# Chandra's first decade of discovery

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**We review some of the many scientific results reported at a symposium held in September 2009 celebrating the 10th anniversary of National Aeronautics and Space Administration's (NASA's) Chandra X-ray Observatory. These results were contributed by scientists who were among the more than 300 symposium participants. We highlight those results that most emphasize the unique imaging and spectroscopic capabilities of Chandra.**

review | X-rays

After many years in the making (1), the Chandra X-ray Observatory, one of the National Aeronautics and Space Administration's Great Observatories, was deployed by the STS-93 crew of the space shuttle Columbia on July 23, 1999. Chandra's official first light image was recorded less than a month later on August 19, 1999. The ensuing decade has witnessed a profound revolution in our understanding of the X-ray universe as a direct consequence of the subarcsecond imaging capabilities afforded by Chandra's unique focusing optics. The symposium Chandra's First Decade of Discovery was held in Boston from September 22–25, 2009, to celebrate this revolution.

Here we review some of the many scientific results contributed by the more than 300 symposium participants. We try to highlight those results that most emphasize the unique imaging and spectroscopic capabilities of Chandra. The review is organized in a manner similar to the topical sessions of the symposium. Each topical session had one invited speaker who reviewed the broader aspects of the topic. These invited speakers have also made written contributions to this volume and are cross-referenced throughout this review.

Unfortunately, not all of the many excellent contributions can be summarized within this short review. The abstracts of all of the contributions along with most of the slide presentations and videos of the oral presentations are available at http://cxc.harvard.edu/ChandraDecade/proceedings.

## Supernova Remnants

We begin with the subject of Chandra's first light image, the supernova remnant (SNR) Cassiopeia A (Fig. 1; ref. 2). Galactic SNRs like Cas A are rich sources of information because Chandra can resolve so much of the structure and hence map out forward and reverse shocks, separate ejecta from presupernova circumstellar and interstellar material, and delineate regions of cosmic ray acceleration. Investigators can also take advantage of the strong broad emission lines from SNR to perform spatially resolved spectroscopy with Chandra and, thereby, map the distribution and measure the mass of the abundant elements from C to Fe in the ejecta. As explained in detail by invited speaker Carles Badenes (3), this mapping helps researchers achieve the ultimate goals of constraining the supernova progenitors (particularly of Type Ia events) and understanding fundamentals of the explosion mechanism (particularly for core-collapse events).

Jae-Joon Lee (4) described observations of G292.0+1.8, the remnant of a core-collapse supernovae with a pulsar in its midst. The Chandra image reveals spectacular substructures including a torus, jet, and an extended central compact nebula or pulsar wind nebula associated with the embedded pulsar.

A much younger remnant, in fact the youngest remnant known in our galaxy, was recently imaged by using Chandra as reported by Kazimierz Borkowski (5). Borkowski and his colleagues determined the young age of this remnant by measuring its expansion with time. It was first discovered in radio observations in 1985. When Chandra observed it some 22 years later it had expanded by ≈16%, a change consistent with an age of only about 140 years (compared with ≈300 years for Cas A and older ages for the historical SNRs like Tycho and Kepler, whose supernova events were observed as bright "guest stars" in the days before telescopes were invented). Chandra has since observed the remnant again to confirm the expansion and young age.

There was also a detailed report on the Chandra monitoring campaign of SN 1987A in the Large Magellanic Cloud presented by Sangwook Park (6). The SN 1987A remnant has expanded to an angular size of only 1.6 inches during its 22-year lifetime; Chandra is the only X-ray observatory that can measure radial expansion on such miniscule scales.

## Compact Objects

A SNR often contain central compact objects (CCOs). These are thought to be neutron stars formed in the core collapse supernova explosions of massive stars. These stars are often just tiny dots embedded in the extensive X-ray glow of their accompanying remnants. Unless they pulse, or are extremely bright, or radiate at dissimilar energies, CCOs can be difficult to detect in young SNRs.

**Neutron Stars.** The CCO in the Cas A SNR was first identified in the Chandra first light image and was one of Chandra's first scientific discoveries (7). The spectrum is consistent with a blackbody but the inferred luminosity of the object implies a radius of <0.5 km, suggesting the emission is perhaps from a hot spot on a larger compact object. Hot spots should produce pulsations as the star rotates but pulsations have not been detected. The Cas A CCO is now used as a prototype of a class of likely neutron stars with no radio pulsations. It has been shown (8) that these could be low magnetic field objects with hydrogen atmospheres if they had radii of ≈5 km but that would require they be (very small) quark stars of very low mass. Craig Heinke (9) reported an intriguing alternative model for the neutron star atmosphere composed of carbon rather than H or He. This model fits the data well and gives a radius consistent with theoretical predictions for neutron stars. Heinke suggests the carbon atmosphere is a signature of youth in that H and He accreted from the remnant can burn to C during the first 1,000 years or so before a thick H layer accumulates at later times.

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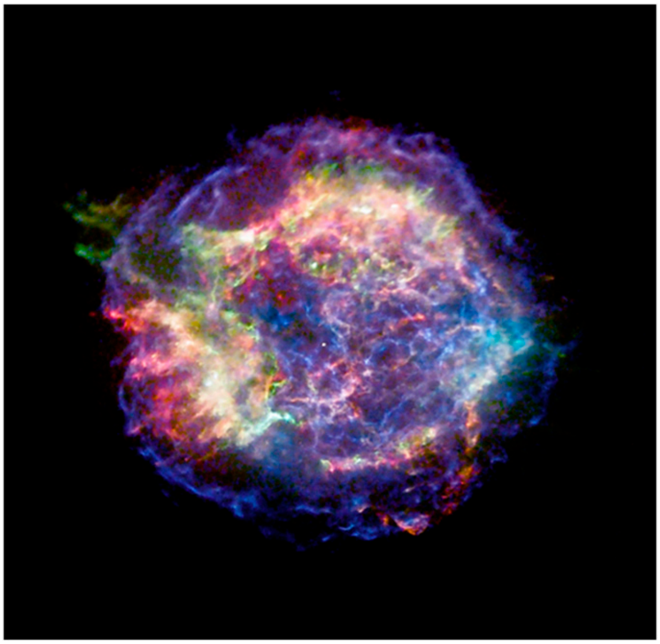


**Fig. 1.** Energy-colored photon counts image of the Cassiopeia A supernova remnant observed by Chandra. Red (0.5–1.5 keV) green, (1.5–2.5 keV), and blue (4.0–6.0 keV) are individually logarithmically scaled to bring out the fine structure. Red and green are thermal radiation from the ejecta that has passed through the hot reverse shock. The blue outer filamentary structure is dominated by high-energy synchrotron emission from electrons accelerated at the forward shock.

Compact objects can radiate for periods of time far in excess of the lifetime of their progenitors—and much longer than the time it takes for their expanding remnants to fade. Thus, compact objects are found in a wide range of environments, not just within the SNRs in which they were formed.

Isolated neutron stars (INSs) are often difficult to identify because they are small and hot, making them faint at other wavelengths. Derek Fox (10) reported on a campaign to discover isolated neutron stars. The campaign has identified the eighth known INS and has the potential to double or triple the total number of known INSs.

Invited speaker Victoria Kaspi (11) discussed how the diverse observational behavior exhibited by neutron stars can be unified by a basic physical picture that attributes most of the diversity to differences in age and magnetic field.

**Pulsar Wind Nebulae.** Kaspi pointed to studies of rotation-powered pulsars as one of Chandra's greatest legacies because of Chandra's unique ability to resolve the complex structures within their pulsar wind nebulae (PWN); many of which are just a few arcseconds across.

The Vela pulsar is one of the best studied examples of a PWN. George Pavlov (12) reported on recent Chandra observations of this source. The first Chandra observation of the Vela pulsar showed a stunning picture (see ref. 13 for details) that includes two arcs, inner jets along the direction of proper motion, a faint hook ahead of the compact PWN, and asymmetric diffuse emission.

Pavlov reported in the meeting on new observations taken as recently as July 2009. The observations show a significant change of the compact pulsar wind nebula. The system is clearly highly dynamic with X-ray-emitting structures varying in brightness on timescales of a week and moving outward at greater than half the speed of light.

## Stars and Star Formation

SNRs and their CCOs represent, along with stellar-mass black holes and white dwarf stars, the X-ray-emitting endpoints of stellar evolution. Chandra has also contributed to profound insights into the physics of stellar birth and planet formation. These contributions are possible because X-rays penetrate the thick dust that envelops surrounding protostars and trace the energetic interactions between stars and their surroundings. Invited speaker Eric Feigelson (14) presented a thorough overview of the many exciting phenomena revealed by X-ray studies of stars, the star-formation process, and the effects of X-ray irradiation from stars on their environment.

**Young Star Clusters.** Most stars form in clusters within giant molecular clouds before dispersing on ≈100 Myr timescales. Young clusters in the Milky Way are favorite targets of X-ray study because of the many high energy processes connecting stars and their natal environments. Several investigators reported on surveys of young star clusters at the meeting. The first of these was an interim report on a wide field survey of the Eta Carina region led by Leisa Townsley (15). Carina is a starburst cluster, an example of the large-scale star formation seen in starburst galaxies. The Carina complex is composed of at least 10 young stellar clusters covering a range of about 0.1–3 Myr in age. Carina contains at least 60 massive O and early-B stars, including an O2 star of initial mass well over 100 $M_\odot$. The luminous blue variable η Car and bright diffuse X-rays hint that the Carina complex might have seen cavity supernovae. These supernovae are often faint in optical light because they occur within hot tenuous bubbles or cavities formed by earlier stellar winds and supernovae. Kenji Hamaguchi (16, 17) has also confirmed a neutron star exists in the field, suggesting that at least one supernova has already occurred in this young star complex.

The Carina program, which involved archival data and 20 dedicated pointings, resolved >14,350 point sources, making it, by far, the largest collection of point sources detected for a single Chandra program. Because young stars remain X-ray bright for a relatively short time, most of the sources are expected to be premain sequence stars associated with the multiple generations of star formation in this region. The evidence for young stellar ages is that 87% of the X-ray point sources have counterparts in deep infrared images. The detections include 117 massive stars, including OB stars, Wolf-Rayet stars, and luminous blue variables.

Using simulations and other observed source properties to ascertain a statistical sense of the populations, Townsley's group has developed a Bayesian source classifier. Their main result is that it appears that the stars are clustered in distinct groupings, suggesting that the bulk of the star formation is occurring sporadically and resulting in these smaller clusters.

There is significant diffuse X-ray emission from the Carina complex. The precision of the Chandra optics allows the group to remove the 14,000-plus point sources and still find structured excess emission. In general, this emission is softer than the expected temperature of stellar winds or coronae. The low temperature is evidence that this is indeed real diffuse emission and not unresolved faint sources. The substructure within the emission shows that while the emission is generally consistent with cool thermal plasma, there is a narrow band centered near η Carina that

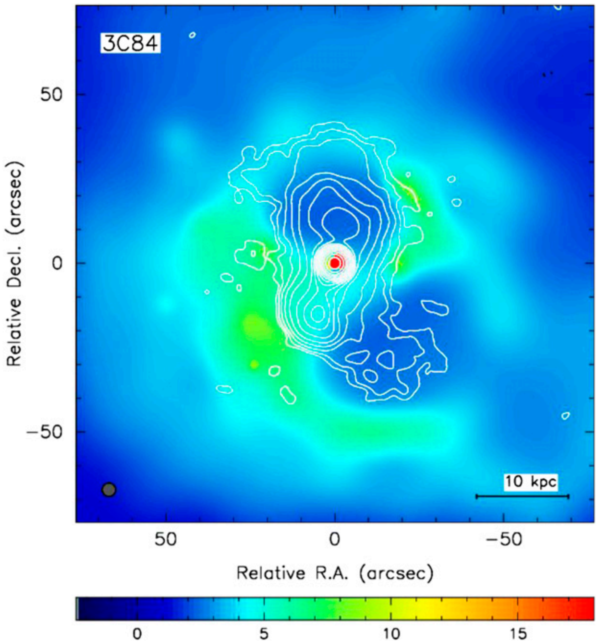


**Fig. 2.** Chandra image of the Perseus cluster of galaxies. Color denotes relative X-ray intensity ranging from yellow (high) to dark blue (low). Contours denote Very Large Array observations at 1.4 GHz. Contour levels start at 1 mJy per beam (5-inch beam) and increase by a factor of two to just below the peak of 21.7 Jy per beam. At the center is the cluster central radio galaxy NGC 1275. Radio emission fills the X-ray cavities. Note the steepest part of the radio contours abuts the brightest part of the eastern patch of X-ray emission. [Reproduced with permission from ref. 60 (Copyright 2002, John Wiley and Sons).]

is rich in iron. This enrichment could be attributable to O star winds or to one or more supernovae.

**Stellar Jets.** Many X-ray jets have been discovered thanks to the unprecedented resolving power of Chandra. The first convincing evidence of X-ray jets from stars came from the objects HH2 (18) and HH154 (19). Although more sources were detected later, HH154 remains unique, being the nearest and the most luminous among the stellar jets: The details of the relevant jet morphology can be studied to a level impossible with more distant objects such as AGN.

Rosaria Bonito (20) reported investigating the mechanisms of X-ray emission from jets through analysis of multiepoch Chandra data of HH154 spanning four years.

Bonito and colleagues find that the X-ray source consists of an unresolved, point-like component with no detectable proper motion and an elongated component with a proper motion, consistent with a shock moving away from the parent star. They have developed numerical models of jets where X-rays are generated by jet impacts onto the circumstellar medium. A hydrodynamic model of a randomly ejected pulsed jet reproduces the knotty morphology observed.

**Accretion and High-Resolution Spectroscopy.** In addition to the highest spatial resolution ever achieved in X-ray astronomy, Chandra also boasts two transmission grating spectrometers with exceptional resolving power. The gratings have been used extensively to study emission and absorption lines and edges in sources as diverse as bright nearby stars and powerful distant AGN.

One of the early highlights of the Chandra mission was the discovey of X-ray emission from accretion of protoplanetary disk material onto the young T Tauri star TW Hydra (21). The key evidence for the process was a suppressed forbidden line that indicated that the X-rays were being emitted by a high density plasma but other explanations were possible. Nancy Brickhouse (22) reported on a deep observation of TW Hydra that resolved many X-ray emission lines from the source. Brickhouse used detailed modeling of the accretion flow (following Cranmer; ref. 23), to match all of the observed emission line temperature and density diagnostics confirming that one is observing the accretion shock.

## The Solar System

Like most stars, the Sun was also likely part of a group or cluster of stars in its youth. The planets and their moons, comets, and other rocks and stones are the most tangible remains of those formative years. The Sun currently emits X-rays, although weakly, as well as a wind of energetic charged particles that cause X-radiation when they interact with solar system bodies.

Carey Lisse (24) summarized the many X-ray discoveries within our solar system made with Chandra and other X-ray satellites. The discovery of high energy X-ray emission in 1996 from Comet Hyakutake revealed a new class of solar system X-ray emitting object (25). Subsequent detections of the morphology, spectra, and time dependence of the X-rays from >20 comets have shown that the very soft (energy < 1 keV) emission is due to a charge–exchange interaction between highly charged solar wind minor ions and the comet's extended neutral atmosphere (26, 27). Recently it has been demonstrated that the spectra of comets correlates well with the ionization state of the solar wind (27).

Several other solar system objects are now known to shine in the X-ray, including Venus, Mars, the Moon, the Earth, Jupiter, and Saturn (28). Like comets, the X-ray emission from the Earth's geo-corona, the Jovian aurora, and the Martian halo are all driven by charge exchange between highly charged minor (heavy) ions in the solar wind and gaseous neutral species in the bodies' atmosphere. The first soft X-ray observation of Earth's aurora by Chandra shows that it is highly variable, and the Jovian aurora is a fascinating puzzle that is just beginning to yield its secrets. The nonauroral X-ray emissions from Jupiter, Saturn, and Earth, and those from disks of Mars, Venus, and the Moon are mainly produced by scattering of solar X-rays. However, the mechanisms are far from completely understood and there are several ongoing projects. One is a study of the emission from the comet 17P/2007 Holmes, which experienced an optical outburst of nearly 10 magnitudes becoming one of the brightest optical comets in the Chandra era and yet was nearly invisible in X-rays. Meanwhile, 8P/2008 Tuttle, observed near the minimum of the solar cycle ranks among the brightest of the X-ray comets. Further, the Jovian system as a whole is a puzzle with hard X-rays seen from the poles of Jupiter and with detections of Io, Europa, Ganymede, and the Io plasma torus. The latter links Io to Jupiter and may provide the anomalous sulfur-oxygen-carbon ratios observed in Jupiter's polar X-radiation.

Bradford Wargelin (29) and Jonathan Slavin (30) each presented studies of X-ray emission generated by charge exchange between solar wind ions and inflowing neutral H and He from the Local Interstellar Cloud that surrounds the solar system. They compared Chandra Deep Field-South observations collected during solar maximum and solar minimum that also sample different lines of

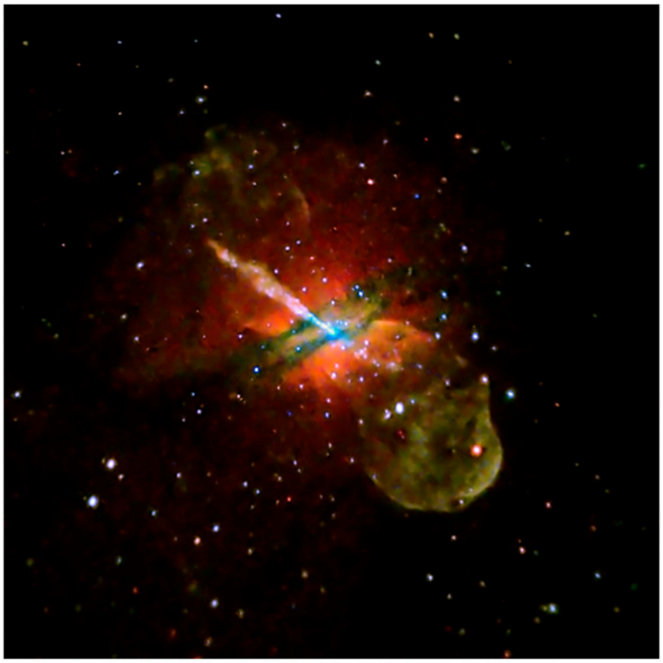


**Fig. 3.** Chandra X-ray image of the nearby galaxy Centaurus A. North is up, and east is to the left. A strong dust lane in the galaxy is viewed nearly edge-on and runs across the middle of the image from southeast to northwest. A supermassive black hole at the center of the galaxy powers the narrow (white) jet beaming toward the northeast. Colors depict X-ray energy ranges red (0.5–1.0 keV), green (1.0–1.5 keV), and blue (1.5–2.0 keV). Absorption due to the dust lane creates the blue-green band. Thermal emission from hot gas appears red. Nonthermal emission from the jet to the northeast and the shocked region surrounding the radio lobe to the southwest appears yellow-green to white. The X-ray jet extends for ≈13,000 light years away from the central black hole. The distance from the AGN to the shock front in the southwest is ≈17,600 light years.

sight through the solar helium focusing cone (into which the Sun's gravity focuses neutral He as it moves relative to the surrounding medium) with data on solar wind composition from the ACE satellite. They used this comparison to constrain the level of hot-gas emission from the Local Bubble and to study the solar wind spatial and temporal variability. These studies of nearby gas can have important implications for the interpretation of diffuse warm and hot gas observed at larger distances.

## Globular Clusters

Most young star clusters are unbound and will disperse after only one or so orbits around the Galaxy. However, there are hundreds of massive, old, bound clusters in the Milky Way and in other large galaxies, particularly the early type ellipticals. These globular clusters are composed of some 1 million stars and contain hundreds of faint point-like X-ray sources. The clusters are so dense—most of their stars are contained within a region only a few parsecs across—that only the high angular resolution of Chandra can resolve all their X-ray emitters. Interestingly, although X-ray sources make up only a tiny fraction of the many stellar objects in globular clusters, X-ray studies have historically led to some of the most important breakthroughs in our understanding of the dynamical processes unique to these dense stellar environments.

X-ray sources have long been known to be orders of magnitude more abundant per unit mass in globular clusters than in the rest of the galaxy. Invited speaker David Pooley (31) pointed out that, thanks to the discovery of >1,500 X-ray sources in Chandra observations of >80 galactic globular clusters, it is now clear that the number of X-ray sources in a globular cluster correlates very well with its encounter frequency. This correlation points to dynamical formation scenarios for the X-ray sources and shows them to be excellent tracers of the complicated internal dynamics of globular clusters. The relation between the encounter frequency and the number of X-ray sources has been used to suggest that we have misunderstood the dynamical states of globular clusters and that most of them are in the relatively early core contraction phase (which is now estimated to last several billion years) and only 20% are in the binary burning phase (with few if any in a deep core collapse state which is part of the later gravothermal oscillation phase; see ref. 32 for details).

Tom Maccarone (33) described many of the important reasons for studying the large and diverse population of extragalactic globular clusters accessible through Chandra. An important and surprising result of this work is that metal-rich globular clusters are significantly more likely to contain X-ray sources than metal poor clusters. Numerous very luminous X-ray sources have been found in extragalactic clusters, providing observational evidence that black holes (rather than only neutron stars as in the Milky Way) are far more common in globular clusters than was once imagined.

## Nearby Galaxies

X-ray sources have been discovered throughout all nearby galaxies imaged with Chandra. Although some sources are associated with globular clusters, many others are aligned with spiral arms, for instance, or are clustered in the nuclear regions where densities are high and high star formation rates are common. These different associations with galactic structure imply different types of X-ray sources. For example, an association with a star-forming region suggests a recently formed compact object accreting from a short-lived massive companion star. Chandra can usually detect ≈100 of the most luminous sources in a typical observation of a normal galaxy located less than ≈100 Mpc distant. That is sufficient to perform studies of the demographics of these populations. However, what is needed is identification of (optical) counterparts or at least some details about source environments. This is a difficult task because the 100 or so detected X-ray sources are embedded in a field of some $10^{10}$ stars of all makes and models. Andreas Zezas (34) reported on such a multiwavelength study of the nearby spiral galaxy M81. Similar studies of Local Group galaxies were presented in posters by Vallia Antoniou (35) (on the SMC), Roy Kilgard (36) (IC 10), and several by a group led by Paul Plucinsky (37–40) (on the galaxy M33).

There is one class of X-ray object found in nearby galaxies, termed the ultraluminous X-ray sources (ULXs), that has become a favorite subject of study in the Chandra era. By definition, their X-ray luminosities, assuming they radiate isotropically, greatly exceed the Eddington luminosity of any known stellar-mass black hole. Thus, they are of interest because they could be the observational signatures of the elusive intermediate-mass black holes that are sought to bridge the gap between single-star remnants of 10–20 $M_{\odot}$ known throughout the Local Group galaxies and the ubiquitous supermassive

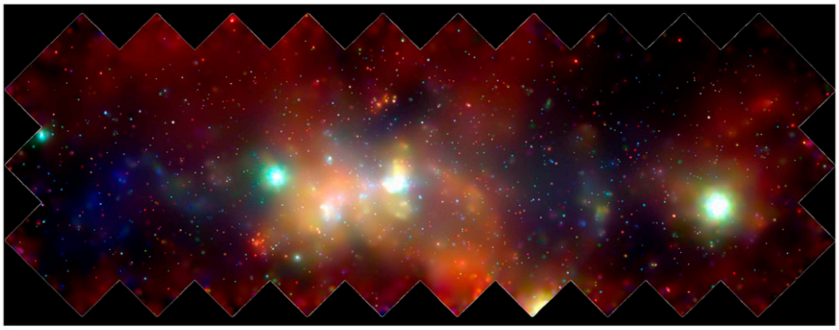


**Fig. 4.** Mosaic of Chandra images of the central region of our Milky Way galaxy. The image is 400 × 900 light years. It reveals thousands of white dwarf stars, neutron stars, and black holes within diffuse multimillion-degree gas. The supermassive black hole at the center of the galaxy is located inside the bright white patch in the center of the image (along with many other sources resolved by Chandra but not visible in this smoothed image). The colors indicate X-ray energy bands—red (low), green (medium), and blue (high).

black holes ($>10^5$ $M_\odot$ or so) thought to populate the centers of almost all galaxies. Roberto Soria (41) gave a thorough review of what we have learned about ULXs in the past decade. He pointed out that roughly 200 ULX candidates have now been discovered. Statistically, they display many of the properties of their lower-luminosity cousins, the X-ray binaries. X-ray spectra and timing initially suggested intermediate-mass black holes for a few of these sources because of an apparent soft spectral component. However, these spectra are dominated by a power law component; ULXs do not seem to exist in the standard thermal-dominated high/soft state and so the analogy to (and extension from) Galactic stellar-mass black hole candidates must be viewed carefully. Instead, Soria notes ULXs seem to be predominantly in a new spectral state he referred to as the Ultraluminous State (42) where most of the power comes from an inner disk region that is modified by a warm-thick Comptonizing corona. Using this model, most ULXs can be explained by a 30–100 solar mass compact accretor although a few ULXs are found in a hard, possibly sub-Eddington, state. Some of these latter sources remain good intermediate-mass black hole candidates (see also ref. 43).

Marat Gilfanov (44) reported the results of a kind of indirect population study; a very interesting and novel X-ray look at the progenitors of Type Ia supernovae. These supernovae are known to result from the thermonuclear explosion of a white dwarf star near the Chandrasekhar limiting mass. What is not known is whether these stars reach such a high mass through slow buildup via accretion of (mainly) H from a main sequence companion or catastrophically through the merger of two white dwarfs in a close binary system. The former has been preferred by theorists because it practically guarantees a near Chandrasekhar mass is reached and, hence, a fixed amount of supernova fuel resulting in the proverbial Type Ia standard candle. Gilfanov showed, however, that the long cycle of classical novae that accompanies the gradual buildup through H accretion along with the usual hard X-ray emission from the accretion process itself would leave a clear residual hot X-ray signature lingering within (primarily massive elliptical) galaxies that is not observed. In fact, Gilfanov finds only ≈5–10% of Type Ia events can have occurred by this path in nearby elliptical galaxies. Therefore, most must be due to rapid merging of white dwarf pairs.

There is another form of warm/hot gas that is predicted to surround massive galaxies and to trace the cosmic web of large-scale structure. The search for this gas through absorption-line spectroscopy and by other means was the main topic discussed by invited speaker Daniel Wang (45). Wang also pointed out that the current failure to locate this gas component may be because it is in a hotter galactic halo or has been somehow pushed away. Both of these arguments must invoke some form of energy feedback on galactic scales. One form of feedback Wang noted is the cumulative effect from winds and supernovae from many massive stars resulting in a superwind as observed in the nearby starburst galaxy M82. The X-ray manifestation of less powerful star-forming activity is a diffuse component of hot gas prevading the disks of spiral galaxies. K. D. Kuntz (46) and Zhiyuan Li (47) presented studies of such hot gas components in several nearby galaxies.

Christine Jones (48) discussed nuclear X-ray emission from hot gas-rich (but otherwise normal) elliptical galaxies. The X-ray morphology of these galaxies often show cavities, bubbles, and related structures. These structures are believed to be caused by energetic bursts of matter and light ejected by a central engine—an active galactic nucleus or AGN—and are strong signatures of feedback.

## Galaxy Groups

Just up the hierarchical ladder from galaxies are galaxy groups that contain up to hundreds of gravitationally bound galaxies and are the main reservior of baryons in the universe. As pointed out by Myriam Gitti (49) (and similarly in a poster presentation by Jan Vrtilek; ref. 50), groups are an excellent target for studies aimed at a better understanding of the feedback process, the mechanisms and timescales of energy injection, and the effects on galaxy and group evolution. Groups are good targets because they have shallow potentials relative to the more massive galaxy clusters so that the hot gas distribution is more extended and feedback can operate over a relatively larger area, which helps make the gas interactions easily apparent even at large distances. In particular, Gitti reported strong shock structures visible in the surface brightness and temperature maps of the Hickson Compact Group 62 observed with Chandra.

Several other Chandra observations of galaxy groups, coupled with radio observations, were reported. For example, Ewan O'Sullivan's (51) Chandra and GMRT study of Stephan's Quintet shows a ridge of X-ray emission in a region where a member galaxy is colliding with a filament of tidally stripped HI gas. This spiral-dominated system appears to be building up its hot gaseous halo by shock-heating HI rather than by accreting primordial material or by stellar winds and supernovae. Similar investigations include those reported by Nazirah Jetha (52), Simona Giacintucci (53), Eric Miller (54), and Laurence David (55). In some of these systems, a central AGN plays a dominant role in shaping the hot gas halos.

## Feedback in Galaxy Clusters

Revealing the critical role of AGN feedback heating in the cores of clusters of galaxies—solving the cooling flow problem—ranks among modern X-ray astronomy's greatest contributions to science so far. As reviewed by invited speaker Elizabeth Blanton (56), the relatively high gas densities at the centers of clusters of galaxies allow that gas to cool quickly thereby decreasing the gas pressure support against gravity resulting in an inward gas flow. The problem is that large amounts of cooling gas is not observed either as optical emission from new stars or as Fe XVII X-ray line emission from gas cooling to below $\approx 10^7$ K

(57–59). Instead, high-resolution Chandra imaging and broadband X-ray spectrophotometry have led to detailed surface brightness and temperature maps that reveal a variety of structures in clusters. These images show AGNs in the centers of cool core clusters that inflate bubbles that rise buoyantly through the intercluster medium and can produce shocks and sound waves and heat the surrounding gas. Unlike the heating due to strong shocks, the gas surrounding these cavities is often rather cool. The cavities are radio emitters. These radio lobes transport energy and matter outward from the central AGN and its host galaxy. Fig. 2 (60) shows an example of the radio lobes and X-ray cavities in the Perseus galaxy cluster. The patterns of the systems of X-ray cavities suggests the radio outbursts are cyclic, their repetition timescales can be calculated, and the energy released by the radio sources can be calibrated. In most cases, the energy injected into the cluster can counteract cooling losses.

Using a sample of nearby galaxy clusters, Rupal Mittal (61) showed that cool cores in galaxy clusters must develop late and that the central cooling time of a cluster is the strongest indication of whether it is a cool core cluster. Mittal finds that all strong cool core clusters have a radio source at their center. Her study clearly demonstrates the need for a heating mechanism and provides statistical and quantitative evidence supporting the AGN heating scenario.

There were also several poster presentations on aspects of cluster merging, a process that can also offset cooling in cluster cores. As pointed out by John ZuHone, Chandra has discovered many "cold fronts" in the hot intracluster medium that appear as sharp discontinuities in the X-ray surface brightness. The temperature is colder on the brighter, denser side of the front suggesting the cool gas is sloshing back and forth in the cluster potential minimum. ZuHone presented simulations where such sloshing is initiated by gravitational disturbances from passing subclusters and showing how sloshing is an additional form of feedback similar in effect to interactions among galaxies in groups.

## Galaxy Cluster Cosmology

Galaxy clusters have long been a favorite subject among cosmologists because they are the most massive objects tugging on the fabric of the universe. Invited speaker Alexey Vikhlinin (62) explained how Chandra observations of clusters place useful and tight constraints on the dark energy equation of state and on cosmological density fluctuations. These measurements can be done efficiently with clusters (Vikhlinin used only ≈90 X-ray clusters to constrain $w_0$ to <3% statistical uncertainty compared with the thousands of clusters needed to do so by using optical observations) due to the fact that X-radiation probes the dominant baryon content of clusters. Vikhlinin finds structure formation is suppressed at redshifts $z < 1$, which is a strong signature of the influence of dark energy.

Thomas Culverhouse (63) described preliminary results from X-ray observations combined with new Sunyaev-Zeldovich Array radio interferometer measurements of clusters at high redshift ($z > 1$). Resulting mass measurements will be used to compare the properties of the high redshift sample to scaling relations derived at lower redshift to test for evidence of cluster evolution. In another work in progress, Nicole Hasler (64) reported using a joint X-ray and Sunyaev-Zeldovich model to do cosmology-independent measurements of cluster gas fractions in a systematic search to detect gas fraction evolution with redshift.

Adam Mantz (65) reported his studies on constraints on galaxy cluster X-ray scaling relations by using a large sample of flux-selected clusters at moderate redshifts. Mantz argued that the large scatter observed in the $L_X$-$M_{cluster}$ relation is caused by excess heating in the central regions of many clusters. He showed that the scatter can be significantly reduced if the innermost regions of cluster cores are ignored in the analysis, which results in a relation consistent with self-similar scaling.

## Active Galactic Nuclei

Intimately connected with the growth of structure are the supermassive black holes (SMBHs) growing in the nuclei of galaxies. The finding that the mass of SMBHs scales with that of their host galaxy spheroids establishes this close link between AGN and star formation. As argued by invited speaker Neil Brandt (66), the Chandra X-ray bandpass is the ideal window for the detection and study of AGN locally as well as in the high redshift universe.

**AGN Evolution.** Extragalactic X-ray surveys have immensely improved our general understanding of how the populations of active galactic nuclei (which represent the majority of the sources in X-ray surveys) evolve across the history of the universe. Shallow, wide, and deep surveys complement each other by covering different regions in the Flux vs. Survey Area diagram. Brandt (66) highlighted the spectacular results from several surveys conducted by Chandra and showed some of the key insights gained from AGN demography and physics. In other contributions, specific results from the ChaMP (67), C-COSMOS (68), AMUSE (69), and AEGIS (70) surveys were summarized. Paul Green (71) described how important it is for theories of coevolution of supermassive black holes and galaxies to know what fraction of galaxies host an actively accreting nucleus—as defined by their X-ray luminosity. Combining 323 X-ray fields analyzed by the Chandra Multiwavelength Project (ChaMP) together with Sloan Digital Sky Survey data, Green derived the AGN fraction in local galaxies as a function of absolute optical magnitude, X-ray luminosity, and redshift ($z$). He also demonstrated the existence of a correlation between the Eddington ratio of low luminosity AGN and their X-ray power-law spectral slope that is remarkably similar to the same relation for stellar mass X-ray binaries (72).

Deeper than ChaMP, the C-COSMOS survey is nearly 1/10th as sensitive as and samples a factor-of-10 larger field area than the deepest Chandra surveys. This combination of depth and area produces large numbers of sources, allows for good statistics on previously sparse samples (e.g., high $z$ quasars), and enables the discovery of rare classes of objects (e.g., double AGNs). The depth of the survey matches the depth of the many complementary imaging bands from radio to UV, which enabled > 95% identification rates, spectral energy distributions, and accurate photometric redshifts to be found rapidly. The wealth of multiwavelength data on many sources already allows a variety of science investigations, and Martin Elvis (73) presented the latest results on coeval growth of SMBH and host galaxies, on dust-obscured galaxies, on the log$N$-log$S$ relation of $z > 3$ quasars, on off-nuclear ULX objects and on double AGNs. The interaction between the SMBHs and the large scale environment and, in particular, the cross-correlation between AGNs and clusters, was explored by Nico Cappelluti (74), who showed how AGN seem to cluster like massive late type galaxies.

A survey of nuclear X-ray activity on early type galaxies in the Virgo cluster was illustrated by Elena Gallo (75). These are galaxies in which supermassive black holes and nuclear star clusters may be equally important. Gallo showed how ≈30% of the galaxies host an accreting black hole with no evidence for an increase in the active fraction with host galaxy stellar mass for Eddington-limited samples.

Finally, scientific results from the AEGIS survey, with an aim to study coevolution of black holes and host galaxies, were presented by Elisa Laird (76) for the AEGIS team. Multiwavelength data are suggesting that typical AGNs at $z \sim 1$ are in massive red host galaxies, that AGN hosts are bulge-dominated, and are found predominantly in dense environments. Several posters highlighted results from other surveys or illustrated specific studies from groups of objects in the surveys mentioned above. In particular, the poster of Heng Hao (77) was the cowinner of the best conference poster by a student. She studies the evolution of the Spectral Energy Distribution shapes near 1 μm for Type 1 AGNs in the COSMOS survey as a function of luminosity, redshift and Eddington ratio.

**Jets and Outflows.** AGN are interesting objects of study in their own right. They display a range of phenomena that reveals their complex inner workings. The superb spatial and high spectral resolution of Chandra have allowed the detection and study of resolved X-ray jets and are giving the first indications of the composition and dynamics of winds and outflows in a variety of astronomical systems. Invited speaker Dan Schwartz (78) described how Chandra observations have revealed X-ray jets in all sorts of galactic (protostars, binaries, rotation-powered pulsars, and black hole binaries) and extragalactic sources (radio sources and quasars). X-ray observations have proven essential for the study of the emission mechanisms of the jets, in revealing the interaction of jets with the intergalactic or intracluster media, and in studying the energy generation budget. Many aspects of jets remain uncertain, including the composition of the jets, the means of jet confinement, and the particle acceleration mechanisms.

Dan Evans (79) showed how the nearby active galaxy NGC 1068—with a $10^7$ $M_\odot$ SMBH accreting at or near its Eddington limit, is an ideal laboratory to examine the role of AGN outflows and feedback. Multiwavelength imaging of this nearby AGN shows that the radio jet, [OIII] emission and X-ray emission are spatially related. Spatially resolved, high-resolution Chandra high-energy transmission grating spectra point to an entirely photoionized narrow line region (NLR), with no indication of collisional ionization from the jet, which means that the AGN radiation field dominates the energetics. Outflows are detected along the NLR ionization cone, with velocities > 500 $km{\cdot}s^{-1}$ extending up to several kpc from the nucleus.

The disk-jet connection was discussed by Joseph Neilsen (80) based on high-resolution grating observations of the microquasar stellar-mass black hole, GRS 1915 + 105. Chandra grating observations show that spectrally hard states (known for their production of optically thick jets) exhibit broad iron emission lines, while softer states produce an accretion disk wind. Comptonization is proposed as the mediating effect in the disk–jet interaction.

One of the extragalactic sources that even more spectacularly shows the interconnection among jets and their environments is Centaurus A, the nearest AGN and extragalactic radio source. Paul Nulsen (81) presented new analyses of Cen A that shows several components including hot gas, dust lanes, a radio lobe surrounded by a shock, and a jet (Fig. 3; ref. 82). Nulsen showed how the X-ray emission surrounding the radio lobe is predominantly synchrotron and similarly for the radio jet, and how a moderate or transient asymmetry in the environment can make the difference between a jet and a lobe.

High-energy transmission grating observations of the X-ray binary Cyg X-1 presented by Manfred Hanke (83) indicated clearly how high-resolution X-ray spectroscopy, combined with timing information and multisatellite campaigns, is crucial in understanding the behavior of this binary system and, in particular, for the study of the very focused wind outflowing from the Roche lobe. The wind's photoionization structure in Cyg X-1 is constrained by X-ray measurements, and the wind absorption needs to be taken into account in soft X-ray model spectra for this source.

**The Galactic Center.** Our own Milky Way galaxy also hosts a supermassive black hole at its center. However, it is extremely underluminous. In fact, it required careful work with Chandra observations to be identified as an X-ray emitter. Invited speaker Sera Markoff (84) reviewed the X-ray studies of the Galactic center region. The region is rich in a large variety of X-ray sources as shown in Fig. 4 (85). There are other low-luminosity supermassive black holes in the local universe. It is thought many of these, including ours, go through quiescent phases for reasons that are still debated.


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