SETTLING OF GAS DISKS IN ELLIPTICAL GALAXIES

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Prominent gas disks and dust lanes are found in a number of elliptical galaxies. It is widely believed that these disks are the result of the tidal capture of material from a nearby galaxy or the accretion of a gas rich companion into a larger galaxy. While a captured gas disk will ultimately settle into a steady-state orientation ("preferred plane"), the disk will initially be time varying due to precessional and viscous forces. We have developed methods for modeling the evolution of such inclined dissipative galactic gas disks (Steiman-Cameron 1984, Ph.D. dissertation, Indiana U.; Steiman-Cameron and Durisen 1986, Ap.J., in press, hereafter SCD), and we here present some of the results of this work.

While the full set of differential equations describing disk evolution must, in general, be solved numerically, certain limiting assumptions allow for analytic solutions, in particular, when: 1) the viscous time scale for inflow is much longer than the time scale for settling; 2) the precession rate is dominated by gravitational forces with viscous forces being a minor perturbation; 3) the initial inclination of the disk relative to a preferred plane is small, and 4) settling takes place in a nearly axisymmetric galactic potential. These conditions are generally met for parameters typical of real galaxies (see SCD). If i_0 is the initial disk inclination ($i=0$ being the steady-state orientation), Ω_p the precession rate due to the non-sphericity of the gravitational potential, and ν the coefficient of kinematic viscosity due to cloud-cloud collisions, then, according to the analytic solution in SCD, the inclination of the disk as a function of time and radius goes as

$$i \cong i_0 \exp\left[-(t/\tau_e)^3\right], \tag{1}$$

where the time constant τ_e is given by

$$\tau_e = \left[\nu(d\dot{\Omega}_p/dr)^2/6\right]^{-1/3}. \tag{2}$$

Note that the settling time scale is a weak function of ν, going only as $\nu^{-1/3}$. In view of the inadequacies of our understanding of cloud-

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cloud collisions, this result gives us confidence that we can nonetheless derive realistic settling times.

For galaxies with extended halos, as appears to be the case for luminous ellipticals, a useful gravitational potential is the self-similar logarithmic potential (Gunn 1979, in Active Galactic Nuclei, eds. C. Hazard and S. Mitton, p. 213.). Model galaxies with this potential have similar concentric isodensity surfaces, a zero-order density profile of $\rho(r) \propto r^{-2}$, and a flat rotation curve. Then

$$\tau_e = r^{4/3} (\nu/6)^{-1/3} (\tfrac{1}{2}\varepsilon v_c \cos i_o)^{-2/3} \tag{3}$$

where ε is the ellipticity of the model galaxy and v_c is the constant circular velocity. Since the maximum radial distance over which a cloud-cloud collision can transport momentum is the epicyclic amplitude of its orbit, the maximum value of ν occurs when the cloud mean free path is equal to its epicyclic amplitude. The value of ν_{max} is then a function only of the cloud velocity dispersion and galactic potential. Settling times determined using ν_{max} represent minimum settling times. Substitution of the expression for ν_{max} that we derive in SCD yields a minimum settling time of

$$(\tau_e/\tau_p)_{min} = 0.404\ (v_c/v_{rms})^{2/3} (\cos i_o)^{-1/3}, \tag{4}$$

where v_{rms} is the cloud rms velocity. The precession period $\tau_p = 4\pi r/(\varepsilon v_c \cos i_o) = 2\tau_o/(\varepsilon \cos i_o)$, where τ_o is the orbit period. We therefore find that the normalized minimum settling time for the self-similar scale free potential is also self-similar and scale free. Calculations for a modified Hubble potential, which has often been used in modeling elliptical galaxies, show very similar results. Substitution of reasonable numbers into (4) shows that settling is slow, with unsettled disks at radii $\gtrsim$ 10 kpc being extremely old, in contrast to earlier work by Simonson (1982, Ph.D. dissertation, Yale U.) which we feel must be in error.

We have also developed numerical solution methods for parameters less restrictive than the analytic solution presented above. These allow us to test the limits of the analytic results and to further explore the characteristics of disk evolution. We find the following: 1) there is good agreement between the analytic solution and numerical simulations, even for moderate (i_o = 40°) initial inclinations; 2) settling is essentially a local process, depending primarily on local properties of the potential and gas disk; 3) minimum settling times for reasonable galaxy parameters are on the order of two or three orbit precession periods or, equivalently, ten to a few tens of orbit periods in galaxies with intrinsic flattenings representative of E3 to E7 ellipticals; 4) the actively settling region is somewhat narrow, with a radial width of about 30% of its outer radius; 5) radial inflow is enhanced during the active settling period.

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