Chapter 3

X-ray observational techniques and data reductions

3.1 Introduction: Observing at X-ray wavelengths

X-ray photons coming from cosmic sources are absorbed by the Earth’s atmosphere and therefore, to study the X-ray emission properties of cosmic sources, X-ray detectors are to be placed above the Earth’s atmosphere via balloons, sounding rockets and satellites. Unlike balloon and rocket, satellite instruments can make continuous, long time observations. In 1970s, dedicated X-ray astronomy satellites, e.g., Uhuru, Ariel 5, SAS-3, OSO-8, and HEAO-1 were launched to study the X-ray emission from a variety of astronomical sources, e.g., active galaxies, binary stars with compact companion (such as black holes, neutron stars, white dwarfs), supernovae and their remnants. Seyfert galaxies nuclei emit a substantial fraction of their bolometric luminosity in X-ray wavelengths. We use XMM-Newton and Suzaku (only for NGC 5135) X-ray observations to study the X-ray spectral properties of Seyfert galaxies of our sample. The following sections describe the XMM-Newton, Suzaku instruments and their data reduction as well as analysis procedures.
3.2 \textit{XMM-Newton} X-ray observations

\textit{XMM-Newton} is one of the cornerstone missions of European Space Agency and was launched on December 10th, 1999. There are three types of science instruments are boarded on \textit{XMM-Newton}, viz., European Photon Imaging Camera (EPIC), Reflection Grating Spectrometer (RGS) and Optical Monitor (OM). There are three units of EPIC, two are equipped with MOS (Metal Oxide Semi-conductor) CCD arrays and the third one with pn CCD arrays. The \textit{XMM-Newton} EPIC cameras offer the possibility to perform extremely sensitive imaging observations over a field of view of 30’ and in the energy range of 0.15 to 15 keV, with moderate spectral ($E/\Delta E \sim 20 - 50$) and angular resolution (FWHM $\sim 6''$). The RGS is best suited for high resolution ($E/\Delta E \sim 100$ to 500) X-ray spectroscopy in the energy range $\sim 0.33 - 2.5$ keV ($\sim 5 - 38$ Å). OM has three optical and three UV filters over the wavelength range of 180 to 600 nm and can provide images of the central part of the field of view with a resolution of $\sim 1''$ and low-resolution grism spectra as well as high time-resolution photometry of the optical counterparts of X-ray sources. The detailed description of the instruments aboard in \textit{XMM-Newton} is given in \textit{XMM-Newton} user support document\footnote{http://xmm.esac.esa.int/external/xmm_user_support/documentation/technical/}.

We use the \textit{XMM-Newton} EPIC camera observations as these are best suited to study the X-ray emitting and absorbing components by modeling the broad-band $\sim 0.5 - 15$ keV spectra. \textit{XMM-Newton} EPIC observations were available for 17/20 of our sample sources. Furthermore, we prefer to use EPIC pn observations over EPIC MOS observations since latter one is susceptible to pile-up for X-ray bright sources and a few sources did not had MOS observations. Also, EPIC pn is equally good as MOS for our purpose of obtaining the X-ray spectral components in 0.5 - 10 keV band. Table 3.1 lists the energy bandpass, sensitivity, field of view, pixel sizes, timing and spectral resolutions of all the \textit{XMM-Newton} detectors.
### Table 3.1: *XMM-Newton* characteristics - an overview

<table>
<thead>
<tr>
<th>Instrument</th>
<th>EPIC MOS</th>
<th>EPIC pn</th>
<th>RGS</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Bandpass</td>
<td>0.15 - 12 keV</td>
<td>0.15 - 15 keV</td>
<td>0.35 - 2.5 keV $^{(1)}$</td>
<td>180 - 600 nm</td>
</tr>
<tr>
<td>Orbital target vis. $^{(2)}$</td>
<td>5 - 135 ks</td>
<td>5 - 135 ks</td>
<td>5 - 135 ks</td>
<td>5 - 145 ks</td>
</tr>
<tr>
<td>Sensitivity $^{(3)}$</td>
<td>$\sim 10^{-14} (4)$</td>
<td>$\sim 10^{-14} (4)$</td>
<td>$\sim 8\times10^{-5} (5)$</td>
<td>20.7 mag $^{(6)}$</td>
</tr>
<tr>
<td>Field of view (FOV)</td>
<td>30$'$</td>
<td>30$'$ $^{(7)}$</td>
<td>$\sim 5'$</td>
<td>17$'$</td>
</tr>
<tr>
<td>PSF (FWHM)</td>
<td>5$''$</td>
<td>6$''$</td>
<td>N/A</td>
<td>1.4$''$ - 2.0$''$</td>
</tr>
<tr>
<td>Pixel size</td>
<td>40 $\mu$m (1.1$''$)</td>
<td>150 $\mu$m (4.1$''$)</td>
<td>81 $\mu$m (9$\times10^{-3}$ Å) $^{(7)}$</td>
<td>$\sim 0.48''$ $^{(8)}$</td>
</tr>
<tr>
<td>Timing resolution $^{(9)}$</td>
<td>1.75 ms</td>
<td>0.03 ms</td>
<td>0.6 s</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Spectral resolution $^{(10)}$</td>
<td>$\sim 70$ eV</td>
<td>$\sim 80$ eV</td>
<td>0.04/0.025 Å $^{(11)}$</td>
<td>350$^{(12)}$</td>
</tr>
</tbody>
</table>

Notes:

1. In the -1 grating order (wavelength range: 5 - 35 Å).

2. The maximum continuous observing time is limited by the time available for observation per orbit and minimum time is limited by the observing efficiency. *XMM-Newton* science observations can only be performed outside the Earth’s radiation belts.

3. Considering observing time of 10 ks.

4. In the range of 0.15 - 15.0 keV and in units of erg s$^{-1}$ cm$^{-2}$.

5. In units of photons s$^{-1}$ cm$^{-2}$.

6. 5$\sigma$ detection of an A0 star in 1000 s.

7. In spectroscopy mode (standard 3 $\times$ 3 pixel on-chip binning applied).

8. 1$''$ with 2 $\times$ 2 binning in default configuration mode.

9. In fast data acquisition mode.

10. At 1 keV energy. At the energy of Fe K$\alpha$ (6.4 keV), the energy resolution of both EPIC cameras is $\sim 150$ eV.

11. Spectral resolution at 1 keV for -1 and -2 grating orders.

12. Resolving power ($\lambda/\Delta\lambda$) with UV and optical grism.
3.2.1 Comparison of \textit{XMM-Newton} with other current generation X-ray observatories

\textit{XMM-Newton} offers high sensitivity, high-resolution spectroscopy (RGS) with simultaneous medium-resolution spectroscopy and imaging (EPIC) and optical/UV observations (OM). EPIC has high sensitivity in $\sim 0.15$ - 15.0 keV energy band and can provide high time resolution as well. Table 3.2 shows the comparison of \textit{XMM-Newton} capabilities with other current generation X-ray observatories. Figure 3.1 shows the comparison of effective areas of \textit{XMM-Newton}, with \textit{Chandra}, \textit{Suzaku} and future mission \textit{Astro-H}. It is evident that \textit{XMM-Newton} has the largest effective area in 0.2 - 10.0 keV energy range and thus it is more sensitive than others in this energy band. Owing to high sensitivity, \textit{XMM-Newton} is very suitable for studying faint and obscured sources (\textit{i.e.}, in Seyfert galaxies AGN emission is supposedly obscured) and that is why we preferred to use \textit{XMM-Newton} observations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Comparison of effective areas of \textit{XMM-Newton}, \textit{Chandra}, \textit{Suzaku} and future mission \textit{Astro-H}.}
\end{figure}
Table 3.2: Comparison of XMM-Newton with other X-ray observatories

<table>
<thead>
<tr>
<th>X-ray telescope</th>
<th>Mirror PSF FWHM [$''$]</th>
<th>Energy range [keV]</th>
<th>$A_{\text{eff}}$ at 1 keV [cm$^2$]$^a$</th>
<th>Orbital target visibility [hr]</th>
<th>Energy resolution at 1 keV [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>XMM-Newton</td>
<td>6</td>
<td>0.15 - 15</td>
<td>4650</td>
<td>36.7$^b$</td>
<td>4 (RGS)</td>
</tr>
<tr>
<td>Chandra</td>
<td>0.5$^c$</td>
<td>0.1 - 10</td>
<td>555 (ACIS-S)</td>
<td>44.4$^b$</td>
<td>1 (HETG)</td>
</tr>
<tr>
<td>ROSAT</td>
<td>3.5</td>
<td>0.1 - 2.4</td>
<td>400</td>
<td>1.3$^d$</td>
<td>500</td>
</tr>
<tr>
<td>ASCA</td>
<td>73</td>
<td>0.5 - 10</td>
<td>350</td>
<td>0.9$^d$</td>
<td>100</td>
</tr>
<tr>
<td>Suzaku</td>
<td>n.a.$^e$</td>
<td>0.2 - 600</td>
<td>1760 (XIS)</td>
<td>0.72$^d$</td>
<td>50</td>
</tr>
</tbody>
</table>

Notes: 

$a$: Mirror effective area.  

$b$: Orbital visibility outside the particle-radiation dominated zone.  

$c$: The Chandra ACIS spatial resolution that is limited by the physical size of the CCD pixels and not by the mirrors.  

d: Low orbit with Earth occultation.  

e: Not available (n.a.).

3.2.2 XMM-Newton data reduction procedure

XMM-Newton data are available in two formats, i.e., Observation Data Files (ODF) and Pipeline Processing System (PPS) products. The ODF contain un-calibrated quantities on a chip-by-chip for the X-ray cameras. Pipeline Processing System (PPS) products are a collection of validated, top-level scientific products including event and source lists, multiwavelength images and cross-correlation products generated at the Survey Science Center (SSC).

Science Analysis Software (SAS)$^2$ is specifically designed to reduce and analyze XMM-Newton data. We used SAS version 7.1 to reduce XMM-Newton data of the Seyfert galaxies of our sample. The SAS is necessary to extract standard (spectra, light curves etc.) and/or customized science products even if one starts with the pipeline processed data products (PPS). Moreover, SAS allows to reproduce

$^2$http://xmm.esac.esa.int/sas/current/documentation/sas_concise.shtml
the pipeline reduction procedure, which are being applied to get the PPS products. It is advisable to start with ODF data rather than PPS data, whenever substantial changes in the software and/or instrument calibrations occurred from the time when the ODF were processed by the SSC pipeline to get the PPS data. The detailed description of XMM-Newton data and its reduction can be found in XMM-Newton website\(^3\). The basic steps of XMM-Newton data reduction using SAS are summarized as below.

(i) *Generating a Calibration Index File (CIF)*: XMM-Newton observation data files contain information about the instrument used, observation date, exposure time, exposure mode, exposure filter etc. In order to calibrate an ODF, one needs to first identify the calibration files (CCF) to be used. This is done by creating a Calibration Index File (CIF) using SAS task ‘cifbuild’. The task ‘cifbuild’ retrieves the observation date from the observation data file to be analyzed, as reported by the ODF Access Layer (OAL), and selects the corresponding calibration files for that given time period.

(ii) *Obtaining the calibrated data (event list)*: SAS tasks ‘epproc’ and ‘emproc’ produce calibrated and concatenated (i.e., one single file including events from all the detector chips) event lists for the EPIC pn and MOS cameras, respectively.

(iii) *Identifying the intervals of flaring particle background*: This can be done by extracting a single event (i.e., ‘pattern zero’ only), high energy (E > 10 and < 12 keV) light curve from calibrated event list using task ‘evselect’. The single event, high energy background light curve is used to identify the intervals of flaring particle background.

(iv) *Creating a Good Time Interval (GTI) event list*: GTI event list is generated by filtering out the intervals of flaring particle background from the calibrated event list using task ‘tabgtigen’ and ‘evselect’.

(v) *Extracting the source and background spectra*: The task ‘evselect’ is used to

\(^{3}\text{http://xmm.esac.esa.int/}\)
extract the source and background spectra from the calibrated GTI event list. The size and co-ordinates of the source and background regions can be obtained from the image (GTI event list) by displaying it using a FITS image viewer package, e.g., ‘ds9’.

(vi) Generating ancillary files and the instrument response functions: To perform quantitative spectral analysis of X-ray data, the ancillary and instrument response matrices files are created using ‘rmfgen’ and ‘arfgen’ tasks for EPIC. EPIC exposure maps can be generated using task ‘eexpmap’ and the amount of pile-up affecting target source can be estimated using ‘epatplot’ task. The extracted source and background spectra along with ancillary and response matrix files can be loaded in the spectral fitting package ‘XSPEC’ for spectral fitting. We use XSPEC version 12.0 to fit the spectra of our sources.

3.3 Suzaku X-ray observations

Suzaku (formerly known as Astro-E2) is Japan’s fifth X-ray Astronomy mission and was launched on July 10, 2005. Suzaku covers the energy range 0.2 - 700 keV with the three instruments: an X-ray micro-calorimeter (X-ray Spectrometer (XRS)), four units of the X-ray Imaging Spectrometers (XISs) and a hard X-ray detector (HXD). XRS is a non-dispersive imaging spectrometer (FWHM \(\sim\) 6.5 eV), however, it prematurely lost its liquid helium of cryogenic refrigerator and is no longer operational. There are 4 units of XIS and each XIS (an X-ray CCD camera) has a single CCD chip with 1024 \(\times\) 1024 pixels, and covers a 18" \(\times\) 18" region on the sky. One unit of XIS is equipped with a back-side illuminated CCD chip, while the rest contain a front-side illuminated CCD. HXD is a non-imaging instrument, which covers the wide energy band of 10 - 700 keV in combination of the GSO well-type phoswich counters (\(>\) 30 keV) and the silicon PIN diodes (\(<\) 60 keV). The HXD is characterized by the low background of \(\sim\) 5 - 10 cts s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\) and its sensitivity is higher than any past missions in the energy range.
from a few tens of keV to several hundreds of keV. The detailed description on the
instruments aboard Suzaku can be found at the Suzaku website\(^4\). Table 3.3 lists
the specifications of all the three instruments of Suzaku. We use Suzaku XISs and
HXD - PIN data to study the broad-band X-ray spectral properties of NGC 5135,
which is one of the Compton-thick sources in our sample.

Table 3.3: Overview of Suzaku instruments

<table>
<thead>
<tr>
<th></th>
<th>XRS</th>
<th>XIS</th>
<th>HXD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>0.3 - 12 keV</td>
<td>0.2 - 12 keV</td>
<td>10 - 600 keV</td>
</tr>
<tr>
<td>Number of units</td>
<td>1</td>
<td>4 (identical units)</td>
<td>1 (4 × 4 = 16 sub-units)</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>30 pixels</td>
<td>1024 × 1024 for each CCD</td>
<td>-</td>
</tr>
<tr>
<td>Pixel size</td>
<td>625 µm × 625 µm</td>
<td>24 µm × 24 µm</td>
<td>-</td>
</tr>
<tr>
<td>Effective area per detector</td>
<td>100 cm(^2) @ 1 keV</td>
<td>400 cm(^2) @ 1.5 keV</td>
<td>160 cm(^2) @ 15 keV</td>
</tr>
<tr>
<td>Energy resolution (FWHM)</td>
<td>6.5 eV</td>
<td>120 eV @ 6 keV</td>
<td>3 keV (10 - 30 keV)</td>
</tr>
<tr>
<td>Field of view</td>
<td>2.9′ × 2.9′</td>
<td>19′ × 19′</td>
<td>0.56′ × 0.56′ (E &lt; 100 keV)</td>
</tr>
<tr>
<td></td>
<td>1.8′ (XRT PSF)</td>
<td>1.8′ (XRT PSF)</td>
<td>4.6′ × 4.6′ (E &gt; 200 keV)</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>1.8′ (XRT PSF)</td>
<td>1.8′ (XRT PSF)</td>
<td>-</td>
</tr>
</tbody>
</table>

3.3.1 Suzaku data reduction procedure

Suzaku data reduction is primarily performed using the HEAsoft\(^5\) (also known as
‘FTOOLS’) package, which is a multimission collection of programs and scripts.
All mission-specific softwares required to calibrate and analyze Suzaku data are
written by the Suzaku instruments teams and are released as a part of HEA-
soft collectively called as “Suzaku FTOOLS”. Suzaku calibration information are
provided via the HEASARC\(^6\) “Calibration Database” (CALDB)\(^7\). The ‘CALDB’
provides index files and other information so that Suzaku FTOOLS can determine
the correct calibration file to use. Standard data formatting and calibration are

\(^4\)http://heasarc.nasa.gov/docs/suzaku/about/overview.html
\(^5\)http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/
\(^6\)http://heasarc.gsfc.nasa.gov/
\(^7\)http://suzaku.gsfc.nasa.gov/docs/heasarc/caldb/caldb_intro.html

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carried out as the part of pipeline processing, and it is recommended to start scientific data analysis from the pipeline processed products. After standard pipeline processing, *Suzaku* event files do not require any particular analysis software, since they comply with FITS event file standards. Nonetheless, the *Suzaku* observer facility recommends ‘xselect’ as a convenient and efficient analysis tool. The ‘xselect’ is a multi-mission program which has been widely used to analyze data from *ASCA*, *ROSAT*, *BeppoSAX*, *Einstein*, *Chandra* and other high energy missions. The ‘xselect’ is used to extract spectra, images, and lightcurves from *Suzaku* data.

### 3.3.1.1 XIS data reduction procedure

*Suzaku* standard pipeline processing produces filtered, calibrated event files and further spectral analysis of XIS data involves following main steps.

(i) *Extracting source and background spectra* : The primary HEASoft task for extracting spectra, light curves, exposure maps from XIS data is ‘xselect’. This task can apply filters which select user-defined times, sky regions and particular event flags.

(ii) *Building the response files (RMF and ARF)* : HEASoft task ‘xisrmfgen’ generates XIS response matrix and takes into account the time variation of the energy response. The task ‘Xissimarfgen’ is a ray-tracing based task which generates the ancillary response files (ARFs) for the *Suzaku* XIS.

(iii) *Combining the spectra taken with XIS0, XIS2 and XIS3* : Three of the XIS units (each with a frontside illuminated (FI) chip) are sufficiently similar and it is recommended to sum up the spectra from these units to obtain higher signal to noise ratio, under most circumstances. However, one should not combine the event files since it will lead to the loss of information critical to downstream software. Also, XIS1 (with a backside illuminated (BI) chip) has a distinctly different response and therefore XIS1 data should not be combined with those from the other three units. XIS2, one of the XIS units with an FI chip, suffered a catastrophic
damage on November 9, 2006 since then, no astronomically useful data have been obtained with XIS2, although some diagnostic mode data are taken. One should therefore expect no cleaned event files for XIS2 in observations taken after November 9, 2006.

The extracted XIS source and background spectra along with response files can be input in XSPEC for spectral fitting. The particle background is a strong function of the location of the Suzaku spacecraft within the geomagnetic field, and therefore, is variable in time. The X-ray background is a function of the pointing direction and therefore, background spectrum should be extracted from the neighboring source-free region(s) of the same CCD chip from the same observation.

### 3.3.1.2 HXD data reduction procedure

Since the HXD is a non-imaging instrument, the analysis of HXD data follows a different path from that used for XIS data analysis. The HXD consists of two independent detector systems, i.e., GSO/BGO phoswich counters and the PIN silicon diodes. The PIN diodes are sensitive below $\sim 60$ keV, while the GSO/BGO phoswich counters detect photons above $\sim 30$ keV. The energy resolution of PIN diodes is $\sim 3.0$ keV, while the phoswich counters have a resolution of $7.6\sqrt{E}$ % (FWHM), where E is the photon energy in MeV. The main steps for the spectral analysis of HXD data are described below.

(i) **Obtaining the appropriate background files**: Since PIN is a collimated instrument, it is not possible to obtain background data from the HXD-PIN observations. Therefore, HXD instrument team has developed a model of the time-variable particle background which is provided to users.

(ii) **Creating a good time interval (GTI) event list file**: GTI event file can be generated by correcting for dead-time. It is necessary to correct for the dead time of the observed spectrum to apply the background file correctly. The dead time correction task ‘hxddtcor’ (included in the Suzaku FTOOLS) updates the exposure
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keyword of the event file.

(iii) Extracting spectra: Source spectra are extracted from calibrated and filtered (GTI) event file.

(iv) Extracting spectra from the background files and correcting (for PIN) for the factor of 10 oversampling: The event rate in the PIN background event file is 10 times higher than the real background to suppress the Poisson errors. Therefore, one should increase the exposure time of derived background spectra and light curves by a factor of 10 using ‘fv’ or ‘fmodhead’.

(v) Selecting the response file: Due to the changes in instrumental settings (bias voltages used on-board and low energy threshold used in processing on the ground), one must choose PIN response matrices that are appropriate for the epoch of observation. These response files are available from the Suzaku calibration database ‘CALDB’.

3.4 X-ray spectral fitting package: XSPEC

XSPEC\(^8\) is a command-driven, interactive, X-ray spectral-fitting program designed to be completely detector-independent so that it can be used to fit the X-ray spectra obtained from any spectrometer. XSPEC has been used to analyze data from ROSAT, ASCA, Chandra, XMM-Newton, Suzaku and other X-ray observatories. I give here a brief description of the basics of XSPEC spectral fitting.

A spectrometer is used to obtain the spectrum of a source, however, the X-ray spectrometer does not give the actual spectrum, but rather, photon counts (C) within specific instrument channels (I). Thus observed spectrum is related to the actual spectrum of source \(f(E)\) by:

\[
C(I) = \int_0^{\infty} f(E) R(I, E) \, dE
\]

\(^8\)http://heasarc.nasa.gov/docs/xanadu/xspec/

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where, \( R(I,E) \) is the instrumental response and is proportional to the probability of the detection of an incoming photon of energy \( E \) to be detected in channel \( I \). From the above equation, one can determine the actual spectrum of a source \( f(E) \), by inverting the equation, thus deriving \( f(E) \) for a given set of \( C(I) \). However, inverting solutions tend to be non-unique and unstable to small changes in \( C(I) \) (e.g., see Blisett and Cruise (1979); Loredo and Epstein (1989)). The usual alternative to obtain \( f(E) \) is to choose a model spectrum for \( f(E) \), that can be described in terms of a few parameters (i.e., \( f(E, p1, p2, ...) \)) and match or fit it to the data obtained by the spectrometer. For each \( f(E) \), a predicted count spectrum (\( C_p(I) \)) is calculated and compared to the observed data (\( C(I) \)). Then a ‘fit statistics’ is computed from the comparison and is used to judge whether the model spectrum fits the data obtained by the spectrometer. The model parameters are varied to find the parameter values that give the best fit statistics. These values are referred to as the best-fit parameters. The model spectrum, \( f_b(E) \), consists of the best-fit parameters is considered to be the best-fit model. Mostly, \( \chi^2 \) fitting statistics is used for determining the best fit model. The \( \chi^2 \) minimization equation can be given as.

\[
\chi^2 = \sum \left(1 - \frac{C_p(I)}{C(I)}\right)^2 
\]

(3.2)

The ‘goodness-of-fit’ is calculated to determine how well the model fits the observed data and confidence intervals for the model parameters are calculated to know the range of values within which one can be confident the true value of the parameter lies.