Mon. Not. R. Astron. Soc. **270,** L1–L5 (1994)

Zwicky 3146: the most massive cooling flow?

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Accepted 1994 June 16. Received 1994 May 9

ABSTRACT

In this Letter we present a deep *ROSAT* HRI image of Zwicky 3146 (or Zw 37-19), a distant cluster with high X-ray luminosity. The X-ray data show that the cluster contains the most massive known cooling flow at 1250 $M_{\odot}$ yr^{-1}, the existence of which has important implications for the formation and evolution of the cluster. The central galaxy in the cluster shows strong optical line emission and a blue continuum, and is also aligned with the X-ray emission.

Key words: galaxies: clustering – galaxies: clusters: individual: Zw 3146 – cooling flows – X-rays: galaxies.

1 INTRODUCTION

The intracluster medium in the cores of most clusters of galaxies at low redshift is sufficiently luminous in the X-ray waveband that it radiates its thermal energy in less than a Hubble time (Edge, Stewart & Fabian 1992). This loss of energy results in an inward, cooling flow of gas. For reviews of cooling flows, the reader is referred to Fabian, Nulsen & Canizares (1984, 1991) and Fabian (1994).

Cooling flows are centred, without exception, on the dominant galaxy of a cluster, and hence the evolutions of both may be linked. Central cluster galaxies often exhibit strong optical line emission (Johnstone, Fabian & Nulsen 1987; Heckman et al. 1989; Baum 1991; Crawford & Fabian 1992) and prominent excess blue continua (Johnstone et al. 1987; McNamara & O'Connell 1989, 1993; Crawford & Fabian 1993). These properties are also seen in distant radio galaxies which appear to be located at the centres of clusters (Chambers, Miley & van Breugel 1987; McCarthy et al. 1987). To establish the mechanisms behind the line emission (see Crawford & Fabian 1992) and the origin of the blue light (see Crawford & Fabian 1993) in cooling-flow clusters may provide important low-power analogies for the study of more distant objects. A vital step in this process is to observe cooling flows at redshifts beyond 0.15. Before the launch of *ROSAT*, this was only possible in one case (3C 295, $z = 0.46$: Henry & Henriksen 1986), because of the difficulty in both finding distant X-ray-bright clusters and resolving the central 100 kpc to establish a representative central cooling time (Edge et al. 1992). The existence of cooling flows had been *inferred* from the presence of optical line emission from the central galaxies (e.g. Nesci et al. 1989; Donahue, Stocke & Gioia 1992), or from the pressure in extended emission-line gas around quasars (Crawford & Fabian 1989; Forbes et al. 1990; Bremer et al. 1992), but direct X-ray confirmation had not been possible. This situation has improved in two ways with the launch of *ROSAT*. The *ROSAT* All-Sky Survey (RASS) has provided a unique chance to identify high-luminosity clusters at redshifts above 0.15, and hence the best candidates for massive cooling flows. In addition, the *ROSAT* HRI is able to resolve the central 100 kpc of a cluster out to a redshift of 0.6.

From our optical follow-up of RASS clusters (Allen et al. 1992; Crawford et al. 1994), Zw 3146, at a redshift of 0.2906, is the most distant cluster of the 71 clusters for which we obtained spectra. The central galaxy of the cluster is the most luminous known in optical lines ($L_{H\alpha} \approx 10^{43}$ erg s^{-1}), and its optical spectrum resembles those of low-redshift massive cooling flows. As part of a larger project to study distant, luminous clusters at high resolution, a *ROSAT* HRI observation was obtained. In this paper we present the X-ray observation and compare it with an optical CCD image of the core of the cluster.

2 RESULTS

A series of *ROSAT* HRI observations, forming a total exposure of 26 580 s, was made on 1992 November 27, 1993 May 17 and 1993 June 10. There were no significant changes in the background between the three sections of the observation, so the data were summed. A CCD image of 1800 s in *R* was obtained in 1992 January, using the Jacobus Kapteyn Telescope (JKT) in photometric conditions with 1.2-arcsec seeing, and is shown in Fig. 1 with the X-ray contours overlaid.

A deprojection of the X-ray surface brightness profile was performed. Fig. 2 shows a set of results for a deprojection of the data using a King-law potential with a core radius of 180 kpc and a velocity dispersion of 1100 km s^{-1} at two different binnings (8 and 16 arcsec). The values of core radius and velocity dispersion used were chosen to give a gas temperature of 10 keV outside the 'cooling radius' (i.e. the radius within which the cooling time is less than the Hubble time), and a gas mass to total mass ratio that is constant with radius and consistent with lower redshift clusters. The effect of changing both is detailed later. This analysis shows that the cluster contains a cooling flow of 1260 ± 100 $M_\odot$ yr^{-1} for the above potential, and if a cluster temperature of 10 keV outside the central 250 kpc is assumed. A Galactic column density of 2.9×10^{20} cm^{-2} (Stark et al. 1992) was used. X-ray observations of lower redshift cooling flows show that excess columns of 10^{21} cm^{-2} are common (White et al. 1991; Allen et al. 1993), so this mass deposition rate is a lower limit as any excess absorption would increase the derived value. The mass deposition profile is close to $\dot{M} \propto R$ (Thomas, Fabian & Nulsen 1987), and implies that 7 $M_\odot$ yr^{-1} kpc^{-1} are deposited over the central 150 kpc of the cluster. Most of the deposition occurs within a radius where the cooling time is less than 3×10^9 yr; even the most conservative estimate for the age of the cluster gives a mass deposition rate above 750 $M_\odot$ yr^{-1}. This implies a deposition integrated over the lifetime of the cluster of greater than 2×10^{12} $M_\odot$ within 150 kpc, making this cluster a prime candidate in which to search for cold gas.

The temperature of 10 keV used is estimated from the luminosity–temperature relation of Edge & Stewart (1991), but could range from 7 to 14 keV. These temperatures can be obtained by changing the velocity dispersion to 900 or 1300 km s^{-1}, but the measured mass-flow rate is not greatly affected (1405 ± 200 or 1160 ± 160 $M_\odot$ yr^{-1} respectively), and the ratio of gas mass to total mass within 0.5 Mpc scales with the predicted mass (0.21 ± 0.02 or 0.11 ± 0.02 respectively). The variation of the core radius by a factor of 2 also alters the determined mass-flow rate by less than 5 per cent. The ratio of gas mass to total mass within 0.5 Mpc, however, is strongly affected by the choice of core radius. Fig. 3 shows the ratio for core radii of 80, 180 and 300 kpc, each with a velocity dispersion of 1100 km s^{-1}. The smaller core radius leads to a much higher gravitational mass in the core, so the ratio is lower in the core but rises gradually with radius. The converse is true for the larger core radius. The choice of 180 kpc gives a constant ratio (i.e. 'gas follows mass'), and for the sake of convenience is the core radius chosen. The value of the ratio at 0.5 Mpc for all three choices of core radius is 0.13, which is equal to the highest value found in the Edge & Stewart (1991) sample. This ratio rises to 0.20 at 1 Mpc. The gas mass is 5.7×10^{13} $M_\odot$ at 0.5 Mpc and 1.43×10^{14} $M_\odot$ at

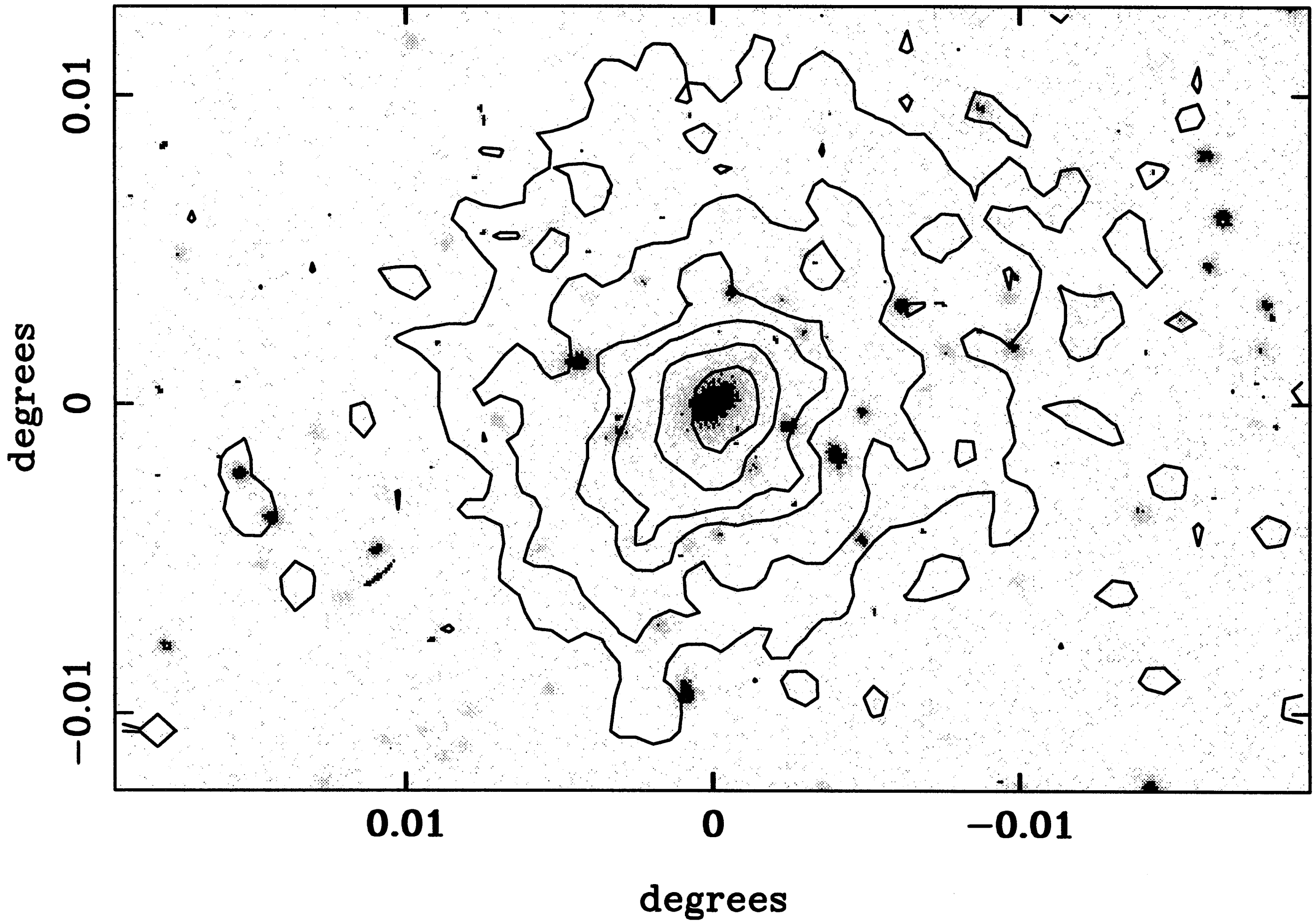

Figure 1. A grey-scale image of the JKT CCD exposure in *R* with the X-ray contours overlaid. The slight offset between the X-ray peak and the central galaxy is within the errors in *ROSAT* pointing position.

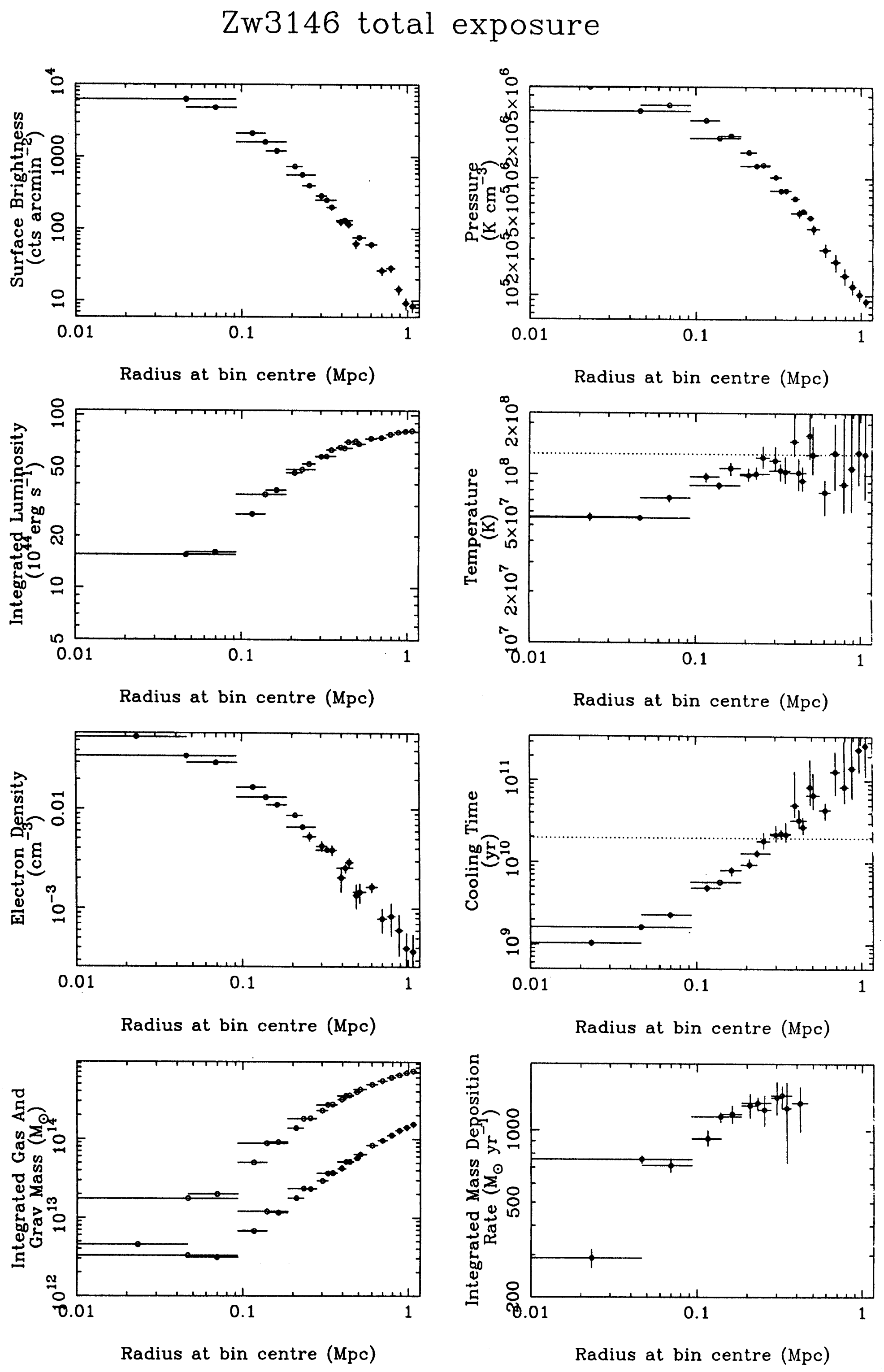

Figure 2. Results from the deprojection of the HRI surface brightness profile using 8- and 16-arcsec binnings. The dotted lines mark the assumed outer temperature of 10 keV and a reference cooling time of 2×10^{10} yr.

1 Mpc. These values are comparable to those for A2163, the most luminous cluster known before the launch of *ROSAT* (Arnaud et al. 1992), which does not contain a strong cooling flow.

An isophotal fitting to the X-ray image gives an average ellipticity of 0.17 ± 0.05 and a position angle of $132° \pm 10°$ out to a radius of 1 arcmin. The same isophote-fitting technique applied to the *R*-band image of the central galaxy gives 0.32 ± 0.05 and $120° \pm 4°$, respectively, out to a radius of 5 arcsec. These results show that the central galaxy and the hot gas (and hence the gravitational potential in the core of the cluster) are aligned to within 15°. This effect is seen in

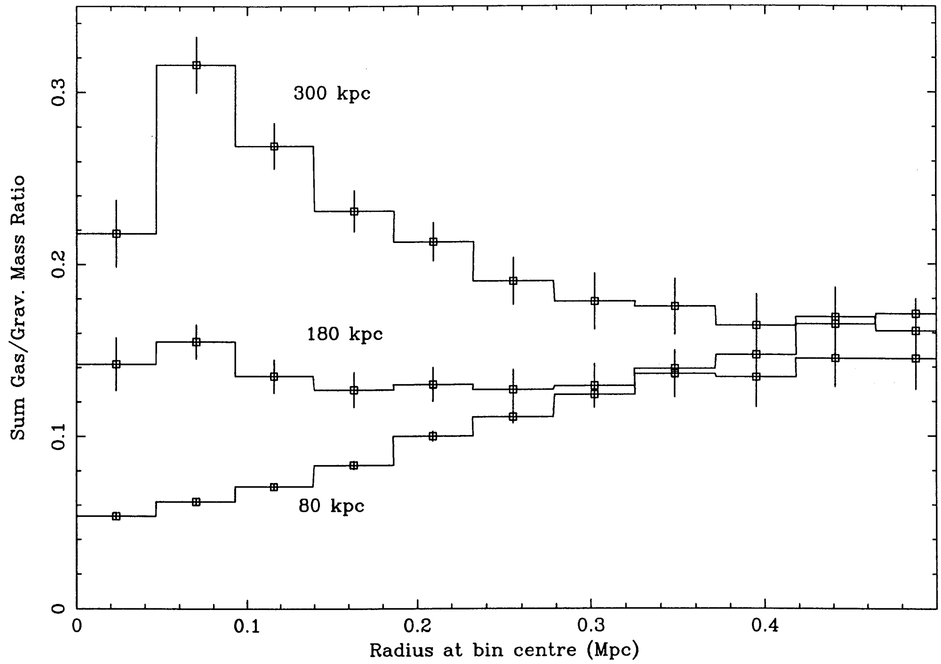

Figure 3. The ratio of the cumulative gas mass to the cumulative gravitational mass versus radius for three different core radii (80, 180 and 300 kpc from bottom to top) and a fixed velocity dispersion of 1100 km s^{-1}.

clusters at lower redshift (A478: White et al. 1994; Centaurus: Allen & Fabian 1994) and intermediate redshifts (Allen et al. 1994).

The *R*-band image contains 33 ± 5 galaxies within 0.5 Mpc of the central galaxy with magnitudes lying between that of the third brightest galaxy, m_3, and m_3+2 after background correction (i.e. a Bahcall number: Bahcall 1977). This is comparable with the Coma cluster and the most luminous clusters known within a redshift of 0.1 (Edge & Stewart 1991). The absolute *R*-band magnitude of the central galaxy is -23.7 ± 0.1 within a metric radius of 20 kpc (analogous to Hoessel, Gunn & Thuan 1980), and subject to a *k*-correction of 0.3–0.4 mag (Metcalfe et al. 1991). After correction for the different bands used, this magnitude is consistent with that expected for a cluster of such a high X-ray luminosity (Edge 1991). Therefore Zw 3146 is consistent with the optical/X-ray correlations observed at lower redshifts.

3 DISCUSSION

From the *ROSAT* Survey, we have discovered a distant cluster with a cooling flow in excess of 1200 $M_\odot$ yr^{-1}. The mass deposition rate is only weakly dependent on the assumed cluster potential. Prior to *ROSAT*, only two clusters of mass-flow rate greater than 700 $M_\odot$ yr^{-1} were known within a redshift of 0.15: A478 (Allen et al. 1993; White et al. 1994) and PKS0745 − 191 (Fabian et al. 1985; Arnaud et al. 1987); none was known at higher redshift (White et al., in preparation). Thus we can conclude that Zw 3146 is the most massive cooling flow presently known, but it is unlikely to be unique. We expect further *ROSAT* HRI imaging to reveal many more such massive cooling flows at redshifts greater than 0.15. Zw 3146 is also one of the most X-ray-luminous known, and is therefore a prime candidate for observations of the Sunyaev–Zel'dovich effect and gravitational lensing. It has the advantage of being at higher Galactic latitude than the two other massive cooling flows (A478 and PKS0745 − 191), which suffer substantial Galactic obscuration.

Zw 3146 contains an extreme central galaxy in terms of its optical properties. The total optical line power represents the maximum kinetic and thermal energy expected to be available in a cluster–cluster merger (Crawford & Fabian 1992), so the emission is at the limit of reprocessing of this energy. In addition, the observed excess blue continuum is amongst the most prominent seen (Allen et al. 1992; Crawford & Fabian 1993; Crawford et al. 1994). Despite the powerful optical line emission and excess blue light, the central galaxy is not a powerful radio source ($P_{1.4\,\mathrm{GHz}} < 10^{25.2}$ W Hz^{-1}: Allen et al. 1994). From the RASS sample and the Einstein Medium Sensitivity Survey, Crawford et al. (1994) show that many of the most powerful line emitters have weak radio sources ($P_{1.4\,\mathrm{GHZ}} < 10^{22-23}$ W Hz^{-1}), and that there is little or no correlation between radio and line powers. The central galaxy of Zw 3146 and those in other X-ray-selected clusters provide an important test for models of the formation and evolution of the massive dominant galaxies in clusters that is free from optical and radio selection effects.

ACKNOWLEDGMENTS

The exceptional properties of this cluster would not have been uncovered without the immense effort of the *ROSAT* team, and we gratefully acknowledge all those at MPE. ACE and ACF also thank Professor Trümper for the hospitality shown on the many visits to MPE over the last four years. The optical data were obtained at the Isaac Newton Group of Telescopes at the Observatorio del Roque de los

Muchachos, which is operated by the Royal Greenwich Observatory on behalf of the PPARC. ACE, CSC, SWA and DAW thank the PPARC for support. ACF thanks the Royal Society for funding.

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