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On dynamical and physical evolution of 95P/Chiron as Centaurs representative

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The long-term orbital evolution modeling of 95P/Chiron (2060) is discussed with its implication to the physical evolution of this representative of Centaurs group. In this work we have carried out the orbital evolution modeling for 33 objects of Centaurs population, and for 2 distant Jupiter-family comets 39P/Oterma and 29P/Schwassmann–Wachmann 1. The calculations were produced for 1 million years backward and forward from the present time. The Everhart implicit single sequence methods for integrating orbits were used. Due to discovered cometary activity in 2060 Chiron it is of interest to reveal Centaurs modeled orbits with small perihelion distances. Such orbits could lead to “waking up” of cometary nature in some Centaurs. The modeled orbital evolution patterns of Centaurs are analyzed and the fraction of potential candidates to comets are discussed.

ДИНАМІЧНА ЕВОЛЮЦІЯ КОМЕТИ 95P/ХІРОН ЯК ПРЕДСТАВНИКА ГРУПИ КЕНТАВРІВ, Коваленко Н.С., Бабенко Ю.Г., Чурюмов К.І. — В роботі обговорюються результати моделювання динамічної еволюції комети 95P/Хірон як найбільш цікавого представника групи Кентаврів. Було проведено чисельне моделювання еволюції орбіт 33 об'єктів групи Кентаврів і 2 віддалених комет групи Юпітера — 39P/Отерма та 29P/Швассмана–Вашмана 1. Чисельне інтегрування із використанням метода Еверхарта було проведено на 1 млн. років у майбутнє та минуле. У зв'язку з відкриттям кометної активності Хірона є цікавим виявлення орбіт Кентаврів з малими перигелійними відстанями. Такі орбіти можуть призвести до “пробудження” кометної природи в деяких Кентаврах. Обговорюється характер змін модельних орбіт Кентаврів і частка потенційних кандидатів у комети.

ДИНАМИЧЕСКАЯ ЭВОЛЮЦИЯ КОМЕТЫ 95P/ХИРОН КАК ПРЕДСТАВИТЕЛЯ ГРУППЫ КЕНТАВРОВ, Коваленко Н.С., Бабенко Ю.Г., Чурюмов К.И. — В настоящей работе обсуждаются результаты моделирования динамической эволюции кометы 95P/Хирон как наиболее интересного представителя группы Кентавров. Было проведено численное моделирование эволюции орбит 33 объектов группы Кентавров и 2 удаленных комет группы Юпитера — 39P/Отерма и 29P/Швассманна–Вашманна 1. Численное интегрирование с использованием метода Эверхарта было проведено на 1 млн. лет в будущее и прошлое. В связи с открытой кометной активностью Хирона представляет интерес выявление орбит Кентавров с малыми перигелийными расстояниями. Такие орбиты могут привести к «пробуждению» кометной природы в некоторых Кентаврах. Обсуждается характер изменения модельных орбит Кентавров и доля потенциальных кандидатов в кометы.

1. INTRODUCTION

The recent years' discoveries of distant minor bodies have changed our ideas about structure, dynamics and formation of the Solar system. In particular, the trans-Neptunian Kuiper Belt objects and Centaurs group objects have been revealed.

TNO's have orbits with semimajor axis exceeding that of Neptune. The first Kuiper belt object was discovered by Jewitt and Luu, and many others have been discovered since. It is estimated that approximately 10^5 objects with diameters of 100–300 km exist in the Kuiper belt. Large heliocentric distances of these objects imply that they could be regarded as a source of ice-rich nuclei of short-period comets. It is widely believed that Centaurs population represents an evolutionary link between trans-Neptunian objects and short-period Jupiter-family comets.

The objects of Centaurs group are located between orbits of Jupiter and Neptune. More than 40 Centaurs objects are currently known. The first representative of Centaurs population, 2060 Chiron was

discovered in 1977 [7]. It moves on its orbit with $P = 50.2$ years, $a = 13.6$ AU, $e = 0.38$, $i = 6.94^\circ$. At aphelion Chiron is 18.8 AU away from the Sun, and in perihelion it approaches the Sun at 8.5 AU.

Cometary activity of Chiron was detected [16] a decade after its discovery. That appears to be atypical for objects at such large heliocentric distances. Sublimation of water ice as the most common consistent of comets can explain the activity up to 5–6 AU. At larger distances cometary nucleus activity is controlled by sublimation of volatile ices such as CH_4 , CO , CO_2 , N_2 , and CN . The detection of CN emission from Chiron has been reported by Bus et al. and that of CO by Womack and Stern. Water ice in Chiron has also been detected [9]. Nevertheless, the mechanism that drives Chiron's activity is still in debate.

The detected cometary activity in 2060 Chiron may serve as a confirmation of the prevailing view that Centaurs are transitional population from trans-Neptunian Kuiper Belt objects to Jupiter-family comets.

The origin of Chiron and other Centaurs is one of the intriguing problems of the Solar system physics, and it has not been solved yet. To determine the origin of Centaurs, their present dynamical state and possible future patterns, physical evolution, we can simulate the dynamical evolution of Chiron and other Centaurs objects by the means of numerical integration. In this work we have carried out the orbital evolution modeling for 33 objects of Centaurs population, and for 2 distant Jupiter-family comets: 39P/Oterma and 29P/Schwassmann–Wachmann 1.

2. METHOD OF NUMERICAL INTEGRATIONS

The numerical integration of chosen Centaurs' orbital evolution was produced to trace them up to 1 Myr backward and forward from the present time. To investigate Centaurs' orbital evolution the program based on the seven-body problem solution (with planets from Jupiter through Pluto) was used. It allows to simulate orbital evolution; to calculate changes in orbital elements with time; to find the minimum distance between Centaurs object and giant planet during each period of revolution; and to find correlation between close approaches to the planets and orbital evolution.

The implicit single sequence methods for integrating orbits proposed by Everhart were used. The step-size of integration is variable. The relative truncation error was set to 10^{-12} . Integrations were stopped when major semi-axis exceeds 100 AU. Starting orbital elements of objects under consideration were taken from <http://ssd.jpl.nasa.gov/data/>.

As a result, the plots of long-term evolution of Centaurs' orbital elements and planetary close approaches were obtained.

Apart of numerical integration of orbits with initial orbital elements, equal to those of chosen Centaurs, 12 variational orbits with slightly different orbital elements (± 1 in last decimal sign after coma) were traced up to ± 200 kyr for each of 3 cometary objects: 2060 Chiron, 39P/Oterma, and 29P/Schwassmann–Wachmann 1.

3. ORBITAL EVOLUTION OF CHIRON

Investigation of Chiron's dynamical evolution has a long history. Numerical integrations were made for different time intervals both backward and forward in time [11; 12; 7; 3; 10]. It was shown that Chiron is presently under "control of Saturn's gravity", and it follows a chaotic (unstable) orbit pattern [11]. Marsden [7] remarked that predictability of the orbit is lost if the integration is extended past any close encounter with Saturn. Slightly different starting values may yield a completely different orbit [12].

The modeling of Chiron and other Centaurs dynamical evolution revealed the variety of individual evolutionary paths. It was shown that their dynamical lifetime is of order $10^{5.5} - 10^{6.5}$ years. The changes in orbits are chaotic due to frequent close approaches to the neighbouring giant planets.

Evolution of Chiron's orbit both forward and backward in time is of similar character, although some asymmetry in time can be observed. The general conclusion is that the past and future orbit of Chiron remains unknown over a long time scale and numerical integrations are of statistical significance only.

Therefore in this work we regard the dynamical evolution of Chiron on the background of general trends in changes of Centaurs' orbits.

Exhibition of Chiron's cometary activity can be chosen as other criterion for solving this problem. Its activity at such large heliocentric distances implies the existence of volatiles with low sublimation temperatures on Chiron's surface. In fact, if Chiron had been on the orbit with small q for some considerable period of time in the past, volatiles that were introduced as a possible explanation of Chiron's activity, would have vaporized completely. Thus, we suggest that Chiron is not in its present orbit with small q for a long period of time.

Due to discovered cometary activity in 2060 Chiron (at the moment it is a lonely active Centaurs object) it is of interest to reveal modeled orbits with small perihelion distances for other Centaurs. Such orbits could lead to "waking up" of cometary nature in other Centaurs.

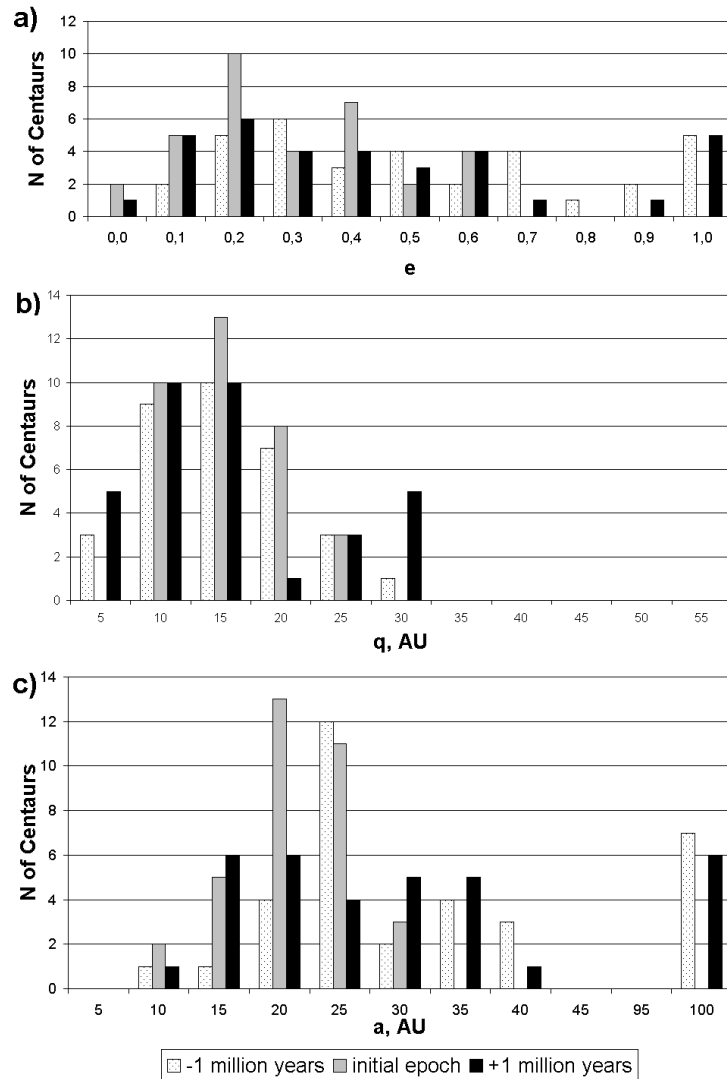


Fig. 1. Changes with time in distribution of 34 Centaurs by eccentricity e (a), perihelion distance q (b), and semi-major axis a (c)

4. RESULTS OF 3 COMETS' LONG-TERM ORBITAL EVOLUTION MODELING

Detailed investigation on the orbital history of Chiron has been made earlier by Hahn and Baily [3], and Nakamura and Yoshikawa [10]. They inferred Chiron's orbital evolution statistically in terms of probability.

In Nakamura and Yoshikawa's calculations for 200 kyr toward the past Chiron's orbit was decreasing from 20–40 AU to the present value in about 75% of the cases. In particular there were 3 cases of direct capture via a single planetary encounter from $a = 100 - 400$ AU. During the future 200 kyr about 70% of orbits increased to 20–30 AU from the present value.

Hahn and Baily pointed out the past/future asymmetry which could not be so clearly seen in Nakamura and Yoshikawa's calculations. Their evolution of orbit perihelion distance q seems to be more complicated than that of the semi-major axis a . About a half of q -orbits stayed between 12 AU and the present value, while another half showed very chaotic variations between the present value and 1–2 AU. Such captures into orbits of $q = 1 - 2$ AU are temporary and rarely stable for more than 2–3 kyr.

Our results also show this past/future asymmetry. The analysis of 13 orbits shows the possibility of frequent close approaches to the giant planets, with Saturn sometimes on distances smaller than 0.1 AU. Close approaches to Uranus reach values of about 0.25 AU, to Neptune — 0.3 AU. Close approach to Saturn on distance 0.006 AU in about 400 kyrs in the future caused the ejection of Chiron from the orbit close to the present one, and resulted in the significant increasing of major semi-axis (more than 100 AU). The chaoticity of orbital changes was revealed as well in the modelling of 12 variational orbits

The statistics on integration of 13 orbits for Chiron is following. For evolution toward the past there were 8 cases when major semi-axis has decreased comparing achievable before values (20–80 AU), in 4 cases it has remained with some deviations at the level of present value, and in 1 case it has increased from 4 AU. In 6 cases q has increased, in 4 remains stable and in 3 cases has decreased to its present value. For modeling evolution toward the future there were 6 cases with no significant changes of a , 4 cases of increasing a up to 17–40 AU, and 3 cases of decreasing a . As for perihelion distance q there are 5 cases of decreasing and 5 cases of retaining near present value of q . In 3 cases modeling toward the future showed the increasing of perihelion distance up to 13 AU.

The modeling of orbital evolution of comet Oterma in the past showed less diversity of a -patterns. For all 13 orbits semi-major axis a in the past were considerably bigger (in 11 cases reaching 100 AU and more) and decreased to its present value. As for perihelion distance q , 5 cases showed q bigger than now, 5 cases — less, in 3 cases q didn't change significantly. In the future the orbital integration modeling showed common trend (12 cases) of increase of semi-major axis a up to the values of 40–100 AU and more. In 1 case a doesn't change significantly. Integrations for q showed equal possibilities for increasing and decreasing perihelion distance (4 orbits for each case) and 5 cases with no strong tendency of decrease or increase.

The results for orbital evolution modeling of comet Schwassmann–Wachmann 1 are more varying. In the past most orbits (12 cases) showed bigger semi-major axis a than now. In 1 case in the past a grew up from 3–4 AU to its present value. In 7 cases q didn't change significantly, in 3 cases it decreased from 10–20 AU, and in 3 cases it increased from 2–4 AU to 6 AU.

In the future in most cases (9 orbits) a shows increasing of its values up to 20–100 AU, in 3 cases it fluctuates around its present value, and in 1 case the decreasing of a to 3 AU is possible. Perihelion distance q will increase in 6 cases up to 9–14 AU, in 4 cases it will decrease to 1–2.5 AU, and in 3 cases it fluctuates with amplitude of 2–8 AU.

5. RESULTS OF CENTAURS' LONG-TERM ORBITAL EVOLUTION MODELING AND CONCLUSIONS

Statistics for orbital evolution modeling for 33 Centaurs and 2060 (95P/) Chiron are shown on Fig. 1 (a,b,c). In general from orbital evolution modeling of 33 Centaurs we have the following results:

- The orbital evolution of Centaurs is strongly chaotic, and characterized by relatively frequent close encounters with the planets. In some cases the process in which particles are “handed off” from the gravitational influence of one giant planet to another occurs among Centaurs objects. Some Centaurs visit a number of different resonances, while others avoid resonances altogether. The cases of ejection from the solar system as well as injection into orbits with smaller q also are not rare.
- Most values of Centaurs perihelion distances q during the period of integration are in the range of 5–30 AU. In the present time the most “habitable” range is 6–20 AU (91%), in the future only 61% of objects have perihelia in this range, and in the past — about 79%.
- Most values of Centaurs semi-major axis are contained in the range 5–40 AU. The general tendency in long-term evolution of a shows more symmetrical behaviour toward the past and toward the future. In present time 85% of Centaurs have semi-major axis located between 10–25 AU. In the past this range contains 49% of Centaurs a , and in the future 46%.
- Our integrations showed that the fraction of objects with perihelion distances less than 5 AU (possible candidates to active comets) in the past is 9%, while in the future it composes 15%. At the same time fraction of objects with semimajor axis less than 10 AU in the past and in the future is about 3–4% (at the present such fraction is 6%).
- Numerical integrations of 2060 Chiron orbital evolution show that in terms of probability it could be regarded as a typical representative of Centaurs population.

To make more confident conclusions about connection between Centaurs and shord period comets it would be useful to compare physical characteristics of such objects, to calculate orbital evolutions for more Jupiter family comets.

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