Cluster science from ROSAT to eROSITA

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Galaxy clusters are one of the important cosmological probes to test the consistency of the observable structure and evolution of our Universe with the predictions of specific cosmological models. We use results from our analysis of the X-ray flux-limited REFLEX cluster sample from the ROSAT All-Sky Survey to illustrate the constraints on cosmological parameters that can be achieved with this approach. The upcoming eROSITA project of the Spektrum-Roentgen-Gamma mission will increase these capabilities by two orders of magnitude and importantly also increase the redshift range of such studies. We use the projected instrument performance to make predictions on the scope of the eROSITA survey and the potential of its exploitation.

1 Introduction

To perform cosmological tests with observations of the galaxy cluster population is one of the major goals of the eROSITA X-ray All-Sky Survey project (Predehl et al. 2011). Galaxy clusters offer themselves as one of a few important cosmological probes that can be used to constrain cosmological parameters essentially by assessing the statistics and growth of the large-scale structure in the Universe (e.g. Böhringer et al. 2011, Vikhlinin et al. 2009). The detection of galaxy clusters in X-rays has the advantage that (i) the X-ray emitting plasma indicates a massive gravitationally bound object which can hold the hot plasma in place and (ii) the X-ray luminosity is tightly correlated to the cluster mass such that we have a method that is nearly mass selective. Therefore X-ray surveys are currently the most efficient approach for cosmological cluster studies.

The ROSAT X-ray All-Sky Survey (RASS, Trümper 1993) offers the best data base to construct a sample of the low redshift galaxy cluster population, which can be used for such cosmological tests. We therefore use our X-ray flux-limited RASS based galaxy cluster surveys REFLEX and NORAS here to illustrate the potential of galaxy cluster studies for cosmology. The eROSITA survey (Predehl et al. 2011) will have a sensitivity which is about 30 times better than that of the RASS and will not only dramatically increase the statistics of the cluster sample, but also bring in a new dimension by allowing us to study the evolution of the galaxy cluster population and the growth of cosmic structure over an extended redshift range up to \( z \sim 1.5 \). In the second part of this article we illustrate these capabilities of the German eROSITA instrument on board of the Russian Spektrum-Roentgen-Gamma space craft for cosmological and astrophysical galaxies cluster studies.

2 The REFLEX galaxy cluster survey

The REFLEX cluster survey covering the southern sky below declination +2.5 deg comprising currently 914 clusters with only 10 objects without spectroscopic redshifts is the best and most complete X-ray galaxy cluster sample available (Chon & Böhringer 2012). The REFLEX II sample as a whole extends the flux limit of REFLEX I from \( 3 \times 10^{-12} \text{ erg/s/cm}^2 \) to \( 1.8 \times 10^{-12} \text{ erg/s/cm}^2 \) in the 0.1-2.4 keV ROSAT band. The construction of the survey is described in detail by Böhringer et al. (2012).

Fig. 1 shows the sky distribution of the extended REFLEX survey (REFLEX II) comprising 914 objects together with the northern NORAS sample. We have conducted a number of cosmological studies with the older REFLEX I sample (Böhringer et al. 2001, 2004, 2011, Collins et al. 2001, Schuecker et al. 2003a,b) comprising 447 clusters. In the top panel of Fig. 2 we show the X-ray luminosity function for the clusters of REFLEX I with a median redshift of \( z = 0.08 \) (Böhringer et al. 2002). We also show a fit of a cosmological model prediction for this function with the cosmological parameters of \( \Omega_m = 0.28, \sigma_8 = 0.79 \), a Hubble constant of \( H_0 = 70 \text{ km/s/Mpc} \) and assuming a flat Universe, where the first two parameters have been varied for the fit. The mass function for the clusters has been calculated based on the recipe of Tinker et al. (2008) and converted to a luminosity function by means of the X-ray luminosity - mass relation from Reiprich and Böhringer (2002). In the lower panel we show how well the two cosmological parameters are constrained. These results provided the best...
constraints of the amplitude parameter of the matter density fluctuations in the Universe, $\sigma_8$, even before the first cosmic microwave results from the WMAP satellite became available. Combining the cluster abundance above a certain X-ray luminosity with the large-scale spatial distribution of the REFLEX clusters Schuecker et al. (2003a,b) obtained similar tight constraints and showed in combination with data from distant supernovae (Perlmutter et al. 1999) that the equation of state parameter, $w$, of Dark Energy is consistent with a value of -1 and thus also with a cosmological constant with an uncertainty of less than 30%, a remarkable result when it was published in 2003.

The REFLEX II galaxy cluster sample increases the size of these studies by a factor of two which already provides additional insights, e.g. into the way the density contrast in the distribution of the clusters is amplified with respect to the density fluctuations of the matter, an effect called biasing. Our results by Balaguera-Antolinez et al. (2011) based on REFLEX II show that this biasing increases with increasing X-ray luminosity of the clusters in the sample exactly in the way predicted by the statistical theory of the large scale structure. This result is a very important reassurance that our theory of structure formation, on which the described cosmological tests rest, cannot be grossly wrong. Further studies on the cosmic large-scale structure and on the constraints of cosmological parameters with REFLEX II are under way and they will pave the way for the data analysis to be performed on the much larger eROSITA cluster sample.

3 eROSITA cluster cosmology

As it has been successfully shown with the REFLEX catalogue, a well-understood large catalogue of clusters of galaxies is an invaluable tool to understand the large-scale structure in our universe as well as cosmology. The future X-ray mission, eROSITA aims to obtain many more clusters by probing deeper flux and higher redshifts. With the eROSITA telescopes we expect an improvement of two orders of magnitude in the sample size compared to the ROSAT survey.

The relevant specification and expected performance of the eROSITA telescope can be briefly summarised as following. Its energy range covers 0.2-10 keV probing much wider energy range than ROSAT. With its angular resolution of less than 13 arcsec on axis and 28 arcsec on average...
over the whole field of view, it improves the sharpness of
the X-ray imaging by a factor of 3 in linear scale.

With the wide redshift coverage of eROSITA clusters of
galaxies also become sensitive probes of dark energy, which is readily shown in Fig. 3. The upper panel shows the growth function of the amplitude of dark matter fluctuations as a function of redshift. The solid line represents the concordance model with the dark energy equation of state parameter, \( w = -1 \). Two curves above this model are for smaller values of \( w \) and the two below are for the larger values. They differ by 25% incrementally. Apart from the lowest redshift it is quite clearly shown that the growth function depends sensitively on the assumptions about the dark energy parameter. The second panel in Fig. 3 shows our prediction for the detected number of clusters with the eROSITA survey assuming that we can confirm the cluster candidate with 100 photon counts. The curves correspond exactly to the cosmological models shown in the upper panel of Fig. 3. By measuring the number count of clusters over a range of redshifts we can clearly distinguish different dark energy models, especially if higher redshifts are included.

While there are some uncertainties in these predictions depending on the exact cosmological model used and due to our currently imperfect knowledge of the redshift evolution of the X-ray luminosity – mass scaling relations, we clearly note that one expects to detect of the order of 100,000 clusters, with a good redshift coverage up to unity and several hundred clusters at redshift up to \( z \sim 1.5 \).

The types of clusters that the eROSITA survey is expected to see is shown in the lower panel of Fig. 3. Here we show the detected number of clusters as a function of redshift according to their masses. There are two clear effects shown. We see that the most massive clusters are becoming rare at the highest redshifts. This is due to the fact that clusters of this mass are just starting to form. The other point shown by the clusters with the least mass is that we will be able to detect many local groups, however, given the sensitivity of the instrument, we run out of them soon after redshift, \( z = 0.2 \).

4 eROSITA cluster astrophysics

The eROSITA survey will also allow us to greatly improve our capabilities of astrophysical studies of clusters. The basis of many of such studies will be the fact that we will detect several thousand clusters with more than 1000 and more than 10000 clusters with more than 500 source photon counts. For these clusters more detailed information can be obtained, for example, on the temperature of the intracluster medium through a spectral analysis of the X-ray radiation as shown in Fig. 4. The simulation shown in the figure was performed for a cluster with a temperature of 4 keV at \( z = 0.2 \) for 1000 source counts in a 2 ks exposure. A realistic instrumental and sky background spectrum were added and subsequently subtracted with a different photon statistical realisation.
With increasing temperature the uncertainty of the temperature measurement gets larger due to the fact that at lower temperature there are more features in the spectrum which change with temperature variations.

The X-ray determined cluster temperature is a much better mass proxy than the X-ray luminosity (e.g. Kravtsov et al. 2006). The eROSITA survey will thus allow very detailed studies of e.g. the X-ray luminosity - temperature relation with an assessment of several important bias effects, which will also lead to an improvement of the mass calibration for the cosmological modeling described above. These photon numbers will also allow important statistical studies on the morphology of galaxy clusters, through the study of substructure characterizations as shown in Böhringer et al. (2011). Such studies will in the end help to characterize the degree of virial relaxation of the clusters as a function of their mass and their redshift, an information that will give insights into the formation history of galaxy clusters and further improve our understanding of making cosmological predictions of the observable statistics of the galaxy cluster population for cosmological tests. Many more interesting studies will be possible, which cannot be described in this short article.

5 Summary

X-ray clusters of galaxies with a well-understood selection function have been one of the most successful tools to investigate variety of astrophysical and cosmological questions. With the expected launch of the eROSITA instrument in 2014 we anticipate a leap forward in understanding the evolution of the large-scale structure and dark energy. We will also obtain a comprehensive picture about the structural evolution of clusters from $z = 1$ to the present. Pointed observations with eROSITA that will be possible after the completion of the survey will enable deeper studies of well-selected study samples of clusters from the eROSITA survey.

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References

Balaguera-Antolínez, A., Sanchez, A., Böhringer, H., et al.: 2011, MNRAS, 413, 386
Böhringer, H., et al.: 2000, A&A
Böhringer, H., Schuecker, P., Guzzo, L., et al.: 2001, A&A, 369, 826
Bühringer, H.; Schuecker, P.; Guzzo, L., et al., 2004, A&A, 425, 367
Böringer, H., et al.: 2008, A&A
Böhringer, H.: 2011, APIC, 1381, 137
Böhringer, H., Chon, G., Collins, C., et al.: 2012, A&A, submitted
Chon, G., Boehringer, H.: 2012, A&A, 538, 35
Collins, C., Guzzo, L., Böhringer, H. et al.: 2000, MNRAS, 319, 939
Kravtsov, A., Vikhlinin, A., Nagai, D.: 2006, ApJ, 650, 128
Pettine, S., Aldering, G., Gladaberg, G., et al.: 1999, ApJ, 517, 565
Priedesl, P., Andritschke, R., Becker, W., et al.: 2011, SPIE, 8145, 247
Reiprich, T., Böhringer, H.: 2002, ApJ, 567, 716
Schuecker, P., Böhringer, H., Collins, C., et al.: 2003a, A&A, 398, 867
Schuecker, P., Caldwell, R., Böhringer, H., et al.: 2003b, A&A, 402, 53
Tinker, J., Kravtsov, A., Klypin, A., et al.: 2008, ApJ, 688, 709
Trümper, J., 1993, Science, 260, 1769
Vikhlinin, A., Kravtsov, A., Ebeling, H., et al.: 2009, ApJ, 692, 1060