My current research interests focus on the observational consequences of galaxy cluster mergers and how they inform the underlying physics of the intracluster medium (ICM) and the use of clusters as cosmological probes. Mergers are violent events – the most energetic since the Big Bang – involving $\sim 10^{64}$ ergs. Most of the energy injected into the ICM is thermalized, either quickly through low Mach shocks or more gradually through the dissipation of the kinetic energy in bulk motions and turbulence generated by the merger. This energy dramatically modifies the state of the ICM for significant periods ($\sim 10^9$ yr), destroying previous structures such as cool cores and creating new, transient structures like radio halos/relics and cold fronts. Also, nonthermal components in the ICM – magnetic (B) fields and relativistic electrons and ions – coexist with the thermal gas, and some of the energy goes into (re-)accelerating these particles and enhancing B, though their dynamical importance is unclear. Investigating these interactions explores the high energy physics of diffuse magnetized plasmas, the growth of large-scale structure in the universe, and the feasibility of using ICM-derived proxies of the cluster mass to make precision measurements of cosmological parameters.

Impact of mergers on SZ-derived proxies of cluster mass

Many projects/missions are currently underway with the goal of detecting clusters through a distortion of the CMB caused by the Sunyaev-Zel'dovich (SZ) effect. SZ surveys have the potential to detect hundreds to thousands of clusters, making them excellent probes of large-scale structure and cosmology[6]. However, I have shown that major mergers temporarily, though significantly, boost the magnitude of the SZ effect[19], denoted by y, which correspondingly boosts the estimated mass of the cluster, especially if the mass is related to the maximum value of y. The evolution of y was followed during major merger events for a set of simulated binary cluster collisions[17], which covered a range of impact parameters and mass ratios. These results were then coupled to a semi-analytically generated set of merger trees, produced assuming the standard ΛCDM cosmology, so that the effect of a small number of clusters with boosted "observed" masses on the total mass function could be evaluated. I found that estimates of the matter density (Ω_M) and power spectrum normalization (σ_8), when measured from the "observed" mass function, were biased at the tens of percent level, comparable to a study that used the same methodology but considered the use of the X-ray luminosity and temperature of clusters as a mass proxy[12]. Though this work shows the maximum value of y to be a poor mass proxy, if one instead integrates y over the whole cluster (denoted by Y), the SZ boost is significantly diminished in magnitude and leads to accurate estimates of the cluster mass. Consequently, the above cosmological parameters, and even the dark energy equation of state parameter w, can be measured to percent precision. Because y is proportional to the pressure along the line of sight, its integral Y is simply proportional to PV, or the total thermal energy in the ICM, which cannot exceed the final equilibrium value after the merger is complete due simply to energy conservation.

The robustness of Y as a mass proxy depends on the radius out to which y is actually integrated, which may vary survey-to-survey. I am interested in extending this work to assess both how sensitive the sizes of boosts are to the integration radius and their resultant impact on the $Y_{<R} - M$ relation. Also, because SZ observations are sensitive to a lower power of the gas density than are X-ray observations, SZ maps of individual clusters will better detect both high pressure regions (shocks) and low density regions (beyond R_{500}), allowing the further exploration of merger-induced structures.

Directly measure ICM bulk velocities in clusters

While the distribution of radial velocities of cluster member galaxies traces the impact velocity of the collisionless component of merging subclusters, and while a detailed study of a shock front can infer the impact velocity of the subcluster gas, only redshift differences detected in X-ray emission lines can directly measure bulk motions in the gas itself. The marginal spectral resolution and unstable gain of CCD detectors has thus far hindered such measurements, relegating such studies to long observations of bright clusters and sometimes conflicting results[3,11]. Taking advantage of the improved stability and resolution of the imaging spectrometers onboard *Suzaku*, I have detected a velocity gradient in the ICM of the Cygnus A cluster, for the first time with this observatory. Previous X-ray[9] and optical[8] observations indicate a merger between two subclusters, at least partially along the line of sight. This new observation independently confirms the merger geometry and dynamics, as well as a hot region in between the subclusters, presumably due to a shock.

I hope to extend this work through similar observations of other potentially line of sight mergers with *Suzaku*. Unfortunately, because a robust result requires the subclusters be caught just before impact, be favorably oriented, and be approaching at a $\Delta v \gtrsim 2000$ km/s, the prospects for future detections are not extensive. However, this work is an important precursor to upcoming missions with microcalorimeters, which will measure much smaller velocity differences and be sensitive enough to detect bulk motions due to turbulence and the infall of less massive subclusters.

Hard X-ray emission from clusters: the case of the Coma cluster

The existence of magnetic fields associated not with cluster galaxies, but with the ICM itself in merging clusters[2], has been apparent since the discovery of diffuse, Mpc-scale synchrotron emission called radio halos and relics. Unfortunately, the average value of B in the ICM has been difficult to determine, though it is certainly in the range $0.1\mu\mathrm{G} < B < 10\mu\mathrm{G}$. The upper end is set by Faraday rotation measure studies, which probe only along narrow lines of sight and are weighted toward higher density regions, and so may not represent the global B field. The lower end of the range comes from measurements and upper limits of inverse Compton emission (IC) at hard X-ray energies, which originates from the same electrons producing the radio halos and relics. Since both the synchrotron and IC luminosities are proportional to the electron density, but only the synchrotron emission depends on B, their ratio leads to an estimate of the average value of B (or lower limit in the case of an IC flux upper limit) in the cluster. The Coma cluster, the first cluster discovered to host a radio halo, has been observed by most missions with sensitivity to hard X-rays[16], and with the *RXTE*[15] and *BeppoSAX*[5] observatories a nonthermal component has been detected. Interpreted as IC emission, the resultant magnetic field strength is $B \sim 0.1 - 0.2\mu\mathrm{G}$. However, a separate analysis of the same *BeppoSAX* data contradicts this result, claiming the hard emission is purely thermal[18]. To attempt to settle this discrepancy, I combined a long observation with the more sensitive *Suzaku* Hard X-ray Detector (HXD) with mosaic *XMM-Newton* observations spatially weighted to match the spatial sensitivity of the non-imaging HXD and also found the emission to be completely thermal in origin, setting an upper limit 2.5× below the previous detections[20]. The extrapolation of an *XMM*-derived temperature map to HXD energies confirms that thermal emission is sufficient to explain the data. Using the same method, we found an upper limit for nonthermal hard X-ray emission from the radio relic region of A3667, corresponding to $B \gtrsim 2.2\mu\mathrm{G}$ [10]. Recent follow-up observations of this region with *XMM* reveal a large background point source population near the relic, obscuring the diffuse emission here as detected by *Suzaku*. Diffuse thermal and/or nonthermal emission is detected coincident with the relic, along with a possible surface brightness discontinuity at the leading edge of the relic, which indicates $B \gtrsim 3\mu$G [4].

However, because the field of view of the *Suzaku* HXD is smaller than either of the instruments on *BeppoSAX* or *RXTE*, the conflicting results for Coma could be explained by uniform surface brightness IC emission beyond the extent of the radio halo. An imaging hard X-ray observatory, like the upcoming *NuSTAR* mission, will be able to determine whether this scenario is indeed the case. On the other hand, coarse imaging is already possible with the coded mask detectors onboard the *INTEGRAL* and *Swift* observatories. By developing a new procedure for analyzing extended emission from a diffuse source, similar to that established for *INTEGRAL*[13], I analyzed survey data from the *Swift* BAT instrument and confirmed that the detected emission is both spectrally and spatially consistent with that expected from the *XMM* temperature map. While the survey data is not yet sensitive enough to determine whether IC emission with a greater extent does exist, I am able to rule out a new model for the production of IC radiating electrons at the virial radius of clusters[7].

Nonthermal emission in an *XMM*-*Swift* survey of clusters

Currently, I am taking advantage of the nearly uniform and all-sky nature of the *Swift* BAT survey data to characterize the nonthermal, hard X-ray emission in clusters. A previous study has already searched for such emission in the 10 clusters detected in the 9 month survey data, finding the emission to be consistent with a thermal origin[1]. My approach is somewhat different, in that I will search for a nonthermal signal from two pre-defined samples: the flux-limited HIFLUGCS clusters[14] and all clusters known to have radio halos or relics. Because HIFLUGCS is a complete sample, I will derive truly physical constraints on the nonthermal emission from clusters by stacking the cluster spectra. Similarly, for the radio halo/relic clusters, which are expected to host nonthermal emission at some level, general limits on the average B field for all the clusters, derived from a stacked spectrum, will be found. As with the *Suzaku* analysis of Coma, I will jointly fit a lower energy spectrum from archival *XMM* data with the *Swift* data for each cluster in order to correctly account for the thermal contribution at hard energies.

The advent of imaging hard X-ray telescopes (*NuSTAR*, *Astro-H*, *IXO*) will open up this field, eventually characterizing the nonthermal electron population in many clusters and leading to the spatial mapping of B in clusters with radio halos and relics. Similarly, advanced radio telescopes, especially those sensitive at low frequencies such as LOFAR and LWA, will expand the sample and perhaps even the the radio halo/relic paradigm itself. Observational constraints on the B field of clusters are crucial if the dynamics of the ICM, from shocks, cold fronts, AGN-blown bubbles and feedback to simply its equilibrium state, are to be understood. These investigations, in conjunction with detailed *XMM*/*Chandra*/*Suzaku* and SZ observations of merging clusters, will create a more complete picture of the physical processes operating during these immense collisions, and whether these events will negatively impact the use of clusters as cosmological probes.

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