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BeppoSAX OBSERVATIONS OF HIGHLY LUMINOUS CLUSTERS OF GALAXIES

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We present an analysis of *BeppoSAX* observations of three clusters of galaxies which are amongst the most luminous in the Universe: RXJ1347-1145, Zwicky 3146 and Abell 2390. We constrain, with a relative uncertainty of between 7 and 42 per cent (90 per cent confidence level), the mean gas temperature in the three clusters. These measurements are checked against any possible non-thermal contribution to the plasma emission and are shown to be robust. We confirm that RXJ1347-1145 has a gas temperature that lies in the range between 13.2 and 22.3 keV at the 90 per cent confidence level, and is larger than 12.1 keV at 3σ level. The existence of such a hot galaxy cluster at redshift of about 0.45 implies an upper limit on the mean mass density in the Universe, $\Omega_{\rm m}$, of 0.5.

1 Introduction

The X-ray emitting gas in clusters of galaxies cools by the emission of energy on a time scale which depends on the temperature and density of the intracluster medium (ICM). Where the density is higher, in the cores of the clusters, the cooling is more efficient and the temperature falls. To support the outer layers of gas, a subsonic flow of gas occurs towards the central region, producing a *cooling flow* that appears in X-rays as an enhancement of the central peak in the surface brightness profile and with a spectrum that presents multiple temperature components.

The stronger the cooling flow, the higher the X-ray luminosity which arises from both the thermal energy lost by the cooling gas and the gravitational work done to maintain the gas at constant pressure. Therefore, to compare global cluster gas properties with theoretical and numerical predictions, that, at present, cannot model the radiative cooling in detail, we need to account fully for the effects of cooling flows on the temperature and luminosity measurements (Fabian et al. 1994, Allen & Fabian 1998, Markevitch 1998).

In this work, we present data collected with the instruments onboard of the Italian-Dutch satellite *BeppoSAX* (Boella et al. 1997) for three highly luminous ($L_{\rm bol} > 10^{45}$ erg s^{-1}), hot ($T_{\rm gas} > 10$ keV), distant ($z > 0.2$) clusters of galaxies with large ($> 1000 M_{\odot}$ yr^{-1}) mass deposition rates in their cores (Allen 2000):

1. RXJ1347-1145 is a lensing cluster at redshift 0.451 found in the *ROSAT* All Sky Survey (Schindler et al. 1995, 1997), with a slightly elongated X-ray structure around a very

peaked central emission as it appears in the *ROSAT* HRI image. Analyses of the *ASCA* dataset provide temperature estimates ranging from $9.3^{+1.1}_{-1.0}$ keV (Schindler et al. 1997), when a single temperature model is adopted, to $26.4^{+7.8}_{-12.3}$ keV (Allen 2000), when a multi-phase gas is considered. Its bolometric luminosity is 2×10^{46} erg s^{-1}, with a depostion rate of about 3000 $M_{\odot}$ yr^{-1}. It has been observed for 73 ksec from *BeppoSAX* on January 2000.

2. Zwicky 3146 (Z3146; z =0.291) is the fourth ranked luminous cluster in the *ROSAT* band as reported in the Brightest Cluster Sample (BCS, Ebeling et al. 1998). Its massive cooling flow i($\sim 2200 M_{\odot}$ yr^{-1}) has been inferred from the strong optical lines and blue continuum exhibited by its central galaxy and has been studied with *ROSAT* HRI (Edge et al. 1994). Allen (2000) quotes an *ASCA* estimate of the gas temperature corrected from the cooling flow of $11.3^{+5.8}_{-2.7}$ keV. It has been observed for 38 ksec from *BeppoSAX* on December 1999.

3. Abell 2390 (A2390; z =0.228) is the sixth ranked luminous cluster in the *ROSAT* band in the northern sky (BCS, Ebeling et al. 1998), has been widely studied in the X-ray waveband (Ulmer et al. 1986, Böhringer et al. 1998) and optically rich (Abell, Corwin & Olowin 1989, Yee et al. 1996). It presents evidence of strong and weak lensing (Pello et al. 1991, Pierre et al. 1996, Squires et al. 1996). For A2390, Böhringer et al. (1998) measure $kT_{\rm gas} \sim 9$ keV when an isothermal model is used to fit the *ASCA* data. Once they add a cooling flow component and consider a *ROSAT* PSPC–*ASCA* joint fit, the temperature rises to $11.1^{+1.5}_{-1.6}$ keV. Using the *ASCA* dataset only, Allen (2000) measures $kT_{\rm gas} = 10.13^{+1.22}_{-0.99}$ keV with a single isothermal model, that rises to $14.5^{+15.5}_{-5.2}$ keV with a cooling flow component (with $\dot{M} \sim 1500 M_{\odot}$ yr^{-1}) is included in the spectral fit. *BeppoSAX* has observed this cluster for 76 ksec on May 1999.

Using data from both the Low Energy (LECS, 0.5–4 keV) and Medium Energy (MECS, 2–10 keV) Concetrator Spectrometer and a joint analysis with the Phoswich Detection System (PDS) data above 15 keV, we show that it is possible to constrain at a high level of significance the hard tail of the bremsstrahlung emission.

2 Spectral analysis

The spectra obtained from the three instruments are plotted in Fig. 2. The results of the fitting analysis are presented in Table 1. As comparison, we show the results for a thermal fit to the MECS data only. In the same Table, we also present the results obtained from fitting two further models that include an additional contribution to the single-phase plasma: (i) a power law that can take into account any non-thermal contamination from an unresolved active galaxy; (ii) an intrinsically absorbed cooling flow component which can model the emission from the central multi-phase gas (see also discussion for the *ASCA* data in Allen & Fabian 1998). The aim in fitting these models is to check the robustness of the gas temperature estimates against any additional contribution to the thermal emission. We note, however, that the LECS, which provides data in the soft X-ray part of the spectrum and is used to constrain the intrinsic absorption and the normalization of the cooling flow component, has an energy resolution (FWHM) of about 11 per cent at 3 keV, that is comparable to *ASCA* Gas scintillation Imaging Spectrometers (GIS) but is poorer by a factor of 4 than the Solid state Imaging Spectrometers (SIS), which also has an effective area larger by a factor of 10 than the LECS. Therefore, any constraint on the modeling of the low-energy spectrum obtained through the "1T+CF" model will be less tight of that provided *ASCA* data (see Allen 2000). In our analysis, we placed lower and upper limit on the intrinsic cluster absorption of 10^{19} and 10^{22} cm^{-2} respectively. We flag as *unc* the values which are unconstrained within these bands by our analysis.

Table 1: Best-fit spectral parameters. The errors are at 90 per cent confidence limit. The absorption is fixed to the respective Galactic value and the redshift to the optical estimate. The model used in XSPEC is `phabs(mekal)` (1T), `phabs(mekal+zphabs(powerlaw))` (1T+pow), `phabs(mekal+zphabs(cfmodel))` (1T+CF). The column "$\dot{M}$-pow" quotes the deposition rate for the 1T+CF model, the photon index of the power law for the 1T+pow model. The column "$L_{2-10\rm keV} - L_{\rm bol}$" quotes either the luminosity in the 2–10 keV band for the fit on only MECS data or the expected contribution in the same band from any power law component (given the nominal values of the fit and upper limit at 90 per cent confidence level for a fixed photon index of 2) or the bolometric value calculated from the 1T+CF model. Note that *unc* means unconstrained.

data	Model	kT keV	abundance $Z/Z_\odot$	χ^2_ν (d.o.f.)	$\dot{M}$-pow	$L_{2-10\rm keV} - L_{\rm bol}$ 10^{44} erg s^{-1}
			RXJ1347-1145			
only MECS	1T	$14.25^{+1.79}_{-1.48}$	$0.51^{+0.19}_{-0.17}$	0.989 (131)	–	83.5
LE+ME+PDS	1T	$14.48^{+1.76}_{-1.46}$	$0.52^{+0.19}_{-0.18}$	0.993 (207)	–	–
	1T+pow	$14.77^{+1.83}_{-1.52}$	$0.52^{+0.20}_{-0.17}$	0.991 (204)	> 3.50	$(0.03, < 13.4)$
	1T+CF	$15.88^{+6.47}_{-2.66}$	$0.55^{+0.21}_{-0.19}$	0.999 (205)	< 1999	204.0
			Z3146			
only MECS	1T	$7.26^{+0.90}_{-0.75}$	$0.33^{+0.13}_{-0.12}$	0.904 (97)	–	32.4
LE+ME+PDS	1T	$7.60^{+0.92}_{-0.77}$	$0.33^{+0.13}_{-0.12}$	0.992 (141)	–	–
	1T+pow	$7.44^{+0.92}_{-0.79}$	$0.33^{+0.13}_{-0.12}$	0.974 (138)	unc	(< 14.2)
	1T+CF	$7.75^{+3.47}_{-0.86}$	$0.33^{+0.14}_{-0.12}$	1.003 (139)	< 1267	69.6
			A2390			
only MECS	1T	$9.76^{+0.76}_{-0.68}$	$0.30^{+0.08}_{-0.08}$	0.991 (142)	–	34.7
LE+ME+PDS	1T	$10.17^{+0.77}_{-0.69}$	$0.29^{+0.09}_{-0.08}$	1.074 (263)	–	–
	1T+pow	$10.19^{+1.71}_{-2.75}$	$0.37^{+0.13}_{-0.12}$	1.041 (260)	$2.69^{+2.68}_{-1.31}$	$(6.4, < 11.6)$
	1T+CF	$10.67^{+0.91}_{-0.80}$	$0.31^{+0.08}_{-0.08}$	1.058 (261)	522^{+308}_{-337}	78.3

The quoted pseudo–bolometric luminosity is estimated over the energy range 0.01–100 keV for the "1T+CF" model.

Generally, all of the spectral fits provide an acceptable reduced χ^2. Only A2390 shows a constrained contribution from a power-law component with a luminosity less than 10^{45} erg s^{-1} (2–10 keV) and a photon index of $2.69^{+2.68}_{-1.31}$ consistent with the typical value for quasars.

3 Conclusions

From the *BeppoSAX* observation, we can constrain the ambient temperature in the clusters of galaxies RXJ1347-1145, Z3146 and A2390 with a relative uncertainty of (17/41), (11/41), (7/9) per cent in the (lower/upper) boundary (at the 90 per cent confidence level) respectively, when a cooling flow model is included in the spectral analysis.

Although the instrument characteristics of *BeppoSAX* do not allow us to constrain firmly any absorption intrinsic to the cluster atmosphere and/or the normalization of the emission from the central cooling gas, the measurements of the ambient gas temperature are in agreement, within the 90 per cent confidence level, with the results from the analysis of *ASCA* data in Allen (2000). In particular, the plasma temperature in RXJ1347-1145 appears well defined between 13.2 and 22.3 keV (90 per cent confidence level) and above 12.1 keV at the 3σ level.

Following the arguments of many authors (e.g. Bahcall & Fan 1998, Donahue et al. 1999, Henry 2000) the existence of such a hot cluster at redshift 0.45 is highly unlikely in an Ein-

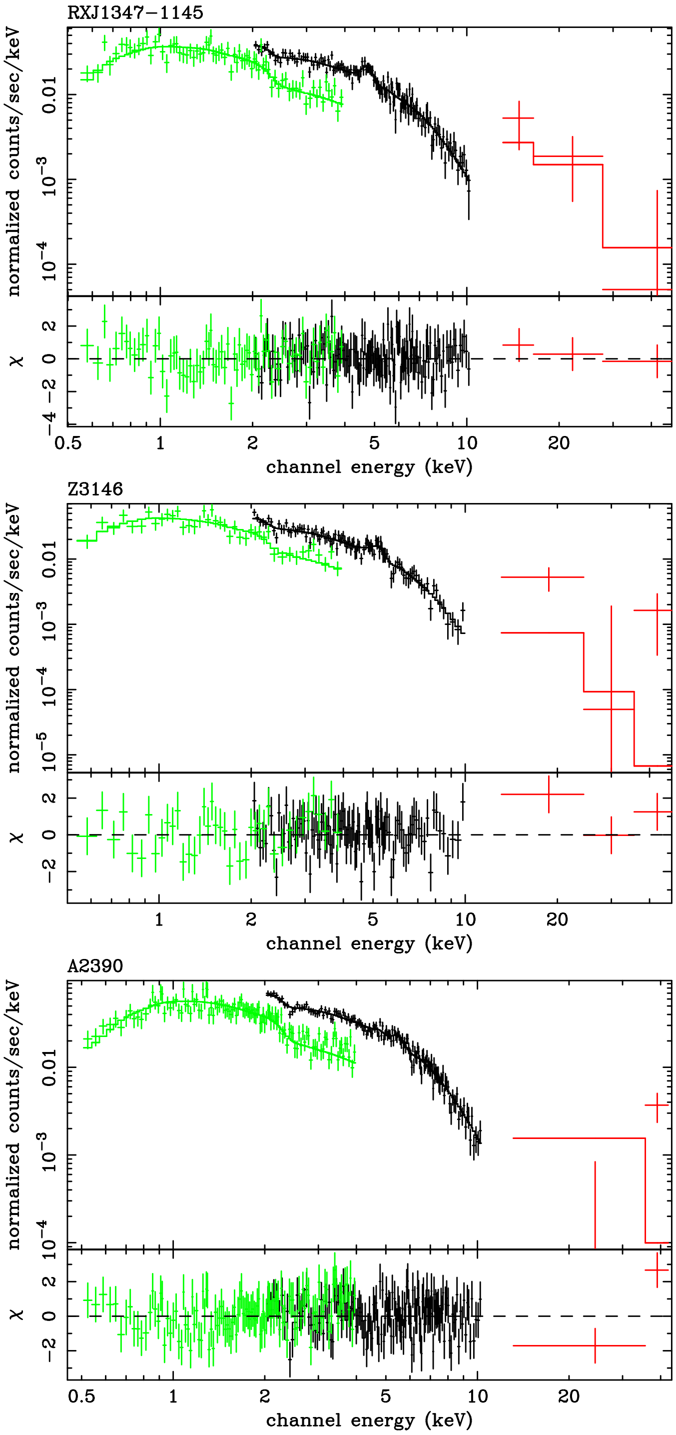

Figure 1: Data and best-fit folded MEKAL model absorbed by Galactic absorption. We plot the result of the joint fit analysis of the LECS, MECS and PDS data and the corresponding residuals in terms of σ.

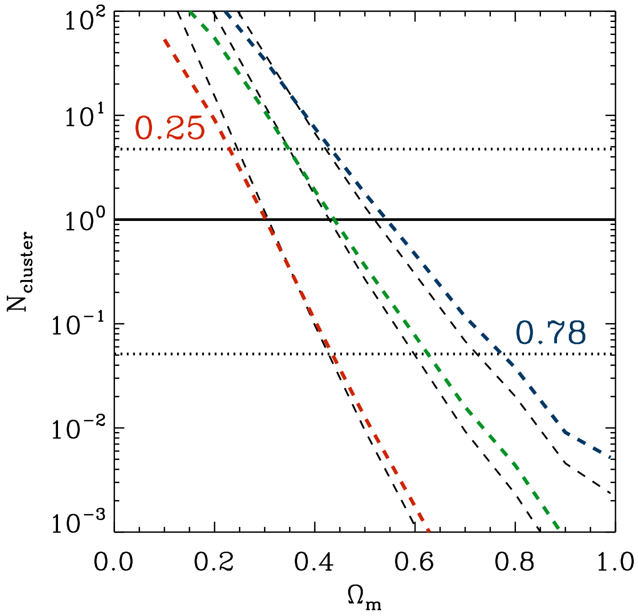

Figure 2: The expected number density of clusters with gas temperature larger than 13.2, 15.9, 22.3 keV (from right to left in the figure, respectively; cf. Table 2 for the constraint on the gas temperature of RXJ1347-1145) in the redshift interval $[0.4, 0.5]$. The dashed lines represent the distribution in a "$\Omega_m + \Omega_\Lambda = 1$" Universe (thick) and in a open Universe (thin). The error bars, around the observed value of 1 cluster with the given characteristics, are at the 90 per cent level of confidence, according to the Poisson single-sided distribution tabulated in Gehrels (1986).

stein – de Sitter universe. We can estimate this probability, calculating the expected evolution of collapsed structures with a given minimum mass according to the Press-Schechter (1974) formalism. Integrating the number of collapsed objects with gravitating mass above that corresponding to a temperature of 15.9 keV over the redshift range of $0.4 - 0.5$, and requiring *at least* the existence of RXJ1347-1145, the single detection provides a stringent upper limit of $\Omega_m <$ 0.46. Considering also the lower and upper end of the range of the acceptable gas temperature of 13.2 and 22.3 keV, with the 90 per cent uncertainty on the single detection, we constrain the cosmological parameter Ω_m between 0.25 and 0.78 (cf. Fig. 3).

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