# X-ray Surveyor Discussion Session Results
# from the X-ray Vision Workshop

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## SUMMARY

This paper summarizes the results of a brainstorming session held during the X-ray Vision Workshop (Oct 6-8, 2015, Washington DC). The workshop was convened to discuss the scientific potential of the *X-ray Surveyor* mission. The *X-ray Surveyor* concept, which was defined by the Astrophysics Roadmap[2], is to effect a 100-fold gain in survey and spectroscopic capability over the *Chandra X-ray Observatory*, while at least matching *Chandra's* sub-arcsecond imaging capability[3].

This paper is intended to inform interested scientists of the growing discussion in our community and to solicit their input in the area of new science that a next generation high-resolution X-ray Observatory may provide for astrophysics. This paper is not an official document and is certainly not the definitive science case for an *X-ray Surveyor* mission. It is, instead, an early input to this discussion, which we hope will lead to a full reference white paper on the *X-Ray Surveyor* concept. A fuller description of the X-ray Vision Workshop, including the talks presented, can be found in the workshop webpage[4].

In the 2-hour brainstorming session, about 50 astronomers addressed four questions:

1. What questions in astrophysics and cosmology can X-ray astronomy best, or uniquely, address?
2. Which of these questions need the high spatial and spectral resolution and large area of *X-ray Surveyor*, and why?
3. What precursor observations can be made, at any wavelength, that would either help define the parameters of the *X-ray Surveyor* or provide inputs for its observing programs?

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[2] http://science.nasa.gov/media/medialibrary/2013/12/20/secure-Astrophysics_Roadmap_2013.pdf)

[3] Gaskin et al., 2015, *SPIE Optical Engineering+ Applications*, pp. 96010J-96010J, doi: 10.1117/12.2190837.

[4] http://cxc.harvard.edu/cdo/xray_surveyor/

4. What modest changes to the *X-ray Surveyor* requirements could have a large pay-off in answering the science questions?

A set of 26 science questions was produced spanning most of astrophysics. From these several big picture themes emerged:

1. *The formation and evolution of the universe*. Hot baryons, which pervade and trace the cosmic web, clusters and groups of galaxies, and individual galaxies, emit uniquely in the X-ray range. Warm/photoionized baryons imprint absorption signatures on the X-ray emission of background sources and thus can be detected in X-ray spectra. With X-ray observations we can also trace the emission of supermassive black holes (BH), and follow their evolution and their relation to, and effect on, the emerging galaxies.
2. *The cycle of stellar formation and death*. This includes a full understanding of the multi-phase interstellar medium (ISM), the detection of highly obscured young stellar objects (YSO), which can only be seen in X-rays, and the effect of supernovae (SN) on their environment.
3. *The study of extreme physics, which can be investigated via the X-ray emission of BHs and neutron stars (NSs)*. These measurements will constrain (a) the spin of BHs and its emergence in the evolution of the BHs, and (b) the equation of state of nuclear density matter in NSs.
4. *The study of astrophysical plasmas*. X-ray observations will determine the microphysics of plasmas in a three-way exchange with laboratory and solar system plasma physics, and state of the art simulations.

All of the questions require the combination of large area and high angular resolution of *X-ray Surveyor*, with high-resolution spectroscopy and large field-of-view being close seconds.

Many precursor observations can be performed to sharpen these questions and to prepare for *X-ray Surveyor*. These observations would use multiple, spectrum-spanning, observatories. In addition, theoretical work (especially advanced simulations) and laboratory measurements will create a stronger basis for defining the *X-ray Surveyor* mission. A series of modest enhancements to the baseline *X-ray Surveyor* concept were proposed; these need scientific study to evaluate the trade-offs involved with implementing them into the mission design.

Clearly this session, and the entire workshop, was just a first step in preparing for the scientific cornucopia of *X-ray Surveyor*. This paper is not an official statement of anything, certainly not of the full *X-ray Surveyor* case. Far more details of some of the science of *X-ray Surveyor* is given in the talks that are available on the web site[5]. Rather it is hoped that this paper will stimulate further thinking and discussion about the *X-ray Surveyor* mission concept.

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[5] X-ray Vision Workshop website:

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## 1. INTRODUCTION

The *X-ray Surveyor* mission concept is the subject of a NASA funded study as one of four potential "Surveyor" missions that might be presented to the 2020 Decadal Study. *X-ray Surveyor* in its configuration c.2015 is conceived as having *Chandra*-like sub-arcsecond angular resolution but over a wide field, and to have roughly 100-fold better performance for both imaging surveys and high-resolution spectroscopy (Weisskopf et al. 2015[6], Vikhlinin et al. 2015[7], Gaskin et al. 2015[8]). With such a large jump in capability, the science that can be done lies well beyond current studies.

The X-ray Vision workshop[9], held at the National Museum of the American Indian[10] in Washington DC, October 6-8 2015, was designed to elicit ideas from the community on how to make use of the power of *X-ray Surveyor*. The formal talks and posters provided a wealth of powerful new observation programs for X-ray Surveyor. As a way to stimulate further out-of-the-box thinking, and to search for emerging themes among the varied science presented, a 2-hour discussion session was held on the second afternoon of the workshop.

The discussion was structured around four different lines of enquiry that began with general science questions and move toward *X-ray Surveyor* specific actions:

1. What science questions in astrophysics and cosmology can X-ray astronomy best, or uniquely, address?
2. Which of these questions need the high spatial and spectral resolution and large area of *X-ray Surveyor*, and why?
3. What precursor observations and/or theoretical calculations can be made, at any wavelength, that would either help define the parameters of the *X-ray Surveyor* or provide inputs for its observing programs?
4. What modest changes to the *X-ray Surveyor* requirements could have a large pay-off in answering the science questions?

This paper presents the results of this "brainstorming" session. It is not an official statement of anything, certainly not of the full *X-ray Surveyor* case. Far more details of some of the science of *X-ray Surveyor* are given in the talks that

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[6] SPIE 2015SPIE.9510E..02W, and arXiv:1505.00814, https://dl.dropboxusercontent.com/u/4936588/smart-x/2015-06-X-ray-Surveyor-HEAD-mission.pdf

[7] https://dl.dropboxusercontent.com/u/4936588/smart-x/2015-06-X-ray-Surveyor-HEAD-science.pdf

[8] *SPIE Optical Engineering+ Applications*, 2015 pp. 96010J-96010J, doi: 10.1117/12.2190837.

[9] http://cxc.harvard.edu/cdo/xray_surveyor/

[10] http://www.nmai.si.edu

are available on the web site[11]. Rather it is hoped that this paper will stimulate further thinking and discussion about the *X-ray Surveyor* mission concept.

## 2. PROCEDURE

The X-ray Vision brainstorming session followed the model used by the "WISE at 5" workshop (Faherty et al. 2015). This method is widely used outside astronomy, and experience has shown that it is effective in getting experts to think "outside the box", and throws up an interesting array of ideas.

Briefly, six tables each with about 8 participants were set up. One person acted as moderator for each table, keeping notes and ensuring equitable discussion. The first enquiry was answered by each of the tables independently. After 20 minutes, everyone except the facilitators moved to another table and tackled the second line of enquiry using the science questions that they found at that table. The procedure was then repeated, until all 4 questions had been answered.

In practice, the session quickly became a lively discussion at all the tables, producing more discussion than normal Q&A periods after talks, and more give and take than in typical panel discussions. As table seats were assigned at random (using playing cards), junior and senior astronomers were thrown into relatively level discussions with each other.

## 3. THE FOUR QUESTIONS

Each of the following sub-sections summarizes the main answers to one of the four lines of enquiry.

### 3.1 *What questions in astrophysics and cosmology can X-ray astronomy best, or uniquely, address*?

A 'wordle' based on the as-written responses from each of the six tables (Figure 1) gives a first impression of the great breadth, but also the clear centers of emphasis of the science that participants felt were best addressed with X-ray astronomy. The most used words were "black holes", "galaxies", "hot", "baryons", "neutron star" and "feedback", followed by "equation of state" and "plasma".

[11] X-ray Vision Workshop website:


Figure 1. A word cloud of the moderators' summaries formed out of the top 150 scientific questions raised. (BHS = black holes.)

Altogether 26 distinct questions were listed and each of them is summarized in Table 1. The wordle reflects four themes that emerged from a detailed inspection of the science questions, which are summarized below:

1. *The formation and evolution of the universe*. Hot baryons, which pervade and trace the cosmic web, clusters and groups of galaxies, and individual galaxies, emit uniquely in the X-ray range. Warm/photoionized baryons imprint absorption signatures on the X-ray emission of background sources and thus can be detected in X-ray spectra. With X-ray observations we can also trace the emission of supermassive black holes (BH), and follow their evolution and their relation to, and effect on, the emerging galaxies.
2. *The cycle of stellar formation and death*. This includes a full understanding of the multi-phase interstellar medium (ISM), the detection of highly obscured young stellar objects (YSO), which can only be seen in X-rays, and the effect of supernovae (SN) on their environment.
3. *The study of extreme physics, which can be investigated via the X-ray emission of BHs and neutron stars (NSs)*. These measurements will constrain (a) the spin of BHs and its emergence in the evolution of the BHs, and (b) the equation of state of nuclear density matter in NSs.
4. *The study of astrophysical plasmas*. X-ray observations will determine the microphysics of plasmas in a three-way exchange with laboratory and solar system plasma physics, and state of the art simulations.

Table 1: Science questions highlighted by the discussion

| THEME | QUESTION |
|---|---|
| BLACK HOLES (BH) | 1. How fast do BH spin? |
| | 2. What is the evolution of spin of BH with redshift? |
| | 3. What is the role of BHs in Feedback? |
| | 4. How do BH and Large Scale Structure and Galaxies co-evolve? |
| | 5. When did the first BH form? At what mass? |
| | 6. What is the role of supermassive BH in the universe? |
| | 7. How and When did the first supermassive BH grow? |
| | 8. How does the central engine of AGN work? |
| HOT BARYONS | 9. What are the elemental abundances of hot baryons? (SNR, ISM…) |
| | 10. What is the baryon fraction and metallicity of galaxy haloes? How do they relate to the host galaxies? How do they evolve with redshift? |
| | 11. How did cosmic structure evolve? (filaments) |
| | 12. What is the physics of hot baryons? What is the origin and fate of baryons above the virial temperature |
| | 13. Where does the gas in the hot IGM originate and how does it get there? |
| | 14. How does feedback heat and enrich gas around galaxies? (CGM and IGM) |
| | 15. What physical processes govern the hot baryons in relation to galaxy formation? |
| | 16. How do studies of the ICM tell us about cluster feedback and evolution? |
| NEUTRON STARS | 17. What is the equation-of-state of neutron stars? (I.e. their mass and radius?) |
| | 18. What is the electromagnetic signature of neutron star mergers? |
| | 19. How can compact objects be used as probes of the laws of physics under extreme conditions? (Includes BH.) |
| STARS AND PLANETARY SYSTEMS | 20. What drives the life cycle of stars from formation to stellar death? |
| | 21. What is the origin and nature of energetic photon and particle radiation from stars and how does it affect their planetary system environment? |
| | 22. What is the composition of cosmic dust? Diagnostics of solid-state baryons |
| | 23. What is the nature of the ISM at all temperatures and phases? |
| PLASMA PHYSICS | 24. What is the microphysics of astrophysical plasmas? |
| | 25. What can X-ray astrophysics teach plasma physicists? |
| | 26. How does the ICM inform us about fundamental plasma physics? |

**3.2 *Which of these questions need the high spatial and spectral resolution and large area of X-ray Surveyor, and why*?**

Fig. 2 shows a wordle of the top 150 words in the full collation of all the coordinators' reports, which gives an impression of the topics covered. High-resolution spectral and spatial X-ray observations are prominent in the wordle. Table A1 lists all of the questions and the capabilities of X-ray Surveyor that they make use of. Note that the check-marked capabilities are those brainstormed. Actual requirements will need careful review.

As the wordle suggests, resolution, both spatial and spectral was very important. Virtually all of the science questions require *both the large area and high angular resolution* of the *X-ray Surveyor*. The majority (17/26) also require the *high spectral resolution* of the X-ray Surveyor calorimeter and gratings; 10/26 of the questions are best addressed with a *large field of view*.


Figure 2. A word cloud formed using the top 150 words in the moderators' summaries.

More detailed explanations for key examples from Table A1 are given below to illustrate the reasoning behind these conclusions:

1. *Understanding black holes, how they work, how they interact with the rest of the universe.* We need high spectral resolution and a high number of photons ($>10^5$) to measure the general relativistically broadened iron line in active galactic nuclei (AGNs) and X-ray binaries, separately from warm absorbers and distant reflectors, to constrain the BH spin. We need high spectral resolution in order to look at structure and motion of plasma near the BH and across the galaxy. We also need a large sample of sources to determine the distribution of spins and so understand their accretion history through cosmic time, and therefore increased sensitivity and field of view.
2. *Hot baryons and the evolution of galaxies and large-scale structure*. We need high spatial resolution to excise point sources from maps of the hot gas in galaxies and low-brightness groups and extremely low brightness cosmic filaments. We also need large effective area to gather enough photons to study the feedback from galaxies into the primordial gas detecting metals in the circumgalactic medium. For galaxy clusters, large effective area is required to collect enough photons for gas velocity measurements in small angular regions; high angular resolution is required to excise point sources and cold fronts, when mapping the gas velocity field. High spectral resolution is needed for diagnosing physical conditions both in emission and absorption.
3. *The ISM in the Milky Way and other galaxies*. To study the dust composition, we need large area and angular resolution at low energies (< 2 keV) to resolve and identify absorption features. Large areas and high angular resolution are needed to study the phases of the ISM in the thick disk of the Milky Way, avoiding faint stellar emission.
4. *Neutron stars as extreme physics laboratories.* We need the sensitivity to detect more neutron stars and measure their spectra. We need to spatially resolve them from other sources in globular clusters. We also need photons and high spectral resolution to measure the photosphere expansion with X-ray emission lines and neutron-star cooling curves.
5. *Stellar birth and death.* YSOs without disks can only be found in X-rays. We need the sensitivity and effective area of the Surveyor in order to resolve stellar sources in dense clusters and increase sample size. Sensitivity and spectral resolution are required for study of supernova spectra and light curves. We need spatial and spectral resolution and sensitivity to study supernova remnant dynamics and composition, and for finding compact objects.
6. *The environment of stars and planets.* High spatial resolution is needed to avoid confusion in crowded stellar clusters. Stars are faint, so large area is needed to study more distant and/or fainter systems.
7. *Plasma physics.* What is the microphysics of astrophysical plasmas (especially high gas/magnetic energy density plasmas and phenomena associated with particle acceleration)? What processes accelerate cosmic rays in galaxy

clusters and SNR? What can we teach plasma physicists based observations of astrophysical plasmas by taking advantage of the parameter space inaccessible for laboratory and in-situ studies? We need angular resolution and area to resolve the dissipation scale of turbulence in galaxy clusters and the structure of shock fronts in clusters and SNR. High spectral resolution (1 eV) is needed to map the line profiles and to detect satellite lines for diagnosing non-Maxwellian plasma.

### 3.3 *What precursor observations and/or theoretical calculations can be made, at any wavelength, that would either help define the parameters of the X-ray Surveyor or provide inputs for its observing programs*?

All of the questions could benefit from precursor observations to better define the samples for *X-ray Surveyor* studies, as shown in Table A2. The observations mentioned in the discussion cover the entire wavelength range, from radio to X-rays, and involve a suite of existing and planned observatories across the full electromagnetic spectrum. SKA, ALMA, JWST, *Chandra*, ASTRO-H, eROSITA were all cited.

On the theoretical side, advanced simulations of galaxy and black hole formation and evolution, space plasmas, neutron star environments, and supernovae are needed to focus some of the science questions that *X-ray Surveyor* will explore. Both theory and laboratory work is needed to produce accurate plasma emission and absorption models that match the data quality from *X-ray Surveyor*.

### 3.4 *What modest changes to the X-ray Surveyor requirements could have a large pay-off in answering the science questions*?

There were a number of suggestions where changes in *X-ray Surveyor* capability, as currently envisioned, could have valuable pay-off (Table A3). The most mentioned were: *larger area, higher overall spatial resolution, smaller calorimeter pixels, larger field of view with high angular resolution, higher energy coverage, long mission lifetime, low background* (e.g. via orbit choice), *agility*, i.e. the capability to slew fast between targets, and *dithering* allows the full angular resolution of the mirror to be exploited, as shown with *Chandra* subpixel imaging and with the *Hubble* “multidrizzle” technique. A large field of regard was not called out, but may be implicit in the ToO observations.

Soft band area increase in the calorimeter to obtain high resolution spectral imaging would be most useful for studying cool phases of the ISM (dust and gas), stellar life cycles and galaxy halos, including the circumgalactic medium. Improvements in the spatial resolution (by a factor of ~ 2) would be useful to resolve smaller structures in the ICM that compare to the scale of the Coulomb mean free path in clusters at moderate distances. Extending the energy range up to at least 20 keV will help resolve the Fe edge features by providing a better continuum reference. A high count rate capability for high-resolution spectra would be useful for studying the ISM in absorption and for neutron-star spectra.

This list is certainly not intended to be exclusive or definitive. Polarimeters, for example, were mentioned several times but did not make it to the final list. In addition, one of the discussion groups suggested a "bonus idea" – using 1 year of *X-ray Surveyor* to carry out a wide field, even all-sky, survey.

Table 2: Desiderata derived from selected science questions.

| |
|---|
| *Study of galaxy formation and of the nature of feedback:* |
| • Gratings area and spectral resolution for absorption lines from the CGM. |
| • Large calorimeter area to look for CGM in emission. |
| • Angular resolution to resolve the galactic cores. Angular resolution <1"will resolve Bondi radii in nearby supermassive BHs such as M87, Sgr A* |
| • Mission length should allow ~1 Ms exposures. |
| • Background rejection for the calorimeter imager to study CGM in emission. |
| • Smaller PSF-matched pixels in the calorimeter to study AGN outflows. |
| *Study of the first BHs and their evolution:* |
| • Large area to detect first BHs; angular resolution reduce the confusion limit to have photon limited sensitivity for multi-Msec exposures. |
| • Large grasp with 1"resolution to find high-z AGN. |
| • Ability to respond fast to high-z GRB. |
| • Better angular resolution to further reduce the confusion limit for high-z sources. |
| • FOV of imager covering all of the 1" resolution area of the telescope. |
| *Determination of the NS equation of state:* |
| • Angular resolution to isolate pulsars in globular clusters. |
| • Spectral resolution and area to look for absorption edges. |
| • High rates of data transfer and timing resolution. |
| *Study of astrophysical plasmas:* |
| • Angular resolution and area to derive a detailed power spectrum of turbulence in galaxy clusters and detect its dissipation scale. |
| • 0.25" resolution will allow to resolve cosmic ray precursor to forward shocks in SNR (SN1006 is best candidate), plus larger area to do it in <1 Ms. |
| • High spectral resolution (1 eV) to map the line profiles and to detect satellite lines for diagnosing non-Maxwellian plasma. |
| • Larger FOV of the calorimeter (large number of angular resolution elements per FOV) and imager to reduce "cosmic variance" uncertainty in measurements of turbulence power spectra in galaxy clusters. |
| • Lower detector background to extend plasma studies into cluster outskirts. |
| • Good pixel-to-pixel calibration of the calorimeter to reduce uncertainty on small-scale turbulent power. |
| *X-ray diagnostic of solid-state baryons:* |
| • High spectral resolution to study the near-edge X-ray absorption fine structure. |
| • Large area and angular resolution if want to extend the study to other galaxies. |
| • Deep gratings observations of bright X-ray binaries with $N_H>10^{22}$ to look for hints of those spectral features. |
| • Lab measurements of the relevant edges (e.g., Fe L edges are poorly measured). |

Detailed examples of these requirements are given in Table 2. All the suggested improvements are summarized in Table A3. Clearly these options need study to turn them into quantitative goals to fold into mission design considerations.

## 4. CONCLUSIONS

The X-ray Vision workshop produced a wealth of potential science investigations that *X-ray Surveyor* can perform spanning virtually all of astrophysics. The brainstorming session described here was an effective means of pulling together many of these into larger themes and exploring how we can prepare for *X-ray Surveyor* with astronomical observations, theory and laboratory measurements. Despite the rich suite of observations proposed it was noted that jumps of this magnitude in capability lead to unexpected discoveries. Past precedents in X-ray astronomy go back to UHURU, though all fields of astrophysics find the same (e.g. ISM[12]). A series of performance enhancements were proposed; these will need further study to hone them into quantitative goals for the mission.

Clearly this session, and the entire workshop, was just a first step in preparing for the scientific cornucopia of *X-ray Surveyor*. This paper is not an official statement of anything, certainly not of the full *X-ray Surveyor* case. Far more details of some of the science of *X-ray Surveyor* is given in the talks that are available on the web site. Rather it is hoped that this paper will stimulate further thinking and discussion about the *X-ray Surveyor* mission concept.

We thank Jackie Faherty for her energetic guidance and help in organizing this brainstorming session, as well as the X-ray Vision organizers, especially Alexei Vikhlinin and Jessica Gaskin, the workshop co-hosts. We thank Marshall Space Flight Center and the Smithsonian Institution for their generous support.

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[12] See, e.g., preface to "*New Perspectives on the Interstellar Medium*", ASP Conference Series 168, Edited by A. R. Taylor, T. L. Landecker, and G. Joncas. Astronomical Society of the Pacific (San Francisco), ISBN: 1-886733-89-9 (1999).

APPENDIX: Tables

Table A1: Science Questions and how they utilize X-ray Surveyor Capabilities.

| SCIENCE | | X-RAY SURVEYOR CAPABILITY | | | | | | |
|---|---|---|---|---|---|---|---|---|
| THEME | QUESTION | AREA | ANG. RES. | TIMING | SI DETECTOR | CALORIMETER | GRATING | FIELD OF VIEW |
| BLACK HOLES (BH) | 1. How fast do BH spin? | ✔ | | | | ✔ | | |
| | 2. What is the evolution of spin of BH with redshift? | ✔ | ✔ | | ✔ | ✔ | | ✔ |
| | 3. What is the role of BHs in Feedback? | ✔ | ✔ | ✔ | | ✔ | ✔ | ✔ |
| | 4. How do BH and Large Scale Structure and Galaxies co-evolve? | ✔ | ✔ | | ✔ | ✔ | ✔ | |
| | 5. When did the first BH form? At what mass? | ✔ | ✔ | | ✔ | | | ✔ |
| | 6. What is the role of supermassive BH in the universe? | ✔ | ✔ | | ✔ | | | ✔ |
| | 7. How and When did the first supermassive BH grow? | ✔ | ✔ | | ✔ | | | |
| | 8. How does the central engine of AGN work? | ✔ | ✔ | ✔ | | | ✔ | |
| HOT BARYONS | 9. What are the elemental abundances of hot baryons? (SNR, ISM…) | ✔ | ✔ | | | ✔ | ✔ | |
| | 10. What is the baryon fraction and metallicity of galaxy haloes? How do they relate to the host galaxies? How do they evolve with redshift? | ✔ | ✔ | | | ✔ | ✔ | |
| | 11. How did cosmic structure evolve? (filaments) | ✔ | ✔ | | ✔ | ✔ | | ✔ |
| | 12. What is the physics of hot baryons? What is the origin and fate of baryons above the virial temperature | ✔ | ✔ | | ✔ | ✔ | ✔ | ✔ |
| | 13. Where does the gas in the hot IGM originate and how does it get there? | ✔ | ✔ | | ✔ | ✔ | ✔ | ✔ |
| | 14. How does feedback heat and enrich gas around galaxies? (CGM and IGM) | ✔ | ✔ | | | ✔ | ✔ | |
| | 15. What are the physical processes governing the hot baryons in relation to galaxy formation? | ✔ | ✔ | | ✔ | | | |
| | 16. How do studies of the ICM tell us about cluster feedback and evolution? | ✔ | ✔ | | ✔ | ✔ | ✔ | ✔ |

Table A1 - continued

| Science | | X-ray Surveyor Capability | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Theme | Question | Area | Ang. Res. | Timing | Si detector | Calorimeter | Grating | Field of view |
| Neutron Stars | 17. What is the equation-of-state of neutron stars? (What is their mass and radius?) | ✔ | ✔ | ✔ | ✔ | | ✔ | |
| | 18. What is the electromagnetic signature of neutron star mergers? | ✔ | ✔ | ✔ | ✔ | | | |
| | 19. How can compact objects be used as probes of the laws of physics under extreme conditions? (Includes BH.) | ✔ | ✔ | ✔ | | ✔ | ✔ | |
| Stars and Planetary Systems | 20. What drives the life cycle of stars from formation to stellar death? | ✔ | ✔ | | | ✔ | ✔ | |
| | 21. What is the origin and nature of energetic photon and particle radiation from stars and how does it affect their planetary system environment? | ✔ | ✔ | | ✔ | | | ✔ |
| | 22. What is the composition of cosmic dust? Diagnostics of solid-state baryons | ✔ | ✔ | | | | ✔ | |
| | 23. What is the nature of the ISM at all temperatures and phases? | ✔ | ✔ | | | ✔ | ✔ | |
| Plasma Physics | 24. What is the microphysics of astrophysical plasmas? | ✔ | ✔ | | | ✔ | ✔ | |
| | 25. What can X-ray astrophysics teach plasma physicists? | ✔ | ✔ | | ✔ | ✔ | ✔ | ✔ |
| | 26. How does the ICM inform us about fundamental plasma physics? | ✔ | ✔ | | | ✔ | | |

Table A2: Precursor Observations.

| THEME | QUESTION | PRECURSOR OBSERVATIONS |
|---|---|---|
| BLACK HOLES (BH) | 1. How fast do BH spin? | ASTRO-H AGN Fe-line |
| | 2. What is the evolution of spin of BH with redshift? | ASTRO-H AGN Fe-line |
| | 3. What is the role of BHs in Feedback? | ***Chandra*** imaging of AGN circum-nuclear regions |
| | 4. How do BH and Large Scale Structure and Galaxies co-evolve? | ***Chandra*** AGN imaging |
| | 5. When did the first BH form? At what mass? | 21cm Reionization surveys (e.g. MWA)<br>JWST UV Lum.fn.<br>eROSITA to find high z AGN<br>CCAT (or similar) to find z~10 AGN |
| | 6. What is the role of supermassive BH in the universe? | |
| | 7. How and When did the first supermassive BH grow? | eROSITA<br>JWST high z IR galaxies |
| | 8. How does the central engine of AGN work? | ALMA/VLBI Imaging of AGN (jets etc.)<br>Ultra-Deep ***Chandra*** grating obs. of AGN |
| HOT BARYONS | 9. What are the elemental abundances of hot baryons? (SNR, ISM…) | Lab X-sections of high ionization species<br>Plasma emission codes<br>3D modeling of SN explosions<br>Deep Chandra SNR observations<br>ALMA SNR survey |
| | 10. What is the baryon fraction and metallicity of galaxy haloes? How do they relate to the host galaxies? How do they evolve with redshift? | All-sky Surveys: X-ray (eRosita), radio, mm/SZ. |
| | 11. How did cosmic structure evolve? (filaments) | eROSITA to find AGNs, clusters<br>Low surface brightness radio; SZ<br>JWST galaxies at high z |
| | 12. What is the physics of hot baryons? What is the origin and fate of baryons above the virial temperature? | Lab X-sections of high ionization species<br>Plasma emission codes<br>All-sky Surveys: X-ray (SRG/eROSITA), radio, mm/SZ.<br>JWST, ALMA surveys of galaxies,<br>***Chandra*** 50Msec survey of deep fields |
| | 13. Where does the gas in the hot IGM originate and how does it get there? | Deep ***Chandra*** gratings obs on a selected background quasar. |
| | 14. How does feedback heat and enrich gas around galaxies? (CGM and IGM) | UV absorption spectra to find candidates for X-ray abs lines.<br>ALMA for mol. Gas in cluster cores.<br>SKA for sub-Bondi imaging |

Table A2 - continued

| THEME | QUESTION | PRECURSOR OBSERVATIONS |
|---|---|---|
| | 15. What are the physical processes governing the hot baryons in relation to galaxy formation? | Inclusion of more small scale physics in galaxy-formation large-scale simulations. Laboratory measurements for thermal models (e.g. APEC). |
| | 16. How do studies of the ICM tell us about cluster feedback and evolution? | UV absorption spectra to find candidates for X-ray abs lines.<br>ALMA for mol. Gas in cluster cores.<br>SKA for sub-Bondi imaging |
| NEUTRON STARS | 17. What is the equation-of-state of neutron stars? (What is their mass and radius?) | Very accurate distances to neutron stars to know their radii from GAIA distance ladder. |
| | 18. What is the electromagnetic signature of neutron star mergers? | A-LIGO detections of gravitational waves |
| | 19. How can compact objects be used as probes of the laws of physics under extreme conditions? (Includes BH.) | ASTRO-H to find targets. |
| STARS AND PLANETARY SYSTEMS | 20. What drives the life cycle of stars from formation to stellar death? | Characterize the stellar populations across Milky Way disk: ***Chandra***, JWST, 30-meter ground-based telescopes. |
| | 21. What is the origin and nature of energetic photon and particle radiation from stars and how does it affect their planetary system environment? | Infrared and CO maps to explore dust in X-ray binary sight lines and outflows (esp. ALMA) |
| | 22. What is the composition of cosmic dust? Diagnostics of solid-state baryons | Deep gratings observations of bright X-ray binaries with $N_H > 10^{22}$ $cm^{-2}$ to look for hints of those spectral features.<br>Lab measurements of the relevant edges (e.g., Fe L edges are poorly measured). |
| | 23. What is the nature of the ISM at all temperatures and phases? | ***Chandra*** grating obs. of Galaxy ISM in absorption.<br>Multi-wavelength imaging follow-up. |
| PLASMA PHYSICS | 24. What is the microphysics of astrophysical plasmas? | ASTRO-H constraints on turbulence power spectrum in clusters near driving scale;<br>***Chandra*** studies of density fluctuations around Coulomb mean free path.<br>ASTRO-H detection of anomalous satellite lines, ionization in clusters: are non-Maxwellian plasmas widespread? |
| | 25. What can X-ray astrophysics teach plasma physicists? | |
| | 26. How does the ICM inform us about fundamental plasma physics? | |

Table A3: Suggested enhancements.

| Scientific Pursuit | | X-ray Surveyor Capability | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Theme | Question | Area | Ang. Res. | Timing | Si detector | Calorimeter | Grating | Field of view | Other |
| Black Holes | 1. How fast to BH spin? | | | | | | | | E>10 keV |
| | 2. What is the evolution of spin of BHs with redshift? | | + | | | simul[1] | | | |
| | 3. What is the role of BHs in Feedback? | | | | | Small[4] | | | E>20keV |
| | 4. How do BH and Large Scale Structure and Galaxies co-evolve? | | + | | | simul[1] | | | |
| | 5. When did the first BH form? At what mass? | | + | | | | | + | |
| | 6. What is the role of supermassive BH in the universe? | | | | | | | + | Long lifetime |
| | 7. How and When did the first supermassive BH grow? | | | | | | | + | E>10keV[2] |
| | 8. How does the central engine of AGN work? | | + | | | | | | |
| Hot Baryons | 9. What are the elemental abundances of hot baryons? (SNR, ISM, IGM) | + [3] | + | | | | | | |
| | 10. What is the baryon fraction and metallicity of galaxy haloes? How do they relate to the host galaxies? How do they evolve with redshift? | + [2] | | | | | | | |
| | 11. How did cosmic structure evolve? (filaments) | | | | | | | | Low background[6] |
| | 12. What is the physics of hot baryons? What is the origin and fate of baryons above the virial temperature? | + | + [5] | | | Small pix[4] | | | |
| | 13. Where does the gas in the hot IGM originate and how does it get there? | | | | | | | | |
| | 14. How does feedback heat and enrich gas around galaxies? (CGM and IGM) | | + | | | | | | Long lifetime |

1. Simultaneous observations with calorimeter and gratings for high R at all energies [TBC].
2. Use coatings, e.g. carbon?
3. Enhanced low E area in calorimeter.
4. Smaller pixels in calorimeter.
5. 0.1 arcsec. E.g. via subaperture imaging.
6. E.g. via choice of orbit.

Table A3 - continued

| SCIENTIFIC PURSUIT | | X-RAY SURVEYOR CAPABILITY | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| THEME | QUESTION | AREA | ANG. RES. | TIMING | SI DETECTOR | CALORIMETER | GRATING | FIELD OF VIEW | OTHER |
| | 15. What are the physical processes governing the hot baryons in relation to galaxy formation? | | | | | | | | Low background<br>Long lifetime |
| | 16. How do studies of the ICM tell us about cluster feedback and evolution? | | +[8] | | | | | | |
| NEUTRON STARS | 17. What is the equation-of-state of neutron stars? (What is their mass and radius?) | + | +[7] | + | | + | | + | Low background<br>Agility[9] |
| | 18. What is the electromagnetic signature of neutron star mergers? | | | | | | | + | Agility[9] |
| | 19. How can compact objects be used as probes of the laws of physics under extreme conditions? (Includes BH.) | | | +[10] | | Small pix[4] | +[10] | | Agility[9]<br>Calibration<br>Polarimeter<br>Long lifetime |
| STARS AND PLANETARY SYSTEMS | 20. What drives the life cycle of stars from formation to stellar death? | | | | | +[3] | | | |
| | 21. What is the origin of stars energetic photon and particle radiation and how does it affect their planetary system environment? | | | | | | | | UV monitor<br>Long lifetime |
| | 22. What is the composition of cosmic dust? Diagnostics of solid-state baryons | | | | | | +[11] | | |
| | 23. What is the nature of the ISM at all temperatures and phases? | | | | | | +[11] | | |
| PLASMA PHYSICS | 24. What is the microphysics of astrophysical plasmas? | | +[8] | | | | | | |
| | 25. What can X-ray astrophysics teach plasma physicists? | | | | | Small pix[4] | | | Sub-eV ΔE in Calorimeter |
| | 26. How does the ICM inform us about fundamental plasma physics? | | | | | | | | |
| NEW | 27. Large area 1 year survey | + | | + | | | | | Agility[9],<br>Dithering<br>Rapid mosaic. |

7. At low energies.
8. 0.25 arcsec to: resolve dissipation scale of turbulence in galaxy clusters (#16), to resolve crowded fields in globular clusters (#17), resolve the cosmic ray precursor in SNR forward shocks (#24).
9. Agility = rapid ToO response; rapid slew and settle.
10. Sub-millisecond timing.
11. High count rate capability.

Table A4: Acronyms and terms used in the text

| Acronym | Meaning |
|---|---|
| AGN | Active Galactic Nucleus |
| ALMA | Atacama Large Millimeter Array. http://www.almaobservatory.org |
| A-LIGO | Advanced-Laser Interferometer Gravitational-wave Observatory. https://www.advancedligo.mit.edu |
| ASTRO-H | Japanese-US X-ray spectroscopy mission (from 2016). http://astro-h.isas.jaxa.jp/en/ |
| BH | Black Hole |
| CCAT | Cerro Chajnator Atacama Telescope. A mm-band survey telescope. https://www.ccatobservatory.org |
| CGM | Circum-Galactic Medium |
| eROSITA | X-ray sky survey experiment on *Spektrum Roentgen-Gamma* http://www.mpe.mpg.de/eROSITA |
| FOV | Field of View |
| GRB | Gamma-ray Burst |
| IGM | Intergalactic Medium |
| ISM | Interstellar Medium |
| JWST | *James Webb Space Telescope*. Optical-infrared 6.5m telescope (from 2018). http://www.jwst.nasa.gov |
| MWA | Murchison Widefield Array. Low frequency radio telescope. http://www.mwatelescope.org |
| NICER | Neutron star Interior Composition Explorer. X-ray timing experiment on the ISS (from 2016), https://heasarc.gsfc.nasa.gov/docs/nicer/ |
| NS | Neutron Star |
| SKA | Square Kilometer Array. Large radio telescope (from ~2020) https://www.skatelescope.org |
| SNR | Supernova Remnant |
| SZ | Sunyaev-Zel'dovich effect |