter with $\sigma = 15$ arcsec. The cross shows the position of galaxy D.

Figure 3 The background-subtracted X-ray surface brightness profile of AX J2019 + 1127 obtained by the Rosat HRI (data points). The profile of the Rosat HRI point-spread function at the same off-axis angle as the source position is also shown (dashed line). The central surface brightness of the point-spread function is set for a point source at the same central surface brightness as the source. Superimposed on the data is the best-fit isothermal β model (solid line) using a core radius of $17'' \approx 150h_{50}^{-1}$ kpc and $\beta = 0.9$, values which are typical for X-ray profiles of nearby rich clusters²⁴. The central surface brightness of the model is $\sim 3.3 \times 10^{-3}$ counts $s^{-1} arcmin^{-2}$.

Currently the most distant galaxy cluster in which an Fe K-line has been detected is at a redshift of $z = 0.54$ (ref. 18). Therefore, AXJ2019 + 1127 is now the highest redshift cluster for which the existence of a metal-enriched intra-cluster medium has been confirmed. The detection of the large iron content at high redshift sets a new limit for the epoch of the enrichment. This favours models where early star burst phases in galaxies are responsible for the metal enrichment of the intra-cluster medium^{19,20}.

More surprisingly, a high iron abundance has been discovered in this 'dark cluster', which is very poor in its galaxy content according to the deep optical searches^{3,4}. The main optical light source from this cluster is galaxy D which has a blue luminosity of $L_B = 1.1 \times 10^{11} h_{50}^{-2} L_\odot$ (where $L_\odot$ is the solar luminosity). Another possible member galaxy is galaxy C (ref. 1) which, however, can contribute only a fraction of the optical luminosity of galaxy D. Therefore, the mass-to-light ratio of the cluster is $ML_B \approx 3,300(kT/8.6 \text{ keV})^{-1} h_{50} M_\odot/L_\odot$. Because, according to our current understanding, the metal enrichment originates in the stars of the cluster galaxies, it is very puzzling that we detect such a high iron abundance in this 'dark cluster'. Therefore, either AXJ2019 + 1127 is a very new and enigmatic object or it has more cluster members at fainter magnitudes that have escaped the deep searches conducted so far. Recently, it has been reported²¹ that there are also some low-redshift clusters that are optically dark but bright in X-rays. Combined with our results, this may indicate that there exist many such objects in our Universe which have eluded optical identification. In any case, AXJ2019 + 1127 provides us with a new means for testing cosmological theory and ought to be well studied in various wavelength bands. □

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Properties of ideal composite knots

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The shortest tube of constant diameter that can form a given knot represents the 'ideal' form of the knot^{1,2}. Ideal knots provide an irreducible representation of the knot, and they have some intriguing mathematical and physical features, including a direct correspondence with the time-averaged shapes of knotted DNA molecules in solution^{1,2}. Here we describe the properties of ideal forms of composite knots—knots obtained by the sequential tying of two or more independent knots (called factor knots) on the same string. We find that the writhe (related to the handedness of crossing points) of composite knots is the sum of that of the ideal forms of the factor knots. By comparing ideal composite knots with simulated configurations of knotted, thermally fluctuating DNA, we conclude that the additivity of writhe applies also to randomly distorted configurations of composite knots and their corresponding factor knots. We show that composite knots with several factor knots may possess distinct structural isomers that can be interconverted only by loosening the knot.

The ideal representation of a knot corresponds to the shortest axial path of an impenetrable tube of uniform thickness forming a given knot type¹. In other words, the ideal form of a knot is the spatial arrangement of the knotted tube with uniform thickness for which the length-to-diameter ratio is the smallest. These configurations can be obtained in computer simulations that maximize the thickness of knotted tubes while maintaining a fixed contour length. In the case of prime knots, computer runs end (in most cases) in the same final configuration, irrespective of the starting configuration of a given knot¹. For composite knots, especially those involving asymmetric factor knots, the simulations frequently end in local minima. To find the global minimum of the length-to-diameter ratio, it is necessary to carry out many independent simulations, testing different ways of combining two factor knots. For example, in searching for the ideal configuration of a composite knot composed of 6_1 and 3_1 factor knots, we created initial configurations where the symmetric 3_1 knot was attached to different loops of the asymmetric 6_1 knot. (The designations of knots follow the standard notation; the first number indicates the minimal number of crossings for a given knot and the subscript denotes the position of the knot among all other knots with the same crossing number³.) When both factor knots are symmetric, for example, 3_1 or 4_1 , all loops are equivalent and there is no need to test many initial configurations. For different joinings of factor knots, the simulations frequently end in visually distinct configurations with similar length-to-diameter ratios, whereas simulations started from a given type of joining usually result in the same kinds of configurations with nearly identical length to diameter ratios. Although we are not sure if we have found the configurations with the smallest possible length-to-diameter ratios for the composite knots analysed, for the purpose of this Letter we designate as ideal the best configurations of the different knots that we have obtained in computer simulations. Figure 1 thus shows the ideal configurations of 16 composite knots where the factor knots range from trefoils up to six-noded knots.