1. INTRODUCTION

One of the surprising legacies of the Chandra era is the discovery of X-ray cavities in virtually every cool-core galaxy cluster (e.g., Birzan et al. 2004; Allen et al. 2006). This led to the suggestion that active galactic nucleus (AGN) heating is responsible for halting the cooling in clusters and keeping cooling flows from actually reaching star-forming temperatures.

The discovery of the cavities allowed estimating the kinetic power of a large sample of radio galaxies, to within about an order of magnitude. The remaining uncertainties result from the fact that the cavity age cannot be determined from imaging studies alone. A range of age estimators have been used in the literature, ranging from the sound crossing time to the buoyant rise time (e.g., McNamara et al. 2000; Fabian et al. 2000; Churazov et al. 2001). Additionally, the orientation of the cavities relative to the line of sight cannot be determined from imaging observations alone, leading to an additional uncertainty in cavity size and age (e.g., Enßlin & Heinz 2002).

Thus, while it is now generally accepted that AGN can release enough energy in principle to heat clusters, the ratio of the energy released by AGN to the heat lost from the cluster gas via cooling is rather uncertain and could be close to unity. Such a low value would put an unrealistically tight constraint on any dissipation mechanism that transfers AGN energy into cluster heat. At the same time, we are still lacking direct evidence for AGN heating in the form of X-ray emission measure maps that show entropy injection around or in the wake of a cavity.

To unambiguously determine the cavity ages, a quantitative spectroscopic approach is necessary: measuring expansion velocities directly will eliminate the ambiguities in guessing the age. Unfortunately, neither Chandra nor XMM-Newton have the high spectral resolution and throughput required for these observations. They further lack the throughput and spectral resolution to map out direct signatures of heating in the temperature and entropy distribution of the cluster gas.

The requirements to solve the outstanding problems in cluster feedback posed by Chandra should be one of the benchmarks for future large X-ray missions, such as the International X-ray Observatory (IXO). We will use the current specifications of IXO in this paper to derive detailed, quantitative predictions for the X-ray signatures of actively jet-driven, expanding X-ray cavities. We find that the observations required to solve the age problem will be feasible with a telescope with specs similar to those envisioned for IXO.

The organization of this paper is as follows: in Section 2, we describe the methods employed in the simulations presented in Section 3, while Section 4 discusses the observational signatures and caveats, and Section 5 presents our conclusions. For reference, we list the current specifications of IXO in the Appendix. Throughout this paper, we use concordance cosmological parameters of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ and cluster metallicities of 0.5 relative to solar.

2. SIMULATIONS

Arguably the most powerful way to make detailed, quantitative observational predictions of complex emitting systems like clusters (which contain gas at different temperatures, densities, velocities, etc.) is by constructing dedicated numerical simulations. This is the avenue chosen in this paper: we ran a series of hydrodynamic simulations of jets in galaxy clusters and then virtually observing them with X-ray telescopes (Chandra and IXO) to study the observational signatures of feedback. Before presenting our results, we will describe the method and initial conditions used.

2.1. Numerical Scheme and Code Description

We use the publicly available FLASH code (Fryxell et al. 2000), which is a modular block-structured adaptive mesh refinement code. It solves the Riemann problem on a Cartesian...
grid using the piecewise parabolic method. Our simulation includes $7 \times 10^5$ dark matter particles. The particles are advanced using a cosmological variable time step leapfrog method. Gravity is computed by solving Poisson’s equation with a multigrid method using isolated boundary conditions.

The size of the computational grid is 2.9 Mpc on a side with a maximum resolution of 174 pc (in our simulations of Cygnus A and Hydra A) and 87 pc (for our simulation of Perseus A), corresponding to a maximum dynamic range of roughly 17,000 and 33,000, respectively. We reserve the highest levels of refinement to the cluster center in a cylindrical region around the jet nozzle in order to resolve the jet injection region and at the same time make the problem computationally feasible.

We inject back-to-back supersonic jets by placing a cylindrical inflow boundary (the “jet nozzle”) into the grid, with fluxes set to the specified jet parameters. This approach eliminates the problem of mass entrainment into the jet, allowing us to cleanly separate the jet and cluster fluids. The location of the “jet nozzle” tracks the dynamical center of the cluster potential. The jets are injected with a velocity of $0.1c$ and an internal Mach number of 37, but varying density (or, in practice, jet cross section) to achieve the desired jet power and thrust. Both the jet fluid and the cluster fluid are assumed to follow an adiabatic equation of state with $\gamma = 5/3$.

In order to reproduce the observed morphologies of radio lobes we impose a sub-grid jitter on the jet axis, confined to a 20’ opening angle and modeled as a random walk in angle. This is known as the “dentist drill effect” (Scheuer 1982) and results in simulated radio lobes with correct aspect ratios of a few (rather than the narrow cocoons often produced in simulations of jets along a fixed axis).

### 2.2. Initial Conditions

We use the S2 galaxy cluster from Springel et al. (2001) as our initial conditions. This is a cosmologically evolved rich cluster with a mass of $M \sim 10^{15} M_\odot$, originally simulated with FLASH (a Lagrangian SPH code Springel et al. 2001). We imported the cluster at redshift $z = 0$ as our initial conditions into FLASH and evolved the cluster for several dynamical times to eliminate any possible transients induced by re-gridding particle data onto our Cartesian mesh before setting off the jet. It is worth noting that this does not affect the level of turbulence present in the simulation (see Section 4.3), which stays roughly constant throughout the initial evolution until it is significantly increased in the wake of the expanding jet. The density of the S2 cluster is appropriate for all the clusters presented in this paper. The temperature profile is appropriate for our simulations of Cygnus A and Hydra A, but we had to adjust the temperature normalization for our simulations of the Perseus cluster, which has a moderately lower temperature.

Because the cluster is fully cosmologically evolved, our simulations incorporate a realistic level of density and temperature sub-structure, as well as a realistic cluster velocity field, including turbulence. We did not, however, include a sub-grid turbulence model in either the simulation (such as employed by Scannapieco & Brüggen 2008) or the virtual observation (see Section 4.3 for further discussion) since we believe that the level of turbulence present is sufficient to represent a realistic cluster velocity field.

### 2.3. XIM: A Virtual Observatory

The simulation output was virtually observed using the publicly available in-house tool XIM (see Heinz & Brüggen 2009). Taking input grids from numerical hydrodynamic simulations, XIM performs spectral modeling of thermal emission, including Doppler shifts and ionization balance, using the APEC database to model the line emission. It then performs spectral projection along an arbitrary line of sight, point-spread function (PSF) convolution, telescope and detector efficiency, and spectral convolution with the detector response (using the proper response files for current and future telescopes). Finally, it adds sky and instrument backgrounds and Poisson counting error.

The code currently does not account for vignetting and uses a simplified mono-energetic PSF in the case of IXO simulations. However, the impact of these limitations on the predictions presented below should be small.

#### 2.4. Fe xxv as a Kinematic Tracer

In this paper, we concentrate on the $\text{K}\alpha$ line from helium-like iron Fe xxv. This line complex is very luminous in the intra-cluster gas and because of the large mass of Fe relative to other abundant species, it is an excellent kinematic tracer (Brüggen et al. 2005). Given the fixed absolute energy resolution of calorimeters, a high-energy line provides the best velocity resolution (ideally, one should use the $\text{K}\beta$ line of Fe xxvi for kinematic mapping; however, the line fluxes would be too low for the required signal to detect the cavities).

Many other lines are present, also showing the kinematic signatures discussed below, but for simplicity and clarity we limited the analysis to Fe xxv. Figure 1 shows the rest-frame multiplet line structure at a plasma temperature of 4 keV for reference.

Given its strength relative to the intercombination lines and the forbidden lines (as well as the satellite lines), the line fluxes would be too low for the required signal to detect the cavities). The code currently does not account for vignetting and uses a simplified mono-energetic PSF in the case of IXO simulations. However, the impact of these limitations on the predictions presented below should be small.

### 3. RESULTS

To investigate the possibilities offered by high-throughput X-ray spectrographs for the study of AGN feedback in clusters, we constructed virtual IXO observations of three representative (benchmark) galaxy clusters with detailed existing Chandra cavity studies: Perseus A, Cygnus A, and Hydra A. The simulations aim to reconstruct, as best as currently possible, the observational characteristics of these sources.

Before presenting the three cases in more detail, it is worth pointing out that X-ray spectro-imaging data are difficult to visualize in two-dimensional figures. The plots in this paper show different spectra from virtual spectral slits placed across that data cube, which clearly resolve the kinematic signatures of cluster feedback. However, a generally much better way to view the data is by animation. For this reason we have

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**Figure 1.** Reference spectrum of the Fe xxv $\text{K}\alpha$ line for a 4 keV thermal plasma, with resonance, intercombination, and forbidden lines labeled. Di-electronic satellite lines are also included.
prepared movies of all three cases that can be viewed at http://www.astro.wisc.edu/~heinzs/feedbackmovies.html.

3.1. Perseus A

The Perseus cluster was the first cluster known to have X-ray cavities. With a mega-second of *Chandra* observing time, this is the best studied cluster to date, displaying rich morphological complexity across all wave bands (e.g., Graham et al. 2008; Fabian et al. 2008; Taylor et al. 2006). As such, it represents the benchmark for numerical models.

As a moderately powerful source, with a jet power somewhere between \(10^{44}\) and \(10^{45}\) erg s\(^{-1}\), it also represents a good example of what has become known as “gentle” or “effervescent” heating (e.g., Ruszkowski et al. 2004).

The detection of a weak shock in the long *Chandra* image (Graham et al. 2008) has provided the most robust power estimate of \(W_{\text{jet}} \sim 10^{45}\) erg s\(^{-1}\), which is the number we chose to use. Given this power estimate, we ran the simulation for 10\(^6\) yr until the size of the shock and cavities corresponded to the observed values.

The central cluster temperature is around 3–4 keV, somewhat colder than the S2 cluster we used as our initial condition. We thus adjusted the cluster temperature in post-processing to ensure the correct line strengths and ratios, fixing the total X-ray power from the cluster to the observed *Chandra* flux.

The resulting simulated *IXO* image and Fe xxv Kα spectrum are shown in Figure 2 for an assumed exposure time of 250 ks, at the Perseus redshift of \(z = 0.01756\). The cavities are clearly visible, as is the classical bright central core of the Perseus cluster. It should be noted that typical clusters exhibit cores that are somewhat less bright, which will increase the detectability of the cavity signal relative to the cluster background.

Figure 2 also shows the spectrum for a virtual spectral slit placed across both cavities (see image for slit placement). Apart from the complex sub-structure of the Fe xxv Kα multiplet, the most striking feature immediately visible from the spectrum is how the lines split at the locations of the cavities and how the split stands out against the cluster background emission.

The two “bubbles” seen in the spectrum correspond to the front and back walls of the cavities, allowing full three-dimensional reconstruction from the imaging spectrum like in the case of supernova remnants. Simply reading off the expansion velocity from the blue- and red-shifted line gives a line-of-sight velocity of \(v_{\text{LOS}} \sim \pm 350\) km s\(^{-1}\), compared to the actual velocity of \(\sim 325\) km s\(^{-1}\) in the simulation.

Thus, *IXO* will be able to clearly resolve the kinematic signature of expanding bubbles around cluster radio sources like Perseus A. It is also clear that an angular resolution of a few arcseconds is vital to resolve the cavities both spectrally and spatially: telescopes like *Astro-H*, with imaging resolution of order arcminutes or worse, will simply smear out the cluster emission to the point where the cavities will not be visible either in the image or the spectrum.

3.2. Cygnus A

As a powerful FR-II source, Cygnus A sits at the upper end of the expected range of cluster radio sources and shows clear cavities and possibly a shock in the *Chandra* image (Wilson et al. 2006). As with most cluster sources, the ambiguities in the interpretation of the imaging data cannot constrain the jet power to better than about an order of magnitude, roughly \(10^{45}\) to \(10^{46}\) erg s\(^{-1}\).

The discovery of giant X-ray cavities in other clusters has shown that powerful outbursts like the one currently observed in Cygnus A might be more common than implied by models of “gentle” cluster heating, making this source an important benchmark.

Our initial numerical simulations of Cygnus A have been presented in Heinz et al. (2006). Here, we will present the virtual *IXO* observation derived from that simulation. We ran the simulation with a jet power of \(10^{46}\) erg s\(^{-1}\) for 21 Myr, at which point the simulation reached the observed cavity and radio lobe size and morphology.

Our virtual 250 ks *IXO* observation is shown in Figure 3, for Cygnus A's redshift of \(z = 0.056\). The two bottom spectra show the Fe xxv Kα line, clearly resolving the two cavities (the two spectra correspond to two virtual spectral slits, one for each cavity). As expected, for such a powerful source it will be easy for *IXO* to resolve the kinematic structure of the line (from our example, we find an observational estimate of \(v_{\text{LOS}} \sim 690\) km s\(^{-1}\) compared to an actual value of \(v_{\text{LOS}} \sim 700\) km s\(^{-1}\), conservatively giving an accuracy of about 10% in the observational determination of \(v_{\text{LOS}}\)).

Ultimately, the accuracy with which the jet power in such a case can be determined from this measurements depends on how robust models of cavity expansion really are. Given that these simulations are still among the first generation of numerical models for jet-driven cavities in realistic cluster atmospheres (i.e., actual collimated jets versus energy-driven bubbles), this is still an open problem, awaiting more systematic future investigations.

However, we can gauge how standard, simple literature models (e.g., Heinz et al. 1998; McNamara et al. 2000; Churazov...
et al. 2001) would fare using accurate velocity measurements; by visual estimate of the cavity size (see dashed ellipses in Figure 3) we find the projected semimajor and semimajor axes in our simulation to be 24 kpc and 33 kpc, respectively. The pressure in the shell is roughly $5 \times 10^{-10}$ erg cm$^{-3}$, which, in a realistic observation with appropriate fitting tools, can be determined from a spectral deprojection of the data. By the usual formula, the power estimate one would infer from the simple-minded one-dimensional cavity models is

$$P \approx \frac{V_{\text{cavities}} P_{\text{shell}}}{t_{\text{age}} (\gamma_{\text{ad}} - 1)} \approx 9 \times 10^{45} \text{ erg s}^{-1},$$

(1)

where $t_{\text{age}}$ is the inferred age of the cavity (from the expansion velocity) and $\gamma_{\text{ad}} = 5/3$ is the adiabatic index of the gas. This value is within 10% of the actual value and indicates that standard tools to estimate the source power can work well if accurate information about pressure and velocity are available.

Realistically, accurate measurements of expansion velocities for cavities not just in one place but across the entire projected face of the cavity would certainly provide critical input to compare against detailed simulations as presented here.

### 3.3. Hydra A

Several clusters that currently contain relatively modest radio sources show fossil cavities that imply much more powerful past outbursts, most notably Hydra A (Wise et al. 2007), MS 0735 (Gitti et al. 2007), and Hercules A (Nulsen et al. 2005).

Confirming the large jet power inferred for these sources via kinematic measurements will be important in determining how much jet power is released in impulsive form compared to the "gentle" effervescent mode of energy release (Roychowdhury et al. 2004). In other words: how common are powerful bursts like those suggested in Hydra A and MS 0735, compared to the gentle sources at Perseus A-like powers and below? Note that Wise et al. (2007) identify multiple powerful outbursts in Hydra A—determining the respective ages would be extremely helpful in constraining duty cycles and injection modes.

In order to investigate the kinematic signature one might expect for an old, powerful source like Hydra A, we used a late time step of our $10^{46}$ erg s$^{-1}$ simulation to represent this case, 150 Myr after the outburst started, roughly corresponding to the case of Hydra A. The cavity sizes are of the same order as those observed in Hydra A, including the north–south asymmetry due to motion of the intra-cluster medium (ICM).

Given the low surface brightness this far out in the cluster and the large angular size of these sources, such observations will be more challenging (requiring multiple long pointings). Still, the virtual mosaic observation (with 250 ks of observing time per tile) in Figure 4 shows that the kinematic structure can be resolved and detected against the cluster background even in these types of sources. Turning this argument around, non-detections would yield meaningful upper limits on the expansion velocities of the cavities for these sources.

### 4. Discussion

#### 4.1. Implications for Other Cluster Radio Sources

The three detailed examples presented above show that a high-throughput, high-resolution spectrograph like IXO’s X-ray Micro-calorimeter Spectrometer (XMS) will be able to resolve the kinematic structure of radio galaxy drive cavities for a significant fraction of the sources in the Chandra archive.

For example, in the case of Perseus A, the large count rate will allow a clear resolution of the iron line in observations as short as 20 ks. This implies that even in clusters with lower surface brightness, IXO would be able to deliver cavity velocities in exposures of moderate length (100–200 ks), even in the presence of sub- or transonic turbulence in the cluster.

In principle, IXO will be able to resolve cavities expanding with velocities as slow as $v_{\text{LOS}} \gtrsim 100 \text{ km s}^{-1}$, though the

![Figure 3. Virtual 250 ks IXO observation of Cygnus A (redshift $z = 0.056$). Top: 0.5–10 keV image. Middle: Fe xxv Ka line of the eastern cavity. Bottom: same for the western cavity. Both cavities will be easily resolved by IXO. Overlaid are the visual best-fit ellipses describing the X-ray cavities.](image3)

![Figure 4. Virtual 250 ks IXO observation of a Hydra A-like radio source. Top: 0.5–10 keV image. Middle and bottom: Fe xxv Ka spectra of both cavities.](image4)
presence of turbulent broadening in the ICM will likely mean a higher threshold. Given that the expected expansion velocity of actively jet-driven cavities for a fixed physical cavity radius $R$ scales like (Heinz et al. 1998)

$$v_{\text{LOS}} \propto \left( \frac{W_{\text{jet}}}{\rho_{\text{ICM}}} \right)^{1/3},$$

(2)

low-power sources like M87 in very dense environments would be more difficult to observe.

We have not run a simulation of a source at low enough power to produce an expansion velocity of this order, and it is unlikely that a coherent radio lobe can be formed that expands at such low velocities (it would presumably be broken up by buoyancy). An observational determination of the expansion velocities will thus also answer the question of whether low-velocity lobe inflation is possible by establishing whether there is a velocity floor for X-ray cavities.

### 4.2. Caveats

The presented virtual observations are based on numerical simulations, and as is unavoidable in such a setup, there are several physical effects that we did not include and that could in principle affect the predicted results.

However, the main point of this paper is to demonstrate that a next-generation high-throughput, high-resolution X-ray spectrograph will be able to determine the expansion velocities of cavities even in a realistic, dynamic cluster atmosphere and to provide realistic estimates of the exposure times and the angular and spectral resolution needed to make such measurements, which should be robust against some of the second-order effects we neglected to include.

We will therefore not go into any detail of the numerical shortcomings (like the absence of magnetic fields, the limitation to non-relativistic simulations, the restriction to purely thermal particle populations, and neglecting effects of radiative transfer like resonant scattering).

In addition, calibration uncertainties present in any X-ray instrument will in principle affect the spectroscopic accuracy. This will mainly affect the accuracy with which temperatures and emission measures can be determined, which will be the limiting factor in more sophisticated X-ray analysis (see Section 4.4). However, for kinematic mapping, systematic errors due to calibration uncertainties should not have any strong effect, since line centroiding depends only on the energy resolution.

### 4.3. Turbulence

Possibly the most important question regarding the possibility of kinematic mapping is the level of turbulence present in the ICM. Very large turbulent velocities would broaden all lines and make kinematic measurements of the sort discussed here more difficult (Inogamov & Sunyaev 2003; Churazov et al. 2004). Our simulations include turbulence on the scales resolved by our grid, though we cannot make any statements regarding the level of sub-grid turbulence.

The cluster-wide random (i.e., turbulent) velocities we find in our simulation have an emission-measure-weighted line-of-sight velocity width of $\Delta v_{\text{turb,FWHM}} \approx 500$ km s$^{-1}$ (FWHM). The (unprojected) turbulent rms velocity in the inner cluster is also about $v_{\text{turb, rms}} \sim 500$ km s$^{-1}$, increasing outward to about $v_{\text{turb, rms}} \sim 800$ km s$^{-1}$ at a cluster radius of 100 kpc. These values are in good agreement with those discussed in, e.g., Sunyaev et al. (2003).

Naturally, the action of a radio galaxy increases the level of turbulence, in addition to driving large-scale bulk flows. This can be seen in Figure 5, which shows the 1$\sigma$, 2$\sigma$, and 3$\sigma$ contours of the emission-measure weighted line-of-sight velocity distribution for different time steps of our simulations. The figure shows the level of background turbulence and the additional velocity components imparted by the radio source (see also Section 4.4), visible as broadened velocity contours.

The initial turbulence included in the simulation is driven by large-scale motions in the cluster (due to infall, galaxy motions, large-scale shear, and rotation). It is conceivable that other agents contribute to the turbulence spectrum (such as plasma instabilities like the recently discovered conductive instabilities Balbus & Reynolds 2008; Quataert 2008), in which case the amount of turbulence reflected in our simulations would be an underestimate. However, since the turbulence in our simulations is already fairly close to transonic, and since plasma instabilities are unlikely to produce highly supersonic levels of turbulence, it is unlikely that we are severely underrepresenting the amount of turbulence one would expect to find in a typical galaxy cluster.

Given the fact that the cavity expansion is clearly detectable in all three prototype cases, we conclude that turbulence will only seriously impede kinematic measurements in weak and old sources (where expansion velocities are small) or if the turbulence is supersonic. Recent upper limits on the turbulent velocity dispersion of less than 274 km s$^{-1}$ in Abell 1835 by Sanders et al. (2010) support the view that turbulence will not be a critical factor in high-resolution kinematic mapping of cluster radio galaxies.

Figure 5 also shows that large-scale mapping of the line-of-sight velocity emission-measure distribution in clusters can be
a powerful tool to search for evidence of AGN activity, even if
cavities in the cluster cannot be resolved. While other agents
can also induce large velocities in clusters (namely, mergers
and harassment), one should expect the velocity signature to
be significantly different: AGN induced turbulence is centrally
concentrated. Such a measurement could conceivably be made
by X-ray telescopes with significantly lower angular resolution
than what is required to determine direct expansion velocities
of X-ray cavities, such as Astro-H.

4.4. Other Prospects for Feedback Studies

Given a spatially resolved high-resolution X-ray spectrum,
more detailed quantitative analysis will be possible. We will list
a few examples beyond the simple kinematic analysis presented
above:

1. **Line stacking.** In order to maximize the kinematic signal,
especially for low-brightness clusters, the spectrum can be
re-gridded onto a logarithmic grid. This will allow
the stacking of different emission lines on top of each
other simply by shifting along the energy axis, reducing
the overall exposure time requirements. In particular, the
Fe XXV Kβ and the Fe XXVI Kα lines lend themselves to
be stacked (due to the simple line structure and high-
velocity resolution), as do the weaker intercombination and
forbidden lines of the Fe XXV Kα line.

More complex deconvolution algorithms could yield
even more powerful diagnostics, including the temperature
structure of the cavity shells from line-ratio variations
across the shell and relative the cluster and the X-ray cavity.

2. **Line-of-sight angles.** From the velocity centroid of the two
cavities, relative to the cluster mean, it will be possible to
determine the mean jet orientation relative to the line of
sight. This will solve the outstanding problem of projection
and foreshortening when estimating the cavity sizes, thus
eliminating the other major uncertainty in determining the
jet power.

3. **Emission measure mapping.** Beyond simple kinematics,
spectral fitting will allow the extraction of the emission
measure distribution in each individual X-ray pixel, al-
lowing multi-phase metallicity, entropy, temperature, and
pressure maps.

When constructing the emission measure map across the
walls of the cavity or across the (presumably turbulent)
wake of ghost cavities, it should be possible to map out the
excess entropy produced by dissipation, allowing the direct
detection of the spectroscopic signature of AGN heating.
From the metallicity inside the cavity wall, it should also
be possible to constrain the origin of the gas.

Given the enormous spectral complexity and the high de-
mands on the calibration of the instrument, this will be a sig-
nificantly more difficult task than simple kinematics. Such
an approach would likely have to be done using techniques
from optical spectroscopy (measuring many individual line
fits rather than fitting global spectra). Because current ther-
mal models in XSPEC are incomplete (e.g., APEC does
not include thermal broadening) a demonstration of this
method using our feedback simulations would be well
beyond the scope of this paper.

5. CONCLUSIONS

We presented detailed quantitative predictions for the
X-ray spectroscopic signatures of AGN driven X-ray cavities in
realistic, dynamic cluster atmospheres, showing that kinematic
measurements of cavity expansion velocities will be possible
against the cluster background emission. Such measurements
will allow the determination of cavity ages, jets powers, and
possibly black hole duty cycles.

Our simulations demonstrate that 2.5 eV spectral resolution
and 5′′ spatial resolution (as would be provided by the IXO)
will be sufficient to make the necessary measurements. Any
significant compromise in angular or spectral resolution would
render these measurements impossible, implying that neither
the current nor any other planned X-ray telescopes (such as
Astro-H) could deliver them.

We also showed that radial emission measure maps of the
cluster line-of-sight velocities can serve as a diagnostic of past
and ongoing feedback (a measurement conceivable even with
low-angular resolution, and thus accessible to Astro-H) and
argued that the velocity offset between the two cavities can
be used to determine the orientation of AGN driven cavities.

APPENDIX

REFERENCE IXO SPECIFICATIONS

For reference (and to facilitate comparisons with other in-
strument concepts), we briefly list the relevant current (2009)
specifications of IXO in this appendix.

1. **Spectral resolution.** IXO will feature an XMS with uniform
2.5 eV spectral resolution up to 7 keV. At the Fe Kα line energy of ~6.7 keV, this corresponds to a spectral
resolving power of 2700, an improvement of roughly 2
orders of magnitude compared to the Chandra resolution
for extended sources. The core XMS array will have
3 arcsec pixels, arranged in a 40 × 40 square for a 2 × 2
arcmin field of view.

2. **Effective area.** Relative to Chandra imaging with the back-
iluminated S3 chip, the effective area will be roughly a
factor 25 higher, about 6000 cm² at 6 keV.

3. **Angular resolution.** The angular resolution of the IXO
telescope mirror assembly will be 5 arcsec on-axis at 7 keV
(5 arcsec half-power diameter), which is very well suited for
cluster studies. It is worth noting that, while the 0.5 abscord
Chandra resolution is necessary for the study of very fine
details (like the sound waves in Perseus and cold fronts in
clusters like Abell 3667), a fair fraction of cluster science
enabled by Chandra could be done at 5 arcsec resolution.

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