BeppoSAX observations of low-energy spectral features in AGN

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The combination of the broad band coverage and moderate spectral resolution of the LECS and MECS instruments on-board BeppoSAX allow the spectra of AGN to be studied in unprecedented detail down to 0.1 keV. We describe the calibration and the performance of the LECS and report on observations of low-energy absorption features in the spectra of both a low (MCG-6-30-15) and a high luminosity (3C 273) AGN. These features provide important diagnostics on the location and nature of the material surrounding the AGN. A comparison of LECS and ASCA/SIS low energy performance is also presented in the case of 3C 273.

1. Introduction

In the last decade, X-ray observations have provided evidence for complex absorption and emission features in AGN spectra, in particular below ~10 keV. Examples of this complexity are the Kα Fe emission [1] at ~ 6.4 keV and the photoelectric absorption from both neutral and highly ionized (warm) material in the line of sight and associated with the active nucleus [2,3]. The Einstein Observatory and, later, the ROSAT Position Sensitive Proportional Counter (PSPC) were the first to provide strong evidence for warm absorbers [4,5]. This absorption was initially detected by the ROSAT PSPC in the spectrum of the Seyfert galaxy MCG-6-30-15 at an energy of 0.8 keV, consistent with a blend of O vii and O viii K-absorption edges.

The Low Energy Concentrator Spectrometer (LECS) is one of the narrow field instruments (NFI) on-board BeppoSAX [6]. It operates in the energy range 0.1–10 keV. The LECS achieves this extended low-energy response by utilizing a driftless gas cell and an ultra-thin 1.25 μm entrance window. The LECS has particularly good spectral resolution at energies ≤0.5 keV, where instruments such as the Solid State Imaging Spectrometer (SIS) on ASCA are not sensitive [7] and where instruments such as the ROSAT PSPC [8] (0.1–2.5 keV) have only moderate spectral resolution. The energy resolution of the LECS is 32% (full width at half maximum, FWHM) at 0.28 keV and 8.8% at 6 keV. The angular resolution at these respective energies is 9.7′ and 2.1′.

The combination of LECS data with simultaneous data from the other NFI on BeppoSAX, in particular the Medium Energy Concentrator Spectrometer [9] (MECS), which has a higher effective area than the LECS above 1.8 keV and operates in the range 1.3–10 keV, provides a powerful tool for soft X-ray spectroscopy of AGN.

2. Calibration and performance of the LECS

Great care has been taken in the ground calibration of the LECS [6]. However, it is difficult to verify the low-energy response of the LECS in-flight. For instance the Crab Nebula is not detected by the LECS below 0.5 keV due to interstellar absorption. After more than a year of BeppoSAX operations sufficient data were acquired to enable a detailed study of the low energy calibration of the LECS [10].

*The SAX satellite is a joint Italian and Dutch programme. AO acknowledges an ESA Fellowship.
Independently, much effort was spent on improving the LECS response matrix and LECS data analysis pipeline for the second release of the BeppoSAX/LECS software\(^2\) and calibration\(^3\) in September 1997.

The changes to the LECS response matrix include an adjustment in the modeling of the LECS energy resolution to account for alterations in instrumental performance between pre-launch ground calibrations and in-orbit operations in a near-vacuum environment. Improvements to the LECS data analysis pipeline involve a more detailed handling of the LECS burst-length correction\(^6\,11\).

Figure 1 shows the weighted average data-to-model ratio of a sample of 8 AGN whose BeppoSAX raw data (Final Observation Tapes) were readily available. The data were prepared with the old, pre-September 1997 processing (as available on the BeppoSAX data archive) and fit with a broken power-law model including galactic and excess photo-electric absorption\[^{10}\]. A systematic feature is apparent at low energies, in fact, just where the effective area of the LECS has a minimum value (see Fig. 3). The maximum amplitude of fit residuals due to this effect is $\pm 25\%$ of the folded model at a given energy between 0.3–0.5 keV. The feature is also very clearly seen in a larger sample of 26 blazar spectra, thereby confirming that its origin is instrumental.

Figure 2 shows that the instrumental feature is strongly reduced using the September 1997 release of the LECS software and response matrix. The maximum amplitude is now 15% between 0.4–0.5 keV. The remaining feature may be caused by uncertainties in modeling the LECS response at higher energies ($>0.7$ keV) where the effective area is much higher, or by an underestimate of the amount of nitrogen in the LECS window. Such effects will be included in forthcoming versions of the LECS response matrix. In addition, we emphasize that there is no systematic instrumental effect of amplitude $>10\%$ in the energy range 0.1–0.3 keV and above 0.5 keV.

\(^2\)Version V1.7.0 of SAXLEDAS of 01 September 1997. See ftp://astro.estec.esa.nl/pub/SAX/SOFTWARE.
\(^3\)LECS response matrix release of 01 September 1997 (LEMAT V3.4.0). See response matrices in ftp://astro.estec.esa.nl/pub/SAX/RESPONSE.
3. LECS/MECS observations of the warm absorber in MCG-6-30-15

The Seyfert 1 galaxy MCG-6-30-15 was observed during the Science Verification Phase (SVP) of BeppoSAX between 1996 July 29 and August 3 [12,13]. An analysis of the LECS and MECS data [12] confirmed the presence of a complex warm absorber. Figure 4 shows that a simple power-law model with neutral absorption gives a poor fit to the spectrum below 2 keV. The time averaged spectrum between 0.1–4 keV can be well described by a model composed of a power-law (Γ = 2.36 ± 0.38), three absorption edges (χ² = 398.1 for 394 degrees of freedom, the uncertainties are Δχ² = 2.71). Two edges have their energies fixed at the physical rest frame energies of the O vii and O viii K-edges (E₁ = 0.74 keV, E₂ = 0.87 keV, τ₁ = 0.91 ± 0.18, τ₂ = 0.03 ± 0.15) and the third edge is at E₃ = 1.12 ± 0.10 with τ₃ = 0.19 ± 0.08 [12]. The third edge is compatible with Ne ix absorption at 1.20 keV.

The 0.7–1.5 keV and 1.5–4.0 keV light curves of MCG-6-30-15 are shown in Fig. 5, together with the corresponding hardness ratio. Flux variations of a factor of 4 occurred during the observation. In fact, in the first 7 hours of the observation the 0.7–1.5 keV count rate increased four-fold. The results of time resolved spectral analysis are shown in Fig. 6. The main characteristics of the temporal behavior during the BeppoSAX observation of MCG-6-30-15 can be summarized as following:

- The continuum flux and slope as well as the warm absorber are variable on time scales shorter than 2 × 10⁴ s.
- The variations in these two components are not always associated.
- The optical depth of O vii remains approximately constant throughout the observation.
- The optical depth of O viii displays a significant change during the low state at the start of the observation. Thereafter it remains constant, even during changes of continuum flux.

The dissimilar variability patterns of O vii and O viii have been observed previously by ASCA.
Multi-zone or stratified warm absorbers in photo-ionization equilibrium have been suggested as a possible explanation [14]. The apparent lack of correlation of the optical depth of O viii with changes in the continuum flux is different from what ASCA observed [16] and may indicate that simple photo-ionization equilibrium does not apply. This, for instance, can be the case if the electron density of the warm absorber medium is low [15], thereby causing the recombination time-scale of the gas to be longer than the variability time-scale of the ionizing continuum source.

4. LECS/ASCA-SIS observations of the warm absorber in 3C 273

The bright quasar 3C 273 was observed quasi-simultaneously by BeppoSAX and ASCA as part of dedicated program to cross-calibrate the detectors on a number of different X-ray astronomy missions. 3C 273 was observed by BeppoSAX between 1996 July 18-21, during the SVP and by ASCA between 1996 July 16-18. Simultaneous fits to the ASCA/SIS0/SIS1 and the BeppoSAX LECS data show a very good agreement [17] between the data sets below 4 keV. In particular there is no evidence for any systematic deviation in the common energy range 0.6–4 keV. The LECS data above 4 keV have been ignored due to systematic effects caused by the off-axis LECS exposure. Figure 7 shows the data-to-model ratio for the best-fit model below 4 keV ($\chi^2 = 491.1$, with 424 degrees of freedom). The model is composed of two power-laws ($\Gamma_{\text{soft}} = 6.5 \pm 1.7$; $\Gamma_{\text{hard}} = 1.66 \pm 0.02$), neutral absorption (galactic and excess) and an absorption edge ($E_{\text{edge}} = 0.58 \pm 0.02$ keV, in the source rest-frame; $\tau = 0.43 \pm 0.19$). The absorption at $\sim 0.6$ keV in the present LECS data set is the first unambiguous detection in 3C 273 of such a feature [18]. The LECS is the only instrument on BeppoSAX capable of detecting this feature, and the SIS only detects the high energy ($\gtrsim 0.6$ keV) spectrum of the absorption. Therefore, the combination of SIS and LECS data provides a very good means of measuring the feature’s spectral
No other absorption edges are apparent in the range 0.1-4 keV. When attempting to fit an absorption edge to a slight dip at \( \sim 1.3 \) keV (source rest frame) in the SIS spectra in Fig. 7, the improvement in fit statistics is insignificant (less than 95% significance with the F-statistic) and the upper limit of the optical depth is \( \tau = 0.07 \) (90% confidence for one parameter of interest).

A satisfactory identification of the single spectral feature must describe the spectrum self-consistently. The feature may be identified with an O \( \text{II} \) or an O \( \text{III} \) K-edge, which have physical rest frame energies of 0.58 and 0.6 keV, respectively. However, if the edge is O \( \text{II} \) the opacity from He \( \text{I} \) may be significant (see e.g., discussion on absorber in PKS 2155-304, based on the XSTAR photon-ionization code, [19]). Finally, an energy shift due to bulk motion of the absorber (and therefore another identification) cannot be excluded.

**REFERENCES**