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COOLING AND THE LONGEVITY OF POLAR RINGS

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ABSTRACT

Many early-type galaxies contain gas in a nearly polar ring. In static potentials the only possible equilibrium configurations for dissipative gas are closed nonintersecting orbits in a preferred plane of the potential. The application of equilibrium models to observed gas velocity fields, however, has proved problematic, suggesting the consideration of a wider range of models including time dependence. As an example of such a configuration we consider gas on a nearly polar orbit in an oblate, rigid potential.

We argue that the rapid evolution of highly inclined rings, observed in previous numerical experiments, is due to both artificial instabilities caused by the lack of radiative cooling and due to the lack of numerical resolution. In static oblate and near-oblate potentials, highly inclined, dissipative rings are long-lived and will develop a *stable* steady state warp, even without self-gravity. The inclusion of radiative cooling, a physical mechanism that is known to act under these circumstances, disposes of the need to invoke either tumbling potentials or supermassive gas rings for stability. For gas at high inclinations the time scales to "find" these equilibria are much shorter than the settling time scale; this casts severe doubts on the validity of the assumption that gas must always move on closed orbits in a preferred plane, often made to infer the structure of the potential well from gas kinematics.

Subject headings: galaxies: formation — galaxies: kinematics and dynamics — hydrodynamics: — methods: numerical

1. INTRODUCTION

Over the last decade it has been established that most early-type galaxies contain a detectable amount of both ionized and neutral gas (for recent reviews, see Schweizer 1986 and Knapp 1989). Much of the gas is at temperatures far below the virial temperature of the potential and is predominantly supported by rotation, forming ring- or disklike structures. Such gas is found over a large spread of radii, ranging from unresolved nuclear gas (Caldwell 1982) to H I rings at 100 kpc (Schneider et al. 1989). In static potentials the only possible equilibrium configurations for the gas are closed nonintersecting orbits in a preferred plane of the potential (Kahn & Woltjer 1959). The properties of these orbits are well understood for many oblate, prolate, and triaxial potentials (Franx & de Zeeuw 1989). However, the application of these equilibrium models to observed gas velocity fields (e.g., Centaurus A, Wilkinson et al. 1986; NGC 5077, Bertola et al. 1991) has proved problematic, suggesting that the underlying equilibrium assumptions may not be valid.

The time-dependent, nonequilibrium evolution of gas in rigid potentials is much less well understood. Qualitatively, the expected behavior can be easily outlined: precession and dissipation, due to gas elements on intersecting orbits, will force the gas to settle eventually into one of the preferred planes of the potential (Kahn & Woltjer 1959; Gunn 1979; Tohline, Simonson, & Caldwell 1982).

For small inclinations with respect to the preferred plane, this settling process can be described by the damped differential precession of the gas about that plane (e.g., Steiman-Cameron and Durisen 1988, 1990). For gas at large inclinations, the situation is more complicated. As an example of such a configuration, consider gas on a nearly polar orbit in an oblate potential. To reach the preferred plane, here the equatorial plane, the gas must inflow considerably to conserve its z-angular momentum. The time scale associated with this inflow is important for several astrophysical problems: first, such a process has been suggested to explain the fueling of nuclear activity in early-type galaxies (Gunn 1979). Second, if early-type galaxies have nonspherical halos, the lifetime of polar gas rings around those objects is possibly limited by the same process. Such lifetime estimates have been used to assess the frequency of gas accretion in S0 galaxies (Schweizer, Whitmore, & Rubin 1983; Whitmore, McElroy, & Schweizer 1987; Whitmore 1991).

In this *Letter* we focus on numerical estimates of the stability and lifetime of highly inclined rings in oblate or near-oblate potentials. We have concentrated on this geometry because it is applicable not only to S0 galaxies but probably also to most elliptical galaxies (Franx, Illingworth, & de Zeeuw, 1991).

Previous numerical simulations of highly inclined rings have been carried out by Habe & Ikeuchi (1985), using an SPH (smoothed particle hydrodynamics) technique, and by Christodoulou & Tohline (1991), using an Eulerian grid code. Both used an azimuthally smooth, circular ring with the orbital speed equal to the circular velocity as the initial condition. Only Christodoulou & Tohline made an effort to start the ring in a near equilibrium configuration although they were restricted to unnaturally "puffed up" rings due to their limited numerical resolution. They found, for substantially distorted potentials (equipotential surface axis ratio 1: ~0.75) and for inclinations of ~80°, a rapid violent evolution that causes most of the material to move into the center within five to 10 orbital periods. This result is puzzling, since observed gas and stellar rings occur preferentially at high inclinations, suggesting a distorted potential (a spherical potential would not have any preferred planes), yet are, as mentioned below, many orbital periods old.

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The purpose of this *Letter* is twofold: first, we argue that the rapid evolution of highly inclined rings, observed in the previous numerical experiments, is due to both artificial instabilities caused by the lack of radiative cooling and due to the lack of numerical resolution (Habe & Ikeuchi 1985; Christodoulou & Tohline 1991). Second, we show that in oblate and near-oblate potentials, highly inclined rings are long-lived and will develop a *stable* warp, even without self-gravity (cf. Sparke 1986). In § 2 we describe our model evolutions and in § 3 we discuss the implications of these simulations.

2. NUMERICAL EXPERIMENTS

The simulations described below are evolved using TREESPH, a general purpose code for evolving three-dimensional self-gravitating fluids, developed by Hernquist & Katz (1989). We refer to this paper for a detailed description of the algorithm and describe it only briefly here. Hydrodynamic properties are determined using SPH (Gingold & Monaghan 1977; Lucy 1977) and assume an equation of state appropriate for an ideal gas. Gravitational forces are computed with a hierarchical tree algorithm (Barnes & Hut 1986). To increase our efficiency, we remove gas from the central 3 kpc where the dynamical times are very short compared to our time scales of interest. We have compared our code with those of Habe & Christodulou (see Christodoulou et al. 1992) and get similar results when identical initial conditions are evolved. Radiative cooling is included down to 10,000 K using "standard" cooling curves (Hernquist & Katz 1989; Katz & Gunn 1991).

To model the host galaxy, we choose an oblate scale-free logarithmic potential with a flattening of $c/a = 0.75$. For our initial conditions we use, similar to Habe & Ikeuchi (1985), a cylindrical ring of radius 30 kpc with $\Delta r = 3$ kpc and $\Delta z = 1$ kpc (referring to the half-width and half-height, respectively). The initial inclination is 80°. At this radius the orbital period is 6×10^8 yr. The ring, represented by 1000 particles, is orbiting at the circular speed of the potential, 230 km s^{-1} and has a mass of $10^8\ M_\odot$. The integration time steps were chosen small enough to conserve the total energy and the z angular momentum to an accuracy of 5×10^{-4} per orbital period. With this mass the self-gravity of the ring is relatively unimportant compared to the galactic potential. This initial condition is clearly not the configuration where the gas orbits are most nearly closed, which in some sense is "closest" to equilibrium. Figure 1 shows the evolution of this initial configuration, with and without cooling, in a potential with a flattening of 0.75.

For the first few orbital periods, the evolution is similar; the gas elements follow the orbits that were set by the initial conditions, forming an elliptical ring in the flattened potential. The subsequent evolution is drastically different, however. In the simulation without radiative cooling most of the material collapses into the center (as it does in simulations of highly inclined rings by Habe & Ikeuchi and Christodoulou & Tohline) and the remaining gas virializes to a temperature of 10^7 K. If the cooling is included in the calculations, the ring stays thin, preserves its identity, and inflow occurs only slowly. The gas remains near the cooling cutoff temperature of 10,000 K and the ring retains its 80° inclination. The mass fraction remaining in the ring, outside of 1/10 the initial radius, is shown in Figure 2.

The cataclysmic evolution in the no-cooling simulation, converting most of the gas's kinetic energy into thermal energy, can be understood as follows: for an adiabatic gas only shocks can increase its thermal energy. In our simulation, the initial shocks during the attempted approach to the equilibrium (e.g., Fig. 1, right-hand column, second panel from top) heat the gas, and "puff up" the ring dramatically. Once the ring is puffy (thickness z), gas-gas collisions occur perpendicular to the ring at speeds $\sim(z/R)v_{\mathrm{circ}}$ that are supersonic. Collisions also occur in the ring plane due to differential precession. All these gas-gas collisions lead to further shock heating; the gas finally virializes under strong inflow to conserve z angular momentum. This instability, however, is not merely a consequence of our particular nonequilibrium initial conditions that cause the

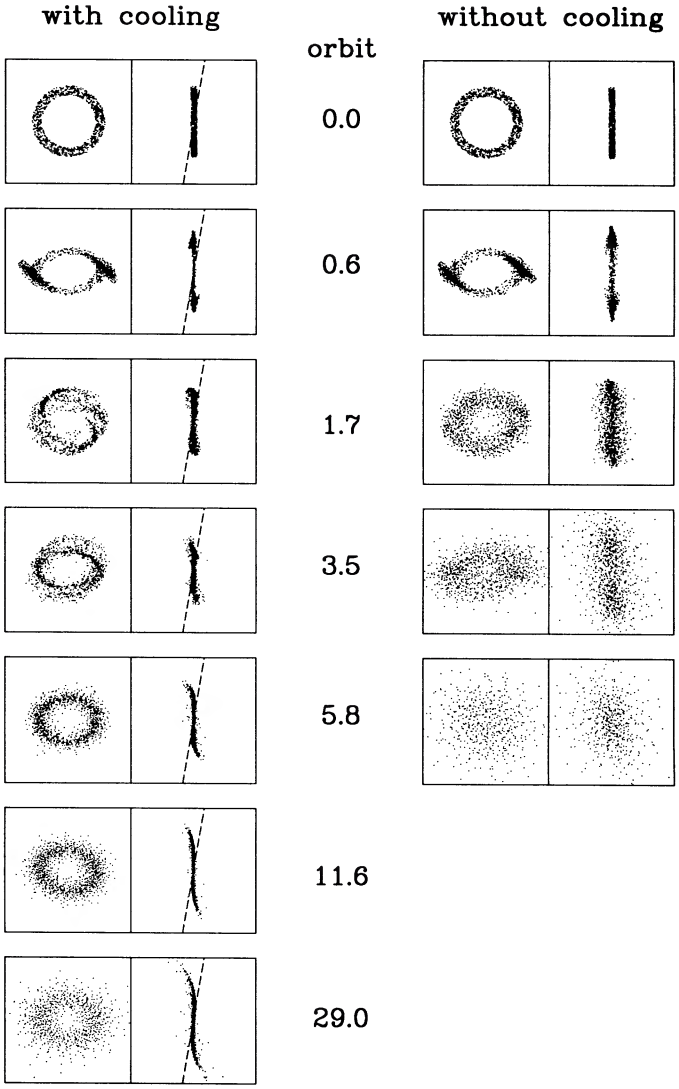

FIG. 1.—Evolution of a large polar ring with and without cooling (*left and right columns*, respectively) in an oblate singular, logarithmic potential. The time indicated is measured in orbital periods. The axis ratios of the equipotential surfaces are 1:1:0.75. For the radial scales of interest the cooling time of initially cold gas is always much less than the dynamical time scale; in this limit the numerical simulations are scale free. The ratio of the ring mass to the enclosed galactic mass is $\sim 10^{-4}$. Initially the rings have a radius of 30 kpc, thickness of 2 kpc, width of 6 kpc, and inclination to the preferred plane of 80°. With this radial scaling the orbital time is 6×10^8 yr and the simulation in the left column extends over a Hubble time. However, it could equally well be interpreted as the evolution of a 2 kpc ring over a 10^9 yr period. The left frame is a face-on view, and the right frame is an edge-on view. The dashed line in the edge-on frames is an inclination of 90°.

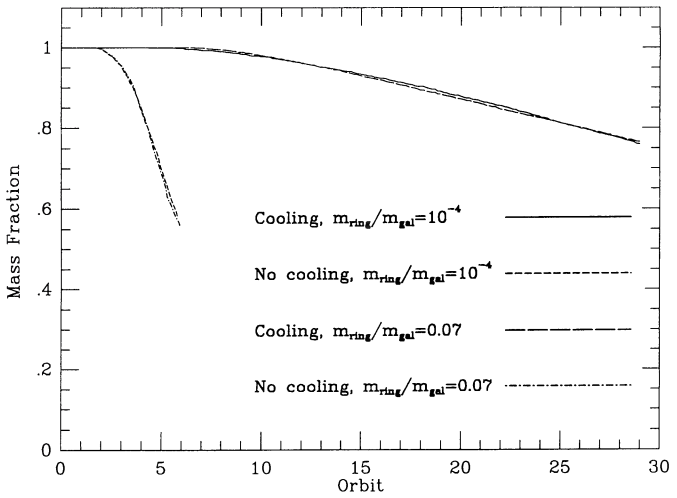

FIG. 2.—The fraction of the original gas mass remaining in the ring for the potential with axis ratios of 1:1:0.75. The rings without cooling show inflow after three orbital periods. If the gas can cool radiatively, inflow occurs only slowly; 80% of the gas survives for more than 30 orbital periods. The simulations with and without self-gravity show nearly identical behavior.

initial shocking. To demonstrate this, we ran the simulation for five orbital periods with cooling, to allow the gas to settle into a near steady state, and then "turned off" the cooling. Subsequently, the thermal energy of the gas increased exponentially with a time scale of $2T_{\rm orbit}$, eventually leading to rapid collapse into the center; the final mass inflow rate was nearly identical to the run without cooling. In this case the heating rises from supersonic compression of the gas along its orbit. In a distorted potential the gas becomes compressed by $1 - c/a = 0.25$ twice per orbit (e.g., Gerhard & Vietri 1986). For a ring with a half-mass radial extent of $\Delta R/R \approx 0.25$ (see Fig. 1, left-hand column, fifth panel, $T = 5.8$), this means a linear compression by $(1 - c/a)\Delta R = 0.0625R$ over a quarter orbital period. For gas at 10^4 K, i.e., $v_{\rm sound} \approx 10$ km s^{-1}, and $v_{\rm circ} = 230$ km s^{-1}, such a compression is supersonic. Since both the disk puffing and the sound speed in the gas scale as $T^{1/2}$, the compression will remain supersonic. Consequently, the thermal energy of the gas is increased by 0.25 of its current value twice per orbit, leading to an instability growing as $e^{T_{\rm orbit}/2}$. Once the ring becomes thickened, gas-gas collisions drive the instability as described above.

The stabilizing influence of radiative cooling can also be easily understood. In the relevant temperature regime the cooling of the gas is so efficient that all the shock energy is radiated away in much less than an orbital time. This keeps the gas temperature close to 10,000 K and the thermal energy of the gas small (here, $E_{\rm therm} \sim 0.01\ E_{\rm kin}$). In the cooling case, the evolution also is driven by the shock compression along the orbit, but since the mechanical energy converted into thermal energy per orbit is only $0.5\ E_{\rm thermal} = {\rm const} \ll E_{\rm kin}$, the evolution is slow.

In the simulation with cooling, a stable warp develops. This warp adjusts itself so that the precession frequency at all radii is equal. For a potential with constant flattening, this implies $\cos(\theta) \propto R$, where $\theta(R)$ is the polar angle of the angular momentum at radius R (Sparke 1986). The resulting warp in our numerical experiments follows exactly this dependence. This warping allows the whole ring to precess in solid body rotation, further diminishing gas collisions. This peudoequilibrium is possible only if the ring is an almost two-dimensional warped sheet, a situation which is maintained only if cooling is included. We checked tht the same qualitative behavior is exhibited in less distorted potentials (specifically for a potential flattening of 0.9), with a general increase in the inflow time scales. Note that such a stabilizing warp can form only at high inclinations ($\gtrsim 60°$) because for smaller values of θ any bend from θ_1 to θ_2 will only result in a small relative change, $\cos(\theta_1)/\cos(\theta_2)$ of the precession frequency.

There are several additional ways to check whether these two evolution scenarios (cooling/no cooling) make sense physically or are just numerical artifacts, e.g., arising from particle discreteness effects. First, we evolved macroscopically identical initial conditions with 1000 and 4000 particles; the kinetic, potential, and thermal energies coincided within 2%–3% over 10 orbital periods. Second, even with only 1000 particles, the final thickness of a ring in a spherical potential (see Fig. 1 in Rix & Katz 1991), agrees to within 25% of the analytic solution for a non–self-gravitating, isothermal layer in an external potential. Third, we find that the thermal energy of the gas in the no-cooling case grows exponentially with a time scale expected for shock heating in the distorted potential.

We ran additional simulations to assess the effects of self-gravity and different initial conditions in estimating evolution time scales. To make self-gravity more important, we increased the ring mass to $5 \times 10^{10}\ M_\odot$, corresponding to a ratio of 1:15 between the ring mass and the enclosed galaxy mass. We picked this ratio as the maximum value for which a rigid host potential could be at all justified. The overall evolution and in particular the inflow rates are virtually unaffected by self-gravity as shown in Figure 2. To determine the sensitivity of the final pseudoequilibrium to the initial conditions, we also ran simulations that started with an orbiting gas blob (Katz & Rix 1992). The blob smeared out to form a ring after ~ 10 orbits and then reached the same pseudoequilibrium.

3. DISCUSSION

The numerical experiments described in the previous section clearly show that the inclusion of radiative cooling is important for understanding the evolutionary time scales of gas in distorted potentials. Cooling is not included in the simulations of Christodoulou & Tohline (1991). Furthermore, it is likely that the limited spatial resolution of both Christodoulou & Tohline and Habe & Ikeuchi does not allow the thermal energy of the ring to remain a tiny fraction of its kinetic energy or for the ring to become thin enough to enter the constant precession state, thus speeding up the ring evolution. In the regime where the cooling time scale is shorter than the dynamical time scale, the "sticky particle" approach of Quinn (1991) may be more appropriate than hydrodynamical simulations without cooling, because gas-gas collisions are modeled to lead to an instant removal of the excess kinetic energy. In fact, Quinn also finds longer evolution time scales than those of Habe & Ikeuchi. Furthermore, the inclusion of cooling greatly reduces the sensitivity of simulations to the particular initial conditions chosen and thus allows more reliable and general conclusions to be drawn from numerical experiments.

Although we have addressed a very specific situation in our simulations, it is clear that radiative cooling of the gas will be important in many more general situations. Therefore, the resulting high-inclination, steady-state warps, eliminating differential precession, are an important class of long-lived configurations. The slow secular evolution of the cooled rings observed in the simulations may be partly driven by numerical effects (e.g., the cooling curve cut-off or artificial viscosity) and is likely to indicate an upper limit on the actual evolution speed of gas rings. Consequently, the presented results translate into increased lifetime estimates for gas rings in distorted potentials. Such estimates for the lifetime, in conjunction with the observed frequency of, for example, polar rings around S0 galaxies, have been used to constrain the frequency of galaxy interactions. In particular, our result reconciles the predominantly near-polar orientation of rings with their old age. The observed orientation bias suggests a substantially distorted potential, because only then would the large precession frequencies prevent the formation of rings at intermediate inclinations or destroy them within a few orbital periods. On the other hand, there is independent evidence, from their azimuthal smoothness and their stellar content, that these rings have existed for at least five to 10 orbital periods.

The elimination of differential precession through warping is only possible at high inclinations and may be the reason gas rings are frequently found in a near-polar orientation.

Finally, the inclusion of radiative cooling, a physical mechanism that is known to act under these circumstances, disposes of the need to invoke either tumbling potentials (Heisler, Merritt, & Schwarzschild 1982; Habe & Ikeuchi 1988) or self-gravity (Sparke 1986) for stability. It should be noted, however, that rings in *tumbling* potentials—although physically a quite different situation—can yield similar projected velocity fields (Steiman-Cameron & Durisen 1984) to the rings presented here. The fact that long-lived, warped near-equilibrium configurations exist outside the stable planes and are "found" by the gas, casts severe doubts on the validity of the assumption that the gas must always move on closed orbits in a preferred plane, often made to infer the structure of the potential well from gas kinematics (e.g., Bertola & Galetta 1978; Schechter, Ulrich, & Boksenberg 1984; Whitmore, McElroy, & Schweizer 1987; de Zeeuw 1991).

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