How does cosmic feedback work and influence galaxy formation?

All large galaxies appear to have a massive black hole at their center. The mass of the black hole is about 0.2% of the mass of the galaxy's bulge. It is now widely considered that the black hole has brought this about by regulating the amount of gas available for star formation in the galaxy. Massive black holes thereby have a profound influence on the evolution of galaxies, and possibly on their formation.

The relative size of a black hole to a galaxy is roughly in the same ratio as a person is to the Earth. Something very small is determining the growth of something very large. This is possible because the gravitational potential well of a black hole is a million times deeper than that of a galaxy (the square of the ratio of the velocity of matter falling into the black hole, 300,000 km/s, to the typical velocity of stars in a galaxy of 300 km/s). As a black hole grows in mass through accreting matter it also releases energy at a level of nearly 100 times the gravitational binding energy of its host galaxy. How much of the energy released actually interacts with the matter in a galaxy is the key question for the evolution of the galaxy. The enormous scales involved mean that it is not straightforward to compute an answer. If the energy is in electromagnetic radiation and the matter is just stars, then very little interaction is possible, but if the matter is dusty gas so that radiation is easily absorbed, or the energy is in mechanical motions in the form of winds or jets then the interaction is considerable and the gas can be driven out of the galaxy.

Observations of feedback from a central black hole on its host galaxy are difficult and depend upon the nature of the gas present. If the gas is highly ionized and at the virial temperature of the galaxy, then it is little affected by radiation but is highly susceptible to jets and winds. X-ray observations are the only direct way to see the gas and how it reacts to the black hole.

Key observational questions regarding feedback include:

- How does energy flow in and around massive elliptical galaxies in groups and clusters?
- How much mass and energy flows out from AGN?

Constraining the dynamics of the gas in clusters is crucial to addressing the first question. IXO's high throughput and high spectral resolution will improve by an order of magnitude measurements of the gas outflow and turbulent velocities. IXO will measure and map the cluster gas velocity field to an accuracy of tens of km/s, revealing how the mechanical energy is dissipated. Observations of the kinematics of the hot gas phase, which contains the bulk of the mass in elliptical galaxies, are only possible in the X-ray band.

Further, IXO observations will sample time variability on shorter timescales than previously accessible and thus probe infalling and outflowing gas near black holes. Both interstellar and intergalactic components can be studied with IXO, including million-degree, collisionally excited plasma or ten-thousand degree photo-ionized gas. For example, IXO will be sensitive to all ionization states from Fe I–Fe XXVI.

How the jet's power, which is highly collimated to begin with, is isotropically communicated to the surrounding gas is not understood. Quasi-spherical shocks and sound waves carrying about the right energy flux are found in the nearest and brightest clusters. Evidence that the jets precess is found in others.

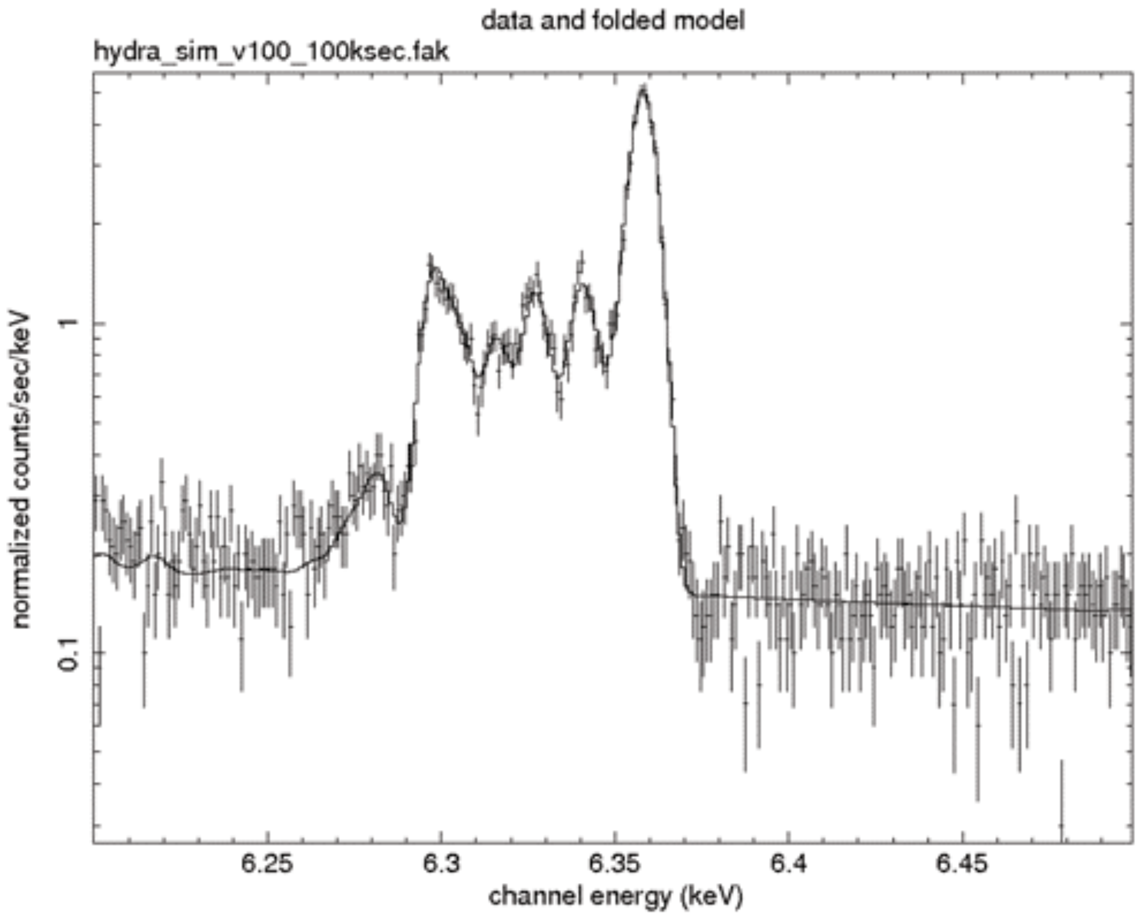

Figure 1. Predicted IXO calorimeter spectra from a 100 ksec observation of Hydra A in an annulus from 100—150 kpc. Only the He-like Fe-Kα portion of the spectrum is shown and includes 100 km/s turbulence.

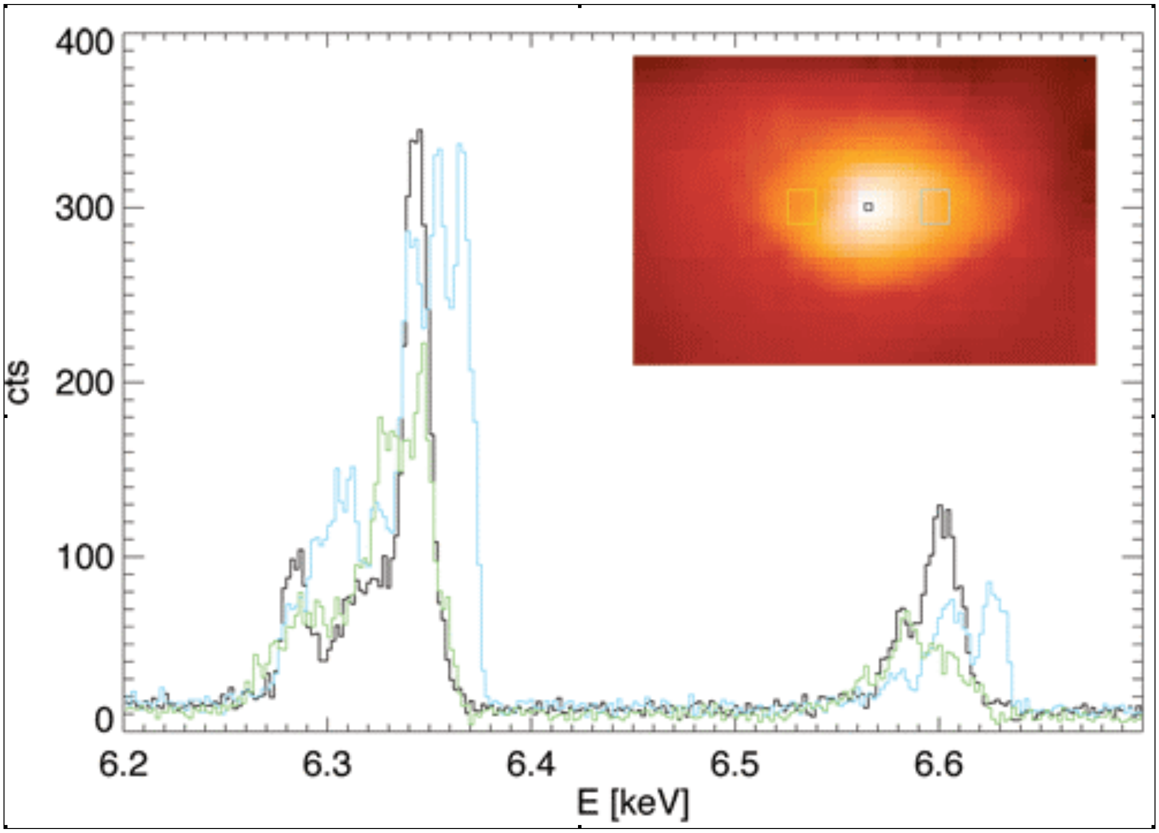

Figure 2. Fe Kα spectra for three lines of sight through Cyg A (the simulated version): One through the center (black curve) that demonstrates the significant turbulent and kinematic broadening of the cluster gas due to the radio galaxy going off, and two through the cavities (blue and green) that clearly 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 IXO would observe of Cygnus A. The simulation is now calibrated against the Chandra flux (it turns out that the numerical simulation was almost perfectly consistent with the observed flux, so no re-normalization of the density was necessary). It uses the appropriate red-shift and hydrogen column. The exposure time was 250 ksec.