Chapter 2

Instrumentation and Data Analysis

2.1 The *XMM-Newton* Observatory

The *XMM-Newton* mission [167–169] of the European Space Agency (ESA) is one of the first cornerstone projects of the "horizon 2000"–program. *XMM-Newton*'s name comes from the design of its mirrors, the highly nested X-ray Multi-Mirrors and in honour of Sir Isaac Newton (1643 – 1727). The *XMM-Newton* observatory was launched on December 10, 1999 the first commercial launch of an Ariane–5 rocket into a highly elliptical 48-hour orbit, ranging from 7,000 km to 114,000 km from Earth. It is one of the most sensitive X-ray observatory ever put in space.

XMM–Newton is the largest scientific satellite ever built in Europe with its 3.8 tonne heavy and 10 metres long body. It is designed for a life time of ten years of operation which has been extended and still working. *XMM–Newton* can observe sources such as hot stars, active or normal galaxies, black holes, neutron stars or supernova remnants.

2.1.1 The Scientific Instrumentation

XMM–Newton is an excellent satellite to study the universe in X-ray wavelengths between 1–120 Å (12 – 0.1 keV). As shown in Figure 2.1, the satellite consists of three co-aligned X-ray telescopes, all of which can be operated simultaneously and independently. The European Photon Imaging Camera (EPIC) have been developed in order to perform spectroscopic measurements as well as imaging of

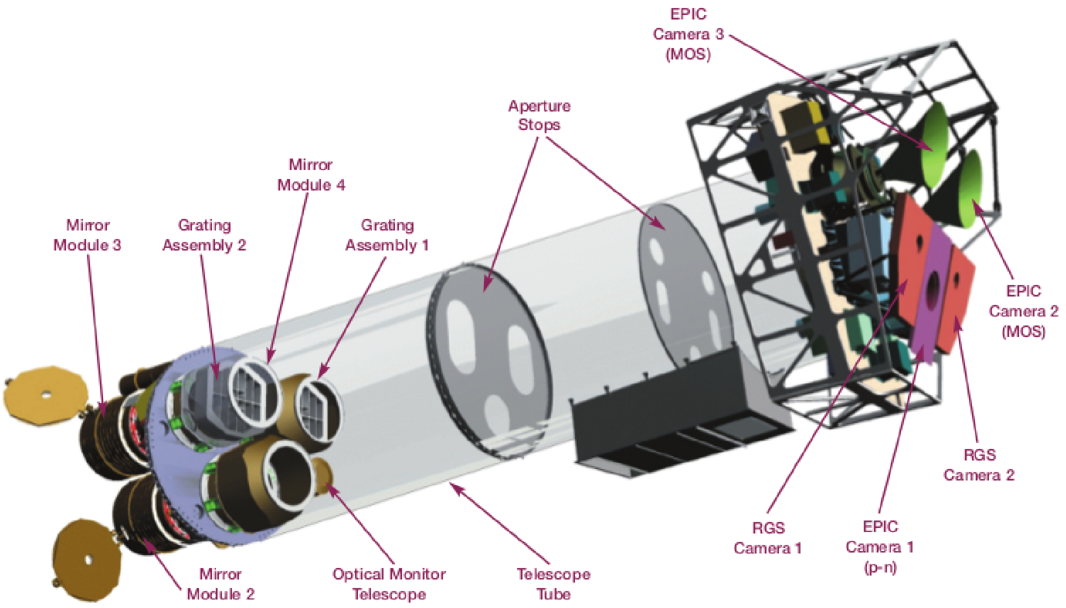

Figure 2.1: The configuration of the *XMM–Newton* satellite. (figure reproduced from Lumb, D. et al. [166]).

X-ray sources. The Reflection Grating Spectrometer (RGS) provide, high resolution analysis of X-ray spectra. For simultaneous observation in UV and optical wavebands, one Optical Monitor (OM) telescope is co-aligned with the X-ray cameras.

2.1.2 The EPIC Cameras

In the *XMM–Newton* satellite, the EPIC consists of three cameras, designed for imaging, observations and spectroscopy. Each EPIC detector consist of the Charged Coupled Devices (CCD) electronic interfaces and radiators to the CCDs. When a photon hits the CCD, the CCDs give a time and a position stamp for each event. The EPIC CCDs are sensitive for photons in the energy range (0.15 – 15) keV.

There are two EPIC cameras which are metal-oxide semiconductor (MOS) CCDs known as MOS1 and MOS2 [170]. The third camera is a positive-negative (pn) CCD detector [171]. The MOS–CCDs share the incoming X-ray flux with the RGS devices because of the geometrical arrangement of the gratings. The pn camera makes use of its own mirror module.

EPIC CCDs can be operated in several different science modes. Full frame mode (or extended full frame for pn) uses the full field of view (FOV). In this mode all pixels of all CCDs are read out. In partial window mode for MOS cameras, the central CCD can be operated in a different mode to the outer chips. For pn there are two partial window options – large and small window. In large window mode, half the area of all the CCDs is read out. In small window mode only part of CCD4 is used. EPIC CCDs can also be operated in timing mode. In Figure 2.2, the focal plane arrangements of the EPIC–CCDs are shown.

EPIC MOS cameras

The two MOS cameras work on the basis of Metal Oxide Semi–conductor technology. The MOS1 and MOS2 cameras are oriented orthogonally to one another so that the chip gaps in one are covered by chips in the other. In the MOS camera CCDs are front illuminated with a 40μm thick layer of sensitive silicon. They cover the bandpass 0.15–12.0 keV and have a $30'$ diameter field of view. The central CCD includes the focal point and the total CCD array has a (2.5×2.5) cm imaging area. On axis spatial resolution is $\sim 5''$ FWHM. The arrangement of the individual CCDs is adapted to the curved geometry of the focal surface determined by the Wolter telescopes. In the standard Full Frame mode the created charge can be read out within 2.6 s. Its design is optimized for recording soft X-ray radiation due to its very good energy resolution in this range.

EPIC pn cameras

The EPIC–pn camera is back-illuminated with a 380 μm thick layer of silicon. This camera has a high detection efficiency over the entire energy band. The pn has a slightly wider bandpass than the MOS cameras, covering 0.15–15.0 keV. The EPIC-pn camera consists of 12 CCDs covering in total (6×6) cm divided into 400 pixels $\times$ 384 pixels. These CCDs are divided into four quadrants of three pn-CCDs each. The centre of the pn detector does not coincide with a chip, so the focal point is offset to chip 0 in quadrant 1. Each quadrant can be controlled independently, having its own readout electronics (EPIC Control Electronics, EPCE) and voltage supply (EPIC Voltage Control, EPVC) to maintain the whole system even when

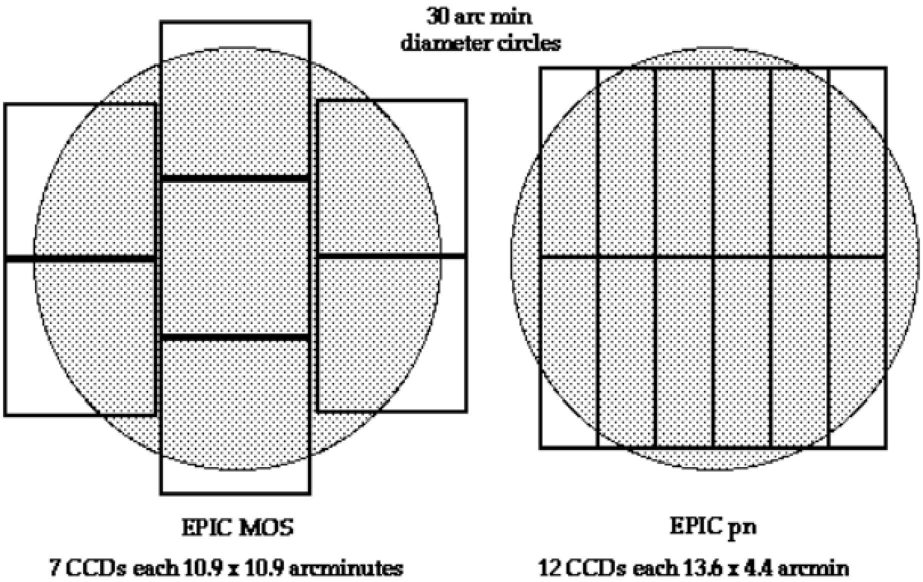

Figure 2.2: The focal plane arrangements of the EPIC–CCDs combined with the 30′ -FOV (figure taken from the *XMM–Newton* Users Handbook).

individual CCDs or quadrants break down.

The angular resolution α, of the pn–CCD (where α= arctan [150.10^{-6} m/7.5 m] = 4.1″) is better than the resolution of the telescope. The EPIC–pn has the best high energy response, making it particularly useful for investigating the Fe K emission around 6.4 keV. The readout time for the pn is 73.4 ms whereas for the MOS cameras 2.6 s. The faster read-out rate of EPIC–pn helps to deal with higher count rates without running into problems with so–called 'pile-up' (discussed in subsection 2.1.4). In this thesis, only calibration of the EPIC–pn camera has been considered.

2.1.3 The Reflection Grating Spectrometer (RGS)

In *XMM–Newton*, there are two identical RGS [172] each of which is made of two parts, an array of reflection gratings and the detector. The detector is built up of nine back-illuminated MOS–CCDs, arranged linearly along the dispersion direction of the spectrometer on the Rowland circle.

In this arrangement, each MOS–CCD contains 768 pixels ×1024 pixels with a pixel size of 27×27 cm^2. This size makes it possible to fit the spectrum of 253 mm in size completely into the array. The energy resolution of this devices is very high – (E/δE) between 200 and 800. Because of this high resolution, RGS is very effective in the (0.35 – 2.5) keV regime (equivalent to 5 – 35Å). In this energy band many emission lines of highly ionized elements due to hot plasma can be studied. Most importantly, the L-shell transitions of heavy elements like Fe and Ni and the K–shell transitions of lighter elements like N, O, Mg, S, Si, Na, Ca, Ar, and Ne.

2.1.4 The Optical Monitor (OM)

The optical monitor (OM) of the *XMM–Newton* is a modified Ritchey–Chrtien telescope [173]. The XMM–OM consists of a telescope module and a separate Digital Electronics Module, of which there are two identical units. There are optics and detectors, the detector processing electronics and power supply units in the telescope module. The 2 m long telescope is mounted on the mirror support platform of *XMM–Newton*. With an aperture of 30 cm, focal ratio of f/12.7 and focal length $\sim$ 3.8 m, FOV $17'$ and at an angular resolution of one arcsec, the OM allows observations in the optical/UV energy range (from 170 to 650 nm). The detector used here is a microchannelplate–intensified CCD [174]. The CCD read–out time is rapid (every 11 ms if the full CCD format is being used). The OM is equipped with a set of broad-band filters for colour discrimination. It is free from any atmospheric extinction, diffraction and background. The OM can be simultaneously used along with the X-ray telescopes for the observation of the same regions. All these make the instrument a powerful and important tool of the *XMM–Newton* observatory.

Calibration

X-ray photons of an object after entering a telescope system, gets affected. This is mainly because of absorption and imperfect focusing by the mirrors. There may also be some imperfection in the filters that might be used in the detectors. But the most important point that affects the incoming photon is the gain from the electronics. In order to get the original unaffected photon we need to correct for all imperfections in the satellite. This is called calibration. Here we will be discussed some relevant points regarding calibration.

Point spread function

The Point Spread Function (PSF), is defined as a function which determines the quality of focusing the photons by the X-ray mirrors [175]. The on-axis PSF is mathematically described by a King function. The extent of each of the X-ray point sources in the X-ray images produced is dependent on the PSF of the camera. The PSF is measured as the FWHM which is the diameter of the PSF at the distance from the centre where only half of the intensity remains. It is always desirable to have smaller PFS value as it means better quality of the measured data. The mean FWHM of the PSF for the mirror assembly related to the EPIC–pn device is 6.6 arcsec and the angular resolution of the Half Energy Width (HEW) is 15 arcsec in the detector plane. For the MOS cameras the PSF at FWHM is 4.3 arcsec and 4.4 arcsec for MOS1 and MOS2 respectively. For the *XMM–Newton* cameras, the PSF varies little over a wide energy range (0.1–6.0 keV). Above these energies the PSF becomes slightly energy dependent. The PSF also depends on the position of the detector.

Pile-up

If more than one photon hits the CCD in the same (or a neighbouring) pixel before the charge has been read out, their energies are merged together and counted as one event. This is called energy pile-up. If one photon hits close to the border of two pixels the energy will be divided between them. This is known as double event and the energy is put together and counted as a single event by the on board software of *XMM-Newton*. Unfortunately if two photons hit two neighbouring pixels, the software cannot distinguish between this case and the double event case. The photon energies are added as in case of a double event, a spectrum suffering from pile-up will have too many counts for higher energies and too few for lower energies.

Effective area

The ability of the telescope to collect photons at various energies is termed as effective area [10]. It has a very strong dependence on energy. The effective area also changes with position on each detector. The largest effective area is found at the centre, which is known as vignetting. In order to perform spectral analysis of a source, these factors must be corrected using an appropriate Area Response Function specific to the position on the detector. The effective area of EPIC-pn is larger than the MOS cameras.

Quantum efficiency

Quantum Efficiency (QE) represents the CCDs sensitivity to light. The QE may be reduced if a photon is absorbed by the depleted silicon. The QE was measured on ground using the Orsay synchrotron, but is also measured during operation, using celestial sources. The QE varies considerably between different energies. A summary of different parameters of the EPIC cameras are given in table 2.1.

Table 2.1: EPIC parameters (from the *XMM–Newton* Users Handbook)

Parameter	EPIC MOS	EPIC pn
Number of CCDs	7	12
Energy Bandpass [keV]	0.15 – 12.0	0.15 – 15.0
Number of pixels	600×600	64×200
Pixel size [μm]	40×40	150×150
Pixel size [arcsec]	1.1×1.1	4.1×4.1
Field of view (FOV) [arcmin]	33.5 (max)	27.5
PSF (FWHM/HEW) [arcsec]	5/14	6/15
Sensitivity † [erg cm^{-2} s^{-1}]	$\sim 10^{-14}$	$\sim 10^{-14}$
Timing sensitivity (ms)	1.5	0.03
Spectral resolution (eV)	70	80
Quantum efficiency (QE; @ 0.5/6.4/8.0 keV)	45%/87%/65%	88%/99%/97%
Operating temperature [^{0}C]	$\sim$ –80	$\sim$ –120

† in an exposure of 10 ks, in (0.15 –15.0) keV

2.1.5 *XMM–Newton* Data Access

Through the *XMM–Newton* Science Archive (XSA) all observational data of the *XMM–Newton* satellite are made public. Observational data can be searched using different parameters e.g. target name, coordinates, observation date etc.

For each observation the collected data from all devices are combined to the Observation Data Files (ODFs). Usually the data are stored in the Flexible Image Transport (FITS) format [176]. The components of an ODF contain information for a single *XMM–Newton* observation. It can be separated into the data of the different CCDs together with the relevant house keeping parameters of the instruments and the spacecraft information. The ODF data are organized according to their observation-ID, which is related to the submitted proposal.

Both raw ODF and processed Pipeline Processing Subsystem (PPS) files are available to download and can be filtered before download to reduce file size. In order to carry out the analysis of the data, a set of Current Calibration Files (CCF) is necessary.

2.1.6 Reduction of *XMM–Newton* Data Files

For every detected individual photon, the instrument record a separate signal. This X-ray “event” is characterized by a “pulse height amplitude” (PHA) that encodes the energy of the incoming photon, the time and position on the detector.

The *XMM–Newton* Science Analysis System, called the XMM–SAS software [177] is a very effective tool to process the ODFs and to evaluate the scientific data. This analysis package has been developed by the *XMM–Newton* Science Operations Center (SOC) in Villafranca near Madrid (Spain) and by the Science Survey Center (SSC) in Leicester. The XMM–SAS contains several routines (“tasks”) to process and explore the scientific exposures performed by the different instruments and to combine them, either by an interactive Graphical User Interface (GUI) or by a command–line script suitable for an automatic run of the reduction.

The data reduction for each of the scientific devices of the *XMM–Newton* is a multi-step procedure. By combining the resulting data files from the ODFs with the CCFs provide calibrated “event files”. This event file is the first step a user does before performing the analysis. The second step is to correct the observation from large flaring events caused mostly by soft photons. The next correction is for time. This is done by identifying the times of high counts and filter them out from the original event file, remaining only intervals of good times. After the creation of a new event file the time-corrected image of the observation has been visualized in order to extract the counts in the source and in the background region. For both areas a spectrum has been created. Standard astronomical tools like the FTOOLS, XSPEC, IDL etc. are able to handle the produced data files. For all extractions reported in this thesis I used a circular region for both the source and the background filtering. I have used XSPEC for the X-ray data.

2.2 Far Ultraviolet Spectroscopic Explorer

The Far Ultraviolet Spectroscopic Explorer (*FUSE*) was launched in June, 1999 on a Delta II rocket and placed in a low earth orbit. *FUSE* is a NASA astronomy mission, developed in cooperation with the Canadian Space Agency and the Centre National d'Etudes Spatiales of France. For eight years the satellite observed thousands of targets and reached its termination in October, 2007. This satellite provides opportunity to study several essential features of astrophysics, mainly the resonance doublet of O VI $\lambda\lambda$ 1032 and 1038 Å that traces gas in the $10^5 - -10^6$ K regime, the ground state electronic transitions of H_2, Deuterium transitions shortward of Lyman alpha, etc. The spacecraft and mission of *FUSE* have been described in detail by Moos et al. [178] and Sahnow et al. [179]. *FUSE* was designed to observe sky in the FUV spectral range from 905 to 1187 Å upto a high resolving power of $(\lambda/\triangle\lambda) \geq$ 20,000 with large effective area (20–70) cm^2. All of the public and proprietary *FUSE* data is stored in the Multimission Archive at the Space Telescope Science Institute (MAST).

2.2.1 *FUSE* Configuration

The optical arrangement in *FUSE* is based on a Rowland circle design having four optical channels as shown in Figure 2.3. Each channel consists of a mirror, a focal plane assembly (FPA), a diffraction grating and a part of a detector. Two mirrors and gratings are coated with lithium fluoride (LiF) over a layer of aluminum. The other two mirrors and gratings are coated with silicon carbide (SiC). The SiC channels cover the wavelength range 905–1104 Å, while the LiF channels cover the 990–1185 Å region. The spectra from the four channels are imaged onto two photon counting micro channel plate (MCP) detectors (labeled 1 and 2), each divided into two individual segments (A and B). Light from the two channels falls onto each detector resulting in eight ~ 90 Å individual spectra. These are identified according to the segments: LiF 1A, LiF 2A, LiF 1B, LiF 2B, SiC 1A, SiC 2A, SiC 1B and SiC 2B.

There are four apertures for simultaneous observations in *FUSE*.

The LWRS is the most commonly used aperture with size 30×30 arcsec^2.

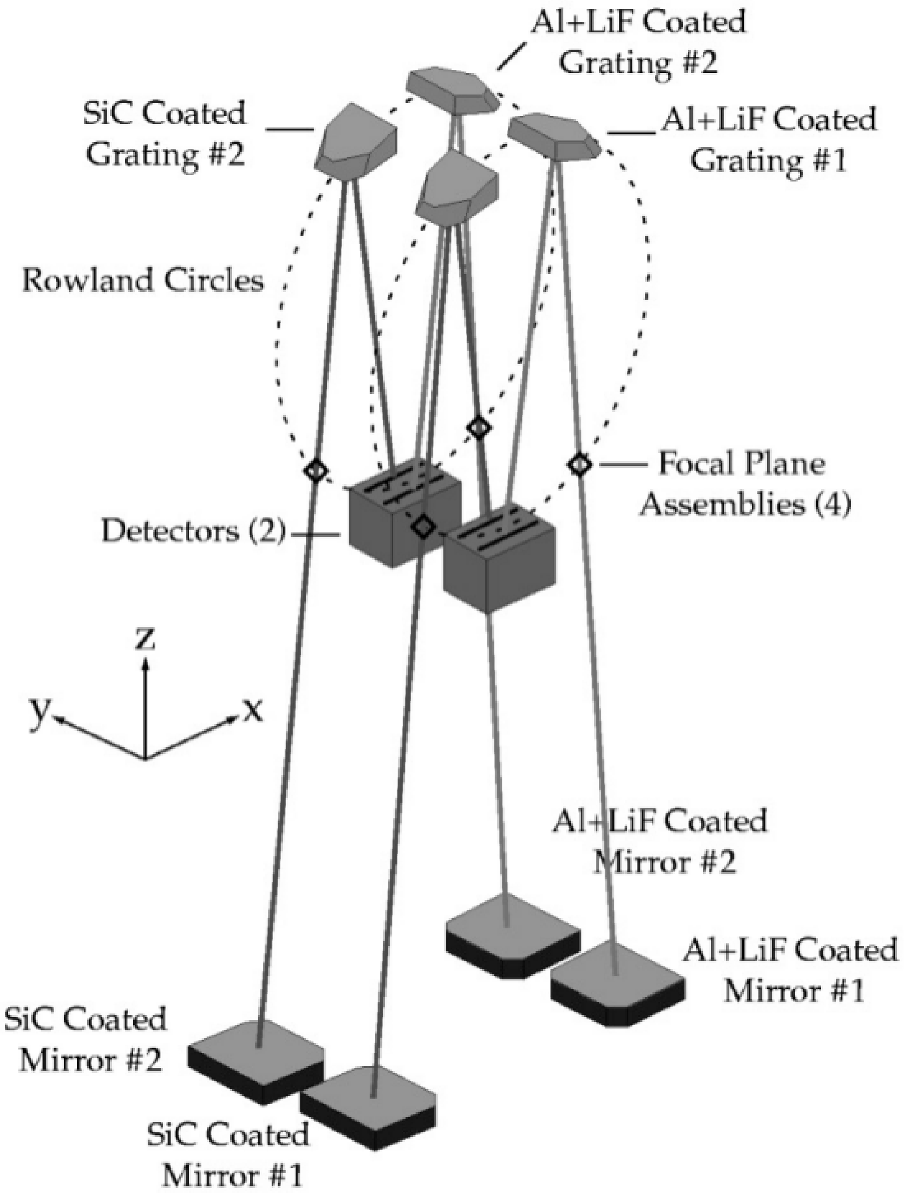

Figure 2.3: The design of *FUSE* instrument optical system. The telescope focal lengths are 2245 mm, and the Rowland circle diameters are 1652 mm (Figure reproduced from Moos et al. [178]).

Table 2.2: *FUSE* wavelength ranges (Å)

Channel	Segment A	Segment B
SiC 1	1090.9–1003.7	992.7–905.0
LiF 1	987.1–1082.3	1094.0–1187.7
SiC 2	916.6–1005.5	1016.4–1103.8
LiF 2	1181.9–1086.7	1075.0–979.2

This low-resolution aperture is intended to observe both the point sources and faint extended objects. LWRS is free from the thermal image motions that occurred on orbit. For nominal operations, LWRS is the default aperture.

MDRS is a medium-resolution aperture having size 4×20 arcsec^2. It is mainly used for point source observation. MDRS gives maximum throughput with minimum airglow contamination. The use of this aperture is not convenient because of thermal drifts of the separate channels, specially the SiC channels with respect to the LiF channels.

With aperture size 1.25×20 arcsec^2, HIRS gives the highest resolution. In this aperture all the light from a point source is not allowed to fall in to the spectrograph. Use of this aperture is limited as it is difficult to maintain channel alignment.

In *FUSE*, there exist a pinhole aperture PINH with size approximately 0.5 arcsec^2 in diameter. This aperture is not used on orbit.

There are two different data recording modes in *FUSE*, Time Tag (TTAG) and Histogram (HIST). These modes are selected depending on brightness of the targets. The brighter targets use the histogram mode since time tagging photons becomes meaningless when the arrival of two photons can not be resolved.

2.2.2 Data Reduction

The *FUSE* data (FITS) files contains Header and Data units (HDUs). The Header part is known as primary HDU (HDU1) which consists of a header and an optional N-dimensional image array. The HDU may be followed by additional HDUs, called "extensions" which may have their own header and data unit. There are two observation-level combined files in *FUSE*. One is the ALL files which contain all of the data for a particular observation. This file extension has 3 arrays: WAVE, FLUX and ERROR. The other is the ANO (All Night Only) files, which contain only data obtained during orbital night. The ANO files are identical to the ALL files, except that the spectra are constructed using data obtained during the nighttime portion of each exposure only.

The FUSE data available at MAST is reduced with CalFUSE [180] software package. CalFUSE is written in C programming language with a series of modules called by a shell script. During it's execution, each module corrects an effect. Main tasks that CalFUSE performs are detector dead time correction, geometric distortion corrections, instrumental effect correction, thermal drift correction, correction for Grating, spacecraft and Mirror Motion, astigmatism correction, Doppler correction, background subtraction, heliocentric velocity correction etc.

To generate combined spectra from each channel, the operation pipeline unified system (OPUS) of CalFUSE can be used. OPUS takes the downloaded *FUSE* data and produces the data files that serve as input to the CalFUSE pipeline. The subsequent execution of CalFUSE pipeline is managed by OPUS. By calling additional routines OPUS combine spectra from each channel and exposure into a set of observation-level spectral files. For each exposure, six data files are created, four of which are raw data files and one set of housekeeping files. All calibration files used by CalFUSE are standard FITS format files, except for the FUSE.TLE file, which is in ASCII format. The FITS files generally contain a minimal header, with the actual data being present in extensions.

FUSE flux calibration is based on model-atmosphere predictions of the spectra of well-studied white-dwarf stars [179]. Count-rate spectra were first extracted using v2.0.2 of CalFUSE for version 008 of the *FUSE* flux calibration. From individual exposures of a single observation, the count-rate spectra are carefully aligned using interstellar absorption features and then combined. In case of multiple observations, the spectra from all observations are combined to produce a final spectrum. A polynomial fit to the surrounding continuum removed all narrow features in the spectrum which may arise due to ISM or photospheric absorption lines and uncorrected detector defects.

CalFUSE provides a mapping between the wavelength and detector pixel position This mapping accounts for both distortions in the detector imaging along the X-coordinate axis (the dispersion direction) and the smoothly-varying dependence of wavelength on detector X position expected from the spectrograph optics. The average dispersion across each of the four FUSE detectors ranges from 0.006 to 0.008 Å per pixel.

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