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Measuring bulk flows of the intracluster medium in the Perseus and Coma galaxy clusters using *XMM-Newton*

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ABSTRACT

We demonstrate a novel technique for calibrating the energy scale of the EPIC-pn detector on *XMM-Newton*, which allows us to measure bulk flows in the intracluster medium (ICM) of the Perseus and Coma galaxy clusters. The procedure uses the fluorescent instrumental background lines present in all observations, in particular, Cu-K α . By studying their spatial and temporal variations, in addition to incorporating calibration observations, we refined the absolute energy scale of the detector to better than 150 km s⁻¹ at the Fe-K line, a large improvement over the nominal calibration accuracy of 550 km s⁻¹. With our calibration, we mapped the bulk motions over much of the central 1200 and 800 kpc of Perseus and Coma, respectively, in spatial regions down to 65 and 140 kpc size. We cross-checked our procedure by comparing our measurements with those found in Perseus by *Hitomi* for an overlapping 65 kpc square region, finding consistent results. For Perseus, there is a relative line-of-sight velocity increase of 480 ± 210 km s⁻¹ (1 σ) at a radius of 250 kpc east of the nucleus. This region is associated with a cold front, providing direct evidence of the ICM sloshing in the cluster potential well. Assuming the intrinsic distribution of bulk motions is Gaussian, its width is 214 ± 85 km s⁻¹, excluding systematic uncertainties. Removing the sloshing region, this is reduced to 20–150 km s⁻¹, which is similar in magnitude to the *Hitomi* line width measurements in undisturbed regions. In Coma, the line-of-sight velocity of the ICM varies between the velocities of the two central galaxies. Maps of the gas velocity and metallicity provide clues about the merger history of the Coma, with material to the north and east of the cluster core having a velocity similar to NGC 4874, while that to the south and west has velocities close to NGC 4889. Our results highlight the difference between a merging system, such as Coma, where we observe a ~ 1000 km s⁻¹ range in velocity, and a relatively relaxed system, such as Perseus, with much weaker bulk motions.

Key words. galaxies: clusters: intracluster medium — galaxies: clusters: individual: Perseus cluster — galaxies: clusters: individual: Coma cluster — X-rays: galaxies: clusters — techniques: imaging spectroscopy

1. Introduction

The velocity structure of the intracluster medium (ICM), the dominant baryonic component of galaxy clusters, remains poorly observationally constrained except in the core of the Perseus cluster (Hitomi Collaboration 2016, hereafter H16). Simulations predict that the ICM should contain turbulent or random motions, and bulk flows caused by the merger of other clusters and subcomponents (e.g. Lau et al. 2009; Vazza et al. 2011). In addition, there can be relative bulk motions of a few hundred km s⁻¹ caused by sloshing of the ICM in the potential well, generated by merging substructures (e.g. Ascasibar & Markevitch 2006; ZuHone et al. 2018). The central active galactic nucleus (AGN), via the action of its jets and inflation of relativistic bubbles, also likely generates motions of a few hundred km s⁻¹ (e.g. Brüggen et al. 2005; Heinz et al. 2010).

Measuring the velocities of the ICM is important for several reasons. Turbulent motions provide additional pressure sup-

port, particularly at large radii, which affects calculations of hydrostatic equilibrium and cluster mass estimates (e.g. Lau et al. 2009). AGN feedback injects a great deal of energy into the ICM which replaces that which is lost radiatively by X-ray emission (reviewed in Fabian 2012). Feedback has to provide distributed heating but how this works depends on the microphysics of the ICM and the balance between turbulence and sound waves or shocks. Measuring the associated velocities would help constrain AGN feedback models. Velocity is an excellent probe of the microphysics of the ICM, such as viscosity, which acts to smooth velocity structure (e.g. Reynolds et al. 2005; ZuHone et al. 2018). Simulations predict a close connection between turbulent thermodynamic and velocity power spectra (Gaspary et al. 2014) which should be tested. In addition, measuring velocities will help explain the processes taking place in cluster mergers and the sloshing of gas in cold fronts, which is believed to last for several Gyr (Ascasibar & Markevitch 2006; Roediger et al. 2012).

Hitomi (Takahashi et al. 2016) with its high spectral resolution microcalorimeter Soft X-ray Spectrometer detector (Kelly et al. 2016) directly determined bulk and random motions in the Perseus cluster by measuring the position and width of the Fe-K emission lines (H16). It found a line-of-sight velocity dispersion of $164 \pm 10 \text{ km s}^{-1}$ between radii of 30 and 60 kpc and a gradient of 150 km s^{-1} bulk flow across 60 kpc of the cluster core. Away from the central nucleus and the northwestern cavity, the dispersion drops to $\sim 100 \text{ km s}^{-1}$ (Hitomi Collaboration 2018a, hereafter H18). Therefore, the Perseus core is not strongly turbulent, despite the obvious impact of the AGN and its jets on the surrounding ICM (e.g. Fabian et al. 2000). Unfortunately, *Hitomi* was lost and will not be available to observe more clusters, in particular merging galaxy clusters which would have probed different physical processes. The next missions equipped with a high-resolution instrument capable of measuring velocities are likely to be *XRISM* (the replacement for *Hitomi*, formerly known as *XARM*), to be launched in 2022, and *Athena* in the early 2030s.

Prior to *Hitomi*, *Suzaku* obtained velocities in several systems using the Fe-K line thanks to its accurate calibration, despite only having a charge-coupled device (CCD) detector. Tamura et al. (2014) examined multiple pointings, placing limits on relative velocities of 300 km s^{-1} over scales of 400 kpc in Perseus while on larger scales below 600 km s^{-1} , with hints of detection of velocity structure at $150 - 300 \text{ km s}^{-1}$ in the cold front 45 to 90 kpc west of the cluster. Ota & Yoshida (2016) examined several clusters with *Suzaku*, including the central region of the Perseus cluster. Systematic errors from the *Suzaku* calibration were around 300 km s^{-1} and it had a large point-spread function (PSF) of around 1.8 arcmin (half power diameter). *Chandra* has also been used to measure gas velocities, finding evidence of bulk motions in merging massive clusters (Liu et al. 2016).

Another direct method for measuring velocities is to use the *XMM* Reflection Grating Spectrometer (RGS) to limit or measure line widths (e.g. Sanders et al. 2010; Pinto et al. 2015). Because of the slitless nature of the RGS, this is only effective in the central parts of peaked clusters. In several systems, limits below 300 km s^{-1} were obtained using this technique (Sanders & Fabian 2013), which agrees with the low turbulent velocities later found by *Hitomi* in Perseus.

There are other indirect methods for measuring motions, including examining resonant scattering (e.g. Werner et al. 2009; Ahoranta et al. 2016; Ogorzalek et al. 2017). Measurements using resonant scattering are currently only possible for low-temperature X-ray emitting gas in elliptical galaxies or the cores of cool-core groups or clusters, except in the Perseus cluster (Hitomi Collaboration 2018c). The power spectrum of density fluctuations has been used to obtain upper limits on the amount of turbulence in some systems (Zhuravleva et al. 2014a). Repeating this analysis on simulated Perseus-like data (Walker et al. 2018a), however, shows that the signal from sloshing gas could contribute strongly outside 60 kpc radius. Turbulence can also be constrained based on arguments about its radial propagation (Bambic et al. 2018).

In this paper, we present a novel technique to calibrate the pn detector of the European Photon Imaging Camera (EPIC) on-board *XMM-Newton*, allowing us to measure bulk motions in clusters of galaxies. Section 2 describes our calibration methods. Using the calibration and the procedures described in Sect. 3, we analyse observations of the Perseus (Sect. 4) and Coma (Sect. 5) galaxy clusters to study bulk motions. Further systematic errors and future improvements are discussed in Sect. 6. Uncertainties quoted are at the 1σ level. Any astrophysical velocities quoted

have a positive sign for material flowing away from the observer. All sky images are shown with north to the top and east to the left.

2. Data calibration

To measure velocities with EPIC-pn we need an excellent characterisation of the energy scale of the instrument. Because the cluster observations we wish to analyse are spread over the lifetime of the mission, we want to study this entire period. The currently-quoted accuracy for the detector energy-scale calibration for imaging modes is better than 12.5 eV (XMM-SOC-CAL-TN-0018). At the energy of Fe-K emission, this is equivalent to roughly 550 km s^{-1} . As we later show, although this quoted accuracy may be an average over the detector at the energy of the Mn-K α calibration line, it appears to underestimate the energy shifts in some locations of the detector at higher energies.

In our analysis we used the *XMM* Science Analysis Software (SAS) version 16.1.0. When transforming from raw (PHA) to corrected (PI) event energies, SAS applies several different corrections to the energies of the observed events using its calibration database. This work is done by EPEVENTS, used as part of EPCHAIN, one of the EPIC-pn data-reduction chains. The effects corrected for include charge transfer inefficiency (CTI), operating along the columns of the detector and gain changes, including those obtained from long-term calibration source monitoring, and the effects of detector temperature variation. The standard calibration uses the measured position of the 5.89 keV Mn-K α and 1.48 keV Al-K α calibration lines with time. EPEVENTS applies a linear correction to events between these energies. Above the energy of Mn-K α it does not introduce non-linearity of the energy scale. Owing to the nature of the development of the calibration, SAS applies several corrections in sequence when converting from PHA to PI values. We continue this trend by applying further corrections to the standard PI values. The current correction procedure is only applicable if the astrophysical line to be examined has an energy above the instrumental Mn-K α , because of the energy scale interpolation used below this energy by SAS. Therefore if using Fe-K to measure redshifts, objects must lie below $z \sim 0.12$.

Our first step is a correction for the average gain of the detector during the observation (Sect. 2.8), the second is a correction for the spatial gain variation across the detector with time (Sect. 2.9) and the final correction is to linearise the energy scale as a function of detector position and time (Sect. 2.10).

2.1. The EPIC-pn detector

The EPIC-pn camera (Strüder et al. 2001) contains a monolithic silicon CCD array, made up of 4×3 CCDs (Fig. 1). Each of the individual CCDs has 64 columns and 200 rows. The detector is read out along the columns as quadrants, each containing three CCDs. There are a variety of operating modes of the detector, but we are primarily interested in Full Frame (FF) and Extended Full Frame (EFF) modes, which read out the whole detector. In the EFF mode the fraction of out-of-time events (Sect. 2.6) is reduced by using longer frame times, at the expense of being more susceptible to pile-up (more than one photon arriving within a frame time). At an energy of 5.89 keV the detector achieved in its first nine months an average of $\sim 150 \text{ eV}$ full width at half maximum (FWHM) spectral resolution.

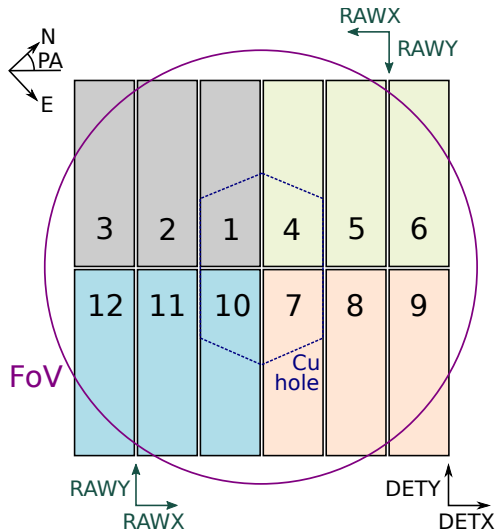


Fig. 1. Geometry of the EPIC-pn detector. Shown are the numbers of the CCDs, the field of view exposed to the sky (FoV), the raw coordinates (RAWX and RAWY), the detector coordinates (DETX and DETY) and the approximate location of the ‘Cu hole’. The position angle (PA) is the angle between the detector and sky coordinates, an example of which is shown. The four quadrants are shaded in different colours.

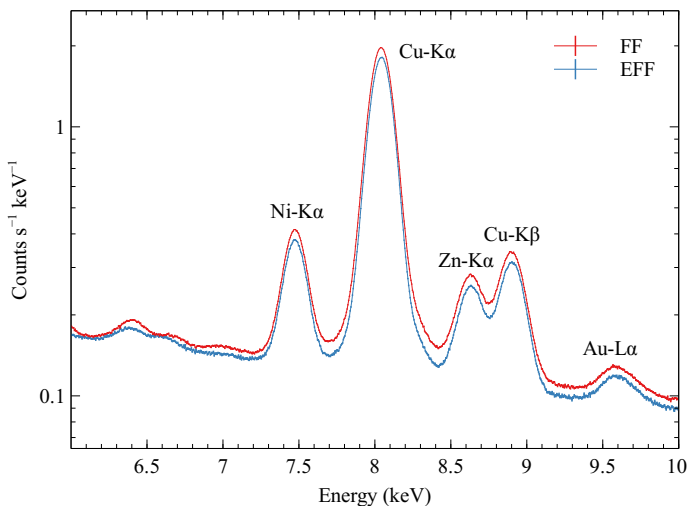


Fig. 2. Total stacked spectra of the fluorescent background emission lines for 32.6 Ms of FF (red) and 19.7 Ms EFF (blue) data. Before stacking the individual spectra, the three orders of correction described in Sect. 2 were applied. Only events with PATTERN==0 were included. Au-L α was not used in our analysis because of its weakness.

2.2. Instrumental background emission lines

To calibrate the energy scale of the detector, we measured the position of fluorescent emission lines produced by elements present in the electronics boards behind the detector, and visible in all observations (Freyberg et al. 2001). The dominant emission line is the Cu-K α line at 8.04 keV (Fig. 2). Weaker surrounding lines include Ni-K α (7.47 keV), Zn-K α (8.63 keV) and Cu-K β (8.90 keV). The spatial variation of the lines depends on the variation in the composition of the electronics boards. The distribution of Cu is relatively flat, except for a lack of emission in the centre of the detector (Fig. 3), which we call the ‘Cu hole’. The presence of this hole leads us to exclude the central part of the detector in our astrophysical analysis, as it cannot be cali-

brated through our procedure, although there is some residual signal from out-of-time events. Ni-K α and Cu-K β /Zn-K α emission shows spatial variation which appears to be anti-correlated.

2.3. Datasets used for calibration

Our calibration analysis made use of two different sets of data. The first was a set of observations of astrophysical objects taken from the *XMM* archive (Table A.4). We obtained as many long public observations using EPIC-pn full-frame modes as possible, manually filtering them by examining the preprocessed images to avoid those with bright X-ray point sources and optical sources. The observations were chosen to cover the full mission lifetime (from 2000 to 2019), although proprietary periods prevented us from analysing some recent data. These astrophysical datasets contain the background Cu-K α , Ni-K α , Zn-K α and Cu-K β fluorescent lines. The observations were split into FF and EFF sets for separate analysis. Those with a cleaned exposure of less than 10 ks were ignored. The cumulative exposures as a function of revolution for the two modes are shown in Fig. 4, where the *XMM* revolution is around 47.9 hours, or two days.

For the energy scale correction (Sect. 2.10) we also made use of detector calibration observations (Table A.5). We ignored those datasets where the cleaned exposure was less than 10 ks (the filtering is described in Sect. 2.5). EPIC-pn includes a ^{55}Fe radioactive calibration source which can be viewed by the detector, illuminating much of the field of view with a spectrum of Al-K α , Mn-K α and Mn-K β emission lines, with energies of 1.48, 5.89 and 6.49 keV, respectively. The half life of the source is 2.7 years, so it has become much fainter over the mission lifetime. The illumination of the detector by the source is also not flat, with some CCDs having poor coverage.

2.4. Spectral models

When fitting the spectral lines, we used the line shape measurements of Hölzer et al. (1997) for Mn-K α , Ni-K α , Cu-K α , Mn-K β and Cu-K β . We implemented an XSPEC model for each line, summing the provided Lorentzian fit sub-components. The shift in the energy of a line is parametrised by a redshift, measuring the fractional energy shift (not a real physical redshift). For the weaker Zn-K α line we made a model containing two Lorentzians with the energies taken from Bearden (1967), assuming a flux ratio of 0.52 for the ratios of the K α_2 and K α_1 lines, similar to the other K α lines in Hölzer et al. (1997), and choosing line widths of 3.3 and 2.4 eV, respectively.

2.5. Selected events

In our spectral analysis, we only considered single-pixel events (PATTERN==0), which have the best energy resolution. When examining real cluster emission, we only examined events with FLAG==0, which discards bad pixels and neighbouring regions, and the outer part of the detector which is not illuminated by the sky. When examining the fluorescent lines and calibration source, we instead filtered with (FLAG & 0xfa097d)==0, which also includes events outside the sky field of view, enabling us to improve our understanding of the detector near its corners.

To reduce the effect of the flaring component of the *XMM* background, we applied a uniform maximum count rate threshold of 1.0 ct s $^{-1}$ in 100s bins, in the 10 to 15 keV band with FLAG==0 and PATTERN==0.

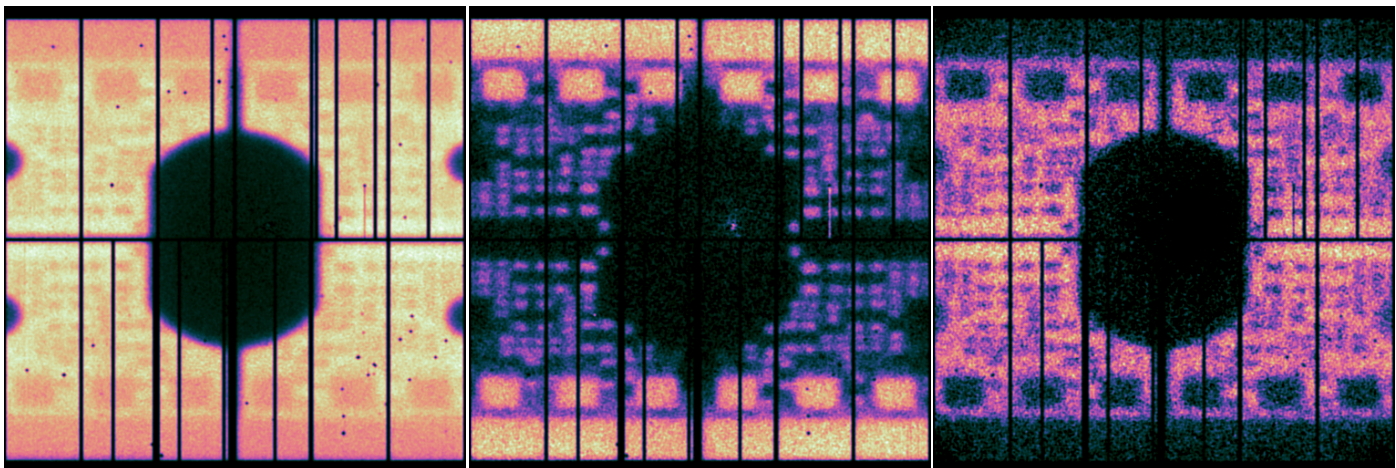


Fig. 3. Images of the detector in different fluorescent lines, created from stacked astrophysical observations. Shown are images in Cu-K α (left; 7.805 to 8.285 keV), Ni-K α (centre; 7.280 to 7.680 keV) and Cu-K β and Zn-K α (right; 8.455 to 9.075 keV). Approximate background has been subtracted using scaled continuum images on either side of the lines. Some residual astrophysical emission can be seen in the centre of the image. The total exposure is around 64 Ms after cleaning for flares, combining both FF and EFF data and using PATTERN ≤ 4 . The image was binned by 64 detector coordinate units and smoothed by a Gaussian of $\sigma = 1$ pixel width.

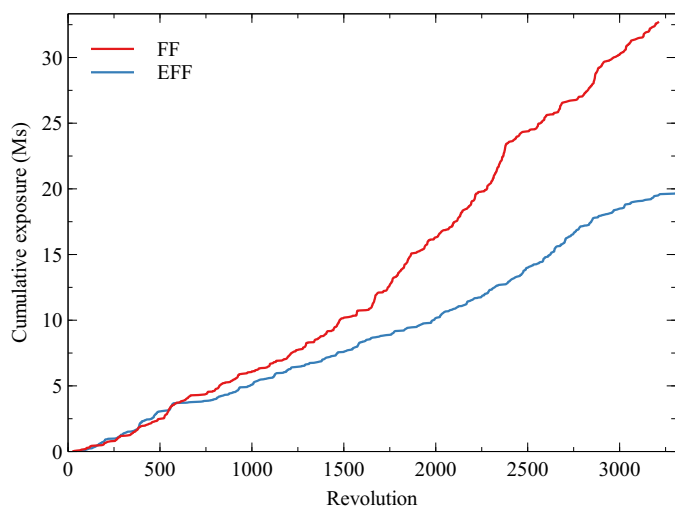


Fig. 4. Cumulative FF (red) and EFF (blue) cleaned exposure of the astrophysical datasets used in the calibration as a function of time (in *XMM* revolutions).

When extracting spectra, we binned them by the standard factor of five PI channels (i.e. 5 eV bins). Slightly improved uncertainties on measured line energies could have been obtained using a factor of one, although this would have meant we could not have used the standard response matrices.

2.6. Out-of-time events

If a photon hits the detector while it is being read out, it will be recorded with a wrong RAWY position, producing an out-of-time (OoT) event. For bright sources these events can be seen as a stripe along the RAWY direction. In FF mode, the fraction of events which are OoT is 6.3 per cent, while it is 2.3 per cent in EFF mode.

In our analysis we accounted for OoT events with an OoT event file, created by running EPCHAIN a second time with the parameter ‘withoutoftime=yes’. This option randomly shifts events along the RAWY axis, before the standard gain and CTI

corrections are applied. We extracted OoT spectra using the same extraction regions as the sources. These spectra were used as background spectra when spectral fitting, scaling the exposure times up by the appropriate fractions shown above. If we added the source spectra together, these background spectra were similarly added. The effect of correcting for OoT events in our analysis was small; the galaxy cluster astrophysical results differed by less than their statistical uncertainties.

2.7. Response matrix

When fitting spectra we used a response matrix with fine energy bins (0.3 eV) created with RMFGEN. This energy bin size is sufficient to resolve velocities down to $\sim 15 \text{ km s}^{-1}$. With larger binning, line energies tend to be discretised onto the energy grid and error bars are often asymmetric. For the stacked and calibration observations, the response matrix was generated using an early observation, 0114120101, and for small RAWY coordinates, giving the highest achievable energy resolution. A variable Gaussian smoothing component was used when fitting, to account for the change in energy resolution over the detector position and over time. EPIC-pn response matrices only differ between spatial positions and observations in their spectral resolution. Fitting for the energy resolution significantly reduces the storage and computational time which would be required to make individual responses.

The ancillary response file used for fitting the calibration observations and fluorescent line data was generated from the same observation, disabling the effect of the mirrors and the detector filter (using parameters `modelfiltertrans=false` and `modelfilterarea=false`), which do not affect the background lines.

2.8. First order gain correction (mean Cu-K α)

The first order energy correction we made was to measure the average ‘redshift’, z , of the Cu K α line in each observation and correct it back to zero. The total Cu-K α spectrum was extracted from each observation, including events outside the sky region, but excluding the central Cu hole. The hole was defined as a polygon with DETX and DETY coordinate pairs of 7601, 4390, -6209, 5255, -4531, 5978, -2361, 6383, -480, 6181, 995,

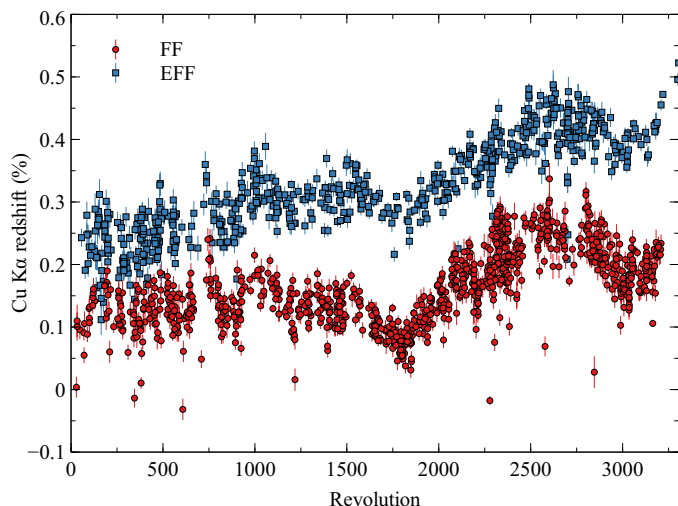


Fig. 5. Best-fitting Cu-K α redshifts for individual astrophysical observations as a function of time (in *XMM* revolutions). A 0.1 per cent correction is 8 eV at the energy of Cu-K α .

5573, 2094, 4994, 3133, 3905, 3136, -6116, 1747, -7447, 300, -8286, -1232, -8459, -3431, -8459, -4646, -8228, -5688, -7794, -6874, -6926, -7616, -6052.

We fitted the spectrum between 7.00 and 9.25 keV by a model with Cu-K α , Cu-K β , Ni-K α , Zn-K α and powerlaw components. The redshift of each line component was allowed to vary independently. We applied smoothing by a common variable-width Gaussian component, to allow for changes in energy resolution. The spectra were fitted by minimising the C-statistic in XSPEC.

Figure 5 shows the Cu-K α redshifts of the astrophysical observations as a function of time. It can be seen that there is a systematic offset between FF and EFF observations, which widens with time. At the 8 keV energy of Cu-K α , the maximum shift is around 20 eV for FF and 35 eV for EFF modes.

We corrected observations for their average Cu-K α gain shift by scaling the PI values of the observation by $1 + z$. In detail, we take the integer PI value in an event file, add a uniformly-distributed random number between zero and one, scale by $1 + z$, then round downwards back to an integer value.

2.9. Second order gain correction (stacked Cu-K α)

After correcting for the average Cu-K α redshift in each observation, we measured the Cu-K α redshift as a function of detector position and time. We stacked the spectra from the astrophysical observations in time bins of 500 revolutions (overlapping, as the bins start in 250 revolution intervals), examining the FF and EFF modes separately. As the detector is read out in columns, we stacked the spectra for each CCD in bins of 1×20 raw detector pixels. We fitted each spectrum between 7.7 and 8.4 keV, by the Cu-K α model with variable redshift (z) and smoothing, plus a powerlaw.

Figure 6 shows the redshift in six non-overlapping revolution intervals as a function of position, for the FF and EFF modes. Excluding the central Cu hole region, in FF mode the position of the Cu-K α line is shifted between around -0.2 and +0.8 per cent (-15 to +65 eV), with shifts most positive furthest away from the readout, and most negative in the centre of the CCDs. In EFF mode there is a different distribution in shift over the detector, with a range of around -0.5 to +0.6 per cent (-40 to +50 eV),

with the most positive shifts in the centre of each CCD, and the most negative shifts furthest from the readout. The difference between the FF and EFF maps is fairly constant in time.

The ranges of the shift appear to increase with time, but change fairly gradually, allowing us to correct for this effect. To correct the gain for an observation, we took the average Cu-K α line shift, when measured from the uncorrected observation (as in Sect. 2.8) and the correction map with the central revolution closest in value with the observation revolution. Each PI value was corrected by the combined shifts, looking up the correction on the map according to CCD number and pixel coordinate.

We tested that the PI scaling procedure works to correct the stacked Cu-K α line energy by correcting the input event files and repeating the procedure in this section. We found that the produced maps are centred around zero shift, with a standard deviation close to the average statistical uncertainty on each line measurement.

Another test is to look for position-dependent energy changes which are not corrected by the average Cu-K α for an observation and the time-dependent average detector maps we have produced here. This may occur, for example, if there are random fluctuations in the gain of each CCD within single observations. To test for this, we extracted and fitted the spectra from individual CCDs for each observation which went into the stacking analysis, after applying our correction for the average Cu-K α and the time-dependent detector maps in this section, excluding the central Cu-K α hole. The distribution of residual Cu-K α redshifts was well modelled by a Gaussian distribution, after excluding points with large error bars. We modelled the intrinsic distribution of the points before measurement uncertainties for each CCD as a Gaussian. Figure 7 shows the obtained Gaussian centre of the distribution and the intrinsic distribution width (σ) for each CCD in the two different detector modes.

This analysis shows no evidence of strong variation within observations of the Cu-K α line energy. We see a systematically low Cu-K α energy after correction, but this is only of the order of 0.005 per cent. This may be because when we corrected for the average Cu-K α energy for an observation, we fitted the whole fluorescent line complex energy range, but when we examined spatial bins, we only fitted for the Cu-K α line. The shape of the underlying continuum may affect the Cu-K α line energy slightly. The corrected Cu-K α values have a distribution width of around 0.01 per cent, which is very good for our purposes ($\sim 30 \text{ km s}^{-1}$).

We also tested a modified version of the 1st and 2nd order corrections, where an initial 1st order correction was done to each CCD, rather than to the detector as a whole. The changes to the galaxy cluster astrophysical results, using these corrections instead of those we present, were much smaller than the statistical uncertainties.

2.10. Energy scale correction

After applying the correction for the observation-specific Cu-K α position and our correction maps (the gain corrections), it became apparent that the energies of other lines required further correction. The data preferred Zn-K α and Cu-K β line redshifts greater than zero, and Ni-K α line redshifts less than zero (Fig. 8). We examined calibration observations, also finding that the Mn-K α and β lines were at too high energies.

We found that a linear model, where observed line positions are compressed in energy by some factor proportional to their energy difference from the Cu-K α line, modelled these shifts well. Unfortunately the correction factor has both spatial and time dependence. Figure 9 shows this energy scale correction factor as

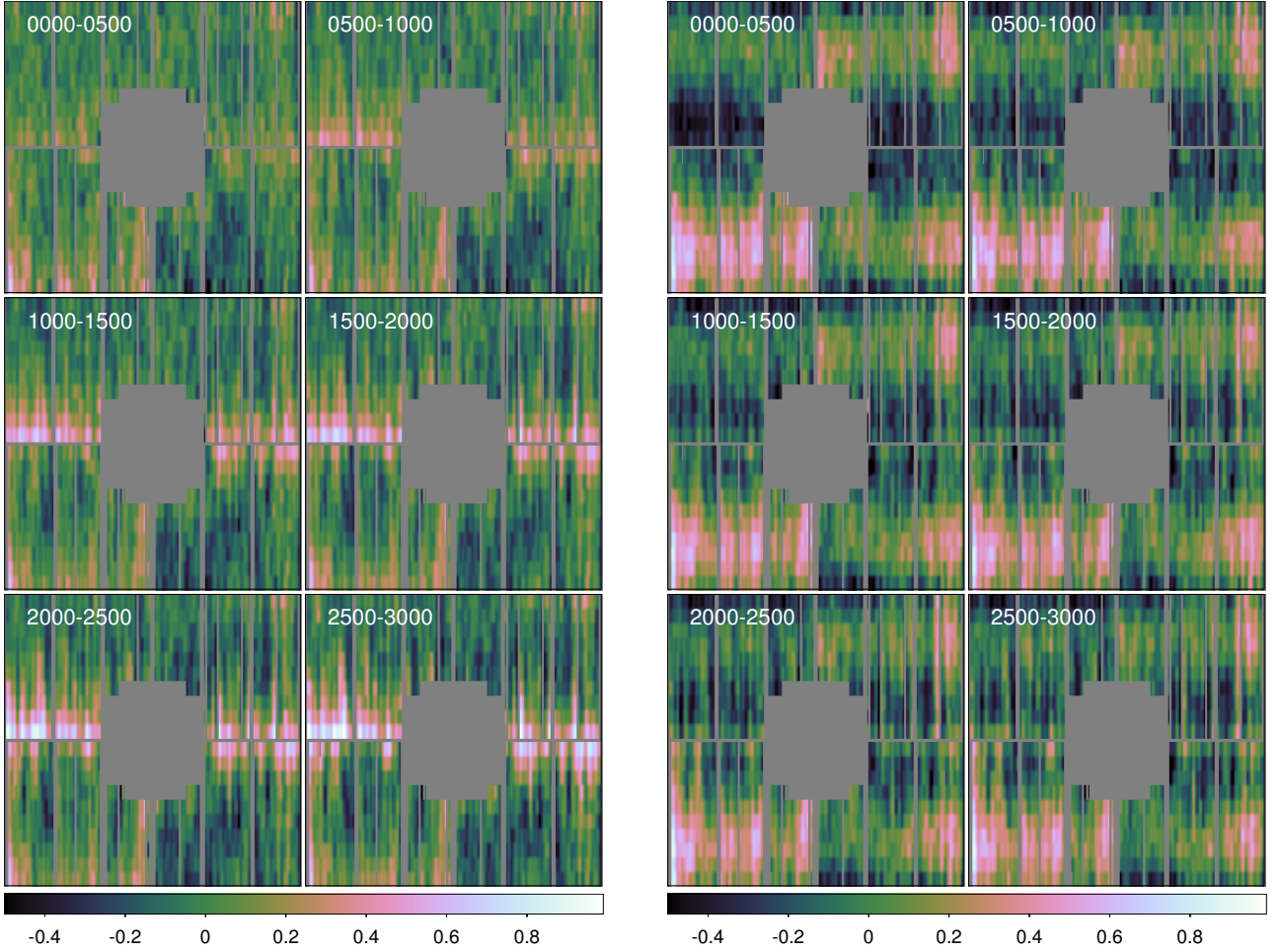


Fig. 6. Redshift of the Cu-K α line (in per cent) as a function of detector position over the mission lifetime in FF (left) and EFF (right) modes, after correcting for the average value. The range shown in the top-left of each panel is the *XMM* revolution. The shift has been measured in 1×20 pixel regions and a $\sigma = 2$ pixel Gaussian smoothing applied for display. Detector regions with a large uncertainty in a combined error map have been masked out.

a function of time for each CCD. These results were obtained by fitting a spectral model made of Mn-K α , Mn-K β , Ni-K α , Cu-K α , Zn-K α and Cu-K β lines (the ‘6-line’ model). The redshifts of the lines were parametrised by an energy correction factor multiplied by the difference in the expected energy of each line to the Cu-K α line energy (-2.150 , -1.555 , -0.570 , 0.590 and 0.865 keV, respectively). The Cu-K α line position was free in these fits. We also included powerlaw components (each with a free slope) between energies of 5.2 and 7.1 keV, 7.1 and 8.0 keV, and 8.0 and 9.5 keV to account for continuum and broad line components. The line components were convolved by a Gaussian broadening component parametrised by its energy width. As the calibration source becomes weaker with time and has spatial variation, we fitted both stacked calibration observations (below 7 keV) and stacked calibration plus real observations (above 7 keV), in bins of revolution. We fitted the spectrum between 5.825 and 6.245 keV, 6.375 and 7.000 keV, 7.170 and 7.795 keV, and 7.905 and 9.200 keV (as in Fig. 8). The energy ranges chosen were designed to exclude the asymmetries seen in the Mn-K α and Mn-K β line shapes by excluding the broader lower energy part of the line below the peak. We used the same response and ancillary response as previously (Sect. 2.7) and minimised the C-statistic in the spectral fits. We did not find any difference when

comparing FF and EFF mode data, so we combined both in this analysis.

Figure 9 shows that there is an increasing energy scale compression (PI values are compressed around the Cu-K α line) in each CCD with time. There appears to be an offset at zero revolutions, and in some CCDs a jump is seen at around revolutions of 250. The plot includes a constant plus linear with time model, fitted excluding datasets below a revolution of 250 and by minimising the χ^2 . To avoid the fits being strongly biased by the points with small error bars (particularly those early in the mission when the calibration source was strongest), we increased the error bars on the data points by adding 10^{-4} keV $^{-1}$ in quadrature.

We do not know the physical origin of this non-linearity in the PI values from the detector. It is affected by the ageing of the detector unit in space, although it was apparent from launch. By examining spectra in different spatial bins, we found that differences were clearer in the RAWX axis of the CCDs (i.e. groups of columns were more different). There is also some variation in the RAWY axis, with the steepness of the slope in time being stronger towards large RAWY values.

To remove this effect from our astrophysical data and calibration observations, we fitted stacked spectra in bins of 250 revolutions, and 4×2 spatial bins in each CCD (using inclusive

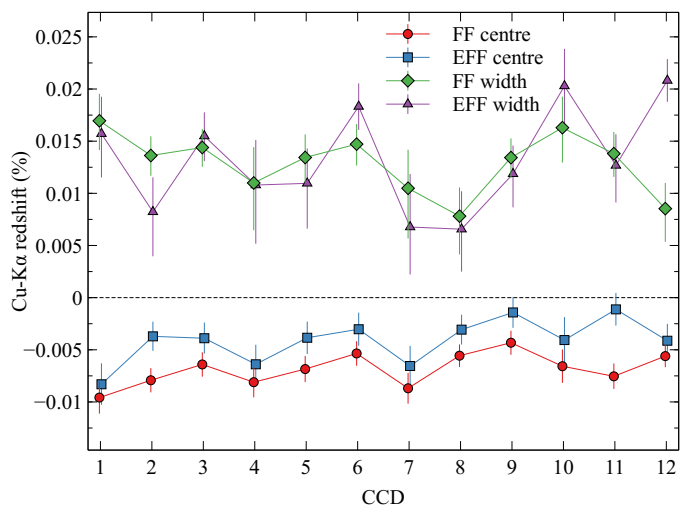


Fig. 7. Intrinsic Gaussian centre and width (σ) of the distribution of Cu-K α redshifts in each CCD for the observations which went into the stacking analysis, after correcting each observation for the average Cu-K α value and the time-dependent maps (Fig. 6). This analysis excludes observations with statistical uncertainties on the Cu-K α redshift of greater than 0.1 per cent. Results for FF and EFF modes are shown separately.

pixel ranges in RAWX of 0-16, 17-32, 33-48 and 49-64 and in RAWY 0-110 and 111-200). As above, the spectra were fitted (taking both stacked calibration and observational data) with the ‘6-line’ model and the energy scale correction factor was obtained. We fitted the energy correction factors as a function of time for each spatial region with a linear model in time as in Fig. 9, excluding the first time bin.

To correct the PI values for an event file, we compute the correction factors as a function of position given its revolution number. For revolutions below 250, we just use the results for that time bin, but for the others use the linear relation fitted to all the time bins. We choose a correction factor given by which RAWX bin the event is in, but use linear interpolation of the correction factors in RAWY.

To test how well the energy scale correction worked, we corrected our input event files and stacked them in revolution bins, including calibration observations (for the Mn-K α and β lines) and standard observations (for Ni-K α , Zn-K α and Cu-K β). Figure 10 shows the maps of the residual energy correction factor, after all our corrections. The corrections are well-scattered around zero.

There may be some variation in the correction factor between observations. We checked for this by fitting the spectra extracted from CCDs in the corrected calibration observations for the residual correction factor. Assuming the distribution can be represented as a Gaussian, we measured the width beyond what is expected from the statistical uncertainties. Figure 11 shows the centre and width of the distribution for each CCD. We obtain centres close to zero, with offsets less than about 10^{-4} keV $^{-1}$ and a width around 1.5×10^{-4} keV $^{-1}$. We excluded observations 0060740801 and 0108860301 in this analysis, as they showed very anomalous values of the correction factor. Including these observations in this analysis makes little difference to the results, but we suspect there is some problem with these individual observations, a small fraction of the sample.

We also examined the distribution of the residual correction factor for individual astrophysical observations. This is much harder to measure as the Ni-K α , Zn-K α and Cu-K β lines are

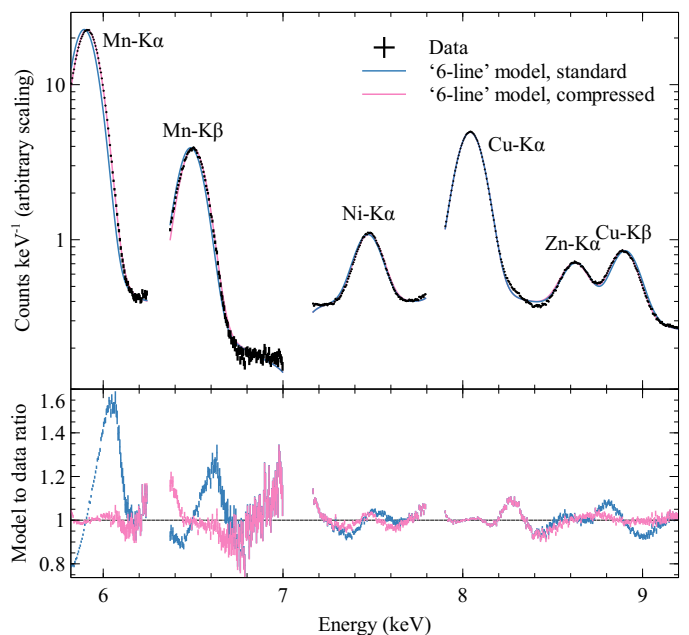


Fig. 8. Demonstration of the necessity of an energy scale correction. Shown in black are the total spectra of calibration observations between revolutions of 1000 and 1500 (< 7 keV) and the total spectra of calibration observations plus stacked observations in the same time period (> 7 keV), outside the Cu hole region. The count axis for data > 7 keV has an arbitrary scaling. The top panel shows the models and data, while the bottom panel shows their ratio. There are two ‘6-line’ models. One (blue) assumes that the lines are at their standard energies. The other (pink) has a linear compression model for the line energies about Cu-K α where $\delta E/E = 0.0013$ keV $^{-1}$. The poorly-modelled line wings do not affect the best-fitting compression factors.

weaker and closer to the Cu-K α . We therefore measure the residual factor in CCD quadrants (Fig. 1) rather than in CCDs, and limit the analysis to those observations where it can be measured in each quadrant to better than 2×10^{-3} keV $^{-1}$. This signal is difficult to measure, as the individual measurements have an average statistical error of 1.1×10^{-3} keV $^{-1}$ and the statistical width is an order of magnitude smaller. Using the same Gaussian distribution assumption, we find consistent values of the width parameter. The centre parameter appears a bit larger, on average around 7×10^{-5} keV $^{-1}$, perhaps indicating that the linear correction model becomes inadequate at this high level of precision, or there is slightly inaccurate modelling of the details of the lines.

If we instead examine whole observations rather than separate quadrants, we decrease the measurement errors by a factor of two. In this case we obtain an average residual correction factor of $(7 \pm 1) \times 10^{-5}$ keV $^{-1}$ and a distribution width of $(9^{+3}_{-4}) \times 10^{-5}$ keV $^{-1}$.

In summary, these tests show that we have accurately calibrated the scale of the detector in different spatial regions. Summing the residual correction factor offset and distribution width for the calibration observations (10^{-4} keV $^{-1}$ and 1.5×10^{-4} keV $^{-1}$, respectively), our energy scale appears accurate to better than 2.5×10^{-4} keV $^{-1}$, or 150 km s $^{-1}$ (rounding up) at the energies of cluster Fe-K emission. When we simultaneously fit the spectra from observations at different epochs and with different detector positions, we may obtain better precision, as some of the calibration differences will cancel out.

The overall accuracy of the correction for a single observation is determined by the precision to which the Cu-K α line energy can be measured. In archival astrophysical observations

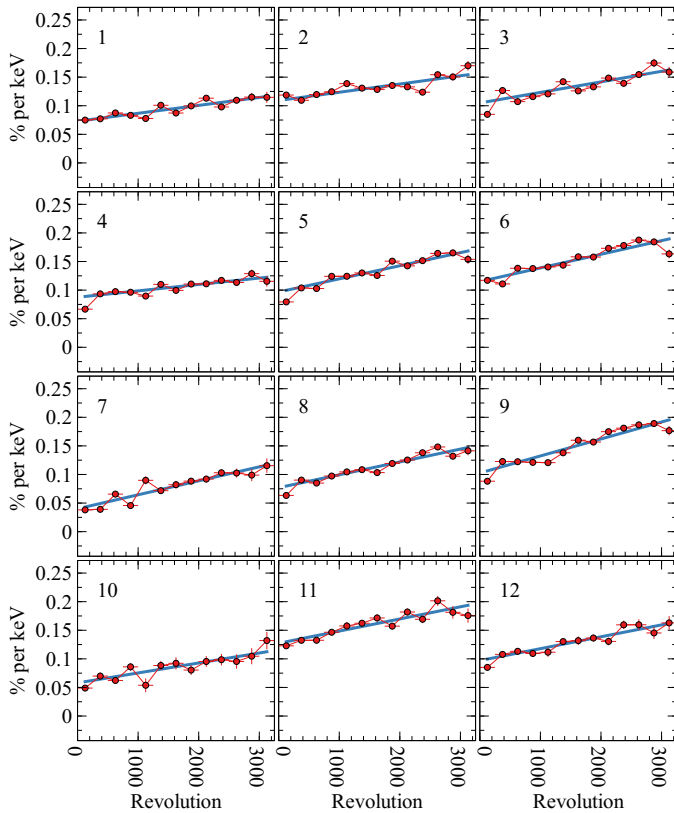


Fig. 9. Energy scale correction factor for each CCD as a function of time. Positive values mean that events have too low an energy at high energies and too high an energy at low energies. This plot shows the results of fitting the ‘6-line’ model to stacked calibration observations and observational datasets after gain correction, excluding the Cu hole. The lines show linear plus constant fits to the results excluding the first revolution bin.

(Table A.4), for an exposure time of T_{exp} , the Cu-K α redshift uncertainties have a functional form of $10^{-4} A(T_{\text{exp}}/10 \text{ ks})^{-1/2}$, where A is between 1.6 and 2.5. This individual uncertainty is significantly smaller than the statistical uncertainty on astrophysical redshift for a single observation. This systematic error will be reduced if multiple observations are combined, as it is random and Gaussian. Therefore, this systematic error is unimportant, except perhaps for extremely bright regions, such as the core of the Perseus cluster, which we cannot examine here owing to a lack of offset observations.

We applied further checks on the calibration procedure using the Perseus and Coma datasets in Appendix A.

3. Data analysis

Described here are the data analysis procedures applied to the observations of the Perseus and Coma clusters (observation details are listed in Table 1). Firstly, we processed each observation data file with the standard EPCHAIN SAS tool. To filter bad time intervals from flares, we applied the same 1.0 ct s^{-1} rate threshold as described in Sect. 2.5. The event files were energy corrected using the three steps described in Sect. 2, where we applied an overall gain correction using the observation Cu-K α redshift, the spatial and time-dependent gain map correction and finally the energy scale correction. When analysing spectra, we used only single-pixel events (PATTERN==0) to be consistent

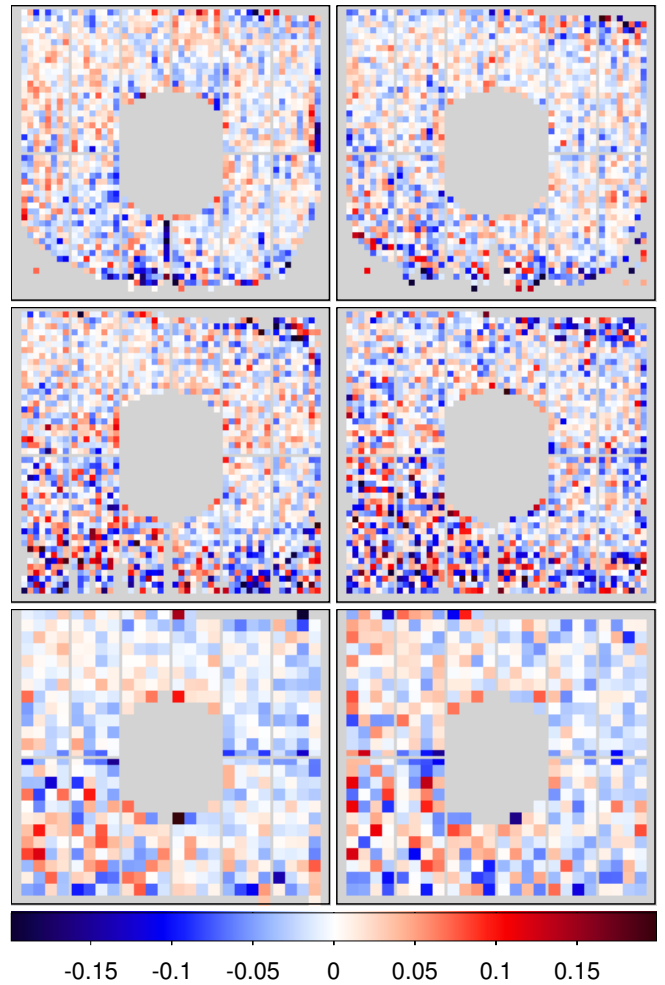


Fig. 10. Maps of the residual energy correction factor in stacked observations, after applying our correction to this in the individual observations. The units are per cent per keV. The panels show revolution bins of 0-500, 500-1000, 1000-1500, 1500-2000, 2000-2500 and 2500-3000 (left to right and top to bottom). The uncertainty of these values is not the same across the detector or in time, so we use 8 and 16 pixel binning. The statistical uncertainty is much larger in the bottom-left area because of the non-uniformity of the calibration source. Pixels where the uncertainty is larger than 10^{-3} keV^{-1} are not shown.

with our calibration analysis. We also filtered using FLAG==0 to avoid regions close to CCD edges or bad pixels.

When spectral modelling within XSPEC, we used the APEC spectral code (Smith et al. 2001) to model cluster emission, absorbed with a PHABS (Balucinska-Church & McCammon 1992) component to account for Galactic photoelectric absorption. We used APEC version 3.0.9, which includes corrections derived from the *Hitomi* observations (Hitomi Collaboration 2018b) and assumed the Solar abundance ratios of Lodders & Palme (2009) used in the *Hitomi* analysis. In the fits the temperature, metallicity, redshift and normalisation were allowed to be free. The spectra were fitted between 4.00 and 9.25 keV, avoiding low energies where our energy corrections are most likely incorrect, but allowing us to derive a temperature using the continuum. We assumed a Galactic column density of $1.4 \times 10^{21} \text{ cm}^{-2}$ for Perseus and $8.54 \times 10^{19} \text{ cm}^{-2}$ for Coma (Kalberla et al. 2005), although the absorbing component has only a weak effect in the energy range examined. As background components we in-

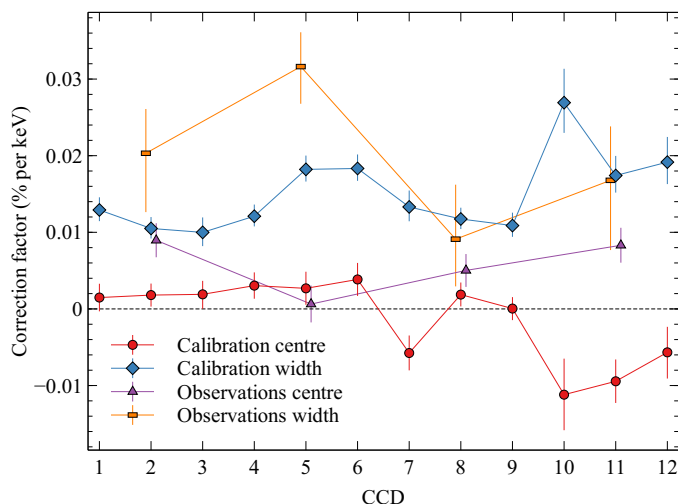


Fig. 11. Distribution of residual correction factors (centre and width) obtained for each CCD, after correcting the calibration observations and refitting them. These results primarily use the Mn-K α and β lines. Also shown are the distribution of correction factors obtained in each quadrant (three CCDs) for the individual astrophysical observations after correction, obtained from the Ni-K α , Zn-K α and Cu-K β lines.

cluded Cu-K α , Ni-K α , Zn-K α and Cu-K β lines, and a power-law component with its photon index fixed at 0.136 (an average taken from our archival observations). The redshifts of the background lines were tied together and allowed to vary. Although these background redshifts are not astrophysically interesting as they should be zero, they allowed us to test our gain correction. The normalisations of the lines and powerlaw were free to vary. For the background components we used an ancillary response file which did not include the effect of the filter or mirrors. We minimised the C-statistic when fitting the spectra.

We used the response matrices generated for each observation and spatial region. Spatial weighting maps with the number of counts between 3.00 and 7.00 keV were used when making the responses. We used the same 0.3 eV energy bin size in the response matrices as for our calibration analysis. No additional broadening was used in these fits, however. The ancillary response files were also calculated using the same spatial weighting maps.

There were multiple observations for each spatial region we examined. We tried two techniques for fitting the spectra. The first, with which we show the results for the individual spectral regions, was to do a joint simultaneous fit of the spectra. In this analysis we only included a spectrum for an observation if there were more than 2000 counts between 4.00 and 9.25 keV, to be able to sufficiently constrain the velocity. We allowed the normalisations of each component to be separate in each observation, but forced metallicities, temperatures and APEC redshifts to be the same. The background line energies were allowed to vary between observations. The second technique was to add the spectra from the different observations together and to create average weighted response and ancillary response files, using the number of counts between 4.00 and 9.25 keV as a weighting factor. The total spectrum was fitted, reducing the number of free parameters, improving the speed of the fitting procedure and making it easier for XSPEC to find the best-fitting parameters. We used this technique when fitting to produce the spectral maps of the clusters. As we will show, there is generally good agreement between the ‘joint’ and ‘total’ fitted results.

We also repeated the fits for the total spectra with the SPEX spectral code (Kaastra et al. 1996) instead of APEC, using version 3.04 with version 3.04.00 of its atomic code and tables. As the SPEX plasma model was designed to be used within SPEX only, we tabulated the lines and continuum produced by the model at 0.02 dex temperature intervals and exported it into XSPEC in APEC table format¹. This allowed us to use exactly the same modelling procedure for the two codes. As we show later, there is very good agreement between the APEC and SPEX results.

4. The Perseus cluster

The Perseus cluster, Abell 426, is the X-ray brightest galaxy cluster in the sky. There is clear evidence of feedback in the centre of the cluster, where the lobes of the central AGN, 3C 84 are displacing the ICM (Böhringer et al. 1993; Fabian et al. 2000). The AGN is also generating weak shocks in the ICM. Ripples, which may be sound waves generated by the AGN activity, are observed (Fabian et al. 2003). If sound waves, these ripples could combat a significant fraction of the radiative cooling taking place in a distributed fashion (Sanders & Fabian 2007). Alternatively, the surface brightness fluctuations in the cluster, if interpreted as turbulence, could energetically offset the radiative cooling taking place (Zhuravleva et al. 2014a), although sloshing of the gas in the potential well could be a significant contribution to the density variations with increasing radius (Walker et al. 2018a).

There is a well-known east-west asymmetry in the X-ray surface brightness (Churazov et al. 2003). The cluster is also extended in this direction on the largest scales. These edges in surface brightness and temperature are seen out to 700 kpc radius (Simionescu et al. 2012; Urban et al. 2014; Walker et al. 2018b). An explanation for these structures is that the gas is sloshing in the potential well of the system (Markevitch et al. 2001; Churazov et al. 2003; Walker et al. 2017), caused by a disturbance to the potential because of a minor-merger, as is also seen in simulations of clusters (e.g. Ascasibar & Markevitch 2006). In Perseus there is a chain of galaxies in the western side of the cluster which may be responsible for the sloshing (Churazov et al. 2003).

Perseus was the main target for observation by *Hitomi* (H16), providing an excellent opportunity to compare our technique with high resolution spectroscopy.

4.1. Fitting spectra from regions

In Perseus we made 21 non-overlapping regions by hand (Fig. 12 left panel) containing similar numbers of counts in the Fe-K complex (around 1000, but increasing to 4500 in the centre; Fig. 12 top-right panel), and following the surface brightness contours, such as those generated by cold fronts. We excluded bright point sources by hand, as automatic source detection was confused by the strong spatial variation of the source. Unfortunately, with the archival pointings the main AGN feedback region and main *Hitomi* pointing is within the Cu hole, so we cannot examine this area. However, the offset pointing of *Hitomi* mostly overlaps with our data, so we created an additional region for comparison with this (Region 22), which overlaps with our other regions 1 and 2. Region 22 is very similar to region 6 in H18, although the PSF of *XMM* is much smaller than *Hit*

¹ Code available at https://github.com/jeremysanders/spex_to_xspec

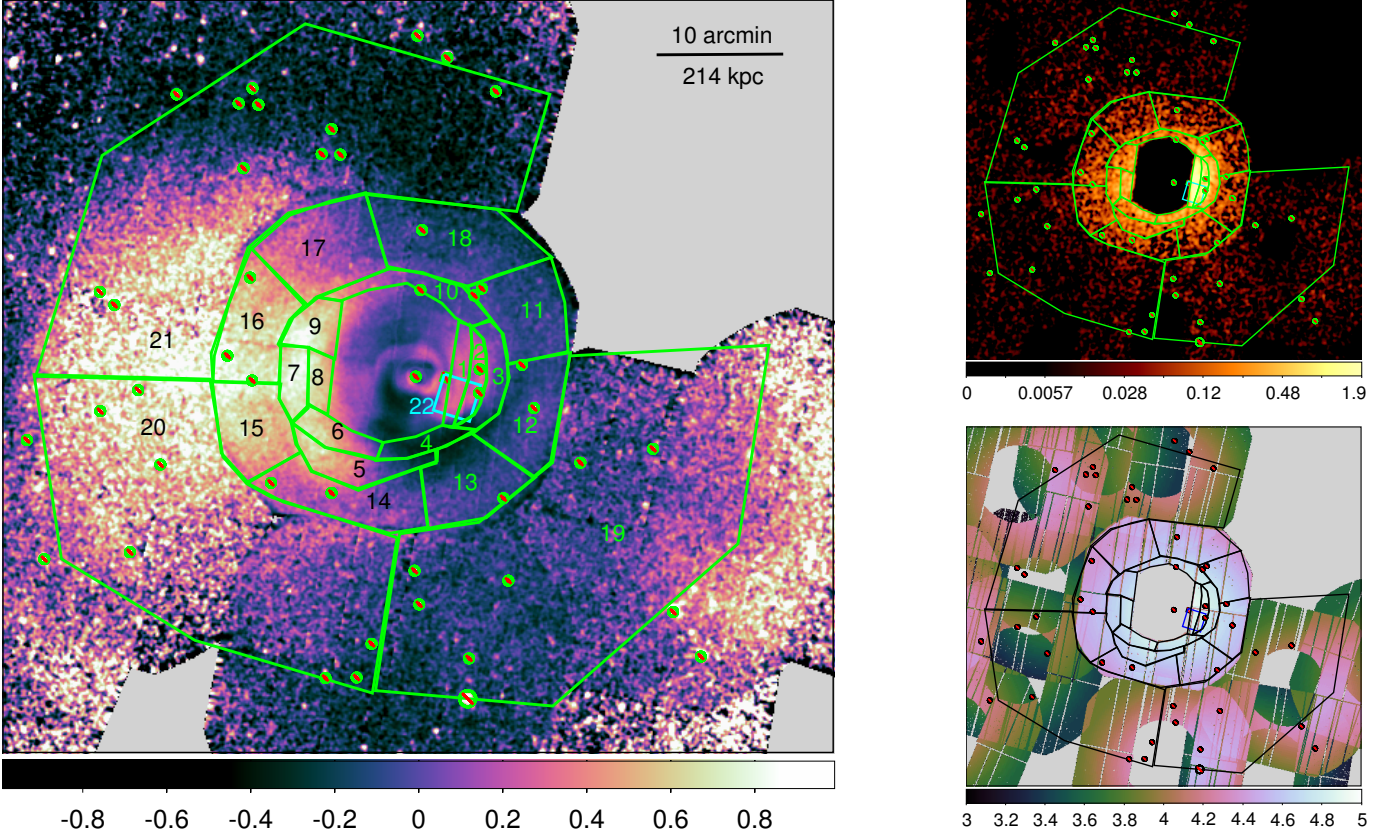


Fig. 12. Regions examined in Perseus, chosen to cover areas with similar numbers of counts in the Fe-K complex. (Left panel) Regions plotted on the fractional difference in 0.5 to 2.0 keV surface brightness from the average at each radius. Region 22 overlaps with other regions as it covers the outer *Hitomi* pointing. (Top-right panel) Fe-K count map, showing the number of counts in each 3.2 arcsec pixel in the Fe-K complex (6.50 to 6.90 keV, restframe), after subtracting neighbouring scaled continuum images (6.06 to 6.43 and 6.94 to 7.16 keV, restframe). Gaussian smoothing of $\sigma = 4$ pixels was applied. (Bottom-right panel) Exposure map, plotting the total Fe-K exposure (log s) excluding the Cu hole and accounting for vignetting.

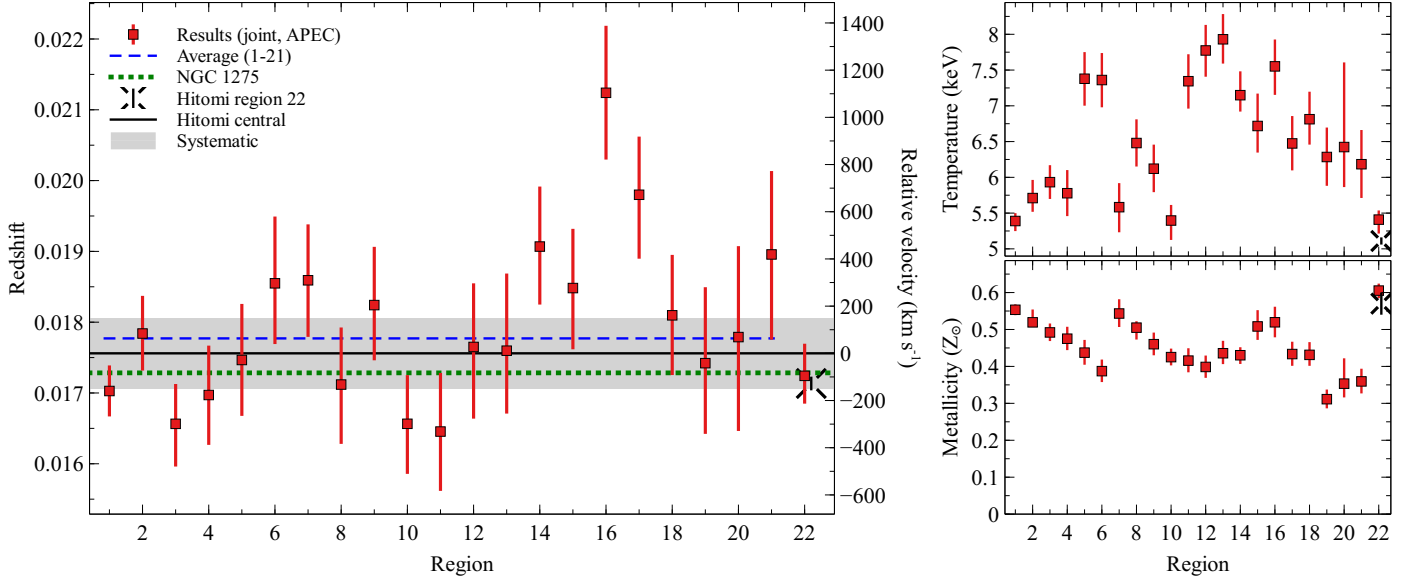


Fig. 13. Results for the Perseus regions. Shown are the best-fitting values and statistical uncertainties for the joint fit using the APEC model. (Left panel) Redshifts and velocities. The average shown is the weighted average for the non-overlapping regions 1 to 21. The right axis shows the redshifts as velocities relative to the H16 result ($z = 0.01756$). The NGC 1275 velocity of $z = 0.017284$ is from H18. Region 22 was chosen to overlap with the outer *Hitomi* pointing, for which we also show their result. (Right panels) Temperatures and metallicities. Also shown are the values for the outer *Hitomi* pointing from Hitomi Collaboration (2018d) and Simionescu et al. (2019).

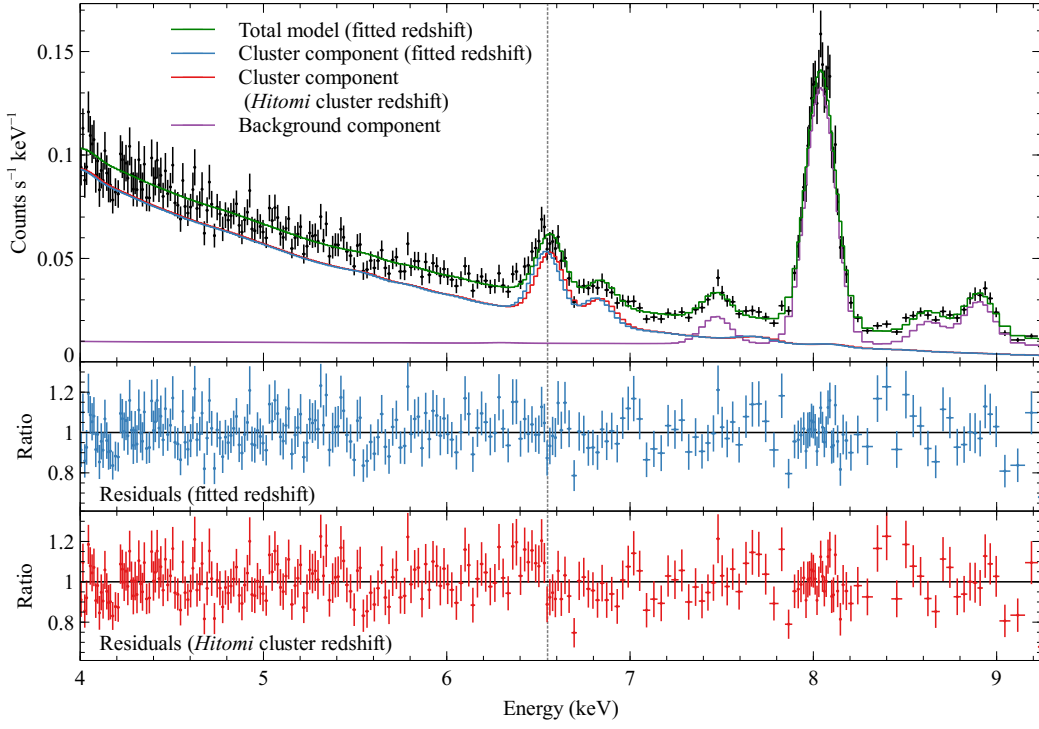


Fig. 14. Example fit of the total spectrum for region 16 in Perseus, rebinned for display to have a signal to noise ratio of 10 in each spectral bin. The vertical line is at an energy of 6.55 keV. (Top panel) Fitted data and best-fitting cluster model (fitted redshift), showing its cluster and background components. Also shown is the cluster component with the redshift changed to the *Hitomi* cluster value. (Centre panel) Residuals of the total best-fitting model. (Bottom panel) Residuals of the total model with the APEC redshift changed to the *Hitomi* value.

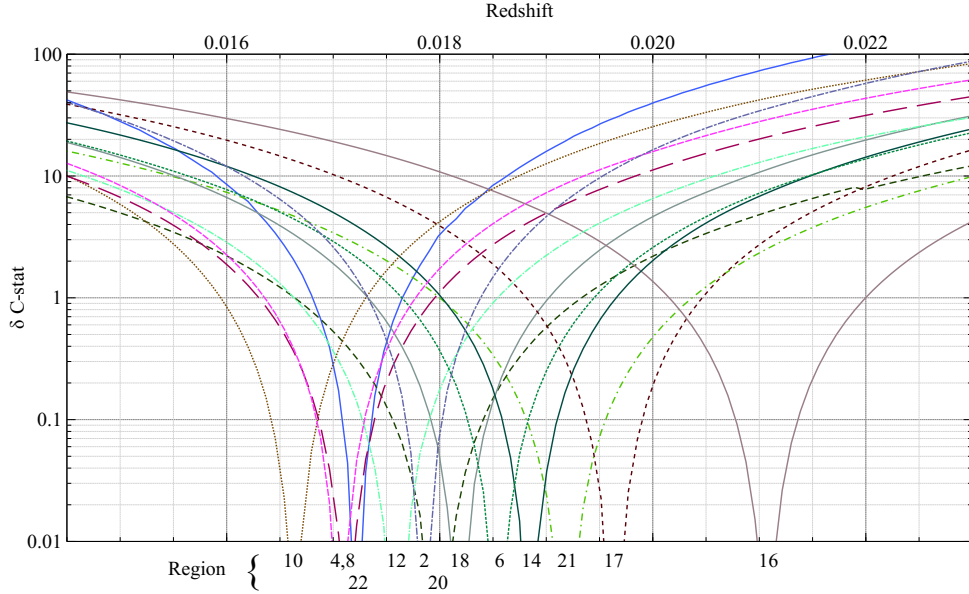


Fig. 15. Change in fit statistic as a function of redshift for selected regions in the Perseus cluster, for the total spectral fits.

omi so our result will be less effected by flux from neighbouring regions.

Figure 13 (left panel) shows the redshifts and velocities (relative to the H16 average velocity) we obtained for the regions in Perseus. Plotted are the results from joint simultaneous fits with the APEC model. In Fig. 13 (right panels) we also show the best-fitting temperatures and metallicities in each region. We list the results of the spectral fits in Table 2.

For our region 22 which overlaps with the outer *Hitomi* pointing, we obtained a redshift of 0.0172 ± 0.0004 (all uncertainties quoted only include statistical errors), while a value of 0.0171 ± 0.0001 was found using *Hitomi* (H18), with a model for the PSF. The difference between these is within the statistical uncertainties, even if systematic effects are not included. We note, however, that there is a small portion of the *Hitomi* pointing region we cannot examine and that the PSF of *Hitomi* could blur out some signal over the cluster despite the applied

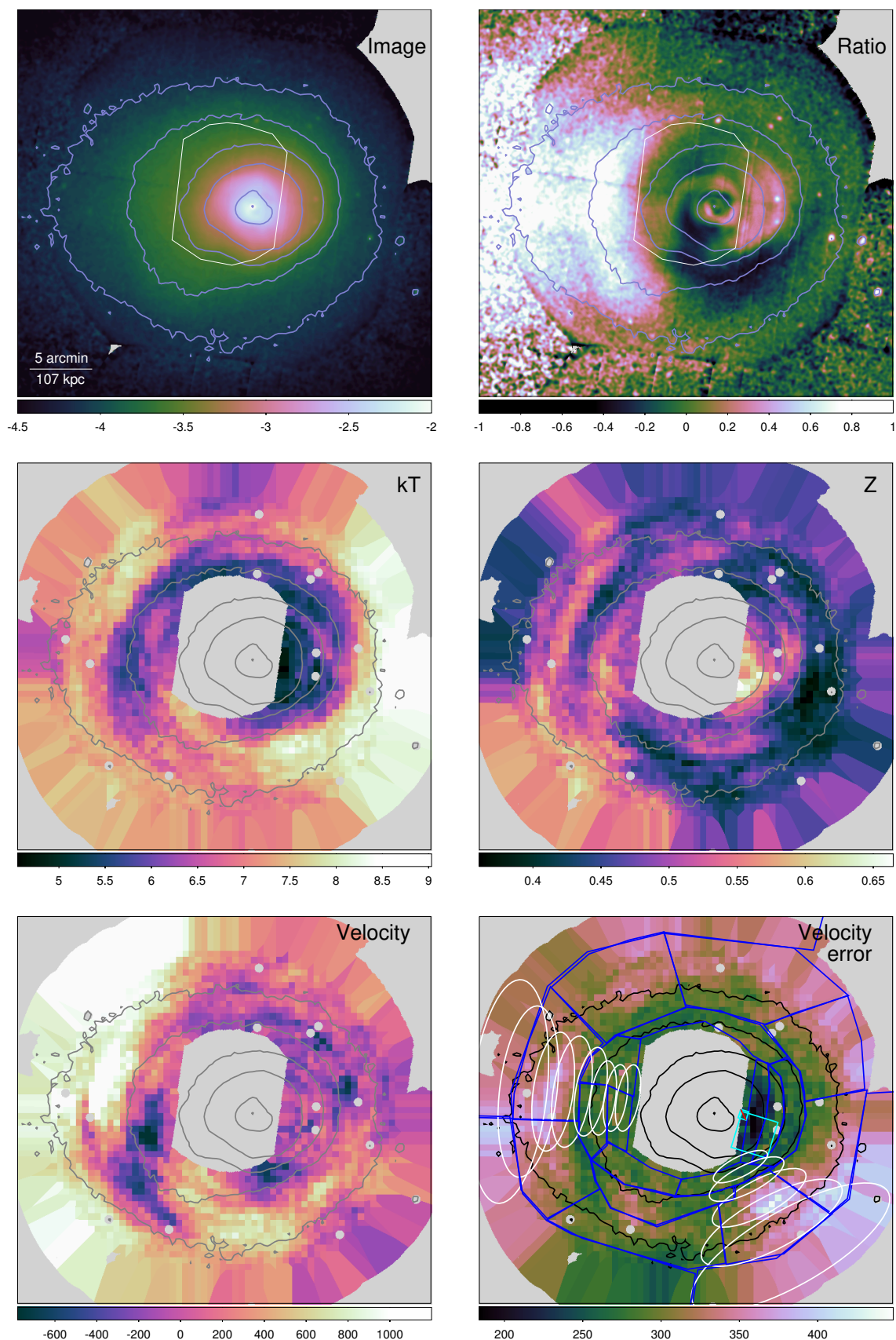


Fig. 16. Perseus cluster maps. Shown is the 0.5 to 2 keV X-ray surface brightness and contours ($\log \text{cts s}^{-1}$ per 1.6 arcsec pixel; top left), fractional difference of surface brightness to radial average (top right), temperature (keV; centre left), metallicity ($Z_{\odot}$; centre right), velocity relative to the cluster value in H16 (km s^{-1} ; bottom left) and 1σ statistical uncertainty on velocity (km s^{-1} ; bottom right). Maps were created by a moving 3:1 elliptical region (rotated to lie tangentially to the nucleus) containing ~ 700 Fe-K counts (see example ellipses in velocity error plot). The pixels are not statistically independent.

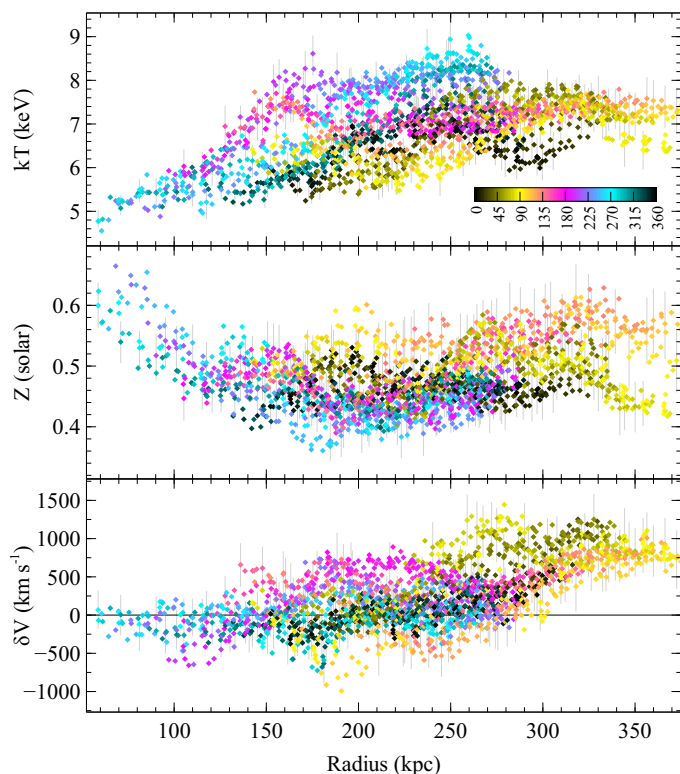


Fig. 17. Radial profiles of temperature, metallicity and velocity pixels from the Perseus maps in Fig. 16 coloured by position angle. Error bars are only shown for every 10 points. Radii are from the position of 3C 84. Nearby points are not statistically independent.

correction. We can also compare our temperature value for that region ($5.42^{+0.12}_{-0.15}$ keV) with the *Hitomi* PSF-corrected continuum (5.11 ± 0.05 keV) and line temperatures (5.00 ± 0.16 keV) from *Hitomi* Collaboration (2018d). Our temperature value is 6 to 8 per cent greater, although again our region does not overlap exactly with the outer *Hitomi* pointing, which also includes cooler gas at smaller radii. We obtain a metallicity (dominated by the Fe lines) of $0.61 \pm 0.02 Z_{\odot}$, while Simionescu et al. (2019) obtained a consistent Fe metallicity of $0.57 \pm 0.03 Z_{\odot}$ with *Hitomi*.

The average value of the redshift in the non-overlapping regions 1 to 21 is 0.01767 ± 0.00015 , agreeing with the value obtained by H16 for the central region (0.01756). The fit of a constant value for the regions is poor (reduced $\chi^2 = 37.3/20 = 1.86$). If we assume the intrinsic bulk velocities come from a Gaussian distribution and obtain the model parameters, we find a central redshift of 0.01778 ± 0.00025 and a distribution width of 0.00071 ± 0.00030 or 214 ± 85 km s $^{-1}$.

The offset between the average and Gaussian centre is probably caused by the higher velocities in regions 14–18, which are 200–300 kpc from the nucleus to the east, appearing to have systematically larger velocities than those on the other side (regions 11–13). The eastern regions are on average 480 ± 210 km s $^{-1}$ higher than the H16 average result, while those to the west are consistent at 20 ± 190 km s $^{-1}$ relative to *Hitomi*. Regions 14 to 18 have systematically higher surface brightnesses at that radius (Fig. 12 left panel). The cluster is also cooler towards the eastern side (Fig. 13 top-right panel). To see the significance of the signal in this region, we show an example spectrum for region 16 (Fig. 14). We show the residuals for a model with the best-fitting redshift and those using the reference cluster *Hitomi* value. If the cluster redshift is used, there are clear positive and negative

residuals either side of the He-like Fe xxv line complex, indicating a line shift. In Fig. 15 we show the change in fit statistic if the redshift is varied from the best-fitting value and the spectra refitted, for selected spatial regions. The curves are smooth and only have a single minimum, and only become asymmetric far from the best-fitting redshifts, showing that the best-fitting values and statistical uncertainties are robust.

If we model the distribution of velocities in only the central region (regions 1 to 10) as a Gaussian we find a central redshift of 0.01739 ± 0.00021 , while the distribution width is small (28 to 173 km s $^{-1}$; at the 1σ level).

There are further possible systematic errors, which we discuss in Sect. 6.1, although they appear unimportant compared to the energy calibration and statistical uncertainties.

4.2. Spectral maps

We can see the velocity, temperature and metallicity structure better by making a smooth map of the cluster. To do this we extracted and fitted spectra from regions over the cluster, moving in grid with a spacing of 0.5 arcmin. To make the regions better follow the steeply-peaked surface brightness profile of the cluster, we used elliptical regions with a 3:1 axis ratio, rotating them so that the longest axis lay tangentially to the vector to the central AGN. We adaptively changed the radii of the ellipses to have ~ 700 counts in the Fe-K complex after continuum subtraction, to have similar uncertainties on the velocities. Point sources were excluded from the regions. The map was created by fitting the total spectra rather than by a joint fit. We used the same response matrix for all the pixels, but created weighted-average ancillary responses for each ellipse, created from the individual ones for each observation.

Figure 16 shows the resulting maps of the velocity, temperature and metallicity. For comparison we also show an X-ray image of the cluster from *XMM*, and the fractional difference of the X-ray image to the average at each radius from the nucleus. The temperature plot shows that there is a cool spiral of gas going from the west of the cluster to the east via the north. Its outer edge varies from ~ 170 to 260 kpc radius. The outer edge of the cool spiral can be seen in the surface brightness image, although there is another region of higher surface brightness which lies at larger (~ 330 kpc) radius to the east. There is a spiral metallicity structure associated with the cooler spiral. To the east of the core, the low temperature spiral gas has low metallicity, with the hotter material at smaller and larger radii having higher metallicities.

Examining the velocity structure, there appears to be a clear correlation between the temperature and velocity maps. These correlations can also be seen in radial profiles of the maps (Fig. 17). The cool spiral has lower velocities, while the material lying outside it to the east and south has larger velocities. There is possibly higher velocity material to the south-west, although that location is close to the edge of the field of view and the elliptical regions are rather large, smoothing out small scale structure. We do not see clear velocity structure within the cool spiral. These maps suggest that some of the regions in Fig. 12 could contain velocity structure within them which is being averaged out. Better regions could be defined from the velocity map itself, but this is likely to bias the resulting velocities towards the extremes.

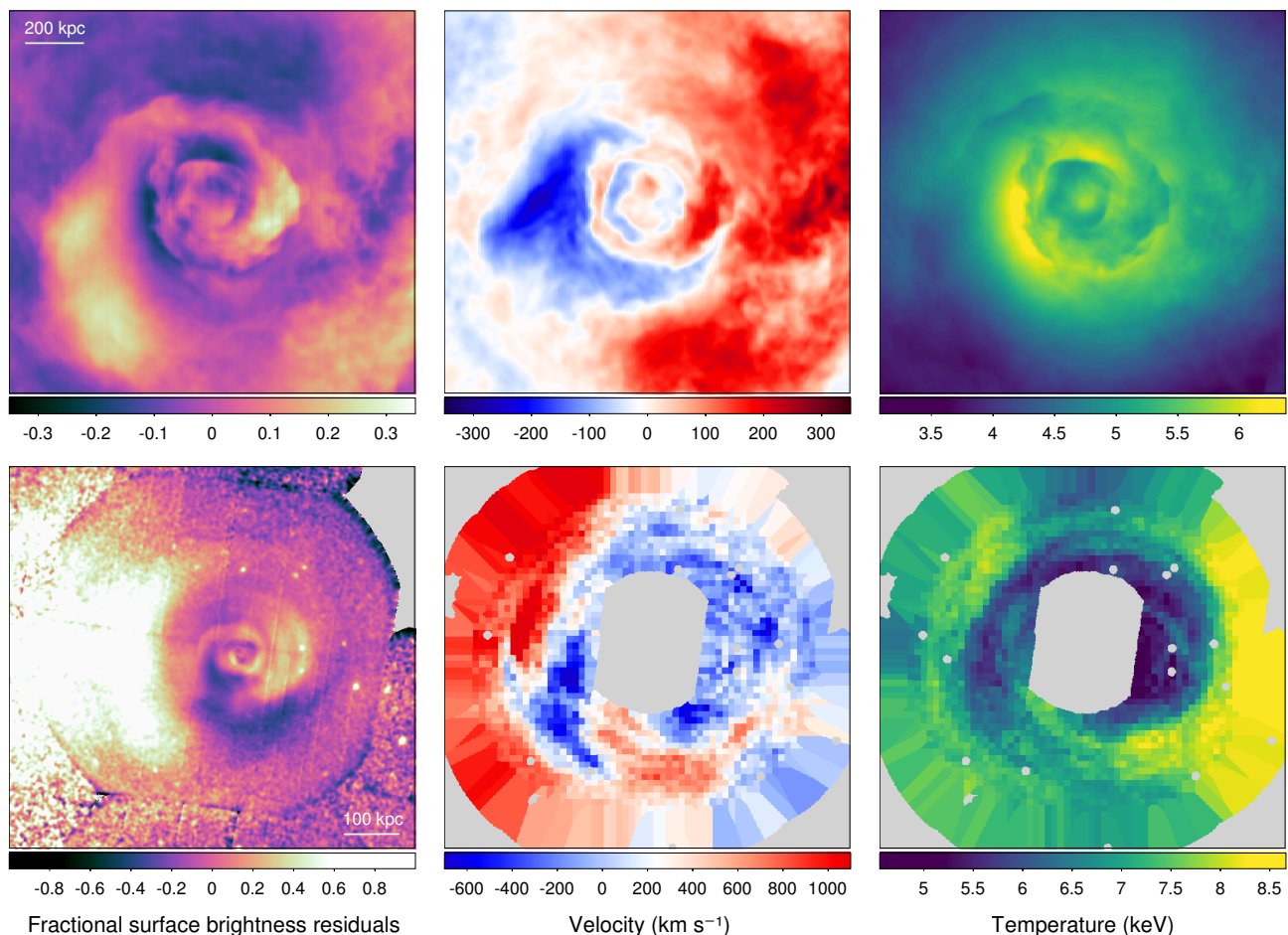


Fig. 18. Comparison of a sloshing simulation (top row) and data for the Perseus cluster (Fig. 16; bottom row). The columns show surface brightness residuals (left), velocity (centre) and temperature (right). The simulation is of a Perseus-like cluster which has bulk sloshing motions and turbulence initiated by an off-centre encounter with a subcluster of 1/5 its mass, from [ZuHone et al. \(2010, 2018\)](#).

4.3. Perseus discussion

Other than *Hitomi*, previous measurements of the velocity structure in Perseus include those of [Dupke & Bregman \(2001\)](#), who claimed a 1000 km s^{-1} velocity difference on 30 arcmin scales on an axis inclined with a position angle of 135° , 45° to the major east-west axis of the cluster. This is on larger scales than we probe here, so we cannot make comparisons.

[Tamura et al. \(2014\)](#) examined multiple pointing positions in the Perseus cluster and in the core using *Suzaku*. On larger scales they limited motions to $< 600 \text{ km s}^{-1}$. Our results are consistent with this on limit. They found a hint of bulk motions around -150 to -300 km s^{-1} around 45 to 90 kpc to the west of the cluster centre. This is a high surface brightness region inside the inner western cold front and includes our regions 1, 2 and 22. Their result is roughly consistent with our results, with regions 22 and 1 being lower than the *Hitomi* average by $\sim 220 \text{ km s}^{-1}$, although the lower surface brightness region 2 is greater than *Hitomi* by $\sim 50 \text{ km s}^{-1}$. More detailed comparisons are difficult as their results are measured relative to each other and their reference region is inside the Cu-hole in our data. [Ota & Yoshida \(2016\)](#) placed limits on the velocities in Perseus of 860 km s^{-1} at the 90 per cent level, which is consistent with our results.

We found evidence of a bulk motions of $\sim 480 \pm 210 \text{ km s}^{-1}$ away from the observer, at a radius 250 kpc to the east of the Perseus cluster core. At this radius the gas velocities are unlikely to be affected by the central AGN. High spatial resolution maps

(Fig. 16) suggest that there is a good correlation between the structure of the cold front to the east, as seen in temperature map, and the gas velocity. The material at smaller radius with lower temperature appears to have a low negative velocity, while the hotter gas outside this radius has a high positive velocity. This cooler material has a spiral-like twisted structure. Such structures are seen in simulations of ICM sloshing in cluster potential wells. Figure 18 compares a simulation of a Perseus-like cluster with bulk-sloshing motions and turbulence initiated by an off-centre encounter with a subcluster, with our Perseus maps. The surface brightness residuals, temperature and velocity have similar morphologies to what we see in Perseus, and are indicative of sloshing, although the simulations are not an exact match to what is observed.

Unusually, the higher surface brightness, cooler material has a lower metallicity than the hotter material at larger radius and at smaller radius, which is somewhat contrary to simulations of sloshing of gas in potential wells (e.g. [Roediger et al. 2012](#)), where high metallicities are correlated with high surface brightnesses, and as seen in other clusters (e.g. Centaurus; [Sanders et al. 2016](#)). There is also an unusual surface brightness structure at the temperature interface. Moving across the front, the X-ray surface brightness is higher than the radial average, but drops temporarily at the interface between the hotter and colder gas. Usually across sloshing structures there are an alternate series of cooler, metal rich relatively-brighter, and hotter, metal

poor and relatively-fainter regions. The lack of a typical alternating structure in Perseus may indicate that the structure is not simple sloshing. It is possible that there are additional structures induced by a merging subcluster, as is indicated by the east-west chain of galaxies (Churazov et al. 2003).

ZuHone et al. (2018) simulated the emission-weighted velocity field in Perseus from sloshing motions, projecting it along different lines of sight. The range of line shifts found in the simulations was between ~ -250 and 300 km s^{-1} . We find velocities which are a bit larger than this ($500 \pm 100 \text{ km s}^{-1}$), although the measurement uncertainties and $\sim 100 \text{ km s}^{-1}$ systematic uncertainties could bring these into agreement. Alternatively, if there is an undergoing merger, then this could also be responsible for the increased velocities, although the excess chain of galaxies lies to the western and not the eastern side.

If the gas were sloshing in the potential well, it might be expected to see a corresponding negative velocity in the cold front on the other side of the core at smaller radius (ZuHone et al. 2018). The average velocity for regions 1 to 3 on the western side of the core where the X-ray surface brightness is high, is $-150 \pm 90 \text{ km s}^{-1}$. This magnitude of this velocity is much lower than our detection to the east.

Assuming a Gaussian distribution, the width of the velocities for all the non-overlapping regions is $260^{+85}_{-70} \text{ km s}^{-1}$. If we examine the distribution of velocities in the inner regions (1 to 10), the width is lower ($110^{+100}_{-75} \text{ km s}^{-1}$) and close to the 100 km s^{-1} Doppler width of the Fe-K line as observed by *Hitomi* regions where there is no AGN disturbance (H18), although the spread of bulk velocities and the line width are not necessarily measuring the same set of motions.

Examining the velocity map structure inside the cold front to the west shows little evidence of structure. This western cold front appears much more typical, with cooler, more metal rich and higher surface brightness material inside the front and the opposite outside. There is little evidence of a change in velocity across this edge to the west, but there is a possible high velocity region to the south outside the front, seen in region 14.

5. The Coma cluster

The Coma cluster, Abell 1656, contains two dominant galaxies, which are NGC 4874 and NGC 4889. The two galaxies have a large velocity difference of $\sim 700 \text{ km s}^{-1}$ between them (Fitchett & Webster 1987), likely caused by a major merger in the cluster. The flat central X-ray surface brightness supports the idea that the cluster is unrelaxed (Briel et al. 1992; White et al. 1993). The cluster hosts a giant radio halo (Willson 1970), indicating it is a merging system. In addition, an analysis of the velocity distribution of the galaxies in Coma shows that there are subgroups associated with the two central galaxies (Adami et al. 2005) and up to 15 further subgroups in the system. A weak lensing analysis (Okabe et al. 2010) also suggests multiple substructures within the cluster, two of which are associated with the central galaxies. It is unclear which of the two central galaxies is the newest arrival in the cluster, although the velocity structure of the Coma galaxies appears to better match NGC 4874 (Adami et al. 2005).

Previous *XMM* observations have shown that the group NGC 4839 to south of the cluster (Neumann et al. 2001) appears to be merging, as indicated by a temperature enhancement between the group and the cluster. There is also a radio relic in the direction of the merging group (Jaffe & Rudnick 1979; Giovannini et al. 1985).

In addition, there is another group to the east seen by its X-ray emission (Vikhlinin et al. 1997), associated with NGC

4911 and NGC 4921. This system has an estimated mass of $5 - 8 \times 10^{12} M_{\odot}$ (Neumann et al. 2003). The outer edge of its X-ray emission lies at the edge of the radio halo (Simionescu et al. 2013).

There are also a number of cooler denser arms of X-ray emitting gas that extend into the core of the cluster, which may be stripped material from merging subclusters (Sanders et al. 2013), some of which appear connected to the NGC 4911/4921 structure.

5.1. Results

Owing to the lower total number of counts in the Fe-K complex in Coma compared to Perseus, we split the cluster into 11 regions, with ten in the centre and one in the merging NGC 4839 group (Fig. 19 left panel). The group region also contains gas ahead of the group in the cluster, as there were not enough counts to make a pure extraction region, and it is therefore not a clean measurement of its properties. In this system we are able to get complete coverage of the central region (Fig. 19 right panels), because of the large number of separate pointings with different positions. We arrange our central regions in a 3×3 grid, with the central box split into two to separate the two central galaxies.

Figure 20 (left panel) shows our obtained velocities for the different regions, compared to the velocities of the central galaxies and merging group. Plotted are the velocities of the two central galaxies, NGC 4889 and NGC 4874, and modelled values for the NGC 4839 and NGC 4911 groups using a substructure analysis (Adami et al. 2005). The temperatures and metallicities we obtain for the regions are shown in Fig. 20 (right panels). We list the results of the spectral fits in Table 3.

The results show that we obtain gas velocities which are very similar to the optical velocities of the two central galaxies, appearing to cluster around these values. The regions in the centre, to the west, to the south-west and to the south have velocities consistent with NGC 4889, while those to the north-west, north, north-east, east and south-east appear to better match NGC 4874. The reduced- χ^2 for a single velocity value for regions 1 to 10 is poor ($1.7 = 15/9$). If we model the intrinsic velocity distribution of the jointly-fitted results for these regions by a Gaussian, we obtain a central redshift of 0.02250 ± 0.00045 and a width of $0.00083^{+0.00062}_{-0.00050}$ ($100 - 440 \text{ km s}^{-1}$), although a Gaussian distribution appears to be a poor model given the data.

We can see the structure in more detail by mapping the parameters on smaller spatial scales. We moved a 4 arcmin radius circular region across the cluster in increments of 1 arcmin. The spectra were added in each region to make total spectra and fitted using the same model as previously. Similarly to Perseus, we used an average response matrix for all regions but created separate weighted ancillary responses for each region. Figure 21 shows the best-fitting temperature, metallicity and velocity for the nearest overlapping position, when the data are sufficient to constrain the parameters to the level given. For the velocity parameter we also show the statistical uncertainty for each position. Statistical uncertainties on the other quantities, such as temperature, increase in the outer parts, because of the declining surface brightness. We also show images of the cluster to the same scale, and a map generated from the fractional difference of the average surface brightness at each radius. Values in the maps are not statistically independent, unless they are separated by more than 8 arcmin.

There is interesting structure in the maps, with the temperature, metallicity and velocity providing complementary information. The gradient in temperature across the core of the cluster

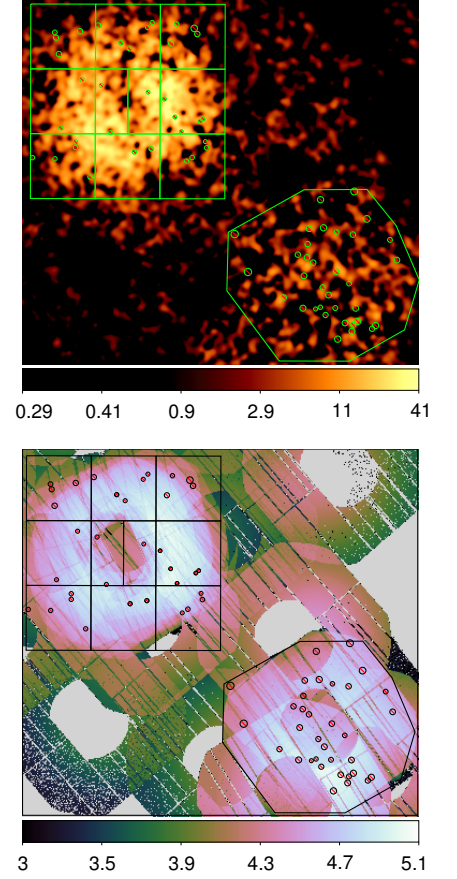
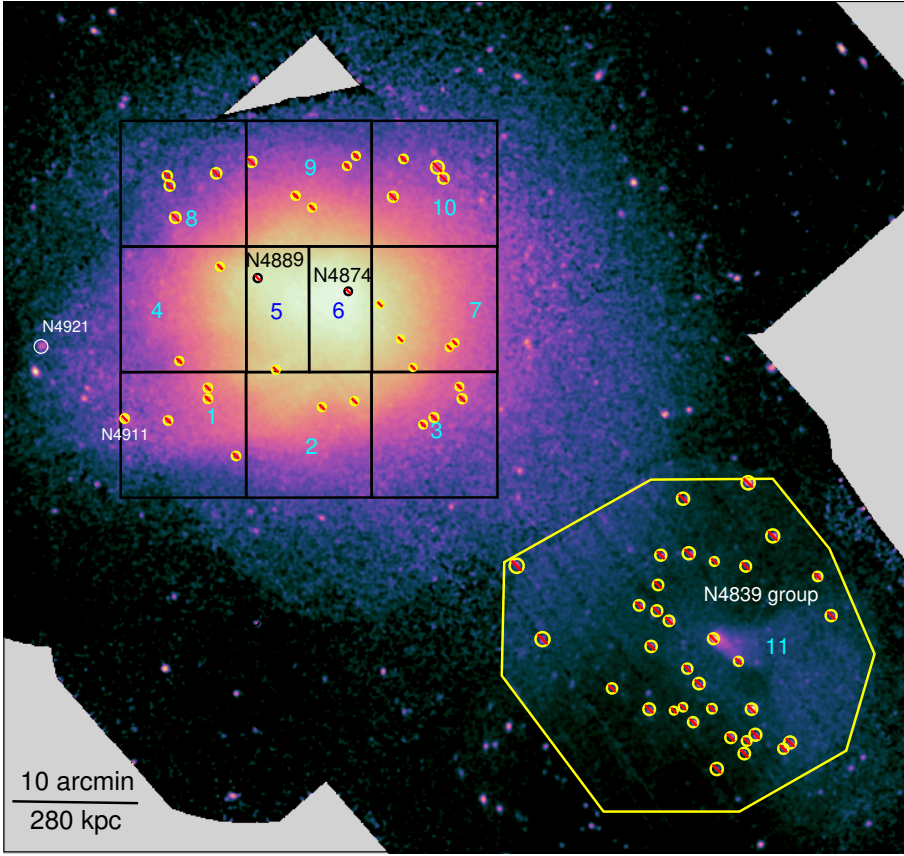


Fig. 19. Regions examined in Coma. (Left panel) The regions plotted on an exposure-corrected surface brightness image in the 0.5 to 2.0 keV band. (Top-right panel) Image in the Fe-K band, after subtracting continuum, in 10^{-3} counts per 1.6 arcsec pixel. (Bottom-right panel) Fe-K exposure map in log s, including the effect of vignetting and the Cu hole.

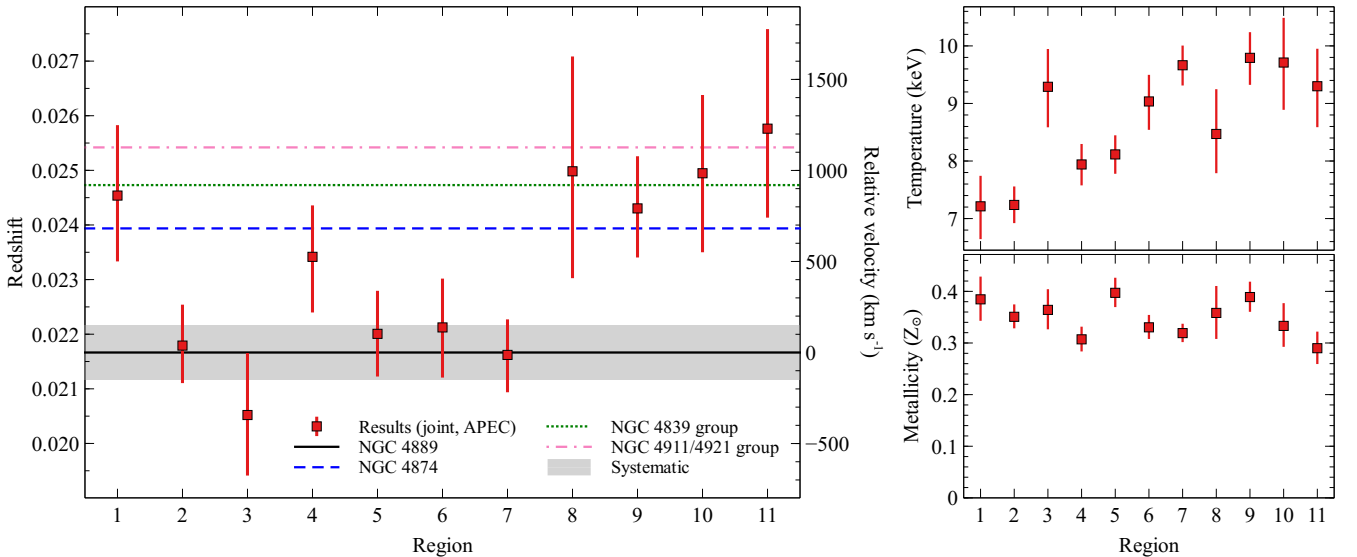


Fig. 20. Results for the Coma regions. Shown are the best-fitting values for the joint fits using the APEC model. (Left panel) Redshifts and velocities. The right axis shows the redshifts as velocities relative to the redshift of NGC 4889. (Right panels) Temperatures and metallicities.

has been seen using *ASCA* (Donnelly et al. 1999), *XMM* (Arnaud et al. 2001) and *Chandra* (Sanders et al. 2013). The boundary between the hot and cold emission has a similar shape to the surface brightness ratio image. The hotter gas appears to lie outside of

the northern surface brightness edge. Using *Chandra* we found cool arms of dense gas which are hinted at with this analysis.

There is a region extending north-south of high metallicity gas which lies between the two central galaxies. As the individual regions showed, the gas to north and west of the cluster has

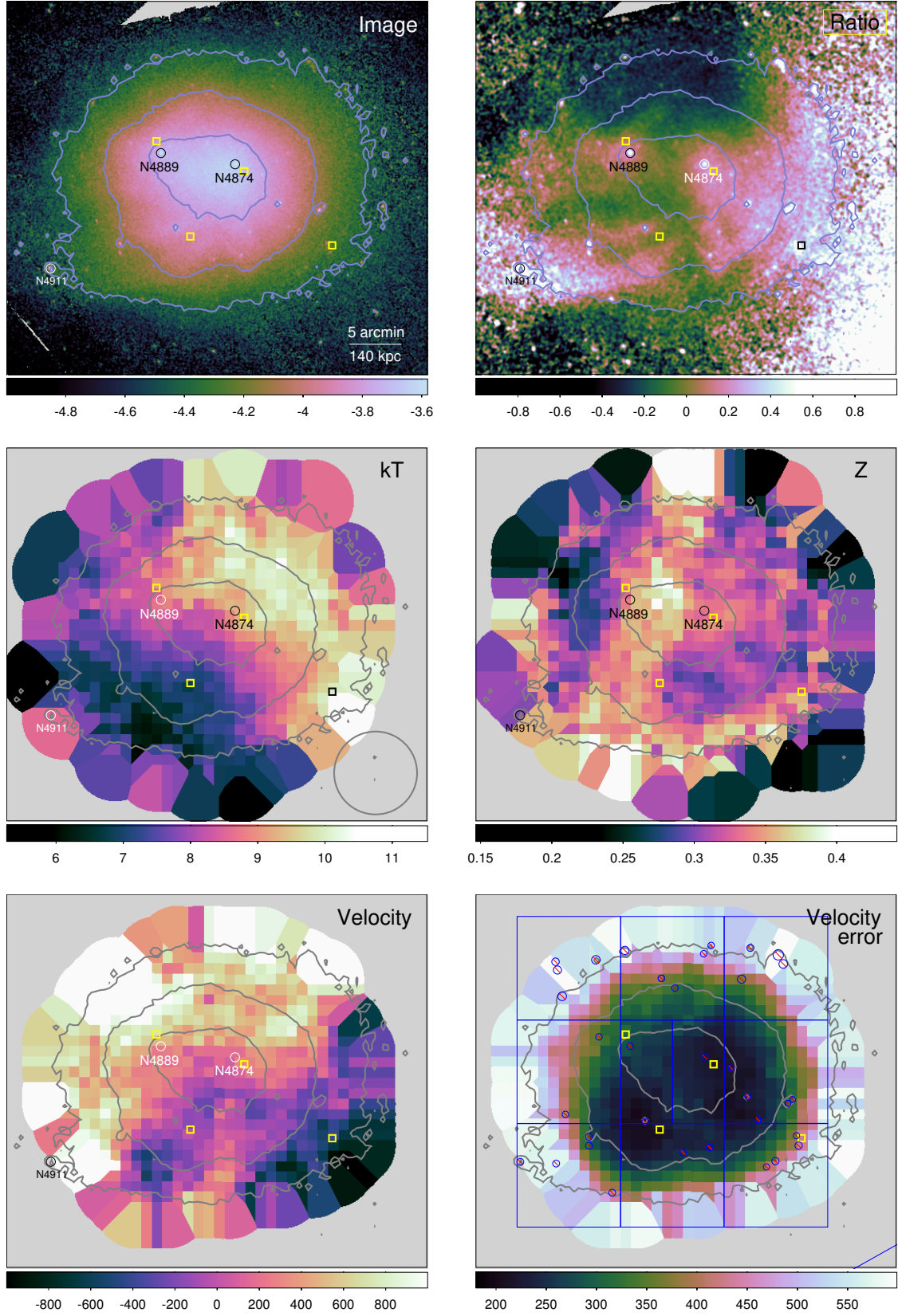


Fig. 21. Coma cluster maps. Shown is the 0.5 to 2.0 keV X-ray surface brightness with contours ($\log \text{cts s}^{-1}$ per 1.6 arcsec pixel; top left), fractional difference of surface brightness to radial average (top right), temperature (keV; centre left), metallicity ($Z_{\odot}$; centre right), velocity relative to NGC 4889 (km s^{-1} ; bottom left) and 1σ statistical uncertainty on velocity (km s^{-1} ; bottom right). Spectral results were obtained from spectra extracted from a sliding 4 arcmin radius extraction region (circle) over a grid. Regions where the uncertainty on the temperature is $> 1 \text{ keV}$, metallicity $> 0.07 Z_{\odot}$ or velocity $> 600 \text{ km s}^{-1}$ are not shown. The position of the four central lensing-map peaks of Okabe et al. (2010) are indicated by squares.

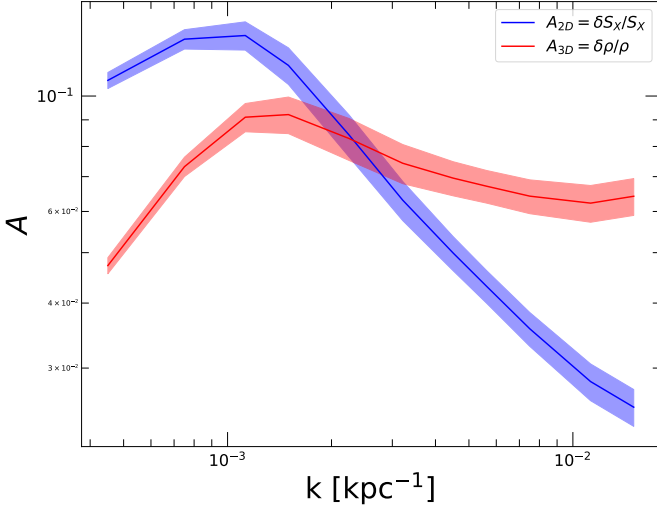


Fig. 22. Amplitude of gas density fluctuations in the Coma cluster as a function of the wave number $k = 1/\ell$. The curves show the amplitude of projected surface brightness fluctuations (red) and the amplitude of 3D density fluctuations (blue). The uncertainties are indicated by the shaded areas.

a higher redshift than that to the south and east. The north-south higher metallicity gas appears to have lower velocity than the surrounding material. There is also a weaker extension of high metallicity gas from NGC 4889 to NGC 4874 and beyond, which also has lower velocity.

To the south-east and south-west of the two central galaxies are regions with around 400 km s^{-1} lower velocities, while to the north the velocity jumps up by around 700 km s^{-1} , in line with the measurements for the individual regions.

5.2. Power spectrum of density fluctuations

Recent theoretical progress has shown that the velocity field in galaxy clusters can be constrained using the power spectrum of density fluctuations (Schuecker et al. 2004; Churazov et al. 2012; Gaspari & Churazov 2013). In the presence of random, isotropic gas motions, the amplitude of density fluctuations is linearly related to the velocity dispersion of turbulent motions (Gaspari et al. 2014; Zhuravleva et al. 2014b), provided other contributions to surface brightness fluctuations are not important (Walker et al. 2018a). The velocity dispersion indirectly recovered through this method can be compared with the direct measurements we present.

We extracted count images in the 0.5–2.0 keV band from all available *XMM* pointings. We used the XMMSAS task EEXPMAP to compute an effective exposure map of each observation, taking vignetting and quantum efficiency into account. To model the particle background, we extracted count images in the same energy band as for our observations from a large set of filter-wheel-closed (FWC) data. We rescaled the FWC images to match the count rates measured in the unexposed corners of the three EPIC detectors. We then combined the data from all observations and from the three EPIC cameras to create a mosaic image of the cluster, and we applied the same procedure to the exposure and background maps. Point sources were detected using the XMMSAS task EWAVELET and excised from the image. We also masked the region surrounding the infalling galaxy group around NGC 4839 to avoid inducing additional fluctuations in the main cluster.

To determine the amplitude of density fluctuations in Coma, we followed the procedure outlined in Eckert et al. (2017). Namely, we determined the ellipticity and the ellipse angle of the observed emission using a principal component analysis, and we fitted the large-scale gas distribution with an elliptical beta model, which was found to describe the gas distribution accurately. We then constructed a model image by convolving the best-fitting model with the exposure map and adding the model particle background. Finally, we used the modified Δ -variance method of Arévalo et al. (2012) to reconstruct the power spectrum from the residual image in a region of 1.5 Mpc radius. For more details on the reconstruction of the power spectrum we refer to Arévalo et al. (2012).

In Fig. 22 we show the amplitude of surface-brightness fluctuations $A_{2D}(k) = \sqrt{2\pi k^2 P_{2D}(k)}$ as a function of the wave number $k = 1/\ell$. On the same figure we show the three-dimensional amplitude of density fluctuations $A_{3D} = \delta\rho/\rho$, which is recovered after correcting for projection effects using the window function $W(k)$ (see Eq. 11 of Churazov et al. 2012). We calculated the window function numerically by simulating fluctuations on top of the best-fitting three-dimensional model and computing the ratio between 3D and projected power spectra.

The Coma power spectrum recovered here agrees well with the measurements of Churazov et al. (2012) over the common range of scales. The fractional amplitude of density fluctuations peaks at $1/k \approx 1 \text{ Mpc}$. This agrees with the results of Khatri & Gaspari (2016), albeit with an overall lower normalisation. The difference with the latter analysis probably lies in the treatment of the NGC 4839 group, which the authors did not mask out from their residual image. We measure a maximum 3D amplitude $A_{\text{max}}(\delta\rho/\rho) = 0.092 \pm 0.008$. In case the detected fluctuations can be entirely ascribed to random gas motions, the maximum amplitude is linearly related to the 1D Mach number $M_{1D} = \sigma_v/c_s$ as $M_{1D} \approx 2.3 A_{\text{max}}(\delta\rho/\rho) = 0.22 \pm 0.02$ (Gaspari et al. 2014). Given the average sound speed in the medium $c_s = (\gamma kT/\mu m_p)^{1/2} \approx 1480 \text{ km s}^{-1}$, surface-brightness fluctuations in the Coma cluster imply a velocity dispersion $\sigma_{1D} = 310 \pm 25 \text{ km s}^{-1}$, which matches well with the dispersion of the line-of-sight bulk velocities we present.

5.3. Coma discussion

The Coma cluster is a complex merger environment. In addition to the two-subclusters which presumably hosted the two central galaxies, NGC 4889 and NGC 4874, there is the well-known NGC 4839 group to the south and a group containing NGC 4911/4921 to the east.

Previous studies have suggested that the NGC 4839 group is currently merging with the cluster and has not yet passed through the cluster centre (Neumann et al. 2001). Evidence of this includes the high temperature region between the group and cluster, and its morphology, with the most of the group galaxies on the cluster-side of the group, and a tail of X-ray emission on the other side. However, it has been recently argued that a post-merger scenario better matches the observed features when compared to simulations (Lyskova et al. 2019). We find that the gas velocity of the group (including some material between the group and cluster) is consistent with the optical velocity of the group. The gas in the group should be slowed down as it interacts with the cluster by around 540 km s^{-1} (Neumann et al. 2001), while the galaxies are not affected. We do not find evidence of this, although our measurement uncertainties are large, and the spectrum also includes some cluster emission.

Examining the individual regions in the Coma cluster, we find the X-ray gas appears to trace the optical velocities of the two central galaxies. The central cluster regions suggest velocities which are lower than that of the NGC 4911/4921 group. A map of the gas velocity (Fig. 21 bottom-left panel), shows that there is lower velocity material extending from NGC 4889 to the south-east and to the south-west of the cluster core, while the material to the north and east of the core better matches the NGC 4874 velocity. This material with velocities similar to NGC 4889 also has higher metallicity and lower temperature. An alternative origin for the high velocity gas is that it is material stripped from NGC 4911/4921 group, although the cool arms seen in the cluster core appear to be lower velocity material.

The higher metallicity north-south filament might be stripped material or a residual core from a merging subcluster, possibly the one which contained NGC 4889, considering the similarity in velocity. In addition, there are the arms of cool material extending towards the east which are likely to be stripped from the NGC 4911 subcluster (Neumann et al. 2003; Sanders et al. 2013). These arms make a U-shaped structure, however, with NGC 4889 at the tip of one of the arms and the group at the bend.

Adami et al. (2005) found that the galaxies within their cluster-core subcomponent have a velocity distribution peaking between the velocities of the two central galaxies. In contrast, Gerhard et al. (2007) found that the main component of the intracluster planetary nebulae within the cluster core have a peak velocity of $\sim 6500 \text{ km s}^{-1}$ ($z \sim 0.022$), close to that of NGC 4889, rather than NGC 4874. Our velocity for the gas in the central region (regions 5 and 6) is similar to NGC 4889. However, if we take the whole examined cluster centre (regions 1–10), the modelled Gaussian distribution has a centre of 0.0225, or a weighted average of 0.0227; both of these values are close to the average velocity of the two central galaxies.

Biviano et al. (1996) also examined the velocity distribution of the galaxies in the cluster, finding a velocity gradient in the faint galaxies, decreasing from the north-east to south-west. This is similar to the morphology of the gas velocity seen in our maps, although the galaxy velocity gradient covers a wider spatial area. This velocity distribution is reminiscent of rotation, although the connection between structures in the velocity map and the other X-ray properties argues against this simple interpretation.

Okabe et al. (2010) found several weak-lensing subclumps within Coma, the inner four of which are indicated in Fig. 21. Two of these clumps are clearly associated with the central galaxies. Andrade-Santos et al. (2013) modelled the X-ray emission using the inner three mass peaks under the assumptions of slow motions and no gas, and found a good agreement with the ICM distribution. This model predicts that the south-east subclump lies around 400 kpc from the cluster mid-plane, in contrast with the two central galaxies, which would lie at ~ 120 and ~ 10 kpc, for NGC 4889 and 4874, respectively. Examining our maps, it is possible that the subclumps may be associated with some of the features we see. For example, the south-east subclump is coincident with a region of lower velocity, lower temperature and high metallicity. It is, however, unclear without further work whether subclumps could be entirely responsible for the structures.

If we take the line-of-sight velocity width of the bulk motions (V_{los}), we can estimate the ratio of energy density in bulk motions to the thermal energy density, using $f_{\text{bulk}} = V_{\text{los}}^2 \mu m_p / kT$ (Werner et al. 2009), where μ is the mean particle mass, m_p is the proton mass and kT is the temperature ($\sim 8.5 \text{ keV}$). This measure excludes any turbulent component along the line of sight.

Taking our Gaussian width of $100 - 440 \text{ km s}^{-1}$, implies that $f_{\text{bulk}} < 0.15$, at the 1σ confidence level. This estimate, however, assumes a Gaussian distribution of the gas velocity, which may not be the case. In addition, simulations show that the assumption of a symmetric velocity distribution lead to overestimates of the pressure support from motions (Vazza et al. 2018).

6. Discussion

6.1. Further possible systematic uncertainties

There are possible systematic uncertainties which may be present in addition to the energy calibration uncertainty. As stated in Sect. 3, we fitted the spectra jointly (producing the results above) or fitted the total spectra. Figure 23 shows the difference between the two by plotting bars between the two sets of results. The variation in redshift is small (much smaller than the statistical error bars), except for region 8 in Coma.

Systematic errors may also be caused by the choice of spectral model. Inaccuracies in modelling may lead to shifts in the convolved line shape. We plot the results for the APEC and SPEX models when fitting the total spectra in Fig. 23. There is little difference between the results using the two models, suggesting this effect is not important. However, deviations from a thermal plasma could theoretically affect our results.

Another effect which may give systematic errors is if the temperatures obtained by spectral fitting are systematically too large or small. This may occur, for example, if instrument calibration inaccuracies lead to a too flat or too steep spectrum, changing the best-fitting temperature. Schellenberger et al. (2015) found that the temperatures of hot galaxy clusters were different in *Chandra* and *XMM* data, probably caused by calibration differences. However they found that this effect is relatively small in hard energy bands like we have used, with offsets of less than 10 per cent for high-temperature systems.

To test for errors caused by incorrect temperatures we created modified versions of our SPEX table model, where for a particular line temperature we calculated the model continuum using a temperature which was 10 per cent greater or smaller than this. We refitted the spectra with these two models, showing the difference between them and the standard model in Fig. 23. The effect of continuum inaccuracies appears small for these data. We found that the obtained temperatures changed by around 3 per cent from the temperatures using the standard SPEX model, indicating that the obtained temperature was dominated by the spectral line shape rather than the continuum.

Another potential systematic is that we previously assumed a slope for the powerlaw background component which was fixed. To check the effect of this assumption, we refitted the spectra using powerlaws which differed in their index by 0.2. The changes in the obtained redshifts was very small, with a maximum redshift difference of 10^{-4} , and an average of 2×10^{-5} .

Our analysis does not apply a heliocentric correction for the motion of the *XMM* spacecraft in the solar system to the energy scale. This correction, however, is relatively small as the maximum heliocentric velocity is $\sim 30 \text{ km s}^{-1}$.

The fluorescent X-ray emission line originates below the detector, unlike the astrophysical and calibration lines which come from the top. The detector could have a different response to these two X-ray sources. Figure 11 suggests that this effect is not important, as we see consistent averages and widths of residual correction factor between the astrophysical observations (in quadrants) and calibration observations (for each CCD).

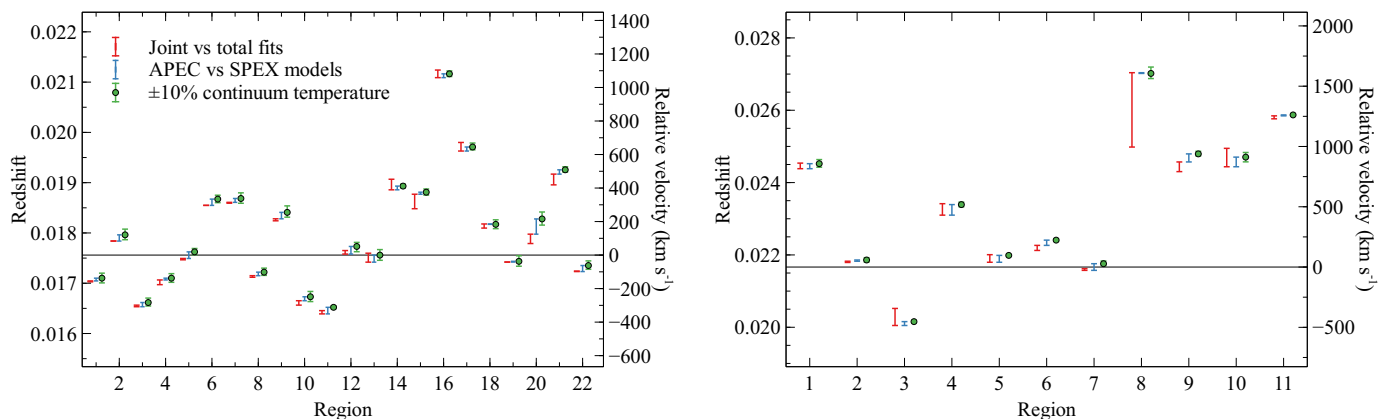


Fig. 23. How further systematic effects change the obtained Perseus (left panel) and Coma (right panel) redshifts. For each region, the ends of the leftmost (red) bars are the results for the joint and for the total spectral fits, using the APEC model. The ends of the centre (blue) bars are the results using the APEC and using the SPEX spectral models, when fitting the total spectra. The right (green) points show the effect of using a continuum for the SPEX model which is for a temperature which is 10 per cent greater or less than the line temperature, fitting the total spectra.

These results demonstrate that the above systematic effects are small compared with the measurement and energy calibration uncertainty.

6.2. Future improvements to the method

There are several possible future improvements that could be made to map velocities in extended objects with EPIC-pn. Firstly, it should be possible to calibrate the energy of events made of doubles, where the signal is split between two pixels. Including doubles would approximately increase the number of X-ray events by 80 per cent, although they would have poorer spectral resolution (by up to 10 per cent for Fe-K) than the single-pixel events.

We have not attempted to model the Al-K α lines around 1.5 keV from the calibration source. This would probably not be directly useful for analysing Fe-K from clusters, given the large difference in energy. However, monitoring the shift of this line may provide more information about the change in energy scale we see at larger energies, allowing us to model its effects better. The Al-K α is also a detector background line. We also could examine the fluorescent detector lines from Ti, V, Cr, Au and Mo, although these are much weaker than the other lines we used. The Mo-K α line is at 17.5 keV and so could provide an extreme reference value for the energy scale. Ti, V and Mo is also visible in the Cu hole, so would allow some sort of calibration for the central part of the detector.

Furthermore, it may be possible to calibrate the Cu hole region using calibration observations. Calibrating the central region would allow the analysis of a many archival observations where the cluster is placed in the centre. If we corrected the overall gain of the detector using Cu-K α as we currently do, we could fit for gain and the energy correction factor in the centre using Mn-K α and β in calibration observations. This technique could be tested in other regions of the detector where we have the other reference lines. It may, however, be difficult to constrain these parameters in later times in the mission, when the calibration source has weakened.

One could redo the EPIC-pn energy calibration from scratch, working from raw PHA values to build up a complete model of the energy scale and avoiding the multiple correction factors currently employed. This would probably be a very time-consuming project, however.

Observations where the target is offset from the centre of the detector best make use of our data analysis method. We have obtained data for the Virgo and the Centaurus cluster using targeted observations of this nature and plan to publish them in future works.

Although *XRISM* with its high-spectral resolution X-ray spectrometer should launch in a few years, *XMM* EPIC-pn has the advantage of a much larger field of view, allowing larger fractions of a cluster to be probed without many pointings. In addition, the better angular resolution of *XMM* enables point sources to be more easily excluded from the analysis and for different structures to be separated.

7. Conclusions

We describe and demonstrate a novel technique to use background X-ray lines seen in the spectra of the *XMM* EPIC-pn detector, calibrating the absolute energy scale of the outer part of the detector to better than 150 km s⁻¹ at Fe-K. Using this technique we map the bulk velocity distribution of the ICM over a large fraction of the central Mpc of two nearby clusters of galaxies, Perseus and Coma.

We are able to independently confirm our calibration procedure using a 65 kpc-square region in Perseus, where we find a velocity consistent with results using an overlapping pointing by *Hitomi*. There is no evidence of significant motions over much of the cluster, and our average velocity measurement is close to the *Hitomi* central pointing. However, to the east of the cluster core we observe a shift in velocity of 480 ± 210 km s⁻¹ (statistical). This is spatially coincident with a cold front, seen as an edge in surface brightness and temperature and is direct evidence of gas sloshing in the potential well of the cluster. Excluding this region, we find that the width (σ) of the bulk velocity distribution is 20–150 km s⁻¹, if modelled with a Gaussian distribution. This width is consistent to the *Hitomi* line width measurements in the core of the cluster, excluding the regions containing strong feedback.

In the Coma cluster, we find that the velocity of the gas is close to the optical velocities of the two central galaxies. The ICM to the north and east of the core has a velocity close to that of NGC 4874, while that to the south and south-west has a lower velocity similar to NGC 4889. The NGC 4911/4921 group, which may have passed through the centre of the cluster, has a consistent optical velocity with some of the higher velocity

regions to the north and east. Cooler and denser filaments which were thought be stripped from the subgroup, appear, however, to have a substantially lower velocity close to that of NGC 4889. The velocity of material located near the merging subgroup NGC 4839 is consistent with its optical velocity, although the measurement uncertainties are large.

Our results highlight the differences between a relatively relaxed galaxy cluster, such as Perseus, and the product of an ongoing merger, such as Coma. In the relaxed system, where *Hitomi* previously determined a low amount of turbulence, we see a narrow range in velocity, except for some evidence of the ICM sloshing in the potential well at the level of a few hundred km s^{-1} . In the merging system, where one would expect high levels of turbulence, we see a large $\sim 1000 \text{ km s}^{-1}$ range in velocity, with significant structure in our maps.

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References

- Adami, C., Biviano, A., Durret, F., & Mazure, A. 2005, *A&A*, 443, 17
Ahoranta, J., Finoguenov, A., Pinto, C., et al. 2016, *A&A*, 592, A145
Andrade-Santos, F., Nulsen, P. E. J., Kraft, R. P., et al. 2013, *ApJ*, 766, 107
Arévalo, P., Churazov, E., Zhuravleva, I., Hernández-Monteagudo, C., & Revnivtsev, M. 2012, *MNRAS*, 426, 1793
Arnaud, M., Aghanim, N., Gastaud, R., et al. 2001, *A&A*, 365, L67
Ascasibar, Y. & Markevitch, M. 2006, *ApJ*, 650, 102
Balucinska-Church, M. & McCammon, D. 1992, *ApJ*, 400, 699
Bambic, C. J., Pinto, C., Fabian, A. C., Sanders, J., & Reynolds, C. S. 2018, *MNRAS*, 478, L44
Bearden, J. A. 1967, *Rev. Mod. Phys.*, 39, 78
Biviano, A., Durret, F., Gerbal, D., et al. 1996, *A&A*, 311, 95
Böhringer, H., Voges, W., Fabian, A. C., Edge, A. C., & Neumann, D. M. 1993, *MNRAS*, 264, L25
Briel, U. G., Henry, J. P., & Böhringer, H. 1992, *A&A*, 259, L31
Brüggen, M., Hoeft, M., & Ruszkowski, M. 2005, *ApJ*, 628, 153
Churazov, E., Forman, W., Jones, C., & Böhringer, H. 2003, *ApJ*, 590, 225
Churazov, E., Vikhlinin, A., Zhuravleva, I., et al. 2012, *MNRAS*, 421, 1123
Donnelly, R. H., Markevitch, M., Forman, W., et al. 1999, *ApJ*, 513, 690
Dupke, R. A. & Bregman, J. N. 2001, *ApJ*, 547, 705
Eckert, D., Gaspari, M., Vazza, F., et al. 2017, *ApJ*, 843, L29
Fabian, A. C. 2012, *ARA&A*, 50, 455
Fabian, A. C., Sanders, J. S., Allen, S. W., et al. 2003, *MNRAS*, 344, L43
Fabian, A. C., Sanders, J. S., Ettori, S., et al. 2000, *MNRAS*, 318, L65
Fitchett, M. & Webster, R. 1987, *ApJ*, 317, 653
Freyberg, M. J., Pfeffermann, E., & Briel, U. G. 2001, The XMM-Newton EPIC-pn Camera: Spatial Distribution of the Internal Background Fluorescence Lines, Tech. Rep. CAL-TN-0066, XMM SOC
Gaspari, M. & Churazov, E. 2013, *A&A*, 559, A78
Gaspari, M., Churazov, E., Nagai, D., Lau, E. T., & Zhuravleva, I. 2014, *A&A*, 569, A67
Gerhard, O., Arnaboldi, M., Freeman, K. C., et al. 2007, *A&A*, 468, 815
Giovannini, G., Feretti, L., & Andernach, H. 1985, *A&A*, 150, 302
Heinz, S., Brüggen, M., & Morsony, B. 2010, *ApJ*, 708, 462
Hitomi Collaboration. 2016, *Nature*, 535, 117
Hitomi Collaboration. 2018a, *PASJ*, 70, 9
Hitomi Collaboration. 2018b, *PASJ*, 70, 12
Hitomi Collaboration. 2018c, *PASJ*, 70, 10
Hitomi Collaboration. 2018d, *PASJ*, 70, 11
Hölzer, G., Fritsch, M., Deutsch, M., Härtwig, J., & Förster, E. 1997, *Phys. Rev. A*, 56, 4554
Jaffe, W. J. & Rudnick, L. 1979, *ApJ*, 233, 453
Kaastra, J. S., Mewe, R., & Nieuwenhuijzen, H. 1996, in *UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas*, ed. K. Yamashita & T. Watanabe, 411–414
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, *A&A*, 440, 775
Kelley, R. L., Akamatsu, H., Azzarello, P., et al. 2016, in *Proc. SPIE*, Vol. 9905, *Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray*, 99050V

Table 1. Cluster observations analysed. Shown are the observation identifier, date, nominal pointing position (J2000) and exposure after cleaning. We note that short observations were effectively excluded from the joint spectral analysis because of the minimum count criterion.

OBSID	Date	RA (deg)	Dec (deg)	Exposure (ks)
Perseus cluster				
0085110101	2001-01-30	49.9507	41.5117	22.4
0085590201	2001-02-10	49.9570	41.0964	35.3
0151560101	2003-02-26	49.1792	41.3247	19.3
0204720101	2004-02-04	50.4108	41.5286	6.0
0204720201	2004-02-04	50.8483	41.5281	20.7
0305690101	2006-02-10	49.5112	41.2833	22.9
0305690301	2006-02-11	49.9608	41.8929	15.6
0305690401	2006-02-11	50.4738	41.8250	22.7
0305780101	2006-01-29	49.9500	41.5113	72.2
0405410101	2006-08-03	50.2500	41.9347	11.4
0405410201	2006-08-03	49.6664	41.1087	8.3
0673020201	2011-09-10	50.7818	41.2099	17.9
0673020301	2011-08-19	50.5417	41.3833	12.0
Coma cluster				
0058940701	2003-06-10	193.8542	27.2294	12.0
0124710101	2000-06-21	194.1987	27.4019	24.2
0124710201	2000-06-11	194.4271	27.7272	30.0
0124710301	2000-06-27	194.6342	27.4033	14.2
0124710401	2000-06-23	195.0192	27.5233	8.4
0124710501	2000-05-29	194.8646	27.7814	19.9
0124710601	2000-06-12	194.7083	27.9811	4.7
0124710701	2000-06-24	194.3654	28.1447	0.4
0124710801	2000-12-10	195.3567	27.7314	18.7
0124710901	2000-06-12	195.1362	27.9497	16.5
0124711101	2000-06-24	194.6521	28.3989	16.7
0124711401	2000-05-29	194.9446	27.9500	14.2
0124712001	2000-12-10	194.7083	27.9811	10.8
0124712101	2000-12-10	194.3654	28.1447	20.2
0124712401	2002-06-05	195.4592	28.1578	12.1
0124712501	2002-06-07	195.1521	28.4208	21.1
0153750101	2001-12-04	194.9446	27.9500	17.3
0300530101	2005-06-19	194.9300	27.9833	17.0
0300530201	2005-06-17	194.9561	27.9708	1.5
0300530301	2005-06-11	194.9625	27.9426	22.9
0300530401	2005-06-09	194.9445	27.9200	12.8
0300530501	2005-06-09	194.9155	27.9200	18.1
0300530601	2005-06-07	194.8975	27.9426	15.5
0300530701	2005-06-07	194.9039	27.9708	17.3
0403150101	2006-06-14	194.4272	27.3194	27.9
0403150201	2006-06-11	194.4272	27.3194	36.2
0403150301	2006-06-17	194.4198	26.9371	37.6
0403150401	2006-06-21	194.4198	26.9371	45.4
0652310201	2010-06-18	194.3512	27.4978	0.1
0652310401	2010-06-24	194.3512	27.4978	8.7
0652310701	2010-06-16	194.3512	27.4978	3.2
0652310801	2010-12-03	194.3512	27.4978	4.4
0652310901	2010-12-05	194.3512	27.4978	3.4
0652311001	2010-12-11	194.3512	27.4978	0.5
0691610201	2012-06-02	194.3527	27.4952	26.4
0691610301	2012-06-04	194.3527	27.4952	18.3

- Khatrri, R. & Gaspari, M. 2016, *MNRAS*, 463, 655
Lau, E. T., Kravtsov, A. V., & Nagai, D. 2009, *ApJ*, 705, 1129
Liu, A., Yu, H., Tozzi, P., & Zhu, Z.-H. 2016, *ApJ*, 821, 29
Lodders, K. & Palme, H. 2009, *Meteoritics and Planetary Science Supplement*, 72, 5154
Lyskova, N., Churazov, E., Zhang, C., et al. 2019, *MNRAS*, 485, 2922
Markevitch, M., Vikhlinin, A., & Mazzotta, P. 2001, *ApJ*, 562, L153
Neumann, D. M., Arnaud, M., Gastaud, R., et al. 2001, *A&A*, 365, L74
Neumann, D. M., Lumb, D. H., Pratt, G. W., & Briel, U. G. 2003, *A&A*, 400, 811
Ogorzalek, A., Zhuravleva, I., Allen, S. W., et al. 2017, *MNRAS*, 472, 1659

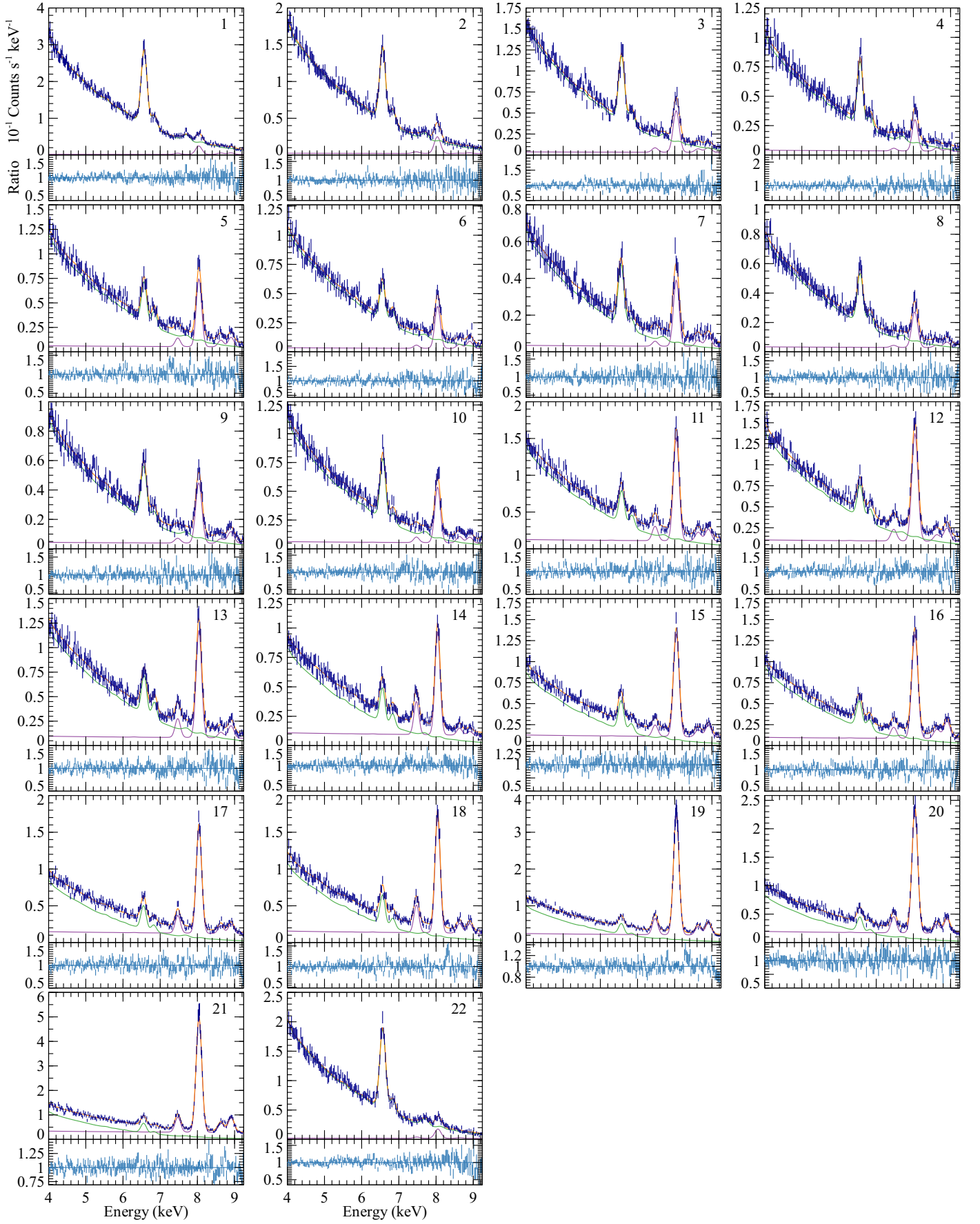


Fig. 24. Total spectra and APEC fits for the Perseus cluster regions. The top panels shows the spectra (blue), total best-fitting model (orange), foreground components (green) and background components (purple) in units of 10^{-1} cts $^{-1}$ keV $^{-1}$. The bottom panels show the ratio between the spectrum and model.

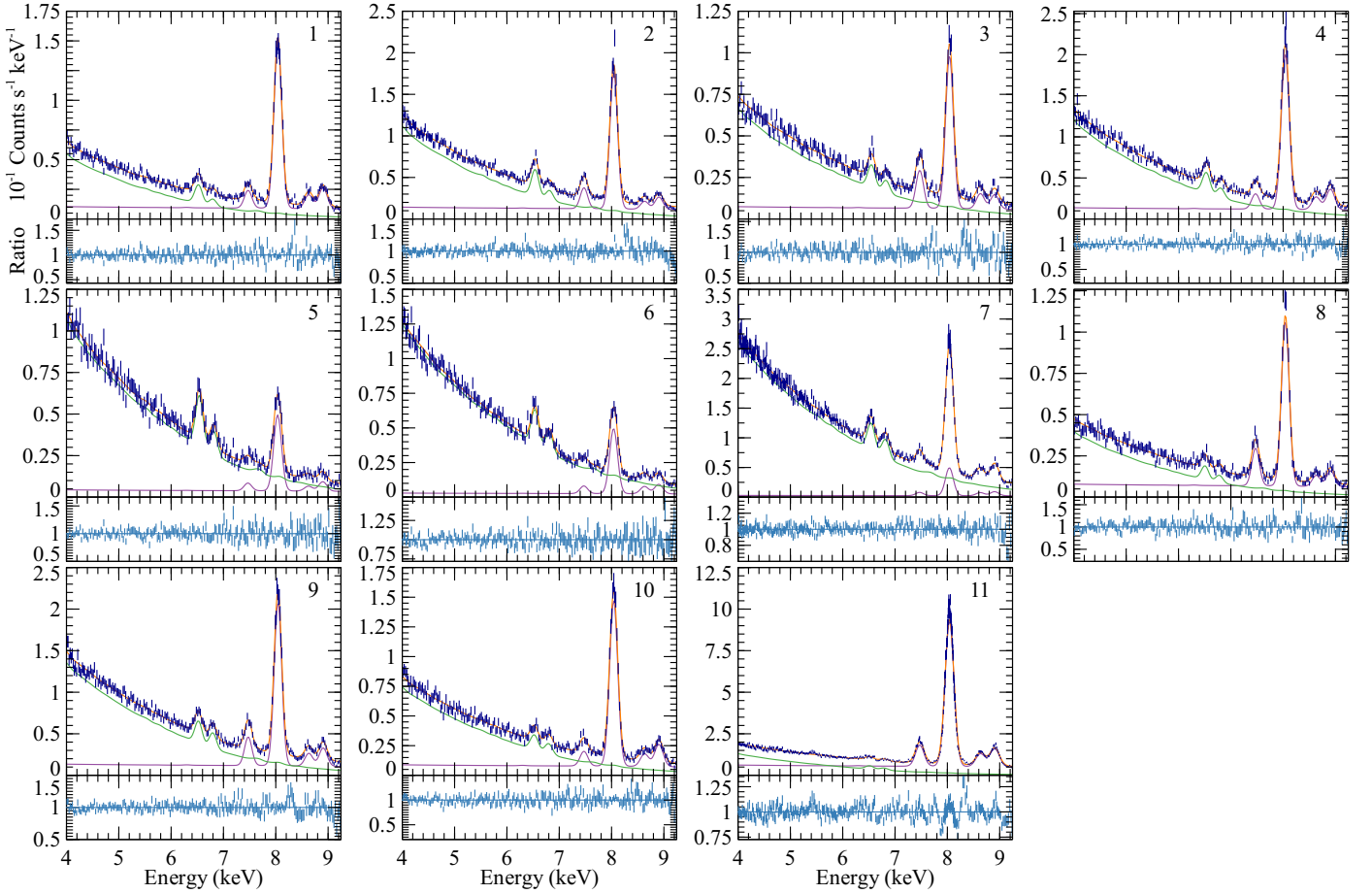


Fig. 25. Total spectra and APEC fits for the Coma cluster regions. The top panels shows the spectra, total fit, foreground fit and background fit in units of $10^{-1} \text{ cts}^{-1} \text{ keV}^{-1}$. The bottom panels show the ratio between the spectrum and model.

Okabe, N., Okura, Y., & Futamase, T. 2010, *ApJ*, 713, 291
Ota, N. & Yoshida, H. 2016, *PASJ*, 68, S19
Pinto, C., Sanders, J. S., Werner, N., et al. 2015, *A&A*, 575, A38
Reynolds, C. S., McKernan, B., Fabian, A. C., Stone, J. M., & Vignello, J. C. 2005, *MNRAS*, 357, 242
Roediger, E., Lovisari, L., Dupke, R., et al. 2012, *MNRAS*, 420, 3632
Sanders, J. S. & Fabian, A. C. 2007, *MNRAS*, 381, 1381
Sanders, J. S. & Fabian, A. C. 2013, *MNRAS*, 429, 2727
Sanders, J. S., Fabian, A. C., Churazov, E., et al. 2013, *Science*, 341, 1365
Sanders, J. S., Fabian, A. C., Smith, R. K., & Peterson, J. R. 2010, *MNRAS*, 402, L11
Sanders, J. S., Fabian, A. C., Taylor, G. B., et al. 2016, *MNRAS*, 457, 82
Schellenberger, G., Reiprich, T. H., Lovisari, L., Nevalainen, J., & David, L. 2015, *A&A*, 575, A30
Schuecker, P., Finoguenov, A., Miniati, F., Böhringer, H., & Briel, U. G. 2004, *A&A*, 426, 387
Simionescu, A., Nakashima, S., Yamaguchi, H., et al. 2019, *MNRAS*, 483, 1701
Simionescu, A., Werner, N., Urban, O., et al. 2013, *ApJ*, 775, 4
Simionescu, A., Werner, N., Urban, O., et al. 2012, *ApJ*, 757, 182
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, *ApJ*, 556, L91
Strüder, L., Briel, U., Dennerl, K., et al. 2001, *A&A*, 365, L18
Takahashi, T., Kokubun, M., Mitsuda, K., et al. 2016, in *Proc. SPIE*, Vol. 9905, *Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray*, 99050U
Tamura, T., Yamasaki, N. Y., Iizuka, R., et al. 2014, *ApJ*, 782, 38
Urban, O., Simionescu, A., Werner, N., et al. 2014, *MNRAS*, 437, 3939
Vazza, F., Angelinelli, M., Jones, T. W., et al. 2018, *MNRAS*, 481, L120
Vazza, F., Brunetti, G., Gheller, C., Brunino, R., & Brügggen, M. 2011, *A&A*, 529, A17+
Vikhlinin, A., Forman, W., & Jones, C. 1997, *ApJ*, 474, L7
Walker, S. A., Hlavacek-Larrondo, J., Gendron-Marsolais, M., et al. 2017, *MNRAS*, 468, 2506
Walker, S. A., Sanders, J. S., & Fabian, A. C. 2018a, *MNRAS*, 481, 1718

Walker, S. A., Zuhone, J., Fabian, A., & Sanders, J. 2018b, *Nature Astronomy*, 2, 292
Werner, N., Zhuravleva, I., Churazov, E., et al. 2009, *MNRAS*, 398, 23
White, S. D. M., Briel, U. G., & Henry, J. P. 1993, *MNRAS*, 261, L8
Willson, M. A. G. 1970, *MNRAS*, 151, 1
Zhuravleva, I., Churazov, E., Schekochihin, A. A., et al. 2014a, *Nature*, 515, 85
Zhuravleva, I., Churazov, E. M., Schekochihin, A. A., et al. 2014b, *ApJ*, 788, L13
Zuhone, J. A., Markevitch, M., & Johnson, R. E. 2010, *ApJ*, 717, 908
Zuhone, J. A., Miller, E. D., Bulbul, E., & Zhuravleva, I. 2018, *ApJ*, 853, 180

Table 2. Results from fits for the Perseus cluster regions. The columns show temperatures (kT ; keV), metallicities (Z ; $Z_{\odot}$) and redshifts (z). ¹ Jointly-fitted results using APEC model. ² Total-fitted results using APEC model. ³ Total-fitted results using SPEX model. The spectral fits to the total spectra with the APEC model are shown in Fig. 24.

Region	kT^1	kT^2	kT^3	Z^1	Z^2	Z^3	z^1	z^2	z^3
1	5.4 ± 0.1	5.4 ± 0.1	5.6 ± 0.1	0.55 ± 0.01	0.55 ± 0.01	0.58 ± 0.02	0.0170 ± 0.0004	0.0170 ± 0.0004	0.0171 ± 0.0004
2	5.7 ± 0.2	5.7 ± 0.2	5.9 ± 0.2	0.52 ± 0.03	0.52 ± 0.02	0.54 ± 0.02	0.0178 ± 0.0005	0.0178 ± 0.0005	0.0180 ± 0.0005
3	5.9 ± 0.2	5.9 ± 0.2	6.1 ± 0.2	0.49 ± 0.02	0.49 ± 0.02	0.51 ± 0.03	0.0166 ± 0.0006	0.0165 ± 0.0006	0.0166 ± 0.0006
4	5.8 ± 0.3	5.8 ± 0.3	6.0 ± 0.3	0.48 ± 0.03	0.47 ± 0.03	0.49 ± 0.03	0.0170 ± 0.0007	0.0171 ± 0.0007	0.0171 ± 0.0007
5	7.4 ± 0.4	7.5 ± 0.4	7.5 ± 0.4	0.44 ± 0.03	0.42 ± 0.03	0.44 ± 0.03	0.0175 ± 0.0008	0.0175 ± 0.0008	0.0176 ± 0.0008
6	7.4 ± 0.4	7.4 ± 0.4	7.4 ± 0.4	0.39 ± 0.03	0.38 ± 0.03	0.39 ± 0.03	0.0185 ± 0.0009	0.0185 ± 0.0009	0.0187 ± 0.0009
7	5.6 ± 0.3	5.6 ± 0.3	5.8 ± 0.3	0.54 ± 0.04	0.54 ± 0.04	0.56 ± 0.04	0.0186 ± 0.0008	0.0186 ± 0.0008	0.0187 ± 0.0008
8	6.5 ± 0.3	6.5 ± 0.3	6.6 ± 0.3	0.50 ± 0.03	0.50 ± 0.03	0.53 ± 0.04	0.0171 ± 0.0008	0.0172 ± 0.0008	0.0172 ± 0.0008
9	6.1 ± 0.3	6.1 ± 0.3	6.3 ± 0.3	0.46 ± 0.03	0.46 ± 0.03	0.48 ± 0.03	0.0182 ± 0.0008	0.0183 ± 0.0008	0.0184 ± 0.0008
10	5.4 ± 0.2	5.4 ± 0.2	5.6 ± 0.3	0.43 ± 0.02	0.42 ± 0.02	0.44 ± 0.03	0.0166 ± 0.0007	0.0167 ± 0.0007	0.0167 ± 0.0007
11	7.3 ± 0.4	7.3 ± 0.4	7.4 ± 0.4	0.42 ± 0.03	0.41 ± 0.03	0.43 ± 0.03	0.0165 ± 0.0008	0.0164 ± 0.0009	0.0165 ± 0.0009
12	7.8 ± 0.4	7.7 ± 0.4	7.7 ± 0.4	0.40 ± 0.03	0.39 ± 0.03	0.40 ± 0.03	0.0177 ± 0.0010	0.0176 ± 0.0010	0.0177 ± 0.0010
13	7.9 ± 0.3	7.8 ± 0.4	7.9 ± 0.4	0.44 ± 0.03	0.43 ± 0.03	0.45 ± 0.04	0.0176 ± 0.0010	0.0174 ± 0.0009	0.0176 ± 0.0009
14	7.1 ± 0.3	7.2 ± 0.4	7.4 ± 0.4	0.43 ± 0.02	0.42 ± 0.04	0.44 ± 0.04	0.0191 ± 0.0008	0.0189 ± 0.0008	0.0189 ± 0.0008
15	6.7 ± 0.4	6.7 ± 0.4	6.8 ± 0.4	0.51 ± 0.04	0.50 ± 0.04	0.52 ± 0.04	0.0185 ± 0.0009	0.0188 ± 0.0008	0.0188 ± 0.0008
16	7.6 ± 0.4	7.6 ± 0.4	7.4 ± 0.4	0.52 ± 0.04	0.51 ± 0.04	0.52 ± 0.04	0.0212 ± 0.0009	0.0211 ± 0.0009	0.0212 ± 0.0009
17	6.5 ± 0.4	6.4 ± 0.4	6.6 ± 0.4	0.43 ± 0.03	0.43 ± 0.03	0.45 ± 0.03	0.0198 ± 0.0009	0.0196 ± 0.0008	0.0197 ± 0.0008
18	6.8 ± 0.4	6.8 ± 0.3	6.9 ± 0.4	0.43 ± 0.03	0.43 ± 0.03	0.45 ± 0.03	0.0181 ± 0.0008	0.0182 ± 0.0008	0.0182 ± 0.0009
19	6.3 ± 0.4	5.9 ± 0.4	6.2 ± 0.4	0.31 ± 0.03	0.29 ± 0.02	0.30 ± 0.03	0.0174 ± 0.0010	0.0174 ± 0.0011	0.0174 ± 0.0011
20	6.4 ± 0.9	6.4 ± 0.9	7.0 ± 0.6	0.35 ± 0.06	0.34 ± 0.05	0.38 ± 0.05	0.0178 ± 0.0013	0.0180 ± 0.0013	0.0183 ± 0.0014
21	6.2 ± 0.5	6.1 ± 0.5	6.4 ± 0.5	0.36 ± 0.03	0.35 ± 0.03	0.37 ± 0.04	0.0190 ± 0.0012	0.0192 ± 0.0012	0.0193 ± 0.0012
22	5.4 ± 0.2	5.3 ± 0.2	5.6 ± 0.2	0.61 ± 0.02	0.60 ± 0.02	0.63 ± 0.02	0.0172 ± 0.0004	0.0172 ± 0.0004	0.0174 ± 0.0004

Table 3. Results from fits for the Coma cluster regions. The columns show temperatures (kT ; keV), metallicities (Z ; $Z_{\odot}$) and redshifts (z). ¹ Jointly-fitted results using APEC model. ² Total-fitted results using APEC model. ³ Total-fitted results using SPEX model. The spectral fits to the total spectra with the APEC model are shown in Fig. 25.

Region	kT^1	kT^2	kT^3	Z^1	Z^2	Z^3	z^1	z^2	z^3
1	7.2 ± 0.6	7.4 ± 0.5	7.5 ± 0.5	0.38 ± 0.04	0.38 ± 0.04	0.40 ± 0.04	0.0245 ± 0.0012	0.0244 ± 0.0012	0.0245 ± 0.0012
2	7.2 ± 0.3	7.2 ± 0.3	7.3 ± 0.3	0.35 ± 0.02	0.35 ± 0.02	0.37 ± 0.02	0.0218 ± 0.0007	0.0218 ± 0.0007	0.0219 ± 0.0007
3	9.3 ± 0.7	8.5 ± 0.6	8.8 ± 0.5	0.36 ± 0.04	0.32 ± 0.03	0.33 ± 0.03	0.0205 ± 0.0011	0.0200 ± 0.0010	0.0202 ± 0.0010
4	7.9 ± 0.4	8.0 ± 0.3	8.2 ± 0.4	0.31 ± 0.02	0.31 ± 0.02	0.32 ± 0.03	0.0234 ± 0.0010	0.0231 ± 0.0009	0.0234 ± 0.0009
5	8.1 ± 0.3	8.0 ± 0.3	8.1 ± 0.4	0.40 ± 0.03	0.38 ± 0.03	0.40 ± 0.03	0.0220 ± 0.0008	0.0218 ± 0.0008	0.0220 ± 0.0008
6	9.0 ± 0.5	8.8 ± 0.5	8.9 ± 0.4	0.33 ± 0.02	0.31 ± 0.03	0.32 ± 0.02	0.0221 ± 0.0009	0.0223 ± 0.0009	0.0224 ± 0.0009
7	9.7 ± 0.3	9.6 ± 0.3	9.7 ± 0.3	0.32 ± 0.02	0.32 ± 0.02	0.33 ± 0.02	0.0216 ± 0.0007	0.0216 ± 0.0007	0.0218 ± 0.0007
8	8.5 ± 0.7	8.5 ± 1.0	8.5 ± 0.7	0.36 ± 0.05	0.33 ± 0.05	0.34 ± 0.05	0.0250 ± 0.0020	0.0270 ± 0.0019	0.0270 ± 0.0019
9	9.8 ± 0.5	9.8 ± 0.5	9.8 ± 0.5	0.39 ± 0.03	0.38 ± 0.03	0.39 ± 0.03	0.0243 ± 0.0009	0.0246 ± 0.0009	0.0248 ± 0.0009
10	9.7 ± 0.8	9.8 ± 0.8	9.9 ± 0.7	0.33 ± 0.04	0.34 ± 0.04	0.35 ± 0.04	0.0249 ± 0.0014	0.0244 ± 0.0014	0.0247 ± 0.0014
11	9.3 ± 0.7	9.4 ± 0.7	9.4 ± 0.6	0.29 ± 0.03	0.30 ± 0.03	0.31 ± 0.03	0.0258 ± 0.0017	0.0258 ± 0.0017	0.0259 ± 0.0017

Appendix A: Additional consistency checks

As there are multiple observations for each object, we can check for consistency between them in different regions. For these comparisons we employed the same spectral modelling as used in the astrophysical cluster analysis.

There are two observations of the Perseus cluster, 0085110101 and 0305780101, which are aimed close to the central nucleus (with an offset of 10s of arcsec) and have similar roll angles. We extracted spectra from five different regions. These include a total comparison region made of an annulus centred on the coordinate 03:19:56.9, +41:31:35 between radii of 6.70 and 12.75 arcmin, designed to exclude the Cu-hole and include most of the detector. We also made four further regions consisting of this annulus split into the different detector quadrants. We fitted these spectra in each region with the APEC code plus background model, allowing independent redshifts and normalisations for the observations, but jointly fitting the temperature and metallicity.

Figure A.1 shows the Cu-K α redshifts (top panel) and astrophysical redshifts (bottom panel) for each of these different regions. The corrected Cu-K α redshifts for each of the observations are consistent with zero. The astrophysical redshifts for each of the observations should also be consistent in each of the regions.

The results agree well between the observations, except for a $\sim 2\sigma$ difference for CCDs 4-6, ignoring the systematic uncertainty. The original disagreement may be caused by the short 16 ks exposure time for CCDs 4-6 (the exposure for CCDs 1-3 is 31 ks). Including the systematic uncertainties on the two data points makes the difference insignificant.

For the Coma cluster we cannot make exact consistency tests as the observations have a different pointing positions, so any differences may be caused by astrophysical signal. However, despite this we compared the redshifts for each observation in the extraction regions 1–10 (Fig. 19) and looked for any additional evidence of variation within the region. In this analysis, we jointly fitted the temperature and abundance for each spatial region, but allowed the redshifts and normalisations to be free for each observation. Figure A.2 (left side) shows the obtained Cu-K α redshifts after correction. The horizontal axis shows the observation, indexed by its order in the Coma observations listed in Table 1. As during the joint fits of astrophysical spectra, we ignored those observations for which there were less than 2000 counts between 4.00 and 9.25 keV in the extraction region. Similarly, Fig. A.2 (right side) shows the astrophysical redshifts for the regions and observations.

Both the Cu-K α and astrophysical redshifts appear consistent for each region. We note again that for the astrophysical results, there may be real astrophysical differences in these datapoints. There are no obvious trends observed with observation number, however. To quantify the scatter for the astrophysical redshifts, we modelled the additional width of points beyond the uncertainties for each dataset in a region by a Gaussian model. We increased the statistical uncertainties on the astrophysical redshift input datapoints by the uncertainties on the Cu-K α redshift and by a systematic of 150 km s^{-1} , adding in quadrature. Figure A.3 shows the posterior probability distribution on the Gaussian σ , obtained from a Markov Chain Monte Carlo analysis assuming a Gaussian distribution. There appears to be no significant evidence of a width beyond the statistical uncertainties in any region. In regions 2, 5 and 9 there is very marginal evidence of additional spread, which may be because of the velocity structure seen in the maps (Fig. 21).

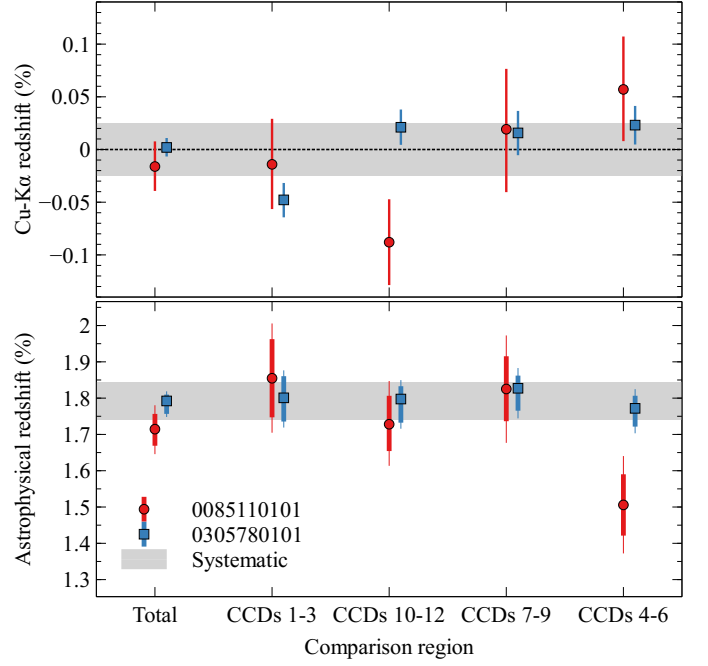


Fig. A.1. Comparison of redshift between the two central observations of Perseus, 0085110101 and 0305780101, for different detector regions. (Top panel) Comparison of Cu-K α redshifts after correction, with an estimated systematic of 75 km s^{-1} . (Bottom panel) Comparison of astrophysical redshifts, with two sets of error bars showing the statistical uncertainty on the redshift after correcting for the Cu-K α best-fitting redshift, and the error bars extended by the uncertainty on the Cu-K α redshift. Shown is the systematic of 150 km s^{-1} .

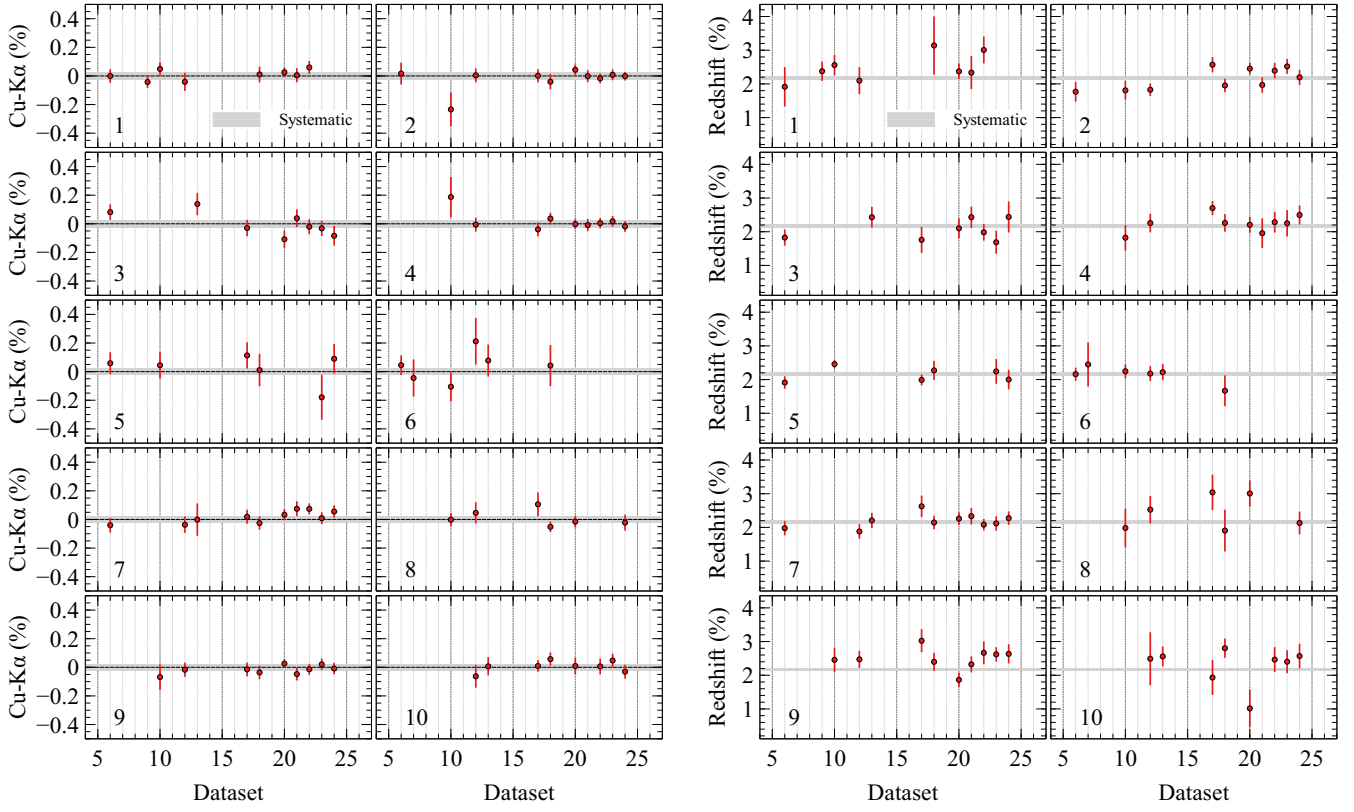


Fig. A.2. Cu-K α (left side) and astrophysical (right side) redshifts for regions 1–10 in the Coma cluster, as a function of observation. The dataset number is the number of the observations in Table 1. Systematic uncertainties of 75 and 150 km s⁻¹, respectively, are shown as a grey shaded region.

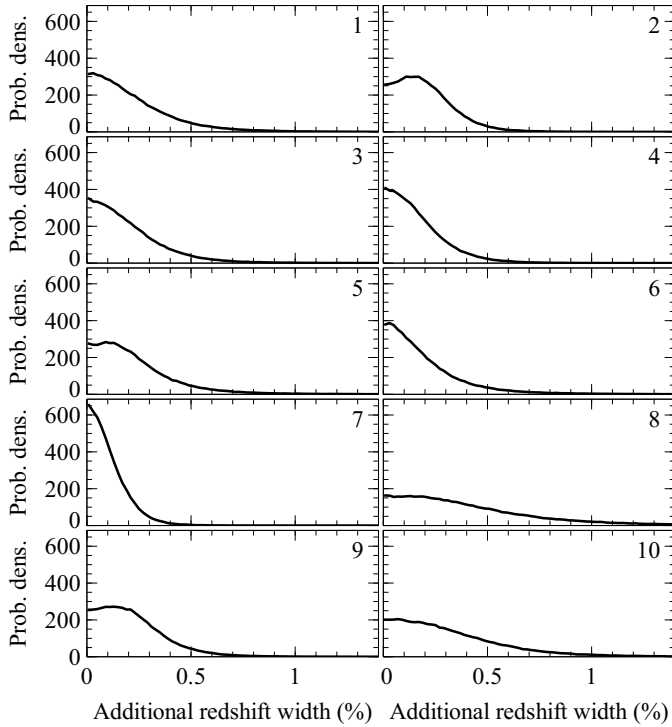


Fig. A.3. Posterior probability density distributions for the additional velocity width (σ) between observations, for regions 1–10 in the Coma cluster.

Table A.4. List of astrophysical datasets used for the calibration, showing revolution, observation identifier, mode (M; E is EFF and F is FF) and clean exposure (ks).

Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.
0029	0116320801	F	18.8	0033	0117710701	F	12.3	0033	0117710601	F	13.1	0048	0095011101	F	28.0
0057	0122520201	E	24.8	0070	0123700101	F	30.5	0071	0123700201	F	29.7	0073	0123700401	F	12.8
0077	0123900101	E	28.4	0086	0124711401	E	14.3	0086	0124710501	E	20.5	0089	0125960101	F	31.4
0093	0124710901	E	16.8	0093	0124710201	E	30.0	0098	0124710101	F	24.6	0099	0124711101	E	17.8
0100	0112570401	F	23.6	0100	0097820101	F	34.5	0101	0124710301	F	14.6	0106	0110980401	E	27.7
0113	0127921001	E	44.6	0118	0112370101	F	36.9	0119	0112371001	F	38.2	0120	0112370301	F	36.1
0122	0112371701	F	20.2	0128	0109920101	E	22.9	0129	0109930101	F	31.6	0131	0110660101	E	10.2
0132	0112230701	E	11.8	0133	0112230801	E	15.2	0137	0112231001	E	20.2	0139	0112970701	E	16.9
0143	0112970401	E	19.1	0144	0112970801	E	11.6	0149	0105260701	E	14.9	0149	0105260601	E	17.0
0151	0094800201	E	10.6	0153	0105260901	E	17.9	0154	0105260801	E	14.3	0155	0105260201	E	12.9
0159	0112980201	E	21.8	0164	0105870201	E	28.8	0164	0105870101	E	11.9	0167	0041170201	E	35.6
0167	0106460101	E	37.5	0176	0109950101	E	14.7	0176	0109950201	E	17.3	0178	0110980101	E	36.8
0182	0108670101	F	45.8	0183	0109980301	E	17.1	0184	0124712101	E	20.2	0184	0124710801	E	19.0
0184	0124712001	E	11.2	0188	0103860901	F	17.0	0191	0108860101	F	16.6	0191	0105660101	E	16.8
0194	0111000101	F	26.0	0195	0109860101	E	30.0	0196	0021540201	F	42.1	0197	0111190701	F	50.7
0198	0050140201	E	39.4	0199	0093640401	E	13.7	0199	0010420201	E	11.0	0200	0109910101	E	39.1
0201	0037950101	F	17.5	0202	0080540101	E	26.3	0202	0084230301	E	12.7	0203	0109980101	E	17.2
0207	0021540101	F	25.5	0210	0085110101	F	28.1	0211	0135120201	E	15.2	0215	0085590201	F	35.2
0218	0041170101	E	37.2	0232	0022340201	F	44.1	0253	0084230601	E	16.5	0254	0092850201	F	21.0
0258	0112810101	F	14.2	0258	0112290201	F	22.9	0259	0107860201	F	16.2	0260	0070340201	E	18.0
0260	0112850101	F	13.0	0264	0111550101	F	36.1	0264	0111550201	F	31.3	0267	0012440301	E	25.3
0268	0111550301	F	14.8	0268	0061740101	E	24.6	0271	0111550401	F	77.0	0273	0112250201	E	25.3
0274	0111160101	E	37.4	0276	0109660801	F	41.3	0280	0108460301	F	12.0	0281	0136950201	F	24.1
0281	0109660901	F	11.5	0281	0094800101	E	22.6	0282	0109661001	F	58.8	0286	0112650101	E	16.4
0286	0112650301	E	13.1	0286	0112650201	E	17.6	0287	0111110401	E	19.6	0287	0111110501	E	17.5
0287	0109520501	E	17.7	0287	0111110301	E	17.7	0288	0111110101	E	15.9	0299	0108060501	E	35.3
0299	0108060401	E	17.9	0300	0112250301	E	19.2	0300	0112240301	E	24.1	0305	0035940301	E	27.7
0310	0107860401	F	25.4	0311	0091140401	E	24.5	0317	0111160201	E	29.1	0318	0112972101	E	17.8
0321	0112480101	E	13.8	0322	0112230301	F	16.2	0325	0109260201	E	25.1	0339	0108860501	F	16.6
0339	0085150101	F	38.3	0342	0085150301	F	25.0	0342	0085150201	F	24.7	0345	0022740201	F	22.9
0345	0094530401	E	14.1	0348	0028740301	F	19.7	0348	0084230701	E	19.8	0349	0022740301	F	28.4
0353	0055990201	E	12.3	0354	0028740101	F	25.0	0354	0028740201	F	27.4	0354	0049340201	F	21.4
0358	0041180301	F	16.5	0358	0005210101	E	21.4	0361	0056021601	E	15.4	0363	0012440201	E	23.4
0366	0021140201	F	35.4	0367	0137550901	F	30.3	0368	0025740201	F	31.7	0368	0056020701	E	22.0
0369	0084230201	E	20.9	0373	0092850501	F	34.8	0374	0093030101	E	29.6	0377	0093200101	F	32.2
0377	0041180801	E	14.9	0378	0084230401	E	11.5	0379	0046340101	F	39.1	0379	0027340101	F	31.0
0381	0112570101	F	55.0	0382	0085220201	E	35.6	0384	0112570201	F	49.8	0384	0108060601	E	39.1
0385	0108060701	E	64.4	0386	0108061901	E	34.7	0386	0108061801	E	48.2	0387	0085220101	E	14.9
0388	0107260101	E	35.1	0388	0108062101	E	39.4	0389	0108062301	E	70.6	0390	0112570301	F	34.2
0392	0112680101	E	21.6	0392	0109520101	E	19.5	0392	0109520201	E	18.6	0393	0112681001	F	20.8
0393	0109520601	E	16.8	0394	0109520301	E	16.0	0394	0112680401	F	19.8	0395	0091770101	F	21.4
0398	0025740401	F	12.2	0399	0083950101	E	12.4	0400	0091140201	E	23.4	0401	0109880101	E	78.9
0402	0136040101	F	14.3	0411	0112231601	E	17.5	0412	0028540601	E	19.3	0417	0026340101	E	18.9
0417	0058940101	E	20.4	0420	0093190501	F	23.7	0421	0110870101	F	20.4	0421	0051610101	E	12.3
0423	0022340101	F	17.2	0426	0110980801	E	31.3	0428	0026340301	E	15.7	0428	0112520101	F	25.5
0431	0136000101	F	13.9	0436	0049340301	F	20.9	0438	0135980201	F	25.5	0441	0083960101	F	15.0
0445	0055990501	E	13.5	0449	0082140301	E	25.6	0451	0067170101	F	37.0	0452	0044350101	F	11.2
0454	0041180401	F	17.2	0455	0104260101	F	26.5	0455	0056020901	E	15.5	0456	0012850201	F	20.5
0456	0124712401	E	12.8	0457	0112521301	F	14.3	0457	01126812501	E	21.1	0457	0070340701	E	28.0
0461	0049150301	E	14.1	0464	0093190301	F	26.9	0466	0103060301	E	34.3	0467	0110900201	E	36.7
0467	0110980201	E	47.8	0469	0108260201	E	48.5	0469	0112850201	F	14.3	0470	0008030201	F	12.1
0471	0110980601	E	26.6	0472	0108860701	F	14.5	0473	0103660101	E	21.7	0475	0112551501	E	15.6
0475	0112300101	E	21.8	0476	0109661201	E	44.1	0481	0112680501	E	16.1	0481	0112681301	E	12.1
0482	0105261401	E	10.8	0483	0086950201	E	20.8	0484	0112960101	F	29.4	0484	0103060201	E	22.0
0484	0105261501	E	16.6	0485	0105261601	E	16.7	0485	0112251301	E	23.3	0485	0108670201	F	27.3
0488	0112370701	F	42.5	0488	0112370801	F	33.4	0490	0112370601	F	31.0	0492	0084230501	E	24.9
0492	0056022201	E	12.6	0504	0112500101	E	19.4	0509	0070341201	E	13.4	0522	0147510101	F	65.7
0523	0147510801	F	37.6	0524	0147510901	F	34.8	0525	0147511001	F	67.2	0526	0147511101	F	36.7
0527	0147511201	F	21.2	0528	0147511301	F	20.3	0529	0093030201	E	35.3	0529	0147540101	F	19.2
0530	0141150201	F	31.0	0536	0142860201	F	31.4	0538	0149670101	F	18.6	0540	0147800101	F	84.1
0543	0150050101	E	19.2	0544	0147511601	F	90.2	0547	0147511701	F	85.7	0548	0147511801	F	73.9
0550	0020540401	F	42.3	0551	0021740201	E	35.5	0553	0094310201	F	61.6	0554	0112230201	E	19.3
0554	0056021001	E	22.1	0555	0140210201	E	31.2	0555	0146510301	F	19.3	0556	0152200101	E	40.5
0556	0144310101	E	16.7	0557	0152330101	F	24.1	0557	0136340101	F	17.0	0557	0109540101	E	44.2
0558	0145020201	F	46.2	0558	0109661101	E	40.5	0559	0148310101	E	33.4	0559	0152860101	F	23.6
0562	0057740301	E	56.6	0563	0105860101	E	26.4	0563	0142770101	F	15.3	0564	0112372001	F	23.3
0565	0152360101	F	31.8	0565	0108460101	F	20.5	0566	0057740401	E	56.8	0566	0110940101	E	14.0
0567	0105261301	E	34.6	0570	0112680301	E	17.3	0571	0105261701	E	15.3	0573	0037982401	E	10.3
0573	0093060401	E	12.9	0574	0110910201	E	18.5	0576	0148650101	F	39.2	0577	0135950301	F	26.8
0578	0146510401	F	30.4	0580	0145480101	F	13.1	0584	0145020101	F	25.5	0586	0145190201	F	15.9
0587	0152150101	F	19.8	0589	0151560101	F	19.6	0590	0145190101	F	12.9	0603	0140210101	E	28.2
0606	0151900101	F	22.3	0608	0145840201	F	17.3	0611	0145840101	F	17.8	0613	0149010201	F	47.4
0627	0148960101	F	48.3	0631	0149160201	F	20.7	0633	0147630101	F	17.2	0638	0148960901	F	21.3
0639	0148961301	F	32.8	0641	0148961601	F	11.2	0641	0058940701	E	12.3	0642	0156360101	F	22.3

Table A.4. continued.

Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.
0643	0141150101	F	13.2	0645	0150320201	F	23.8	0647	0148990101	F	19.5	0651	0147610101	E	12.2
0651	0141380201	F	11.4	0652	0151581301	F	13.2	0652	0148960401	F	25.9	0654	0143210801	F	22.2
0656	0141570101	E	19.4	0656	0153450101	F	42.5	0659	0151490101	F	19.1	0660	0148580101	F	11.4
0664	0150680101	F	27.1	0665	0150350101	F	21.6	0666	0147330201	F	35.2	0668	0148620101	E	13.0
0690	0112490101	E	14.9	0709	0149670301	F	22.6	0722	0147890101	E	19.8	0730	0200240401	E	13.8
0736	0149240101	F	35.0	0737	0203130201	E	16.9	0737	0202190201	E	20.0	0744	0200130101	F	10.1
0749	0204870101	F	29.8	0756	0205190201	F	20.0	0756	0205190101	F	25.3	0757	0206300101	F	15.2
0758	0205990101	F	34.8	0759	0200750401	F	43.1	0760	0203610201	F	14.5	0761	0204720201	F	20.7
0765	0203980101	E	23.0	0767	0201901901	E	11.0	0776	0201900801	E	11.6	0777	0201900901	E	18.5
0787	0205070401	F	13.1	0787	0201980101	F	24.5	0788	0202670501	E	19.3	0789	0202670601	E	31.2
0797	0200470101	F	39.3	0800	0206080101	F	59.1	0801	0206340201	F	15.6	0801	0206180101	F	11.8
0802	0205220101	F	27.0	0804	0206180201	F	26.7	0806	0206850101	E	49.8	0808	0201901201	E	12.7
0809	0205370201	E	29.4	0810	0205370101	E	29.9	0811	0201902401	E	19.6	0812	0203170101	F	30.5
0814	0202190301	E	13.9	0816	0205010101	F	22.3	0817	0201900301	E	11.1	0817	0200500201	F	22.5
0818	0202650101	F	31.0	0819	0202730101	F	29.1	0821	0200340101	E	61.1	0822	0205010201	F	18.9
0822	0204180101	F	23.9	0823	0204040101	F	66.5	0826	0202730301	F	30.4	0827	0206060101	F	16.6
0830	0201690301	F	16.0	0831	0201901801	E	17.6	0832	0201900101	E	20.0	0832	0200270101	F	28.6
0834	0206230101	F	31.2	0838	0201670101	F	15.7	0841	0204040301	F	48.3	0843	0202270101	E	31.6
0846	0201902001	E	21.0	0848	0201670201	F	13.1	0849	0202370201	E	12.6	0852	0201902101	E	22.8
0853	0204540101	F	14.2	0854	0205450201	F	29.3	0869	0203040501	E	16.2	0874	0201510101	E	28.6
0874	0205670101	F	24.2	0875	0203750101	E	36.2	0876	0202130101	E	25.1	0882	0203610401	F	20.8
0884	0207380101	F	18.7	0884	0203020201	F	12.1	0885	0201902201	E	18.8	0886	0200250101	F	27.7
0888	0201470101	F	12.3	0889	0201902501	E	15.6	0893	0201903001	E	16.2	0894	0206340101	F	29.4
0895	0201901001	E	16.6	0895	0200780301	F	26.2	0895	0201902701	E	16.2	0898	0206060201	F	24.7
0899	0200780201	F	22.0	0902	0201903101	E	15.2	0904	0204530101	F	18.6	0908	0204540201	F	17.9
0910	0203880101	F	42.3	0911	0202130201	E	15.9	0911	0201902601	E	18.7	0913	0201900401	E	13.5
0915	0206010101	E	19.5	0915	0207060101	F	22.5	0916	0204460101	F	24.9	0918	0200650101	E	43.5
0919	0200800101	F	24.5	0921	0210270101	F	21.9	0922	0206090101	F	24.6	0923	0205090101	F	21.3
0923	0201901501	E	19.4	0924	0203170301	F	67.8	0925	0201900601	E	21.6	0925	0203690101	F	27.9
0925	0210270201	F	17.8	0926	0201330201	E	23.7	0927	0201751301	F	16.5	0928	0210490101	E	72.6
0929	0201690201	F	17.2	0929	0210480101	F	39.9	0931	0202370301	E	12.6	0931	0202080201	E	14.6
0932	0200920101	E	63.9	0935	0202130301	E	30.3	0946	0200770101	F	36.2	0960	0206640101	E	12.6
0973	0303950101	F	43.5	0975	0201902301	E	12.3	0976	0303260201	E	40.5	0977	0210280101	F	67.4
0984	0203450101	E	32.8	0988	0302540201	E	10.2	0990	0203450201	E	20.3	0993	0201902901	E	18.5
0993	0206490301	E	17.1	0997	0303260501	E	16.9	0997	0201330101	E	23.0	0998	0305860401	F	27.9
0998	0200800201	F	41.9	1006	0300530601	E	15.7	1006	0300530701	E	17.6	1007	0300530401	E	13.2
1007	0300530501	E	18.1	1008	0300530301	E	22.9	1008	0302580701	E	19.7	1009	0211280101	E	29.1
1009	0302580501	E	31.5	1012	0300530101	E	17.1	1014	0302581501	E	20.1	1016	0304320301	F	29.3
1017	0304320201	F	60.0	1021	0303670101	E	37.2	1024	0301250101	E	14.8	1029	0302460101	E	22.3
1030	0305930101	F	40.0	1033	0304940101	F	23.0	1035	0305720301	F	17.1	1038	0302500101	F	66.4
1039	0302780101	E	64.1	1040	0302580901	E	16.7	1047	0303820101	F	10.0	1049	0300800101	E	30.0
1049	0305720101	F	10.6	1058	0307110101	E	11.3	1065	0302580401	E	10.5	1069	0302581801	E	19.0
1071	0302800101	F	18.3	1077	0300140201	E	13.2	1081	0302581601	E	19.5	1082	0306080101	F	37.2
1086	0306060201	F	48.5	1089	0305060101	E	23.4	1091	0300210201	E	10.4	1092	0305860301	F	30.8
1095	0303820201	F	28.6	1097	0306060101	F	70.1	1098	0300430101	F	91.5	1101	0305800101	E	14.7
1113	0301290101	F	46.2	1113	0302610401	E	19.5	1114	0300210701	E	16.4	1114	0300140101	E	25.5
1116	0301900501	F	17.2	1118	0304190101	F	50.3	1119	0302582201	E	24.9	1120	0302320201	F	14.1
1120	0302610701	E	17.7	1120	0305800901	E	15.1	1121	0311200101	E	29.9	1121	0311200201	E	28.6
1124	0302610601	E	13.9	1125	0305780101	E	76.2	1127	03008210401	E	31.1	1130	0306490201	F	14.6
1130	0300780301	E	23.1	1131	0305690101	F	22.9	1131	0305690401	F	22.8	1131	0305690301	F	16.5
1132	0306490301	F	11.8	1133	0306490401	F	15.2	1134	0302030101	E	39.6	1162	0302970301	E	19.1
1163	0303820301	F	20.0	1171	0404910801	E	14.2	1172	0311190101	F	66.0	1173	0404190101	F	29.9
1174	0302580301	E	41.1	1184	0301900601	F	19.3	1186	0400130201	E	23.1	1187	0302582301	E	23.3
1188	0402530201	E	73.5	1189	0304320801	F	32.4	1191	0403150201	F	36.8	1191	0305801101	E	11.9
1193	0403150101	F	29.1	1194	0403150301	F	38.8	1196	0403150401	F	45.8	1198	0403100101	E	53.1
1198	0300211401	E	18.3	1199	0402250201	E	18.8	1200	0402830101	F	16.9	1201	0402560301	F	41.6
1202	0404060201	F	19.8	1205	0402560401	F	22.6	1206	0403760301	F	21.1	1207	0405770101	F	22.1
1210	0404910201	E	15.4	1211	0402560501	F	47.4	1211	0406210201	F	26.3	1212	0402560701	F	23.6
1213	0406200101	E	89.3	1214	0402750201	E	22.4	1215	0402560601	F	28.3	1218	0405410201	F	10.7
1218	0405410101	F	12.8	1219	0404010101	E	21.3	1228	0400620101	F	84.7	1235	0405550401	E	19.7
1237	0404800101	F	21.0	1238	0401730101	F	27.1	1239	0401730201	F	33.0	1240	0401730301	F	32.9
1249	0403760201	F	14.0	1254	0404520201	F	28.4	1262	0400830301	E	39.0	1272	0401920101	E	23.6
1272	0404910701	E	17.3	1273	0404190201	F	42.0	1277	0404520101	F	18.2	1278	0406210101	F	74.3
1280	0401130101	F	31.1	1287	0402750601	E	21.8	1287	0404120101	F	26.4	1288	0404410201	E	40.3
1290	0402560801	F	42.7	1290	0404410101	E	36.0	1291	0400800201	E	16.2	1291	0402560901	F	39.7
1293	0402561001	F	45.9	1294	0402561101	F	41.6	1294	0402561201	F	35.3	1295	0402561301	F	31.1
1295	0402561401	F	39.5	1296	0402561501	F	38.2	1304	0401040101	E	28.5	1304	0406000101	F	13.3
1305	0400010301	F	24.4	1311	0401521201	E	13.6	1312	0400490201	E	43.6	1314	0404750101	E	30.1
1337	0410581101	E	13.2	1338	0402430701	F	21.4	1339	0402430301	F	52.0	1340	0402430401	F	36.1
1341	0400010201	F	51.6	1345	0401170101	F	56.2	1356	0501170101	F	27.8	1357	0505460201	F	20.3
1357	0505460101	F	20.8	1359	0504260101	E	60.7	1362	0501170201	F	27.2	1364	0503600401	F	13.3
1365	0413380501	F	19.3	1367	0505460501	F	15.4	1368	0501110201	E	32.9	1372	0504240101	F	67.6
1373	0404840201	F	38.5	1378	0502020101	E	21.7	1380	0502020201	E	31.9	1382	0504780501	E	76.0
1383	0504780601	E	23.4	1388	0505930101	F	23.7	1390	0504780101	E	16.4	1391	0403760701	F	27.1
1392	0500940101	F	10.2	1393	0504780201	E	22.0	1395	0505760201	F	35.4	1396	0505760101	F	23.7

Table A.4. continued.

Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.
1397	0502430101	E	32.9	1397	0504360101	F	24.9	1400	0504780301	E	40.1	1401	0504780401	E	13.9
1403	0501730101	F	31.5	1404	0504990101	F	15.0	1405	0506260301	F	48.9	1405	0506670201	F	14.5
1406	0500670301	F	19.5	1407	0501280101	F	30.5	1407	0500670401	F	13.4	1408	0505230401	E	33.8
1409	0502070201	F	35.7	1411	0504140101	F	37.0	1416	0505150101	E	19.1	1423	0505200101	E	24.9
1428	0505150201	E	18.2	1430	0502430201	E	33.4	1435	0503750401	F	16.1	1435	0503750301	F	17.4
1436	0503750501	F	16.5	1440	0504320201	F	18.3	1443	0505382201	F	12.1	1444	0504320101	F	23.1
1444	0505383001	F	13.6	1445	0503750101	F	67.4	1446	0500940201	F	20.3	1447	0500730201	F	27.1
1448	0503600101	F	14.6	1448	0505460301	F	24.4	1449	0502950101	E	39.7	1450	0500730101	F	21.1
1451	0503630201	F	20.1	1456	0505382501	F	16.7	1457	0502690601	E	23.1	1457	0501110101	E	28.6
1458	0502690101	E	27.0	1460	0505381801	F	12.3	1460	0505383301	F	13.7	1461	0502430301	E	74.2
1462	0504160101	F	44.8	1463	0505382001	F	12.2	1464	0503490201	F	96.4	1465	0502430401	E	20.9
1466	0502690201	E	49.7	1468	0502860101	E	37.8	1469	0502120101	F	67.6	1470	0502160101	F	61.6
1473	0500760101	F	43.3	1473	0505760401	F	23.5	1474	0504360201	F	28.7	1475	0505760301	F	38.1
1476	0505760501	F	28.9	1477	0511380101	F	38.1	1479	0511380201	F	12.5	1479	0511380301	F	27.1
1481	0505930401	F	16.4	1484	0503230101	E	12.4	1487	0502070101	F	76.9	1496	0511380601	F	14.2
1497	0502950201	E	10.7	1501	0506260401	F	49.1	1502	0505150401	E	14.2	1502	0505150301	E	10.5
1504	0505210401	E	17.1	1514	0500540101	E	44.2	1517	0510990101	E	27.7	1519	0506130201	E	11.3
1524	0505930301	F	36.2	1526	0502760101	E	19.3	1529	05052940301	F	12.6	1537	0501650201	F	25.7
1537	0504630101	E	23.7	1543	0550460101	F	17.0	1546	0556300101	F	19.3	1547	0556280101	F	25.0
1548	0556200101	E	33.3	1548	0556200301	E	25.6	1549	0556200501	E	62.8	1555	0551630301	E	29.0
1559	0555880201	E	26.6	1562	0551870301	E	15.3	1565	0550931001	F	15.8	1565	0551870501	E	15.4
1569	0553911401	F	20.8	1569	0553910901	F	19.8	1570	0555780101	F	82.8	1571	0555780201	F	93.7
1572	0555780301	F	88.1	1573	0555780401	F	69.2	1574	0551850201	E	32.0	1575	0551830101	E	49.9
1576	0551780201	E	23.3	1577	0551780301	E	30.3	1578	0551780401	E	23.4	1579	0550360101	E	16.2
1580	0551830201	E	59.5	1582	0556020101	E	30.6	1584	0555220201	E	63.4	1586	0553911101	F	17.8
1591	0552080101	E	20.6	1592	0551780501	E	20.4	1600	0555880101	E	18.4	1600	0553650101	E	17.1
1610	0553650201	E	21.6	1618	0551850401	E	45.8	1619	0554120101	F	21.0	1620	0553180101	E	37.2
1622	0551850101	E	34.6	1634	0554121301	F	29.9	1637	0550460801	F	21.6	1637	0553880201	F	23.7
1638	0553880301	F	35.5	1644	0552580201	E	53.9	1645	0556090101	F	36.0	1646	0551280101	E	40.4
1647	0551280201	E	38.3	1650	0550540101	F	62.1	1652	0553780101	F	46.1	1653	0553030101	F	66.3
1653	0551090101	F	13.5	1654	0550460301	F	18.6	1655	0550540201	F	15.0	1656	0552860101	F	31.8
1656	0551600101	F	34.5	1657	0555220301	E	42.8	1658	0554680101	F	86.1	1660	0553911701	F	10.6
1663	0555780501	F	80.6	1665	0555780601	F	73.1	1666	0555780701	F	85.5	1668	0555780801	F	69.9
1669	0555780901	F	75.2	1670	0551040101	F	38.1	1671	0555781001	F	88.6	1672	0555782301	F	85.9
1673	0551630101	E	25.6	1678	0551630201	E	16.4	1679	0552510101	F	90.1	1681	0554680201	F	45.2
1684	0554680301	F	45.5	1688	0556240501	F	32.2	1691	0551851301	E	27.9	1700	0551851201	E	55.7
1709	0551630601	E	13.6	1710	0554120701	F	12.2	1711	0550460601	F	14.7	1714	0550460701	F	11.0
1715	0556280301	F	56.1	1716	0556280201	F	25.2	1724	0605540301	E	35.5	1729	0601210301	F	23.1
1731	0604010201	F	16.4	1732	0604010301	F	13.2	1733	0602200101	E	16.5	1733	0601930101	F	24.2
1736	0603590201	F	59.4	1738	0601930501	F	82.6	1739	0603590101	F	54.1	1745	0603260601	E	12.6
1747	0602010301	F	80.3	1748	0602440101	F	55.3	1749	0601930301	F	21.2	1750	0601212401	F	22.0
1750	0601212601	F	15.1	1753	0604960301	F	81.3	1755	0602920101	F	25.6	1758	0603150401	F	32.7
1758	0605470201	E	20.1	1759	0604960201	F	83.2	1761	0603050101	E	71.5	1763	0601970101	F	33.9
1764	0604960101	F	78.7	1765	0604960401	F	98.5	1767	0601930401	F	53.0	1770	0603050201	E	58.7
1771	0604280101	F	67.5	1774	0605540101	E	96.2	1775	0603890101	F	12.7	1779	0601080101	E	45.4
1779	0601930201	F	27.6	1786	0601212501	F	27.3	1786	0601212301	F	27.3	1788	0601212901	F	28.5
1788	0601213001	F	33.3	1794	0601210401	F	30.8	1794	0601210201	F	30.7	1794	0601210501	F	35.6
1795	0601210901	F	28.4	1795	0601210601	F	29.9	1795	0601210701	F	31.8	1798	0601211301	F	26.5
1801	0601210801	F	19.8	1802	0601211601	F	25.2	1803	0601211501	F	30.7	1804	0601211701	F	15.1
1806	0601211101	F	24.7	1807	0601211201	F	24.4	1811	0601830501	F	15.2	1812	0604870301	F	72.7
1814	0601211401	F	27.2	1817	0601211001	F	21.5	1819	0601211801	F	19.2	1820	0601212101	F	27.8
1822	0601212201	F	19.7	1826	0601212001	F	22.6	1826	0601260101	E	42.2	1827	0600040101	F	43.6
1827	0602340201	F	13.7	1827	0601211901	F	25.7	1828	0601830401	F	14.5	1828	0605470601	E	22.2
1829	0604873401	F	76.4	1830	0604873901	F	65.6	1831	0601212801	F	14.8	1834	0605540201	E	85.5
1837	0601260201	E	20.3	1839	0602010101	F	71.9	1840	0601212701	F	30.1	1840	0605470501	E	16.7
1842	0605000301	E	15.5	1844	0604890101	E	38.0	1845	0604961101	F	87.5	1846	0603500201	F	27.0
1847	0604961201	F	93.4	1848	0602340101	F	17.1	1849	0604960701	F	54.9	1851	0606370601	F	18.4
1851	0610980201	F	19.7	1852	0604960501	F	38.6	1854	0601600101	F	17.8	1856	0604960601	F	78.3
1861	0604960801	F	74.1	1864	0604960901	F	66.5	1865	0604961001	F	75.0	1867	0604961801	F	79.2
1869	0603751001	E	44.8	1876	0603500701	F	13.5	1880	0601213401	F	10.5	1886	0656200701	E	16.9
1893	0603501001	F	25.8	1896	0602060101	E	12.6	1897	0600830301	F	28.7	1897	0656200101	E	11.8
1898	0600830501	F	27.5	1899	0603500301	F	13.9	1900	0604740101	E	47.3	1902	0656200201	E	15.8
1903	0655830101	F	12.6	1908	0653450501	F	26.0	1909	0652010301	E	20.0	1909	0654440201	E	21.4
1913	0651240201	E	26.8	1914	0655300101	F	25.8	1914	0650860101	F	19.1	1916	0653450601	F	20.2
1919	0651790301	F	14.6	1920	0652950301	F	10.8	1922	0654440101	E	52.1	1925	0651790201	F	18.4
1926	0653770301	F	34.4	1928	0652010201	E	33.0	1929	0652010401	E	26.7	1934	0653450701	F	25.5
1936	0651590101	E	17.4	1938	0650510101	F	74.8	1939	0650510201	F	76.8	1940	0653450401	F	26.8
1941	0652450101	F	36.0	1944	0650510301	F	66.5	1947	0650510401	F	39.3	1951	0651240101	E	18.6
1952	0652400101	F	27.7	1953	0652400501	F	14.6	1954	0650510501	F	59.7	1955	0650510601	F	89.3
1956	0650510701	F	60.5	1959	0651710101	F	24.7	1960	0651710201	F	37.9	1960	0652400401	F	29.9
1967	0652400301	F	28.7	1968	0652400201	F	30.4	1975	0653050201	E	20.3	1976	0653050401	E	67.5
1977	0653050501	E	60.9	1978	0653050601	E	15.1	1980	0653580101	E	18.7	1981	0653050301	E	15.5
1990	0652810101	F	15.2	1991	0655340101	F	74.7	1992	0652810301	F	20.6	1993	0653040101	E	61.0
1994	0652810201	F	20.9	1994	0555220101	E	44.0	1995	0652810401	F	24.7	1996	0653050801	E	49.0
2003	0651580101	E	54.2	2005	0655346801	F	34.0	2009	0653450201	F	26.0	2012	0653290101	F	18.7

Table A.4. continued.

Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.
2012	0653290201	F	20.8	2012	0652401001	F	25.1	2014	0651910401	F	27.7	2015	0652401101	F	27.8
2017	0654030101	F	57.7	2018	0651910501	F	24.7	2019	0652401201	F	22.4	2019	0651910601	F	22.8
2022	0651770201	E	54.2	2023	0652460201	E	23.1	2023	0654080401	F	16.9	2024	0652210101	E	88.7
2025	0652401401	F	28.9	2026	0652401301	F	19.7	2028	0651910701	F	23.6	2029	0652400701	F	24.3
2029	0652400801	F	18.1	2030	0651770101	E	60.7	2031	0651890101	E	46.6	2034	0651890201	E	32.2
2036	0655343801	F	71.1	2038	0652400601	F	20.8	2041	0651890301	E	68.1	2043	0655300301	F	29.7
2046	0651890401	E	61.6	2051	0651630101	E	31.9	2052	0651630201	E	13.8	2054	0651370601	F	13.2
2055	0655570901	F	14.1	2056	0655571401	F	15.0	2069	0651630501	E	20.4	2069	0604300601	F	26.5
2070	0604300701	F	29.5	2071	0604300801	F	29.9	2072	0604300901	F	18.3	2073	0604301001	F	33.2
2074	0653040201	E	47.8	2075	0651460101	F	36.8	2076	0654440401	E	26.8	2081	0650180201	F	11.8
2082	0655300601	F	26.6	2083	0651580601	E	21.6	2083	0651460201	F	11.7	2090	0677700135	F	11.0
2090	0677700101	F	97.7	2090	0677700140	F	11.3	2092	0674380201	E	34.6	2092	0674490701	E	10.1
2093	0677710135	F	10.9	2093	0677710101	F	84.1	2094	0673150201	F	12.4	2097	0677720139	F	10.6
2097	0677720101	F	69.6	2097	0677720138	F	10.4	2097	0677720135	F	12.2	2098	0674370201	E	38.0
2102	0673310101	F	32.1	2105	0675010801	E	16.5	2111	0675010101	E	49.6	2112	0675010401	E	22.2
2115	0672130101	F	78.8	2117	0670780101	F	33.1	2118	0675010601	E	44.5	2119	0672130601	F	71.5
2120	0672130701	F	71.3	2121	0674380501	E	20.8	2122	0672870101	F	31.7	2123	0672130501	F	25.2
2123	0674560201	E	43.4	2128	0677590101	F	83.1	2128	0675790132	F	11.0	2132	0673110201	F	26.0
2133	0677690133	F	11.4	2133	0677690101	F	90.1	2136	0673080101	F	59.9	2137	0677580101	F	91.6
2137	0677580139	F	10.5	2137	0677580133	F	11.4	2141	0673020301	F	13.0	2141	0674380101	E	18.3
2144	0673100101	F	33.7	2145	0670950101	F	95.3	2147	0673170101	F	17.5	2147	0674670101	E	35.0
2149	0677181301	F	22.1	2152	0673020201	F	19.3	2154	0673710301	F	13.8	2162	0670870101	E	76.6
2164	0675060101	F	65.6	2167	0675010901	E	32.6	2168	0677182301	F	10.2	2168	0672420101	E	41.4
2169	0672420201	E	48.9	2170	0673180401	F	18.4	2170	0672420301	E	40.6	2171	0673150401	F	27.0
2171	0674490401	E	20.2	2172	0675010501	E	47.2	2178	0677730101	F	94.8	2178	0677730132	F	10.8
2178	0677730140	F	11.9	2178	0677730139	F	11.0	2183	0673150301	F	26.1	2183	0677180701	F	13.9
2187	0673830201	E	50.5	2188	0674491101	E	21.5	2191	0677740138	F	10.9	2191	0677740140	F	10.0
2191	0677740132	F	10.7	2191	0677740101	F	99.9	2191	0677740135	F	10.4	2193	0677750138	F	11.0
2193	0677750132	F	10.2	2193	0677750101	F	97.8	2193	0677750134	F	11.0	2193	0677750135	F	10.9
2195	0675010701	E	39.9	2197	0673000101	F	92.5	2198	0673851601	E	11.3	2203	0671010101	F	18.1
2203	0674380701	E	38.8	2205	0673750101	F	18.4	2207	0670350501	F	16.7	2207	0673830101	E	51.6
2210	0673851101	E	28.8	2211	0677610138	F	12.2	2211	0677610132	F	11.0	2211	0677610101	F	86.9
2212	0674660201	E	12.9	2213	0677620138	F	11.3	2213	0677620101	F	78.4	2213	0677620132	F	10.4
2214	0672190301	F	84.8	2215	0677640101	F	83.7	2215	0677640137	F	11.0	2215	0677640138	F	11.0
2216	0679600101	F	22.5	2218	0677670101	F	78.6	2218	0677670132	F	11.0	2225	0674491201	E	15.5
2226	0671090101	F	21.2	2228	0672990401	E	13.6	2229	0673770101	F	31.4	2230	0671700101	F	68.1
2231	0673850601	E	16.8	2239	0673020401	F	14.3	2246	0674491501	E	19.5	2247	0671010201	F	14.8
2250	0675010201	E	66.5	2251	0671010401	F	18.3	2253	0675010301	E	53.6	2255	0673851501	E	14.9
2263	0673850901	E	11.6	2264	0674380301	E	40.4	2264	0673150501	F	13.1	2265	0673170201	F	53.1
2267	0674370101	E	78.9	2268	0690743801	F	18.6	2268	0673180201	F	10.4	2269	0671010301	F	21.6
2276	0690740501	F	16.8	2276	0694440801	E	17.5	2278	0677760101	F	64.2	2279	0694440701	E	15.2
2279	0693661901	E	15.3	2279	0693300101	F	24.7	2280	0677770140	F	14.3	2280	0677770139	F	11.0
2280	0677770131	F	13.4	2280	0677770101	F	102.1	2282	0673002301	F	77.0	2283	0693661701	E	12.3
2283	0693010101	E	14.1	2285	0690740601	F	23.9	2285	0692900201	E	13.8	2285	0693660701	E	17.3
2286	0694440401	E	26.3	2286	0691610201	E	27.6	2287	0691610301	E	19.4	2289	0693010301	E	30.6
2289	0693190101	F	51.1	2290	0693180201	F	21.3	2291	0693010601	E	21.3	2291	0693010401	E	14.2
2291	0693010501	E	20.2	2292	0690740901	F	11.8	2292	0693661001	E	18.8	2293	0692830201	E	13.2
2293	0693160101	F	16.9	2295	0690780201	F	19.4	2297	0690741101	F	21.7	2299	0690741201	F	21.5
2301	0673770301	F	28.4	2302	0677600101	F	88.5	2303	0693661101	E	20.8	2304	0690741601	F	25.6
2304	0690741701	F	10.3	2304	0690741801	F	17.9	2306	0677631201	F	19.1	2307	0694440101	E	13.9
2307	0694440201	E	25.9	2308	0694440501	E	26.6	2308	0690741901	F	16.3	2309	0694440601	E	26.0
2310	0677660238	F	10.3	2310	0677660201	F	73.4	2311	0677650132	F	13.3	2311	0677650101	F	77.8
2314	0690742001	F	11.3	2314	0693661301	E	38.1	2315	0677681231	F	11.6	2315	0677681239	F	11.1
2315	0677681201	F	95.8	2315	0677681233	F	11.1	2316	0693970301	F	36.4	2317	0693300301	F	20.8
2318	0690742201	F	19.1	2319	0693180901	F	24.9	2319	0690742301	F	23.4	2320	0690742801	F	15.9
2320	0693661501	E	42.9	2322	0690742601	F	24.5	2322	0693660301	E	28.2	2323	0690743301	F	11.1
2323	0690742901	F	21.6	2323	0693970401	F	24.0	2324	0700380901	E	21.6	2324	0690743001	F	28.2
2326	0692830101	E	18.8	2327	0690743901	F	26.7	2327	0690743701	F	26.2	2328	0690743201	F	28.4
2329	0693661601	E	34.2	2329	0693661401	E	24.0	2330	0690744001	F	22.2	2330	0690744101	F	17.3
2331	0694640201	F	39.9	2331	0694640301	F	35.5	2332	0694640401	F	37.2	2333	0690743601	F	15.5
2333	0690743501	F	22.1	2334	0694640501	F	30.0	2334	0694640601	F	35.7	2335	0690742401	F	23.0
2335	0694640101	F	34.5	2337	0694640901	F	37.2	2339	0700381201	E	18.4	2340	0693970101	F	22.0
2341	0693660401	E	37.2	2342	0690752001	F	22.1	2342	0690742101	F	22.2	2343	0694641101	F	35.5
2343	0694641001	F	40.8	2344	0694641301	F	41.5	2344	0694641201	F	35.5	2346	0694641401	F	30.1
2347	0694640701	F	37.8	2349	0694641501	F	34.5	2349	0694640801	F	35.4	2350	0694641601	F	23.9
2351	0690744601	F	26.0	2351	0690744501	F	22.2	2352	0690743101	F	22.8	2355	0693180101	F	33.8
2356	0690744301	F	22.7	2358	0690744401	F	20.6	2358	0693662501	E	25.5	2360	0677810101	F	100.3
2360	0677810132	F	11.1	2360	0677810141	F	10.2	2361	0677800101	F	110.3	2361	0677800143	F	13.0
2361	0677800133	F	11.1	2362	0692931301	F	14.6	2366	0690742701	F	26.1	2367	0690744801	F	25.2
2367	0690744901	F	20.5	2367	0690745001	F	23.7	2368	0690750101	F	24.9	2369	0690750301	F	19.5
2369	0690750501	F	24.0	2369	0690750401	F	24.4	2370	0691840101	F	98.1	2372	0690744701	F	28.3
2372	0690744201	F	25.0	2373	0690750601	F	29.3	2374	0677820101	F	90.2	2375	0690750701	F	24.3
2376	0677830101	F	111.3	2376	0677830145	F	17.1	2377	0693741601	F	15.5	2377	0677850101	F	52.5
2378	0677840101	F	80.8	2379	0690750801	F	22.9	2379	0690751101	F	25.5	2379	0690751001	F	22.2
2379	0690750901	F	22.2	2380	0677850901	F	25.8	2381	0693662301	E	29.1	2381	0690751301	F	22.2

Table A.4. continued.

Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.
2381	0690751201	F	26.6	2383	0690751501	F	27.8	2383	0690751401	F	23.1	2384	0690751601	F	23.7
2390	0691950201	E	90.2	2391	0690751801	F	22.9	2391	0690751901	F	22.1	2391	0693010801	E	26.5
2393	0693011001	E	11.1	2394	0692934301	F	26.3	2395	0691950101	E	72.3	2396	0693820201	F	35.2
2396	0693820101	F	28.4	2398	0693660501	E	13.8	2402	0690470401	F	18.5	2402	0700182401	E	18.9
2405	0694670101	E	61.2	2405	0693220201	F	16.8	2412	0693450201	F	12.1	2413	0694500101	E	86.9
2419	0691010101	F	28.3	2421	0692932501	F	16.8	2421	0691011001	F	25.9	2422	0691010901	F	17.3
2424	0690751701	F	14.6	2425	0692932201	F	11.7	2426	0692932601	F	10.8	2427	0692932001	F	13.6
2428	0692050101	E	96.9	2430	0692932701	F	17.0	2431	0691820101	E	42.7	2434	0690470101	F	28.5
2435	0693190401	F	82.0	2438	0692930101	F	17.3	2439	0691670101	F	46.3	2440	0690470201	F	28.3
2440	0694380101	E	51.5	2449	0677761101	F	30.2	2451	0691670201	F	25.1	2455	0725290101	F	69.4
2456	0725300101	F	62.3	2458	0723800901	E	62.1	2459	0723801001	E	68.3	2463	0725310101	F	86.4
2465	0723801601	E	12.7	2466	0723801701	E	37.0	2467	0724770801	E	14.3	2470	0723220101	F	70.6
2471	0723801301	E	61.7	2472	0723802001	E	23.4	2473	0723780201	F	16.5	2476	0723802101	E	81.1
2477	0723802201	E	84.4	2478	0723800601	E	14.8	2487	0723800701	E	50.8	2488	0724770501	E	17.9
2490	0723780501	E	15.1	2490	0723800301	E	79.4	2491	0721890401	E	13.2	2491	0723780601	E	23.3
2498	0722270101	F	43.4	2502	0721740101	E	38.9	2505	0723801101	E	43.8	2507	0723160601	F	11.4
2510	0720700101	F	96.8	2513	0723801201	E	43.6	2515	0723160701	F	17.4	2518	0721890201	E	20.8
2519	0723180101	F	16.5	2521	0725220201	E	36.7	2528	0723780201	E	15.4	2531	0723290101	E	65.9
2533	0724771001	E	10.2	2539	0723650701	F	15.2	2540	0723650201	F	15.2	2541	0723160501	F	13.3
2546	0723650801	F	28.8	2546	0725240101	E	17.7	2548	0723650901	F	31.5	2549	0723780301	E	12.2
2551	0722700201	F	81.5	2554	0722310201	F	46.0	2554	0723800801	E	43.4	2555	0723160901	F	16.3
2556	0722700101	F	104.4	2558	0722360301	F	91.3	2560	0723800701	E	13.1	2562	0722660101	E	30.9
2563	0722660201	E	34.9	2567	0723650601	F	17.7	2568	0721820201	E	25.1	2574	0722670101	F	58.6
2575	0721890101	E	16.7	2575	0722670201	F	53.6	2575	0723650401	F	11.2	2578	0728170101	F	18.8
2580	0722900101	E	10.9	2583	0722360201	F	70.9	2584	0723650501	F	11.2	2584	0723800201	E	72.5
2585	0723801501	E	97.3	2586	0723800101	E	60.6	2587	0723650301	F	17.9	2590	0720700301	F	49.2
2590	0747190101	F	24.1	2590	0747190132	F	12.5	2591	0747190333	F	11.1	2591	0722140401	F	21.1
2591	0747190301	F	36.3	2591	0720700401	F	19.6	2592	0747190601	F	20.6	2592	0723800401	E	43.8
2594	0723800501	E	68.3	2595	0720700201	F	43.1	2597	0720253101	F	29.3	2600	0720253401	F	24.1
2600	0720253201	F	21.2	2600	0720253301	F	28.2	2602	0723180801	F	10.6	2602	0723651201	F	28.8
2602	0723651101	F	10.1	2609	0745130201	E	44.1	2610	0744100201	F	19.5	2612	0744410101	E	22.4
2612	0744410501	E	18.0	2613	0723270101	E	63.6	2619	0744390401	F	14.6	2619	0744410701	E	19.8
2620	0744410801	E	12.5	2621	0741200601	F	13.6	2622	0744410301	E	10.6	2624	0744410401	E	13.9
2624	0744412201	E	17.0	2625	0744410201	E	21.2	2626	0744413601	E	13.2	2626	0744413501	E	40.8
2627	0744413901	E	28.8	2627	0744413801	E	23.5	2634	0744410601	E	25.8	2638	0744400101	E	37.5
2639	0744100501	F	11.2	2641	0747590131	F	13.9	2641	0747590101	F	53.4	2642	0744390301	F	19.3
2643	0744100101	F	20.5	2644	0744412601	E	19.1	2645	0744400501	E	87.6	2646	0741300401	E	78.8
2647	0744401301	E	74.1	2650	0744390201	E	18.3	2653	0744400401	E	82.6	2654	0743220201	F	20.3
2657	0741160101	E	43.0	2657	0744390101	F	19.6	2662	0744930301	E	24.8	2665	0742430201	F	14.7
2668	0742830101	F	118.9	2672	0747390101	F	110.5	2675	0742430101	F	15.1	2676	0747400101	F	120.0
2677	0747430101	F	110.4	2678	0743220101	F	16.9	2678	0740900101	E	19.7	2679	0741930101	E	105.9
2680	0743220301	F	16.9	2684	0747440101	F	109.8	2685	0741440101	F	46.0	2687	0743650801	F	23.2
2687	0743650701	F	23.5	2688	0744930201	E	29.4	2690	0743420801	F	16.4	2690	0741300101	E	34.7
2698	0744870201	E	59.3	2700	0741890901	E	16.1	2700	0741891001	E	15.5	2701	0741890201	E	24.5
2701	0741891101	E	16.5	2701	0741890801	E	17.0	2702	0741891901	E	17.2	2702	0741891801	E	13.6
2702	0741891401	E	15.8	2702	0741891201	E	14.8	2704	0741891701	E	17.5	2704	0741890501	E	19.0
2704	0741891301	E	18.9	2705	0741300301	E	69.5	2705	0741891601	E	10.7	2706	0741890601	E	20.5
2707	0741890301	E	22.4	2707	0741890401	E	20.6	2710	0743940201	F	67.8	2713	0744413701	E	33.4
2720	0743020201	E	51.4	2723	0744412301	E	29.2	2724	0744412501	E	24.7	2727	0743940101	F	75.7
2730	0744414101	E	14.7	2734	0744411301	E	22.5	2735	0742700401	F	18.2	2737	0745120101	E	76.7
2743	0744460101	E	38.7	2746	0744413101	E	13.5	2748	0744411901	E	25.9	2749	0741980101	E	34.1
2752	0743850101	E	85.3	2757	0744412701	E	22.7	2759	0744413001	E	14.7	2760	0741160201	E	37.1
2761	0744412001	E	12.2	2761	0741160301	E	34.9	2762	0748190101	F	43.9	2764	0744411701	E	18.5
2767	0744930401	E	52.0	2770	0747410101	F	48.9	2772	0747420101	F	56.4	2774	0744411201	E	20.6
2776	0747190801	F	79.5	2777	0742430301	F	51.9	2778	0744400201	E	48.1	2778	0744410901	E	16.8
2781	0741300201	E	82.7	2785	0744400301	E	72.2	2785	0744411101	E	12.6	2788	0744411401	E	15.1
2795	0740640101	E	10.2	2797	0764800101	F	29.5	2800	0741450101	F	44.5	2801	0764800301	F	28.5
2802	0764800401	F	18.2	2804	0743630801	F	21.5	2805	0743930101	E	29.7	2806	0764800201	F	25.1
2807	0744412401	E	21.7	2807	0764800501	F	48.8	2808	0764800601	F	48.2	2812	0742510701	F	15.0
2813	0764800801	F	27.8	2815	0761020301	F	18.5	2816	0764800901	F	40.7	2817	0770180101	F	35.3
2820	0762800101	E	11.7	2821	0762920201	F	14.4	2823	0762950301	F	17.2	2827	0742250601	F	78.7
2829	0761950101	F	23.5	2829	0763670201	E	31.5	2831	0770180201	F	50.2	2833	0762470101	F	72.0
2833	0770580501	F	20.9	2834	0744411501	E	22.1	2835	0760940101	E	76.3	2836	0744413301	E	22.1
2837	0744411801	E	22.2	2839	0761590401	F	17.8	2839	0744413201	E	19.1	2839	0760740401	F	21.3
2842	0744412101	E	18.9	2842	0764800701	F	49.8	2843	0764640101	E	41.6	2843	0770180401	F	45.2
2844	0761590701	F	18.7	2846	0760740301	F	11.2	2846	0741300501	E	20.1	2847	0741300601	E	59.2
2848	0762801101	E	17.1	2849	0762870601	E	21.0	2849	0761730401	F	18.7	2849	0760740201	F	15.1
2850	0762920701	F	16.0	2850	0770180301	F	49.7	2852	0760340201	E	75.1	2855	0762070101	E	101.8
2857	0760540101	F	81.5	2858	0762290401	F	14.4	2859	0761940301	F	24.0	2859	0762520201	F	80.4
2861	0762220101	F	87.6	2862	0762290501	F	30.2	2863	0744411001	E	38.0	2864	0761100101	F	113.5
2865	0762950101	F	17.8	2865	0770180501	F	46.3	2866	0761100201	F	109.7	2867	0761100301	F	119.2
2869	0761100401	F	108.3	2871	0762290201	F	20.7	2873	0761590301	F	19.5	2873	0761112101	F	15.0
2874	0762920501	F	21.3	2874	0729160601	F	11.4	2876	0770180701	F	37.2	2879	0744411601	E	24.4
2880	0761101001	F	110.3	2881	0770180601	F	44.9	2882	0765040801	F	12.1	2882	0770180801	F	62.2
2883	0763180301	F	27.4	2884	0763180201	F	25.2	2884	0764430101	F	26.6	2884	0762801001	E	21.3

Table A.4. continued.

Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.	Rev.	OBSID	M	Exp.
2885	0762750201	E	67.9	2887	0760080101	E	20.3	2891	0770190301	F	24.2	2892	0764400301	F	10.5
2893	0770190201	F	19.6	2895	0760080201	E	15.1	2895	0765000601	F	13.2	2900	0760080301	E	14.3
2901	0770190501	F	29.4	2901	0761210101	F	57.5	2902	0763670301	E	21.3	2904	0770190701	F	40.9
2904	0761730501	F	46.4	2905	0770190801	F	31.4	2906	0762260101	F	16.0	2909	0722370201	F	38.8
2912	0760870101	F	83.0	2915	0762520301	F	35.1	2917	0764400601	F	23.0	2920	0761550201	E	59.7
2922	0762630201	F	16.4	2924	0762871101	E	20.6	2930	0762260301	F	23.2	2932	0765020701	F	17.7
2934	0744413401	E	20.3	2940	0762870401	E	24.7	2942	0762950201	F	12.9	2943	0761020201	F	22.0
2943	0762440101	F	14.4	2948	0762520101	F	23.9	2951	0762870901	E	48.1	2953	0762290101	F	35.0
2956	0765030701	F	16.0	2957	0762440201	F	21.9	2959	0763160201	F	36.8	2959	0763230201	E	16.9
2959	0762870301	E	19.2	2961	0762870501	E	14.1	2961	0762870201	E	16.3	2962	0763230101	F	20.9
2964	0763300301	F	13.7	2965	0790180301	F	22.4	2966	0761070101	E	67.8	2966	0763300201	F	11.2
2967	0765041301	F	14.1	2967	0761070201	E	75.7	2972	0762920601	F	19.5	2980	0761950201	F	32.8
2981	0761940401	F	15.9	2982	0765040101	F	11.3	2984	0764430201	F	21.9	2986	0760970101	E	56.8
2989	0762440301	F	19.9	2992	0762920401	F	12.9	2992	0762440501	F	17.6	2992	0762440401	F	17.1
2992	0780790201	F	17.2	2996	0783881001	E	52.5	2999	0784390301	F	25.2	3002	0780790501	F	21.1
3002	0784690601	F	26.9	3003	0783880501	E	26.9	3004	0783520201	F	17.6	3004	0790630101	F	32.9
3007	0784090201	F	22.3	3011	0783670101	F	21.9	3013	0783881201	E	14.0	3014	0784610301	F	25.0
3020	0782330101	F	30.1	3022	0780790101	F	14.9	3022	0780790401	F	16.6	3023	0783880201	E	48.2
3025	0783880101	E	59.8	3026	0783530301	E	26.2	3026	0783880901	E	42.9	3027	0782330301	F	92.2
3029	0783880601	E	79.5	3030	0781200101	E	21.3	3032	0783881301	E	16.7	3032	0790180701	F	51.0
3033	0785100101	F	17.1	3033	0785100201	F	17.8	3034	0785100601	F	21.9	3034	0785100401	F	16.6
3034	0785100701	F	16.2	3034	0785100301	F	17.8	3034	0785100501	F	15.9	3035	0785100901	F	16.8
3035	0785101001	F	17.1	3035	0785101101	F	15.9	3035	0785101201	F	18.2	3035	0785100801	F	17.5
3036	0785101401	F	16.6	3036	0785101501	F	16.0	3036	0785101301	F	13.4	3036	0785101601	F	16.6
3041	0762550401	F	55.6	3042	0782360201	F	30.5	3047	0785101801	F	16.7	3047	0785101901	F	16.6
3047	0785102001	F	16.5	3047	0785102101	F	19.6	3054	0785102501	F	16.7	3054	0780450101	F	19.3
3054	0785102201	F	13.9	3054	0785102301	F	16.7	3054	0785102401	F	16.7	3055	0780450801	F	19.8
3059	0784390401	F	41.0	3059	0783880701	E	52.3	3060	0784980101	E	75.3	3061	0783520301	F	52.1
3062	0781040101	F	72.3	3068	0783880301	E	47.2	3080	0783160101	F	72.3	3085	0792790101	E	44.3
3086	0784690701	F	24.3	3088	0784790101	F	17.0	3092	0784090301	F	19.4	3094	0792780201	F	16.1
3099	0783110401	F	27.7	3100	0783881401	E	31.2	3100	0783450101	F	10.5	3108	0784690201	F	25.9
3119	0784370101	F	17.1	3125	0793581201	F	19.1	3125	0783881901	E	27.5	3126	0793580101	F	16.9
3128	0780450501	F	11.6	3128	0780451101	F	10.7	3129	0780451601	F	23.3	3130	0780451201	F	20.3
3130	0780451701	F	14.0	3130	0780452001	F	17.8	3130	0780451801	F	11.5	3130	0780451901	F	13.8
3131	0783520501	F	66.3	3131	0780452101	F	14.8	3131	0793581401	F	14.6	3132	0792780101	F	20.7
3132	0783880401	E	34.2	3135	0781200401	E	15.6	3136	0782150101	F	52.3	3140	0783881701	E	20.0
3142	0784330201	F	68.3	3145	0780452401	F	11.3	3149	0784370201	F	19.9	3156	0784521101	F	17.7
3159	0790660101	F	26.9	3160	0781210301	F	52.0	3163	0784521201	F	31.7	3163	0784521301	F	23.1
3164	0782400101	F	105.1	3165	0784521501	F	10.4	3170	0784610201	F	20.4	3171	0782670201	E	52.7
3172	0783110501	F	17.4	3174	0803050801	F	40.5	3175	0803050501	E	81.9	3178	0800400601	F	23.4
3180	0781590201	E	14.4	3181	0781590301	E	12.4	3181	0784350101	F	21.6	3182	0803050201	F	10.3
3182	0781590401	E	13.3	3183	0781590501	E	13.5	3186	0801790401	F	10.9	3187	0802750301	F	15.5
3188	0803050101	E	98.3	3190	0804270101	F	16.5	3194	0801310101	F	88.3	3195	0804270401	F	14.3
3196	0803050301	F	97.9	3200	0804270901	F	16.4	3205	0804271301	F	16.5	3207	0795710101	F	33.2
3209	0801790601	F	19.3	3209	0803670601	E	48.2	3219	0803670501	E	101.4	3300	0803671001	E	41.4
3305	0803671101	E	34.8												

Table A.5. List of calibration datasets used, showing revolution, observation identifier, exposure identifier, mode and clean exposure (ks).

Rev.	OBSID	Exp. ID	Mode	Exp.	Rev.	OBSID	Exp. ID	Mode	Exp.
0042	0119100201	030	FF	17.6	0055	0122310201	003	FF	31.2
0055	0122310301	003	FF	49.4	0080	0124700101	003	FF	61.3
0124	0128720901	001	FF	30.0	0125	0110010101	002	FF	15.3
0125	0110010101	015	FF	55.0	0131	0129121101	011	FF	16.6
0150	0105262301	003	FF	23.8	0249	0108860301	010	FF	19.4
0309	0060740801	002	FF	21.3	0332	0068940101	003	FF	34.2
0402	0153950201	009	FF	19.9	0407	0154150201	006	FF	19.4
0429	0134521501	002	FF	24.7	0440	0153950801	002	FF	16.6
0508	0001730501	002	FF	17.7	0532	0136540601	008	FF	18.9
0533	0156960501	003	FF	19.0	0534	0156960301	003	FF	15.7
0572	0134522201	005	FF	35.8	0605	0134522301	005	FF	42.2
0649	0151370501	003	FF	14.8	0709	0160362701	005	FF	34.3
0722	0147131101	010	FF	20.0	0735	0162160601	014	FF	16.4
0759	0134921001	026	FF	28.7	0766	0134540701	005	FF	41.2
0857	0134540801	005	FF	44.4	0942	0134540901	005	EFF	44.2
0981	0160363001	005	FF	44.4	1051	0134921101	026	EFF	30.2
1227	0410780201	003	FF	27.5	1319	0134722101	005	EFF	49.4
1354	0510390101	016	FF	48.3	1408	0410780401	003	FF	39.2
1413	0510780101	001	EFF	37.2	1455	0411081901	003	FF	14.8
1477	0511180301	003	FF	21.7	1478	0412580301	003	FF	40.7
1490	0500630101	002	FF	42.8	1497	0414380301	003	FF	15.2
1568	0552810501	003	FF	17.9	1587	0410780601	003	FF	33.6
1607	0510780201	001	EFF	42.5	1662	0412580401	013	FF	31.6
1796	0510780401	001	EFF	45.9	1809	0412990601	001	FF	34.6
1816	0510390301	016	EFF	36.3	1820	0411083201	601	FF	35.9
1848	0412580601	013	FF	31.4	1895	0656580101	001	FF	29.2
1904	0656380101	601	FF	23.4	1952	0410780701	003	FF	25.7
1961	0510780501	001	EFF	45.4	1979	0412601201	009	FF	27.9
2001	0656380801	601	FF	22.3	2002	0656381301	601	FF	18.8
2027	0412580701	003	FF	32.0	2049	0677380101	003	FF	20.7
2094	0658800101	601	FF	11.6	2095	0658800301	003	FF	24.1
2096	0658800501	003	FF	13.2	2143	0410780901	003	FF	30.7
2163	0510780601	601	EFF	42.6	2173	0670880601	002	FF	20.3
2196	0677380201	003	FF	118.7	2209	0412580801	003	FF	31.3
2266	0411780801	001	FF	79.2	2266	0411780831	001	FF	15.6
2266	0411780832	001	FF	18.3	2266	0411780833	001	FF	18.3
2266	0411780834	001	FF	25.9	2319	0410781001	003	FF	26.2
2359	0411781301	001	FF	73.0	2383	0701381101	003	EFF	40.9
2398	0701381201	003	EFF	44.2	2452	0411781701	002	FF	64.0
2499	0727571001	003	FF	30.1	2508	0412602501	003	FF	27.7
2514	0510781201	016	EFF	45.2	2624	0744414001	003	FF	26.4
2631	0727770501	001	FF	77.5	2632	0727771001	001	FF	33.1
2632	0727771101	001	FF	33.1	2674	0744450401	016	FF	45.6
2687	0727571301	003	FF	30.0	2688	0744930501	003	FF	19.2
2696	0510781301	016	EFF	38.4	2726	0727771301	001	FF	80.6
2838	0658801401	003	FF	23.1	2839	0658801501	003	FF	21.3
2840	0658801601	003	FF	21.7	2841	0658801701	003	FF	19.6
2874	0727571501	003	FF	29.0	2892	0727760701	003	FF	51.0
2916	0658801901	003	FF	25.7	2924	0658802001	003	FF	23.2
2930	0658802101	003	FF	19.5	2933	0658802201	003	FF	19.5
3007	0658802401	003	FF	19.3	3009	0658802501	003	FF	19.3
3012	0658802601	003	FF	15.0	3013	0658802701	003	FF	14.9
3058	0727571701	003	FF	29.1	3163	0784520101	002	FF	25.1
3241	0795781001	003	FF	27.9	3287	0791781401	600	FF	46.0