Summary of Ph.D. Thesis entitled

"Problems in stellar and planetary dynamics"

by Gareth Kennedy, submitted November 2008,

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This thesis is concerned with a range of problems in stellar and planetary dynamics, specifically the destruction of globular clusters as they orbit the galaxy; the disruption of stellar binaries by the massive black hole in the centre of the Milky Way; and a new method for discovering low mass extrasolar planets which are not detectable using available methods. Investigations into these problems make extensive use of a new formulism developed by Rosemary A. Mardling that predicts the long-term stability of three-body problem systems. This formulism predicts systems that are unstable to the eventual escape of one of the masses in a random walk process; it is referred to as the Mardling stability criterion (MSC) throughout this thesis.

The relevant dynamical theory covering the concerning the two-body and three-body problem as well as the stability in the three-body problem is outlined in Chapter 1. This chapter introduces the MSC as a method for quickly determining stability in the general three-body problem. It allows one to predict systems that will be unstable to the escape of one of the bodies; the most likely body that will eventually escape the system depends on the mass ratios between the three bodies. For globular clusters the three bodies are particles representing a star in the cluster, the cluster core and the galaxy. In this case the mass ratios between these bodies mean that the escaping body will be the star and therefore the MSC can be used to predict the escape of stars from globular clusters. In the case of a stellar binary encountering a massive black hole, close encounters will result in the loss of one of the binary components while distant encounters result in the escape of the black hole, which is equivalent to the escape of the binary.

The first project presented in Part I examines the escape of stars from globular clusters on eccentric orbits with the galaxy. Previous studies quantify the escape of stars from clusters using

the tidal radius of the cluster. Two of these tidal radius estimates from the literature are given in Chapter 2 and are based on the tidal field of the galaxy balancing that of the cluster for various types of star-cluster orbits.

In Chapter 3 we introduce a globular cluster model which uses a Plummer potential as the cluster potential and investigates the effect this has on the Kepler elements for stellar orbits within the cluster. The MSC is applied to the star-cluster-galaxy system in Chapter 4 by approximating this system as three point masses. The predicted occurrence of unstable systems is compared to numerical results for the stability of three bodies taking the cluster potential as the Plummer potential. It was found that the Plummer potential stabilises the orbits of stars that come within the core of the cluster compared to the equivalent orbits in a point mass potential.

Chapter 5 presents a more sophisticated cluster model than the three-body model which is also less computationally demanding than a direct N-body simulation. This model was actually developed before the three-body model presented in Chapter 4, when we thought that the galactic orbit of the cluster might be changed by the additional mass loss of stars on unstable orbits. The galactic orbit of the cluster was not found to significantly change on the timescales simulated, however the cluster model produced interesting results for escaping stars. The model presented in Chapter 5 is tested against an N-body simulation using the fraction of escaping stars as a function of the distance from the cluster centre. Similar results are found for this model as were found using the results from an N-body simulation provided by Holger Baumgardt. The cluster model developed in Chapter 5 is used to estimate the tidal radius for a range of eccentricities and perigalacticon distances that include clusters on very wide galactic orbits, which are not possible to model using N-body simulations for realistic numbers of stars. These tidal radius estimates from simulated clusters were then compared with estimates from the literature and with the predictions using the MSC determined in Chapter 4.

There was good agreement between the tidal radius estimates for simulated clusters, the more recent tidal radius estimates from the literature and the predictions using the MSC, which provided encouragement to apply these predicted tidal radii to real clusters. Chapter 6 compares the tidal radius estimates based on observations of clusters in the Milky Way globular cluster system to predicted radius estimates determined using the MSC. It was found that the different estimates for the tidal radius could not be distinguished using current cluster observations. A summary of results for Part I is given in Chapter 7 along with the ramifications for this work in the context of the capture of dwarf spheroidal galaxies by the Milky Way galaxy.

The second project presented in Part II is a continuation of previous work begun during my honours thesis (Kennedy 2001). The emphasis of this project has been substantially changed in the intervening years due to the discovery of hypervelocity stars in the Milky Way (Brown et al. 2005). The physical problem under investigation is the tidal disruption of a stellar binary if it encounters a massive black hole within a particular distance. Sufficiently close encounters result in the capture of one star and the ejection of the other for cases where the binary is initially on a parabolic orbit relative to the black hole. Thus the encounter between a stellar binary and the black hole can produce hypervelocity stars, as predicted by Hills (1988).

The conditions in the galactic centre are reviewed in Chapter 8 with particular emphasis on dynamical interactions that can result in binaries encountering the massive black hole or that can also produce hypervelocity stars. In Chapter 9 estimates from the literature are given for the maximum pericentre distance of the binary-black hole orbit for which the tidal disruption of the binary is expected. These maximum pericentre distances are then compared to detailed scattering experiments conducted by the author over a wide range of relative orbital inclinations and stellar binary eccentricities. We find that estimates of the cross-section for exchange in the literature are roughly consistent with the results from the scattering experiments presented here. However the theoretically estimated maximum pericentre distances fall short of the numerical values, and fail to explain the dependence of this distance on the inclination and orbital eccentricity of the stellar binary.

The dependence of the maximum pericentre distance on inclination and binary eccentricity for binary-black hole orbits with eccentricity of 0.9 is examined in Chapter 10. The dependence on inclination and binary eccentricity of the maximum pericentre distance for which the binary is disrupted is predicted using the MSC and confirmed by comparison with the results from scattering experiments. Future extension of the MSC to distinguish between which of the three masses will eventually be ejected will allow that criterion to be used to predict the maximum pericentre distance for parabolic binary-black hole orbits.

In Chapter 11 the velocities found for the ejected star from parabolic binary-black hole orbits are used to predict the distribution of hypervelocity stars as they leave the galactic centre. This velocity distribution is found to be insensitive to the orbital eccentricity of the stellar binary, but strongly dependent on the choice of distribution for its semi-major axis. A summary of the results for Part II is presented in Chapter 12.

The final project presented in Part III examines the possibility of detecting low-mass planets which have been captured into the 2:1 mean motion resonance. The first of two chapters in this part is an original paper submitted for publication in a peer reviewed journal by Rosemary Mardling and myself. The second chapter is original work conducted by the author on existing data using the theory presented in the submitted paper.

Chapter 13 uses the formulism that the MSC is based on to study the stability of planetary systems with a hypothetical planet in the internal 2:1 resonance and to provide simple expressions for the libration period and the change in the observed orbital period. Using simulated data it is shown in Chapter 13 that it is possible to identify the existence of a low-mass companion in the internal 2:1 resonance by calculating the orbital period using piecewise sections of radial velocity data.

In Chapter 14 preliminary results are presented for the existence of a low mass companion to the known Jupiter mass planet HD 121504 b. The existing data for this planetary system is analysed using the theoretical approach and a similar data analysis method introduced in Chapter 13. It is concluded that HD 121504 is likely to contain a low mass planetary companion with mass in the range of $14\mathrm{M}_\oplus \lesssim m_i \sin i \lesssim 30\mathrm{M}_\oplus$. It is strongly recommended that further observations for HD 121504 be made with as large a time resolution as possible to confirm these preliminary results. If this is confirmed it will represent a significant discovery and a vindication of the Mardling stability criterion that underlies this thesis.