STABILITY OF THE 3:1 RESONANCE LOCKING IN THE 55 CANCRI PLANETARY SYSTEM. F. Marzari, *Dept. of Physics, University of Padova, Italy, marzari@pd.infn.it*, H. Scholl, *Observatoire de Nice, France*, P. Tricarico, *Washington State University, USA*.

The most crowded extrasolar planetary system discovered so far is the one around main-sequence star 55 Cancri(= ρ^1 Cancri). Four planets are known to orbit the star with semimajor axes ranging from 0.038 to 5.26 AU while the nominal orbital eccentricities range from approximately 0. to 0.44 [1]. The inner planet, 55 Cnc e, is the lowest mass extra-solar planet yet found around a Sun-like star being a Neptune-mass planet. The central star is a solar–type star with an age of about 5 Gyr. This suggests that the planetary orbits have already undergone evolutionary processes like migration due to interactions of the planets with an early disk and/or scattering of planetesimals and planetary embryos, and tidal interaction with the central star.

The key for the stability of the system appears to be the resonance locking between the second and third planet of the system named planet b and c, respectively. Zhou et al. [2] showed that the argument $\Theta_2 = \lambda_b - 3\lambda_c + 2\varpi_c$ librates around 90° together with the apsidal longitudes $\Delta\tilde{\omega} = \varpi_c - \varpi_b$. The libration of Θ_2 protects the two planets from close approaches and grants long term stability to the system.

We are exploring the dynamical stability of the 3:1 resonance locking between planet b and c by using the Laskar's Frequency Map Analysis [3] (hereinafter FMA). The major advantage of this method is to require short term numerical integrations to outline the stability properties of a dynamical system. The FMA method measures with high precision the main frequencies of the system and it computes their diffusion rate in the phase space. Orbits with lower diffusion rate are the most stable in time. A large number of fictitious systems (more than 2×10 4) have been numerical integrated as a full N–body problem with SyMBA [4] for 10^5. This interval of time is long enough to measure the secular frequencies of both planets b and c and their temporal variations. A short timestep (1 hr) is adopted in the numerical integration to account for the short orbital period of the planets and their high eccentricities. The initial semimajor axis, eccentricity, and orbital angles of planets b and c are randomly sampled around their nominal values. Planet e and d have fixed initial orbital elements equal to the nominal ones. All the orbits of the planets are coplanar. At the end of each numerical integration we retain only those simulations where one of the following critical arguments, $\Theta_1 = \lambda_b - 3\lambda_c + 2\varpi_b$, $\Theta_2 = \lambda_b - 3\lambda_c + 2\varpi_c$, or $\Theta_3 = \lambda_b - 3\lambda_c + \varpi_b + \varpi_c$, librates over the whole timespan. To all these simulations we apply the FMA by performing a detailed spectral analysis of the complex signal $h + ik$ for both planet b anc c as described in [5]. The the non–singular variables h and k are defined by $h = e\,cos(\varpi)$ and $k = e\,sin(\varpi)$.

The free (that in case of long term stability of the orbit can be termed proper) frequencies g_b and g_c of the two planets are computed over running windows covering the 10^5 yr of the numerical integration and free (or proper) eccentricities e_{fb} and e_{fc} are derived from the amplitude of gs in the power spectrum of the first window. An average libration amplitude D of the critical argument is estimated for each system as mean of the maximum libration amplitude over shorter sub-windows. For each value of (e_{fb}, e_{fc}, D) we estimate the diffusion rate as the negative logarithm of the standard deviation of the frequencies g_b and g_c calculated on all the windows. To be conservative, we choose the higher value between the standard deviation of g_b and g_c and we compute $\sigma = -log_{10}(s_g/g)$. This number will measure the chaotic diffusion of the orbits and will allow to outline the most stable region in the phase space.

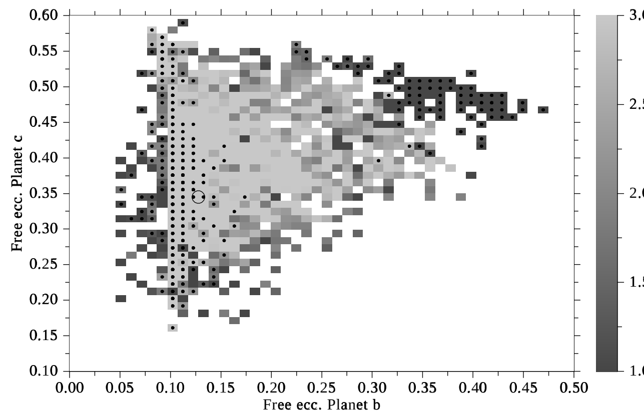

Figure 1: Diffusion map of the 3:1 resonance between planet b and c in 55 Cnc. The coordinate of the x-axis is the free eccentricity of planet b while the coordinate of the y-axis is the free eccentricity of planet c. The empty circle represents the nominal planetary system.

In Fig. 1 we show the diffusion map in the space (e_{fb} , e_{fc}). About 2800 different resonant systems are plotted. Different gray levels represent values of σ ranging from 1 to 3 (see the scale to the right of the Figure). Light gray shading corresponds to large values of σ (about 3), low diffusion rate, and it implies higher stability. The dark regions have small values of σ (around 1), a fast diffusion rate, and are highly chaotic. Chaos leads to instability that causes a fast increase of the eccentricity on the planets. Close approaches begin to occur and we assist to the onset of a 'Jumping Jupiter' phase ([6] , [7]). The planets have chaotic orbits frequently altered by mutual gravitational encounters until one or more planets are ejected out of the gravity field of the star on a hyperbolic orbit. The system is left in a stable configuration with a lower number of planets. Small dots mark those systems where apsidal libration occurs simultaneously to the libration of one of the possible 3:1 resonance critical arguments. The triangular shaped stable region outlined in Fig. 1 is limited at low eccentricities by the values of the mutual forced eccentricity of the two planets. Stable apsidal libration occurs only for low values of e_{fb}. An additional region of apsidal libration is located at large values of both e_{fb} and e_{fc} but it is highly chaotic (dark shading). For larger values of e_{fb} the stability region shrinks and a stable resonance locking is allowed only for a restricted range of e_{fc} around ~ 0.4.

Fig. 2 illustrates the diffusion map in the (D , e_{fb}) space. Most of the stable planetary systems have libration amplitudes lower than $\sim 130^\circ$ while apsidal libration can occur for any value of D. Low D resonance locking requires low values of e_{fb} while the highest values of e_{fb} can be reached only for D larger than 60°.

In conclusion, the 3:1 resonance in the 55CNC system appears to cover a wide region in the phase space and it is characterized by long term stability (low diffusion speed in the phase space). Apsidal libration is not essential to stability, but it is present in a large fraction of cases. While in resonance, the free eccentricity of planet b cannot be larger than ~ 0.4 while that of planet c can reach also ~ 0.6 but only for low values of e_{fb}. The forced eccentricities limit from below the range of values for both e_{fb} and e_{fc}. The libration amplitude of the critical argument of the resonance has to be smaller than $\sim 130^\circ$. These dynamical properties of the 3:1 resonance can set constraints on the trapping mechanism, possibly related to the migration, of one or both the planets in the early phases of evolution of the planetary system. We intend to perform a further analysis of the stability of the system for different values of the masses of the planets, within the observational ranges, and for different mutual inclinations between the planets.

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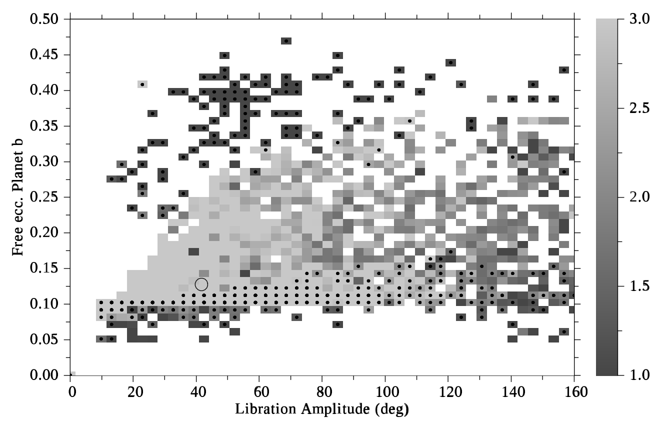

Figure 2: Diffusion map plotted in the plane of the libration amplitude of the resonant argument vs. free eccentricity of planet b.