Science with the International X-ray Observatory

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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 question in contemporary astrophysics and cosmology:

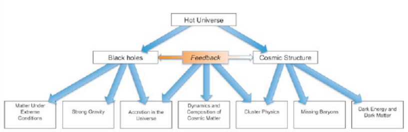
- How do black holes grow and influence the Universe?
- How does matter behave under extreme conditions?
- How do the hot and cold components of the Universe co-evolve?
- How do galaxies and their environments become chemically enriched?

To address these questions, IXO will employ optics with 20 times more collecting area at 1 keV than any previous X-ray telescope. The focal plane instruments will deliver up to **100-fold increase in effective area for high resolution spectroscopy** from 0.3-10 keV, deep spectral imaging from 0.2-40 keV over a wide field of view, unprecedented polarimetric sensitivity, and microsecond 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 source: point sources marking accreting supermassive black holes in galactic nuclei – the Schwarzschild radii of which are comparable to the size of the Solar System, a few light minutes across – and the extensive atmospheres of clusters of galaxies, often more than a million light-years across. 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 inextricably 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 hole mass to a fixed fraction of its host galaxy's bulge – a two-way connection that has come to be called "feedback". On the smallest scales, **X-rays provide the only electromagnetic spectral signatures from the regions of strong gravity near black holes and neutron stars.**

One of principal aims of the IXO will be to determine the properties and evolution of accreting black holes, the energetics and dynamics of the hot gas in large cosmic structures and the connection between these two phenomena; ie, to **understand cosmic "feedback".** This key objective, and it's interconnections, are summarized in the figure below.



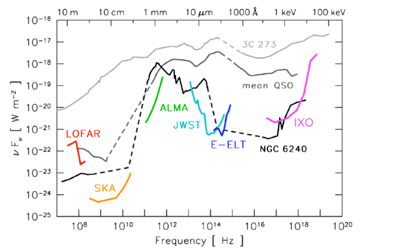
A Versatile Observatory

The IXO is a versatile observatory, optimized to make breakthrough observations in several key areas of black hole and cosmic structure physics. However, the leap in effective area and high-resolution spectroscopic capabilities will enable breakthroughs in a very wide range of astrophysics, spanning cosmic to local scales (ie, mapping the Solar wind via charge exchange on comets and planets). IXO is crucial to the advancement of astrophysical knowledge and has been designed to be complementary to the next generation of observatories such as ALMA, LSST, JWST, and 30m ground based telescopes. Modern astrophysics is panchromatic and many of the data sets obtained by these new observatories will require IXO data to produce the highest quality science.

Black Holes

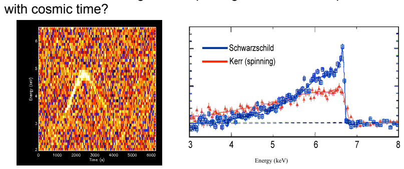
The IXO has the capability to study astrophysical black holes on all scales, from the event horizon to the largest radio lobes, and from stellar mass black holes in Galactic binaries out to the most distant parts of the observable Universe. The major questions to be addressed by IXO are:

- **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 10^6 M existed as early as z=10–11. 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 6240 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 future 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?



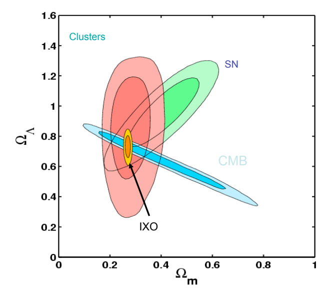
- In luminous systems, the accretion flow forms a thin disk of gas orbiting the black hole. To a very good approximation, each parcel of gas follows a circular test particle orbit. Observations of AGN with XMM-Newton have revealed evidence for "hot spots" on the disk that light up in the iron Kα line, 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 broad iron Kα (upper right) lines will yield spin measurements for hundreds of AGN including, for the first time, objects at significant cosmological distances.

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 > 10^7 K) gas, which can be probed only in X-rays. IXO's high spectral resolution and large throughput will measure bulk motions and turbulence an order of magnitude better than previous observatories. 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



Shown above are dark energy and matter constraints from current work, and in yellow and orange the **factor of 10 improvement** in those constraints that will be made with the IXO. Below is a Chandra image of the cluster Abell 2029, which is representative of the sort of hot, dynamically relaxed clusters that will be observed for this work.

Cosmic Feedback

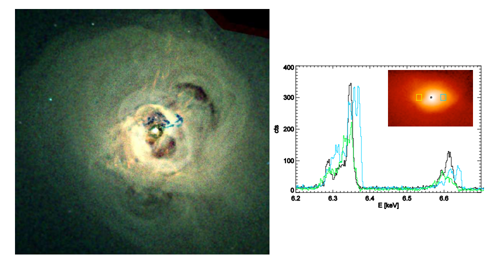
An extraordinary recent development in astrophysics has been the realization of the close linkage between the two dominant processes producing radiation in the Universe, namely fusion in stars, and accretion onto black holes. The physical process underpinning this relationship has become known as feedback, 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 attack 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 bulges and cluster cores

X-ray observations of gas in the bulges 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 collimated to begin with, is isotropically spread to the surrounding gas is not clear. The obvious signs of heating include bubbles blown in the intracluster gas by the jets and nearly quasi-spherical ripples in the X-ray emission that are interpreted as sound waves and weak shocks (ie, 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 bulk kinetic energy is converted to heat. **Observations of the kinematics of the hot gas phase, which contains the bulk of the mass in elliptical galaxies, are only possible at X-ray wavelengths.**



To the upper right is an simulated IXO image and Fe K-alpha spectra for three lines of sight through Cyg A, whose central black hole is blowing cavities in 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 galaxy going off, and two through the cavities (blue and green) that clearly show the kinematic signature of the expanding shell. The western spectrum is especially clear (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 line of sight velocity of the gas of 700 km/s relative to the cluster gas. The regions that the spectra were extracted from are shown in the inset, which is simply the 6.2-6.8 keV image the IXO would observe of Cygnus A.