EFFECTS OF ACTIVE GALAXY FEEDBACK ON THE INTRACLUSTER MEDIUM

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EXECUTIVE SUMMARY

The research team has used Blue Waters to apply a novel approach to a key question regarding the intracluster medium (ICM), the hot plasma trapped in the gravitational potential wells of galaxy clusters: namely, how relativistic jets produced by accreting black holes regulate the radiative cooling of the ICM. The team uses hydrodynamical simulations of cluster cores with a subgrid model for black hole accretion to study the ability of jets to efficiently and uniformly deposit heat into the ICM. The model improves on existing techniques by directly measuring the accretion rate onto the black hole, linking it to a model of the accretion disk, and using the result to determine the feedback efficiency. In 2019, the researchers have used parts of this framework to study the role of jet precession and ICM turbulence in making feedback more isotropic.

RESEARCH CHALLENGE

Loss by the ICM should cause the gas to lose pressure support against gravity, condensing to form stars at prodigious rates. Generally, this star formation is not observed; instead, cluster central galaxies are overwhelmingly "red and dead," with little or no star formation and very old stellar populations. Some heating process must offset the radiative cooling. The most likely candidate is energy input by the supermassive (approximately 109 solar mass) black holes (SMBHs) found at the centers of clusters. When actively accreting matter and producing relativistic jets, these are the central engines of what are called active galactic nuclei (AGN). High-resolution X-ray and radio observations clearly show AGN disturbing and heating the ICM gas.

However, tuning the amount of feedback to match the cooling rate and distributing it so that the gas is evenly heated are serious theoretical problems. This requires connecting processes occurring in accretion disks around black holes smaller than the solar system with plasma physics as much as 30,000 light years away. The modeling of AGN feedback usually involves a subgrid model and considerable simplification of the complex physics involved in the region surrounding the AGN's central black hole. Such approaches still have major shortcomings. Often, the multiphase structure of the gas is not incorporated, and accretion rates are estimated using spherically symmetric models applied to data on scales much larger than the accretion region. The efficiency of feedback is taken to be a constant, tuned to roughly reproduce the central entropies of clusters.

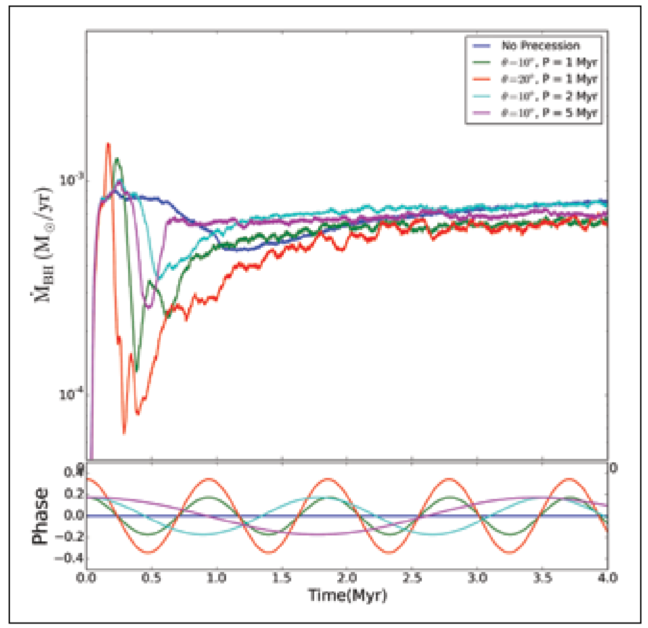

Figure 1: (Top panel) Accretion rate versus time for precessing jets with different periods and precession angles. (Bottom panel) Precession phase versus time. Time is measured in millions of years (Myr).

The research team's approach, which borrows from techniques used in star formation and stellar evolution, applies a sink particle model to directly measure the accretion rate onto the black hole plus accretion disk system. The core of the cluster is resolved at scales of a few light years, allowing the complex gas structure in the vicinity of the AGN to be directly simulated. The efficiency and mode of feedback, as well as the growth rate of the black hole, are determined by matching the sink particle formalism to a model of the accretion disk that is informed by accretion disk simulations in the literature.

METHODS & CODES

This work uses the adaptive mesh refinement (AMR) hydrodynamics plus N-body code FLASH 4. FLASH 4's AMR is an Eulerian flow simulation method that allows high-resolution meshes to be placed only in regions of interest. It also uses a hydrodynamics solver based on the piecewise-parabolic method. In local idealized simulations, turbulent stirring is imposed in a manner that follows a Kolmogorov-like spectrum by adding a divergence-free, time-correlated velocity evolved by an Ornstein–Uhlenbeck random process. Radiative cooling using a metallicity-dependent cooling function assures that the gas reaches the densities needed to trigger feedback events.

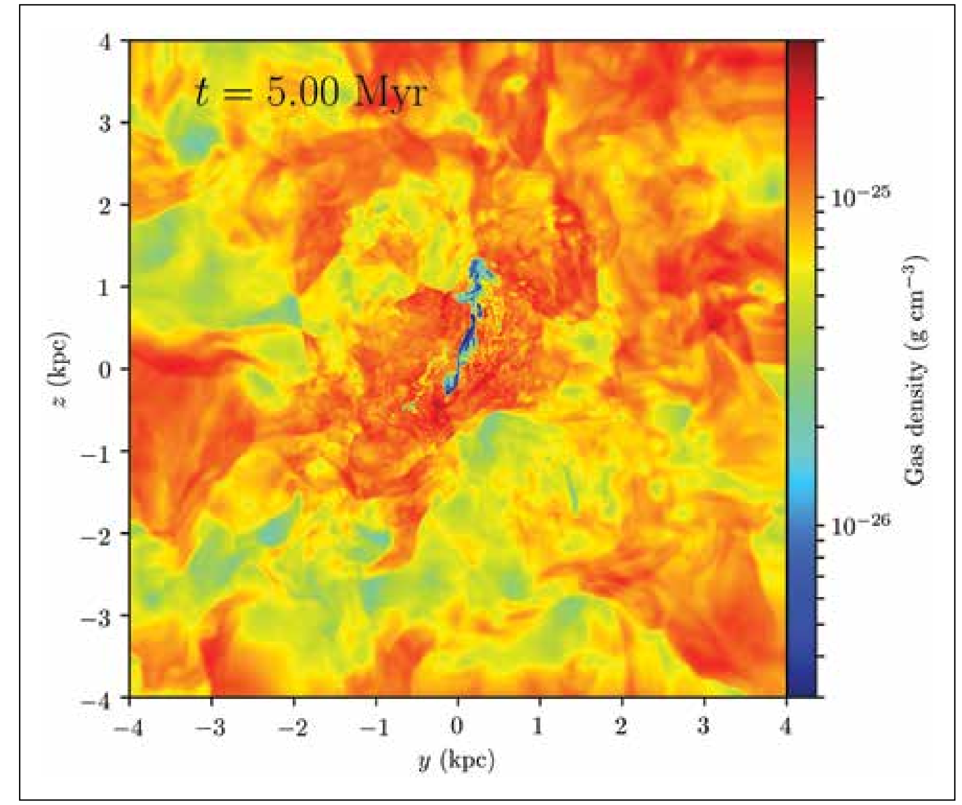

Figure 2: Gas density slice from a FLASH simulation including jet precession and turbulent driving. The region shown is 8 kiloparsecs (about 26,000 light years) across.

RESULTS & IMPACT

The researchers have used parts of the subgrid framework outlined above to study the ability of jet precession and turbulence to isotropize heating of the ICM. Accretion rates are measured using fluxes on a control surface surrounding the AGN, and feedback efficiency is held constant. They allow the AGN jet to precess, constraining the precession angle and period with observations of jet morphology in radio and X-ray maps. In some simulations, they introduce turbulent stirring to model the effects of galaxy wakes and cluster mergers. The team used recent Hitomi observations of the Perseus cluster to set the stirring energy.

They have conducted isolated cluster-core simulations with stationary and precessing jets as well as without turbulence and with weak or strong turbulence corresponding to different turbulent velocity dispersion values. Fig. 1 shows an example of the evolution of accretion rate in the team's simulations. The researchers have found that precession helps jets deposit energy in a more distributed manner but suppresses accretion onto the SMBH by sweeping away a larger volume of gas. Larger precession angles seem to contribute to a time lag between accretion and feedback.

Fig. 2 shows an example of one of the runs with both precessing jets and turbulent driving. The researchers have discovered that while turbulent driving itself enhances the kinetic energy of the ICM and triggers accretion, with precessing jets and weaker turbulent driving, the gas primarily passes through strong shocks produced by the jet, and cavity-like structures are formed. However, the situation changes with stronger turbulence, where the jet material gets blown away and the accretion process is enhanced by inflow of hot gas, allowing more energy to be deposited in the ICM. This coupling between jet precession and turbulent driving thus helps to regulate AGN feedback.

WHY BLUE WATERS

Numerous complex physical processes are involved in the ICM. The required dynamic ranges in space and time are very large. These features make the ICM a natural setting for simulation studies that exploit the unique characteristics of Blue Waters. The researchers' improved approach to measuring accretion rates and introducing feedback increases the complexity of the simulations in the innermost region close to the SMBH, which inevitably increases the cost. The computing ability of Blue Waters provides resources for such calculations to be done.

PUBLICATIONS & DATA SETS

Y. Lu and P. M. Ricker, "AGN feedback from precessing jets on the turbulent intracluster medium," presented at the 234th Meeting of the American Astronomical Society, St. Louis, MO, U.S.A., June 11, 2019, Paper id. 228.04.