Planck early results. IX. XMM-Newton follow-up for validation of Planck cluster candidates

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Planck early results. IX. XMM-Newton follow-up for validation of Planck cluster candidates

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ABSTRACT

We present the XMM-Newton follow-up for confirmation of Planck cluster candidates. Twenty-five candidates have been observed to date using snapshot (~10ks) exposures, ten as part of a pilot programme to sample a low range of signal-to-noise ratios (4 < S/N < 6), and a further 15 in a programme to observe a sample of S/N > 5 candidates. The sensitivity and spatial resolution of XMM-Newton allows unambiguous discrimination between clusters and false candidates. The 4 false candidates have S/N ≤ 4.1. A total of 21 candidates are confirmed as extended X-ray sources. Seventeen are single clusters, the majority of which are found to have highly irregular and disturbed morphologies (about ~70%). The remaining four sources are multiple systems, including the unexpected discovery of a supercluster at z = 0.45. For 20 sources we are able to derive a redshift estimate from the X-ray Fe K line (albeit of variable quality). The new clusters span the redshift range 0.09 ≤ z ≤ 0.54, with a median redshift of z ~ 0.37. A first determination is made of their X-ray properties including the characteristic size, which is used to improve the estimate of the SZ Compton parameter, YSZ. The follow-up validation programme has helped to optimise the Planck candidate selection process. It has also provided a preview of the X-ray properties of these newly-discovered clusters, allowing comparison with their SZ properties, and to the X-ray and SZ properties of known clusters observed in the Planck survey. Our results suggest that Planck may have started to reveal a non-negligible population of massive dynamically perturbed objects that is under-represented in X-ray surveys. However, despite their particular properties, these new clusters appear to follow the YSZ-YX relation established for X-ray selected objects, where YX is the product of the gas mass and temperature.

Key words: cosmology: observations – galaxies: clusters: general – galaxies: clusters: intracluster medium – cosmic background radiation – X-rays: galaxies: clusters

1. Introduction

The Planck satellite has been surveying the sky across nine frequencies in the microwave band since August 2009. The resulting data set allows the detection of galaxy clusters through the Sunyaev-Zeldovich (SZ) effect (Sunyaev & Zeldovich 1972), the spectral distortion of the cosmic microwave background (CMB) generated via inverse Compton scattering of CMB photons by the hot electrons in the intra-cluster medium (ICM). The total SZ signal is expected to be closely related to the cluster telescope reflectors provided in a collaboration between ESA and a scientific consortium led and funded by Denmark.
mass (e.g., da Silva et al. 2004) and its brightness is insensitive to redshift dimming. As a result, SZ surveys can potentially provide unbiased cluster samples, covering a wide range of redshifts, that are expected to be close to mass-selected. As compared to other SZ instruments, Planck brings a unique nine-band coverage from 30 to 857 GHz and a relatively high, band-dependent spatial resolution of 5–10 arcmin. Most crucially, the Planck SZ survey covers an exceptionally large volume, being the first all-sky survey capable of blindly detecting clusters since the ROSAT All-Sky Survey (RASS) in the X-ray domain. As a consequence, Planck is detecting previously unknown, massive clusters that do not appear in other SZ surveys. Its all-sky coverage allows detection of the rarest clusters, the most massive objects lying in the exponential tail of the mass function. These are the best clusters for precision cosmology: their abundance evolution is the most sensitive to the cosmological parameters (Voit 2005), and their gas mass fractions can be used as distance indicators (Allen et al. 2008). In addition, clusters in this high-mass regime are X-ray bright, making their observation easier, and their ICM is expected to be the least affected by non-gravitational processes. These newly-discovered Planck clusters will thus also be ideal targets for studying the physics of the gravitational collapse that drives all cluster formation.

The Planck survey is providing a sample of cluster candidates. Any such survey sample is expected to include a fraction of false detections, due for example to fluctuations in the complex microwave astrophysical sky. In addition, as a result of Planck’s moderate spatial resolution at SZ frequencies with respect to typical cluster sizes, a Planck cluster candidate SZ measurement essentially provides only coordinates and total SZ flux estimates; these estimates are further hampered by the flux-size degeneracy discussed extensively in Planck Collaboration (2011d). A vigorous follow-up programme is therefore required to scientifically exploit Planck cluster candidate data. Such a programme includes candidate confirmation, which is the final part of the catalogue validation, in addition to redshift measurements, estimation of relevant physical parameters (including cluster size, allowing precise SZ flux estimates), and investigation of scaling properties. In particular, measurement of the relation between the SZ “luminosity” and the mass as a function of redshift, \( z \), is essential for calculation of the survey selection function and for related cosmological applications.

The all-sky nature of the Planck survey means that confirmation and redshift measurement of cluster candidates is not a trivial task. In the optical domain, the only publicly available large survey is the Sloan Digital Sky Survey (SDSS). Although cross-correlation with this survey can be used to confirm candidates up to \( z \sim 0.6 \), it covers only part of the northern sky. Furthermore, optical confirmation is hampered by the relatively large Planck source position uncertainty, which can be up to 5′ (Planck Collaboration 2011d). To discriminate between a true counterpart and a chance association with low-mass systems at various redshifts within the Planck error box, optical mass and spectroscopic redshift or photometric redshift estimates with a wide-field, multi-band, instrument are required.

In contrast, confirmation in X-rays offers definite advantages. Above the Galactic Plane, the detection of extended X-ray emission is an unambiguous signature of a cluster, and the density-squared dependence of the X-ray emission reduces projection effects nearly to zero. Furthermore, the low space density of groups and clusters in a typical X-ray exposure makes spurious association with a Planck candidate unlikely. For instance, the XMM-LSS survey found 29 systems in 5 deg\(^2\) using 10 ks XMM-Newton exposures (Pacaud et al. 2007). Such a detection rate corresponds to only a 10 per cent probability of finding a cluster by chance within a 5′ aperture, the conservative Planck error box. Finally, as both X-ray and SZ observations probe the same medium, spurious associations can be readily assessed from a consistency check between the X-ray and SZ flux, assuming a reasonable redshift range (as illustrated in Sect. 3.2).

In this context, and because of its superior sensitivity, XMM-Newton (Jansen et al. 2001) is the best instrument for following up newly-detected Planck clusters up to high redshift. A short snapshot XMM-Newton exposure is sufficient to confirm any Planck cluster candidate at least up to \( z \sim 1.5 \) (Sect. 2.4), and for the X-ray brightest objects, provides the source redshift from the iron K line (Sect. 4.1). Because of their high mass, clusters are expected to be larger than 1″ and the XMM-Newton spatial resolution is sufficient to discriminate between a point source and extended emission.

In order to assess the galaxy cluster nature of the Planck SZ sources and to help guarantee the integrity of the final Planck SZ legacy catalogue to be released in 2012, we have thus proposed to use XMM-Newton to confirm the highest significance cluster candidates discovered by Planck. This validation programme consists of snapshot (~10 ks) observations and is undertaken via an agreement between the ESA XMM-Newton and Planck project scientists. In this paper we present the definition and results of this programme. To date, 25 Planck SZ sources have been observed, making use of XMM-Newton Director’s Discretionary Time. Of these, 21 sources have been confirmed. In compliance with Planck policies for follow-up, the XMM-Newton data of the 25 Planck sources are made public along with the publication of the Early Release Compact Source Catalogue (ERCSC).

The XMM-Newton follow-up for validation is the backbone of a larger programme for the confirmation and redshift measurement of Planck SZ cluster candidates. The Planck collaboration has also been granted time on the following facilities: the ENO, the ESO/MPG 2.2 m and the Palomar telescopes. Observations with these facilities are ongoing or being processed. Some optical results from the ENO observations are presented together with the XMM-Newton results in this paper (Sects. 4.2 and A.1). Other early astrophysics results on clusters of galaxies are presented in Planck Collaboration (2011d,f,g,h).

We adopt a ΛCDM cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \). The factor \( E(z) = \sqrt{\Omega_M (1 + z)^3 + \Omega_{\Lambda}} \) is the ratio of the Hubble constant at redshift \( z \) to its present day value. The quantities \( M_{500} \) and \( R_{500} \) are the total mass and radius corresponding to a total density contrast \( \delta = 500 \), as compared to \( \rho_c(z) \), the critical density of the Universe at the cluster redshift; thus \( M_{500} = (4\pi/3) 500 \rho_c(z) R_{500}^3 \). The quantity \( Y_X \) is defined as the product of \( M_{500} \) and the gas mass within \( R_{500} \) and \( T_X \), the spectroscopic temperature measured in the [0.15–0.75] \( R_{500} \) aperture. The SZ signal is characterised by \( Y_{500} \) throughout. This quantity is defined as \( Y_{500} D_A^2 = (\sigma_T/m_e c^2) \int PdV \). Here \( D_A \) is the angular-diameter distance to the system, \( \sigma_T \) is the Thomson cross-section, \( c \) is the speed of light, \( m_e \) is the electron rest mass; \( P = n_e T \) is the pressure, the product of the electron number density and temperature, and the integration is performed over a sphere of radius \( R_{500} \). The quantity \( Y_{500} D_A^2 \) is the spherically integrated Compton parameter and \( Y_{500} \) is proportional to the apparent magnitude of the SZ signal from within \( R_{500} \).

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2 http://www.sdss.org/
2. The XMM-Newton validation follow-up of Planck cluster candidates

2.1. The Planck survey

Planck (Tauber et al. 2010; Planck Collaboration 2011a) is the third generation space mission to measure the anisotropy of the CMB. It observes the sky in nine frequency bands covering 30–857 GHz with high sensitivity and angular resolution from 31’ to 5’. The Low Frequency Instrument (LFI; Mandoesi et al. 2010; Bersanelli et al. 2010; Mennella et al. 2011) covers the 30, 44, and 70 GHz bands with amplifiers cooled to 20 K. The High Frequency Instrument (HFI; Lamarre et al. 2010; Planck HFI Core Team 2011a) covers the 100, 143, 217, 353, 545, and 857 GHz bands with bolometers cooled to 0.1 K. Polarisation is measured in all but the highest two bands (Leahy et al. 2010; Rosset et al. 2010). A combination of radiative cooling and three mechanical coolers produces the temperatures needed for the detectors and optics (Planck Collaboration 2011b). Two data processing centres (DPCs) check and calibrate the data and make maps of the sky (Planck HFI Core Team 2011b; Zacchei et al. 2011). Planck’s sensitivity, angular resolution, and frequency coverage make it a powerful instrument for Galactic and extra-galactic astrophysics as well as cosmology. Early astrophysics results are given in Planck Collaboration (2011b–z).

2.2. Blind detection of SZ clusters in Planck

The blind search for clusters in Planck data relies on a multi-matched filter (MMF) approach (Melin et al. 2006)\(^3\). This detection algorithm operates on all-sky maps divided into a set of overlapping square patches, using simultaneously the 6 frequency maps of the HFI instrument (Planck Collaboration 2011d). Within the algorithm, the SZ spectral signature and the universal pressure profile derived by Arnaud et al. (2010) are used as spectral and spatial templates, respectively. In such a blind search, the position, the characteristic scale of the profile ($\sim R_{500}$) and the amplitude ($\sim Y_{500}$) are left free, being optimised by the MMF algorithm. In practice the algorithm is run in an iterative way: after a first detection run to locate candidates, consecutive runs on sky patches centred on the candidate positions refine the estimated signal-to-noise ratio (S/N) and other properties.

Cluster candidates then undergo a validation process, extensively described in Planck Collaboration (2011d). This process includes internal quality checks (e.g., map artefacts, cross-comparison between detection algorithms, SZ spectral signature, astrophysical contamination by Galactic dust, point sources or structures in the CMB) and cross-correlation with ancillary data and catalogues allowing known clusters to be identified. This process produces a list of new Planck SZ cluster candidates above a given S/N threshold (S/N = 4 in this work).

2.3. XMM-Newton target selection

From the list of new potential clusters detected as SZ sources in the Planck survey, we selected 25 targets in a two step process:

1. Pilot programme: 10 targets were selected on the basis of the Planck survey as it stood at the end of October 2009, i.e., ~62% sky coverage. These targets were explicitly chosen to sample the lower range of signal-to-noise ($4 < S/N < 6$) in order to better characterise the nature and quality of the SZ signal.

2. High S/N programme: a further 15 targets were chosen in the spring of 2010 when the first full-sky coverage was close to completion (99.5% sky coverage). In contrast to the pilot programme, here we focused on high-significance SZ sources (S/N > 5) and selected candidates starting from the highest S/N.

In both cases the selection process was intimately linked to the Planck-HFI data time ordered information processing status, calibration, attitude and map versions (as of Dec. 7, 2009 and April 19, 2010 for the two programmes, respectively). The choice of targets was also constrained by their XMM-Newton visibility in a period of 2–3 months following their submission to the science operations centre. For both programmes, maps and spectra of each potential target were visually inspected, including re-processing with aperture photometry methods. Cross-correlation with the RASS Bright Source Catalogue (RASS-BSC, Voges et al. 1999) and Faint Source Catalogue (RASS-FSC, Voges et al. 2000) was undertaken. For the two targets of the pilot programme falling in the SDSS area, we ran a dedicated algorithm to search for galaxy overdensities (Fromenteau et al., in prep.), allowing us to track significant concentrations of matter down to $\sim 0.6$. These two targets were chosen to test the SDSS based confirmation at high S/N. The first candidate, PLCK G070.8–21.5, was not confirmed (see Fromenteau et al., in prep., for discussion); the other candidate, PLCK G214.6+37.0, is discussed in Sect. 7.2.1. Detailed searches in XMM-Newton, Chandra and Suzaku observatory logs were also undertaken in order to avoid duplication of performed or accepted observations with similar facilities.

Six of the ten pilot programme targets were confirmed (see Table 1); two of these are multiple systems. Taking into account the result of the pilot project, for the second programme we set a lower S/N threshold of $S/N = 5$ and refined and strengthened the selection criteria. In particular, we required that the source be independently detected by at least two of the three blind detection methods, and more quality flags were considered. The internal checks were very similar to those defined for constructing the early SZ (ESZ) sample (Planck Collaboration 2011d), which benefit from the result of the XMM-Newton Pilot programme. We also performed a search for emission in the RASS hard band images, looking for X-ray signatures beyond those recorded in the RASS source catalogues. However, RASS information never took precedence over the internal Planck quality flags. Note that two of the false candidates of the Pilot programme (PLCK G343.4–43.4 and PLCK G226.1–16.9) were associated with a RASS-FSC source that XMM-Newton subsequently revealed to be several point sources (see Sect. 3.2). Thus association with an RASS source alone is not sufficient for cluster candidate confirmation.

The ESZ sample (Planck Collaboration 2011d) consists of a high signal-to-noise, i.e., primarily $S/N \geq 6$, list of 189 clusters and cluster candidates based on data from the first 10 months of the Planck survey. Ten of the 21 objects presented in the present paper passed the S/N ESZ selection criteria and are thus part of the ESZ sample released to the community in January 2011. The original S/N of their detection in the Planck maps is given in Table 1, whereas the S/N values provided in Table 2 are derived from the 10 month Planck maps on the basis of which the ESZ sample was constructed.

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\(^3\) Results from other methods have been cross-compared to those from the MMF search, including from the PowellSnakes-based algorithm (Carvalho et al. 2009).
Table 1. Observation log of the XMM-Newton validation follow-up.

| Name              | S/N | RA_{SZ} (deg) | Dec_{SZ} (deg) | OBSID          | Filter | $t_{exp}$ (ks EPN) | Clean fraction (MOS/EPN) | Confirmed |
|-------------------|-----|---------------|---------------|---------------|--------|-------------------|--------------------------|-----------|
| PLCK G277.8–51.7 | 6.1 | 43.596        | –58.964       | 0656200301    | THIN   | 16.5              | 0.5/0.2                  | Y ESZ     |
| PLCK G334.8–38.0* | 4.9 | 313.177       | –61.202       | 0656200701    | THIN   | 21.2              | 0.8/0.5                  | Y         |
| PLCK G250.0+24.1 | 4.9 | 143.042       | –17.647       | 0656200401    | THIN   | 10.4              | 0/0                      | Y         |
| PLCK G286.3–38.4 | 4.7 | 59.800        | –72.067       | 0656200501    | THIN   | 13.6              | 0.7/0                    | Y         |
| PLCK G004.5–19.5 | 4.6 | 289.226       | –33.509       | 0656201001    | MED    | 10.0              | 1/0                      | Y         |
| PLCK G214.6+36.9* | 4.2 | 137.206       | 14.642        | 0656200101    | THIN   | 17.6              | 0.7/0                    | Y         |
| PLCK G070.8–21.5 | 4.1 | 321.410       | 19.941        | 0656200201    | MED    | 25.4              | 0.4/0/...                | Y         |
| PLCK G317.4–54.1 | 4.1 | 355.247       | –61.038       | 0656200801    | THIN   | 12.0              | 0.9/0/...                | Y         |
| PLCK G226.1–16.9 | 4.0 | 93.139        | –19.040       | 0656200601    | MED    | 10.0              | 0.7/0/...                | Y         |
| PLCK G343.4–43.4 | 3.9 | 320.145       | –53.631       | 0656200901    | MED    | 10.0              | 0.9/0/...                | Y         |
| PLCK G287.0+32.9 | 10.2| 177.714       | –28.074       | 0656201201    | THIN   | 10.0              | 0.7/0.4                  | Y ESZ     |
| PLCK G171.9–40.7 | 10.7| 48.231        | 8.380         | 0656201101    | THIN   | 10.0              | 1/0.8                    | Y         |
| PLCK G285.0–23.7 | 8.3 | 110.805       | –73.457       | 0656201401    | THIN   | 10.0              | 0.9/0.6                  | Y ESZ     |
| PLCK G271.2–31.0 | 8.3 | 87.315        | –62.087       | 0656201301    | THIN   | 10.0              | 1/1                      | Y ESZ     |
| PLCK G262.7–40.9 | 7.4 | 69.624        | –54.309       | 0656201601    | MED    | 14.7              | 1.0/9                    | Y ESZ     |
| PLCK G308.3–20.2* | 7.4 | 229.588       | –81.523       | 0656201501    | MED    | 10.0              | 1/1                      | Y ESZ     |
| PLCK G337.1–26.0* | 6.4 | 288.583       | –59.513       | 0656201701    | MED    | 13.7              | 1/1/1                    | Y ESZ     |
| PLCK G292.5+22.0 | 6.2 | 180.241       | 39.889        | 0656201801    | MED    | 13.2              | 0.6/0.5                  | Y ESZ     |
| PLCK G205.0–63.0 | 6.1 | 41.593        | –20.527       | 0656201901    | THIN   | 11.7              | 1/1                      | Y         |
| PLCK G241.2–28.7 | 5.9 | 85.768        | –36.022       | 0656202001    | THIN   | 10.0              | 1/1                      | Y         |
| PLCK G286.6–31.3 | 5.9 | 82.8430       | –75.164       | 0656202101    | THIN   | 10.0              | 0.7/0.3                  | Y ESZ     |
| PLCK G018.7+23.6 | 5.6 | 255.553       | –1.004        | 0656202201    | THIN   | 7.2               | 1/1                      | Y         |
| PLCK G100.2–30.4 | 5.5 | 350.589       | 28.563        | 0656202301    | THIN   | 10.0              | 0.9/0.7                  | Y         |
| PLCK G272.9+48.8 | 5.1 | 173.310       | –9.479        | 0656202601    | THIN   | 11.7              | 0/0                      | Y         |
| PLCK G285.6–17.2 | 5.2 | 130.956       | –71.190       | 0656202501    | THIN   | 10.0              | 1/1                      | Y ESZ     |

Notes. The 10 targets of the pilot programme are listed first. Column (1): Planck source name. Asterisked objects denote sources that were found to be multiple systems in X-rays. Column (2): signal-to-noise ratio of the detection of the Planck cluster candidate in the version of the Planck-HFI maps available for each programme. Columns (3) and (4): right ascension and declination of the Planck observation identification number, filter used, on-source exposure time with the XMM-Newton cluster detection is the soft energy band (energy below 2 keV), for which the signal-to-noise ratio reaches a maximum. We calculated expectations for XMM-Newton sensitivity in that band for two representative values of the SZ flux from within $R_{500}$: $Y_{500} = 5 \times 10^{-4}$ arcmin$^{-2}$ and $Y_{500} = 2 \times 10^{-3}$ arcmin$^{-2}$. In each case, the expected cluster luminosity $L_{500}$ for various redshifts was estimated using the $L_{500} - D_{\text{SZ}}/Y_{500}$ relation of Arnaud et al. (2010), assuming self-similar evolution. We then derived the corresponding total XMM-Newton count rates, $R$, in the [0.3–2] keV band for the EPIC MOS–CCD (hereafter eMOS) and pn–CCD (hereafter ePIV) camera (Turner et al. 2001; Strüder et al. 2001). We used the xspec software (Arnaud 1996) to simulate an absorbed thermal model (assuming $kT = 7$ keV, $N_{\text{H}} = 2 \times 10^{20}$ cm$^{-2}$), convolved with the instrument response. The corresponding angular extent $R_{\text{500}}$ estimated from the $L_{500} - M_{500}$ relation of Pratt et al. (2009). The signal-to-noise ratio of the detection is then given by $S/N = \sqrt{T_{\text{exp}}} / (\sqrt{R_{\text{500}} A (2 R_{\text{bg}} A))}$, where $T_{\text{exp}}$ is the exposure time, $R_{\text{bg}}$ is the background count rate, and $A = 4 \pi R_{\text{500}}^2$ is the integration area in square arc minutes. We assumed a $[0.3–2]$ keV band background count rate of $R_{\text{bg}} = 4.5 \times 10^{-3}$ counts s$^{-1}$ arcmin$^{-2}$, as estimated from the blank sky backgrounds of Read & Ponman (2003). Figure 1 shows the resulting S/N of an XMM-Newton detection as a function of redshift.

Since the goal of the XMM-Newton observations is confirmation of new Planck SZ cluster candidates, the nominal observing time was set to 10 ks (net EPIC camera time) per target. Such a snapshot observation is sufficient to detect the cluster – if real – at better than $10\sigma$ up to $z = 1.5$ (Fig. 1). The nominal setup used the THIN filters (unless optical loading had to be avoided) and EFF mode for the EPIC camera. The boresight was optimised to avoid camera gaps.

2.5. XMM-Newton data reduction

We produced calibrated event lists using v10.0 of the XMM-Newton science analysis system (SAS). Observations were cleaned for periods of high background due to soft proton flares, pattern-selected and corrected for vignetting as described in Pratt et al. (2007). Point sources were identified from the small scales of wavelet-decomposed images in the [0.3–2] and [2–5] keV bands. These sources were excluded in the analysis of confirmed clusters, with the exclusion radius matched to the point spread function (PSF) size (which varies across the detector).

Above $\sim 2$ keV the XMM-Newton background is dominated by particle events. We subtracted this background using a
stacked event list built from observations obtained with the filter wheel in the closed position, recast to the pointing position and renormalised using the count rate in the high energy band free of cluster emission. The remaining background (due to the cosmic X-ray background of unresolved AGN and Galactic emission) was estimated from the particle-background subtracted emission from an annulus beyond the cluster emission. For the spectral analysis, we modeled this background emission as arising from two thermal sources and a power-law source with index $\Gamma = 1.4$, taking into account the absorbing Galactic column density in the direction of the object (see, e.g., De Luca & Molendi 2004).

As Table 1 shows, the observations are of variable quality. In three cases the $\epsilon_{\nu}$ data were completely contaminated by soft proton flares and formally had no useful observing time. For two of these observations, the $\epsilon_{\nu}$ data were completely contaminated too. In these instances, we used $\epsilon_{\nu}$ data only (uncleaned in the last two cases). The power-law index in the background model was left free, which empirically produces a relatively good fit to the background spectrum. The spectroscopic results for these objects should be treated with caution.

Spectral fits were undertaken in the [0.3–10] keV energy range, after binning the spectra to a minimum of 25 counts per bin and excluding background fluorescence line regions. The cluster component was modelled with an absorbed power-law model with the reference solar abundances from the data of Anders & Grevesse (1989). The hydrogen column density $N_{\text{H}}$ was fixed at the 21 cm value from Dickey & Lockman (1990), except for PLCK G286.3–38.4, PLCK G308.3–20.2 and PLCK G018.7+23.6. Their best fit $N_{\text{H}}$ values were found to be significantly higher by a factor 1.8, 1.8 and 2.4, respectively. These clusters are located at low latitude, in regions of high IR dust emission (Snowden et al. 1997, Fig. 11). The 21 cm value is the total $N_{\text{H}}$, measured from X-ray data, due to a non-negligible H$_2$ contribution. To check this hypothesis, we used the IRIS maps (Miville-Deschênes & Lagache 2005) as tracers of the dust emission and the correlation between the Galactic dust emission and the total hydrogen column density (Boulanger et al. 1996) to estimate the $N_{\text{H}}$ values at the cluster locations (see Pointecouteau et al. 2004). A better agreement was found with X-ray values, with ratios of 1.30, 1.06 and 1.48. It must also be noted that the PLCK G286.3–38.4 observation is highly contaminated by solar flares and only $\epsilon_{\nu}$ data are used. Some residual background may also affect the low energy part of the spectrum and thus the $N_{\text{H}}$ estimate.

3. XMM-Newton validation: methods and outcome

The observations were completed by the end of October 2010. The median clean $\epsilon_{\nu}$ observation time is 7 ks (Table 1). Of 25 targets, 21 are confirmed as X-ray extended sources. Only four targets with $S/N \leq 4.1$ were not confirmed. The confirmation status of each XMM-Newton observation is given in Table 1.

3.1. Confirmed cluster candidates

Our procedure for candidate cluster confirmation consists of identifying an extended X-ray source coincident with the Planck SZ source and checking that the SZ and X-ray properties are consistent. Generally, a candidate cluster (or supercluster) is clearly visible within 5’ of the Planck candidate position, in which case we simply have to confirm the X-ray source extent. This is achieved by comparing the surface brightness profile extracted in the [0.3–2.0] keV band with the XMM-Newton PSF. A typical cluster $\beta$-model with a cusp (Eq. (2) in Pratt & Arnaud 2002) is also fitted to the data. Figure 2 shows this comparison for the highest-$z$ confirmed extended source.

17 systems show extended emission from a single source and are confirmed as new clusters of galaxies. Using the Fe K line in the X-ray spectrum we have estimated a redshift for all these objects, albeit with large uncertainties in some cases (see Sect. 4.1). We have also calculated the $Y_5$ parameter (Sect. 5.1). A final check of the candidate confirmation is the good agree-
Fig. 3. *XMM-Newton* images of all confirmed cluster candidates, except for the two triple systems which are shown on Fig. 12 and discussed in Sect. 7, in the [0.3–2] keV energy band. The observations of PLCK G272.9+48.8 and PLCK G250.0+24.1 suffer from high background that has only been crudely subtracted. Image sizes are $3\theta_{500}$ on a side, where $\theta_{500}$ is estimated from the $M_{500}$–$Y_X$ relation (see Sect. 5.1). Images are corrected for surface brightness dimming with $z$, divided by the emissivity in the energy band, taking into account galactic absorption and instrument response, and scaled according to the self-similar model. The colour table is the same for all clusters, so that the images would be identical if clusters obeyed strict self-similarity. The majority of the objects show evidence for significant morphological disturbance. A yellow cross indicates the *Planck* position and a red/green plus sign the position of a RASS-BSC/FSC source.

The *XMM-Newton* images of confirmed single and double systems are shown in Fig. 3. In each panel, the *Planck* source centre position is marked with a cross; in addition, when rele-
vant a red/green plus sign shows the associated RASS-FSC/BSC source.

3.2. False cluster candidates

In some cases a source is not clearly visible in the image and then the relatively large FWHMs of the HFI beams (~4.5–9.5', Planck HFI Core Team 2011b) complicate source search and confirmation. For these observations we employ the approach described in Šuhada et al. (2010), applying the XMM-Newton–SAS source detection algorithms eboxdetect and emldetect to the images to determine whether an extended source lies within the Planck beam. In brief, images produced in the [0.35–2.4] keV band and eboxdetect is first run in local mode, where the background is estimated locally for each source. Sources found in this first step are then excised, leaving an image suitable for background estimation. The background image is modeled with two components, a vignetted component to represent the X-ray background, and a non-vignetted component to represent the particle and instrumental background. The model is based on a linear combination of two templates based on vignetted and non-vignetted exposure maps, and is fit to the source-subtracted image. We then re-run eboxdetect with this model background. All sources found in this step are then analysed with the maximum likelihood (ML) task emldetect, that analyses each source by fitting with a 2D King function convolved with the PSF. The log of the detection likelihood of each source as defined in the code is \[
\text{det}_\text{ML} = -\ln P_{\text{rand}},
\]
where the latter is the probability of the observed counts arising from Poisson fluctuations. We set the minimum \(\text{det}_\text{ML} = 6\), corresponding to a \(\geq 3\sigma\) detection. In addition to the above, we also searched for possible extended sources using visual inspection of a wavelet-smoothed image.

Figure 4 illustrates application of the method for the false source PLCK G226.1–16.9. This candidate was the lowest S/N candidate of the Pilot sample (S/N = 4.0) and located close to a RASS-FSC source, which may have been the cluster counterpart. The top panel shows the raw XMM-Newton image and the reconstructed epn ML source image. The RASS-FSC source located at 0.8' from the Planck source is clearly detected with XMM-Newton (red plus sign in the top panels). The surface brightness profile is well fitted by a point source convolved with the XMM-Newton PSF (bottom left panel). The source spectrum is clearly a power law, and thermal emission from a 0.3 solar abundance ICM is rejected at high confidence at all redshifts and temperatures. This source is most likely an AGN and is definitively not the Planck counterpart.

The source list produced by the ML method includes two potentially extended sources, only one of which is within 5' of the Planck source position (source labelled A in the figure). It is located ~0.8' from the RASS-FSC source position and is much fainter, showing the capability of XMM-Newton to separate sources. The source has an estimated [0.35–2.4] keV flux of \(\sim 2 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1}\), which is more than 5 times lower than that expected from the SZ source even if located at \(z \sim 1.5\). Furthermore its extent (although not well constrained) is small and it is perfectly coincident with a 2MASS galaxy. This source again could not be the Planck counterpart. Finally, from a wavelet-smoothed image, there was a hint that another source, located 3.5' away from the Planck candidate position, was extended, although it was not classified as such with the ML method (source labelled B). We extracted its profile and confirmed it as extended, although the extent was not very significant (bottom right panel of Fig. 4). However, its flux was half that expected from the observed Planck flux, even for a cluster at \(z = 1.5\). Nevertheless, in view of possible errors in the Planck position, we re-analysed the Planck data by re-extracting the signal exactly at the position of the source. The SZ detection was no longer significant, leading us to conclude that source B was definitively not the counterpart to the Planck candidate. From the XMM-Newton observation we thus concluded that this Planck candidate was a false detection.

4. Redshift estimate

4.1. XMM-Newton estimates

The ICM has a typical abundance of 0.3 times solar, implying that metals are present in large amounts (see Balestra et al. 2007; Leccardi & Molendi 2008; Maughan et al. 2008, for recent work on metals in the cluster context). The spectroscopic sensitivity of XMM-Newton allows the measurement of the intensity and centroid energy of the strongest line emission, namely the Fe K and Fe L line complexes (respectively found at \(E \sim 6.4\) and \(E \sim 1 \text{ keV at } z = 0\)). As a consequence the Fe line emission can be used to constrain the cluster redshift. We have thus searched for their signature in the XMM-Newton observations, focusing mainly on the Fe K complex, which is about 10 times as strong as any other line emission in the ICM. A clear detection then provides an estimate of the X-ray redshift \(z_{\text{X-ray}}\).

The intrinsic spectral resolution of XMM-Newton is \(\Delta E \sim 150 \text{ eV at } 6.4 \text{ keV and } \Delta E \sim 100 \text{ eV at } 3.2 \text{ keV};\) the ener-
gies here correspond to the Fe K complex centroid energy for a cluster at a redshift of $z = 0$ and $z = 1$, respectively. Such resolution allows centroid determination to typically $10$–$15$ eV for high quality spectra, of the same magnitude as the systematic uncertainty of the calibration of the energy reconstruction (about $5$ eV and $10$ eV in the central CCD of the ems and emx camera, respectively). The overall energy uncertainty would yield a typical corresponding redshift uncertainty of $\Delta z \sim 0.002$. In practice, the limiting factor affecting the accuracy of the redshift determination is the statistical uncertainty in the spectrum, which is linked to the observation duration and overall quality (background conditions). Furthermore, Planck-detected clusters are mostly massive, hot objects with low Fe K line equivalent widths (Rothenflug & Arnaud 1985). This makes $z_{\mathrm{Fe}}$ determination more difficult than for cooler objects.

To estimate $z_{\mathrm{Fe}}$ using xspec we first performed a spectral fit of the region corresponding to the maximum significance of the detection (defined from the surface brightness profile in the soft band), with the redshift as one of the free parameters. The abundance was left free to fit within a typical cluster range (0.2–0.6 times solar). From this starting point we investigated the $\chi^2$ in the $kT$–$z_{\mathrm{Fe}}$ plane using a regular grid. The best fitting $kT$ and $z_{\mathrm{Fe}}$ values were recovered from a simple maximum likelihood analysis, whereupon these best fitting values were used as input for a final spectral fit. When a two- or three-peak likelihood analysis, whereupon these best fitting values were used $kT$ and $z_{\mathrm{Fe}}$ values and chose the redshift giving the best spectral fit as defined by the $\chi^2$ and the null probability hypothesis.

This redshift estimation process is illustrated by three cases in Fig. 5 with the left panel showing a fully degenerate case, the middle panel a double-peaked case and the right panel a well-constrained case. These redshifts are flagged with quality values $Q_z = 0, 1, 2$, respectively, in Table 2. The few cases where no redshift estimate was possible are flagged with $Q_z = -1$.

4.2. Optical estimates

For three clusters, we have estimated the redshift either from existing optical archive observations or dedicated follow-up observations as part of the overall Planck cluster candidate validation programme. The most recent corresponds to telescope time acquired by the Planck consortium at the ESO telescopes, Observatorio del Teide (Tenerife, Spain – AO 2010A and 2010B). The details of the observation setup and data processing can be found in Appendix A1.

- PLCK G100.2–30.4. The source was observed in 4 bands (griz) with the CAMELOT camera at the 0.82-m IAC80 telescope. After data reduction, we derived a photometric redshift of $z_{\text{photo}} = 0.38 \pm 0.04$, using the urw code (Benitez 2000). This estimate is compatible within $3\sigma$, with the $z_{\text{Fe}} = 0.31$ derived from the X-ray spectroscopy.

- PLCK G285.0–23.7. We reduced the ESO NTT/SUSI2 archive images for this object, deriving a red-sequence redshift of $z_{\text{photo}} = 0.37$. This estimate is in good agreement with the X-ray spectroscopic redshift $z_{\text{Fe}} = 0.39$.

- PLCK286.3–38.4. ESO NTT/SUSI2 images and NTT/EMMI spectroscopic archive data targetting the X-ray source RX J0359.1–7205 were available. From a poor quality NTT/EMMI spectrum, we extracted a redshift of $z_{\text{spec}} = 0.307 \pm 0.003$, backed-up by the presence of two absorption line features (Hβ and Mg i). Again this value agrees well with the X-ray spectroscopic redshift of $z_{\text{Fe}} = 0.31$.

Finally, the source PLCK G262.7–40.9 appeared to be one of the ACT SZ optically-confirmed clusters (Menanteau et al. 2010), accepted for observation by Chandra after it was scheduled for observation with XMM-Newton. The reported photometric redshift is $z_{\text{photo}} = 0.54 \pm 0.05$, in disagreement with our X-ray–derived value of $z_{\text{Fe}} = 0.38$ at the $3\sigma$ level. Although slightly weak, the Fe K line is clearly seen in the X-ray spectrum (see Fig. 5 right panels). We thus adopt the X-ray estimate. However, optical spectroscopic observations are clearly needed to confirm the cluster redshift. All compiled and derived optical redshifts are reported in Col. 6 ($z_{\text{spec}}$) in Table 2.

5. Physical parameter estimates of confirmed clusters

5.1. XMM-Newton data

For all single clusters (17 systems) or obvious sub-components in double and triple systems (4 objects), the X-ray peak position was taken to be the (sub-)cluster centre. For these systems we undertook a more in-depth analysis assuming that a spherically symmetric approximation is appropriate.

Surface brightness profiles, centred on the X-ray peak, were extracted in the [0.3–2] keV band in $3'3$ bins. Deprojected, PSF-corrected gas density profiles were then calculated using the method described in Croston et al. (2008). Global cluster parameters were then estimated self-consistently within $R_{500}$ via iteration about the $M_{500}$–$Y_X$ relation of Arnaud et al. (2010, see also Pratt et al. 2010), viz.,

$$E(z)^{3/5}M_{500} = \left[ \frac{Y_X}{2 \times 10^{44} M_\odot \text{keV}} \right]^{0.561 \pm 0.018} h^{-1} M_\odot, \quad (1)$$

assuming the standard evolution predicted by the self-similar model purely based on gravitation. In addition, the X-ray luminosity in the [0.1–2.4] keV band interior to $R_{500}$, $L_{500}$ was calculated as described in Pratt et al. (2009). All resulting X-ray properties are summarized in Table 2. Errors include only statistical uncertainties. We did not attempt to include systematic errors due to redshift uncertainty or high background level; such estimates are beyond the scope of the paper. The results for this sample are not used for quantitative statistical study (e.g. derivation of scaling laws), which would require redshift confirmation (sources with $Q_z < 2$) and deeper XMM-Newton observations.

The X-ray position for single systems is compared to the Planck position in Fig. 6. The offset behaviour is similar to that observed for known clusters in the ESZ sample (see Planck Collaboration 2011d, for discussion). Except for the outlier PLCK G18.7+23.6, the positional offset is less than $2''$ and is clearly dominated by the Planck reconstruction error which peaks at that value. A physical offset is also expected, especially for merging clusters. Such an offset would contribute less with increasing $z$ as it would be more and more poorly resolved. The small residual systematic variation of the offset with $z$, for $z > 0.2$, suggests that physical offsets may indeed slightly contribute. This is likely to be the case for PLCK G18.7+23.6, a highly disturbed object at $z = 0.09$, the lowest $z$ of the sample, and which has an offset of $3'$ corresponding to $0.3 R_{500}$. In all
| Name       | S/N  | R800 | XeX | TeX | log(TeX) | Y800 | Y1000 | M800 | M1000 | log(M800) | Log(M1000) |
|------------|------|------|-----|-----|----------|------|-------|------|-------|-----------|------------|
| PKL2 G850.2-237 | 11.5 | 0.54 | 1.37 | 0.39 | 0.37a    | 0.54 | 0.47  | 0.52 | 0.54 | 0.47b     | 0.47b       |
| PKL2 G878.0-32.9 | 10.6 | 1.37 | 0.54 | 0.47 | 0.47b     | 0.47b| 0.47b | 0.47b | 0.47b | 0.47b     | 0.47b       |
| PKL2 G719.7-40.7 | 10.6 | 0.54 | 0.47 | 0.47 | 0.47b     | 0.47b| 0.47b | 0.47b | 0.47b | 0.47b     | 0.47b       |
| PKL2 G320.1-12.5 | 8.5  | 0.54 | 0.47 | 0.47 | 0.47b     | 0.47b| 0.47b | 0.47b | 0.47b | 0.47b     | 0.47b       |

Notes: Column (2): signal-to-noise ratio derived from the 10-month Planck maps on the basis of which the ESZ sample was constructed. Columns (3)–(8): right ascension and declination of the peak of the X-ray image (J2000). Column (9): redshift from X-ray spectral fitting. Column (10): optical redshift. Column (11): Quality flag for the X-ray redshift measurement (see Sect. 4.1). Column (12): total epic count rates in the [0.3–2] keV band, within the maximum radius of detection given in Col. (13). Columns (14)–(20): R800 is the radius corresponding to a density contrast of 500, estimated iteratively from the M800–Y800 relation (Eq. (11)), where Y800 = M800/T X = the product of the gas mass within R800 and the spectroscopic temperature T X, and M500 is the total mass within R500. Log(Y500) is the luminosity in the [0.1–2] keV band and in the R500 aperture. Y500 is the spherically integrated Compton parameter measured with Planck, centred on the X-ray peak, interior to R500 as estimated with XMM-Newton.

6. X-ray and SZ properties of newly detected clusters

In this Section we consider the 17 systems confirmed as single-component clusters of galaxies, leaving aside the multiple systems which are discussed in the next section.

6.1. RASS properties

We extracted 2° × 2° count images in the [0.5–2] keV hard band from the RASS data at the position of each cluster. We excised events associated with known RASS-BSC and RASS-FSC sources (Voges et al. 1999, 2000). We then carefully followed the methods described in Böhringer et al. (2000) and Reiprich & Böhringer (2002) to compute background corrected growth curves and estimate an associated detection radius, Rd. The background was estimated from an outer annulus with 15° < θ < 90°. When allowed by the quality of the growth curve, the count rate within the R500 aperture was either taken as the count rate within Rd when Rd < R500 or interpolated on the curve when Rd > R500. In the case of low quality growth curves, we computed a direct integrated count rate from the map within an aperture of R500. Assuming the best fitting XMM-Newton spectral parameters for each cluster (i.e. z, temperature, abundance, Galactic N(H)) we derived the [0.1–2] keV band RASS flux.
Fig. 5. Top row: redshift determination from XMM-Newton spectroscopy in the $kT$-$z$ plane. Red, green and blue contours trace 68, 95 and 99.9 percent confidence levels, respectively. The black error point shows the final best-fitting spectral results with associated statistical errors. Bottom row: $\text{PLCKG100.2−30.4}$ (red and black points) and $\text{PLCKG277.8−51.7}$ (green points) spectra. Only the data points above 2 keV are shown for clarity but data down to 0.3 keV are used in the spectral fitting. The line is the thermal model for the best-fitting redshift. The position of the redshifted Fe K line is marked. From left to right the figures are for sources PLCK G100.2−30.4, PLCK G277.8−51.7 and PLCK G241.2−28.7.

Fig. 6. Distance of blind SZ position to X-ray position, $D_{SZ-X}$, as a function of $D_{SZ-X}$, normalised to the cluster size $\theta_{500}$, for single confirmed systems. The clusters are colour-coded according to redshift. Note that the offset is typically less than 2' and always less than $\theta_{500}$.

The RASS values are compared to the XMM-Newton values in Fig. 8. There is a good agreement after taking into account the RASS statistical errors. The slight offset (<20%) is likely due to systematic errors linked to the RASS background estimate and/or calibration uncertainties. The most significant outlier at high flux is PLCK G18.7+23.6. A bright point source is present at the centre of this object (see Fig. 3) that cannot be excised from the RASS data and which contaminates the signal. From the XMM-Newton image (Fig. 3), the known

Fig. 7. Comparison of the Planck blind and X-ray constrained $Y_{500}$ measurements for single confirmed systems (see text, Sect. 5.2). The ratio is correlated with the ratio of the corresponding characteristic size, $\theta_{500}$.
RASS-FSC or RASS-BSC sources within the Planck error box for 15 of the candidates can be clearly identified with the clusters. Those are indicated in Fig. 8. The two clusters with no RASS-FSC or RASS-BSC association, PLCK G287.0+32.9 and PLCK G292.5+22.0, are in fact detected in RASS, but at low S/N (2 and 3, respectively; see also Sect. 6.4).

6.2. The \( L_x-z \) plane and comparison with RASS catalogues

In Fig. 9, the new clusters are shown in the \( L_x-z \) plane, plotted together with the clusters from large catalogues based on RASS data outside the Galactic Plane: REFLEX (Böhringer et al. 2004) in the Southern sky; NORAS (Böhringer et al. 2000); BCS (Ebeling et al. 1998); and eBCS (Ebeling et al. 2000) in the Northern Sky. The NORAS is not flux limited. The REFLEX flux limit of \( 3 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) is shown. It is similar to that of the eBCS+BCS limit of \( 2.8 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \). Also shown are clusters from the published catalogues of the MACS survey with their corresponding flux limit. MACS is based on the RASS-BSC but in contrast to the above surveys, the X-ray extent of the RASS source is not a selection criterion, allowing more distant (but massive) clusters to be found (Ebeling et al. 2001). Published MACS catalogues are the \( z > 0.5 \) catalogue (Ebeling et al. 2007) and the \( 0.3 < z < 0.5 \) brightest cluster catalogue (Ebeling et al. 2007, hereafter bright MACS). Luminosities plotted in Fig. 9 are the homogenised values given in the MCXC (Meta-Catalogue of X-ray detected Clusters of galaxies Piffaretti et al. 2011).

The present sample of new Planck-detected systems spans a redshift range of \( 0.1 \leq z \leq 0.6 \), with 15 out of 17 clusters above \( z = 0.25 \), a medium-distant redshift region of the \( L_x-z \) plane that is sparsely-populated by the RASS catalogues. As a consequence, our current sample has X-ray luminosities well below the flux limit of HIFLUCGS (Reiprich & Böhringer 2002) and REFLEX-DXL (Zhang et al. 2004), two high-luminosity X-ray selected samples that stand as the counterparts to our present high S/N SZ sample. The closest sample in X-ray luminosity and redshift to the new Planck clusters are the MACS clusters, although the Planck clusters go to lower luminosity.

Most of the new Planck clusters naturally fall below the REFLEX flux limit or, equivalently, the BCS+eBCS limit in the North. However, three clusters lie well above this limit: PLCK G18.7+23.6, PLCK G171.9–40.7, PLCK G271.2–31.0, in order of decreasing X-ray flux (Figs. 8 and 9). As discussed above, PLCK G18.7+23.6 at \( z = 0.09 \) has a very bright central source and very diffuse ICM emission. It may have been misclassified as a point source in the REFLEX survey. We also note that this cluster, although not included in the ESZ sample, is the brightest X-ray cluster of the sample due to its low redshift \( z = 0.09 \), PLCK G271.2–31.0 simply falls in the Large Magellanic Cloud LMC2 region, which was excluded in the REFLEX survey (see Böhringer et al. 2001, Table 1). However, PLCK G171.9–40.7 at \( z = 0.27 \) has a flux of \( 5.7 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) (from fully consistent ROSAT and XMM-Newton measurements), and is a northern sky cluster that fulfills the BCS flux and sky position criteria. Thus a priori, it should have been included in that survey. Finally, six new clusters at \( z \geq 0.3 \) are above the MACS flux limit. Of these, four are not associated with a RASS-BSC source and so could not be found in a MACS-like survey, and the other two are at lower declination than considered by MACS.

6.3. Gas morphology and scaled density profiles

Figure 3 shows \([0.3-2] \text{ keV} \) XMM-Newton images of the newly-discovered clusters. Each image corresponds to the same physical size in units of \( R_{500} \) and is corrected for surface brightness dimming with redshift and divided by the emissivity in the \([0.3-2] \text{ keV} \) energy band. As detailed in Arnaud et al. (2002, Sect. 3.2), the emissivity is computed from a redshifted thermal model convolved with the instrument response and taking into account Galactic absorption. The resulting image is proportional to the predicted gas mass and temperature profile.

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The visual impression is confirmed and quantified when one looks at the density profiles of the clusters shown in Fig. 10. They are plotted together with the density profiles of similar mass clusters from the representative X-ray-selected samples REXCESS (Bohringer et al. 2007) and EXCIPRES (Arnaud et al., in prep.). For all three samples, the radii are scaled by \(R_{500}\), estimated from the \(M_{500} - Y_{X}\) relation (Eq. (1)). The thick lines show the mean profile. While the two X-ray-selected samples agree to a remarkable degree, the \textit{Planck}-selected sample clearly consists of systems with much flatter density profiles, and the corresponding mean profile is significantly flatter than that of the X-ray selected samples. This shape is due to a number of very disturbed clusters with very flat profiles in the new \textit{Planck}-discovered cluster sample. Let us consider the ten clusters with the flattest density profiles, flatter than the mean profile of all the \textit{Planck} clusters and flatter than all the REXCESS profiles. These ten objects include PLCK G18.7+23.6 at \(z = 0.09\) discussed above, PLCK G286.6–31.3 at \(z = 0.21\) that is just at the \textit{REFLEX} flux limit and PLCK G292.5+22.0 at \(z = 0.30\) that is just at the MACS flux limit (Fig. 9). The other seven clusters lie at medium flux limit and PLCK G292.5+22.0 at \(z = 0.30\) that is just at the MACS flux limit (Fig. 9). The other seven clusters lie at medium flux limit and PLCK G292.5+22.0 at \(z = 0.30\) that is just at the MACS flux limit (Fig. 9). The other seven clusters lie at medium flux limit and PLCK G292.5+22.0 at \(z = 0.30\) that is just at the MACS flux limit (Fig. 9).

As compared to X-ray selected clusters, the new clusters fall on the low luminosity side of the \(L_{500} - Y_{X}\) relation (bottom left panel of Fig. 11). In other words, they are under-luminous at given \(Y_{500}\). If the mass is indeed tightly related to \(Y_{X}\) we then expect them to be underluminous at a given mass. This trend is consistently observed in the bottom-right panel, where \(M_{500}\) is estimated from \(Y_{X}\): the new clusters fall towards the high-mass, low-luminosity side of the \(M_{500} - L_{500}\) relation. However, confirmation requires independent mass estimates, e.g., from lensing data.

As shown by Pratt et al. (2009), the underluminous region of the \(L-M\) plane is populated by morphologically disturbed systems. This once again suggests that the majority of the new \textit{Planck}-detected systems are disturbed, in agreement with the above discussion on the morphology and the scaled density profiles.

The dispersion of the new clusters about the \(M_{500} - L_{500}\) relation also seems higher than that for X-ray selected objects. This suggests the existence of new extreme low-luminosity, high-mass objects that are being revealed by \textit{Planck}. The two prominent outliers are PLCK G287.0+32.9 (\(z = 0.39\) and
Fig. 11. Scaling relations for the 17 new confirmed single-component clusters (red symbols). Black points show clusters in the Planck-ESZ sample with XMM-Newton archival data as presented in Planck Collaboration (2011g). The solid black line denotes the corresponding scaling relation fits in each panel. The blue lines in the top and bottom right panels denote the predicted $Y_{500}$ scaling relations from the REXCESS X-ray observations (Arnaud et al. 2010). The blue line in the bottom left panel is the Malmquist bias corrected $M-L$ relation from the REXCESS sample (Pratt et al. 2009; Arnaud et al. 2010). In all figures, $R_{500}$ and $M_{500}$ are estimated from the $M_{500}-Y_{X}$ relation of Arnaud et al. (2010). Top row: relation between apparent SZ signal ($Y_{500}$, left) or intrinsic Compton parameter ($D_{A}^{2}Y_{X}$, right) and the corresponding normalised $Y_{X}$ parameter. Bottom row: relation between X-ray luminosity and $Y_{500}$ (left) and between mass and luminosity (right panel). The new clusters are on average less luminous at a given $Y_{500}$, or more massive at a given luminosity, than X-ray selected clusters.

PLCK G292.5+22.0 ($z = 0.3$), detected by Planck at high S/N values of 10.6 and 6.9, respectively. They belong to the very hot ($T \approx 10$ keV) and very massive ($M_{500} \approx 10^{15} M_{\odot}$) cluster category (Table 2) and are the only two clusters associated with neither a BSC nor an FSC source (Sect. 6.1 and Fig. 8). The flux of PLCK G292.5+22.0 barely reaches the MACS limit for a mass of $M_{500} \sim 9.2 \times 10^{14} M_{\odot}$. It has a very disturbed morphology (Fig. 3) and a flat density profile with a scaled central density of $4 \times 10^{-3}$ cm$^{-3}$ (Fig. 10).

7. Further analysis of multiple systems

7.1. Double systems

Two of the new Planck sources (PLCK G308.3−20.2 and PLCK G337.1−26.0) were revealed by the XMM-Newton validation observations to be double systems. X-ray images of these systems are included in the gallery in Fig. 3.
7.1. PLCK G308.3−20.2

Two clusters with quite regular morphology are clearly detected in the XMM-Newton snapshot observation for this candidate (denoted A and B in Fig. 3). The Planck position is very close (1.5′) to that of the northern cluster A. This cluster is very hot ($T_X \sim 10$ keV) and massive (Table 2). From the X-ray spectroscopy, we estimated its redshift to be $z = 0.48$. This estimate is robust, with a quality flag of 2 as reported in Table 2. The second component, B, lies 7′ to the South-East of A. The lack of statistics prevents us from deriving a sufficiently reliable redshift estimate. Assuming it lies at the same redshift as A, its $Y_X$ parameter is 6.0 times less than that of A, and its derived mass is 2.7 times less. Both clusters are seen as well-separated sources in RASS: A is associated with a RASS-BCS source; whereas B coincides with a RASS-FSC source.

7.1.2. PLCK G337.1−26.0

The distance between components A and B (Fig. 3) is 8.1′. Both have regular morphologies, and exhibit strong Fe K lines, allowing individual redshift estimation. They are found to lie at two clearly different redshifts: $z_{Fe} = 0.26$ for A; and $z_{Fe} = 0.12$ for B. A is the hotter of the two with $T_X = (6.2 \pm 0.2)$ keV and thus the more massive. The $Y_X$ of cluster A is 15 times larger than that of B, making it the main contributor to the Planck SZ signal.

The two clusters are seen as separate sources in RASS: cluster A as a RASS-BCS source; and B as a RASS-FCS source. The XMM-Newton emission coincides perfectly with the RASS emission in each case. Additionally, the two clusters are also found 40′ off-axis in a PSPC pointed observation of a globular cluster, NGC 6752 (Johnston et al. 1994), where they are listed as sources within the globular cluster (sources 1 and 2 in Johnston et al.’s Table 8). Lacking spectroscopic information, Johnston et al. (1994) could not specify the exact nature of the sources, which they assumed to be of Galactic origin. Note that it is not surprising that the sources were not identified as extended sources, in view of the large PSPC PSF (90% encircled energy diameter of ~6′) at such off-axis angle.

7.2. Triple systems

PLCK G214.6+37.0 and PLCK G334.8−38.0 were included in the XMM-Newton pilot programme and are detected in the Planck survey with $S/N$ of 5.0 and 4.1, respectively. The wavelet-filtered X-ray surface brightness contours are overlaid on the Planck maps in the left-hand panels of Fig. 12. For both sources, the XMM-Newton observation revealed three extended X-ray components; their extended nature is evident in the surface brightness profiles shown in the right-hand panels.

7.2.1. PLCK G214.6+37.0

The Planck SZ source candidate position is located ~ 5′ from the two southern components (A and B). A third component, C, lies approximately 7′ to the North (Fig. 12, top panels). X-ray spectral analysis of the Fe K line indicates a redshift of $z_{Fe} \sim 0.45$ for the brightest component. None of the sources is particularly
hot, luminous, or massive (i.e., $M_{500} < 2.5 \times 10^{14} M_{\odot}$). A RASS-FSC source lies in the South-East and its counterpart is easily seen with XMM-Newton. It is associated with a point source and is unassociated with the SZ emission.

PLCKG214.6+37.0 falls in the SDSS area. We investigated the SDSS-DR7 database using refined positional information from the XMM-Newton observation. We identified two bright galaxies with spectroscopic redshifts of $z = 0.45$ whose positions coincide with the peak of components A and C, respectively. Furthermore, a bright galaxy with a photometric redshift of 0.46 lies very close to the B X-ray peak. We also ran a dedicated algorithm (Fromenteau et al., in prep.) to search for an overdensity of SDSS galaxies at the location of the Planck SZ source. While we were unable to differentiate the three sub-structures, the analysis suggests the presence of a massive structure ($\sim 10^{15} M_{\odot}$) at $z \sim 0.45$ around A and B. A further cross-correlation with SDSS-DR7 LRGs and the SCs catalogue from the SDSS-DR7 (Liivamägi et al. 2010) hints that this triple system is encompassed within a very large-scale structure located at $z \sim 0.45$, and whose centroid lies about $2^\circ$ to the South (see Appendix B for further details).

Thus there is good agreement between all redshift estimates, including the redshift of component A estimated from the XMM-Newton observation, the optical SDSS redshifts of the three components, and that of the larger-scale environment. This agreement strongly argues in favour of a real structure of (at least) three clusters, likely forming the core of a larger-scale super cluster.

7.2.2. PLCK G334.8--38.0

Two extended X-ray components separated by $7^\prime$ are clearly visible in the XMM-Newton image (denoted A and B in Fig. 12, bottom panels). The Planck SZ source candidate position lies between and slightly to the south of the components. A third fainter component, C, is seen $5^\circ$ to the South. The spectral analysis of component A suggests a redshift of $z_{\text{Fe}} \sim 0.35$. Although, this estimate, based on the Fe L complex detection, has to be taken with caution, we adopted it as the redshift for all three X-ray components. Despite limited statistics, we derived temperatures of (2--3) keV (with large uncertainties for cluster C), suggesting masses of $(0.5--1) \times 10^{14} M_{\odot}$. The only RASS source found in the vicinity of the SZ source is clearly not associated with the three XMM-Newton components, and coincides with an off-axis point source seen in the XMM-Newton image.

7.3. Comparison of X-ray and SZ properties

As a first comparison of the X-ray and SZ properties, we simply compared the $Y_{500}$ Planck measurement with the predicted value from the summed contribution of the various components, derived from their estimated $Y_X$ values.

For PLCKG308.3--20.2, the predicted summed contribution from A and B represents 46% of the total measured SZ signal (with 40% from A alone). In the case of PLCK G337.1--26.0, this amounts to 76% of the measured $Y_{500}$ (with 62% coming from component A). The presence of component B marginally enhances the expected SZ signal. As the two clusters are not physically connected, no enhanced SZ emission is expected from their surrounding (i.e., due to mergers, shocks, etc.). We recall that the reconstruction error in the SZ position for Planck blind SZ detections is $2^\prime$ on average (Melin et al. 2011). The fact that the Planck SZ position lies almost in the middle of the two components (i.e. 3.3' and 4.7' from A and B, respectively) is probably coincidental.

The Planck $Y_{500}$ values of PLCK G214.6+37.0 and PLCK G334.8--38.0 were recomputed at a fixed "barycentric" position of the three components (black cross in Fig. 12). The sum over the three components of PLCK G214.6+37.0 yields $Y_{500,\text{pred}} = 3.2 \times 10^{-6} \text{arcmin}^2$, i.e. 25% of the measured value. It is 35% of the 1$\sigma$ lower limit of $Y_{500}$, and consistent within its 3$\sigma$ error range.

In the case of PLCK G334.8--38.0, $Y_{500,\text{pred}} = 1.4 \times 10^{-6} \text{arcmin}^2$ accounts for only ~21% of the measured SZ signal and 29% of its 1$\sigma$ lower limit. However, the predicted value is consistent within the 3$\sigma$ error range of the Planck value, that includes uncertainties on the structure size. We also note that a fortuitous association between a spurious detection by Planck and such an association of extended X-ray sources is quite unlikely. Indeed, such a configuration of multiple massive halos either physically connected or associated by projection effect is not usual, making this source even more puzzling. The formal discrepancy between the SZ and X-ray signal is likely partly due to lack of constraints on the structure size in the SZ measurement, even when the position is fixed to the X-ray position. It could also be the result of an under-estimate of the structure’s redshift. Redshift measurements of various components are definitely required to assess the nature of this association and the Planck source.

For all systems, the cumulative contribution predicted by the $Y_X$ measurements do not match the measured SZ signal, although it is compatible in all cases within the 3$\sigma$ uncertainty on $Y_{500}$. However, the SZ flux is estimated assuming a single component that follows the universal pressure profile, an inadequate approach for these systems. Due to its moderate spatial resolution at SZ frequencies (i.e., 5--10'), Planck cannot separate the emission of the two or three components contributing to the overall signal. Nevertheless, a proper multi-component analysis can be carried out in the future. From the X-ray constraints on the system geometry, a spatial template can be built to improve extraction of the $Y_{500}$ signal for each component. Indeed, such a detailed study might allow us to ascertain whether SZ or X-ray emission emanates from the regions between the main system components. The current XMM-Newton snapshot observations are not deep enough to build such an accurate template (i.e., measurement of the pressure profiles of the individual components). Together with accurate redshift measurements, deeper X-ray observations are needed to derive the pressure profile of individual clusters.

8. Conclusion and perspectives

In the framework of an XMM-Newton DDT validation programme, the first 21 new SZ-detected clusters in the Planck survey have been confirmed. Six of these were confirmed in an initial Pilot programme, the results of which were used to improve the quality assessment and selection processes of cluster candidates. The Pilot programme also clearly demonstrated the efficiency of XMM-Newton for Planck candidate confirmation. Based on the detection of extended emission, snapshot exposures have been shown to be sufficient for unambiguous discrimination between clusters and false candidates. Importantly, for redshifts at least up to $z = 1.5$, the spurious association of Planck candidates with faint extended sources in the position error box can be distinguished via a consistency check between the X-ray and SZ flux. A further 15 candidates were confirmed in a second programme focussed on high S/N detections. The 100% success
rate above S/N = 5 is the first illustration of the capability of the Planck survey to detect new clusters via their SZ signature.

Except for two clusters, all confirmed single or double clusters are associated with RASS-BSC or FSC sources. The two non-associations are in fact detected in RASS, but at a low S/N of 2–3. The presence of significant RASS emission is thus a positive indicator of the validity of a Planck cluster candidate in the presently-covered $z$ range. However, association with a RASS source within the position error box is not, by itself, sufficient for cluster candidate confirmation. Two of the false candidates in the Pilot programme, as well as one of the confirmed triple systems, were each associated with a single RASS-FSC source that XMM-Newton subsequently revealed to be a point source. Furthermore such spurious association, and also the number of real candidates not detected in RASS, is expected to increase when probing higher $z$, i.e., at lower Planck S/N, or later in the mission.

The XMM-Newton validation programme brings clear added value to simple candidate confirmation. The X-ray flux measurement and refined position is essential information for optimisation of deeper follow-up observations for detailed X-ray studies. The refined position is also useful for optical follow-up, such as for redshift measurements. Importantly, the determination of the exact cluster centre and extent allows a refined estimate of the SZ flux from Planck data. For the X-ray brightest objects, XMM-Newton can directly provide the source redshift from the Fe K line in the spectrum. For the present sample of confirmed candidates, 17 of 27 individual clusters (including those in multiple systems) have high quality redshift measurements. The new clusters span the redshift range $0.09 < z < 0.54$, with a median redshift of $z = 0.37$.

In addition, the XMM-Newton validation programme has provided a preview of the properties of the new clusters that Planck is discovering. Of the 21 confirmed candidates, 17 are single clusters, most of which are found to have highly irregular and/or disturbed morphologies (i.e. ~70% from visual check). Two more confirmed candidates were revealed to be double systems, one of which is a projection of two physically independent clusters at different redshifts. More unexpected are two further newly-discovered triple systems that were not resolved by Planck. One of these is a true cluster association at $z \sim 0.45$, as confirmed both from the XMM-Newton data and in our subsequent analysis of SDSS data. It likely forms the core of a larger-scale supercluster, and is the first supercluster to be discovered via the SZ effect. Theoretically, the SZ signal from such a supercluster is expected to arise from the sum of the signal from the individual clusters, plus a possible additional contribution from a filamentary inter-cluster gas structure, the existence of which has not yet been observationally proven. This Planck-XMM-Newton discovery may open the way to constrain the existence and properties of such filamentary matter, via deeper combined Planck SZ and X-ray studies. The current XMM-Newton snapshot observations do not allow conclusive comparison between the SZ and X-ray signals. Deeper observations are needed, sufficient to determine the pressure profile of individual subclusters.

The Planck SZ survey has already started to complement existing X-ray surveys, particularly above $z \sim 0.3$. Notably, it is finding new clusters below the flux limit of catalogues based on extended RASS source detection, such as the REFLEX survey, and new clusters brighter than the flux limit of the MACS survey above $z = 0.3$. Such discoveries are due to a combination of larger effective sky coverage and the intrinsic limitations of a RASS-based cluster survey. In practice, surveys considering extended RASS sources, such as REFLEX, have a higher flux limit than that corresponding to Planck’s sensitivity. By considering RASS-BSC sources without extent criteria, the MACS survey reaches a lower flux limit, at the price of extensive optical confirmation follow-up that does not cover the whole sky. Furthermore, the RASS-BSC detection algorithm was primarily designed for point source detection and can miss very diffuse sources similar to the clusters with flat morphology that Planck is revealing. Four of our confirmed clusters are above the MACS limit but are not associated with a RASS-BSC source.

For the single-component clusters, we have been able to derive the first estimates of their physical properties such as $L_{100}$, $Y_X$ (with $M_{500}$ estimated using $Y_X$ as a mass proxy), and density profiles. These properties suggest that the new clusters are massive, dynamically-complex, objects. These SZ-selected objects have, on average, lower luminosities, flatter density profiles, and a more disturbed morphology than their X-ray selected counterparts. As a result, the dispersion around the $M$–$L$ relation may be larger than previously thought, with new clusters like PLCK G292.5+22.0 at $z = 0.3$ barely reaching the MACS flux limit for an estimated mass of $M_{500} \sim 10^{15} M_\odot$. This suggests that there is a non-negligible population of massive, dynamically perturbed (merging) clusters that do not appear in all-sky X-ray surveys. Furthermore, as the bulk of cluster cosmology is currently undertaken using X-ray-selected samples, the lack of these clusters may have implications for measures of the cosmologically-sensitive exponential end of the mass function.

The above preview of newly-detected Planck cluster properties must be confirmed with deeper, multi-wavelength, follow-up observations. Such observations include optical redshift confirmation (see the ENO observations presented here), detailed pressure profiles from deeper XMM-Newton observations and mass estimates. The latter require the combination of lensing, optical and X-ray data, in view of the highly unrelaxed nature of the objects.

Continuation of the confirmation of Planck candidates and the characterisation of the Planck selection function constitutes a major effort, and requires a good understanding of the properties of the newly-discovered clusters. As we have shown in this paper, XMM-Newton can play a major role in this process. The XMM-Newton validation programme is presently ongoing. It is currently focussed on Planck detections both in the S/N > 5 range and at lower S/N, thus potentially leading to the discovery of more distant clusters.

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Appendix A: Redshift determination based on optical counterparts

A.1. PLCK G100.2−30.4

We observed PLCK G100.2−30.4 with the CAMELOT camera on the 0.82-m IAC80 telescope at the Observatorio del Teide (Tenerife, Spain), as part of a validation campaign for newly detected Planck clusters that started in semester 2010 A. We obtained four images in the Sloan g, r, i and z-bands, all centred at the location of the Planck cluster candidate, with a field of view of 7´ and a pixel scale of 0.304. The integration time achieved in each filter was approximately 3 ks, yielding a limiting magnitude of 22.9, 21.7, 20.1 and 20.2 for g, r, i and z, respectively, for a 5σ detection.

Image data reduction was undertaken using standard IRAF routines. The source detection, catalogue extraction and photometry measurements on the processed images were performed using SExtractor (Bertin & Arnouts 1996). Sources were identified independently in the four bands using a 1.5σ SExtractor detection threshold in the filtered maps (i.e. equivalent to S/N ~ 3). The colour–composite image of the g, r and i filters (see Fig. A.1) clearly shows an excess of red galaxies at the location of the X-ray detection.

We have obtained photometric redshifts for all galaxies in the field using the nz code (Benítez 2000). We use the photometry information from the g, r and i-bands, as they provide more reliable redshift estimates. From the final galaxy catalogue, we identify eight galaxies located within a radius of 1.5´ from the peak of the X-ray emission which all have a photometric redshift estimate of about 0.38. Based on this information, we estimate the photometric redshift of the cluster to be $z_{\text{phot}} = 0.38 \pm 0.04$.

A.2. PLCK G285.0−23.7

After a detailed search in the ESO archive of all existing observations within 5´ around the location of PLCK G285.0−23.7, we found ten images taken with SUSI2 and three spectra taken with EMMI, all obtained at the ESO-NTT 3.5 m telescope. The first panel in Fig. A.2 shows the resulting colour composite of the central region of this cluster, based on V (1600 s) and R band (1680 s) images with the SUSI2 instrument at NTT.

Publicly-available WFPC2 images for this region also exist in the HST archive. The second panel in Fig. A.2 shows the reduced colour composite based on the F814W and F606W filter images. Both images have an integration time of 1200 s. From the colour–redshift relation for those images, we derived a redshift for this cluster of $z \sim 0.37$.

A.3. PLCK G286.3−38.4

After a detailed search in the ESO archive of all existing observations within 5´ around the location of PLCK G286.3−38.4, nine images (NTT/SUSI2), and three spectra (NTT/EMMI) were found. The spectroscopic data from NTT/EMMI are associated with a proposal to characterise the optical counterpart of a potential galaxy cluster associated with the X-ray source RX J0359.1−7205.

We undertook data reduction of the three EMMI spectra using standard IRAF routines. Figure A.3 shows the combined

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5 http://archive.eso.org
6 http://www.eso.org/sci/facilities/lasilla/telescopes/ntt/
7 http://archive.eso.org/wdb/wdb/hst/science/query
Appendix B: Search for large scale structure in the field of PLCK G214.6+36.9 using SDSS

We searched for superclusters in the direction of PLCK G214.6+36.9 by calculating the luminosity density field of the spectroscopic sample of luminous red galaxies (LRG) from the SDSS DR7. To correct for the finite width of the survey magnitude window, galaxy luminosities were weighted. Superclusters are delineated by an appropriate luminosity density level. For the LRG superclusters, we set this level at 3.0 times the mean density. This level was obtained by comparing the SDSS main galaxy sample superclusters with those in the LRG sample in the volume where these samples overlap. The procedure is explained in detail in Liivamägi et al. (2010).

The best candidate is a supercluster containing 10 LRGs with a mass centre at RA = 137.5°, Dec = 13.6°, lying at z = 0.45. Since each LRG likely indicates the presence of a galaxy cluster (like the two LRGs that lie in the observed X-ray clusters) the supercluster is likely to contain 10 clusters. The estimated total luminosity of the supercluster is $3 \times 10^{13} L_\odot$, the maximum extent about 70 h$^{-1}$ Mpc. The co-moving distance along the line-of-sight between the two LRGs hosted by the X-ray clusters is about 4.1 h$^{-1}$ Mpc. Using a $M/L$ value of 200 (in solar units), the total mass of the supercluster is about $10^{15} M_\odot$. This supercluster is typical among other LRG superclusters at that distance. Figure 12 shows the projected luminosity density contours of the candidate supercluster, together with the location of the PLCK G214.6+36.9 and the X-ray clusters.

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Fig. A.3. Reduced spectrum for PLCK286.0-38.4, based on the EMMI data obtained from ESO archives. A cross-correlation analysis yields a redshift of $z = 0.307$, which is consistent with the preliminary estimate of the two absorption features Hβ and Mg-I which are also indicated in the figure.

Fig. B.1. Projected luminosity density map for the best supercluster candidate. The X-ray sources are marked by triangles, the SZ source by the cross. The minimum density level and the level step are $10^{-11} L_\odot$ per square degree.

final spectrum. Although this spectrum has a very low signal-to-noise ratio, a preliminary redshift estimate could be obtained from cross-correlating the reduced spectrum with a reference template spectrum for an early-type galaxy (taken from http://www.arcetri.astro.it/~k20/), using the IRAF routine XCOR. The derived redshift estimate is $z = 0.307 \pm 0.003$, although the significance of the cross-correlation peak is very low. Nevertheless, this redshift estimate is apparently compatible with the preliminary identification of two absorption features (Hβ and Mg-I) in the reduced spectrum (see Fig. A.3), which gives us more confidence in the result.
