Science with the International X-ray Observatory

Andrew C. Fabian1 and the IXO Science Definition Team

1University of Cambridge, United Kingdom

Exploring The Hot Universe with IXO

The International X-ray Observatory (IXO) is a next-generation facility designed to address some of the most fundamental questions in contemporary astrophysics and cosmology:

- How do black holes grow and influence the Universe?
- How does matter behave under extreme conditions?
- How do the hot and cold components of the Universe co-evolve?
- How do galaxies and their environments become chemically enriched?

To address these questions, IXO will employ optics with 20 times more collecting area at 1 keV than any previous X-ray telescope. The facility’s new instruments will deliver up to 100-fold increases in effective area for high-resolution spectroscopy from 0.3-10 keV, deep spatial imaging from 0.2-40 keV over a wide field of view, unprecedented polarimetric sensitivity, and microradian spectroscopic timing with high count rate capability.

The Hot Universe

High-energy phenomena – particularly in the X-ray band – characterize the evolution of cosmic structures on both large and small scales. The X-ray sky is dominated by two kinds of sources: point sources such as massive black holes in galaxies, and extended sources such as clusters of galaxies and AGN. These phenomena are inexorably linked. The energy liberated by growing black holes regulates the infall of gas in galaxies and clusters, while some analogous process, still poorly understood, ties the growth of black holes in galaxies to the activities of the Sun. X-ray astronomy has played a crucial role in studying both these phenomena over the last 30 years. But what is perhaps most remarkable is the discovery, within the last 10 years (by the X-ray observatories XMM-Newton and Chandra), that these phenomena are intricately linked. The energy liberated by growing black holes regulates the infall of gas in galaxies and clusters, while some analogous process, still poorly understood, ties the growth of black holes in galaxies to the activities of the Sun.

Cosmic Feedback

X-ray observations reveal the largest bound structures in the Universe and their evolution on cosmological timescales. IXO’s unprecedented capabilities will enable us to confront the following key questions:

- How did large scale structure evolve?
- Where are the missing baryons in the nearby Universe?
- What is the nature of Dark Matter and Dark Energy?

The dominant form of baryons in clusters of galaxies is hot (T > 10⁷ K) gas, which can be probed only in X-rays. IXO’s high spectral resolution and large throughput will measure bulk motions and turbulence in an order of magnitude better than previous observations. This will allow observers to separate relaxed clusters from those that have recently undergone mergers. For relaxed clusters, high-precision X-ray measurements will enable the reliable estimation of dark energy parameters with minimal and well understood systematics in a fashion that complements other measurements and cosmological constraints.

Black Holes

The IXO has the capability to study astrophysical black holes on all scales, from the event horizon to the largest radio lobes, and from stellar mass black holes in Galactic binaries out to the most distant parts of the observable Universe. The major questions to be addressed by IXO are:

- When were the first massive black holes formed? How does accretion power in the Universe evolve, and what role does it play in the co-evolution of black holes and galaxies?

Models suggest that black holes as massive as 10⁶ M⊙ existed as early as z=11-12. IXO will discover and study these objects, the accretion light of which is rendered invisible in other wavebands due to intergalactic absorption and dilution by their host galaxy.

Sensitive X-ray observations are needed to disentangle the power associated with black hole accretion from that due to star formation. A prominent local example is NGC 4240 whose light is dominated by stellar processes in all but the X-ray band; in which dual, heavily obscured black holes in an active growth phase are revealed. The figure above shows that similar objects can be well studied by IXO and other major facilities up to z=10.

- How does matter behave close to the event horizon of a black hole? Does it obey the predictions of general relativity? Are black holes in the centers of galaxies spinning, and does that spin evolve with cosmic time?

In luminous systems, the accretion flow forms a thin disk of gas orbiting the black hole. To a very good approximation, each parcel of gas follows a circular test particle orbit. Observations of AGN with XMM-Newton have revealed evidence for “hot spots” on the disk that light up in the iron Kα line, allowing us in principle to observe their motions. In the time-energy plane, these features will appear as “arcs”, each corresponding to an orbit of a given bright region (upper left). The IXO will be the first observatory with sufficient collecting area to trace these hot spots near the event horizon on sub-orbital timescales.

In addition, IXO will revolutionize spin measurements in AGN. Measurement of the iron Kα (upper right) line yields spin measurements for hundreds of AGN including, for the first time, objects at significant cosmological distances.

To the upper right is an simulated IXO image and Fe Kα line spectra for three lines of sight through Cyg A, whose central black hole is believed to be illuminating the surrounding gas. One through the center (black curve) that demonstrates the significant turbulent and kinematic broadening of the cluster gas due to the radio jet. One through the center (blue) and one through the central (green) that clearly show the kinematic signature of the expanding shell. The western spectrum is essentially flat (blue). The blue- and red-shifted peaks in that line are clearly resolved from the cluster gas (the cluster itself has some rotation, so even the regular cluster gas is shifted from the cluster center). The energy separation between the approaching and receding wall of the cavity can be read off easily and agrees with the actual physical size of the interstellar medium. The red lines of the kinematics of the hot gas phase, which contains the bulk of the mass in the central galaxies, are only possible at X-ray wavelenghts.

Cosmic Structure

X-ray observations reveal the largest bound structures in the Universe and their evolution on cosmological timescales. IXO’s unprecedented capabilities will enable us to confront the following key questions:

- How did large scale structure evolve?
- Where are the missing baryons in the nearby Universe?
- What is the nature of Dark Matter and Dark Energy?

The dominant form of baryons in clusters of galaxies is hot (T > 10⁷ K) gas, which can be probed only in X-rays. IXO’s high spectral resolution and large throughput will measure bulk motions and turbulence in an order of magnitude better than previous observations. This will allow observers to separate relaxed clusters from those that have recently undergone mergers. For relaxed clusters, high-precision X-ray measurements will enable the reliable estimation of dark energy parameters with minimal and well understood systematics in a fashion that complements other measurements and cosmological constraints.

Sensitive X-ray observations are needed to disentangle the power associated with black hole accretion from that due to star formation. A prominent local example is NGC 4240 whose light is dominated by stellar processes in all but the X-ray band; in which dual, heavily obscured black holes in an active growth phase are revealed. The figure above shows that similar objects can be well studied by IXO and other major facilities up to z=10.

- How does matter behave close to the event horizon of a black hole? Does it obey the predictions of general relativity? Are black holes in the centers of galaxies spinning, and does that spin evolve with cosmic time?

In luminous systems, the accretion flow forms a thin disk of gas orbiting the black hole. To a very good approximation, each parcel of gas follows a circular test particle orbit. Observations of AGN with XMM-Newton have revealed evidence for “hot spots” on the disk that light up in the iron Kα line, allowing us in principle to observe their motions. In the time-energy plane, these features will appear as “arcs”, each corresponding to an orbit of a given bright region (upper left). The IXO will be the first observatory with sufficient collecting area to trace these hot spots near the event horizon on sub-orbital timescales.

In addition, IXO will revolutionize spin measurements in AGN. Measurement of the iron Kα (upper right) line yields spin measurements for hundreds of AGN including, for the first time, objects at significant cosmological distances.

Cosmic Feedback

An extraordinary recent development in astrophysics has been the realization of the close linkage between the two dominant processes producing radiation in the Universe, namely fusion in stars, and accretion onto black holes. The physical process underlying this relationship has become known as feedback, and the concept of cosmic feedback underpins many of IXO’s key goals. The great leap forward in capabilities provided by this observatory will allow us to tackle the feedback problem from several angles, to address the key underlying question:

- How did feedback from black holes influence galaxy growth?

Both mechanical and radiative forms of feedback are best studied in X-rays. The mechanical forms of feedback rely on dynamical (ram) pressure to accelerate gas to high speeds, shocking it to high temperatures where it can only be detected in X-rays. Gas accelerated by radiation pressure or radiative heating is likely to be cold and dusty. The interaction is therefore much more difficult to observe directly, although X-ray and far infrared emission can emerge from the inner regions where the interaction occurs and reveal the Active Galactic Nucleus (AGN) itself.

Thermal regulation of gas in bubbles and cluster cores

X-ray observations of gas in the bubbles of massive galaxies and the cores of galaxy clusters indicate that the energy transfer process must be subtle. The heat source—the accreting black hole—is roughly the size of the Solar System, yet the heating rate must be tuned to conditions operating over scales 10 decades larger. How the jet power, which is highly estimated to begin with, is isotropically spread to the surrounding gas is not clear. The obvious signs of heating include bubbles forming in the intracluster gas by the jets and nearby quasi-spherical shells in the X-ray emission that are interpreted as sound waves and weak shocks (e., the Chandra image of the Perseus cluster below). The spectral resolution and sensitivity of IXO are needed to study the crucial "missing" step in which the kinetic energy is converted to heat. Observations of the kinematics of the hot gas phase, which contains the bulk of the mass in the central galaxies, are only possible at X-ray wavelengths.