Fifteen years of Chandra operation: scientific highlights and lessons learned

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ABSTRACT

NASA's Chandra X-Ray Observatory, designed for three years of operation with a goal of five years is now entering its 15-th year of operation. Thanks to its superb angular resolution, the Observatory continues to yield new and exciting results, many of which were totally unanticipated prior to launch. We discuss the current technical status, review recent scientific highlights, indicate a few future directions, and present what we feel is the most important lesson learned from our experience of building and operating this great observatory.

Keywords: X-ray Astronomy, Chandra X-ray Observatory, High-energy astrophysics

1. INTRODUCTION

Almost fifteen years after launch, *Chandra* continues to be one of the world's most powerful tools for exploring the Universe and its extreme and interesting physics as part of the desire to understand our place in the Universe and the fundamental laws that govern it. From the edge of space-time around black holes (BHs), to the outer reaches of the known Universe, the *Chandra* X-ray Observatory is deepening our understanding of the behavior of matter and energy under conditions that cannot be probed on Earth. *Chandra* is also part of a larger picture wherein high-resolution imaging across a wide band of wavelengths is enabling advances in understanding the cosmos, on scales from the first supermassive black holes (SMBHs) to the characteristics of exoplanets and their atmospheres.

The Observatory and its instrumentation have been described in detail in a number of publications. A complete description may be found in the Chandra Proposer Observatory Guide[2] and references therein. Briefly, Chandra consists of three main elements: (1) the telescope containing the X-ray focusing optics which provides sub-arc-second angular resolution, two X-ray transmission gratings (the low and high-energy gratings) that can be inserted into the X-ray path, and a 10-meter-long optical bench that separates the optics from the focal plane imaging instruments; (2) a spacecraft module that provides electrical power, communications, and attitude control; and (3) the instrument module that holds two focal-plane cameras – the Advanced CCD Imaging Spectrometer (ACIS) and the High Resolution Camera (HRC) – and mechanisms to adjust their position and focus. Chandra is 13.8 m long, has a 19 m wingspan, and a mass of 4800 kg.

ACIS contains two arrays of charge coupled devices that provide position and energy information for each detected X-ray photon. The imaging array is optimized for spectrally resolved high-resolution imaging over 17-arcminute wide field-of-view; the spectroscopy array, when used in conjunction with the high energy transmission grating, provides high-resolution spectroscopy with a resolving power (E/ΔE) up to 1000 over the 0.4-8 keV band.

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The HRC is comprises two microchannel plate detectors, one for wide-field imaging and the other serving as a readout for the low energy transmission grating (LETG). The HRC detectors have the highest spatial resolution on Chandra and, in certain operating modes, the fastest time resolution (16 μs). When operated with the HRC's spectral array, the LETG provides spectral resolution >1000 at low (0.08 – 0.2 keV) energies while covering the full Chandra energy band.

Finally, a system of gyroscopes, reaction wheels, reference lights, and a CCD-based star camera enables Chandra to maneuver between targets and point stably while also providing data for accurately determining the sky positions of observed objects. The blurring of images due to pointing uncertainty is <0.10", negligibly affecting the resolution. Absolute positions can be determined to ≤0.6" for 90% of the observed sources, providing an unrivaled capability for X-ray source localization.

2. TECHNICAL STATUS

Chandra's spacecraft and instruments are in excellent health and performing superbly, a result of sound design and construction, as well as careful and skilled operations over the past 14+ years. Figure 1 summarizes the current state of the Observatory subsystems. Based upon thorough analysis, we have every expectation that the Observatory will continue to be capable of delivering ground-breaking science for a 20-year mission (and likely substantially longer).

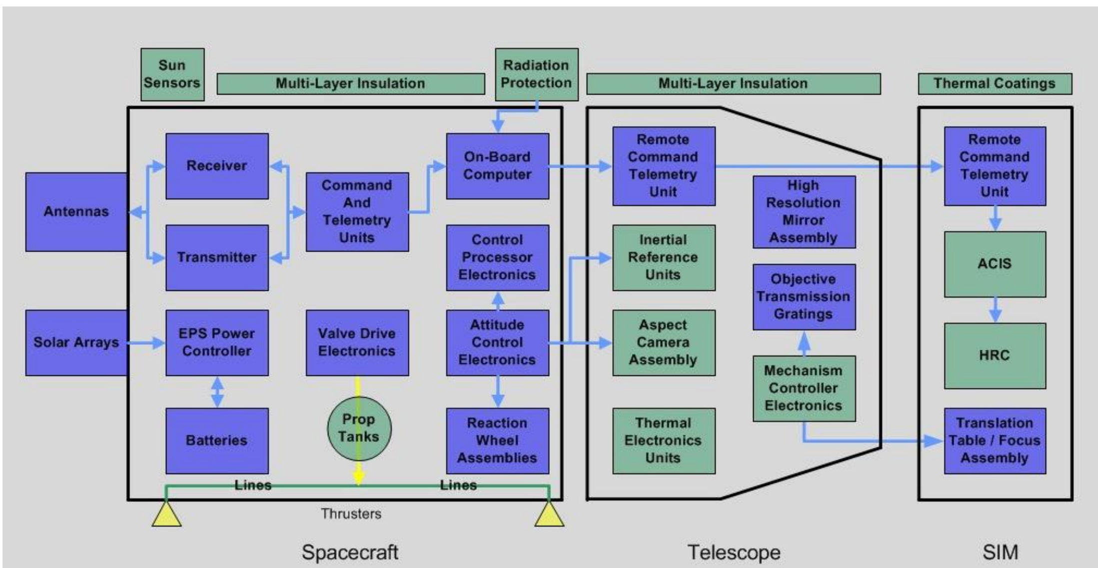

Figure 1. The state of health of the main components within each of Chandra's three major systems, the spacecraft, the telescope and the Science Instrument Module (SIM). Key: blue = no known problems; green = minor problem but meeting all requirements; yellow = moderate problem with manageable performance effects; red = major problem affecting performance. "Radiation Detection" comprises IEPHIN, HRC and ACIS as they apply to this function.

The Observatory has experienced very few anomalies in its first 14+ years of operation; spacecraft performance has been exceptional, and fully single-fault tolerant. That is not to say that the Observatory has not experienced any problems. The spacecraft's multi-layer insulation and other thermal protective surfaces have degraded during the mission due to particle and UV radiation, resulting in elevated temperatures. This has reduced the ability to provide uninterrupted extended observing time at particular spacecraft orientations with respect to the sun. Mitigating the effect has increased the complexity of mission planning. In addition, the insulation degradation has raised the temperature of the Integrated Electron Proton Helium Instrument (IEPHIN, used to safe the science instruments to prevent damage by cosmic rays) to unacceptable levels. As a consequence new, autonomous on-board procedures were developed that use the focal plane x-ray cameras to initiate instrument safing. Another, potentially serious, consequence of the thermal insulation degradation is that the spacecraft's temperature control system no longer adequately maintains the temperature of some of the thruster propellant supply tubes above the freezing point of the hydrazine fuel, introducing a risk of rupturing the tubes. These temperatures are now also managed using mission planning constraints that limit observations in an unfavorable (cold) direction.

Another problem which has had an impact on a subset of scientific observations concerns the ACIS instrument's low-energy detection efficiency which has gradually decreased due to the buildup of contamination on the ACIS optical blocking filter. Of course the contamination has its largest effect at lower energies (<0.5 keV) and the filter transmission currently ~35% of its launch value at 0.7 keV, and ~82% at 1.5 keV. Nevertheless, these values are acceptable when compared to requirements and, based on current extrapolation, requirements will not be exceeded for many years to come

3. RECENT RESULTS

Chandra's ability to locate sources with sub-arc second accuracy enables, e.g., the stacking of X-ray observations at the positions of galaxies found in *Hubble Space Telescope* images to constrain X-ray emission from accreting SMBHs at redshifts $z>6$, and thereby constrain models for the formation and growth of these objects (Figure 2). Some SMBHs in the early Universe likely grew at a prodigious rate, and *Chandra* is proving indispensable at studying this process through observations of active galactic nuclei (AGN) emitting strongly in X-rays. But not all SMBHs grow rapidly. For example, the SMBH, Sgr A*, at the center of the Galaxy is growing very slowly. *Chandra* data has been used to make the first detailed study of the flow of hot gas in the vicinity of Sgr A* and for the SMBH in the nearby galaxy NGC 3115. The results suggest that the flow is a complex mixture of inflowing and outflowing zones, likely driven by the need to transfer angular momentum away from the inflowing material.

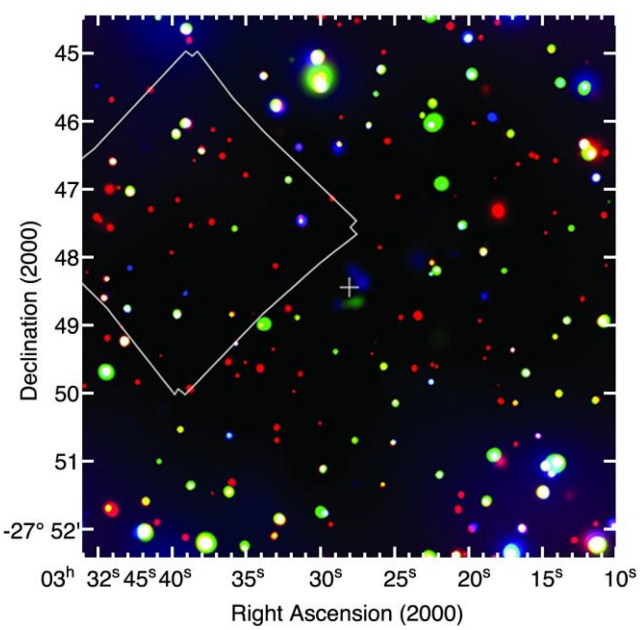

Figure 2: The inner 8′×8′ of the 4-Ms CDFS, the deepest X-ray image currently available [1], with smoothed Chandra images in the 0.5–2.0 keV (red), 2–4 keV (green) and 4–8 keV (blue) bands. The polygon shows coverage by the Hubble Ultra Deep Field. A current Chandra project will extend the total exposure to 7-Ms. Figure adapted from [1]

A recent long observation of the galaxy cluster Abell 133 (Figure 3) has revealed, for the first time, a picture of the conditions in the rarified hot gas, some 1.5 Mpc from the center of the cluster at the virial radius, where gas falling into the cluster from the intracluster medium is predicted to be shocked and thermalized. Extensive surveys of galaxy clusters have shown that *Chandra* measurements may be combined with other observations to place ever tighter constraints on the mix of baryonic matter, dark matter, and dark energy in the Universe. The results show consistency with the picture of the standard cosmological model described by General Relativity (GR), with the energy density dominated by a cosmological constant, and the mass density by dark matter.

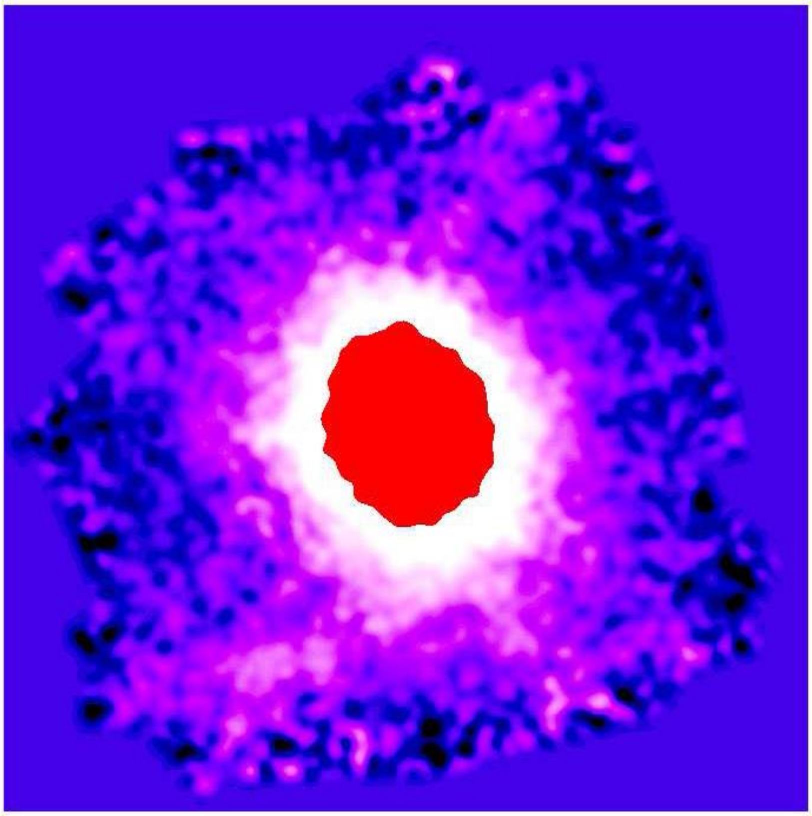

Figure 3: A 2.4 Ms mosaic of Chandra images of the galaxy cluster Abell 133 in the 0.7–2 keV band. All detectable point sources and small-scale clumps were removed and the data smoothed with a σ=30″ (32 kpc) Gaussian. The dynamic range is ~106 and the color map saturates to the red. The circle shows the virial radius. Note filaments in the outer region of the cluster. [2]

On a Galactic scale, observations of a young star cluster have been used in conjunction with infra-red (IR) data to determine the characteristic survival time (~ 6 Myr) of protoplanetary disks. *Chandra* has also detected the transit of an exoplanet in X-rays for the first time, providing evidence for an extended, X-ray absorbing atmosphere. *Chandra*'s unrivaled ability to probe supernova remnants (SNRs) continues with a striking image of the remnant W49B (Figure 4), which provides evidence for an explosion in which a rapidly rotating BH formed and ejected material in a high velocity jet. Another *Chandra* discovery was made when the X-ray Binary (XRB) Cir X-1 transitioned to a low state, and enterprising X-ray astronomers used *Chandra* to detect the natal SNR, which had been hidden from our view by the glare from Cir X-1 since its discovery more than 4 decades ago. At an age < 4600 years determined from the SNR data, Cir X-1 is the youngest known XRB, and affords a golden opportunity to explore how these systems evolve.

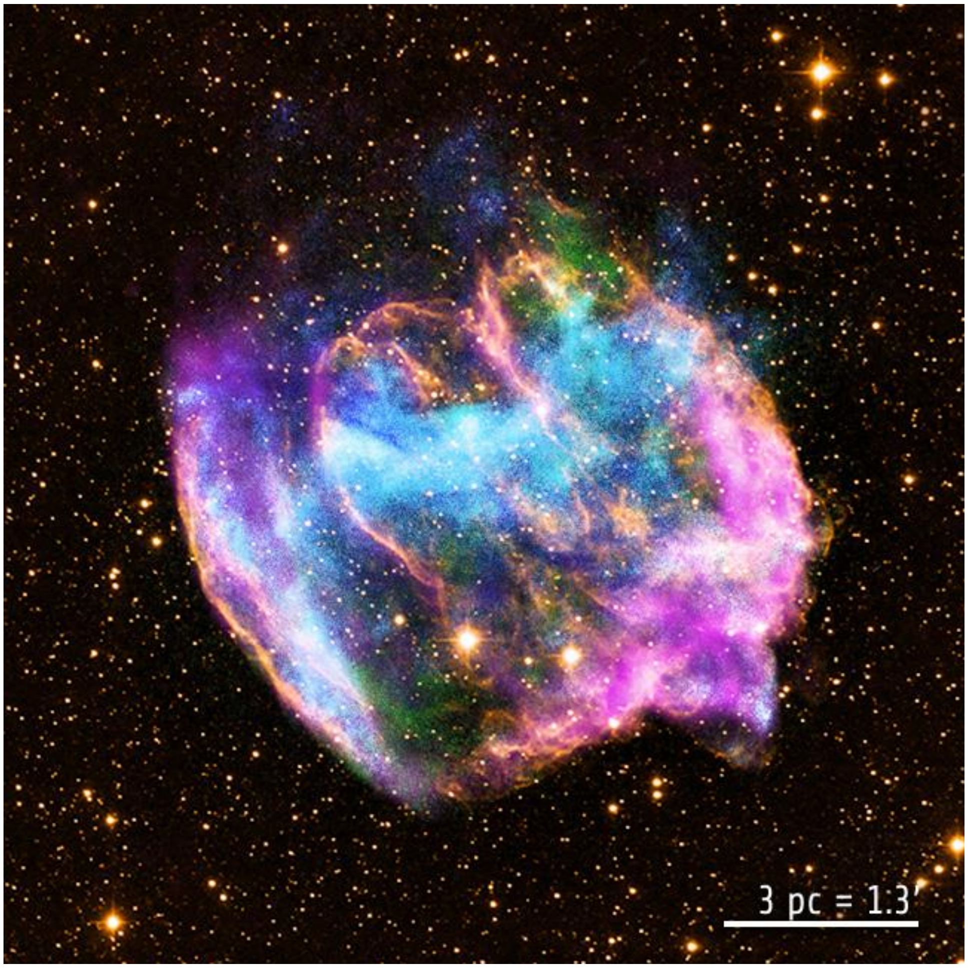

Figure 4: Composite image of W49B, with Chandra X-ray data shown in blue and green, radio data (VLA) in pink and near-IR data (Palomar) in yellow. The distorted shape provides evidence that material near the poles of the SN progenitor, aligned roughly from NW to SE, was ejected at a much higher speed than material near its equator. [3]

4. FUTURE SCIENTIFIC PROSPECTS

It should be noted that Chandra observations are determined through the peer review process.

The increased exposure of the Chandra Deep Field South will enable advances in determining the space density of AGN which will be used to further constrain models for the origin and growth of SMBHs, provide insight into the co-evolution (or not) of SMBHs and galaxies in the redshift range z~1–4, extend our knowledge of star formation versus red shift, and provide a unique set of faint X-ray sources to be used to guide studies in other wavelengths for years to come.

A novel statistical approach applied to substructures merging into clusters may provide much tighter constraints on the self-interaction cross section of dark matter. Sunyaev-Zel'dovich surveys and the upcoming eROSITA (extended Roentgen Survey with an Imaging Telescope Array) X-ray survey mission are (or will be) discovering large numbers of galaxy clusters. When these observations are combined with follow-up Chandra mass determinations, the resulting mass functions will be used to measure the growth of structure in a dark energy dominated Universe and thereby constrain changes in the dark energy equation of state with time.

A much longer Chandra observation of the background blazar 1ES 1553+113 could detect many additional absorption lines due to foreground intergalactic filamentary systems, and thus provide evidence for the whereabouts of the baryons (~ 50% of the total) seemingly missing from the low-redshift Universe.

A very deep observation of 30 Doradus in the Large Magellanic Cloud will use Chandra's superb spatial resolution to study the tableau of stellar evolution presented by one of the most active star-forming regions in the Local Group. Closer to home, Chandra will continue to study the interaction of host stars and their exoplanets. Chandra, along with the Jansky Very Large Array and other telescopes, continues to monitor the passage of the gas cloud G2 around the SMBH Sgr A*. Over the coming months/years, G2 could serve as a source of test particles to probe the flow of matter into a BH, as well as provide unique insights into a range of phenomena driven by previous outbursts in the vicinity of Sgr A*.

5. LESSONS LEARNED

There are two other papers in this conference [4,5] that discuss in some detail the lessons learned in the process of building and operating this Great Observatory. The entire process has taken thirty-eight years (and counting) from the initial unsolicited proposal of Giacconi and Tananbaum in 1976 to the upcoming celebration of the 15-th anniversary of the launch in July 2014. Clearly there were numerous factors that contributed to the outstanding success of the Mission that includes Riccardo Giacconi's Nobel in 2002. Perhaps the foremost amongst these has been the active and dedicated involvement of teams of scientists that have been involved in every aspect of the program including the optics, the spacecraft, the science instruments, the ground and space calibration, and the science and spacecraft operations. These teams both held the line on requirements and also saw to it that there was essentially no "requirements creep" throughout the lengthy development of the mission. They recommended removal of one of the original instruments and signed up, albeit reluctantly, to the bold strategy of changing the mission to one that was unserviceable. This change, which fortunately turned out well, was at the price of one of the most novel instruments that had been originally selected --- an X-ray-sensitive calorimeter, soon to be launched on the ASTRO-H mission discussed elsewhere in these proceedings. We urge those interested in more details of the Chandra-lessons learned by reading the two papers referenced.

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