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# On one property of the movement on the outskirts of the Solar System

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A numerical simulation of the equipotential surfaces of the gravitational field in the immediate vicinity of the Solar System has been performed taking into account gravitational perturbations from the Galactic tide and 355 stars closest to the Sun. It is demonstrated that at certain values of the gravitational potential energy, the Sun shares the equipotential surface with Toliman (Alpha Centauri B), Sirius and Procyon. The use of a method of numerical integration of the equations of motion of 150 test bodies has shown instability of circular orbits with a radius of 60,000 au about the Sun.

*Keywords*: Gravitation, instabilities, methods: numerical, celestial mechanics, comets: general, Oort Cloud, (Galaxy:) solar neighborhood

## 1 Introduction

Cometary nuclei are pristine remnants of the material from the formation of the giant planets and their moons about 4.5 billion years ago. Some fraction of the material originally accreted in the protoplanetary disc was ejected by the gravity of the incipient giant planets to large heliocentric distances, and it has been in storage there since then. According to the Oort cloud hypothesis (Oort 1950), these leftovers serve as a reservoir of comet nuclei. Occasionally, being subject to gravitational perturbations from stars passing close to the Sun or giant interstellar molecular clouds, these remnants are sent towards the inner Solar System as fresh comets. However, in the course of time, the same gravitational perturbations will most likely render the Oort cloud scattered. Therefore, the question of the Oort cloud's stability during the course of the Solar System's evolution has not yet been resolved.

The aim of the present study is to construct a numerical model of gravitational potential in the vicinity of the Solar System, perform a trial numerical integration for the computation of trajectories of small celestial bodies moving in the resulting gravitational field and then to estimate the pattern of changes in their orbital elements.

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## 2 Numerical model of gravitational field

The Solar System is an assemblage of a large number of celestial bodies gravitationally bound to the Sun. The Sun accounts for over 99.8% of the Solar System's mass (The Astronomical Almanac by U.S. Naval Observatory), being close to the Solar System's barycentre (the centre of gravity). For this reason, the Sun holds the motion of the overwhelming majority of celestial bodies under its gravitational sway. Eight major planets with their satellites (moons), as well as dwarf planets, asteroids, comets, objects lurking in the Kuiper belt, meteoroids and gas-and-dust aggregates, all move around the Sun.

The farther away from the barycentre of the Solar System, the weaker the Sun's gravitational pull. In order to define the boundaries of the region of space in which it is feasible to assume the Sun's gravitational attraction to be the dominant force, the concept of the solar sphere of action can be applied (Chebotarev 1965; Balk 1965).

When modelling the motion of bodies within this region of space, the gravitational acceleration towards the Sun is considered to be the main influence while all the other gravitational pulls are deemed as perturbing ones. The radius of the sphere of action of the Sun relative to the Galactic Centre is estimated to be 60,000 au or 0.3 pc (Chebotarev 1965). The region of space in the immediate solar neighbourhood, which is adjacent to the outer boundary of the sphere of action of the Sun, is to be dubbed the outskirts of the Solar System. In this region, the gravitational pull of the Sun is comparable to the gravitational acceleration towards celestial bodies surrounding the Solar System.

Thus, some members of the Kuiper belt population (Allen et al. 2001), as well as some long-period comets, move in interstellar space while remaining deep inside the Sun's sphere of action. As proposed by Jan Oort (Oort 1950), the Sun is surrounded by a cloud (or a halo) of comet nuclei, later named the Oort cloud. It is not yet feasible to observe the Oort cloud directly; however, indirect methods of studying this cloud argue in favour of its existence (Vokrouhlický et al. 2019). Therefore, there is a rich population of comets and billions of cometary-type objects forming a huge, spherically symmetrical cloud on the outskirts of the Solar System, which still lacks convincing observational evidence (Królikowska and Dybczyński 2017). At large heliocentric distances, these celestial bodies move in a gravitational field of a complex configuration.

What determines this gravitational field? First of all, it is the gravitational pull of the nearest stars and gravitational attraction as a tidal force of the Milky Way in its entirety (McMillan 2017).

It is well known that our Galaxy is a collection of hundreds of billions of stars, gas-and-dust clouds and other objects. The diameter of the Milky Way is estimated to be several tens of thousands of parsecs. The Galactic Centre is marked by the central mass concentration. The Sun is at a distance of about 8 kpc from the Galactic centre (Binney and Merrifield 1998). Obviously, the solar neighbourhood radius is far too small as compared to the estimated diameter of the Milky Way.

In order to simplify the numerical model of the gravitational field in the vicinity of the Solar System, the total gravitational potential of the Milky Way is expressed as the sum of gravitational potentials of its components, namely central bulge, disc and halo:

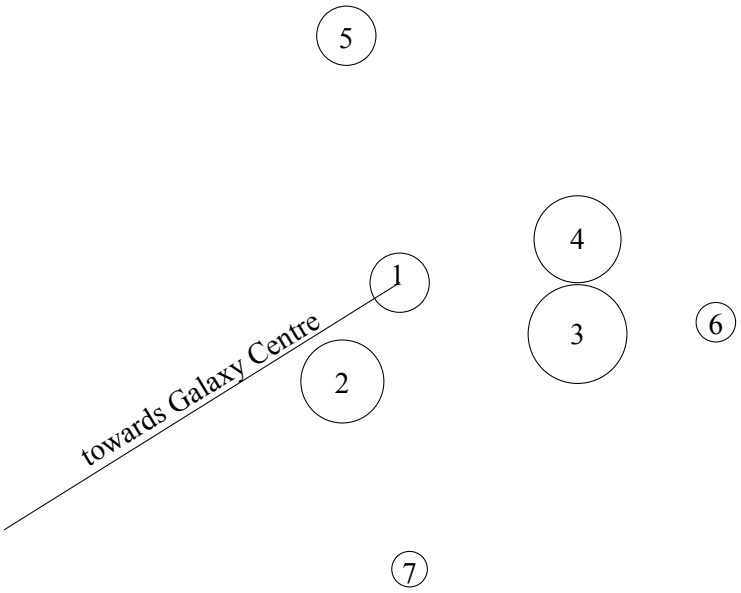



**Figure 1** Equipotential surfaces at small values of gravitational potential energy around the Sun and nearest massive stars, respectively. 1, Sun; 2, Toliman (Alpha Centaurus); 3, Sirius (Alpha Canis Major); 4, Procyon (Alpha Canis Minor); 5, 61 Cygni; 6, Epsilon Eridani; 7, Epsilon Indi.

$$U_{\text{galaxy}} = U_{\text{centre}} + U_{\text{disk}} + U_{\text{halo}}.$$

Numerical expressions have been adopted from the study by Allen et al. (1991).

The masses and positions of the nearest stars are taken from the catalogues by Zakhozhaj (1979–1996) and Oppenheimer (2001). These are among the few reference sources which contain estimates of masses of the nearby stars within 10 pc from the Sun. Gravitational potentials of stars are well described using the point mass approximation.

$$U_i = -G\frac{m_i}{r_i},$$

where $G$ is the gravitational constant, $m_i$ is a star's mass, $r_i$ is the distance to the star.

Assuming additive contribution of the Milky Way components to its total gravitational potential, the summing of all elements of the above equations yields the following:

$$U = -G\sum_{i=1}^{N}\frac{m_i}{r_i} + U_{\text{centre}} + U_{\text{disk}} + U_{\text{halo}},$$

where $N = 355$.

Using this model, we have constructed a set of equipotential surfaces. Figure 1 illustrates equipotential surfaces surrounding nearby stars within 3.5 pc from the Sun.

Red dwarfs are not shown. The value of the constant potential energy is rather small; hence, the equipotential surfaces just slightly deviate from spherical symmetry. The radius of the equipotential surface around the Sun is close to that of the solar sphere of action relative to the Galactic Centre.

## 3 Movement on the outskirts of the Solar System

The simulation of the gravitational field in the vicinity of the Solar System shows that several of the most massive stars or stellar systems can be set apart from among the other nearest neighbours of the Sun. First of all, it is the closest triple-star system Alpha Centauri. Its total mass, including the mass of Proxima Centauri, is more than twice that of the Sun (Anosova et al. 1994). Among equipotential surfaces in the constructed set, there is one that surrounds the Sun and Alpha Centauri system. For the same value of the constant potential energy, there is another surface around neighbouring Sirius and Procyon (see Fig. 2).

For a greater value of the constant potential energy, there is an equipotential surface surrounding all four relatively massive stars (star systems) – namely, the Sun, Alpha Centauri, Sirius and Procyon. Substantially smaller red dwarfs, Luyten's star (near Procyon) and Barnard's star, are also within this equipotential surface.

To estimate the pattern of changes in orbits on the outskirts of the Solar System, we have built trajectories of 150 trial cometary nuclei with original circular orbits at 60,000 au from the Sun. Orbital inclinations were selected randomly within the range from 0 to 180 degrees. The initial period of revolution about the Sun is close to 14,700,000 years.

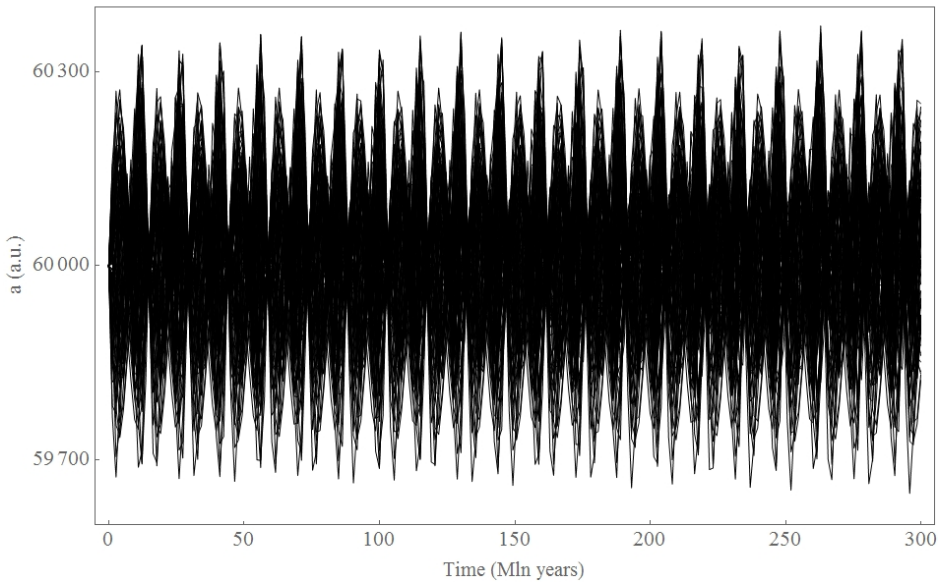



**Figure 2** Semi-major axes of the orbits of 150 trial cometary nuclei.

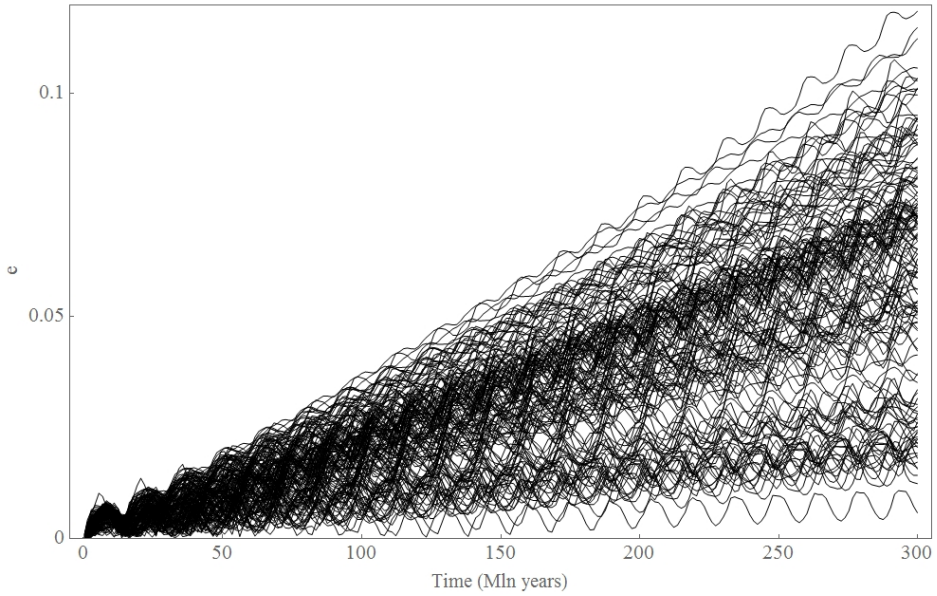



**Figure 3** Orbital eccentricities of 150 trial cometary nuclei in original circular orbits at 60,000 au from the Sun.

The numerical integration of the equations of motion has been performed using the Everhart method (1974) over an interval of 300 million years. The yielded resulting changes in the orbital semi-major axes and eccentricities are given in Figs. 2 and 3.

Semi-major axes of the orbits undergo cyclic oscillations, for which the period is half the respective orbital period while the maximum initial amplitude is about 300 au. The period of cyclic oscillations of the eccentricities equals to the orbital period. Both plots demonstrate secular perturbations to the orbital elements. Even when not factoring in proper motion and close encounters of stars, the trial cometary nuclei move into more and more elliptical (elongated) orbits, gradually shifting closer to the Sun at their perihelia. The orbital planes have not changed noticeably over the integration interval.

## 4 Discussion and Conclusions

The Solar System evolved from the pre-solar nebula about 4.6 billion year ago. Nearly circular orbits of major planets indicate that there have been no secular perturbations in their motion. The farther the distance from the Sun, the greater the contribution of perturbing accelerations in the motion of celestial bodies. This places a constraint on the upper limit of the Oort cloud radius.

The result obtained suggests some instability of motion on the outskirts of the Solar System even within the framework of the afore-described simplified model of the gravitational potential. The orbital eccentricities increase over time spans comparable

to the age of the Solar System. It may result in scattering the orbits of the Oort cloud objects both inward and outward in the Solar System. It can be assumed that in interstellar space there may be regions wherein celestial bodies move along closed trajectories at least for a while, orbiting two or more stars at once. Drawing more specific conclusions requires taking into account the proper motion of stars, choosing a statistically significant number of trial comet nuclei, as well as simulating their motion through adjacent gravitational fields of several closest stellar systems.

## References

Allen R.L., Bernstein G.M., Malhotra R. (2001) in: The Edge of the Solar System, AJ 549, n.2

Anosova J., Orlov V.V., Pavlova N.A. (1994) in: Dynamics of nearby multiple stars. The Alpha Centauri system, A&A, 292,115

Allen C., Santillan A. (1991) Rev. Mexicana A&A, 22, 255

Balk M.B. (1965) in: Elements of space flight dynamics, 204

Binney J., Merrifield M. (1998) in: Galactic Astronomy, 433

Chebotarev G.A. (1965) in: Analytical and numerical methods of celestial mechanics, 309

Chebotarev G.A. (1965) in: Analytical and numerical methods of celestial mechanics, 316

Everhart E. (1974) in: Implicit single methods for integrating orbits, Celestial Mechanics, 10, 35

McMillan P.J. (2017) in: The mass distribution and gravitational potential of the Milky Way, MNRAS 465, 76

Oort J. H. (1950) in: The structure of the cloud of comets surrounding the Solar System and a hypothesis concerning its origin, BAIN 11, 91

Oppenheimer B. (2001) in: Stars within 8 pc of the Sun, J/AJ/121/2189

Vokrouhlicky D., Nesvorny D., Donec L. (2019) in: Origin and Evolution of Long-periodic Comets, AJ 157, n 5

Zakhozhaj V.A. (1979-1996) in: Nearest stars until 10pc, V/101