Abstract of Doctoral Dissertation

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Title of Doctoral Dissertation

The Influence of Gravitationally Unstable Protoplanetary Disks on Type I Migration
（重力不安定原始惑星系円盤のI型惑星移動への影響）

The focus of this thesis is the impact of global structure in two types of astrophysical disks: galactic and protoplanetary.

The first chapter summarises a study on the impact of the global galactic environment on the physical properties of star-forming clouds. This work was the main focus of the Masters thesis and completed for the doctorate. A series of simulations of isolated galactic disks with varying background potentials were performed using an AMR hydrodynamics code. The galactic potentials are expressed by rising, decreasing and flat rotation curves, with the addition of either a massive stellar disk or two-armed spiral patterns. Results from these simulations explored the role of shear and the gravitational stability, Toomre Q, in the fragmentation of the gas disk into clouds. Although the properties of a typical cloud were found to be largely independent of the potential, the production of small and large cloud associations were strongly dependent on the galactic global structure. The addition of the spiral potential made the greatest difference to the clouds, successfully sweeping gas into extended structures.

In a similar system but on smaller scale, protoplanetary disks share an equivalent set of internal forces and an external global potential. The primary research for this thesis considers the instabilities forming in the protoplanetary disks that circle young stars and how this environment affects the evolution of planets forming from the dust and gas.

According to current theories, proto-planets are formed as a consequence of either a series of collisions and mergers between dust and solid material, or through a collapse from gravitational instabilities in the protoplanetary disk. However, the young planet is initially embedded within the protoplanetary disk and interacts with its parent gas disk through the exchange of angular momentum with the surrounding gas. This can cause the orbital radius of the planet to change, leading to a migration through the disk. Evidence for this phenomenon abounds in exoplanet systems, which have large planets on very short orbits that are unlikely to have formed in-situ.

Smaller planets undergo what is referred to as "Type I migration", which presents a major problem for planet formation theories. Numerical estimates of this process typically indicate a rapid inward migration, resulting in the loss of the planet. Young planets are sent into the star within approximately 10^5 years, from a distance of 1 AU, well before the protoplanetary disk can evaporate and remove the fatal gas pull from the planet (within $10^6 - 10^7$ years).

In an attempt to prevent the loss of young planets, various possibilities have been discussed, including sharp changes in disk properties to create planet traps, late formation of planets after the disk has partially evaporated, and gravitational scattering by neighboring planets or planetesimals. However, recent ALMA observations have revealed complex substructures within the protoplanetary disks, including rings and spiral arms which could be results from either Lindblad waves ignited by planets or gravitational instability. Previous work has not typically focused on the effect of such structures formed by borderline stability of the protoplanetary disk on the

migration of planets, typically assuming instead that the disk is homogeneous.

In this research, we perform a series of simulations of protoplanetary disks with different degrees of global structure and follow the migration of a young planet. The isolated protoplanetary disk is simulated using ChaNGa; an SPH hydrodynamics code. The disks exist in a variety of stable to borderline stable and unstable states, corresponding to different values of Toomre Q.

The planet's migration is strongly affected by instabilities that develop within the protoplanetary disk. While the planet's migration in a homogeneous disk moves inwards at a steady velocity, structure-rich disks disrupt this migration and cause a irregular motion through the gas. This is most clearly seen in the torques acting on the planet. These change from a settled constant value in a smooth gas distribution where resonance waves can be maintained, to experiencing strong fluctuations due to the formation of spirals and other features. Fragmentation of the disk can lead to scattering of the planet and ejection from the system. However, even disks with a Toomre $Q > 1$ (representing stability) can still have a strong impact on the planet torques.

Overall, this work strongly suggests that massive or structure rich protoplanetary disks will also have an effect on the migration of the planet. This is expected for all protoplanetary disks in their early years and may apply to a wide variety of disks even at later times. Type I migration is therefore a highly non-linear process and can only be weakly approximated by an analytical expression in the majority of systems.