Unraveling ICM Physics and AGN Feedback with Deep Chandra Observations of NGC 5813

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ABSTRACT Cosmic feedback is currently an extremely active area of research in astrophysics, and has far-reaching consequences for a broad range of research topics. Improving our understanding of feedback will be one of the major science goals of the Athena mission. In kinetic mode feedback, AGN jets inflate cavities in the ICM, which subsequently detach from the jets and rise buoyantly. Although generally the internal energy of these cavities is large enough to offset radiative cooling in the gas, the details of how and where this energy is deposited in the ICM are currently not well understood. AGN outburst shocks, which are driven by the rapid inflation of the X-ray cavities early in their lifetimes, can play an important role in the feedback process. These shocks heat the ICM isotropically and close to the central AGN, as required for AGN feedback to operate. Here we present results from a very deep 650 ks Chandra observation of the nearby galaxy group NGC 5813. NGC 5813 is uniquely well suited to the study of AGN feedback since it shows cleanly separated, regular features from three distinct AGN outbursts, including three pairs of collinear cavities and three elliptical shock front edges with clear temperature jumps. We show that, in NGC 5813, heating from outburst shocks offsets radiative cooling of the gas within at least the central 30 kpc. We also find that the intermediate shock fronts at ~10 kpc are more broadened than can be explained by particle diffusion or PSF smoothing. Instead, the broadening is consistent with the shocks having propagated through a turbulent ICM with a turbulent velocity of roughly 70 km/s. Significant contributions to our understanding of AGN feedback and ICM physics, partially via studies similar to the one described here, will be one of the major achievements of the Athena mission.

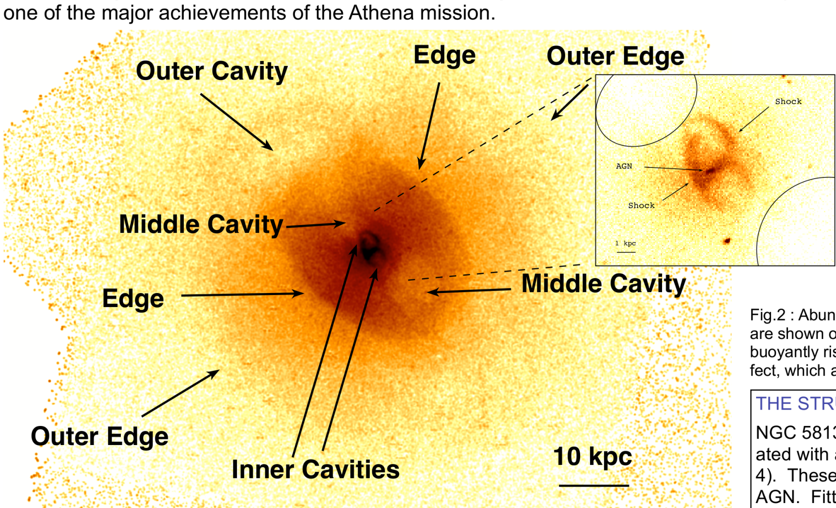

Fig. 1: Deep 650 ksec Chandra image of NGC 5813 in the 0.3-2 keV band, exposure corrected, background subtracted, and smoothed. The image shows three pairs of cavities, bright rims surrounding the inner pair of cavities, two sharp edges to the northwest and southeast, and outer edges.

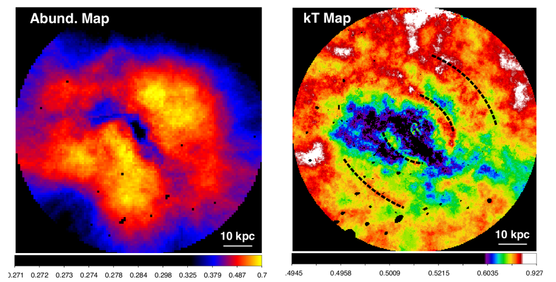

Fig.2 : Abundance (left) and temperature (right) maps. The ~10 kpc and ~30 kpc shock fronts are shown on the temperature map. Cool, high abundance gas has been uplifted by the buoyantly rising X-ray cavities. The projected abundance appears lower due to the Fe bias effect, which arises from fitting multi-temperature emission with a single temperature model.

THE STRUCTURE OF NGC 5813

NGC 5813 uniquely shows three pairs of collinear cavities with each pair associated with an elliptical shock front with a significant temperature jump (Fig.1, Fig. 4). These features are associated with three distinct outbursts of the central AGN. Fitting density profiles to the shock fronts gives Mach numbers of about 1.8, 1.5, and 1.2 for the inner (1 kpc), intermediate (10 kpc), and outer (30 kpc) shocks, respectively.

SHOCK HEATING AND AGN FEEDBACK

At each shock front, we can express the shock heating due to the entropy jump across the front (ΔS) as a fraction of the local thermal energy in the gas (E): $(T\,\Delta S)/E = \Delta\ln(P/\rho^{\gamma})$. This gives an estimate of the number of shocks per local cooling time required to replenish the local thermal energy in the gas. We find that 9, 21, and143 outbursts are required per local cooling time for the 1 kpc, 10 kpc, and 30 kpc shocks, respectively, in order to offset radiative cooling. The shock repetition rate is inferred from the observed shock separations and speeds, while the local cooling times are measured directly from X-ray observations. We find 9, 46, and 111 shocks per local cooling time, respectively, remarkably close to the number required to offset cooling. Thus, we conclude that shock heating alone can offset radiative cooling and regulate AGN feedback in the case of NGC 5813, and is likely important in other systems where shocks are more difficult to detect due to observational constraints. This heating rate is strongest in the core, close to the central AGN, and is roughly isotropic, as required to regulate feedback.

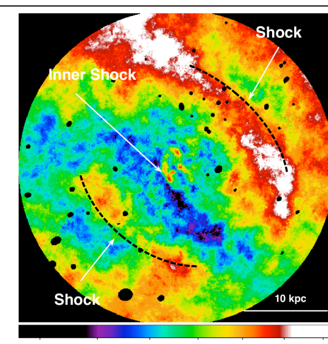

Fig. 3 X-ray temperature map of the central region. The dashed lines trace the prominent 10 kpc shock edges. Even in the smoothed temperature map, shock heated gas is evident just behind the shock fronts.

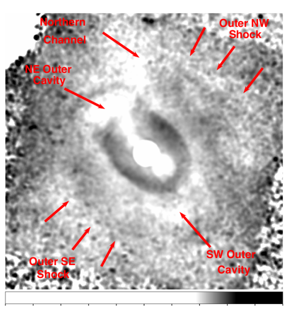

Fig. 4: Image divided by a fitted β-model (central rims are masked out). It more clearly shows the outer edges and SW outer cavity.

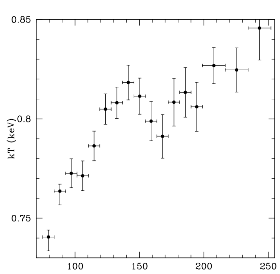

Fig. 5: Temperature profile across the SE outer shock, demonstrating that associated temperature enhancements are found even for the faint, outer shocks.

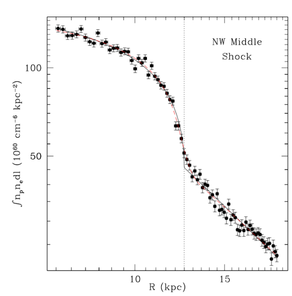

Fig. 6: Fits to the surface brightness profile across the NW 10 kpc shock. The smoothed density jump model (red) is a significantly better fit than the discontinuous model (black).

ICM PHYSICS

Surface brightness profiles across the 10 kpc shocks reveal that the shock fronts are not sharp, but have finite widths (Fig. 6). Fitting the edges with a Gaussian smoothed discontinuous density model shows that the shock widths (~400 pc) are larger than the local PSF, and more than 10x's larger than the local particle mean free path. Thus, the shock broadening cannot be explained due to particle diffusion across the shock front. Using a simple analytic approximation, we find that the measured widths of each shock front are consistent with shock broadening due to propagation through a turbulent ICM, with turbulent speeds of roughly 80 km/s. This is consistent with turbulent velocities found using other, independent methods, and with what is expected based on simulations.

References: Randall et al. 2011, ApJ, 726, 86; Randall et al. 2015, ApJ, 805, 112