

1 The Chandra X-ray Observatory: An Astronomical Facility 2 Available to the World

3 Randall K. Smith

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6 **Abstract** The *Chandra* X-ray observatory, one of NASA's
7 "Great Observatories," provides high angular and spectral
8 resolution X-ray data which is freely available to all. In this
9 review I describe the instruments on *chandra* along with
10 their current calibration, as well as the *chandra* proposal sys-
11 tem, the freely-available *chandra* analysis software package
12 CIAO, and the *chandra* archive. As *chandra* is in its 6th year
13 of operation, the archive already contains calibrated obser-
14 vations of a large range of X-ray sources. The *chandra* X-
15 ray Center is committed to assisting astronomers from any
16 country who wish to use data from the archive or propose for
17 observations.

18 **Keywords**

19 1. Introduction

20 The *Chandra* X-ray Observatory (Weisskopf et al., 2000) was
21 launched on the Space Shuttle Columbia as part of STS-
22 93 and deployed on July 23, 1999, after over 20 years of
23 planning and development. *Chandra* was designed to be a
24 general-purpose X-ray observatory, with a specific focus on
25 high-resolution imaging and spectroscopy. *Chandra's* mir-
26 rors resolve objects smaller than 1", a level comparable to
27 optical telescopes and significantly better than any previous
28 X-ray observatory.

29 *Chandra* is one of NASA's "Great Observatory" mis-
30 sions, along with the Hubble Space Telescope, the Compton
31 Gamma Ray Observatory, and the Spitzer Space Telescope.

R. K. Smith
NASA's Goddard Space Flight Center, Greenbelt, MD 20771 and
Johns Hopkins University, 3400 North Charles Street, Baltimore,
MD 21218
e-mail: rsmith@milkyway.gsfc.nasa.gov

To maximize the scientific return from each of these mis-
sions, NASA created a science center for each mission which
would be responsible for coordinating calibration efforts for
all instruments, organizing proposals for the telescope, devel-
oping software to analyze the data returned, and maintaining
the mission archive. The *Chandra* X-ray Center (CXC) is
located in Cambridge, Massachusetts and has a team of sci-
entists handling all of these duties.

2. Observatory specifications

Chandra, like the Hubble Space Telescope, was launched
into orbit in the Space Shuttle. Unlike the Hubble Space Te-
lescope, after being deployed *Chandra* used a secondary rocket
to boost it into a highly elliptical orbit. Currently, *Chandra's*
apogee is ~139,000 km above the Earth (1/3 of the distance
to the Moon), well outside the Earth's radiation belts, and
its perigee is ~16,000 km, well within them. This elliptical
orbit put it out of reach of any maintenance mission, but al-
lows continuous observing for over 100 ksec (observations
cannot be done within or near the radiation belts). As a result,
Chandra regularly achieves an observing fraction of nearly
70%, extremely high for satellite observations.

2.1. Mirrors

The *Chandra* High Resolution Mirror Assembly (HRMA)
is responsible for its sub-arcsecond imaging. The HRMA
consists of four pairs of nested mirrors in a Wolter Type-I
design. The mirrors are made of iridium-coated glass, and
the entire system has a focal length of 10.07 meters. The
unobstructed geometric effective area is 1145 cm²; in flight
the total effective area is 800 cm² at 0.25 keV, 400 cm² at
5 keV, and 100 cm² at 8 keV. The ghost-free field of view has

62 a 30' diameter, which encompasses the entire ACIS detector
63 array and most of the HRC (see below for details about the
64 *Chandra* detectors).

65 The primary differences between *Chandra* and *XMM-*
66 *Newton* (Gabriel, Guainazzi and Metcalfe, 2005) are found
67 in their mirrors. *XMM-Newton* has three X-ray telescopes,
68 each with 58 nested gold-coated nickel shells, while *Chan-*
69 *dra's* single HRMA has only 4 mirror pairs made of precisely
70 formed iridium-coated glass. As a result, *XMM-Newton* has
71 a larger effective area than *Chandra*, but worse angular
72 resolution.

73 The HRMA was calibrated at the NASA/Marshall Space
74 Flight Center X-ray Calibration Facility pre-flight, and these
75 measurements have been used to cross-check the in-flight
76 calibration with excellent results. More information about
77 the HRMA and the latest calibration can be found at
78 <http://cxc.harvard.edu/cal/Hrma>.

79 2.2. ACIS

80 The Advanced CCD Imaging Spectrometer (ACIS) (Garmire
81 et al., 2003) is the most-used detector on *Chandra*. Unlike
82 *XMM-Newton*, *Chandra* has only a single HRMA and the
83 observer must chose the detector to put into the focal plane.
84 The ACIS is a set of 10 CCDs arranged in two patterns: a 2
85 \times 2 array with a 17' square field of view used primarily for
86 imaging, and a 1 \times 6 array with a 8.5' \times 51' field of view, used
87 primarily for grating observations. The user can select up to
88 6 CCDs to be used for any observation (the 6 CCD limit is
89 set by the power available from the solar panels). The CCDs
90 are operated in single-photon counting mode, which provides
91 modest ($E/\Delta E \sim 50$ spectral resolution) and limited timing
92 information.

93 The ACIS contains 8 'front-illuminated' (FI) and 2 'back-
94 illuminated' (BI) CCDs. The FI CCDs have their gate struc-
95 tures mounted facing the mirrors, while the BI CCDs are
96 inverted. As a result, the BI CCDs have larger effective area
97 at low energies since no X-rays are lost in the gate structures.
98 However, they also have higher backgrounds and initially
99 lower spectral resolution. However, early in the *Chandra*
100 mission, protons from the Earth's radiation belts damaged
101 the FI CCDs with the result that the FI CCD resolution now
102 varies strongly with CCD row number. The CXC has de-
103 veloped algorithms to partially correct this effect as part of
104 CIAO (see Section 3.3).

105 The pixel size of the ACIS CCDs is 0.492" on a side; as a
106 result the ACIS barely samples the full HRMA resolution. To
107 reduce the effect of pixel-to-pixel calibration uncertainties,
108 and to avoid damaging the on-axis pixels, *Chandra* dithers
109 in a 16" lissajous pattern during all ACIS observations. A
110 separate instrument using an optical CCD called the Aspect
111 Camera is used to point *Chandra* and to remove the effect
112 of dither from the final images and event files. The reduc-

tion is handled by the CXC as part of the standard pipeline
analysis (see Section 3.2). For more information about the
ACIS, please see [http://cxc.harvard.edu/proposer/](http://cxc.harvard.edu/proposer/POG/html/ACIS.html)
[POG/html/ACIS.html](http://cxc.harvard.edu/proposer/POG/html/ACIS.html).

117 2.3. HRC

118 The High Resolution Camera (HRC) (Murray et al., 2000)
119 instrument consists of two microchannel plate detectors. The
120 HRC-I is designed for imaging and has a 30' square field of
121 view, while the HRC-S is designed to be used with LETG
122 grating (see Section 2.5) and has a 6' \times 99' field of view. As
123 these are microchannel plate detectors, they have no useful
124 energy resolution but do have better timing and a smaller
125 pixel size than the ACIS detectors. In addition, they do not
126 suffer from photon pileup as happens in CCD detectors when
127 the event rate becomes large.

128 Although the intrinsic timing accuracy of the HRC detec-
129 tors is 16 μ s, in flight the actual event timing is known to
130 approximately 4 ms due to a wiring error. However, it is pos-
131 sible in special cases to regain the 16 μ s accuracy using a spe-
132 cial instrument mode. For more information about the HRC,
133 please see [http://cxc.harvard.edu/proposer/POG/](http://cxc.harvard.edu/proposer/POG/html/HRC.html)
134 [html/HRC.html](http://cxc.harvard.edu/proposer/POG/html/HRC.html).

135 2.4. HETG

136 In addition to the two detectors, *Chandra* has a two different
137 grating assemblies that can be inserted, although only one can
138 be in place at any given time. The High Energy Transmis-
139 sion Grating (HETG) (Canizares et al., 2000) was designed
140 to be used with the ACIS-S detector, although it could be
141 used with ACIS-I or the HRC (in practice this is not useful
142 for scientific observations). The HETG itself contains two
143 different gratings, the High Energy Grating ($\Delta\lambda = 0.012\text{\AA}$)
144 and the Medium Energy Grating ($\Delta\lambda = 0.023\text{\AA}$). These two
145 gratings are arranged so that their dispersion axes are an-
146 gled $\sim 10^\circ$ from each other, so that both dispersed spectra
147 can be independently extracted. The HEG spectral range is
148 1.2–15 \AA (0.8–10 keV), while the MEG spectral range covers
149 2.5–31 \AA (0.4–5 keV). The HEG has twice the resolution of
150 the MEG, balanced by a smaller effective area.

151 Unlike the *XMM-Newton* RGS, the *Chandra* gratings lose
152 resolution quickly for sources larger than a few arcseconds.
153 For point sources, however, the HETG combines high spec-
154 tral resolution with sufficient effective area to measure spec-
155 tra from both Galactic and extragalactic sources.

156 The HETG has significantly overlapping orders, but these
157 can be easily separated using the energy resolution of the
158 ACIS-S CCDs. By design, the HETG suppresses the even
159 order peaks in order to maximize the first order intensity;
160 for bright sources, the 3rd order spectrum can be used and
161 provides even higher resolution. For more information about

162 the HETG, please see [http://cxc.harvard.edu/pro-](http://cxc.harvard.edu/proposer/POG/html/HETG.html)
 163 [poser/POG/html/HETG.html](http://cxc.harvard.edu/proposer/POG/html/HETG.html).

164 2.5. LETG

165 The Low Energy Transmission Grating (LETG) (Predehl
 166 et al., 2000) complements the HETG, providing high resolu-
 167 tion spectra of point sources in the range 1.2–175Å (0.07–10
 168 keV). Unlike the HETG, the LETG has only a single grating,
 169 with resolution $\Delta\lambda = 0.05\text{\AA}$. The LETG can be used with
 170 either the HRC or the ACIS. The HRC-S is needed in order
 171 to get the wide spectral coverage out to 175Å, but the data
 172 are then limited by the lack of energy resolution and the rela-
 173 tively high background in the HRC-S. As a result, a number
 174 of observations have been done using the LETG in combina-
 175 tion with the ACIS-S detector. When used with the ACIS-S,
 176 the spectral range decreases to 1.2–65Å. However, by design,
 177 this arrangement maximizes the effective area and resolution
 178 around the prominent O VII and O VIII lines around 19–
 179 22Å. In addition, in flight the ACIS-S has about 1/4th the
 180 background of the HRC-S.

181 Overlapping orders is also an issue with the LETG. When
 182 used with the HRC-S, which has no intrinsic energy reso-
 183 lution, the orders cannot be resolved directly. As a result,
 184 they have to be determined iteratively (if possible) or sim-
 185 ply modeled. Unlike the HETG, orders up to $m = 10$ can
 186 contribute to the final result, so in many situations this is-
 187 sue must be addressed carefully. For more information about
 188 the LETG, please see [http://cxc.harvard.edu/pro-](http://cxc.harvard.edu/proposer/POG/html/LETG.html)
 189 [poser/POG/html/LETG.html](http://cxc.harvard.edu/proposer/POG/html/LETG.html).

190 3. The Chandra X-ray center

191 The Chandra X-ray Center (CXC) is responsible for operat-
 192 ing Chandra and maximizing its scientific output. This in-
 193 cludes scheduling, operations, calibration, software develop-
 194 ment, and data archiving, as described below.

195 3.1. Proposals

196 The CXC issues a call for proposals once per year, with
 197 proposals usually due sometime in March. Proposals are
 198 welcomed from any astronomer regardless of country, and
 199 are evaluated by an independent international group of as-
 200 tronomers. A complete description of the information needed
 201 for a proposal can be found at [http://cxc.harvard.edu/pro-](http://cxc.harvard.edu/proposer/POG/index.html)
 202 [poser/POG/index.html](http://cxc.harvard.edu/proposer/POG/index.html) and is also available in hard-
 203 copy.

204 Once a year's list of targets has been selected, the CXC
 205 mission operations team sorts the targets into a long- and
 206 short-term schedule. The principal investigator for each ob-
 207 servation is contacted to confirm the final settings for the

208 observation, and then it is passed to the Operations Control
 209 Center (OCC), also located in Cambridge, MA at MIT to be
 210 uploaded to the satellite. Uploads are done approximately
 211 once per day via NASA's Deep Space Network; unscheduled
 212 or continuous contacts are available as needed. This, along
 213 with the need to have 3 days worth of observations uploaded
 214 at all times, limits Chandra's ability to respond to a Target
 215 of Opportunity request; in most cases a 24–48 hour response
 216 is the best possible.

217 3.2. Calibration

218 The CXC calibration team both collects calibration data from
 219 the individual instrument teams (ACIS, HRC, HRMA, LETG
 220 & HETG) and reduces calibration data itself. Calibration
 221 data is regularly obtained from set-aside time to both track
 222 Chandra's performance and to address new needs as they
 223 arise. For example, the SNR E0102 is regularly observed to
 224 track the ACIS effective area, while the star AR Lac was
 225 observed with the HRC-I to measure the HRMA PSF.

226 Complete information about the current calibration status
 227 is available at <http://cxc.harvard.edu/cal>. Currently,
 228 Chandra's absolute positioning is known to 0.6" while rela-
 229 tive positions are known to 0.1". Effective areas for the
 230 different detectors are known to 10–20%, while the energy
 231 resolution is known to 4–5%.

232 There is a yearly calibration workshop held in Cambridge,
 233 MA, where the latest calibration work is presented and the
 234 entire team is available for questioning. The proceedings of
 235 these meetings are also listed on the above website.

236 The work of the calibration group is compiled in the cal-
 237 ibration database (CALDB), which is used by the Chandra
 238 data pipeline and the analysis software.

239 3.3. CIAO

240 The Chandra Interactive Analysis of Observations (CIAO)
 241 software package is comprehensive package of Chandra data
 242 reduction and analysis tools. CIAO was written by profes-
 243 sional programmers at the CXC, working under the direction
 244 of X-ray astronomers to develop software that would (a) pro-
 245 cess data from Chandra into calibrated event lists, images,
 246 and spectra and (b) allow users to analyze these data easily.
 247 The entire CIAO package is freely available both as source
 248 code and precompiled for a range of computer platforms, in-
 249 cluding Linux, OS X, and Solaris. System requirements are
 250 relatively modest, and useful work can be done with a 300
 251 MHz machine with 256 MB of RAM and 5 GB of disk space.
 252 If needed, the CXC will mail a CD containing CIAO (and
 253 the CALDB) anywhere in the world.

254 CIAO contains over one hundred individual programs to
 255 perform various operations. However, to guarantee unifor-
 256 mity of interface and application, almost all of these tools

257 use the same set of code libraries. One such library is the
 258 "Data Model" (DM), which CIAO tools use to access the
 259 raw data files. In practice, tools that use the DM allow users
 260 to filter event data "on-the-fly," selecting only particular re-
 261 gions or times of interest for any individual process, such as
 262 creating a lightcurve or extracting a spectrum. Many CIAO
 263 tools also use a standard parameter interface library, similar
 264 to that used by the IRAF package. Recently, the CIAO devel-
 265 opers have incorporated the S-lang scripting language (see
 266 <http://www.s-lang.org> for more information about S-
 267 lang) into some CIAO tools and developed S-lang interfaces
 268 to many CIAO libraries. This allows users to easily develop
 269 their own CIAO tools which access the same libraries as of-
 270 ficial CIAO tools. These can be submitted to the CXC for
 271 general use (and in some cases official incorporation into
 272 CIAO) at the website [http://cxc.harvard.edu/cont-](http://cxc.harvard.edu/cont-soft/soft-exchange.html)
 273 [soft/soft-exchange.html](http://cxc.harvard.edu/cont-soft/soft-exchange.html).

274 CIAO is extensively documented both on the CXC web-
 275 site (<http://cxc.harvard.edu/ciao>) and within CIAO
 276 itself via the `ahelp` command, which returns a descrip-
 277 tion for every CIAO command as well as a large number
 278 of CIAO terms (e.g. `ahelp dmfiltering` for information
 279 about using DM filters). In addition, the website also con-
 280 tains "threads" with step-by-step descriptions of common
 281 tasks as well as "why threads" describing *why* particular
 282 tasks are needed. An active helpdesk is also supported where
 283 CIAO experts will answer questions submitted via email or a
 284 web interface. Approximately twice per year, 2–3 day CIAO
 285 workshops are held where CXC scientists describe how to
 286 reduce X-ray data using CIAO and users can get hands-on
 287 experience with immediate assistance from these experts.

288 3.4. Archive

289 All *Chandra* observations are stored in the *Chandra* archive,
 290 in a number of formats ranging from very nearly the raw
 291 telemetry to calibrated event lists, images, and spectra. Ac-
 292 cess to this data is determined by its purpose. Data taken
 293 for calibration is immediately available, while guest ob-
 294 server observations are generally restricted to the prin-
 295 cipal investigator for one year. *Chandra*'s Director has
 a pool of timediscretionary available for unexpected op-

portunities; these data are also immediately available to
 all.

Access to the archive is normally done via the
 Internet, using either the standalone "chaser" java
 applet or the web interface "webchaser" available
 at [http://cda.harvard.edu/chaser/main](http://cda.harvard.edu/chaser/mainEntry.do) Entry.do.
 The main archive is stored at the CXC in Cambridge, but a
 mirror site is also available in the UK at the University of Le-
 icester. *Chandra* datasets vary in size from ~ 50 MB to over
 2GB, depending on the detector used, the source flux, and
 the length of the observation. If network speed is a limiting
 factor, a CD-ROM can be made at the CXC and sent to the
 user.

4. Conclusions

Chandra's launch opened the new era of X-ray astronomy,
 adding capabilities in the X-ray that could finally match op-
 tical telescopes in angular and spectral resolution. The open
 proposal process allows any astronomer to use *Chandra*'s
 capabilities, and the relatively modest computing require-
 ments combined with the open archive allow relatively easy
 access to *Chandra* datasets. The CXC has actively supported
 the COSPAR X-ray astronomy schools in the past, and re-
 mains committed to supporting the use of *Chandra* around
 the world.

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 on any issue.

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