

25 Years of Groundbreaking Discoveries with Chandra

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Abstract

The *Chandra X-ray Observatory* is a mainstay of modern observational astrophysics. With the highest angular resolution of any X-ray facility, its imaging and spectral capabilities in the 0.5-10 keV band have led to both unique and complementary breakthroughs in nearly all areas of the field. Now more than a quarter century into its mission, *Chandra* continues to provide unique information on the contributions of compact objects to the evolution of galaxies, the nature of supernova explosions, the impact of energetic jets from supermassive black holes on their host environments, and the fate of exoplanet atmospheres in systems rich with stellar flares. Here we provide a summary of *Chandra* results – one that is embarrassingly incomplete, but representative of both the exquisite past and promising future for *Chandra*’s contributions to high energy astrophysics and all of mainstream astronomy.

1 Introduction

As recently as 50 years ago – an eye blink in the history of astronomy – our knowledge of the high energy universe was confined to a small catalog of discrete sources

accompanied by apparently diffuse X-ray emission filling the sky. Today, this hazy X-ray background has been resolved into a speckled array dominated primarily by black holes, and we recognize a sky teeming with X-ray emission produced by objects from within our own Solar System to the very edge of the known Universe. This revolution has been brought about, largely, through the development of telescopes with mirrors capable of producing images of the X-ray sky.

The *Chandra X-ray Observatory* (*Chandra*) represents the current pinnacle in such facilities. With mirrors capable of resolving sources separated by less than $1''$, the observatory can distinguish discrete sources from diffuse emission, image extremely small structures, and measure proper motions and expansions of objects over time periods of years to decades. With a typical total background of ~ 2 counts per million second integration within a resolution element of $\lesssim 1''$ radius, *Chandra* is able to detect exceedingly faint objects – both very low luminosity nearby sources and luminous sources at high redshift. These capabilities open unique avenues of study that have resolved the diffuse X-ray background into point sources, separated emission from discrete sources in external galaxies to reveal the intervening interstellar medium (ISM), identified neutron stars (NSs) and clumps of metal-rich ejecta in supernova remnants (SNRs), and resolved shocks in merging galaxy clusters.

Chandra's high resolution mirrors are accompanied by two detectors, each capable of detecting individual X-ray photons – a CCD camera that offers both imaging and moderate spectral resolution spectroscopy, and a microchannel device that provides slightly higher resolution imaging along with fast timing capabilities. Each camera has both imaging and spectroscopy arrays, the latter used to read out X-rays dispersed through one of two transmission grating spectrometers that can be inserted into the beam to provide spectra with a resolving power of ~ 100 – 1000 over the 0.25–10 keV bandpass. This powerful combination has been used to push the forefront of high energy astrophysics, breaking completely new ground and establishing X-ray observations as a crucial component of mainstream astronomical investigations.

Here we present an overview of highlights from the first quarter century of studies with *Chandra*. A complete summary is far beyond the scope of this article, but the reader is referred to [1] for a more expansive treatment. This overview is organized around contributions to three fundamental questions of modern astrophysics: How Did We Get Here? How Does the Universe Work?, and Are We Alone?

2 Key Insights on Our Origins

Throughout a star's birth, life, and death, whether on its own or with a partner in a binary, there are key high-energy processes that provide unique information on how the stars, planets, and elements in our Galaxy came to exist in their present form and distribution. Stars, their explosions, and the explosions of their remnants, are the engines by which a galaxy is populated with a rich assortment of heavy elements. The contributions of previous generations of stars can be estimated by the population of compact objects they have left behind: white dwarfs, neutron stars, and black holes. The latter two are most easily observed by their production of X-rays in accreting binaries.

2.1 Stellar Birth and Growth

Many key insights can only be learned studying stars in the dense regions in which they form, for which *Chandra*'s spatial resolution and ability to detect highly embedded sources is essential. Young stars of all masses emit X-rays, with the X-ray luminosity decreasing with age (t) as $t^{-1/2}$, which is driven by the convective turnover rate [2]; M stars, for example, can have elevated X-ray emission for up to 5 billion years. *Chandra* observations of young stellar clusters can identify up to twice as many young stars as those identified by an IR-excess using *Spitzer*. The larger samples made possible by *Chandra* observations have led to key discoveries on the formation, structure, and populations of young stellar clusters and subclusters. For example, NGC 2024 and the Orion Nebula Cluster were found to have older populations in the outskirts of the clusters and younger populations in the cores, implying that cluster formation is a slow process, contrary to standard, simple models of star formation [3]. In a detailed survey of 17 star-forming regions, four distinct classes of spatial structure — long chains of subclusters, clumpy structures, isolated clusters with a core-halo structure, and isolated clusters well fit by a single isothermal ellipsoid — were identified [4], and further support was found for a universal X-ray luminosity function [5], which is closely related to the initial mass function.

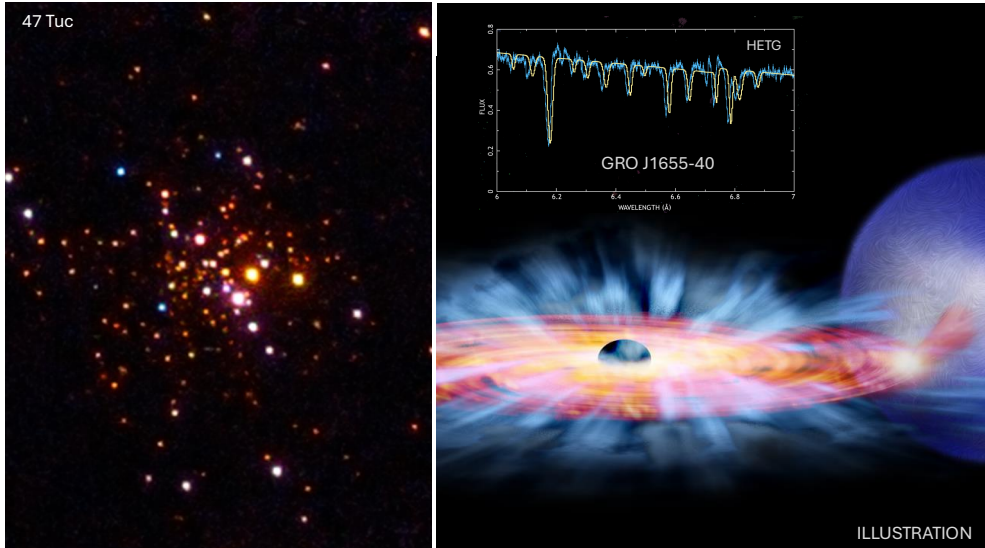


Fig. 1 *Chandra* studies of stellar systems and X-ray binaries. *Left:* *Chandra* image (0.5–1.5 keV in red, 1.5–2.5 keV in green, 4.0–6.0 keV in blue) of the inner $1.8' \times 2.3'$ of the globular cluster 47 Tuc reveals a large and diverse population of close X-ray binaries and their progeny, including low-mass X-ray binaries, millisecond pulsars, cataclysmic variables, and magnetically active BY Dra binaries (credit: NASA/CXC/Michigan State/A. Steiner et al. [129]). *Right:* Artist's impression of the wind coming off the accretion disk in a black hole binary (credit: NASA/CXC/M. Weiss). The inset shows a portion of the measured *Chandra* absorption spectrum of GRO J1655–40 in blue and a model in yellow at the expected wavelengths without bulk outflow. Credit: NASA/CXC/U. Michigan/J. Miller et al. [22]

The growth of pre-main sequence stars via steady accretion can be probed in X-rays produced by the shocks formed by the accretion stream being magnetically funneled onto the stellar surface. *Chandra* High Energy Transmission Grating (HETG) observations of TW Hya show how the X-ray line ratios allow determination of the mass infall rate and details of the coronal emission [6]. The *Chandra* high resolution spectra revealed the presence of both a $\sim 10^7\text{K}$ coronal plasma and a $\sim 2.5 \times 10^6\text{K}$ plasma due to the accretion shock. The electron density determined from He-like Ne IX agreed with accretion models, but the density determined from O VII is a factor of 4 lower, a finding which necessitated the development of a new model of an accretion-fed corona.

Extreme episodic accretion, such as during FU Orionis (FUor) type outbursts [7] have the highest stellar accretion rates. X-ray and infrared observations can probe these heavily obscured sources, and again *Chandra*'s resolution is critical to associate any X-ray emission in the direction of an outburst with the actual star undergoing an FUor outburst; X-ray observations with poorer spatial resolution can be ambiguous because crowding can be an issue [e.g., 8, 9]. For example, the namesake of the class, FU Ori itself, was shown by *Chandra* to have confusion of its X-ray emission with a companion $0.20''$ away [10]. Such resolution was also necessary for the direct X-ray detection of a protostar outflow [11], only possible with *Chandra*, which detected shock-heated material at the leading edge of the outflow at a temperature of $\sim 10^6\text{ K}$.

2.2 Stellar Life

The production of X-rays by pre-main sequence and young stars has direct and potentially devastating consequences on both the survival of the proto-planetary disks at early phases and the stripping and chemistry of planetary atmospheres at later phases. The high energy radiation of massive stars can accelerate the photo-evaporation of proto-planetary disks, causing them to dissipate and eventually disappear faster than normal; *Chandra* has indeed shown that in regions of Cygnus OB2 with lower stellar densities and fewer high mass stars, the fraction of young stars with disks is $\sim 40\%$, whereas in higher density regions the fraction is $\sim 18\%$ [12]. Later in a star's life, its stellar activity can have a large impact on its planets' habitability, and coronal mass ejections in particular are a severe habitability concern [13], yet their rate of occurrence is not well constrained. *Chandra* has detected one extreme event (mass of $\sim 1.2 \times 10^{21}\text{ g}$ and kinetic energy of $\sim 5 \times 10^{34}\text{ erg}$) with HETG-measured Doppler shifts of $100\text{--}400\text{ km s}^{-1}$ in S XVI, Si XIV, and Mg XII lines [14]; however, substantial numbers of coronal mass ejection characterizations in X-rays will need to wait for future X-ray missions like Lynx.

2.3 Stellar Death

At the end of a massive star's life, the cessation of nuclear fusion in the core begins the process of core collapse and subsequent supernova (SN) explosion. As the cast off stellar ejecta interact with the surrounding medium — itself formed from the progenitor star through its winds — both are heated and emit continuum and line emission in X-rays. In the weeks, months, and years after explosion, these X-rays can

probe the late stage evolution of the massive star, revealing hundreds to thousands of years of pre-supernova mass loss history, information impossible to gather in real time.

In general, the high X-ray luminosities of all types of core-collapse SNe dominate the total radiative output of the SNe starting at an age of about one year. As the SN outgoing shock emerges from the star, its characteristic velocity is $\sim 10^4 \text{ km s}^{-1}$, and the density distribution in the outer parts of the ejecta can be approximated by a power-law in radius, $\rho \propto r^{-n}$, with $7 \lesssim n \lesssim 20$. The outgoing shock propagates into a dense circumstellar medium (CSM) formed by the pre-SN stellar wind, whose density follows $\rho = \dot{M}/4\pi r^2 v_w$ where $\dot{M}$ is the pre-SN mass-loss rate and v_w is the pre-SN stellar wind velocity. The collision between the SN ejecta and CSM also produces a “reverse” shock, which travels outward at $\sim 10^3 \text{ km s}^{-1}$ slower than the fastest ejecta. Interaction between the outgoing shock and the CSM produces a hot shell ($\sim 10^9 \text{ K}$), while the reverse shock produces a denser, cooler shell ($\sim 10^7 \text{ K}$) with much higher volume emission measure from which most of the observable X-ray emission arises. By following the evolution of the X-ray (along with radio and optical/UV) emission, *Chandra* observations can measure the temperature and radiative cooling rate and determine the structure of the SN ejecta, structure of the CSM, presence or absence of a dense shell of cold gas surrounding the X-ray emitting region, and details of the star’s pre-SN evolution.

Because these investigations happen in nearby galaxies (tens of Mpc), which have their own heterogeneous populations of X-ray sources, *Chandra*’s sub-arcsecond resolution is required to give an accurate picture of the X-ray emission from young SNe, and it has constrained the steady and episodic mass loss histories of a number of SN progenitors. For example *Chandra* observations have enabled the determination of steady mass loss rates of $\dot{M} \approx (1 - 2) \times 10^{-4} M_\odot \text{ yr}^{-1}$ from the progenitor of the Type IIn SN 1998S, $\dot{M} \approx 2 \times 10^{-6} M_\odot \text{ yr}^{-1}$ from the progenitors of the Type II-P SNe 1999em and 2004et, and $\dot{M} \approx 3 \times 10^{-4} M_\odot \text{ yr}^{-1}$ from the progenitor of the Type IIb SN 2003bg [15–17]. More complicated mass-loss histories involving the stripping of the outer envelopes of massive stars have been revealed by *Chandra* observations of SNe 2004dk and 2014C [e.g., 18–21].

Chandra has also detected heavy elements in prompt X-ray emission months to years after SN explosion with clear evidence for overabundances of Ne, Al, Si, S, Ar, and Fe in SN 1998S [15] and indications of overabundances of O, Ne, and Ni in SN 2003bg [16]. *Chandra* images of the longer lived supernova remnants (SNRs), both those resulting from core collapse of a massive star and those resulting from thermonuclear explosions of white dwarfs, over the past 25 years show the direct and dramatic expansion of heavy elements into interstellar space, beautifully confirming this key phase in the life cycle of stars. Additionally, these SNRs provide rich and unparalleled laboratories for exploring fundamental shock physics, cosmic ray acceleration, and a number of other topics §3.1.

2.4 Stellar Remnants

The neutron stars and black holes left behind by core-collapse SNe are among the most exotic objects in the universe. When one of these compact objects is in a binary and accretes matter from a companion star, the X-ray emission can give unique insights

into not only fundamental physics (e.g., accretion, General Relativity, and quantum mechanics) but also fundamental astrophysics (e.g., star formation history, stellar evolution, and compact object merger). As an example, *Chandra* HETG observations of the black hole binary GRO J1655–40 (Figure 1, right) revealed a rich spectrum with more than 100 blue-shifted absorption lines, primarily from H- and He-like ions of O, Si, Mg, and Fe, indicating the presence of a wind blowing from the black hole accretion disk [22]; detailed modeling shows the wind cannot be driven by radiation or photoionization, but could be due to heating by magnetic turbulent viscosity in the disk.

In addition, these X-ray binaries, as a population, serve as one of the best observational probes of binary stellar evolution [e.g. 23]. With its sensitivity and spatial resolution, *Chandra* observations have established a strong correlation between a galaxy’s high-mass X-ray binaries and its star-formation rate [e.g., 24, and references therein], with the collective X-ray luminosity of a galaxy’s high-mass X-ray binaries related to its star-formation rate (SFR) as $L_X^{\text{HMXB}} (\text{erg s}^{-1}) = 2.61 \times 10^{39} \text{ SFR} (\text{M}_\odot \text{ yr}^{-1})$. *Chandra* observations of 30 early-type galaxies [25] show a scaling between a galaxy’s low-mass X-ray binaries and its stellar mass measured by *K*-band light as $L_X^{\text{LMXB}} (\text{erg s}^{-1}) = 10^{29} L_K (L_{K\odot})$ where $L_{K\odot}$ is the *K*-band luminosity of the Sun.

These results, along with the populations synthesis models they inform, indicate that X-ray binaries will produce the dominant X-ray emission of the early ($z \gtrsim 6$) Universe [26, 27] and be the main heat source of the intergalactic medium prior to the epoch of reionization [e.g., 28].

2.5 X-ray Binary Formation

Understanding the formation of X-ray binaries is one the most difficult problems in astrophysics, due in large part to the complexities of common envelope evolution [e.g. 29]. There is one scenario, however, in which *Chandra* has enabled substantial progress, clearing up several decades-old questions.

Since the discovery of luminous ($\gtrsim 10^{36} \text{ erg s}^{-1}$) low-mass X-ray binaries in the 1970s, it was noted that their formation rate per unit mass is orders of magnitude higher in globular clusters than in the Galactic disk [30, 31]. An additional population of low-luminosity ($L_x \lesssim 10^{35} \text{ erg s}^{-1}$) globular cluster X-ray sources was discovered with the *Einstein* satellite [32, 33] and further explored with *ROSAT* [34].

However, the nature of this low-luminosity population remained elusive for nearly two decades. Early, deep *Chandra* observations [e.g. 35–39] not only discovered many more such sources (Figure 1 left) but also, where *HST* observations were available, allowed for initial progress in classifying the members of this low- L_x population as either quiescent low-mass X-ray binaries, cataclysmic variables, millisecond pulsars, or chromospherically active main-sequence binaries. Although a heterogeneous mix, all are close binary systems or their progeny.

Chandra observations established that the number of X-ray sources in a globular cluster scales with the encounter frequency significantly better than with the mass of the cluster [40], showing that these X-ray sources are largely dynamically formed. *Chandra* also found that a population dominated by quiescent low-mass X-ray binaries

had a very strong dependence on encounter frequency [40–42] while a population dominated by cataclysmic variables had a weaker dependence [43], suggesting the cataclysmic variable population has both primordial and dynamical contributions.

2.6 Compact Object Mergers

The gravitational wave event GW170817 resulted from the merger of two neutron stars and was accompanied by electromagnetic emission across the spectrum, from γ -rays to radio. Because of *Chandra*’s sensitivity, it detected GW170817 in X-rays before other satellites [e.g., 44–46] and can continue to follow its evolution [47]. The X-ray emission to date is well described by a highly relativistic jet launched by the merger remnant and interacting with the surrounding medium.

In addition to synthesizing large amounts of r-process elements, the event is notable because the merged object has a mass of $2.74 M_{\odot}$ [48] and could be either a black hole or massive neutron star. Long term X-ray monitoring with *Chandra* could reveal X-ray emission associated with a spinning neutron star [e.g., 49], whereas a black hole would not be expected to produce substantial late-time X-ray emission.

3 An Unprecedented View of the Physical Workings of the Universe

Our understanding of the Universe is built upon the assumption that the principles of physics as we known them apply everywhere. Yet the vast extremes and complexities encountered in environments from NSs and BHs to the very formation of structure in the early stages after the Big Bang present challenges in unfolding the structure of the known Universe and its contents. Observations of high energy phenomena provide unique insights, and *Chandra*’s contributions in these areas have been immense.

3.1 Supernova Remnants

SN explosions and their remnants play a crucial role in shaping the dynamics and chemical evolution of galaxies, enriching their environments with metals, driving shocks that heat the ISM and trigger new star formation, and acting as particle accelerators to produce an energetic population of cosmic-rays. NSs, formed in core-collapse (CC) SNe, represent the most extreme density and magnetic field conditions in the observable universe, and their properties contain signatures of the explosive process in which they were formed.

Because CC SNRs can result from a broad range of progenitor masses and final stellar configurations, connecting the observed properties to progenitor type provides critical information on the details of these explosive events. Cas A provides an illustrative example of the numerous breakthroughs in *Chandra* SNR studies. The image (Figure 2, left) reveals a complex network of shock-heated ejecta surrounded by a thin rim of synchrotron emission from electrons with energies approaching 100 TeV. Spatially-resolved spectroscopy establishes a clear overturn of the ejecta [50], resulting in Fe being mixed to the outermost regions of the remnant despite being formed near the core. A census of the ejecta composition and mass, from spectra resolved on

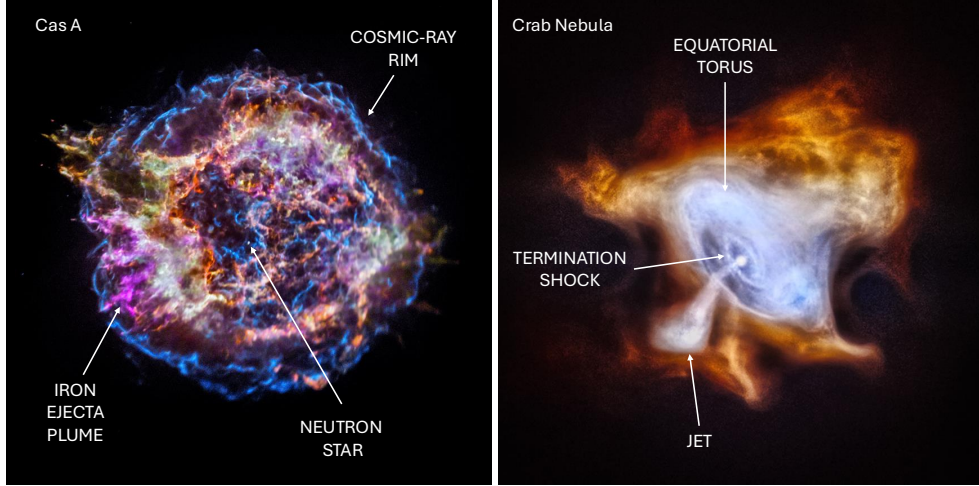


Fig. 2 *Chandra* details on the aftermath of stellar explosions. Left: *Chandra* image of Cas A (red: 0.5-1.5 keV; green 1.5-2.5 keV, blue: 4.0-6.0 keV). The young NS can be seen in the remnant center. Shocked ejecta in the interior is distributed in a complex of clumps and filamentary features. The distinct magenta-colored emission in the southeast is dominated by Fe-L emission (a broad band around 1 keV) from Fe-rich material while a shell of synchrotron emission (blue) identifies sites of particle acceleration to cosmic ray energies. [Credit: NASA/CXC/SAO] Right: *Chandra* image of Crab Nebula (red=0.5-1.2 keV, green=1.2-2.0 keV, blue=2.0-7.0 keV). The central pulsar is surrounded by an inner ring marking the wind termination shock and by an equatorial torus. A prominent jet identifies the direction of the pulsar rotation axis. The emission is hard (blue) near the pulsar, but softer (red) in the outskirts of the nebula due to synchrotron losses from the most energetic particles. [Credit: NASA/CXC/SAO]

small spatial scales, has identified regions where Fe is accompanied by other products of incomplete Si burning, while others are nearly pure Fe produced during complete Si burning [51]. The total inferred mass is $\sim 3.5M_{\odot}$, of which $\sim 0.1M_{\odot}$ is Fe. However, because Cas A is young, the reverse shock has not yet propagated through (and heated) all of the ejecta. Observations with JWST uncover unshocked ejecta in the central regions, along with a wealth of complementary information about Cas A [52].

The very first *Chandra* observations of Cas A identified a faint point source in the remnant center – the NS formed in the SN explosion. Its properties, however, differ wildly from those expected at the time. For example, the Crab Pulsar and its nebula (Figure 2, right), if moved to the same distance, would outshine the Cas A NS by a factor of $\sim 10^4$. No pulsations are detected from the Cas A NS, nor is there any evidence of an associated wind nebula (see §3.2); the emission is completely derived from cooling of the hot NS interior, placing constraints on the equation of state of matter at the extreme central densities [53]. Additional *Chandra* discoveries of such so-called “compact central objects” have now been identified in other young SNRs as well.

Early observations of SN 1987A – barely resolved by *Chandra*, with a diameter of only $\sim 1.2''$ – showed the blast wave beginning to interact with dense clumps at the

inner edge of an equatorial ring, producing bright spots also observed in optical observations, and eventually entering the bulk of the ring material, resulting in an increase in the X-ray brightness, and an accompanying decrease in the observed expansion rate [54]. Most recently, *Chandra* observations show changes in the electron temperature and volume emission measure that indicate that SN 1987A is expanding out of the equatorial ring and into a new region of CSM, and also reveal the presence of an Fe K line that may represent onset of the reverse shock interacting with SN ejecta [55]. Observations of SN 1987A, as it transitions from an SN to an SNR, continue as a legacy of *Chandra*.

X-ray studies of SNRs from Type Ia SNe – known to originate from the complete disruption of a white dwarf star in a binary system, and used widely as cosmological yardsticks – provide signatures of their evolutionary paths, in particular on whether the progenitor systems contain a single white dwarf accreting from a normal stellar companion, or two white dwarfs merging through orbital losses from gravitational wave emission (the so-called “single degenerate” and “double degenerate” evolutionary scenarios). *Chandra* observations of Kepler’s SNR (the remnant of SN 1604) classify this as a Type Ia remnant based on the dominant Si, S, and Fe emission, and the remnant displays substantial shocked CSM in the north, suggesting interaction with mass lost from a fairly massive progenitor – either that of the white dwarf or a companion star. This may provide evidence for single-degenerate progenitor for this system [56].

Additional approaches have been used to classify SNR types based on *Chandra* observations. Moment analysis of SNR morphologies, for example, shows that CC remnants display a lower degree of spherical symmetry and mirror symmetry than those from Type Ia explosions – presumably associated with evolution in complex environments near their birth sites, and/or asymmetries in the explosions themselves [57]. Studies of the Fe K ionization state also identify a distinction between CC and Type Ia remnants, with the former displaying more highly ionized states due to the higher density of the environments [58]. These new methods of differentiating between CC and Ia origins, even for middle-aged SNRs, offer an important tool for SNR demographics.

3.2 Particle Acceleration

With rapid shocks and large kinetic energy reserves, SNRs have long been recognized as potential sites of cosmic-ray acceleration. The identification of nonthermal X-rays from SNR shell clearly demonstrates the presence of electrons with energies approaching energies of $\sim 10^{14}$ eV. All historical SNRs studied with *Chandra* reveal such emission components, most with this nonthermal emission confined to narrow rims (e.g., Figure 2, left). The rim thickness is limited by synchrotron losses in the diffusion and/or advection of relativistic particles downstream of the shock, and provides important information on the magnetic field properties in the acceleration region [59, 60]. These radiative losses also limit the maximum energies of the accelerated electrons, providing a connection between the spectral cutoff, the shock velocity, and the mean free path of the particle transport.

The high resolution offered by *Chandra* provides for measurements of the shock thickness and the expansion rate over multi-epoch observations that address the particle acceleration properties of different SNRs. Combined with X-ray polarization

measurements with the Imaging X-ray Polarimetry Explorer (IXPE), these observations establish constraints on the turbulence levels and size scales in the particle acceleration regions [61].

3.3 Neutron Star Kicks

Many pulsars are known to have large velocities, presumably imparted in the supernova explosion process. The mechanism by which such “kicks” are produced is poorly understood, as are many details of the explosions themselves. Anisotropic neutrino emission can produce NS kicks [62], and are expected to result in alignment between the spin axis and the kick velocity [63] due to the long duration of the neutrino process relative to the initial spin period of the proto-NS [64]. Alternatively, convective instabilities can result in asymmetric ejection of the supernova ejecta, with momentum-conserving recoil of the NS in the opposite direction [65, 66]. *Chandra* observations of young NSs in SNRs yield important constraints on this process. Proper motion measurements from observations taken over large time baselines have established the kick velocity directions (in the plane of the sky). Comparison of the proper motion direction with the distribution of ejecta material measured in *Chandra* observations of these and other SNRs shows a clear anti-correlation that supports the convective instability scenario [67].

3.4 Pulsar Wind Nebulae

Chandra observations of the pulsar wind nebulae (PWNe) produced by some young NSs reveal distinct jet-torus structures. This is seen most dramatically for the Crab Nebula (Figure 2, right; [68]), where the central pulsar is surrounded by a distinct ring at which the cold equatorial electron-positron wind from the inner underluminous region terminates in a shock as it enters the more slowly expanding nebula. The subsequent flow is dominated by an equatorial torus and accompanied by jets aligned with the pulsar rotation axis. Synchrotron cooling of the energetic particles as they diffuse to the outskirts of the nebula is seen as a steeping of the X-ray spectrum, evident as a color change in Figure 2 (right).

Similar jet-torus structures are identified around many young NSs [69–71] – observable only with the high resolution capabilities of *Chandra* in many cases. When observed within their host SNRs, these PWNe provide important insights on the formation and evolution of these systems. In G292.0+1.8, for example, the PWN jet-torus structure [72] reveals a spin axis that is oriented nearly perpendicular to the proper motion of the pulsar, arguing against the spin-kick alignment predicted by anisotropic neutrino emission models. In Kes 75, for which the central pulsar shows magnetar-like properties, *Herschel* emission from the innermost unshocked ejecta – just outside the *Chandra* boundaries of the PWN – establish abundances that, combined with hydrodynamical simulations of the PWN/SNR system, provide evidence for both a low energy explosion and a low progenitor mass, which are associated with explosions that give rise to magnetars [73].

Upon exiting their host SNRs, PWNe form bowshock nebulae as they traverse the ISM. Particles eventually escape downstream to contribute to the Galactic $e^+ - e^-$

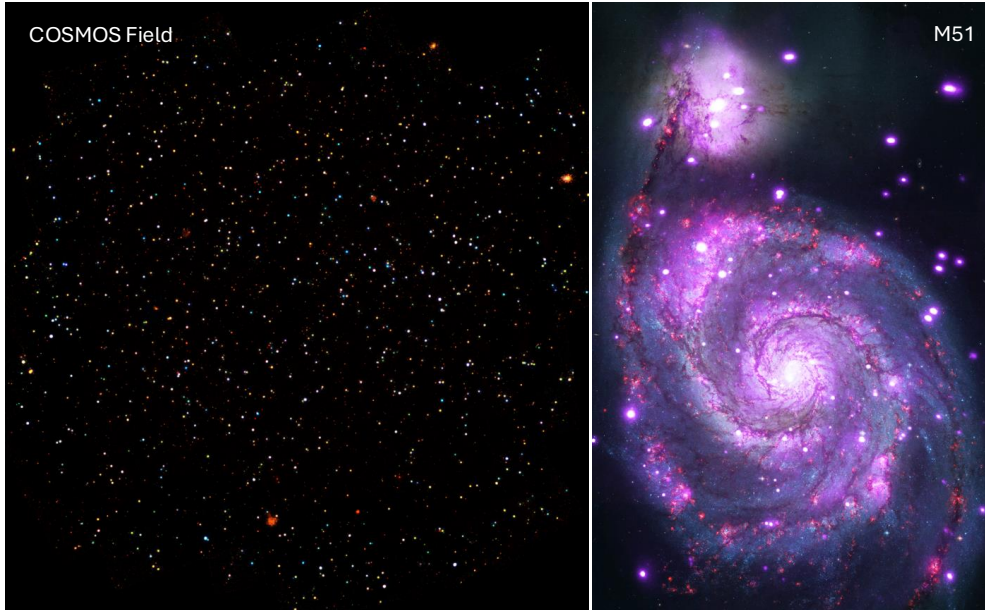


Fig. 3 From deep fields to nearby galaxies, *Chandra* resolves the X-ray sky into discrete sources while separating from the truly diffuse galactic emission. *Left:* Deep X-ray image of the Cosmic Evolution Survey (COSMOS)-Legacy Field, in which $\approx 90\%$ of the CXB is resolved into individual, faint AGN. [Credit: NASA/CXC/ICE/M. Mezcua et al. [130]] *Right:* Composite *Chandra* (pink) and Hubble Space Telescope image of the grand-design spiral galaxy M51, showing diffuse X-ray-emitting hot gas along the spiral arms and numerous point-like high-mass X-ray binaries associated with the star-forming regions of the galaxy. [Credit: Credit: X-ray: NASA/CXC/SAO; UV: NASA/JPL-Caltech; Optical: NASA/STScI; IR: NASA/JPL-Caltech]

cosmic-ray population. Some such systems display connections with long nonthermal filaments that extend in directions unconnected with the pulsar motion or rotation axis, and appear to represent the escape of very energetic particles from beyond the bowshock [74].

3.5 Galaxies

One of *Chandra*'s earliest achievements was to resolve the long-standing mystery of the cosmic X-ray background (CXB), which was seen as a diffuse X-ray glow across the sky. Deep surveys, such as the *Chandra* Deep Field South [75], successfully revealed that this glow is composed of myriad point sources and not truly diffuse emission (Figure 3 left). In fact, the ultra-deep *Chandra* exposures resolved 80 – 90% of the CXB emission into discrete sources [76]. Almost all of the resolved CXB intensity can be attributed to accreting supermassive black holes (SMBHs) in distant galaxies [77]. This census directly traces the cosmic growth of SMBHs [78] and shows that a large fraction of black hole accretion occurs in obscured active galactic nuclei (AGN) only visible in X-rays [79]. Deep *Chandra* surveys have mapped the evolution of the AGN

luminosity function from the local universe to high redshifts, which provides a direct measure of the SMBH accretion history across cosmic time [80].

Chandra's ability to resolve faint X-ray point sources is not only important at large cosmic distances. Long before the launch of *Chandra*, X-ray emission from our own Milky Way was observed as a diffuse glow. It was unclear whether this emission was produced by extremely hot gas with tens of millions Kelvin temperature, or from the blending of densely populated point sources [81]. To resolve this question, *Chandra* observed a carefully selected patch in the Milky Way. These observations revealed that most of the Milky Way's X-ray glow can be attributed to the integrated emission of millions of faint stellar sources, such as accreting white dwarfs, coronally active binary stars, and young stellar objects [82, 83]. Each of these objects leave their own energetic imprint, which collectively builds up the so-called Galactic ridge X-ray emission. These studies also laid the foundation for studying the diffuse X-ray glow associated with other galaxies, such as our cosmic neighbor, Andromeda. The diffuse glow from Andromeda and other galaxies, at least in part, originates from the population of very faint, discrete X-ray sources, similar to the Milky Way [84, 85].

The ability to resolve individual point sources in galaxies had a fundamental consequence: it became possible to separate the emission from discrete, point sources from the truly diffuse gaseous emission. Studying the hot, X-ray-emitting ISM within galaxies provides insights in to the most energetic events in the lives of galaxies (Figure 3 right). The ISM is heated by the energy input from supernovae and SMBHs, therefore its physical properties provide an imprint on the past history of feedback processes [86, 87]. In addition, by studying the chemical composition of the ISM, it became possible to probe how galaxies were enriched by heavy elements. The Milky Way's own ISM was studied by high-resolution spectroscopy with *Chandra's* Low Energy Transmission Grating (LETG) and HETG by detecting absorption features from elements such as Oxygen and Neon [88, 89]. These spectral diagnostics studies offered insights into the physical state, ionization balance, and metal enrichment, thereby painting a picture of our own Galaxy's gaseous ecosystem. Beyond the optically visible regions of galaxies, *Chandra* probed the hot, X-ray-emitting circumgalactic medium (CGM) [90]. In NGC 1961, *Chandra* detected an expansive gaseous halo with $(3 - 7) \times 10^6$ K temperature that extends well beyond the stellar disk [91]. The CGM serves both as repositories for metals expelled by supernovae and stellar winds and as the long-sought reservoirs of shock-heated gas. In the standard picture of galaxy formation, baryons accrete into dark matter potentials, are shockheated to the virial temperature, then radiatively cool to fuel star-formation, which result in the formation of galactic disks [92, 93]. The detection and characterization of the CGM directly confirms this framework and links cosmological gas inflow, virial shock heating, feedback enrichment, and the regulation of galaxy growth.

3.6 Galaxy Clusters

Galaxy clusters, containing hundreds of galaxies embedded in a massive halo of dark matter and hot gas, are excellent laboratories for both astrophysics and cosmology. While the total mass of clusters can reach $10^{15} M_{\odot}$, stars confined within the cluster member galaxies account for only a few percent of this enormous mass. Instead, most of

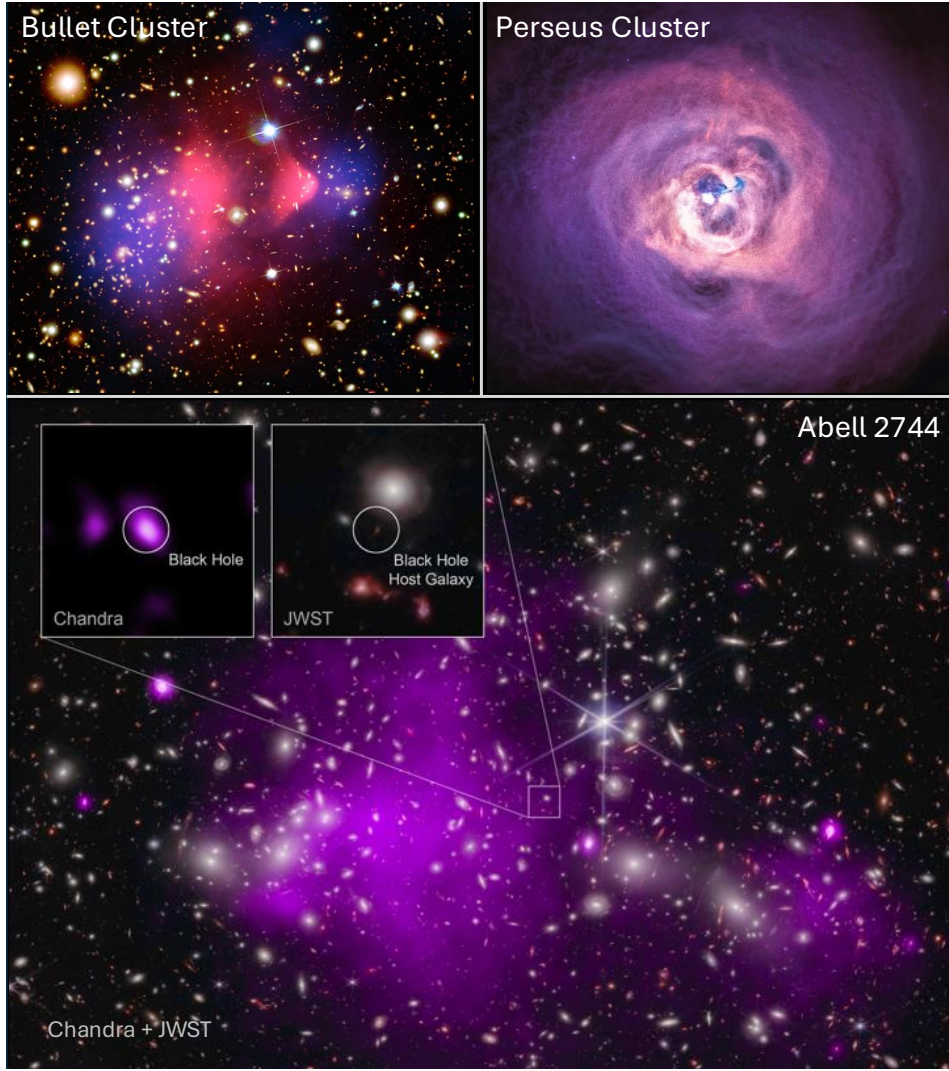


Fig. 4 Chandra observations of galaxy clusters transformed our understanding of dark matter, the gas physics of the ICM, and the emergence of the first SMBHs. *Top left:* Composite image of Chandra X-ray (pink), optical light, and the gravitational lensing mass (blue) map of the Bullet Cluster. The offset between the collisional ICM and the collisionless mass clumps provides direct evidence for non-baryonic dark matter. [X-ray: NASA/CXC/CfA/[94]; Optical: NASA/STScI; Magellan/U.Arizona/D. Clowe et al. [95]; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D. Clowe et al. [95].] *Top right:* Deep Chandra view of the Perseus Cluster, revealing multiple AGN-inflated X-ray bubbles and ripples, illustrating AGN heating in a cool core. [Credit: NASA/CXC/Univ. of Cambridge/C. Reynolds et al. [131]] *Bottom:* Chandra image of the lensing galaxy cluster Abell 2744 (purple) overlaid on the JWST image. The inset panels show the $z = 10.07$ galaxy, UHZ1. The X-ray point source is coincident with the JWST-detected galaxy, revealing a SMBH at cosmic dawn. [X-ray: NASA/CXC/SAO/Á. Bogdán [116]; Infrared: NASA/ESA/CSA/STScI; Image Processing: NASA/CXC/SAO/L. Frattare & K. Arcand]

the baryonic mass is in the form of X-ray emitting hot gas with tens of millions Kelvin temperatures. This intracluster medium (ICM) accounts for $\sim 10\%$ of the mass of galaxy clusters. The remaining $\sim 90\%$ of mass is in the form of dark matter. Chandra observations of clusters allowed us to study the nature of dark matter, the physics of the hot ICM, and the interaction between galaxies and their large-scale environment.

The Bullet Cluster (1E 0657-56) is not only one of the most iconic images featuring Chandra data, but it also provides direct empirical proof for the existence of dark matter. In this system, two galaxy clusters collided with high speeds ($\sim 4500 \text{ km s}^{-1}$). Chandra mapped the distribution of the hot ICM, which contains the bulk of baryonic mass, and identified the characteristic “bullet”-like feature (Figure 4 top left) produced by a shock front that lags behind the galaxy clusters during the collision. At the same time, gravitational lensing maps from optical data established that the distribution of dark matter is offset from the X-ray gas and coincides with the location of the galaxies [94, 95]. The explanation for this offset is that during the collision between the clusters, the collisional X-ray gas slowed down and formed the shock fronts, while the non-collisional dark matter passed through unaffected, as traced by the galaxies. This provides clear evidence that an invisible and collisionless mass component, dark matter, dominates the cluster mass. This discovery not only provided direct evidence for the existence of dark matter, but also placed constraints on the self-interaction cross-section of dark matter particles, ruling out a range of exotic models [96].

Galaxy clusters are also powerful cosmological probes. Specifically, X-ray measurements of the total and baryonic cluster mass (inferred via the temperature and density profile of the ICM) and the evolution of cluster number counts as a function of redshift can be used to test models of structure growth. By tracing how the abundance of massive clusters declines at higher redshifts, Chandra measurements confirmed the existence of dark energy. Higher redshift clusters are expected to be less common than they would be in a universe without the accelerated expansion of the universe (Figure 5 left). This imprint of the dark energy was directly probed by Chandra data of a few dozen well-characterized clusters, and provided measurements of the cosmological matter density Ω_M and dark energy equation-of-state parameter w_0 . Specifically, the Chandra observations of clusters demonstrated that an equation-of-state parameter of $w \simeq -1$ provides the best-fit, which is consistent with a cosmological constant, in agreement with the Λ cold dark matter (CDM, where Λ is the cosmological constant) paradigm [97, 98]. The accuracy of these cosmological parameters rival those from the cosmic microwave background and Type Ia supernovae. In addition, the degeneracy directions of cluster cosmology are orthogonal to those of other probes (Figure 5 right), providing an independent and powerful pillar of observational cosmology.

In many cluster cores, the cooling time of the dense X-ray emitting gas is much shorter than the age of the cluster. As a consequence, a substantial fraction of this gas is expected to cool to low temperatures, which could drive rapid starformation with rates of hundreds of solar masses per year. Initial X-ray spectra showed little to no evidence for gas at $kT \lesssim 1 \text{ keV}$ (where T is the temperature and k is the Boltzmann constant), a discrepancy dubbed as the “cooling-flow” problem. High-resolution *Chandra* imaging revealed that jets from the central SMBH inflate buoyant bubbles

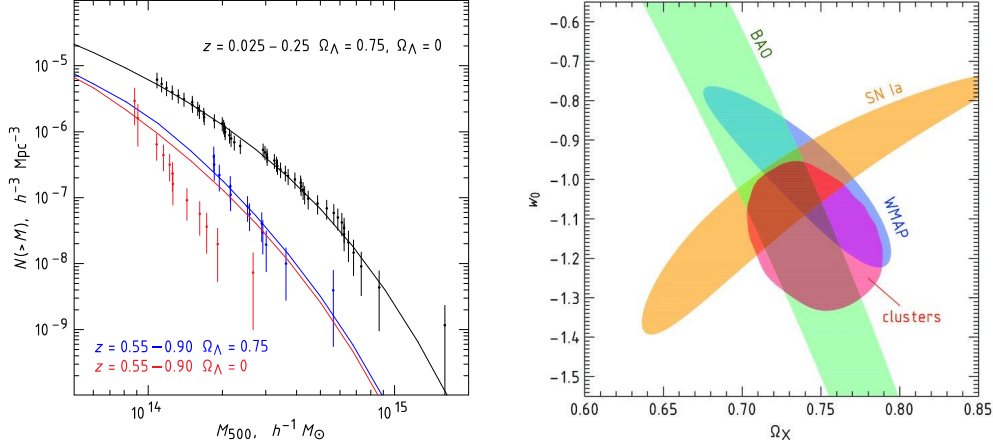


Fig. 5 *Chandra* observations of galaxy clusters independently confirm cosmic acceleration and constrain the dark energy equation of state. *Left:* Comoving cluster abundance, $N(>M)$, versus mass, M_{500} , in two redshift bins, derived from *Chandra* observations. Here M_{500} is the mass within r_{500} , the radius enclosing 500 times the critical density at the cluster redshift, and $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. Black data points show the observed abundance in the low-redshift bin ($z = 0.025 - 0.25$) when cluster masses are inferred in a flat Λ CDM cosmology. The solid black curve shows the corresponding Λ CDM mass function. In the high-redshift bin ($z = 0.55 - 0.90$), blue data points and the blue curve show the observations and the Λ CDM prediction, while the red data points and red curve show the same sample and prediction when masses are recomputed in a matter-only universe. The suppression of high-mass clusters in Λ CDM (blue/black) versus the matter-only case (red) illustrates that dark energy slows the growth of massive structures at early times. Error bars are 1σ . *Right:* Constraints in the $\Omega_X - w_0$ plane from galaxy clusters (red) compared with other probes all favoring $w_0 \simeq -1$. $\Omega_X = 1 - \Omega_M$ denotes the present-day dark-energy density parameter. Regions correspond to 68% CL. BAO, baryon acoustic oscillations; WMAP, Wilkinson Microwave Anisotropy Probe. [[98] ©AAS. Reproduced with permission.]

in the ICM, thereby displacing cooling gas and injecting mechanical energy [99]. More recently, deep *XMM-Newton* Reflection Grating Spectrometer (RGS) observations have detected Fe XVII emission from cooler gas at $0.3 - 0.7 \text{ keV}$ [100], demonstrating that a modest cooling flow, albeit with rates below the classical predictions, is present in many cool core clusters. The Perseus Cluster provides one of the most vivid examples of AGN feedback in action. *Chandra* data show two roughly symmetric, $\sim 10 \text{ kpc}$ bubbles, where radio observations reveal relativistic plasma filling the cavities. These bubbles are surrounded by ripple-like surface brightness fluctuations that are weak shocks propagating through the ICM [101, 102] (Figure 4 top right). These features indicate repeated AGN outbursts in the past that inflated bubbles and drove waves through the ICM. The energy input injected by the SMBH is sufficient to heat the gas and offset most radiative losses, and suppress star formation in cluster cores. Nevertheless, a small amount of low-temperature gas persists, and its ultimate fate is still under active investigation. Overall, *Chandra* observations did not only address the classical cooling-flow problem but also demonstrated that the SMBH in the central galaxy can profoundly influence the thermal state of the entire cluster core [103].

3.7 Supermassive Black Holes

The high resolution imaging of Chandra was essential in studying SMBHs across a wide range of masses and cosmic times. Chandra explored the lowest mass SMBHs in nearby dwarf galaxies to the most massive ellipticals, and from the local universe to the cosmic dawn.

In the nearby universe, one of *Chandra*'s key achievement was the direct detection of a binary SMBH system in an ongoing merger. Chandra observations of NGC 6240, a nearby merger remnant galaxy, detected not one but two luminous X-ray point sources associated with the optical core of the galaxies. Each of these nuclei showed characteristic signatures of accreting SMBHs, such as absorbed luminous X-ray emission and strong Fe K α lines [104]. The two SMBHs, separated by ≈ 1 kpc, are orbiting each other and are predicted to coalesce in a few hundred million years. This discovery confirmed that galaxy mergers can bring SMBHs into close proximity, which can then result in their eventual merger. Chandra observations of other interacting galaxies detected many similar systems, clearly indicating that the formation of binary SMBHs is a common evolutionary stage of mergers [105, 106]. By measuring the properties of binary SMBHs, Chandra can place constraints on these early phases of SMBH binary evolution, which at a later stage will be the source of low-frequency gravitational wave signals and will be targeted by next-generation space-based observatories, such as LISA.

By the early 2000s, it was well established that virtually all Milky Way-sized and more massive galaxies host a SMBH. However, the presence of SMBHs in the much lower mass dwarf galaxies remained debated. That changed with the Chandra imaging of the dwarf starburst galaxy Henize 2-10. By combining the Chandra X-ray data with high-resolution radio observations, a hard X-ray source was detected in the core of this galaxy, attributed to an accreting SMBH [107]. This detection showed that even low stellar mass galaxies can host and grow SMBHs. Following this discovery, Chandra studies of other dwarf galaxies identified further SMBH candidates, many of which were also identified in multi-wavelength observations in the radio, infrared, and optical bands [108, 109].

Shortly after its launch, Chandra revolutionized our view of relativistic jets. Its first celestial target, the quasar PKS 0637-752, revealed a $\gtrsim 100$ kpc X-ray jet with four distinct knots aligned with previously identified radio features [110]. Deep Chandra imaging of the massive elliptical galaxy M87, then resolved its jet into multiple synchrotron-emitting knots, which extending beyond ~ 5 kpc [111]. Additionally, *Chandra*'s High Resolution Camera (HRC) could even track proper motions associated with the innermost knots over a five year baseline, measuring relativistic speeds on sub-kpc scales [112]. Many *Chandra* observations of quasar jets have revealed extended emission coincident with radio structures, with the X-ray emission attributed to inverseCompton (IC) scattering of CMB photons. Since the CMB energy density scales as $\rho_{\text{CMB}} \propto (1+z)^4$, this mechanism substantially boosts X-ray brightness at $z \gtrsim 1$. Modeling the X-ray (IC) to radio (synchrotron) flux ratio provides both the magnetic field and its particle spectrum of the jet. From these parameters, the jets enthalpy flux can be computed (and can be as high as $\sim 10^{46}$ erg s $^{-1}$), which directly links X-ray jet observations to powerful AGN feedback [113]. Over the past 25 years, *Chandra*

has turned jet detections into precision experiments, using X-ray-bright outflows as laboratories for particle acceleration and as tracers of cosmic feedback.

Understanding the origin of the first SMBHs is a fundamental challenge. Theoretical studies proposed two broad seeding pathways: “light seeds” from the remnants of Population III stars ($M_{\text{seed}} \sim 10 - 100 M_{\odot}$) [114] and “heavy seeds” from the collapse of pristine gas clouds ($M_{\text{seed}} \sim 10^4 - 10^5 M_{\odot}$) [115]. To distinguish between these scenarios, SMBHs must be observed close to their formation epoch ($z \gtrsim 9$). However, the faint and likely obscured nature of these first SMBHs makes this a daunting challenge. A breakthrough came when JWST identified a population of galaxies at $z = 9 - 12$, and ultra-deep *Chandra* observations of this same field detected X-ray point sources associated with two of these galaxies: UHZ1 and GHZ9 at $z \approx 10.1$ (≈ 460 million years after the Big Bang) [116–118] (Figure 4 bottom). The X-ray luminosities of the sources imply black hole masses of a few times $10^7 M_{\odot}$, which corresponds to $\sim 2040\%$ of the stellar mass of their host galaxies, far exceeding the local ratio of $\sim 0.2\%$. The existence of such massive black holes so early, combined with their unusually high $M_{\text{BH}}/M_{\star}$ ratios (where $M_{\star}$ is the stellar mass), strongly favors the “heavy seed” scenario. These detections provide the most compelling evidence to date that some of the first SMBHs formed through the collapse of massive gas clouds.

4 An Exploration of the Solar System and Stellar Habitability

From the earliest recognition of other planets within the Solar System, the notion that they might harbor some form of life has captivated the thoughts of philosophers and scientists alike. While our understanding of this question has become highly refined over long periods of investigation, efforts persist to identify signatures of life beyond Earth. Detailed studies of our own Solar System form the bedrock for understanding the conditions under which other forms of life, if they exist, would need to develop, and X-ray observations play a unique role in probing the physical conditions within the Solar System as well as the impact of solar radiation. These, in turn, inform studies of other stellar systems that host planets.

4.1 Solar System Objects

The solar wind – a stream of energetic electrons, ions, and entrained magnetic field – provides the energy source for multiple sources of X-ray emission within the solar system. The early work that launched the field was directed at detecting X-ray from the moon, produced by fluorescence from particles impacting the surface [119].

To date, *Chandra* has detected X-rays From Venus, Earth, Mars, Jupiter and its moons Io and Europa, Saturn and its rings, Pluto, multiple comets, and even a transit of the Crab Nebula by Saturn’s moon Titan (see review by [120]). The X-ray emission results from a variety of processes – charge exchange, scattering of solar X-rays, fluorescence following solar X-ray photoionization, and bremsstrahlung and line emission from collisions with energetic particles. Which of these processes dominates is dependent upon the conditions of both the solar wind and the environment at the interaction site.

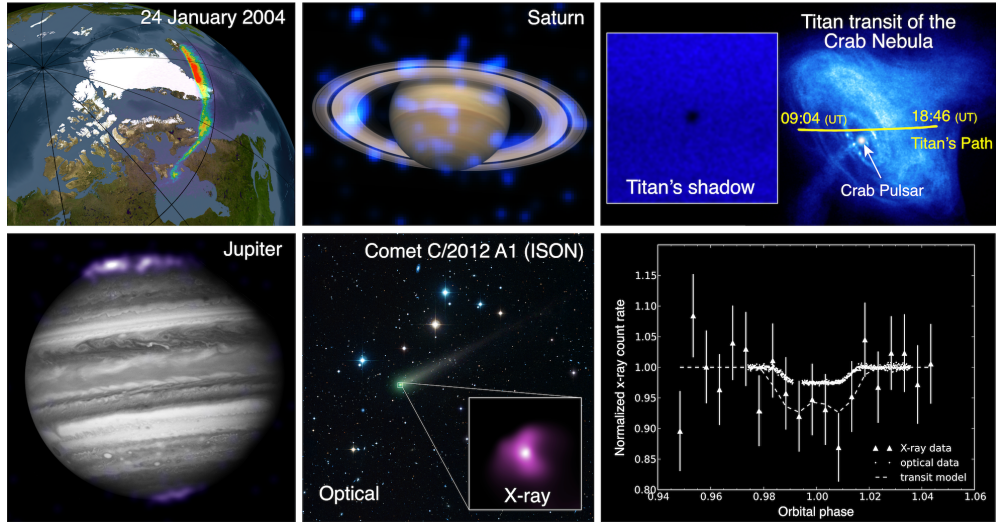


Fig. 6 *Chandra* investigations of planets within the Solar System and beyond. Counter-clockwise from upper right: Saturn’s moon Titan transiting the Crab Nebula; Saturn, showing X-rays (blue) from disk and rings; X-ray aurorae from Earth; aurorae from Jupiter; SWCX emission from Comet C/2012 A1; X-ray transit of HD 189733. Error bars are 1σ . Bottom right plot adapted with permission from [122], AAAS. Credit: top left (X-ray aurorae), NASA/MSFC/CXC and [132]; top left (Earth model), NASA/GSFC/L. Perkins and G. Shirah; top middle (X-ray), NASA/MSFC/CXC and [133]; top middle (optical), NASA/ESA/STScI/AURA; top right, NASA/CXC/Penn State and [134]; bottom left (X-ray), NASA/CXC/ SwRI/R. Gladstone; bottom left (optical), NASA/ESA/Hubble Heritage (AURA/ STScI); bottom middle (X-ray), NASA/CXC/Univ. CT and [135]; bottom middle (optical), DSS, Damian Peach (damianpeach.com).

Figure 6 displays results from several of the Solar System objects, with images of X-ray aurorae from the Earth (upper left) and Jupiter (lower left). Fluorescence and scattering of solar X-rays are observed from both Saturn’s disk and its rings (middle top) while solar wind charge exchange (SWCX) dominates the emission from Comet C/2012 (lower middle). The transit of the Crab Nebula by Titan is shown at upper right; the shadow is larger than the diameter of its solid surface, consistent with absorption by Titan’s upper atmosphere.

4.2 Exoplanets

Despite contributing substantial advances in studies of X-rays from Solar System objects, the nearest extrasolar planets are far too distant to detect X-ray emission with *Chandra*. Yet the question of habitability of such exoplanets is heavily dependent upon the behavior of their hosts stars – in particular as to whether or not planetary atmospheres can survive long episodes of X-ray radiation and flaring in young stellar systems, and whether the effects of planets around their host stars impact that stellar behavior. Studies with *Chandra* have yielded crucial information in this area.

Photoevaporation of exoplanet atmospheres, energized by extreme ultraviolet and X-ray radiation from both quiescent and flaring stellar activity, is an important consideration for habitability. While population studies of stellar activity provide broad

insight into the evolutionary impacts for different star classes, an important question is whether the presence of exoplanets themselves might impact the stellar activity, possibly through tidal interactions. *Chandra* studies of HD 189733 AB and CoRoT-2 AM have provided evidence for influence of hot Jupiters on the rotation activity of the host stars, indicated by the planet-hosting stars in each of these systems having higher X-ray fluxes than the similar coeval companion stars [121]. In addition, observations of the Hot Jupiter HD 189733b show a deeper transit than observed in the optical (Figure 6, lower right), indicating the presence of a thin outer atmosphere that is opaque to X-rays [122]. *Chandra* observations of the brown dwarf - M dwarf pair NLTT 41135/41166 – two stars separated by only $2.5''$, and thus resolvable in X-rays only by *Chandra* – show that N41135 is more than ten times as bright as N41136, a similar star but without an identified companion, suggesting that the presence of the planetary companion contributes to enhanced stellar activity [123].

More direct investigations of habitability center on quantitative assessments of how stellar activity impacts putative atmospheres. *Chandra* and HST observations of Barnard’s star, for example, show that the quiescent X-ray/UV flux is not sufficient to destroy the atmosphere of a habitable-zone terrestrial-like planet, but that sustained flaring at observed rates could result in rapid atmospheric mass loss for planets in this system or around other old M dwarfs [124]. Similarly, a study of the triple system LTT 1445, resolvable in X-rays only by *Chandra*, shows that planets orbiting LTT 1445A receive X-ray flux from all three stars in the system, but that even though C dominates the overall X-ray flux from the system, it does not impact the planets around A more than the emission from A itself [125]. The conclusion is that, if starting with an Earth-equivalent amount of water, exoplanet LTT 1445Ad could maintain an atmosphere with water for over 1 Gyr.

Studies of larger stellar populations provide additional important constraints on the question of habitability. X-ray studies of a volume complete sample of 441 M/K/G stars using *Chandra*, XMM-Newton, eROSITA, and ROSAT data [126] show that while M-type stars show higher levels of X-ray activity than solar-type stars, more than 60% of all nearby M stars (and 80% of early M stars) have L_x/L_{bol} values within the normal range for G stars (where L_{bol} is the bolometric luminosity), indicating that such stars are potential hosts for habitable planets. On the other hand, *Chandra* observations of 24,000 stars in 40 star-forming regions reveal frequent and powerful flares from over 1000 stars that could result in complete evaporation of any associated exoplanet atmospheres over a time period of less than 5 million years [127].

With an eye toward future telescopes that will provide capabilities for direct-imaging of exoplanets, [128] investigated a sample of stars for which the habitable zone extends beyond the angular scale that will be resolvable by future telescope facilities, and for which Earth-sized planets with albedos similar to Earth would be detectable. From a total sample of 229 stars, X-ray data identify 29 systems with $(L_x/L_{\text{bol}}) \lesssim (L_x/L_{\text{bol}})_{\odot}$, making these prime candidates for habitable exoplanet searches. However, nearly 70% of the full sample currently lacks X-ray observations. *Chandra* studies of this sample would provide an extremely important pathfinder for future Habitable Worlds Observatory searches for habitable worlds.

5 *Chandra* for the Future

As of this writing, *Chandra*’s high angular resolution capabilities remain unique. No other X-ray observatory, operating or in development, has *Chandra*’s ability to image cosmic sources on sub-arcsecond scales, or to cover ~ 9 orders of magnitude in flux. These unparalleled features ensure that *Chandra* will be an integral element of observational astrophysics well into the future and offer a powerful complement to other observatories like HST, JWST, and the upcoming Nancy Grace Roman Space Telescope. The results from the observatory and its robust community have demonstrated the crucial role that *Chandra* observations play in addressing a vast array of problems in astrophysics – including, as has been so often the case, many that have not yet been anticipated.

Examples of *Chandra* studies in the immediate future include an ongoing *Chandra* Legacy Program (CLP) to complete observations of all 74 galaxies from the multiwavelength Physics at High Angular resolution in Nearby Galaxies (PHANGS) survey to accompany high-resolution data from AstroSAT, HST, Very Large Telescope(VLT)/Multi Unit Spectroscopic Explorer (MUSE), Atacama Large Millimeter/-submillimeter Array (ALMA), and JWST that will probe the physics of baryon cycles and feedback in nearby galaxies. Deep observations of the Perseus Cluster form the core of another CLP aimed at investigating the transport and dissipation of energy within its core, providing crucial information on AGN feedback from massive central galaxies in cool core clusters.

Approved programs for future studies include major programs investigating exoplanets, impacts on habitability by stellar activity, and observations of Jupiter to study aurorae above the poles and to correlate X-ray behavior with in-situ measurements from the Juno probe. Observations of 38 JWST-observed protostars in OMC-2 will trace the evolution of magnetic activity in the population.

Chandra will support an extended monitoring campaign of M87 with the Event Horizon Telescope in a “movie” campaign to connect variability in the near-horizon plasma to the behavior of the larger-scale jet. Among dozens of time domain studies, *Chandra* Target of Opportunity (TOO) programs will monitor and characterize the X-ray counterparts of binary NS mergers and NS-BH mergers found by Laser Interferometer Gravitational-Wave Observatory (LIGO)/Virgo – events for which we now know the rates are quite low, making it crucial to maintain *Chandra*’s capabilities to pursue such important but rare opportunities. An additional TOO program will study the anticipated thermonuclear event from the naked-eye recurrent nova T Corona Borealis. With crucial capabilities that will continued to grow with the emergence of observations from the Vera Rubin Observatory and the launch of Roman, *Chandra* will continue to contribute broadly to time domain science.

The long time baseline provided by *Chandra*, coupled with the high angular resolution, offers important capabilities for dynamical studies. Future observations will include continued monitoring of SN 1987A as it transitions from a supernova into an SNR, measurements of structure changes in Cas A over the past 7% of its lifetime, and proper motions of neutron stars to constrain kick velocities that probe asymmetries in SN explosions.

The longevity and success of the *Chandra* mission are due to the robust design of the observatory and to the diligence and dedication of its operations and science staff. The current health of the observatory is excellent, with no known issues that will prevent efficient and outstanding performance through the current decade, and likely well beyond. With a prognosis for continued outstanding scientific productivity, and a growing community of resourceful researchers, *Chandra* is well-positioned to continue its remarkable success as one of NASA’s flagship observatories for exploring the universe for many years to come.

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