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学位論文題目	The Theory of Motion and Ephemerides of The Second Neptunian Satellite Nereid
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論文内容の要旨

The problem of obtaining accurate ephemerides for the second Neptunian satellite Nereid has intrigued many astronomers since its discovery by Kuiper in 1949. That is because of its bizarre orbit. The satellite's orbit has unusually large eccentricity ($e \sim 0.75$) which is considered as the most eccentric known natural satellite in the solar system. This very elongated orbit renders the usage of the classical methods for expanding the disturbing function in terms of the eccentricity, that is because of the slow convergence of the power series solutions especially at higher orders.

In this work we aim to study the dynamical motion of the second Neptunian satellite Nereid using both analytical and numerical methods. We construct an analytical theory of the motion of a highly eccentric Nereid which accurately represents a real satellite system, then we pose emphasis upon comparison with numerical integration of the equations of motion. The theory is elaborated by the use of Lie transformation approach advanced by Hori's device. This method enables us to express the relations between the osculating and the mean elements in an explicit form instead of the implicit form arised by Poincare'-von Zeipel's approach. By the virtue of Hori's perturbations method, we can also get the inverse transformations easily. The main perturbing forces on Nereid which come from the solar influence are only taken into account through the present theory. The disturbing function is developed in powers of the ratio of the semimajor axes of the satellite and the Sun. To avoid the slow convergence of the power series solution, the disturbing function is put in a closed form with respect to the eccentricity of Nereid. In addition, replacing functions of the true anomaly by expressions involving the mean anomaly is also avoided, and the eccentric anomaly of Nereid has been adopted as independent variable. The present theory includes secular perturbations up to the fourth order, short and long period perturbations up to the third order and small parameter e (which defines the ratio between the orbital period of Nereid and that of Neptune) $\sim 6 \times 10^{-3}$. The results of the present theory satisfy the required accuracy for future observations. We intend to develop this theory to be applied on the retrograde satellites of the major planets. The dissertation is organized as following:

In chapter 1 we give a general introduction which includes the advantages of the use of the analytical techniques and their expected outcome. A review on Nereid, the second Neptunian satellite, and its enigmatic according to different sources are summarized. Chapter one contains also a section about the classification of natural satellites according to their orbits and perturbing forces. Then we pose the motivation and aim of this study.

Chapter 2 contains the method that we have used, equations of motion and the disturbing function. Hori's perturbation method is introduced briefly, and some of the merits and demerits of canonical methods in celestial mechanics have been shown. This chapter includes also procedures for obtaining the osculating orbital elements starting from the mean elements and conversely. We implement each procedure for digital computations by constructing a computational algorithm described by its purpose, input and its computational sequence.

In chapter 3 we dealt with the circular planar restricted three-body problem. In this case, the inclination of Nereid to the orbital plane of Neptune is zero. The osculating orbital elements of the fictitious Nereid are evaluated and given in figures. The results are compared with those computed by the numerical integration of the equations of motion. The residuals are tabulated and showed also by figures. At the end of this chapter we give a short note about d'Alembert characteristics which permit the validity of the analytical expressions based on Lie transform approach.

Chapter 4 is devoted to the circular nonplanar restricted three-body problem. In this case we take the inclination of Nereid into account and deal with the nonplanar solution for a real Nereid. The analytical expressions of the short, intermediate and long periodic perturbations are evaluated. After elimination of the short and intermediate terms, the Hamiltonian system equations are solved in e,I and ω using Jacobi's elliptic function (Kinoshita and Nakai,1999), whereas the longitude of ascending node and the mean anomaly are expressed in Fourier series expansion. By this solution we got the mean elements which are used for evaluating the osculating orbital elements and ephemerides of Nereid. All these processes are summarized in a computational algorithm and carried out by the powerful MATHEMATICA software package. Moreover, the analytical expressions are transformed into FORTRAN format and programmed to be easy to handle.

We compared the analytical results with those computed by the direct numerical integration of the equations of motion for short and long periodic perturbations. As a result of this comparison, the global internal accuracy of the present theory reached 0.3km in the semimajor axis, 10^{-7} in the eccentricity and 10^{-5} degree in the angular variables over a period of several hundred years. The behavior of the orbital motion of the satellite is exhibited in analytical expressions, tables and figures. The way of comparison is discussed briefly. Finally, we close this research by discussion and conclusions. By this end we provide to the observers an efficient analytical theory, capable of generating accurate ephemerides for the motion prediction of highly eccentric Nereid.

論文の審査結果の要旨

海王星の外側の衛星ネレイドは、約半世紀前に発見された暗い（約19等）衛星で、非常に大きな離心率（約0.75）を持つことと、海王星からの距離が比較的大きい、すなわち太陽の摂動が強いために、その軌道運動には謎の部分が多い。一方、純粋理論的見地、すなわち天体力学における摂動論を展開するという観点から見ると、軌道離心率が大きいことは、摂動関数を離心率のべき級数に展開するという通常の手法では級数展開の収束が悪いことを意味し、したがって高精度の解析的理論を構築することは、従来不可能であった。

申請者は、この困難を克服すべく、離心率が大きい軌道に対しても有効な摂動論を構築し、その応用としてネレイドの場合に適用することによって、以下のような重要な結果を得た。

1．Lie-堀の正準摂動論に基づき、以下の手法を採用することによって、摂動関数について離心率についてのべき展開を行わない摂動論の構築法を確立した。

1）まず、短周期項（ネレイドの場合、海王星の周りの衛星の公転運動に相当し、周期は約360日）および中間周期項（ネレイドの場合、太陽の周りの海王星の公転運動に相当し、周期は約165年）の消去に関しては、各段階で正準変換を行った。

2）長周期項（ネレイドの場合、海王星の周りの衛星の軌道の近点の永年的移動に相当し、周期は約１万９千年）については、通常の正準変換ではなく、木下・中井（1999）のヤコビ楕円関数による解析解を援用した。

2．上記構築法を試すために、円制限平面三体問題（海王星の軌道を既知の円軌道と制限し、ネレイドの軌道面を海王星の軌道面と同じにとった場合）について適用し、運動方程式の数値積分で得られた数値解と比較することにより、数百年の間、海王星中心の角度で0.03秒（実距離にして800m）という高精度を得た。

3．さらに、実用上重要な衛星の軌道が傾いている場合に対しても、同様に摂動論を構築し、平面問題と同じく数値解との比較により、ネレイドの場合で、数百年の間、海王星中心の角度で0.2秒（実距離で６ｋｍ）の精度を持つ解析解を構築することに成功した。

申請者によって得られた結果は、ネレイドそのものの半径が約170ｋｍであること、また海王星中心の角度観測精度で０．２秒角は、地球からの角度観測精度に換算すると0.006秒角に相当することからみて、近未来の観測方法・機器の進展を見据えてもなお、実用上十分な精度の解析解ということができる。ちなみにすばる望遠鏡の角度分解能は0.2秒角である。

以上のように、従来不可能であった、大きい離心率と強い太陽摂動を持つ衛星軌道の解析的理論の一般的構築法を開発し、かつ実用に耐えるまでの解析解を実際に求めて見せたことは、理論天体力学の新しい地平を切り開いたものであり、評価できる。