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NUMERICAL SIMULATIONS OF GALACTIC WAKES

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It has long been supposed that the passage of a galaxy through a gaseous medium may produce an observable wake in the form of enhanced X-ray emission. This enhancement may be the result of a bow shock or, depending on the boundary conditions one assumes, a reflection shock downstream from the galaxy. The general problem of flow past a gravitating body has been studied previously by several authors. To simplify the calculations, one often assumes a point mass for the gravitating body (appropriate for accretion onto a compact object: *e.g.* numerical simulations by Fryxell et al., 1991 ApJ 371, 696 and references therein; Hunt 1971 MNRAS 154, 141) and either hypersonic or subsonic flow (e.g., analytic treatments by Ruderman & Spiegel 1971 ApJ 165, 1; Miller 1986 MNRAS 220, 713). A numerical calculation allows for arbitrary Mach number M as well as a nonsingular potential, which is more appropriate than a point mass when considering flow past a galaxy.

We have performed a series of numerical simulations which examine the simple but realistic case of a galaxy with a smooth potential corresponding to a King profile, and with no interstellar medium. This corresponds to the case of an early-type cluster galaxy that has previously been stripped of its gas. The simulations provide a numerical basis for future work involving galaxies with interstellar media. We use a time-explicit finite difference code (Lufkin & Hawley 1992, ApJ submitted) to obtain solutions to the nonlinear equations for adiabatic flow in axisymmetry. The computational grid covers a region extending 500 kpc from a stationary galaxy radially and along the symmetry axis. We use a graded mesh, allowing for full resolution near the galaxy. Because the assumed potential has a finite depth, no artificial inner boundary condition is necessary; reflection symmetry at the axis is assumed. With a total grid size of 64 radial × 128 vertical, each run requires approximately 5 minutes of cpu time on the NCSA Cray-2.

The initial configuration is that of uniform flow parallel to the axis throughout the computational domain. Gas enters at the $-z$ boundary, with velocity v_0 and temperature T_0. One can express the equations describing the flow in such a way that the gas density enters only through a logarithmic derivative. The flow is therefore insensitive to the value of the ambient density, provided the cooling time is long compared to a dynamical time. Hence, for a given perturbing potential, the flow properties are completely determined by the ambient temperature and velocity. However, because the X-ray emissivity is proportional to the square of the density, we choose ambient densities that are consistent with pressure equilibrium with a hot cluster atmopsphere.

The target galaxy has a potential well of finite depth corresponding to a velocity dispersion of about $250\,\mathrm{km\,s^{-1}}$ inside of 10 kpc. The highest velocities we consider here ($\sim 3000\,\mathrm{km\,s^{-1}}$) are probably rare in real clusters, but not impossible, as 3-D velocity dispersions exceed $2000\,\mathrm{km\,s^{-1}}$ in rich clusters. The mean free path is $l \sim 30\,T_8^2\,n^{-1}$ pc. Thus, shocks need be considered collisionless only at high temperature and low density (i.e., for a total number density $n \lesssim 10^{-2}$). Results are as follows:

- A bow shock develops quickly, within about one core radius of the center of the galaxy. The wings of the bow shock then stretch out along the Mach cone, with the flow asymptotically reaching a steady state. Full development of the shock takes less than about 5×10^8 yr. The shock arises solely from the gravitational perturbation caused by the galaxy's potential well, as there are no physical obstructions.
- The shock strength is sensitive to $\eta \equiv \frac{\text{local freefall time}}{\text{local crossing time}}$. That is, for a given impact parameter, a fluid particle is deflected most efficiently when the incident velocity is low, but not subsonic. We therefore see the strongest shocks at intermediate Mach numbers ($M \sim 2$) and low temperatures ($T \sim 10^7$ K).
- The Mach cone is a fair approximation to the shape of the wake, but is exact only in the weak-shock limit ($\eta \gg 1$). If the gas is heated significantly, the increased pressure buoys the shock out, so that the wake is slightly wider than one would expect from the Mach angle $\alpha = \sin^{-1}(1/M)$.
- The upstream flow is very nearly incompressible, as predicted analytically (references above).
- The perturbed velocity field shows no evidence of turbulence. This conclusion may change if 1) Axisymmetry is broken (full 3-D) or, 2) An obstruction is placed in the galaxy, either as a hard boundary or as a dense interstellar medium.
- The induced drag on the galaxy, calculated by direct summation, is within a factor of two of the value one would predict using analytic estimates for flow of a collisionless gas past a point mass. The drag rate is found to be inversely proportional to the gas velocity, also in agreement with the classical formula.
- The derived X-ray surface brightness profiles are neither limb-brightened nor limb-darkened. A mild density enhancement just at the shock is offset by the greater column through the interior.
- The wakes produced in low-temperature gas should be bright enough to observe with ROSAT. However, the low-temperature gas in clusters has been observed to have considerable filamentary structure on scales smaller than the size of the wakes (e.g., Sarazin et al. 1992 ApJ 389, L59).
- Wakes in hot gas ($T \sim 10^8$ K) are probably not observable. The simulated wake with $M = 2$ and $T = 10^7$ K is ten times brighter (bolometric luminosity, background subtracted) than the $M = 2, T = 8 \times 10^7$ run, assuming both have a total number density equal to 10^{-2} cm^{-3}. The former, with a conservative bolometric correction (25%), should be detectable by the proportional counter with S/N=5 in a five-minute integration. The low densities typical of hot, extended cluster atmospheres could make the latter very difficult to see, even if the hot gas is smoothly distributed.
- If wakes are seen in X-ray images, then they may provide direct measurements of galaxy velocities transverse to the line of sight. This assumes, however, that the temperature and the gas velocity with respect to the cluster mean are known. Wakes may also be illuminated by head-tail radio sources, where jets of relativistic particles are ejected transverse to the flow.