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X-ray wakes in Abell 160

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ABSTRACT

'Wakes' of X-ray emission have now been detected trailing behind a few (at least seven) elliptical galaxies in clusters. To quantify how widespread this phenomenon is, and what its nature might be, we have obtained a deep (70 ks) X-ray image of the poor cluster Abell 160 using the *ROSAT* HRI. Combining the X-ray data with optical positions of confirmed cluster members, and applying a statistic designed to search for wake-like excesses, we confirm that this phenomenon is observed in galaxies in this cluster. The probability that the detections arise from chance is less than 3.8×10^{-3}. Further, the wakes are not randomly distributed in direction, but are preferentially oriented pointing away from the cluster centre. This arrangement can be explained by a simple model in which wakes arise from the stripping of the interstellar media of their host galaxies as a result of ram pressure against the intracluster medium through which they travel.

Key words: galaxies: clusters: individual: Abell 160 – galaxies: kinematics and dynamics – X-rays: galaxies.

1 INTRODUCTION

With the advent of satellite-based X-ray astronomy, it was discovered that elliptical galaxies can contain as much interstellar gas as their spiral kin (for example, see Forman et al. 1979). In the case of ellipticals, however, this interstellar medium (ISM) predominantly takes the form of a hot plasma at a temperature of $\sim 10^7$ K. The vast majority of elliptical galaxies are found in clusters, which themselves are permeated by very hot gas – the intracluster medium (ICM) – at a temperature of $\sim 10^8$ K. The existence of these two gaseous phases raises the question of how they interact with each other. The collisional nature of such material means that one might expect ram pressure to strip the ISM from cluster members. But since the ISM is continually replenished by mass loss from stellar winds, planetary nebulae and supernovae, it is not evident a priori that galaxies will be entirely denuded of gas by this process.

Observing the X-ray emission from individual cluster galaxies is quite challenging, since they are viewed against the bright background of the surrounding ICM. Sakelliou & Merrifield (1998) used a deep *ROSAT* observation to detect the X-ray emission from galaxies in the moderately rich cluster Abell 2634. They showed that the level of galaxy emission is consistent with the expected X-ray binary content of the galaxies, and hence that there is no evidence of surviving ISM in this rich environment.

When one looks in somewhat poorer environments, one does see evidence for surviving interstellar gas, and for the stripping process itself. The best-documented example is M86 in the Virgo cluster, which, when mapped in X-rays, reveals a tail or plume of hot gas apparently being stripped from the galaxy by ram pressure (Rangarajan et al. 1995, and references therein). A similar process appears to be happening to NGC 1404 in the Fornax cluster, which displays a clear wake of X-ray emission pointing away from the cluster centre (Jones et al. 1997). Evidence for a 'cooling wake' formed by gravitational accretion is found in the NGC 5044 group where a soft, linear X-ray feature is seen trailing from NGC 5044 itself (David et al. 1994).

Given the difficulty of detecting such faint wakes against the bright background of the ICM, it is quite possible that this phenomenon is widespread amongst galaxies in poor clusters. This possibility is intriguing, since wakes indicate the direction of motion of galaxies on the plane of the sky, and it has been shown that this information can be combined with radial velocity data to solve for both the distribution of galaxy orbits in a cluster and the form of the gravitational potential (Merrifield 1998). The existing isolated examples do not tell us, however, how common wake formation might be amongst cluster galaxies: although the observed wakes might represent the most blatant examples of widespread on-going ISM stripping, the galaxies in question might have merged with their current host clusters only recently, or be in some other way exceptional.

In order to obtain a more objective measure of the importance of ram pressure stripping in poor clusters, and the frequency with which it produces wakes behind galaxies, we need to look at a

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well-defined sample of cluster members within a single system. The cluster Abell 160 provides an ideal candidate for such a study. Its richness class of 0 makes it a typical poor system. It lies at a redshift of $z = 0.045$, and hence at a distance of 270 Mpc,[1] which is sufficiently close to allow galactic-scale structure to be resolved in its X-ray emission and corresponds to a size scale of $\sim$79 kpc arcmin^{-1}. Furthermore, its Bautz–Morgan class of III means that it contains quite a number of comparably luminous galaxies, and one might hope to detect ISM emission most readily from such a sample. In addition, its Rood–Sastry classification of C means that its members are concentrated towards the centre of the cluster: galaxies lying in the cluster core, where the ICM density is high, will be most affected by ram pressure stripping. Finally, Pinkney (1995) has obtained positions and redshifts for an almost complete, independently defined set of galaxies in the field of Abell 160, providing an objective sample of cluster members for this study.

We therefore obtained a deep *ROSAT* HRI X-ray image of Abell 160 in order to investigate ISM stripping in this typical poor cluster. We use a Galactic H I column density towards A160 of 4.38×10^{20} cm^{-2} (Stark et al. 1992) throughout this paper. In the next section, we present the X-ray observation and the redshift data employed. Section 3 describes an objective method for detecting and quantifying wake features in the X-ray data, and Section 4 presents the results of applying this approach to the Abell 160 data. We conclude in Section 5 with a discussion of the interpretation of the results.

2 X-RAY DATA AND OPTICAL REDSHIFTS

Abell 160 was observed with the *ROSAT* HRI in three pointings (1997 January and July, and 1998 January) for a total integration time of 70.4 ks (see Table 1). The data were reduced with the *ROSAT* Standard Analysis pipeline, with subsequent analysis performed using the IRAF/PROS software package.

Point sources detected in the three X-ray observations were used to examine the registration in relation to the nominal *ROSAT* pointing position. A *Digitized Sky Survey* image of Abell 160 was employed to provide the optical reference frame. The second observation set was shifted ~ -0.9 arcsec east and $\sim$1.7 arcsec south, and the third set was shifted $\sim$0.3 arcsec east and $\sim$1.8 arcsec south. Registration of all three sets of observations was then within 0.5 arcsec of the optical reference, tied down to five sources. A grey-scale image of the merged X-ray data set is shown in Fig. 1.

The centroid of the diffuse X-ray emission in this image was calculated by interpolating over any bright point sources, and projecting the emission down on to two orthogonal axes. Fitting a Gaussian to each of these one-dimensional distributions then gives a robust estimate for the centroid of the emission. This procedure yielded a location of

$$\left.\begin{array}{l}\alpha_{2000.0} = 01^{\rm h}13^{\rm m}05^{\rm s}\\ \delta_{2000.0} = +15°29'48''\end{array}\right\} \pm 43\,\mathrm{arcsec},$$

which was adopted as the cluster centre for the subsequent analysis.

Pinkney (1995) obtained redshifts for the 94 brightest galaxies in the field of A160 using the MX multi-object spectrograph on the Steward Observatory 2.3-m telescope. Fig. 2 shows the resulting velocity distribution. In order to investigate the X-ray properties of normal cluster members, we have excluded the central galaxy since it contains a twin-jet radio source (Pinkney 1995), so its X-ray emission may well contain a significant contribution from the central AGN. There are 91 galaxies within 8000 km s^{-1} of the twin-jet source ($v_{\rm TJ} = 13\,173 \pm 100$ km s^{-1}); some of these form a background cluster detected at approximately 18 000 km s^{-1}. After further eliminating galaxies outside the field of view of the HRI, we end up with a sample of 35 cluster members whose X-ray emission we wish to quantify. This subsample, highlighted in Fig. 2, has a line-of-sight velocity dispersion of 560 km s^{-1}, directly comparable to other poor clusters. The locations of these galaxies are marked on Fig. 1 where the different symbols indicate different subsamples of galaxies based upon optical luminosity, as described in the figure caption.

[1] We adopt a value for the Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1} throughout this paper.

Table 1. *ROSAT* HRI observations of Abell 160.

Observation start date	Observation end date	Number of OBIs used[a]	Total time (s)
1996 Dec 30	1997 Jan 19	14	36 965
1997 Jul 01	1997 Jul 30	8	16 501
1997 Dec 30	1998 Jan 07	10	16 943

[a] OBI = ROSAT Observation Interval.

3 DETECTING WAKES

Having combined the optical cluster member locations with the X-ray data, we now turn to trying to see whether there is X-ray emission associated with any individual galaxy, and whether it takes the form of an X-ray wake. On examining Fig. 1, the eye is drawn to a number of cases where there is an enhancement in the X-ray emission near, but offset from, the optical galaxy position – see, for example, the galaxy at RA $1^{\rm h}12^{\rm m}38^{\rm s}$, Dec $15°28'03''$. It would be tempting to ascribe these near-coincidences to X-ray wakes. However, it is also clear from Fig. 1 that there are many apparent enhancements in the X-ray emission that are totally unrelated to cluster members: some will be from foreground and background point sources, while others are probably substructure or noise associated with the ICM itself. What we need, therefore, is some objective criterion for assessing the probability that any given wake is a true association rather than a chance superposition. Further, even if we cannot unequivocally decide whether some particular feature is real, we need to be able to show that there are too many apparent wakes for all to be coincidences.

The test adopted to meet these requirements is as follows. First, for each galaxy we must seek to detect the most significant wake-like emission that might be associated with it. We must therefore choose a range of radii from the centre of the galaxy in which to search for a wake. Scaling the wakes previously detected in other clusters to the distance of Abell 160, we might expect enhanced X-ray emission at radii $r < 8$ arcsec, equivalent to a galaxy distance of approximately 10 kpc. We also want, as far as possible, to exclude emission from any faint central AGN component in the galaxy, so we only consider emission from radii $r > 3$ arcsec. Balsara, Livio & O'Dea (1994) found wake-like structure in high-resolution, hydrodynamic simulations with a scalelength of $\sim$2 arcsec at the distance of Coma (see also Stevens, Acreman & Ponman 1999); in the poor environment of Abell 160 we expect wakes to be longer as their formation should be dominated by ISM

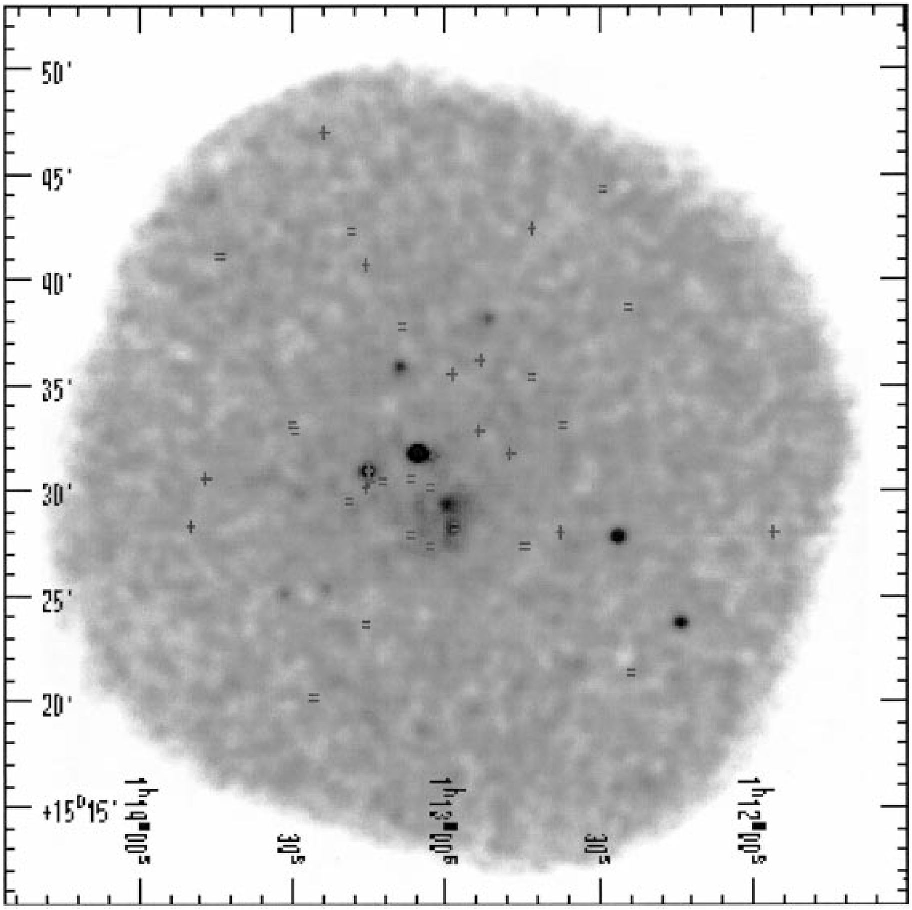

Figure 1. Grey-scale *ROSAT* HRI image of Abell 160, smoothed using a Gaussian kernel with a dispersion of 8 arcsec. The positions of the 35 cluster galaxies with measured redshifts studied in this paper are marked with symbols, such that the brightest 15 are marked with '+' and the fainter 20 with '='. These subsamples are discussed later in the paper.

stripping. We adopt the annulus $3 < r < 8$ arcsec to search for wakes: counts in annuli with larger inner and outer radii were also performed but did not improve the statistical results described below.

In our chosen annulus, we search for the most significant emission feature by taking a wedge with an opening angle of 45°, rotating about the centre of the galaxy in 10° increments, and finding the angle that produces the maximum number of counts in the intersection of the wedge and the annulus. Finally, the contribution to the emission in this wedge from the surrounding ICM is subtracted by calculating an average local background between radii $25 < r < 60$ arcsec, centred on the galaxy and each comparison region at the same cluster radius (see below), to give a brightest wake flux, f_{wake}.

To provide a diagnostic as to the nature of this wake, its direction on the plane of the sky, Θ, was also recorded. This angle was measured relative to the line joining the galaxy to the cluster centre, so that $|\Theta| = 0°$ corresponds to a wake pointing directly away from the cluster centre, while $|\Theta| = 180°$ indicates one pointing directly towards the cluster centre.[2]

Having found this strongest wake feature, we must assess its significance. To do so, we simply repeated the above procedure using $n_{\mathrm{comp}} = 100$ points for each galaxy at the same projected distance from the cluster centre, but at randomly selected azimuthal angles. These comparison points were chosen to lie at the same distance from the cluster centre so that the properties of the ICM and the amount of vignetting in the *ROSAT* image were directly comparable to that at the position of the real galaxy. As noted above, counts in 'background annuli' were also acquired

[2] Under the assumption of approximately spherical symmetry in the cluster, there is no physical information in the sign of Θ.

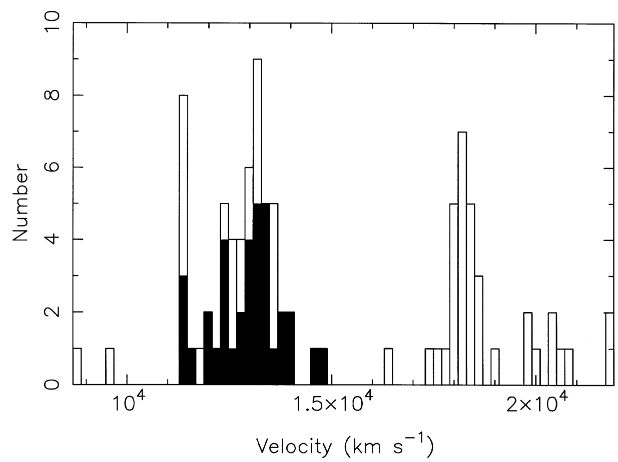

Figure 2. Histogram showing the distribution of velocities of galaxies in the field of Abell 160. The subsample of galaxies taken to be cluster members, and which are in the field of view of the *ROSAT* High Resolution Imager (HRI), is highlighted as a solid histogram.

and all these counts were averaged together in order to obtain a value for the background to be subtracted from the counts in each wedge region. Fewer comparison regions were used for the 12 galaxies closest to the cluster centre, as otherwise the count regions would overlap.

The comparison regions and real data were then sorted by their values of $f_{\rm wake}$, from faintest to brightest, and the rank of the galaxy (i.e. the position of the real data in this ordered list), $\mathrm{Rank}_{\rm gal}$, computed. The statistic

$$k = \frac{\mathrm{Rank}_{\rm gal}}{n_{\rm comp} + 1} \quad (1)$$

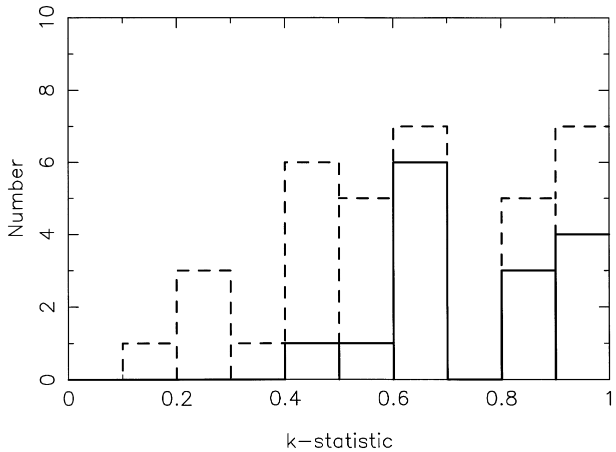

Figure 3. Histogram of the values of the k statistic derived for both the complete sample of 35 cluster members (dashed line) and for the subsample of the 15 brightest cluster members (solid line).

was then calculated. Clearly, if all the apparent galaxy wakes were spurious, then nothing would differentiate these regions from the comparison regions, and we would expect k to be uniformly distributed between 0 and 1. For significant wake features, on the other hand, we would expect the distribution of k values to be skewed towards $k \sim 1$.

As an additional comparison to the X-ray emission around galaxies in Abell 160 we performed the same analysis on 70.4 ks of 'blank field' data, extracted from the *ROSAT* Deep Survey, which encompasses ~1320 ks of HRI pointings towards the Lockman Hole (see e.g. Hasinger et al. 1998). We searched for wake-like features around 35 random positions across this HRI field, using comparison regions for each 'galaxy' as defined above.

4 RESULTS

We have applied the above analysis to the confirmed cluster members using IRAF software packages and the merged QP data file. Fig. 3 shows the distribution of the k statistic for both the complete sample of 35 galaxies and the subsample of the 15 brightest galaxies. The full sample of A160 galaxies yields a reduced chi-squared value of $\chi^2 = 1.617$ when fitted by a uniform distribution, which is approximately a 3σ deviation; the probability of obtaining $\chi^2 \geq 1.617$ for 34 degrees of freedom is only $\sim 5.1 \times 10^{-3}$. The full sample has $\langle k \rangle = 0.628$ and the subsample of the 15 brightest galaxies yields $\langle k \rangle = 0.741$; indeed, selecting subsamples of the 20 or so optically brightest galaxies always gives $\langle k \rangle > 0.7$ and the distributions are clearly skewed towards $k = 1$. This suggests that we have detected significant wake-like excesses in these data.

Kolmogorov–Smirnov (KS) tests were performed to compare

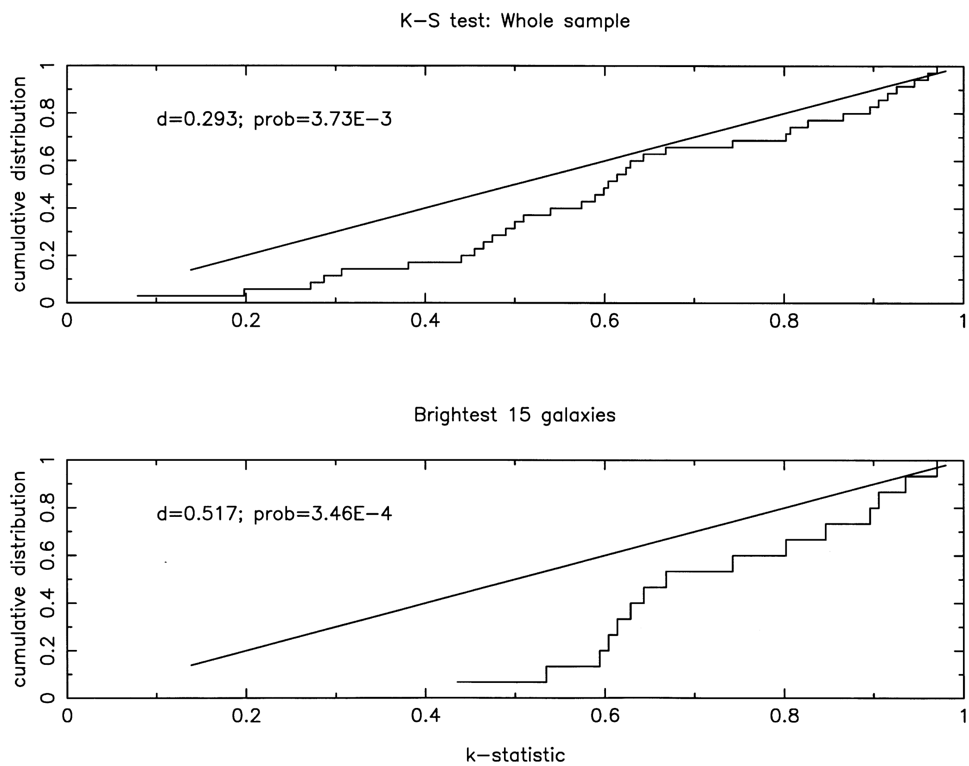

Figure 4. Plot of the cumulative distributions of the Kolmogorov–Smirnov test for the whole sample of 35 cluster galaxies (top panel) and for the subsample of the 15 optically brightest galaxies (bottom panel); d and *prob* are explained in the text.

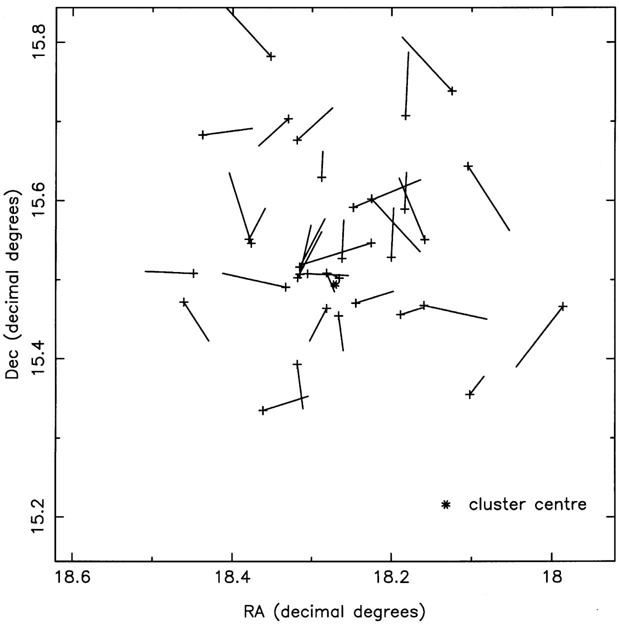

Figure 5. Directions of the wake-like features found for the 35 cluster galaxies in Abell 160. The positions of the galaxies are marked by crosses, and the lines represent the wakes. Length of line is proportional to wake strength (as determined by the k statistic). The centre of the cluster is also shown for reference.

the k statistic results to a uniform distribution. Fig. 4 presents these test results for the complete sample of galaxies as well as the brightest 15 subsample. The figure's annotation gives the values of the KS statistic, d, which is simply the greatest distance between the data's cumulative distribution and that of a uniform distribution, and *prob*, which is a measure of the level of significance of d. The probability of the detected features arising from chance is less than 3.5×10^{-4} for the bright sample and 3.8×10^{-3} for the entire sample of 35 galaxies. It is clear from Fig. 4 that the more luminous galaxies do not follow a uniform distribution in k-space.

The analysis applied to the Deep Survey 'blank field' data yielded a mean value for the k statistic of $\langle k\rangle = 0.48$, indicating that the results are uniformly distributed in k-space and that we do not detect 'wakes' in this comparison field. Indeed, assuming a uniform distribution for k, the fit to the data has a chi-squared value of $\chi^2 = 1.015$, implying that the values of k are uniformly distributed to high precision.

In order to investigate the nature of the wake-like excesses in the A160 data, we now consider the distribution of their directions on the sky. Fig. 5 shows the directions of the strongest wake-like features found using the k statistic analysis, for all 35 cluster members. The lines on this figure represent the wakes and their lengths are drawn proportional to wake strength.

The azimuthal distributions of the counts found in some of the highest-ranked wakes are shown in Fig. 6. The wake profiles show wakes for these galaxies to be statistically significant with a mean net count of ~ 5, corresponding to a mean net X-ray flux of $1.7\times10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The wake fluxes translate into X-ray luminosities in the range $(1\text{–}2)\times10^{40}\,\mathrm{erg\,s^{-1}}$. Grebenev et al. (1995) used a wavelet transform analysis to study the small-scale X-ray structure of the richness class 2 cluster Abell 1367: they found 16 extended features, of which nine were associated with galaxies and had luminosities in the range $(3\text{–}30)\times10^{40}\,\mathrm{erg\,s^{-1}}$. They concluded that the features could be associated with small galaxy groups, as suggested by Canizares, Fabbiano & Trinchieri (1987), rather than individual galaxies. The wake-like features we have detected have X-ray luminosities of the same order as individual galaxies in Abell 160, and the emission is clearly confined to extensions in specific directions away from the galaxies. Furthermore, the features noted by Canizares et al. (1987) have size scales $\sim 1'$, much larger than the expected wake size at the distance of A1367 and so not directly comparable with the current work.

Fig. 7 shows the distribution of apparent wake angles as a function of the radii of the galaxies in the cluster, for different strengths of wake as quantified by the k statistic. As we might expect, for low values of k where the wake is almost certainly a noise feature, the values of $|\Theta|$ are randomly distributed between 0° and 180°. However, for values of $k > 0.7$, which are unlikely to be attributable to noise, there is only one wake pointed at an angle of $|\Theta| > 135°$. If the distribution of wake directions was intrinsically isotropic, the probability of finding only one of the 12 most significant wakes in this range of angles is only 0.01. Given the a posteriori nature of this statistical measure, its high formal significance should not be over-interpreted. None the less, there definitely appears to be a deficit of wakes pointing towards the cluster centre.

5 DISCUSSION

As a first attempt at an objective determination of the frequency of wakes behind cluster galaxies, we have found significant excesses of X-ray emission apparently offset from their host galaxies. Before exploring the possible astrophysical meaning of such features, we must rule out more prosaic possibilities.

If the X-ray emission were truly centred on the galaxies, we would still detect offset X-ray emission if there were significant positional errors in the optical galaxy locations. The uncertainties on these positions, however, are much less than the radii at which we have detected the wakes, so this possibility can be excluded. Similarly, an overall mismatch between the optical and X-ray reference frames would produce offsets between X-ray and optical locations of coincident sources, but the distribution of apparent offset directions shown in Fig. 5 is not consistent with the coherent pattern that one would expect from either an offset or a rotation between the two frames.

We could explain the excess of sources where the X-ray emission lies at larger radii in the cluster than the optical position if the spatial scale of the optical data had been underestimated relative to that of the X-ray data. But both the *ROSAT* and optical data image scales are extremely well calibrated. Further, if such mismatch in magnification were responsible for the effect, one would expect the radial offsets to increase with distance from the field centre, and Fig. 7 provides no evidence that the wakes become more radially oriented at large distances from the cluster centre.

A further possibility is that the distorted nature of the X-ray emission could arise from an asymmetry in the *ROSAT* HRI point-spread function (PSF). Such asymmetries are documented (see, for example, Morse et al. 1995), but the observed shape of the HRI PSF actually becomes tangentially extended at large off-axis angles, so one would expect the wakes to be oriented at angles of $|\Theta| \sim 90°$. The three wakes at very large radii and $|\Theta| \simeq 70\text{–}120°$ in Fig. 7 could well result from this phenomenon, but there is no evidence for any such effect at smaller radii.

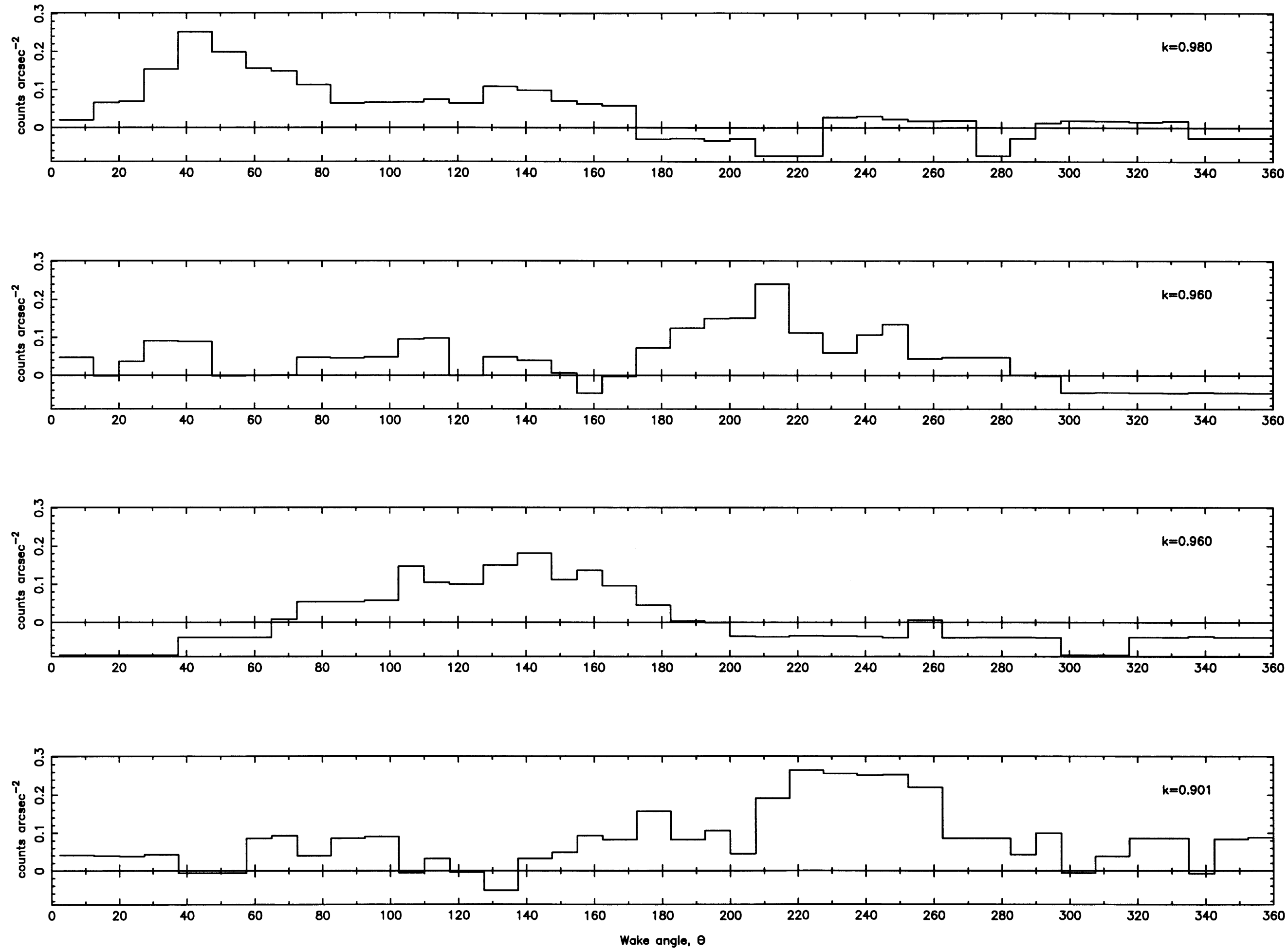

Figure 6. Azimuthal distributions of the counts around four galaxies for which $k > 0.9$. Here the azimuthal angle (with respect to the parent galaxy) is defined such that 0° corresponds to north on the sky and the angle increases anticlockwise. The values of k for each galaxy are noted in the panels.

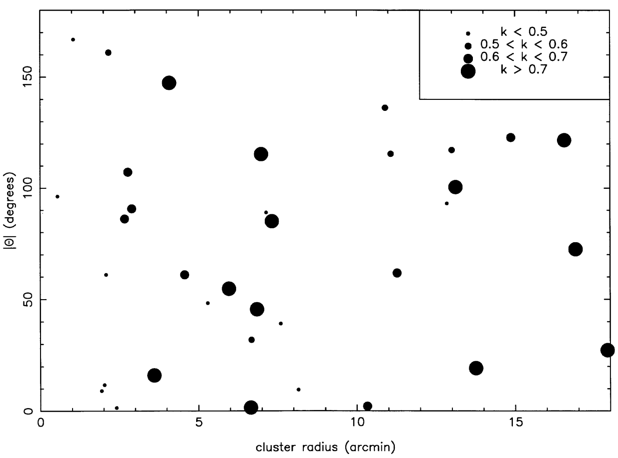

Figure 7. Scatter plot of the projected angle $|\Theta|$ of the 35 brightest wedge features as a function of distance from cluster centre. Larger point sizes reflect greater values of the k statistic found for each galaxy, as given in the key to the figure.

We are therefore forced to return to trying to find an astrophysical explanation for the bulk of the observed wakes. As discussed in the introduction, an individual galaxy can emit at X-ray wavelengths because of both its hot ISM component and its contingent of X-ray binaries. Such emission could extend to the radii where we have been searching for wakes, or appear to do so as a result of the blurring influence of the PSF, so we might expect some wake-like features to appear simply due to this component. Such asymmetric wake features could arise from Poisson noise on intrinsically symmetric emission, or it could reflect a real asymmetry in the emission. For example, the emission from X-ray binaries could be dominated by one or two ultraluminous sources in the outskirts of a galaxy, leading to an offset in the net X-ray emission. Even the X-ray wake phenomenon that we are seeking to detect can be described as an asymmetric distortion in the normal ISM emission. How, then, are we to distinguish between these possibilities?

Perhaps the best clue as to the nature of the detected asymmetric emission comes from the distribution of the angles at which it is detected, Θ. As we have described above, there is a deficit of wakes pointing towards the cluster centre. It is hard to see how such a systematic effect can be attributed to any of the more random processes such as Poisson noise on a symmetric component, or even the azimuthal distribution of X-ray binaries within the galaxy. It therefore seems highly probable that we are witnessing the more systematic wake phenomenon that we seek. If a wake indicates the direction of motion of the galaxy, then the deficit of detections at large values of $|\Theta|$ implies that the production mechanism becomes ineffective when a galaxy is travelling out from the cluster centre. This conclusion has a simple physical explanation: if a galaxy is travelling on a reasonably eccentric orbit, by conservation of angular momentum it will spend a large fraction of its time close to the orbit's apocentre. During this period, its velocity is slow and the ICM it encounters is tenuous, so it is able to retain its ISM. In fact, continued mass loss from stellar winds and planetary nebulae means that the amount of gas in its ISM will increase. Ultimately, however, its orbit will carry it inward towards the core of the cluster. At this point, the galaxy is travelling more rapidly, and encounters the higher-density gas near the centre of the cluster, so ram pressure stripping becomes more efficient, and a wake of stripped ISM material will be seen behind the infalling galaxy. By the time the galaxy passes the pericentre of its orbit, the ISM will have been stripped away to the extent that the outgoing galaxy does not contain the raw material to create a measurable wake, explaining the lack of detected wakes at large values of $|\Theta|$.

This simple picture seems to fit the data on Abell 160 rather well; a similar scenario was invoked by McHardy (1979) to explain the locations of weak radio sources in clusters. It is also notable that the beautiful wake feature behind NGC 1404 in the Fornax cluster detected by Jones et al. (1997) is oriented such that it points radially away from the cluster centre. Clearly, though, more deep X-ray observations of clusters are required if we are to confirm the widespread applicability of this scenario.

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