Simulating the source parameter recovery capability from coronal X-ray spectra: the SAX/LECS and the ASCA/SIS cases

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Abstract.

We have studied the performance of global χ^2 fitting applied to low-resolution X-ray spectroscopy, focusing on the retrieval of source parameters, with emphasis on the coronal metallicity. The study has been conducted by fitting large numbers of simulated spectra with known characteristics, and studying the distribution of the best-fit parameters, using the responses of the LECS detector onboard the SAX satellite and of the SIS detector onboard the ASCA satellite.

The simulations have been done under the hypothesis that the intrinsic source spectrum can be described by two discrete temperatures. The performance of the fitting process has been studied both in the case in which just the global metallicity is left free to vary and in the case in which the abundance of each element is independently left free to vary in the fit process.

1. Introduction

The interaction between the intrinsic complex spectral shape (dominated by emission lines), the instrumental response, the uncertainties in the underlying atomic physics and the fitting process make the evaluation of the confidence regions for the best-fit parameters of coronal spectra, even only considering the presence of statistical noise in the observed spectrum, not obvious. The χ^2 fitting process in principle supplies rigorous criteria for the evaluation of confidence regions on the fitted parameters (Lampton et al. 1976; Avni 1976), which are however, strictly speaking, only valid in the presence of a number of clearly defined theoretical assumptions. The applicability of the above framework to the determination of several parameters from the low- or moderate-resolution X-ray spectra of coronal sources (i.e. with resolutions $\Delta E/E \gtrsim 10\%$) is however not granted, and needs to be verified experimentally. Moderate resolution X-ray spectra have in the last few years frequently been used to determine, under the assumption that the intrinsic thermal structure can be approximated in some pre-defined parametric way (most often simply with two discrete iso-thermal components, i.e. a two-temperature model, although also other parameterizations have been used), both the parameters of the thermal structure (temperatures and emission measures) as well as the elemental abundance in the emitting plasma. The abundance pattern in the plasma has been modeled either as a single parameter in the fit (i.e. assuming solar abundance ratios) or as individually varying abundances for the different elements contributing to the observed spectrum.

The determination of the coronal abundance mix is obviously of interest, given, for example the dependence of the plasma cooling function on its composition. Also, if the photospheric abundance mix is known, possible differences between the photospheric and coronal abundance patterns would point toward the presence of fractionation mechanisms. Such mechanisms are for example observed in the solar wind, in which a selective enrichment is seen, depending on the first ionization potential (FIP) of the element.

A reliable determination of the uncertainties on the parameters retrieved from the best-fit process as a function of, for example, source spectrum statistics, or of the spectral parameters themselves (for example how does the sensitivity to metal abundance vary as a function of source temperature) is necessary to assess the significance of the eventual observed "anomalous" abundance patterns. Given the strongly non-linear nature of the process leading from the intrinsic physical parameters to the observed spectrum and back to the best-fit parameters, simulations are necessary to evaluate the size and shape of the confidence regions on the derived best-fit parameters.

We have undertaken a program of simulations to determine the capability of χ^2 fitting in retrieving the spectral parameters using coronal spectra obtained from present-day non-dispersive X-ray spectrometers. We have been considering data from the two instruments with the combination of spectral resolution and coverage more favorable for the study of coronal spectra, i.e. the SIS onboard the ASCA satellite and the Low-Energy Concentrator Spectrometer (LECS) onboard the SAX satellite.

In the first part of the simulation work abundances in the source spectrum have been modeled as varying in lockstep (i.e. with solar abundance ratios), and fit with a model in which only the global abundance Z is left free to vary. Results of this work for both the LECS and the SIS have been discussed in detail in Favata et al. (1997). In the present paper we briefly review these results, as well as present preliminary results for the case in which the coronal abundance ratios are non-solar, and thus individual metal abundances are left free to vary in the fitting process.

2. Instrumental characteristics

The LECS instrument (Parmar et al. 1997) is a Xe-filled drift-less gas scintillation proportional counter with a thin entrance window, providing continuous energy coverage in the spectral range from 0.1 to 10 keV. Its absolute spectral resolution is energy-dependent (varying as $E^{+0.5}$), and becomes comparable to the resolution of the CCD-based SIS detector at $\simeq 0.5$ keV.

The SIS instrument is a CCD-based non-dispersive X-ray spectrometer, providing energy coverage in the band from 0.5 to 10.0 keV, with an approximately constant absolute energy resolution, which is effectively decreasing with time because of the radiation damage of the CCD chip (Dotani et al. 1996). At the time of the launch the effective resolution was $\simeq 100$ eV at 1 keV, with the precise value depending on the details of the instrumental mode being used. The effective area and the spectral resolution of both instruments are shown in Fig. 1 of Favata (1997).

The two instruments are somewhat complementary: the better spectral resolution of the SIS at higher energies has as counterpart the significantly broader energy coverage of the LECS, extending down to 0.1 keV. The additional energy coverage of the LECS is specially relevant to coronal sources because of (1) the high photon flux at low energies for typical coronal sources and (2) the relatively line-free nature of the spectrum visible between $\simeq 0.15$ and $\simeq 0.4$ keV.

3. The simulations

The aim of the present work is mainly to assess the intrinsic limitations of the χ^2 fitting process in retrieving the spectral parameters of coronal low-resolution spectra. For this purpose, an extensive set of simulations has been performed. For most simulations, the source spectrum has been assumed to be emitted by two distinct isothermal components, i.e. a so-called "two-temperature" spectrum, and the same two-temperature model has been used for fitting the spectra. In some cases, more complex source spectra such as power-law distributions have been considered. For each set of parameters, 300 simulations were performed, and the distribution of the best-fit parameters and reduced χ^2 values analyzed.

Most of the two-temperature simulations were done assuming an intrinsic source spectrum with temperatures of 0.5 and 2.0 keV, with identical emission measures; the simulations have been performed for metallicities of 0.15, 0.5 and 1.0 times the solar value and with 2500, 10 000 and 40 000 source counts. The MEKAL (Mewe et al. 1995) plasma emission code as implemented in XSPEC V. 9.01 has been used all along. The fits have been performed in two ways: with the global metallicity left free to vary, and with freely varying individual abundances.

3.1. Globally varying abundance

The results for simulations of fits with one single abundance parameter Z are described in Favata et al. (1997), and will not be reported in detail here for reasons of space. The main results of the Z-only simulations were (1) the better capability of the LECS in comparison with the SIS in determining the source metallicity at a given source statistics, (2) the presence of a strong correlation (specially in the ASCA case) between the derived metallicity and the ratio between the soft and hard emission measure, and (3) the better capability of the SIS in constraining the cool temperature in the spectrum, contrary to the intuitive expectation based on the softer pass-band of the LECS. This last point demonstrates the importance of basing the assessment of instrumental capabilities on detailed simulations rather than on intuitive considerations.

3.2. Individually varying elemental abundances

For the purpose of studying the confidence regions of the best-fit individual abundances, source spectra were simulated with solar abundance ratios, and were fitted by leaving the individual abundances, in the fit process, free to vary. Typical results from the fits are shown in Figs. 1 and 2 for the LECS and SIS respectively. In both figures the total number of counts in the source spectrum was 40 000.

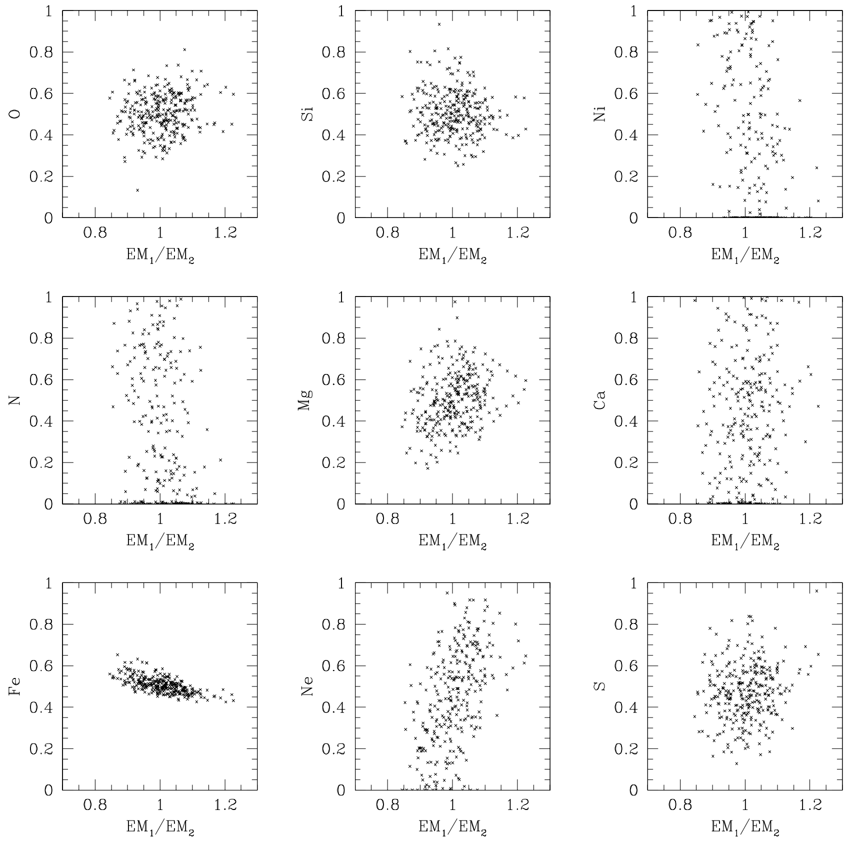

Figure 1. SAX LECS spectra, fit with individual elemental abundances as free parameters: scatter plots of the best-fit individual abundances versus the emission-measure ratio, for a set of 300 realizations, with source coronal abundances 0.5 times solar and with 40 000 counts accumulated per spectrum.

As shown in Fig. 3 when all the abundances are left free to vary, the Fe abundance is determined within $\simeq \pm 20\%$, (at the 90% confidence range) in a spectrum with 40 kcts and intrinsic abundance 0.5 times the solar value, with the LECS determination somewhat better than the SIS one, similarly to the result of the fits with global varying abundances (see Favata et al. 1997). Elements

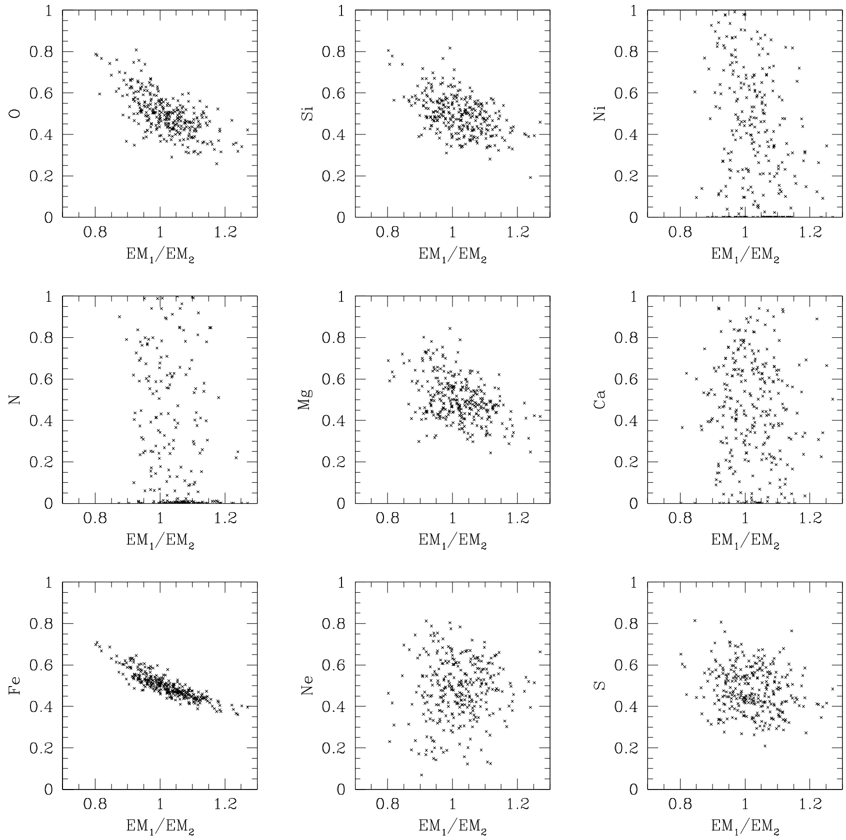

Figure 2. As in Fig. 1 but for the ASCA SIS detector. The spectral parameters and the statistics of the spectra are the same as for the LECS-based simulations of Fig. 1.

such as O, Mg, Si and S are determined (both by the SIS and by the LECS) within ± 40–60% of the actual value, while N, Ar, Ca and Ni are intrinsically ill-determined (in spectra with the temperatures and count statistics assumed here; for sources with significant hotter plasma components – and significant higher statistics – this may improve), with ranges larger than 100% even in these high-statistics spectra. These accuracies degrade rapidly with decreasing source statistics: if the observed spectrum has 10 kcts (see Fig. 4), the Fe abundance can be determined to within $\simeq \pm 40\%$, while none of the other metal abundance can be determined to better than a factor of two (with some of them being even more ill-determined).

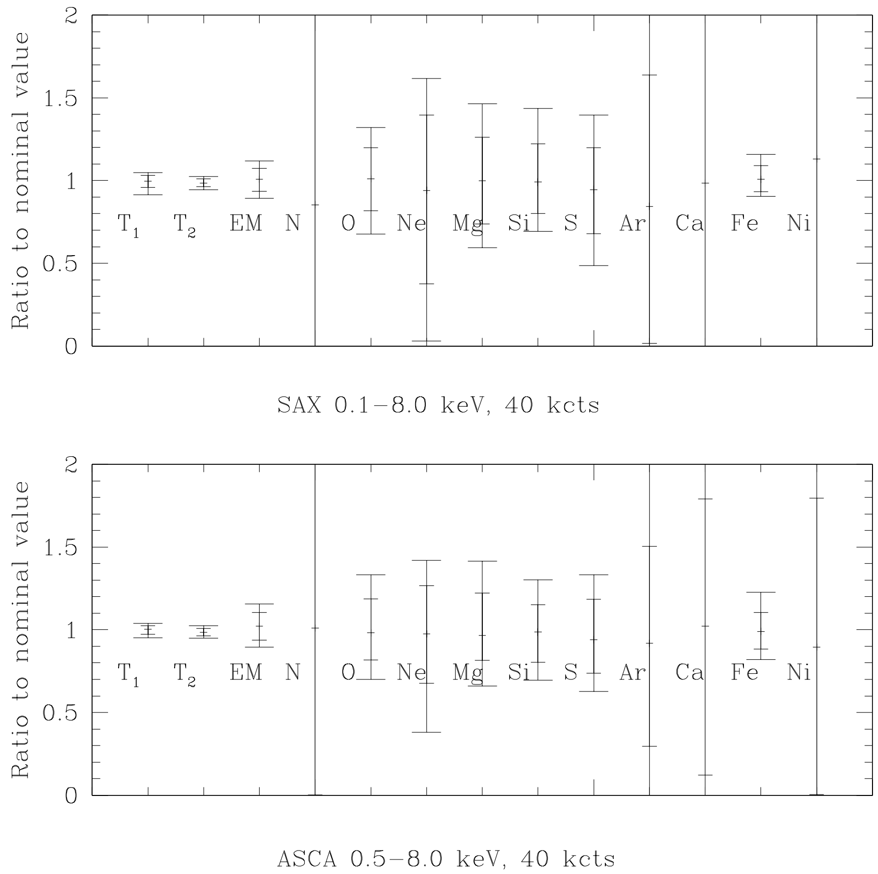

Figure 3. The median best-fit value for all the parameters for the simulations shown in Figs. 1 and 2, together with their 68% and 90% ranges. For ease of display the ratio to the parameter in the source spectrum is reported, thus normalizing all the parameters to 1. The source spectrum is a two-temperature one, with $Z = 0.5$, and all the abundances free to vary in the fitting process. The simulated spectra had 40 kcts.

4. Results

Under the assumption that the metallicity in the source is described as a single parameter (Z), the LECS detector was already shown to be more sensitive to metallicity variations in coronal sources than the SIS (Favata et al. 1997), given the same number of counts in the spectrum. Typical 90% ranges for the global metallicity, for LECS spectra with $\simeq 10\,000$ counts, are of $\simeq \pm 5\%$ for the source temperatures and $\simeq \pm 15\%$ for the source metallicity. While the sensitivity of the SIS to the source temperature is comparable (also at $\simeq \pm 5\%$ in spectra with $\simeq 10\,000$ counts), the sensitivity to coronal metallicity variations is lower, with a 90% range of $\simeq \pm 40\%$.

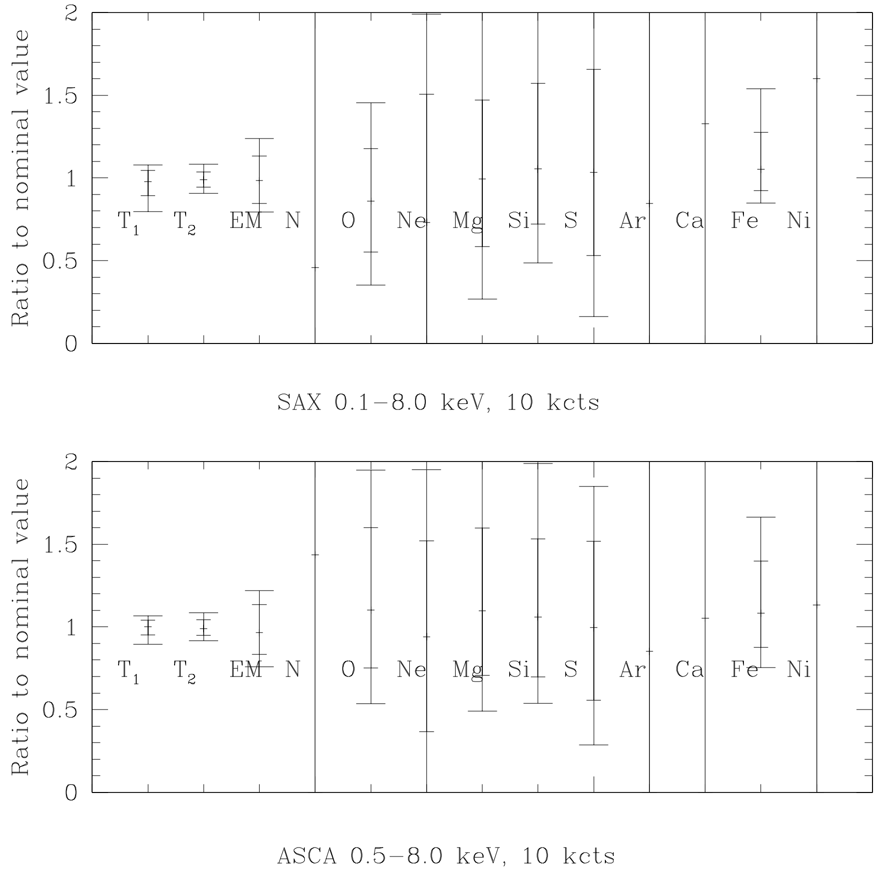

Figure 4. Same plot as in Fig. 3, but for the case of 10 kcts in the simulated spectra.

When all the abundances are fitted simultaneously, the LECS retains its better sensitivity to the Fe abundance, which is the one driving the determination of the global abundance. The reason for the better sensitivity of the LECS lies in the different diagnostics which drive the fitting process in the two cases: in both cases the Fe abundance is essentially determined by balancing the spectrum in the region between 0.7 and 1.2 keV, (where Fe L line emission dominates and where the statistics are best) with the available continuum emission. The region around 1 keV is thus acting as a sort of "pivot" for the fitting process. In the case of the SIS, little free continuum is usually available. The highest-statistics continuum region is between 0.5 and 0.7 keV, in which however the detector's resolution is lowest, and thus the continuum contribution may not be easily disentangled from the nearby line emission. The continuum in the hard tail of the spectrum, typically the small regions between the major K-complexes of heavier elements has, for most coronal sources, low intrinsic source flux, and thus low signal to noise ratio. For LECS spectra the region below 0.5 keV supplies a very well constrained determination of the continuum, and makes the fitting process more robust, explaining the smaller confidence regions.

The correlation between best-fit Fe abundance and best-fit emission-measure ratio is stronger for SIS-based fits (Fig. 2) than for LECS-based ones (Fig. 1). This is a consequence of the lack of continuum in the SIS spectrum: the same balance in the fit can be obtained by decreasing the metallicity and removing hot plasma, or by increasing the metallicity and adding hot plasma.

The uncertainties for elements other than Fe are always significantly larger than for Fe itself, both in the SIS and in the LECS fits, although the SIS performs somewhat better thanks to its higher spectral resolution. Such uncertainties should be taken into account when discussing observed coronal abundance patterns. The coronal abundance of some elements (such as N) appears to be intrinsically ill-determined, and thus special care should be taken in considering these abundance values.

5. Discussion

The simulations shown here assess the influence of the photon noise on the determination of abundances using X-ray spectra from the LECS and the SIS detectors. However, this is an exercise conducted under ideal conditions (i.e. perfectly well known detector response and plasma emission mechanisms). In real cases systematic effects will also be present, i.e. imperfectly know detector calibration, uncertainties in the plasma emission codes, and unknown emission-measure distribution in the source.

These effects are likely to influence the abundance determination in a significant way. While the simulations shown here are thus an upper limit to the achievable accuracy, they show that systematic errors which would often be considered as acceptable, or even negligible, are likely to induce sizable systematic shifts in the source abundance determination. For example, the statistical noise level in a 10 000 counts coronal spectrum is, in the peak (i.e. around 1 keV) $\simeq 2.5\%$ per resolution element (obtained by adding up the counts in the energy range corresponding to the FWHM resolution at 1 keV), with a 40 000 counts spectrum having a noise level twice lower ($\simeq 1.2\%$). A spectrum with this high statistics induces a spread of $\simeq$ 50% in the determination of the abundance of O, Mg, Si and S (with all the other elements except Fe having larger uncertainty). It is then plausible that similar levels of systematic errors in the instrumental response, when present in energy ranges in which the spectrum has high signal-to-noise (and in which the lines of the relevant elements lie) can induce comparable *systematic* shifts in the best-fit parameters. Similar systematic shifts (as shown by Favata et al. 1997) can also be induced by assuming too simplistic an emission-measure distribution for the source.

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