The sailboat island and the New Horizons trajectory

Silvia M. Giuliatti Winter *, Othon C. Winter, Ernesto Vieira Neto, Rafael Sfair

Univ. Estadual Paulista – UNESP, Grupo de Dinâmica Orbital e Planetologia, Guaratinguetá CEP 12516-410, Brazil

1. Introduction

New small satellites (Buie et al., 2013; Showalter et al., 2011), discovered after the launch of the New Horizons spacecraft in 2006, raised new questions on the origin of the binary system composed by Pluto and Charon. The distance between Pluto and Charon is \( d = 19,571 \) km, and the satellites Styx, Nix, Kerberos and Hydra are all located exterior to Charon’s orbit. Pluto has about twice the size of Charon (the mass ratio is \( \mu = 0.1165 \)), while the small satellites have diameters smaller than 100 km (Tholen et al., 2008).

Since the discovery of the new satellites many attempts have been made in order to locate stable regions which could shelter satellites, debris or even a ring. These studies could help the New Horizons mission to discover new objects and avoid possible hazards.

Stable regions were found for a sample of test particles in orbits around Charon and also around Pluto (for example, Stern et al. (1994) and Nagy et al. (2006)). These stable regions are formed by families of periodic and quasi-periodic orbits explored in detail in Giuliatti Winter et al. (2010) and Giuliatti Winter et al. (2013).

In the study of the planar S-type orbits (those orbits around one of the two massive bodies) of the Pluto–Charon binary system, Giuliatti Winter et al. (2010) identified an island of stable trajectories in the semi-major axis \( a \) versus eccentricity \( e \) diagram of initial conditions (Fig. 1). A peculiar feature of this stable trajectories is that they might have initial eccentricity up to 0.9. Due to its shape, this island has been called sailboat island. In order to better understand the reason for this stable island, Giuliatti Winter et al. (2014) (see their Fig. 1) analyzed the family of periodic orbits responsible for such stability. The inclusion or not of an eccentricity for Charon does not make a significant change in this stable island. Therefore, the analysis was made considering the planar circular restricted three-body problem. Using Poincaré surfaces of section, it was possible to find the initial conditions for the periodic orbits.

The external region, beyond the orbit of Charon, was also analyzed by several authors. Süli and Zsигmond (2009) extended the work by Nagy et al. (2006) through an analysis of the spatial elliptic restricted three-body problem for a time-span of \( 10^4 \) orbital periods of the binary. Stability maps for the \((a \times e)\) and \((a \times I)\) orbital element spaces were generated near the satellites Nix and Hydra, which were assumed to be massless bodies. As a result they found that these small satellites are located in stable zones near mean motion resonances, while the unstable zone is larger than
are also present in Fig. 2. The sailboat island of stability is located at \( a = (0.5d, 0.7d) \) for large values of the eccentricity of the particles. \( d \) is the distance between Pluto and Charon. The system (Pluto–Charon-test particles) was numerically integrated for \( 10^4 \) orbital periods of the binary (--65,000 days). Although other stable regions are also present in the interval \( a = [0.3d, 0.5d] \), this figure displays only the sailboat island.

The dynamical structure of the external region by numerically simulating a sample of test particles under the gravitational effects of Pluto, Charon, Nix and Hydra. They found that, as expected, the effects of Nix and Hydra decrease the external stable region. Agglomerates of particles can survive for \( 10^5 \) orbital periods of the binary in some regions, coorbital to Nix and Hydra and between their orbits. Lee and Peale (2006) studied in detail the orbits of the two satellites Nix and Hydra. Their analytic theory showed that the azimuthal periods of both satellites are shorter than the Keplerian orbital periods. From the direct numerical integrations they verified the increasing influence of the 3:2 mean-motion commensurability on the orbital motion of Nix and Hydra as their masses increase.

In this study we analyze if the sailboat island can pose a threat for the New Horizons mission during its closest approach to Pluto system in July 2015 (Section 2) and the highest probable location of objects from the sailboat island (Section 3). In the final section we discuss our results.

2. The risk for the New Horizons mission

As discussed before stable regions are present between the orbits of Pluto and Charon due to a family of periodic orbits (Giuliatti Winter et al., 2010). To obtain the stable regions the restricted 3-body problem, Pluto–Charon and a test particle, was numerically integrated for \( 10^4 \) orbital periods of the binary. The distance between Pluto and Charon was adopted to be 19,571 km and the mass ratio of the binary was assumed to be \( \mu = 0.1165 \) (Buie et al., 2006). The gravitational effects of the new discovered small satellites, Styx, Nix, Kerberos and Hydra, were neglected since they are too far to disturb the system.

One of these stable regions, the sailboat island, is located in a region at \( a = (0.5d, 0.7d) \) for large values of the eccentricity of the particles, \( e = (0.2, 0.9) \). Fig. 1 shows the location of the sailboat region in the diagram \( a \) versus \( e \). This diagram represents the initial semimajor axis and eccentricity of those test particles which remain in the system for the whole time of the numerical simulation (T = 65,000 days, which corresponds to \( 10^4 \) orbital periods of the binary). The parameters of the test particles, which are the longitude of the pericentre (\( \sigma \)) and the inclination (\( I \)), were assumed to be 0, and the epoch of the pericentre \( \tau = 0 \). This region is formed by a family of periodic and quasi-periodic orbits. As analyzed in Giuliatti Winter et al. (2010), other stable regions are also present in \( a = [0.3d, 0.5d] \) (see their Fig. 1a, left-hand column); however, in this work only the sailboat island will be analyzed.

Giuliatti Winter et al. (2014) have analyzed the extent of the sailboat region for different initial values of \( \sigma \) and \( I \). They concluded that the sailboat region is present for the values of \( I \) between 0 and 90° and for only two small intervals of \( \sigma \), \([-10°, 10°]\) and \([160°, 200°]\).

Fig. 2 displays the largest quasi-periodic orbits for different values of the inclination of 60 test particles in the rotational reference system. This reference system is centered in Pluto and rotates with the same angular velocity as Charon. The \( x \)-axis lies along the line connecting Pluto and Charon, \( y \)-axis is perpendicular to it and the \( z \)-axis is perpendicular to the \( xy \) plane. The nominal and the Deep Inner SHBOT trajectories of the New Horizons spacecraft, and the Lagrangian point \( L_3 \) are also present in Fig. 2.

The New Horizons team studied several alternative flybys in order to avoid impact during the closest approach with Pluto. One alternative flyby is called Deep Inner SHBOT (Safe Heaven By Other Trajectory) that gets closer to Pluto, about 3000 km from its surface, than the nominal flyby (12,500 km from Pluto’s surface). It is an attempt to avoid possible debris around Pluto that will be removed due to the drag caused by the extended upper atmosphere of Pluto. They adopted a conservative Pluto atmospheric model (Krasnopolsky and Cruikshank, 1999) and assumed Pluto’s atmosphere is seasonal, when calculating the clearing due to atmospheric sweeping. For instance, considering this model, debris with altitudes up to 2000 km would be removed within just \( 5 \times 10^3 \) yrs. However, they used a model that is the best representation of the current state of Pluto’s atmosphere (Zhu et al., ...)
(again, to be conservative), when calculating the potential effects on the spacecraft flying through that region (H. Weaver, private communication). In the first case, conservative means a less dense atmosphere was used when calculating the clearing due to atmosphere sweeping. In the second case, conservative means a denser atmosphere was used when calculating the potential effects on the spacecraft flying through that region (e.g. for heating).

In Fig. 2a the atmosphere of Pluto was neglected while in Fig. 2b those trajectories which cross the atmosphere of Pluto were removed. In order to visualize better the effects of the atmosphere of Pluto we show the projection of the trajectories in the xy, xz and yz Cartesian planes (Fig. 3). As stated before the dashed line represents the nominal trajectory of the New Horizons spacecraft, the dot-dashed line is the trajectory of the Deep Inner SHBOT and Pluto is located at (0,0). In the right column of Fig. 3 the atmosphere of Pluto was included and those trajectories of the test particles that got inside the extended atmosphere were removed. In all these plots the nominal orbit of the New Horizons will get close to the orbits of the test particles, but no collision was detected. The closest distance to the New Horizons spacecraft trajectory is about 1650 km.

The main difference between the two samples of trajectories when the atmosphere of Pluto is included can be seen in the xy plane. As discussed in Giuliatti Winter et al. (2014) the orbits that are closer to Pluto have larger eccentricities and these are the orbits that are removed when the atmosphere of Pluto is taken into account. Note that the trajectories form a surface which envelops Pluto, and also its polar region. In order better to understand the trajectories which cover the polar region, we selected one of them to show its temporal evolution. Fig. 4 shows this representative trajectory (selected from Fig. 2). It is a test particle with the following initial conditions: $a = 0.6d$, $e = 0.37$, $I = 90^\circ$, $\Omega = 0$ ($\Omega$ is the longitude of the ascending node), $\sigma = 0$ and $\tau = 0$. The trajectory was numerically integrated for 50,000 days. Each plot in Fig. 4 shows a snapshot of the orbit during 30 days. In the first column the orbit is projected in the xy space after 49,400, 49,550, 49,700 and 49,850 days.

Fig. 3. Projections of 3-D plots of Fig. 2. Trajectories of a representative sample of test particles of the sailboat island. In the right column the trajectories of the particles that cross the atmosphere of Pluto, up to 3000 km from its surface, were removed. The dashed line represents the nominal trajectory of the spacecraft and the dot-dashed line is the Deep Inner SHBOT trajectory.
Therefore, these kind of trajectories, with large values of $I$, can pose as a risk for the New Horizons spacecraft in the case of considering the alternative Deep Inner SHBOT trajectory.

The size of the test particles dictates the dynamical system to be analyzed. Giuliatti Winter et al. (2014) derived a crude estimative of the size of the objects that could populate the sailboat region. By analyzing the tidal damping in their eccentricities they concluded that the timescale for the circularization of their orbits is longer than the age of the solar system if these objects were smaller than 500 m in radius.

Fig. 4. Each column shows a snapshot (during 30 days) of the orbit projected in the $xy$, $xz$ and $yz$ planes. In each line, from top to bottom, the orbits are seen after 49,400, 49,550, 49,700 and 49,850 days of numerical integration. Note that this is always a polar trajectory.

If the sailboat island is populated by $\mu$m-sized bodies, the effects of the solar radiation pressure has to be taken into account (Pires dos Santos et al., 2013). We have analyzed the effects of the solar radiation pressure in the sailboat island for $\mu$m-sized particles. Our results show that for a sample of 1 $\mu$m sized particles only a small portion of the initial set (less than 30%) are removed from the system. The increase in the size of the particles increases the number of the particles that survive after $10^4$ orbital periods of the binary. Therefore, the sailboat island can shelter bodies smaller than 500 m in radius and also $\mu$m sized particles.
3. Density of the sailboat island

In this section we verify where is the most populated area in the sailboat island. Since there is no observational data of particles in the Pluto–Charon system, it is difficult to compute an absolute value for a density in this region. Therefore, we measure a relative density, i.e. a density value that can be compared with the density of other regions of the system. We considered the well-known stable region of circular and quasi-circular orbits close to Pluto (Stern et al., 1994; Nagy et al., 2006), with $0.1d < a < 0.15d$ and $0 \leq e < 0.1$, as the standard region for comparison.

By following trajectories of 800 test particles located in the sailboat island for a timespan of 60 days, we stored the location of the particles at equal time intervals ($\Delta t = 6 \times 10^{-3}$ day). The xy plane, where the points were stored, was divided into small boxes of $25 \times 25$ km. The same procedure was adopted for particles located in the standard region. The results, presented in Fig. 5, show the density of particles along the equatorial plane of the Pluto–Charon system in terms of a color code.

For clarity only half of the space is plotted ($y < 0$), since the other half ($y > 0$) is symmetric about the Pluto–Charon line ($y = 0$ axis). The darker blue color indicates the areas with the highest density of particles. There are only two areas with such color. The blue region near Pluto, which is occupied by particles from the standard region, and an area, beyond seven thousand kilometers (>0.35d), which is occupied by particles from the sailboat island.

Fig. 6 shows a contour plot of Fig. 5. The darker green regions are those regions with a larger number of points (higher density). $L_3$, $L_4$ and $L_5$ indicate the Lagrangian equilibrium points and the blue triangles are the points where the New Horizons spacecraft crosses the Pluto–Charon plane if it is in the nominal trajectory (NH) or in the Deep Inner SHBOT trajectory (SHBOT). The gray shadows cover $28^\circ$, $r = 0.71d$ and $\Phi = 102^\circ$, measured from the line connecting Pluto and Charon ($y = 0$ axis). They encompass the position of denser regions which may pose some hazard to the New Horizons mission. It is worth to point out that in the Pluto–Charon binary system the Lagrangian equilibrium points $L_4$ and $L_5$ are no longer stable points, the coorbital particles with Charon survive less than one year (Giuliatti Winter et al., 2013). These darker regions could be spotted by the New Horizons cameras in order to look for debris or even small particles.

4. Final comments

In this work we have analyzed the relevance of the sailboat island of stability for the New Horizons mission.

We explored the possibilities of the spacecraft to cross the region of orbits associated to the sailboat island. We verified that the nominal trajectory of the spacecraft does not enter this region, and the closest distance from it is about 1650 km. On the other hand, the alternative trajectory called Deep Inner SHBOT will cross this region, since there is a set of stable highly inclined (even polar) orbits originated from the sailboat island. The inclusion of the drag caused by an extended upper atmosphere of Pluto produces a cavity inside the stable region, but does not remove these highly inclined orbits. Therefore, from our analysis, the nominal trajectory of the New Horizons spacecraft is safer than the Deep Inner SHBOT.

We also identified the most probable locations of particles associated with the sailboat island, which can be visually explored by the spacecraft along its Pluto’s flyby in order eventually to discover new bodies.

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References