An August Week: Chandra Science for the Next Decade

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It was an august week. Quite literally—it was actually August, the 16-19th to be precise. About 120 scientists from around the world converged on the Harvard campus in Cambridge, Massachusetts, to discuss, debate, implore, propose, and invoke a host of other verbs on the topic of *Chandra* Science for the Next Decade.

The CXC sponsors a summer workshop every year. Under the sage stewardship of Director's Office scientist Paul Green, we have tackled a range of highly topical subjects on just about all of the areas of astrophysics that *Chandra* has addressed, with each workshop having concentrated on a particular one. In early 2016 the thought was to tackle something a bit different.

The idea for the meeting was catalysed by a confluence of very encouraging developments associated with the *Chandra* mission. A detailed engineering study of the spacecraft and subsystems in 2014 had found no inherent problems with operations over the next ten years and beyond. The Senior Review enthusiastically endorsed the mission, saying "There appears to be no impediment to many more years of X-ray observations under the CXC stewardship. The 2016 Senior Review Panel enthusiastically endorses the recommendation to extend the mission through 2020 and beyond." NASA is presently in the process of extending the current *Chandra* operations contract out to September 2027. Acceptance of the X-ray Surveyor, now called *Lynx*, as a NASA Mission Concept Study, also heralds the prospects of a new generation X-ray facility, the next step after *Chandra*.

With the prospect that *Chandra* will be in operation for at least another ten years, it was time to reassess where we were with the mission and where was the mission going? Is there anything we have been missing in terms of maximizing the scientific return, and answering major outstanding science questions? And what are these questions going to be in the next decade? What should *Chandra* be doing in the coming years to pave the way for the next generation? How can *Chandra* be best deployed to synergize with new present and near-future capabilities such as ALMA, SKA, LSST, JWST and eROSITA?

A committee of experts was assembled for the Scientific Organizing Committee in February last year, with the author of this article and Chryssa Kouveliotou tasked as chairs. Newly arrived CXC scientist Rudy Montez was dragooned into leading the Local Organizing Committee, and what a fantastic impressment that turned out to be. Initial meetings were convened with the usual delusional wild exuberance typical of the early days of conference planning, in which time to organize stretched to infinity, the number of people we could invite to give talks numbered in the hundreds, all the shortcomings of all the previous conferences any of us had ever been to could be eliminated by the genius of our logistics and the cunning of our method, and minor trifling details like budgets need not be considered. And it was by then into March. The meeting was scheduled for mid-August. What the heck were we thinking?

Paul Green has a special talent for organizing the summer workshop and combined with some years of experience marshalled things along and got them all running as if on a frictionless plane. (On hindsight, the fact the Paul had stepped down from this role should probably have set off some alarm bells had we been paying more attention.) He had put some jolly helpful notes and guidelines together that identified all the many dates by which key milestones had to be passed and crucial minutiae in place in order for the whole process not to concertina into itself and end in a sort of discordant concertina-like chaotic dissonance. I don't think we made a single one of those deadlines.

But somehow—the details are just a blur—everything was made to fall into place and we had a workshop: *Chandra Science for the Next Decade.*

To mix things up a bit, we had decided to try and arrange talks more along physics-based lines rather than topic based. Hence your dismay when your talk on *Chandra* observations of clusters of galaxies was bookended by talks on stellar coronae. The flimsy excuse was that both were observations of what are essentially optically-thin plasmas.

Next Decade workshop attendees discussing the future of the Chandra X-ray Observatory.

Next Decade workshop logo displayed on opening day

And it worked, we think: Scientists in every field listened to talks by scientists in just about every other field.

The meeting spanned three full days, starting on Tuesday Aug 16th and ending on Friday Aug 19th. Tuesday was originally a set-up day, but encouraged by IT tech Ray Hemonds' calm assessment that things could be ready by lunch, we scavenged the afternoon to get going. And there really was only one person who could get things going.

Inauguration (biggest ever)

We were honoured to have the first *Chandra* director, Harvey Tananbaum, open the meeting. Harvey of course is the one of the main reasons *Chandra* has been such a roaring success, and he is now deeply interested in seeing the capabilities of *Chandra* be surpassed by a successor. His address built on *Chandra* to extend hope and inspiration to the younger generation of scientists who must inevitably be the ones to build the next generation of missions.

The first session opened with the CXC Director, Belinda Wilkes, giving the State of the Observatory Address, in which, we are glad to report, the traditional conclusion resounded loud and clear "the state of the Observatory is strong!". *Chandra* was launched on July 23 1999 and at the time of Belinda's talk we were just entering our 17th year of operations, with no engineering reasons preventing a further 10 years of operation. But this is not to say we are without challenges going ahead. Belinda noted that the contamination continues to build up on the ACIS filters, sapping our low energy effective area. And the spacecraft thermal insulation is degrading slowly, leading to warming and limits to dwell times at certain solar pitch angles. While this means more complicated scheduling and splitting up longer observations into smaller bites, we still do not have restrictions on accumulated observing times for more problematic areas of the sky. This will eventually change, with the ecliptic poles becoming more difficult to point at.

But the good news by far outweighs the bad: *Chandra*'s science impact continues to be exceptionally high, with 6563 refereed papers up to the beginning of August 2016. This translates to a mean of about 450 papers per year. *Chandra* has also been the focus of about 320 PhD theses worldwide. After 8 years from observation, 90% of *Chandra* data have been published in one or more papers. Our science covers the gamut from solar system objects to the high-redshift universe and everything in between.

Belinda concluded with the Big Questions the meeting was conceived to help define: What major science should *Chandra* address in the next decade? What preparatory science needs to be done to pave the way for *Lynx* and Athena? How can the enormously valuable archive of existing observations be best exploited? How can *Chandra* best be deployed to support multi-wavelength facilities such as ALMA, LOFAR, MWA, LIGO, eROSITA, JWST, LSST, TESS, and then SKA… And what else is needed to facilitate the best science: software updates, additions? Easier data access? More interfacing with other major facilities? Many of these questions were addressed at least to some extent in the next two days.

Madness in our Method

Science sessions kicked off within the loose category of "Methods". Martin Elvis argued that commercial space ventures will result in greatly reduced launch costs of missions in the next decade, which will mean we can launch more of them and continue to enjoy an improving panchromatic space-based vista onto the universe. It does sound good and will be great if it works out that way. Winston Churchill's "you can always count on the Americans to do the right thing, after they have tried everything else" does spring to mind though—is the private sector the final answer, or will it all end up costing the same in the end as the inevitable raison d'être of for profit commerce seeking to make as much profit as possible runs its course? Does it work with other mission instruments and subsystems that are already built by the private sector, or do our own "private sector"

Andrea Comastri speaking on the outstanding problems on the nature of supermassive blackholes.

institute labs and facilities do better? It is going to happen though, so let's hope for the best.

Paul Green, fresh, sprightly and smiling as one relieved of a mighty organisational burden, spoke about joint programs. These are important to multi-mission science, avoiding multiple applications to different peer reviews whose available time allocations are not coordinated and might not even overlap very much. Joint programs greatly lower the barriers to meritorious multi-mission projects. A new Joint Contingent Large Programs category was added in Cycle 18 to render large joint programs more feasible. Does more need to be done? Do we need to increase the allotment of joint program and joint contingent large program time? Expanding the program to JWST is being worked; should we expand also to survey facilities such as GAIA, Euclid, TESS and eROSITA? What about new ground-based facilities such as LOFAR and LSST? While immediate answers to these questions were not forthcoming at the meeting, these are clearly things we needed to think more about and soon. Input from the discussions at the meeting triggered by Paul's talk was in fact fed into subsequent decisions later in the year on how to proceed for Cycle 19. One outcome was the expansion of Cycle 19 joint program time, facilitating removal of the Joint Contingent Large Programs proposal category.

Techniques borrowed from the fields of Data Mining and Knowledge Discovery applied to *Chandra* data were the subject of a presentation by Raffaele D'Abrusco. Raffaele emphasised the advantages techniques such as pattern recognition and examining the parameters of our data along different lines to those dictated by our traditional classification schemes can bring. Such techniques will be increasingly important as the legacy of the *Chandra* archive and the samples of the different astrophysical objects continues to grow. And in the theme of new techniques applied to X-ray astronomy, Rosanne Di Stefano highlighted the suitability of *Chandra* data obtained over baselines now exceeding 15 years and in the future hopefully exceeding 25 years, for investigating proper motions. Fast-moving neutron stars, either isolated or in quiescent X-ray binaries, could be a particularly interesting class of sources that are difficult to identify but that could pop out due to palpable proper motion.

Accretion, Cosmology, posters and drinks

Accretion is the ultimate driver of the emission from a large fraction of X-ray sources we study. Two sessions were devoted to talks with an accretion theme, spread across two days. Andrea Comastri gave an invited talk on Active Galactic Nuclei (AGN) physics and evolution, touching on the outstanding problems including the nature of supermassive black hole progenitors—were they light, stellar mass seeds or heavy, and in the thousands of stellar masses?—where and how the first black holes form and grow, and whether quasars contributed to reionization? In what would be a recurring very large project theme throughout the meeting, Andrea argued that a modest 10-15 Ms survey would be needed to address black hole growth in the high-z Universe and the links between central black holes and host galaxy evolution.

David Pooley spoke about the advantages of X-rays for microlensing quasars. X-rays originate from a much more compact region than visible light and provide a far cleaner microlensing signal. This signal is continuing to be applied to problems such as probing quasar accretion disks on microarcsecond scales and assessing the dark matter content of elliptical galaxies. The future is promising provided observations can continue to be made into the next decade: dense temporal sampling of caustic crossings can reveal the detailed structure of the X-ray emitting regions, while the increasing time baseline will provide more powerful probes of dark to stellar matter density ratios.

Stephanie LaMassa speaking about rare high luminosity and high z AGN.

Becky Canning speaking on black hole evolution and cosmic structure.

The symbiosis of AGN and their host galaxies—the ubiquitous "feedback" problem—was touched on by Peter Maksym and Stephanie LaMassa. Peter approached the problem from the perspective of studying the complicated processes at work in the inner kiloparsec of nearby AGN, utilizing *Chandra*'s spatial resolution capabilities to find, perhaps not surprisingly, substantial complexity on sub-arcsecond scales and evidence for large AGN variation and mode switching on short (<<Myr) time scales. He also highlighted the ACIS contaminant as a major problem for further progress due to the relatively soft nature of the diagnostic X-rays. Stephanie pointed out that wide area surveys are the best way to discover the rare high luminosity and high z AGN that can uncover how they evolve and help resolve the relationships between black hole growth and star formation. Her existing work on the "Stripe 82X" survey is helping to fill in our gap in understanding supermassive black hole growth. Of course, the next step would be an even larger survey expanded threefold to 100 deg^2.

AGN also provide signposts to structure in the Universe and in a convenient segue into the first session loosely based on the theme of cosmology, Becky Canning presented results of a survey of AGN in massive galaxy clusters and asked how the evolution of black holes relates to the evolution of cosmic structure? She found that the number density of X-Ray AGN in clusters depends inversely on the host cluster's mass, and work is ongoing on a larger "2nd Generation" survey that should help in understanding the redshift evolution of X-Ray AGN in clusters. *Lynx*, of course, will clean up, but Becky pointed out that much progress will also be made using new facilities in the next decade such as eROSITA combined with WFIRST and ground-based telescopes.

Marat Gilfanov presented results on fluctuations in the CXB surface brightness on scales larger than an arcminute. They discovered a significant large scale structure signal produced by unresolved clusters and groups of galaxies at redshift z~0.6. The number density of galaxy clusters as a function of mass and time places strong constraints on the equation of state of dark energy. Devon Hollowood pointed out that the Dark Energy Surveyor (DES) will use the cluster richness mass proxy, but that the mass-richness relation is not yet well-characterised. He has used *Chandra* observations of the hot cluster gas to quantify the scatter in the mass-richness relation that will be invaluable for the interpretation of the DES results.

Finally in the last talk of the session, Anastasia Fialkov artfully staved off the mad rush to drinks with a compelling argument for synergy between radio 21 cm surveys and high-redshift X-ray surveys to study the ionization and heating of the IGM by high-redshift X-ray sources that imprinted their signature in the neutral hydrogen 21-cm signal from early epochs (z~10-30). Beer and wine kindly sponsored by Harvard College Observatory served in custom-printed "Next" glasses (logo designed by CXC graphic designer Kristin Divona) accompanied celebratory poster viewing and ardent scientific discussion that lasted almost until the start of the first session the next day...

Wednesday

It was to be a packed schedule, touching dexterously upon many of the outstanding problems of high-energy astrophysics. "Outflows 1", hinting subtly that, yes, there would at some point in the future be an "Outflows 2", got us off to a whirlwind start. Winds whirling from hot stars and injecting feedback energy into their environments and the major role *Chandra* has played in advancing our understanding was the topic of the invited presentation by Jesus Toala. Jesus highlighted of the importance of high-resolution X-ray spectra for constraining and testing radiatively-driven stellar wind theory, while *Chandra*'s spatial resolution has been put to work unveiling wind-blown bubbles from massive stars and complexes, enabling measurement and characterization of injection energy. The next vital steps? Large Ms-type studies of lower metallicity regions such as the SMC to

Lidia Oskinova speaking on the winds of massive stars.

probe the role of metals both for metal line-driven outflows in general and on the evolution of massive stars.

Lidia Oskinova then provided a convincing case based on *Chandra* spectroscopy that the winds of the majority of normal massive stars are best studied in X-ray wavelengths. High resolution *Chandra* spectra have demonstrated that X-rays from main-sequence O stars are generated very close to the photosphere and that the hot plasma occupies a large volume and is expanding supersonically. Meanwhile luminous blue variables are X-ray dark, but X-rays and spectral line profiles can be used as diagnostics of mass loss and clumping in OB supergiants, although UV and X-ray observations are required to remove degeneracies. Desiderata for the future include a 1 Ms HETG spectrum of an O star such as ζ Pup. Lidia also noted the potential for neutron stars in high mass binaries for probing massive star winds.

Joey Neilsen shifted the theme to winds from stellar mass black holes, that have been revealed in all their glory and gory detail by high resolution *Chandra* spectra showing ubiquitous blueshifted ionized absorption lines in outbursting high-inclination systems. But Joey pointed out that winds are generally not detected during harder more jet-dominated states. The solution to why not is important for understanding outbursts and how winds might regulate mass accretion, but will require greater theoretical understanding of ionization of disks and winds, thermal instabilities and the wind formation processes in general. Toward much higher mass black holes, Francesco Tombesi showcased the utility of HETG spectra for showing that winds as well as jets play a role in injection of energy into host galaxies. He made the case for future very deep *Chandra* HETG observations, with the unique combination of high-resolution spectra and 0th order imaging, to shed more light on the complex environment in radio and seyfert galaxies.

Salvo Sciortino got us going again after an invigorating coffee break, with an invited talk on stars and exoplanets. The latter of course is a relatively recent addition to high-energy astrophysics, and Salvo presented the case that close-in planets might interact magnetically with the host star corona. The jury is, we think, still out on whether there is any significant interaction, and further work by *Chandra* both on this and exoplanet occultation will be challenging in terms of exposure times required, although the science is compelling. *Chandra* remains essential for deep studies of crowded star-forming regions and some fascinating results are emerging from combined long-term optical monitoring revealing spots and circumstellar disks and simultaneous X-ray observations of flares and other modulations. Cecilia Garraffo followed up with a new idea that promises an explanation for the hitherto puzzling distribution of the rotation velocities of stars in young clusters. Cecilia has performed sophisticated MHD wind simulations that show the

Joey Neilsen speaking on winds from stellar blackholes.

complexity of surface magnetic field is vital for controlling angular momentum loss. Young zero age main sequence stars have complex surface magnetic field morphology that transitions in a pseudo-random way to less complex, at which point magnetic braking is greatly enhanced. *Chandra* serendipitous stellar surveys in the archive and the next decade will play a major role in testing the theory.

Two talks then addressed the hot plasma medium associated with galaxies. Scott Randall argued for the role of heating of the intracluster medium of clusters of galaxies by weak shocks, many of which can occur over the gas cooling timescale. *Chandra* can detect the shock signatures but making progress in the next decade will require long Ms or great observations. Smita Mathur reviewed spectroscopic observations along different sightlines that indicate the presence of a warm-hot circumgalactic medium that might contain the Galaxy's missing baryons. Future observations could extend to other galaxies, though exposure times would be very costly. Joseph Burchett continued the discussion of missing baryons in galaxy clusters in the next session, but of which we give a timely mention here. *Chandra* provides the hot gas mass, while UV and optical spectroscopy probes the warm phase. Characterizing higher redshift clusters and resolving local substructure around individual galaxies are primary next decade goals, requiring extensive new observations but also utilizing growing *Chandra* and HST archives.

Ken Ebisawa returned to our Galaxy with a presentation on the nature of the "Galactic Ridge X-ray Emission (GRXE)"—apparently diffuse emission along the Galactic plane thought to be due to a myriad unresolved point CVs and coronally active stars. Ken noted that there does now appear to be a diffuse emission component, but he also used multiwavelength follow-up of *Chandra* sources to identify a new class of source that might contribute a non-negligible fraction of the GRXE. The best guess as to what these sources are? Detached white dwarf - M dwarf binaries accreting the winds of their companions.

Structure of the Cosmos

It was a good sounding heading and these sessions covered some marvelously varied but sometimes surprisingly connected talks. Pepi Fabbiano delivered a tour de force invited review on *Chandra*'s contribution to galaxy evolution, showcasing progress made on how the final stages of the evolution of different stellar populations, such as supernovae and stellar remnants in binary systems, contribute, together with the gamut of AGN activity and the transfer of energy to hot halos. What for the next decade? *Chandra* spatial resolution is of course paramount, with deep halo studies, of which there are presently very few, and deep studies of circumnuclear regions being highest on the list. This is one of the many fields for which the low energy response is vital and Pepi suggested that observations requiring the low energy response be prioritized.

Dascheng Lin explained how hyper-luminous ($>10^{41}$ erg/s) off-nuclear X-ray sources (HLXs) are strong candidates for the elusive intermediate mass black holes (IMBHs) expected from various processes such as runaway merging of massive stars in young compact star clusters resulting from galactic mergers, or the collapse of Population III stars in the early Universe. *Chandra*'s spatial resolution combined with time domain surveys will present a powerful combination for finding and understanding these objects in the next decade. Scott Barrows continued on this theme, presenting impressive work on a procedure for matching archival *Chandra* data with overlapping coverage of galaxies from optical databases such as the SDSS and *Hubble* to identify offset AGN, ultraluminous X-ray sources, and HLXs. The offsets indicate galaxy mergers that are otherwise very difficult to find. A catalogue of 300 HLXs candidates and 21 IMBH candidates is also expected shortly.

Daniel Wang gave an invigorating talk on the latest from our Galaxy's own supermassive black hole, Sgr A*. *Chandra* has made impressive observations of the Sgr A* region, revealing flares on the central source that make up ⅔ of its observed counts. A massive star colliding wind model appears to match the observations of the accretion flow. Daniel explained that more counts ($> 10^4$) are needed to study the timing and spectral properties of the flares, and that future multi-wavelength coordinated observations should provide valuable insights into the nature of the flare emission and the role of strong gravity.

Too much discussion of cosmic structure inevitably leads down the perilous road to cosmology. Steve Allen's invited talk summarized the latest results on cosmology from galaxy cluster studies and the view of the next decade. Cluster counts as a function of mass and redshift have been crucial in building the current picture of a universe dominated by dark matter and dark energy. He concluded with

Daniel Wang speaking on the supermassive black hole in our Galaxy.

a resounding "The prospects for progress over the next decade are outstanding", citing new cluster catalogs, hundreds of times larger and with far greater redshift reach, being constructed across a variety of wavelengths. *Chandra* follow-up observations will be vital to exploit these, but large amounts of exposure time will be needed, say 0.5-1.0 Ms/yr over 5-10 years.

The last two cosmology talks, or more correctly, talks that your capricious SOC placed into a cosmology session, dealt with early black hole formation. Kevin Schawinski has been in search of the "missing seeds". There are very massive quasars at z~6 with very low space densities but a distinct lack of AGN at z>6 in deep *Chandra* pointings. Kevin concludes that black hole seed formation at z>6 is highly inefficient and suppressed in most galaxies. Extensive surveys exploring the AGN luminosity function at $4<z<10$ are needed to further understand the seed formation suppression. Nico Cappelluti then pointed out that all the high-redshift AGN that could be detected will be seen in EUCLID, WFIRST, JWST or HST catalogues. The searches for these objects could be more sensitive if the priors from these optical and infrared detections were used. Combinations of filters could also be chosen to maximize the sensitivity of such surveys.

The 30-year Visionary NASA/Astrophysics Division Roadmap identified 4 probes that should be considered in the 2020 Decadal Survey. The science session finished with a talk by Feryal Ozel on the X-ray Surveyor mission concept, later to be named *Lynx*, prior to a discussion session on major missions and synergies. Feryal, the co-chair (with A. Vikhlinin) of the X-ray Surveyor Science and Technology Definition Team, presented their progress on the mission design and summarized the key science that *Lynx* can address, ranging from the first black holes to missing baryons

to transit absorption spectroscopy of exoplanets. The theoretical studies of the mission requirements have produced spectacular advances; however, there are challenges, not least of which is the construction of lightweight high angular resolution mirrors, to conform to the Roadmap definition. *Lynx* will be the natural successor to the fantastic legacy that *Chandra* will leave behind, with spatial and low-energy spectral resolution as the distinguishing quantum leaps forward over current missions and Athena in the late 2020's.

Panel Discussion: Synergies with Major Facilities

The panel on *Chandra* Synergies with Major Facilities in the coming decade included speakers representing current (*Hubble*, *XMM-Newton*, *NuSTAR*, LoFAR) and future (eRosita, Euclid, WFIRST, JWST) missions.

Norbert Schartel gave a very detailed description of the complementarity of the two missions, *Chandra* and *XMM*. He pointed out that 400 ks of joint *Chandra*/*XMM* observations covering all classes of objects is available per year and stressed the excellent synergy of the two missions. Finally he noted that *XMM* is focusing on Legacy programs dedicating ~6 Ms over 3 years, and pointed out that if the *Chandra* available time would increase to 1Ms, it would allow for large joint programs. Daniel Stern focused on the spectral range complementarity between *NuSTAR* and *Chandra*, resulting in the most oversubscribed joint program in the last cycle. He also discussed the status of Euclid and WFIRST and commented that the most likely synergy between *Chandra* and these future missions would be follow-up observations of specific targets. Paul Nandra discussed the status of eRosita, an ESA all sky X-ray survey mission, and pointed out that the best synergy would be *Chandra* follow-up of selected eRosita sources (clusters, AGN, transients). He also presented the complementarity between *Chandra* and ATHENA (currently scheduled to launch ~ 2028), as an optimistic look at the *Chandra* future. Rachel Osten discussed the unique science resulting from combining *Chandra* and *Hubble* observations and how it can be maximized by combined programs, such as joint community-enabling initiatives (e.g., supermosaics, Spectroscopic Legacy Archive). She also commented on the extraordinary science combined JWST/*Chandra* observations of transients would afford. Reinout Van Weeren discussed the X-ray–radio synergies giving an excellent presentation of the Radio landscape in the next decade—he noted that the radio community is currently focusing on Large Surveys. The Radio observations seamlessly complement the X-ray data of most astrophysical sources, e.g., compact objects, AGN, clusters.

Audience discussion was vigorous, with many questions levied at such a valuable assemblage of panelists before fatigue and the want of evening entertainment and dinner drew the day to a close.

Poster Panoply

About 45 posters were on display throughout the meeting, ranging from instrument presentations such as Catherine Grant's "Seventeen Years of the Advanced CCD Imaging Spectrometer" to John ZuHone's "The Galaxy Cluster Merger Catalog", and all science inbetween. Pat Broos showcased his impressive work with Leisa Townsley on their ACIS Extract software on Galactic star clusters, while Leisa made the case for *Chandra* observations of infrared dark clouds. Several posters dealt with archival research and Ian Evans expounded on the magnum opus that is Release 2 of the *Chandra* Source Catalog that will "roughly triple the size of the original catalog released in 2009 to an estimated 350,000 detections". Due near the end of this year, we are told.

Using "background" X-ray sources to investigate the WHIM and our Galaxy's ISM was a recurring theme throughout the meeting. Daniel Rogantini furthered the cause of impressive lanterne rouge speaker Sascha Zeegers (see the last meeting session described later) with a poster expounding on the use of synchrotron measurements of fine structure at the Fe K edge to probe grain composition. A similar theme, but silicon-based, was presented by Norbert Schulz, while Lia Corrales reported the preliminary discovery of a dust scattering halo around a recently discovered X-ray transient, SWIFT J174540.7-290015. David Principe's poster extended this to the edge-on pre-MS transitional disks of T Cha and RY Lup whose X-ray emitting coronae shine through the disks and reveal some interesting structure.

Young pre-main-sequence stars in the cluster IC 348 were the targets of a large HETG program described by David Huenemoerder. This work, and Herman Marshall's talk on similar HETG observations of X-ray binaries in M31 (see below), shows that source confusion is not usually an issue for overlapping HETG spectral arms, even in complicated source regions. Costanza Argiroffi and co-workers stretched the bounds of the HETG in yet another dimension by applying its spectacular wavelength precision to detect a 30-40 km/s blueshift of gas accreting onto the classical T Tauri star TW Hya.

X-ray emission from stars was the topic of several other campaigns, with Scott Engle presenting both on the surprising X-ray emission from Cepheids by an as yet unidentified mechanism and on the activity-rotation-age relationship for M dwarfs that are the low hanging fruit of exoplanet surveys. More on the low-mass end came from your present author and co-author Nick Wright, who have

found that the rotation-activity relation for sun-like stars extends to fully-convective M dwarfs, implying that radiative-convective tachoclines are not an important ingredient in stellar dynamos. At higher masses, Joy Nichols analysed the line profiles on the O4 If star ζ Pup to look for co-rotating interacting regions and clumpy wind signatures, while Victoria Grinberg expostulated on the use of HMXBs for probing the clumpy winds of massive stars—something also touched upon by Lidia Oskinova's talk mentioned above. Margarita Karovska's poster highlighted *Chandra*'s sub-arcsecond resolution applications to imaging wind-accreting objects such as the Mira binary and other symbiotics. The related cataclysmic variables were SOC expert Koji Mukai's focus, who presented progress understanding the populations of vanilla non-magnetic objects as well as rare X-ray bright CVs.

Black holes of the more modest variety featured through Jifeng Liu's poster arguing ULXs are stellar mass black holes with supercritical accretion rather than intermediate mass black holes, Shuping Yan's work on the "heartbeat" of microquasar GRS 1915+105, Antonella Fruscione's analysis of ULXs in colliding ring galaxies, and Dan Milisavljevic's search for "baby black holes" undergoing accretion and revealed within the thinning debris of recent supernovae.

Bigger ones of the AGN kind, beginning with our own Sgr A* and its environs and the lure of future observations thereof, was the topic of Fred Baganoff's work, while next door in the Andromeda galaxy the central black hole has the attention of Shuinai Zhang whose analysis of *XMM-Newton* data on the bulge suggests that the currently quiescent nucleus had a characteristic luminosity of ~$10^{43.5}$ erg/s, about 400,000 years ago. SOC member Francesca Civano has far too many AGN in the 4.6 Ms COSMOS Legacy Survey and so emphasised the glamorous high redshift Universe in her poster. Erendira Huerta analysed and modelled archival high-resolution X-ray spectra of AGN to examine halos and outflows, and Malgosia Sobolewska presented the first results from her X-ray study of "compact symmetric" young radio sources that will be important for constraining models for the earliest stage of radio source evolution and their interaction with the interstellar environment of their host galaxies. Eric Miller showcased a fossil group in formation in the form of Shakhbazyan, a remarkably compact collection massive, red-sequence galaxies.

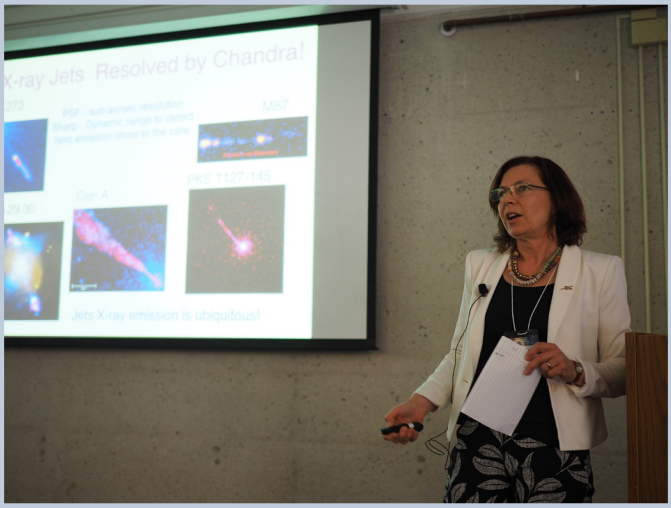
On larger scales, galaxy clusters featured in Gagandeep Anand's presentation on the "wide angle tail" hosting galaxy cluster Abell 623, Emmet Golden-Marx's multiwavelength follow-up observations of the COBRA high-*z* galaxy cluster survey of "bent lobe" sources in clusters, and Vijaysarathy Bharadwaj analysis of *Chandra* observations of the type II AGN hosting intermediate redshift galaxy cluster ACT J0320.4+0032. Gerrit Schellenberger looked to the future and *Chandra* follow-up of (probably only some of) the 100,000 expected eROSITA detected clusters. Taweewat Somboonpanyakul discussed galaxy clusters hiding in plain sight—why didn't we see them before?!—while Rachel Paterno-Mahler's poster dealt with *Swift* characterization of a strong lens cluster sample.

Several more "technical" posters described various aspects of the *Chandra* archive, data sets, bibliography and software systems, and Laura Brenemen described the promise of the Arcus mission concept for studying the evolution of structure and feedback. All in all, an embarrassment of inspirational riches to talk about over cups of tea and coffee in the morning and glasses of wine and beer in the evening.

More Accretion, Outflows and Hot Thermal Plasmas

In short, everything that was not already covered, except for transients and periodic sources, formed the basis of Friday's first session. Jeno Sokoloski got us going with an entertaining invited talk on "Flows and shell burning of accreting white dwarfs"—novae and symbiotic stars, in essence. Jeno presented some spectacular spectra of nova explosions as well as highlighting the value of resolved observations of nova blasts and remnants, all seasoned with tantalizing hints from gamma ray observations that novae are the sites of some interesting particle acceleration processes.

Jun Yang presented her large X-ray pulsar database compiled from *Chandra*, *XMM-Newton* and RXTE observations of the SMC. The data provide a valuable glimpse into binaries and pulsars in a low metallicity environment, but also highlight the importance of knowing the distance to the sources. Herman Marshall then dazzled the assemblage with HETG observations of the M31 bulge. So many spectra of X-ray binaries! They all overlap in a complicated way but Herman convinced us (I think!) that data can be disentangled. Back in the SMC, Vallia Antoniou was due to talk about the Visionary Project to survey key regions of the galaxy. But… she just had her baby Konstantina and delegated the task to Andreas Zezas, who touched upon all ground-breaking science the survey is producing. Again, the theme of the low-metallicity environment is a constant undercurrent, and the major pièce de résistance will be X-ray binary formation as a function of stellar population age. Javier Garcia brought up the problem of bright hard-state accretion disk truncation in black hole binaries whose ambiguity in current data remains unresolved and a source of major contention in the field, especially for interpreting measurements of black hole spin. The answer lies in extending to higher energies with joint *Chandra*/*NuSTAR* observations to break the degeneracy in current models.



Aneta Siemiginowska speaking on relativistic jets from AGN.

Morning coffee, though welcome, provided less physical stimulus than high-resolution spectroscopy in the hands of invited speaker Jon Miller. Jon emphasised that *Chandra* remains the flagship high-resolution mission and discussed how *Chandra* spectroscopy of black holes across the mass scale can make key progress over the next decade. Demosthenes Kazanas talked about black hole accretion disk winds, and their importance for angular momentum transport and feedback into their environments. He suggested that that successful wind modelling of HETG X-ray data of GRO 1655-40 using the same techniques as for AGN disk winds argues for the universality of accretion disk wind properties across the entire ($10\ M_\odot$–$10^9\ M_\odot$) black hole mass range. Missagh Mehdipour continued the theme of black hole disk winds and outflows with impressive modelling of extensive multi-satellite data on NGC 7469 that mapped the ionisation, chemical, and dynamical structure of the outflow.

Myriam Gitti pressed on with feedback in cool-core galaxy clusters from AGN outflows. She noted that future radio surveys with LOFAR and SKA have the potential to increase the number of known radio mini-halos to ~1000 objects. Synergies of these radio surveys with current and future X-ray observations will be crucial for establishing the radio mini-halo origin. Aneta Siemiginowska switched gears to relativistic jets from AGN. After 16 years of *Chandra* observations there are now about 100 X-ray jets associated with radio galaxies and quasars. But these are generally shallow ~10ks observations and key jet physics requires much deeper observations that must surely be made by *Chandra* in the next decade.

Among the black holes, Maurice Leutenegger did a cameo on OB stars winds and assessing the uncertainties on mass loss rate estimates based on X-ray spectral line profiles. They are crucial measurements and uncertainties are now probably at a level of about 50%—much less than the factors of a few difference between theory and measurement, with measurements always lower.

The afternoon ushered in the hot thermal plasmas. Helen Russell's lucid invited talk went back to feedback in galaxy clusters by AGN and driving of both hot and cold gas flows. Helen showed some impressive ALMA data revealing several kpc long molecular gas filaments. Radio bubbles supply large-scale heating to stabilise cluster atmospheres and lift gas in their wakes. In the next decade, *Chandra* observations of X-ray structure coupled with ALMA molecular gas tracers will be a powerful diagnostic of cluster feedback.

Redshifts diminished in the next three talks on stars and exoplanets. Tom Ayres showcased *Chandra* observations of the α Cen that have revealed a solar-like magnetic cyclic variation of X-rays, pointing out that if we are sending missions to the α Cen system we must continue to observe and characterize it in detail don't miss Tom's article on alpha Cen on page 1 of this issue). Scott Wolk presented evidence that there might be some observable degree of magnetic interaction between stars and close-in planets, and that the latter might in fact inhibit stellar angular momentum loss. He also noted that transit absorption measurements in X-rays can help characterise planetary atmospheric extent and chemical composition. Slightly further afield, Ignazio Pillitteri highlighted the synergy between *Chandra* and Gaia observations of young stellar clusters, where *Chandra* pinpoints the young stars and Gaia tells us about their motion and distance, allowing us to unravel cluster structure and dynamical evolution.

In the countdown to the Key Legacy Projects panel discussion, Alessandro Paggi wrapped up with some tantalizing snippets on X-ray mass profiles from the *Chandra* Gal-

Tom Ayres speaking on solar-like variations of X-rays from α Cen.

axy Atlas being developed by Paggi and co-workers. This rich resource is already producing interesting results on gas structure, with NGC 4649 having a smooth, essentially hydrostatic equilibrium gas structure while NGC 5846 shows evidence of sloshing and galactic interaction.

Panel Discussion: Key Legacy Projects

So, we had sat through two and a half days of a meeting in which speaker after speaker had made a case that large amounts of exposure time were needed to push forward with key science. But what are the key projects *Chandra* really needs to do? Everyone has an opinion and it was time for another panel discussion! Our panelists were chosen for both their relevant expertise but also their experience with *Chandra*. Daniel Wang, PI of numerous *Chandra* programs on Galactic as well as extragalactic objects, both point sources and diffuse emission; Alexey Vikhlinin, SAO lead for the *Lynx* effort and PI of numerous *Chandra* observations of galaxy clusters; Fabrizio Fiore, Director of Osservatorio Astronomico di Roma specializing in extragalactic high energy astrophysics and cosmology with extensive *XMM-Newton* and *Chandra* experience; and Leisa Townsley, probably *Chandra*'s most successful large project PI and pioneer of studies of massive star forming regions. Oh, and there was one more sitting at the end of the table—a British holiday maker bearing a striking resemblance to supernova remnant and plasma physics expert Martin Laming of the Naval Research Laboratory, who could not attend himself due to cumbersome military travel approval processes. Each had 10 minutes to summarize their key project that *Chandra* must do in the next decade.

So what were their key projects? In brief, Wang: further observations of Sgr A* and surrounding regions; megaseconds required. Vikhlinin: Deep imaging of faint, extended objects to make use of *Chandra*'s excellent capability to isolate and remove faint point sources, such as cluster and galaxy group outskirts, high-density large scale structures and galaxy cluster progenitors; circumgalactic media and galaxy winds, Galactic ISM; quite a few megaseconds required. Townsley: the big picture of Galactic star formation by surveying whole giant molecular filaments (in Leisa's words, "study the forest ecology, not just the butterflies and tigers"); several megaseconds required. Fiore: the first black holes in joint observations with JWST; observations of candidate first galaxy groups and clusters selected by radio and FIR surveys; formation of the first structures and the role of feedback using joint *Chandra* and JWST observations; and again joint JWST and *Chandra* observations of shocks and halos in unbiased AGN surveys; in all, several megaseconds required. The British holiday maker favoured deep observations of supernova filaments in order to resolve the fundamental physics of astrophysical shocks; but it needs megaseconds.

Raffaela Margutti speaking on X-rays from supernovae.

The common thread through these presentations and subsequent discussion was that very large programs are needed in order to enable all this key but expensive science. Note that in the last AO there was no very large program ("X-ray Visionary Program" as it was last called) category. While presentations and discussion were going on, SOC wizard Francesca Civano implemented a live text feed such that comments and questions could be submitted by members of the audience either signed or anonymously. The need for very large programs came up again and again, with comments submitted by some surprising names including Luke Skywalker and Genghis Khan. We are pleased to report that the clamour was not ignored and that VLPs ("Very Large Programs") are back for this coming AO.

The reward for having survived the panel discussion was a delightful conference dinner and drinks, accompanied by the unburdened, relaxed Paul Green and guitarist friend Bill Morris, with a guest appearance on violin by Chelsea MacLeod.

It's always difficult being on the last day

But kickoff by Raffaela Margutti went down like an opening keynote, and gave one the rather unsettling feeling that we are just wasting time on our current science and should switch to studying supernovae! X-rays from SNe can be broadly categorized under the heading of interaction of the blast with the progenitor environment, and Raffaela covered the different aspects that X-rays can teach us about the astrophysics of the progenitors—pinning down the end of lifetime structure and mass loss, for example—as well as the nature of the explosion itself. Kari Frank followed up in the same context with a presentation on SN1987a that *Chandra* has observed at 6 month intervals for the last 16 years. Struggling to compress all the science this entails into his contributed talk, Kari just slapped up a banner "Lots of interesting results!". In short, measurements of the blast tell

Musical entertainment during the dinner banquet from (left to right) Paul Green, Bill Morris, and Chelsea MacLeod.

us all about the circumstellar medium and blue supergiant progenitor mass loss at the time of collapse, as well as enabling dissection of the blast energetics, all in unprecedented detail. Observations will continue into the next decade. Kazimierz Borkowski expanded the topic to other expanding SNe observed by *Chandra* that are revealing the details of the explosion and progenitor mass loss and structure. The only downside to these spectacular studies is that there is not a huge number of objects to continue with!

While the neutron star from SN 1987a has not been detected yet in X-rays, Slavko Bogdanov talked about the only three transitional millisecond pulsars that had and that are beginning to answer questions regarding how transitions to and from accreting states—presumably responsible for the spinup—occur and how X-ray mode switching, flares, and jet driving occur. Statistics and cool star expert Vinay Kashyap segued to flares on late-type stars observed by *Chandra* gratings that are revealing new and puzzling behaviour in flaring plasma; of note is that harder X-ray emission tends to lag behind full-band integrated light, and that lines formed at similar temperatures do not all respond in the same way.

Down the home straight, Oleg Kargaltsev presented a spectacular invited review on Pulsar Wind Nebulae (PWNe), unequivocally establishing the unique contributions of *Chandra* in that field. He showed that the discovery of PWNe increased dramatically after the launch of *Chandra*, with 90 new PWN found thanks to the unique *Chandra* spatial resolution and low background. Further, besides Crab and Vela, the morphology of multiple PWNe was shown to be clearly affected by the PSR motion (including head-tail PWNe) resulting in elongated structures.

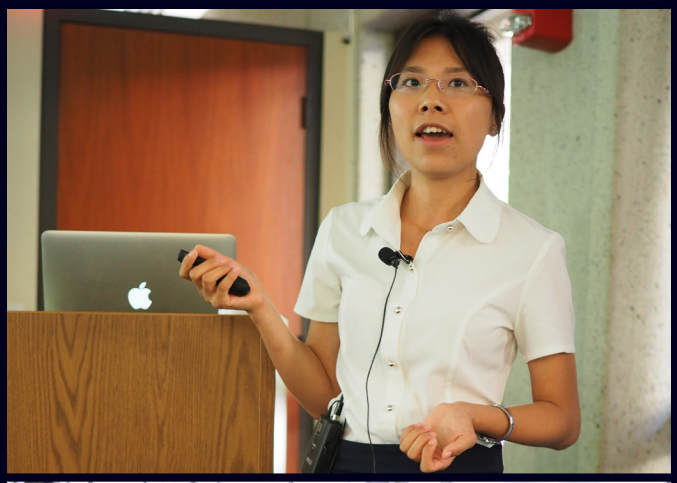
The meeting was wrapped up by a dazzlingly diverse splash of five talks. Chandrayee Maitra presented *Chandra* observations of PSR J0855-4644 that revealed a pulsar wind nebula with a double torus and jet-like structure. Max Bonamente and team discovered a new OVIII K-alpha X-ray absorption line system towards the quasar PG 1116+215 in LETG observations (see the LETG article on page xxviii for further details). The use of the HETG to probe the chemical composition and temperature structure of the ISM of our Galaxy using bright background sources was discussed by Efrain Gattuz, who found predominantly neutral gas but with smaller amounts of gas over a range of ionization states. Konstantina Anastasopoulou has been busy analyzing a deep *Chandra* observation of the X-ray luminous interacting galaxy system Arp 299 and has found a rather large population of 20 ULXs, in addition to diffuse hot gas and an extended soft X-ray plume signalling a large scale outflow.

And at the end of a raucous, chaotic, brilliant three days of the highest level astrophysics, we were left with dust. Interstellar dust, and a masterclass by Sascha Seegers who expounded on all that can be done in the next decade with the *Chandra* HETGS using bright X-ray binaries as background sources. X-ray absorption fine structure can help reveal dust grain composition as well as the bulk chemical composition.

It became obvious during the week that *Chandra* will be tackling absolute top-rank science in the years to come. We have only just started. *Chandra* Science for the Next Decade. It was an august week.[1] It has been an august 16 years. It will be an august Next Decade. ▪

[1] Talks and abstracts can be found at http://cxc.cfa.harvard.edu/cdo/next_decade2016/program.html

Scenes from *Chandra Science for the Next Decade*



(from top to bottom, left to right) Oleg Kargaltsev speaking on pulsar wind nebulae. Jun Yang speaking on X-ray pulsars in the SMC. Salvo Sciortino (left) and Giusi Micela (right) enjoying the selection of posters. Rosanne Di Stefano after speaking about investigating proper motions amongst the Chandra decades-long archive. Synergies with Major Facilities Panelists (left to right): Reinout Van Weeren, Daniel Stern, Norbert Schartel, Rachel Osten, Paul Nandra.

(full article on page xl)

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