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Generation of Internal Waves by Buoyant Bubbles in Galaxy Clusters and Heating of Intracluster Medium

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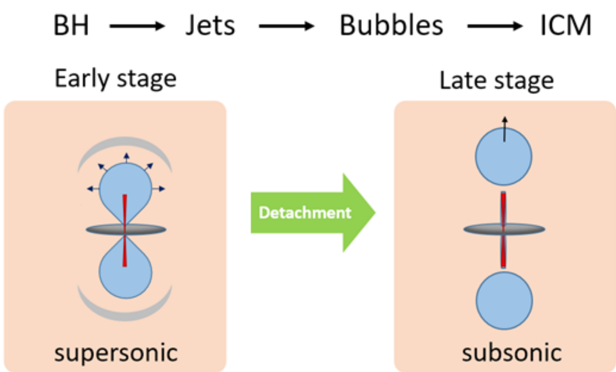
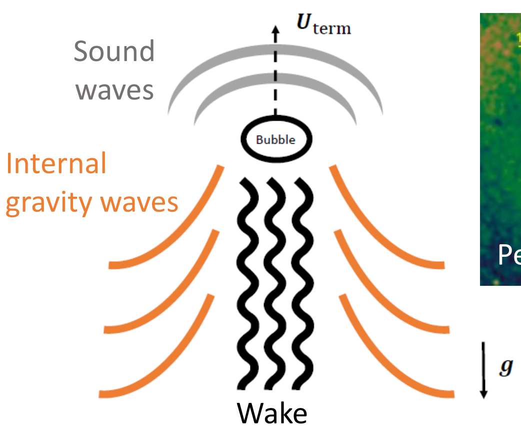
Introduction

Radio-mode of AGN feedback has been widely accepted as the possible heating mechanism in galaxy clusters. X-ray bubbles play a crucial role in transferring the energy from the supermassive black holes to intracluster medium (ICM) in this process. These bubbles are inflated by bipolar jets, and then detach from the cluster center and buoyantly rise outwards, illustrating in the sketch below.



However, numerical simulations face a big challenge in modeling bubble dynamics. Buoyant bubbles are susceptible to the instabilities in hydrodynamic simulations, collapsing once it has risen more than its own height. On the contrary, old bubbles with regular shape far from the cluster center are observed in our nearby clusters (e.g., Perseus). This discrepancy implies that (1) turbulence is overproduced in the simulations and its role in heating the ICM is overestimated; (2) the interaction between the ICM and intact bubbles is missing in the numerical modeling.

Analogy to a boat moving in water, intact bubbles are expected to drive *(internal) gravity waves* in the ICM (orange lines in the sketch below). They may play an important role in heating the cluster gas atmosphere.



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Internal gravity waves

In our numerical simulations, we model the bubbles phenomenologically as rigid bodies buoyantly rising in the stratified cluster atmosphere. We find that the terminal velocities of the flattened bubbles are small enough so that the Froude number Fr < 1. A sufficient condition for efficient excitation of internal gravity waves in stratified cluster atmospheres is flattening of the bubbles in the radial direction.

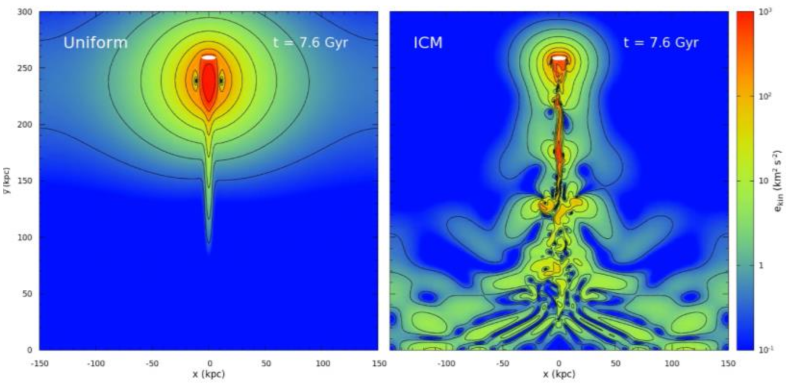
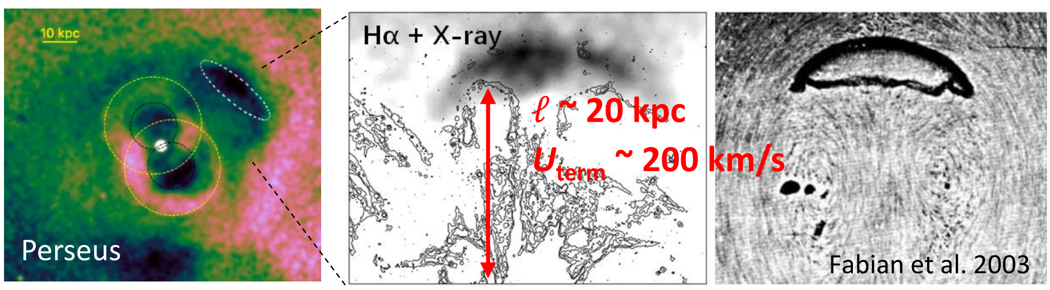


Figure above shows a comparison between the flattened bubbles moving in the uniform and stratified medium. In the latter, the bubble makes a significant impact on the far-field gas. The excited internal waves reveal themselves as a "Christmas tree" pattern.

Bubble terminal velocity

We find a relation between the vertical size ℓ of the vortex behind the rising bubble and the ratio between the bubble's terminal velocity $U_{\rm term}$ and Brunt–Väisälä frequency N of the atmosphere in our simulations, i.e., $\ell \sim U_{\rm term}/N$. It helps us constrain the terminal velocity of the northwestern bubble in the Perseus cluster (~200 km/s; see figure below).



Such a velocity is in line with the gas velocity dispersion in the bubble region measured by the Hitomi satellite, reflecting the effect of bubbles in stirring the ICM.