

Title: Evolution of Hot Gas in Elliptical Galaxies

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This theory grant was awarded to study the curious nature, origin and evolution of hot gas in elliptical galaxies and their surrounding groups. Understanding the properties of this X-ray emitting gas has profound implications over the broad landscape of modern astrophysics: cosmology, galaxy formation, star formation, cosmic metal enrichment, galactic structure and dynamics, and the physics of hot gases containing dust and magnetic fields. One of our principal specific objectives was to interpret the marvelous new observations from the *XMM* and *Chandra* satellite X-ray telescopes.

Thanks to the funding received from NASA, we have made much progress in understanding this new X-ray data. We employ a wide variety of theoretical techniques, always emphasizing the mutual constraints of X-ray, optical and infrared observations. Our success has been possible because of our excellent collaborators: Fabrizio Brighenti in Bologna, David Buote at UC Irvine and Pasquale Temi at NASA/Ames. We have worked closely with David Buote and his excellent team of postdocs in applying for (and obtaining) new X-ray observations specifically tailored to distinguish between our various theoretical models. Likewise we have helped Pasquale Temi obtain and interpret farIR ISO observations of elliptical galaxies that contain hot gas. But our main interest continues to be in developing gasdynamical models to improve our understanding of these remarkable objects. Our research program in Santa Cruz is one of the few theory groups currently focused on gas dynamical and physical problems related to hot gas in galaxies and groups.

Below we briefly summarize the 18 papers we have published with the help of grant NASA 5-8409, including 3 papers in press; we do not include contributions to meetings and several additional papers in preparation. We were particularly pleased to receive an invitation to review our NASA-sponsored work in an *Annual Reviews* article (P12) which also provided an opportunity to sort through the entire literature and update our research priorities for the future. We have not included below shorter (often redundant) papers presented at meetings or work that is still in preparation.

(P1) Spatial Diffusion of X-Ray Emission Lines in the M87 Cooling Flow; Evidence for Absorption

Mathews, W., Buote, D. A. & Brighenti, F. 2001, ApJ, 550, L31

The apparent decrease in hot gas abundances of iron and silicon within 5 kpc from the center of M87 was thought to be due to the outward diffusion of X-ray resonance lines before escaping the cluster gas. But the detailed radiative transfer calculations described here show that the line opacity is insufficient to explain the central abundance dips this way.

(P2) Entropy Evolution in Galaxy Groups and Clusters: a Comparison of External and Internal Heating

Brighenti, F. & Mathews, W. G. 2001, ApJ, 553, 103

The entropy of hot gas in galaxy groups exceeds that received in the accretion shock when the gas fell into the dark halos. Using gas dynamical calculations, we investigate two entropy-increasing scenarios: preheating at high redshifts and internal heating by Type II supernovae associated with star formation. External preheating is unsatisfactory: when the X-ray luminosity is brought into agreement, the current gas entropy is too high. Evolutionary flows with radiative losses and internal heating by SNII or AGN agree much better with X-ray observations.

(P3) Confrontation of Intracluster and Interstellar Gas in Cluster-Centered E Galaxies: M87 (Virgo) and NGC 4874 (Coma)

Brighenti, F. & Mathews, W. G. 2002, ApJ, 567, 130

Chandra observations of cluster-centered elliptical galaxies show that the gas temperature drops from 3-5 keV to the galactic virial temperature ~ 1 keV between 50-10 kpc from the galactic centers. We describe time-dependent gas dynamical accretion flows that agree with these steep temperature gradients provided thermal conduction is suppressed.

(P4) Creation of X-Ray Holes with Cool Rims in Cooling Flows

Brighenti, F. & Mathews, W. G. 2002, ApJ, 574, L11

Gasdynamical models show how density irregularities and large, randomly oriented holes apparent in Chandra images of elliptical galaxies are naturally produced by intermittent AGN heating near the center. The gaseous rims around the X-ray holes are cool, just like the observations. We show with an analytic similarity solution that these cold rims are expected when gas is heated in a region of low entropy.

(P5) Heated Cooling Flows

Brighenti, F. & Mathews, W. G. 2002, ApJ, 573, 542

Cooling flows are not observed to cool. We explore the gasdynamical evolution of hot gas in groups and clusters in which radiative cooling is offset by AGN heating near a central black hole, but the detailed physics of the heating process is unspecified. Many spatial and temporal scenarios are considered for the heating but none of the flows agrees with observed density and temperature profiles, even when the heating parameters are fine-tuned. The computed central temperature gradient is negative, opposite to that commonly observed. Idealized flows in which radiative cooling is perfectly balanced by global heating are grossly incompatible with observations. Feedback-driven flows produce quasi-cyclic variations in the hot gas density profile that do not resemble the observations. If the heating does not extend to the cooling radius, the cooling rate is unchanged but occurs at a larger radius in the flow.

(P6) Dust in Hot Gas: Far-Infrared Emission from Three Local Elliptical Galaxies

Temi, P., Mathews, W. G., Brighenti, F. & Bregman, J. D. 2003, ApJ, 585, L121

Three luminous elliptical galaxies in the Virgo cluster are observed with ISO at 60, 90 and 180 microns. NGC 4472 and NGC 4649 are undetected, but emission from interstellar dust in NGC 4636 is detected at all three wavelengths. We calculate the expected far-infrared emission during the sputtering lifetime of dust expelled from red giants. Dust is heated by both starlight and electron impacts. The far-IR luminosities of NGC 4472 and NGC 4649 are consistent with expectations, but that of NGC 4636 is about 40 times larger. NGC 4636 may have experienced a very recent merger less than a few 10^8 years ago.

(P7) Feedback Heating in Cluster and Galactic Cooling Flows

Brighenti, F. & Mathews, W. G. 2003, ApJ, 587, 580

Evolutionary gasdynamical calculations of hot gas in rich clusters have density and temperature profiles and low cooling rates that agree with observations provided central AGN feedback heating is redistributed by thermal conduction at 0.3 of the Spitzer value. But similar flows with heating and conduction fail on smaller galaxy group scales: when the feedback heating is large enough to reduce the cooling to the observed level, the central gas temperatures and iron abundances are both much too high.

(P8) Rapid Cooling of Dusty Gas in Elliptical Galaxies

Mathews, W. G. & Brighenti, F. 2003a, ApJ, 590, L5

Dusty cores observed in most elliptical galaxies are usually thought to result from recent mergers with dust-rich galaxies even when their environments contain no such galaxies. We argue here that the central dust has a stellar origin. Dust ejected from evolving red giant stars in elliptical galaxies cools rapidly after entering the hot, X-ray emitting gas. Cooling by inelastic collisions between thermal electrons and dust grains can be faster than the galactic dynamical time and the grain sputtering time. Some dust grains survive in the cooled gas.

(P9) XMM-Newton and Chandra Observations of the Galaxy Group NGC 5044. I. Evidence for Limited Multiphase Hot Gas

Buote, D. A., Lewis, A. D., Brighenti, F. & Mathews, W. G. 2003a, ApJ, 594, 741

Using new XMM and Chandra observations, we describe the temperature structure of the hot gas within the central 100 kpc in the bright nearby galaxy group NGC 5044. Within 30 kpc the spatially deprojected data are best described with a range of gas temperatures, $T_c = 0.7 \lesssim T \lesssim 1.3 = T_h$ keV, but $T \approx T_h$ keV beyond. T_h is similar to the dark halo virial temperature. Very little or no gas has $T < T_c$ keV. Fluctuations in the X-ray surface brightness within 20 kpc are consistent with density variations accompanying the temperature variations $T_c \leftrightarrow T_h$ in pressure equilibrium, as expected from intermittent AGN feedback heating.

(P10) XMM-Newton and Chandra Observations of the Galaxy Group NGC 5044. II. Metal Abundances and Supernova Fraction

Buote, D. A., Lewis, A. D., Brighenti, F. & Mathews, W. G. 2003b, ApJ, 595, 151

Using new *XMM* and *Chandra* observations, we present a detailed analysis of the metal abundances in the hot gas within a radius of 100 kpc in the bright galaxy group NGC 5044. The iron abundance drops from about solar within 50 kpc to about 0.4 solar near 100 kpc. Within 48 kpc we obtain $\text{Si}/\text{Fe} = 0.83$ and $\text{S}/\text{Fe} = 0.54$ in solar units, implying that Type Ia supernovae have contributed about 80 percent of the iron mass within 100 kpc. The iron abundance drops by a factor of 2 inside the central 2 kpc.

(P11) Circulation Flows: Cooling Flows with Bubble Return

Mathews, W. G., Brighenti, F., Buote, D. A., & Lewis, A. D. 2003, *ApJ*, 596, 159

We describe a new type of steady state flow for galaxy groups and clusters in which gas moves in both radial directions simultaneously. Hot, buoyant bubbles formed by AGN heating near the center return the inflowing, radiatively cooling gas to distant regions in the flow. The rising bubbles heat the inflowing gas. The emission-weighted temperature profiles in these idealized circulating flows resemble those of normal cooling flows but no gas cools to $T \ll T_{\text{vir}}$ at any radius within the circulating gas.

(P12) Hot Gas in and Around Elliptical Galaxies

Mathews, W. G. & Brighenti, F. 2003b, *Ann. Rev. Astron. & Astroph.*, 41, 191

We review the origin, evolution and physical nature of hot gas in elliptical galaxies and associated galaxy groups. Unanticipated recent X-ray observations with the *Chandra* and *XMM* X-ray telescopes indicate much less cooling than previously expected. Consequently, many long-held assumptions need to be reexamined or discarded and new approaches must be explored. Chief among these are the role of heating by active galactic nuclei, the influence of radio lobes on the hot gas, details of the cooling process, possible relation between the hot and colder gas in elliptical galaxies, and the complexities of stellar enrichment of the hot gas.

(P13) Stellar Orbits and the Interstellar Gas Temperature in Elliptical Galaxies

Mathews, W. G. & Brighenti, F. 2003c, *ApJ*, 599, 992

We draw attention to the close relationship between the anisotropy parameter $\beta(r)$ for stellar orbits in elliptical galaxies and the temperature profile $T(r)$ in the hot interstellar gas through which the stars move. Since the stellar luminosity density and the gas density are accurately known from optical and X-ray surface brightness observations, $\beta(r)$ and $T(r)$ are related by the Jeans and hydrostatic equations. Purely optical determinations of $\beta(r)$ and X-ray determinations of $T(r)$ are currently inconsistent for the bright elliptical NGC 4472.

(P14) Cold Dust in Early-Type Galaxies: I. Observations

Temi, T., Brighenti, F., Mathews, W. G., & Bregman, J. D. 2004, *ApJ*, 151, 237

We describe far-infrared *ISO* observations of 39 giant elliptical galaxies at 60, 100 and 200 μm . The far infrared spectral energy distributions can be modeled with dust at temperatures 20-43 K. The integrated far infrared luminosities do not correlate with optical luminosities. The total dust masses are more than ten times larger than those found with *IRAS*.

(P15) Ultralow Iron Abundances in the Distant Hot Gas in Galaxy Groups

Buote, D. A., Brighenti, F. & Mathews, W. G. 2004, ApJ, 607, L91

A new XMM observation of the outer regions of the galaxy group NGC 5044 indicates hot gas iron abundances of only $Z_{Fe} \approx 0.15Z_{Fe\odot}$ in $r \approx 0.2 - 0.4r_{vir}$ ($r \approx 150 - 350$ kpc). The NGC 5044 group consists of a single giant E galaxy surrounded by ~ 160 dE galaxies extending out to ~ 500 kpc. While the total baryon mass within the virial radius (870 kpc) is within 15% of the cosmic (WMAP) mean value observed in rich clusters, the ratio of total iron mass to optical light in NGC 5044 is about 3 times lower than that in rich clusters. The low gas phase Z_{Fe} in $r > 150$ kpc is also inconsistent with the commonly held notion that newly formed dE galaxies enrich their environments with iron-rich winds.

(P16) Time-dependent Circulation Flows: Iron Enrichment in Cooling Flows with Heated Return Flows

Mathews, W. G., Brighenti, F. & Buote, D. A. 2004, ApJ, (accepted); (astro-ph/0407367)

We develop a new set of integro-differential time-dependent gasdynamical equations that allow hot gas in galaxy groups and clusters to flow simultaneously in both radial directions. Hot centrally heated bubbles move radially out through a denser cooling inflow. Many cluster-centered elliptical galaxies are surrounded by a region of SNIa-enriched gas extending out to ~ 150 kpc. The total iron mass in this region, $\sim 10^8 M_{\odot}$, is comparable to the total iron from all historic galactic SNIae, suggesting that this gas has been circulating for nearly a Hubble time. To maintain the circulation, both mass and energy must be supplied to the inflowing gas over a large volume extending to the cooling radius. These circulation flows are the first gasdynamic, long-term evolutionary models that are in good agreement with all essential features observed in the hot gas: little or no gas cools as required by XMM spectra, the apparent gas temperature increases outward near the center, and the gaseous iron abundance is about solar near the center and decreases outward.

(P17) Absence of Dwarf Galaxies at High Redshifts: Evidence from a Galaxy Group

Mathews, W. G., Chomiuk, L., Brighenti, F. & Buote, D. A., 2004, ApJ, (accepted); (astro-ph/0408144)

The galaxy group NGC 5044 consists of a luminous giant elliptical galaxy surrounded by a cluster ~ 160 dE galaxies. The radial distribution of dwarf galaxies in the NGC 5044 group does not follow a dark matter (NFW) profile, unlike distributions of more luminous galaxies in rich clusters. There is a marked deficiency or absence of dE galaxies in the NGC 5044 group within 350 kpc or $0.3r_{vir}$, i.e. very few surviving dwarfs entered the virial radius at redshifts $z \gtrsim 2 - 3$. The absence of old dE galaxies cannot be a result of dynamical friction.

(P18) The Ages of Elliptical Galaxies from Mid-Infrared Emission

Temì, P., Mathews, W. G. & Brighenti, F., 2004, ApJ, (accepted)

The mid-infrared (10-20 μm) luminosity of elliptical galaxies is dominated by emission from circumstellar dust around red giant stars. As a single stellar population evolves, the rate of dusty mass loss from red giants decreases and so should the mid-infrared luminosity. We used archival ISO observations to determine the surface brightness profiles $\mu_{15\mu\text{m}}(R)$ and fluxes of 17 E galaxies at 15 μm having stellar ages known from optical spectral indices. The ratio $\mu_{15\mu\text{m}}/\mu_{I\text{-band}}$ is systematically higher in elliptical galaxies with ages $\lesssim 5$ Gyrs and in post-merger galaxies, but $\mu_{15\mu\text{m}}/\mu_{I\text{-band}}$ shows no age dependence for ages $\gtrsim 5$ Gyrs. No 15 μm emission is detected from central dust clouds visible in some of our sample galaxies, but several ellipticals have extended regions of 15 μm emission that have no counterparts at other frequencies.

Overall, NAG5-8409 has been a most productive grant for us and continues to inform our understanding of hot gas in galaxy groups and the remarkable physics required to understand them.

Sincerely,

William G. Mathews
Professor of Astronomy & Astrophysics