Shocks and Cavities from Multiple Outbursts in the Galaxy Group NGC 5813: A Window to AGN Feedback

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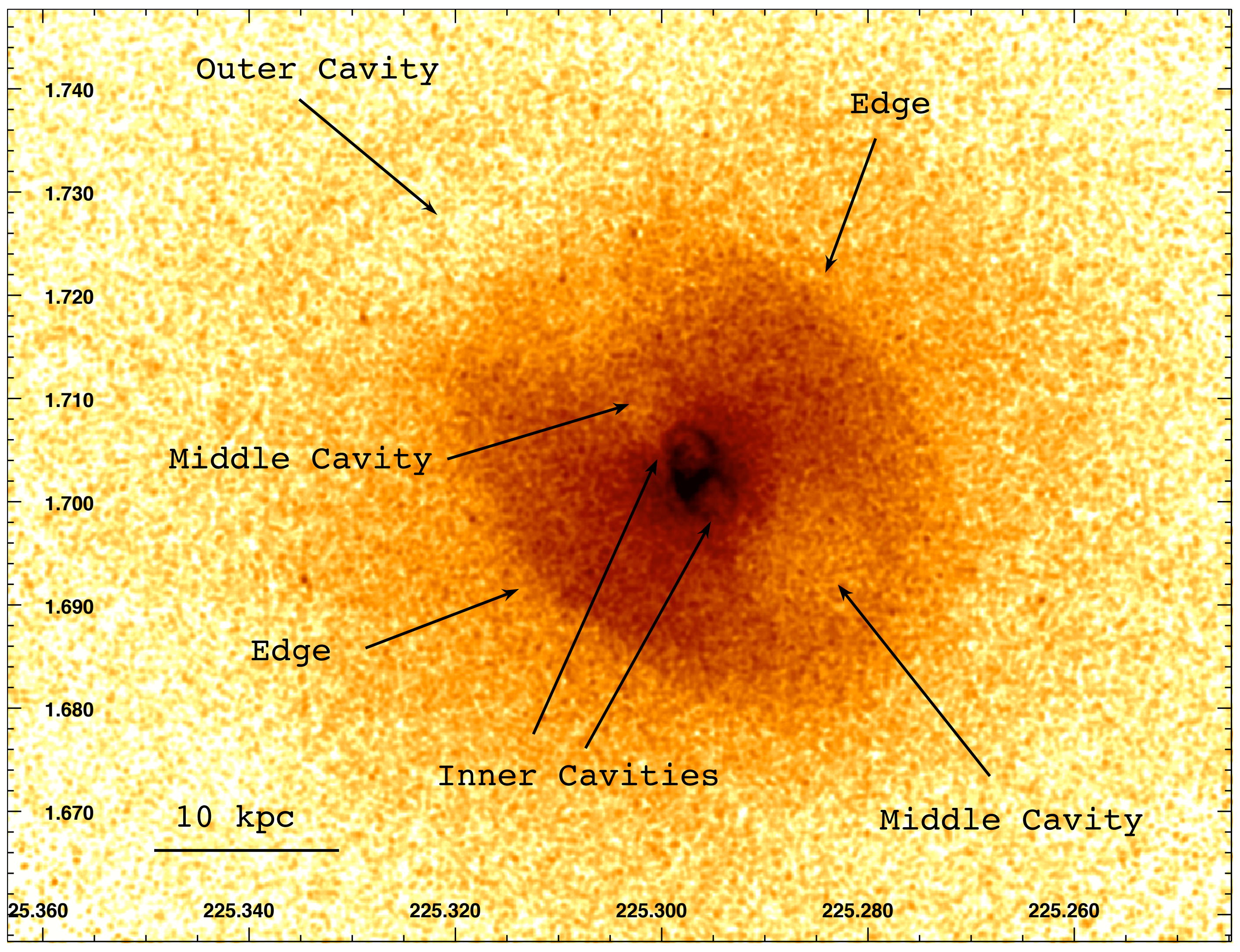
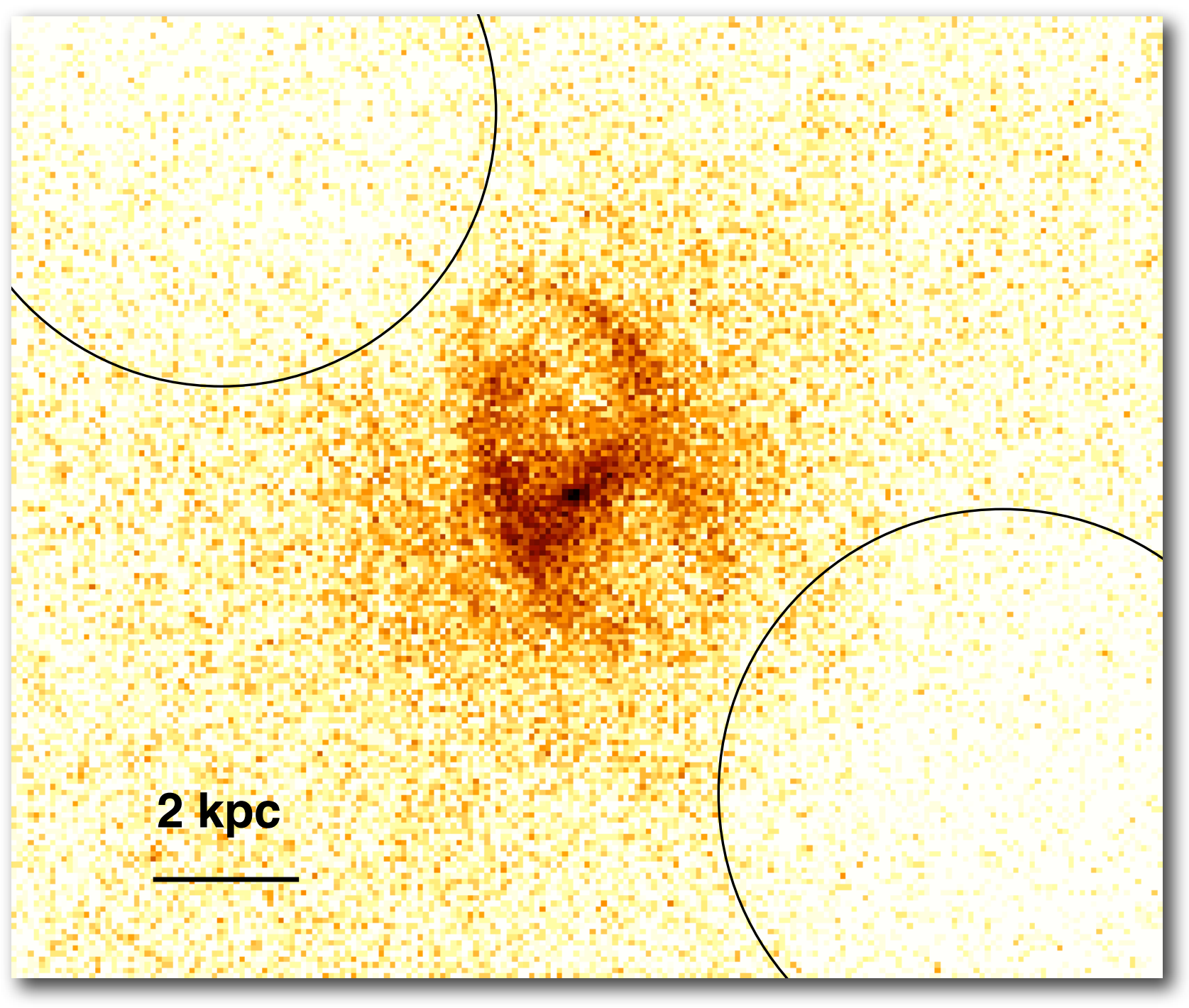
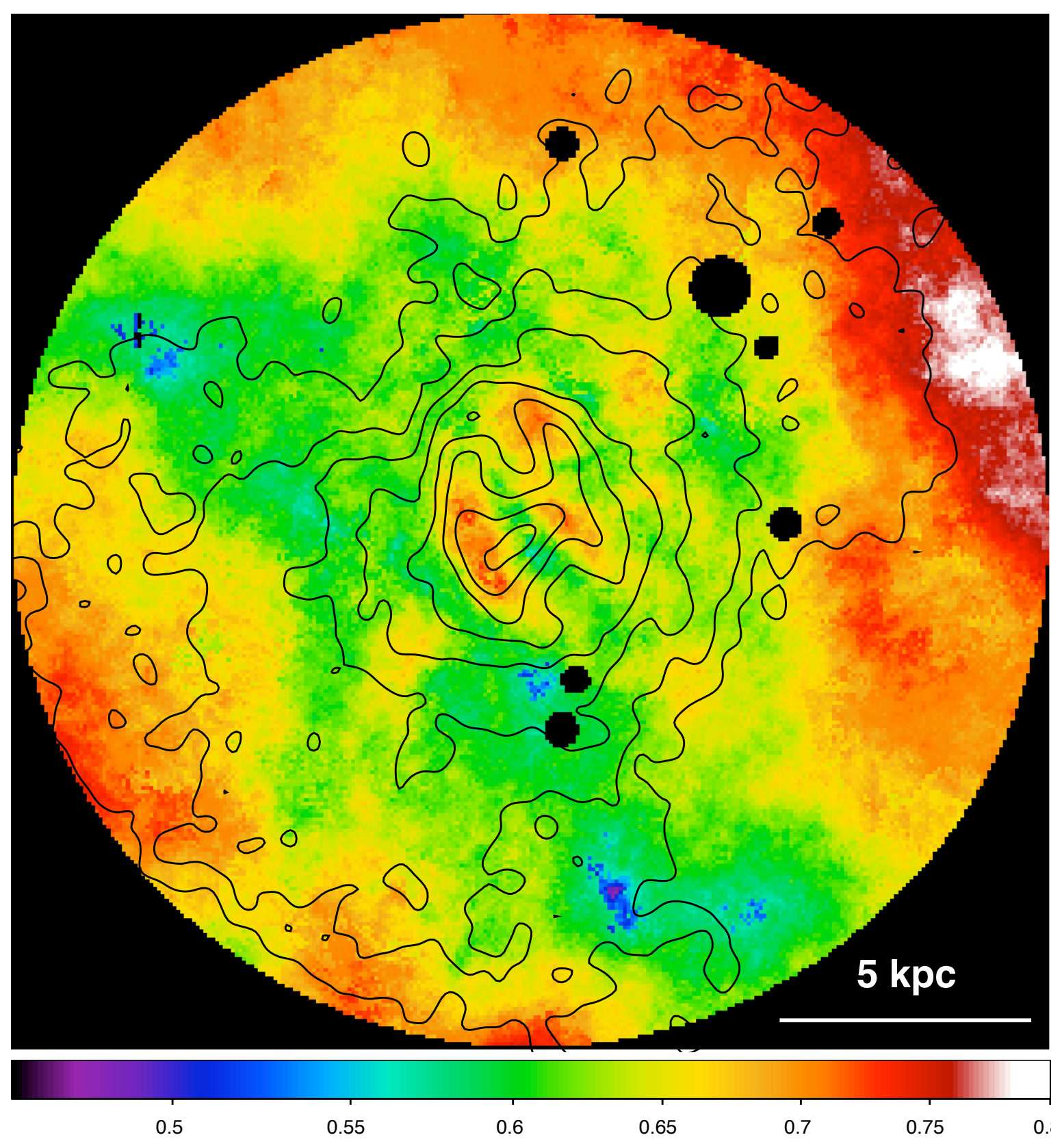
ABSTRACT We present results from Chandra, GMRT, and SOAR observations of NGC 5813, the dominant central galaxy in a nearby galaxy group. We focus on three main results. **1)** The diffuse gas shows clear signatures from three distinct outbursts of the central AGN, with three pairs of roughly collinear cavities. The inner two cavity pairs are associated with unambiguous elliptical shock fronts, with Mach numbers M~1.7 and M~1.5 for the inner and outer shocks, respectively. **2)** The mean power of the two most recent outbursts differs by a factor of six, indicating that the mean jet power varies over long (~10^7 yr) time scles. **3)** The heating from the shocks alone is sufficient to balance radiative cooling of the gas within at least the central 10 kpc, allowing feedback to operate isotropically at small radii. The internal energy of the cavities is not required. With signatures from multiple AGN outbursts in an otherwise dynamically relaxed system, NGC 5813 provides a unique opportunity to study the outburst history and feedback of the central AGN.



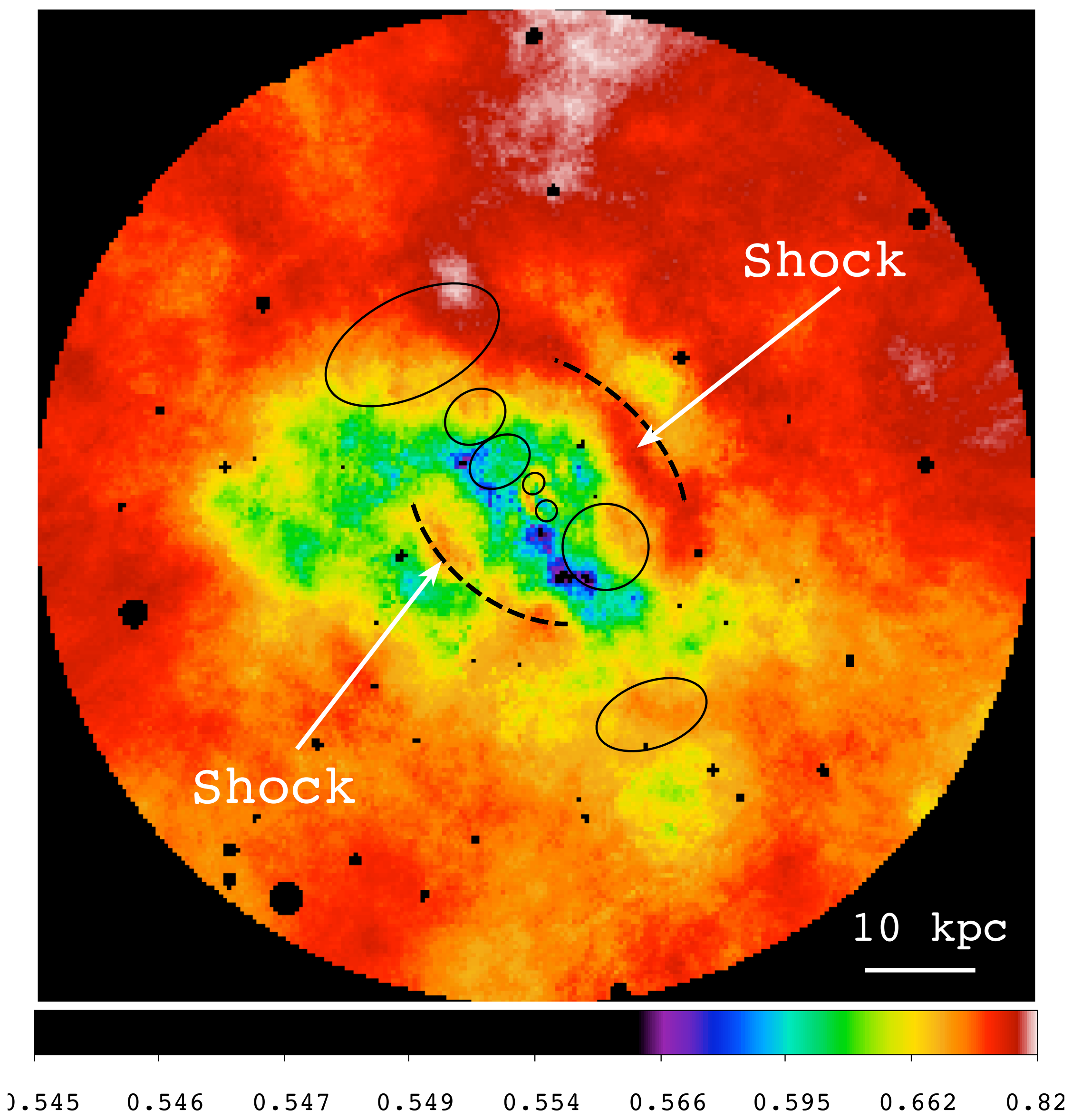
Exposure corrected, background subtracted, 0.3-2.0 keV Chandra image of N5813, smoothed with a 1.5" radius Gaussian. Point sources have been removed and filled in. The image shows two pairs of cavities, plus an outer cavity to the northeast, two sharp edges to the northwest and southeast, and bright rims surrounding the inner pair of cavities.



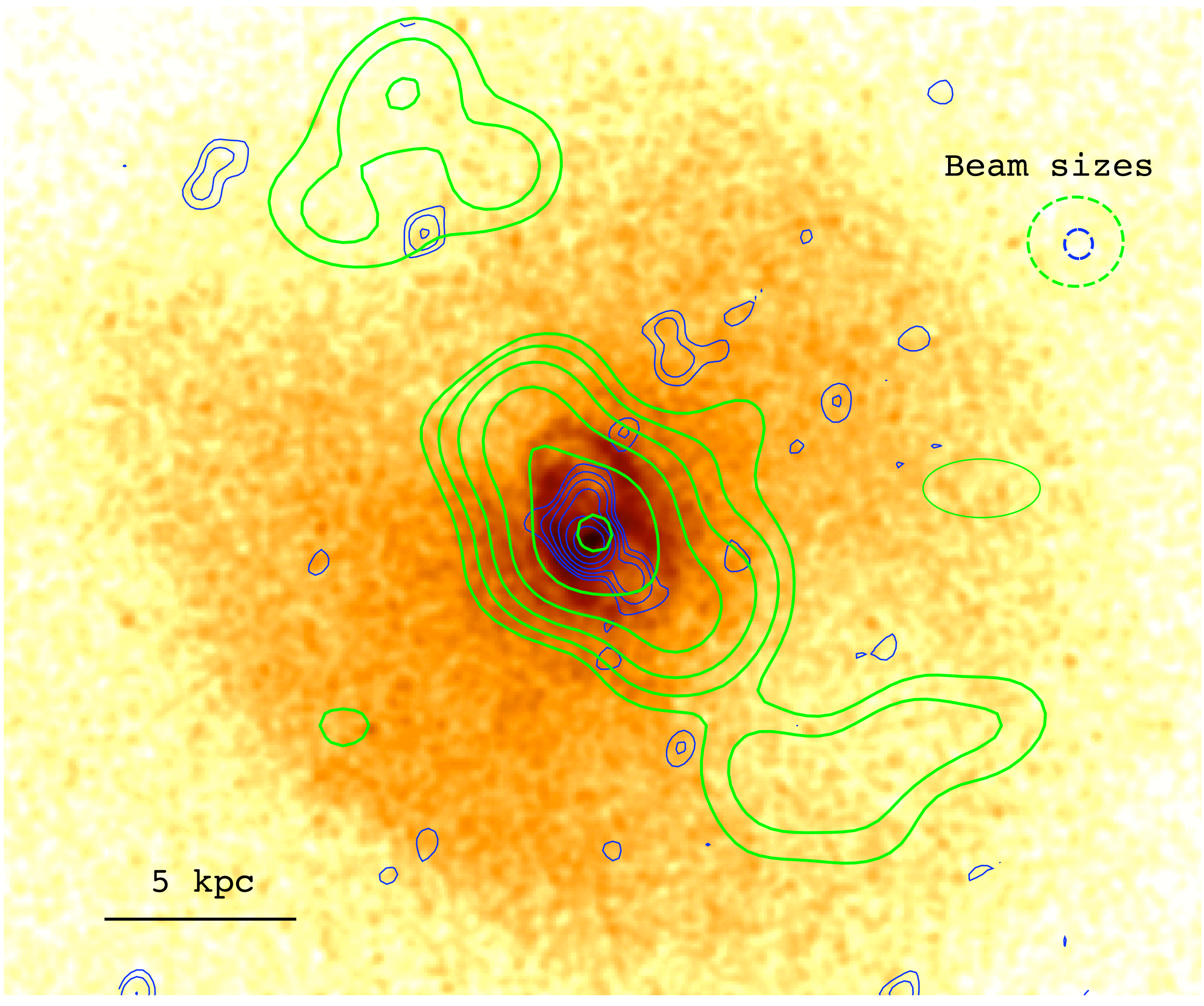
Unsmoothed image of the core, showing the inner cavities and bright rims. The middle cavities are indicated by the black circles. The central point source AGN is visible.



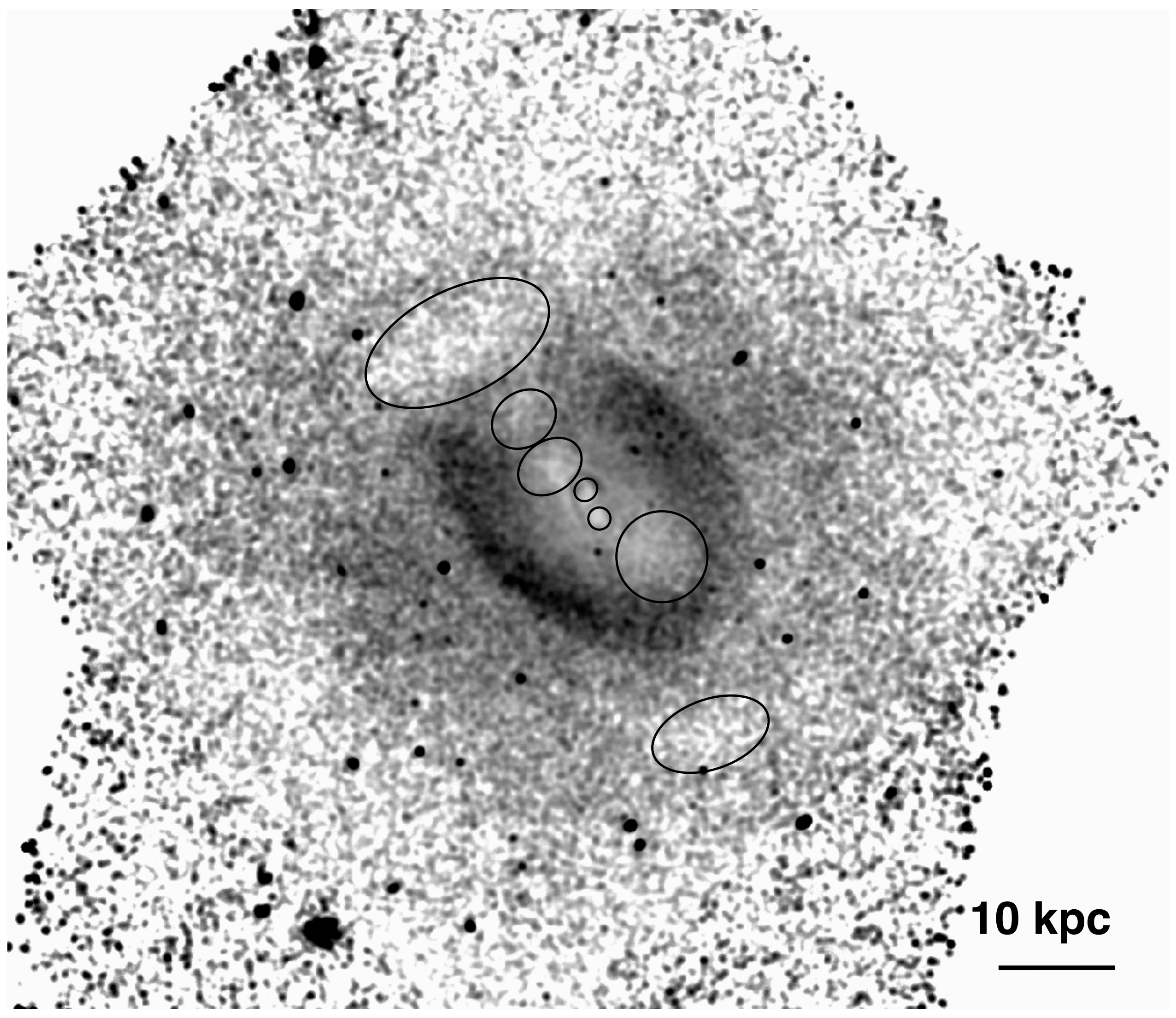
High spatial resolution temperature map of the core, with X-ray brightness contours overlaid. The rims are revealed to be hot gas, shocked by the expanding cavities. Detailed analysis indicates a Mach number of M~1.7



X-ray temperature map. The edges, indicated by the black dashed lines, are revealed to be hot shock fronts. Detailed fits to the emissivity profile indicate a Mach number of M~1.5 for each shock. The locations of the cavities are indicated by the black ellipses. The temperature map also reveals a filament of cool gas, coincident with Hα emission, that has been lifted by the buoyantly rising cavities.



X-ray image with 1.4 GHz VLA (blue) and 235 MHz GMRT (green) contours overlaid. 1.4 GHz emission fills the inner cavities, while 235 MHz emission overfills the inner cavities and is detected in the intermediate cavities. The outer cavities are not detected in the radio. This is consistent with a scenario where a high-energy particle population is injected at each outburst, then ages passively once the cavities detach and rise buoyantly. Radio pressure estimates that assume equipartition and electron dominated pressure show that the cavities are underpressured by two orders of magnitude compared to the surrounding X-ray gas. This indicates that either the pressure is not electron dominated (with the energy in protons about 2000 times the energy in electrons), or that the assumption of hydrostatic equilibrium is invalid.



X-ray image divided by a β-model to highlight faint features. This image reveals a weak outer cavity to the southwest, which is "paired" to the outer southeastern cavity, but lacks a surrounding bright rim of emission. The northeastern cavity is split into two overlapping cavities.

DISCUSSION For each outburst, the total energy is measured by the internal energy of the cavities plus the shock energy (the radiative energy output is negligible). The cavity energy is estimated as 3PV, where P is the gas pressure at the radius of the cavity. The shock energy is estimated by matching 1D hydrodynamic point explosion simulations with the X-ray image (the results of which agree well with simple analytic estimates). The Mach numbers of the shocks give the ages of the outbursts. We find that the mean power of the current outburst (associated with the central cavities) is less than that of the previous outburst (associated with the middle cavities), by about a factor of six (1.5×10^{42} erg/s vs. 1.0×10^{43} erg/s). This demonstrates that the mean jet power of the central AGN varies significantly over the timescale between outbursts (~10^7 yr).

The heating of the ICM locally at each shock front can be determined from the measured shock properties. To offset radiative cooling in the gas, the heating mechanism is required to increase the gas entropy. For weak shocks, the entropy jump ΔS across the shock front is small (5%-10%). Expressed as a fraction of the local thermal energy of the gas E, the heat input at the shock front is

$(T\,\Delta S)/E = \Delta\ln(P/\rho^{\gamma})$. We find this fraction to be 10% and 5% for the inner and outer shocks, respectively. Therefore, 1/0.1 = 10 (1/0.05 = 20) shocks are needed per local cooling time of the gas to offset radiative cooling at the 1.5 kpc (10 kpc) shock front. The cooling time of the gas, measured directly from the X-ray observations, is 2×10^8 yr (9×10^8 yr), so that the outburst interval of 10^7 yr gives 20 (90) shocks per cooling time. Thus, the heat input from shocks alone is sufficient to balance radiative cooling of the gas within at least the central 10 kpc.

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