Spiral Arms and Gaps in Protoplanetary and Protostellar Disks

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We modeled disk systems with properties typical of protostellar and protoplanetary disks to study the formation of spiral arms and gap structures in disks. We considered processes driven by gravitational instabilities (GIs) and embedded planetary cores. In particular, we modeled the development of spiral arms induced by nonaxisymmetric disk instabilities and Type I planetary core migration. Both processes are capable of producing low-m tightly wound spiral modes. Here, m is the azimuthal mode numbers for nonaxisymmetric modes with aziumthal dependence $\propto e^{im\phi}$. Tightly wound low-m modes may appear to show multiple dips. Further, for adiabatic disks with nearly constant specific angular momentum velocity distributions, the Toomre Q-parameter $Q > 10$ everywhere in the disks. The observational properties of the disks are determined from solution of the radiative transfer equation for the reflection of the stellar emission off the dust particles in the disk and through emission from dust particles in the disks, dust particles heated by hydrodynamic processes in the disk and by energy deposition in the disk by radiation from the central protostar using Monte Carlo techniques. The disk dust distribution is inferred from the mass distribution and velocity field of the gas in the disk.

High-resolution observations of protostellar and protoplanetary disks have recently revealed structure in the form of spiral arms and gaps in circumstellar disks. For example, observations of the Herbig-Haro object AB Aur have revealed two elliptical rings with major axes $\sim$ 92 A.U.and 210 A.U., separated by an elliptical gap with major axis 170 A.U. (Fukugawa *et al.* 2004, Hashimoto *et al.* 2011). The ring/gap structure is seen in optically thick IR emission (Fukugawa *et al.* 2004) and optically thin sub-millimeter emission (Henning *et al.* 1998) suggesting that the features extend to the midplane of the disk and are more than corrugations in the surface density. Polarimetric high-resolution images obtained by the *Subaru* telescope have also revealed the presence of several dips in the intensity of the rings interpreted as spiral structures (Hashimoto *et al.* 2011). Hashimoto et al. noted that the appearance of the multi-armed spiral structure was consistent with expectations of GI. However, it was argued that GIs were not likely to be the explanation for the structure because of the large Q parameter estimated for the disk, $Q \sim 10$ (Pietu, Guilloteau, & Dutrey 2005) and other explanations such as gaps cleared by massive planetary cores (*e.g.*, Papaloizou & Terquem 2006) and spiral patterns excited by low-mass planetary cores (*e.g.*, Tanaka, Takeuchi, & Ward 2002) were proposed. We compare our numerical results with AB Aur and other protoplanetary systems to assess the viability of GIs as an explanation for the structure observed in protoplanetary and protostellar dust and gas/dust disks.