Scientist Memoirs: Postprint of Professor Liu Lin' s Scientific Research Achievements, Academic Experience, and Research Insights

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Abstract

This article presents Professor Liu Lin from the School of Astronomy and Space Science at Nanjing University reflecting on the achievements, experiences, and insights from his academic career. Section 1 provides a brief introduction to Professor Liu, reviewing his journey from formative years and academic training to becoming a preeminent figure in celestial mechanics and spacecraft orbital mechanics in China. Section 2 offers a comprehensive overview of Professor Liu' s academic accomplishments. From the early stages of China' s aerospace development, Professor Liu has conducted research on satellite orbit theory, participated in numerous missions and spacecraft models, with relevant results being applied therein; as an expert in celestial mechanics, he has also undertaken multiple studies on the orbital dynamics of small solar system bodies and achieved notable accomplishments; with China' s advancement in deep space exploration, Professor Liu has also contributed to the research and demonstration efforts for China' s lunar and Martian exploration projects. Section 3 of the article introduces Professor Liu' s achievements from over 50 years of dedication to the teaching profession, having educated generations of students, many of whom have become accomplished professionals. In Section 4, Professor Liu shares his experiences and reflections from over 50 years of engagement in teaching and research, imparting his wisdom to young scholars in scientific research and education regarding work methodologies, professional attitudes, and approaches to integrating work and life.

Full Text

Preamble

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Scientific Reminiscence: The Academic Achievements, Experiences, and Insights of Professor Liu Lin

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Abstract

This article is composed based on the narrative by Professor Liu Lin from the School of Astronomy & Space Science at Nanjing University, detailing his academic achievements, experiences, and insights. The first section provides a brief introduction to Professor Liu Lin, outlining his journey from growing up and studying to becoming a leading authority in the fields of celestial mechanics and spacecraft orbital mechanics in China. The second section comprehensively introduces Professor Liu Lin' s academic accomplishments. Since the early days of China' s aerospace development, Professor Liu has conducted research on satellite orbital theory, participated in numerous missions and projects, and applied his relevant achievements within them. As an expert in celestial mechanics, he has also carried out extensive research and achieved results in the field of small bodies dynamics. With China' s advancement in deep space exploration, Professor Liu has been involved in research and feasibility studies related to China' s lunar and Mars exploration programs. The third section highlights Professor Liu Lin' s achievements over more than 50 years in his role as an educator. He has dedicated his life to teaching and educating young scholars, who have flourished in various fields. In the fourth section, Professor Liu Lin shares his experiences and insights from over 50 years of dedication to teaching and research. He passes on his wisdom to younger generations in the fields of scientific research and education, covering aspects such as work methods, attitudes, and work-life balance.

Key words: history, biographies, celestial mechanics

2 Academic Research

My academic research can be divided into three main stages: an early focus on artificial Earth satellite orbital mechanics, a comprehensive expansion into the fundamental theory and applications of small body orbital dynamics beginning in the 1980s, and deep involvement in national major aerospace engineering project demonstration, planning, implementation, and key scientific problem research starting in the 1990s. Representative achievements are primarily reflected in the following areas.

2.1 Artificial Earth Satellite Orbit Theory and Its Application

Due to the significant differences between the orbital motion characteristics of artificial Earth satellites and those of natural small bodies in the solar system, coupled with the requirements for rapid and high-precision orbit determination, the original solar system orbit determination and prediction methods could not be directly applied after the launch of artificial satellites.

2.1.1 Proposal of Artificial Earth Satellite Orbit Theory The first consideration was the selection of coordinate systems, which should obviously be spatial coordinate systems directly connected to the Earth itself, while the sixth orbital element should preferably use the anomaly that directly indicates its spatial position.

To this end, Kozai proposed the mean element method in 1959 [1]. Its core idea was to select mean elements composed only of initial mean elements and long-period perturbation terms as the main part of the small-parameter power series solution, and then provide corresponding long- and short-period terms. Subsequently, to avoid additional perturbation problems caused by the oscillation of the Earth' s equatorial plane, a complex orbital coordinate system related to this was proposed. At the same time, some experts (such as Cook [2]) also provided similar perturbation analysis solutions. However, I have proven that their respective results are equivalent, and the corresponding instantaneous elements are consistent, which eliminated the doubts of domestic engineering application departments about which set of formulas to use. But the focus of the problem was not here, but rather that the theories and corresponding methods of Kozai and other experts had major defects: (1) The choice of coordinate system (a hybrid orbital coordinate system) was complicated and impractical; (2) Regarding the specific construction of the perturbation solution, under certain accuracy requirements (such as first-order meaning), the solution was incomplete and had major defects.

The key to these two problems was caused by the oscillation of the Earth' s equatorial plane and the direct use of the time element anomaly (such as mean anomaly) as the sixth orbital element. In fact, the problem of equatorial plane oscillation is easy to solve, and the additional perturbation caused by it is simple. I have provided a simple and clear expression, making it unnecessary to use the orbital coordinate system proposed by Kozai and other experts to solve it.

Regarding the second and most important problem, this can be said to be a major mistake by Kozai and other experts. Since the sixth element used the mean anomaly M, under the meaning of a first-order solution, it was necessary to use the second-order short-period term of the orbital semi-major axis a. However, they did not provide this term, but instead used a constant term obtained by other authors using canonical transformation methods (which differed from the accurate term in Kozai' s method) as a substitute. This led to errors and confusion in use, which is the trouble caused by the "two-line elements" in the international aerospace community. Regarding this problem, I have strictly provided the correct result using the corresponding method, perfectly solving the professional errors that should not exist in the "two-line elements." The corresponding treatment of this problem has been adopted or reflected in relevant national standards (plans) newly established or implemented in China in the past two years.

2.1.2 Further Refinement of Artificial Earth Satellite Orbit Theory

The refinement of artificial Earth satellite orbit theory (also required by practical applications) includes not only the need for complete orbital solution expressions under certain accuracy requirements as mentioned above, but also the need to eliminate (if possible) various singularities appearing in the corresponding expressions, including commensurability between the orbital period and the Earth's rotation period (as the central celestial body), the state where the orbital inclination is at the critical angle (i = 63°26 or 116°34), small eccentricity orbits, and small inclination orbits. Only by constructing such singularity-free solutions can we truly understand the motion laws of artificial Earth satellites and thus meet the needs of various space exploration missions.

Based on the existence of small-parameter (denoted as) power series solutions, it can be proven that the above various commensurability states will not lead to infinite increase in the amplitude of corresponding periodic terms, and the magnitude of the amplitude is actually ^(1/2). Regarding this theoretical problem, it can be proven from another approach by changing the corresponding small-parameter power series solution to expand according to ^(1/2), but the corresponding expressions of each order function are special functions, which are difficult to use and cannot be promoted. However, it confirms that the singularity problems mentioned above are indeed problems of the expression form of the corresponding perturbation solution and can be solved using corresponding methods. To this end, I have conducted specific research on the above-mentioned critical angle states and provided long-period changes with amplitudes of order ^(1/2). This provides a key approach to constructing singularity-free perturbation solutions for artificial Earth satellite orbital motion: in the expression of perturbation solutions, the treatment of long-period terms should be different from that of short-period terms, and long-period variation terms should be treated together with secular variation terms as the reference orbit of the perturbation solution.

In response to the problems existing in Kozai' s mean element method, based on the above research work, I proposed selecting quasi-mean elements formed by only eliminating short-period variations of the orbit as the reference orbit, and constructing perturbation analysis solutions that are applicable to any orbital eccentricity and any orbital inclination, while simultaneously eliminating commensurability singularities caused by various small denominators. This method is called the singularity-free quasi-mean element method (also known as the Liu Lin method). This method has been widely applied in research and application fields such as orbit design, ground TT&C, space target monitoring, and onboard autonomous orbit prediction and control.

I have also made beneficial advances in the application of canonical transformation methods in orbit theory. I established an internal connection between the above quasi-mean element method and canonical transformation methods, and extended the von-Zeipel method and Hori-Lie method, which were only applicable to canonical conjugate variables, to transformation methods applicable to arbitrary variables. The framework of transformation is not subject to any restrictions of canonical transformation. This method not only eliminates restrictions on the variables used but also retains the characteristics of transformation methods, expanding application functions. Thus, in orbital mechanics, the transformation method can be directly used to construct analytical solutions for the variation of Keplerian elements, making the more intuitive mean element method (or quasi-mean element method) more concise in mathematical expression form, also making people' s understanding of the mean element method (or quasi-mean element method) more profound, and effectively reducing the difficulty of establishing high-order perturbation solutions using the mean element method.

In the traditional research of initial orbit determination methods in celestial mechanics, I broke through the limitation of the two-body problem model, extending the orbit determination method from short-arc orbit determination work only applicable to the two-body problem to short-arc orbit determination work applicable to simultaneously considering various perturbation influences or any motion forms (including the motion of deep space probes during transfer orbit segments). This can not only adapt to the needs of high-precision data orbit determination but also expand the application background, further improving the theory and method of initial orbit determination. However, in the iterative process calculation of multi-data orbit determination for space missions, there is no need to use complex transition matrices that consume a large amount of computing time; the corresponding transition matrix is just a reference ruler.

The above research results have formed a set of artificial Earth satellite orbit theory with an independent and complete system, rigorous mathematical expression, and clear mechanical meaning. It has been widely applied in related fields in China, including satellite overall design, ground TT&C (orbit determination, prediction, and control), space target monitoring, onboard autonomous prediction and control, and other engineering fields. The orbit dynamics theory for Earth satellites can be extended to some corresponding explorations of celestial bodies such as the Moon and Mars.

2.2 Orbital Dynamics of Small Bodies in the Solar System

Orbital resonance in the motion of small bodies in the solar system is a fundamental problem in celestial mechanics. I have conducted in-depth and influential research work with several collaborators. Based on the distribution characteristics of the asteroid belt in the solar system, we established an average analysis model for asteroid orbital resonance motion for various commensurability ratios, discovered new distribution structures of their corresponding libration points, compared the stability characteristics of resonance motion corresponding to different commensurability ratios, and carried out research on long-term orbital dynamic evolution. We established the first analytical model for co-orbital motion, which well demonstrated the distribution characteristics of tadpole-type and horseshoe-type orbits, laying a solid foundation for subsequent related research. For major planetary satellites in different types of orbital resonance states, we established ideal resonance models and analyzed orbital stability regions.

Near-Earth asteroids are a hot issue of international astronomical concern. Their most important orbital dynamic characteristic is the "crossing" of orbits of two celestial bodies, which brings certain difficulties to analysis and numerical research. Collaborating with graduate students, I took the lead in China to conduct in-depth research on the theory and methods of near-Earth object-Earth encounter problems. I made practical improvements to the regularization theory methods of celestial mechanics, established a characteristic numerical model applicable to the long-term evolution of near-Earth asteroid orbits, studied the encounter problems of more than 160 potentially hazardous near-Earth asteroids (PHAs) with Earth within the next 200 years, and achieved prediction accuracy reaching the international advanced level, providing theoretical guidance for domestic related observation equipment. Through the analysis of resonance characteristics in the long-term orbital evolution of near-Earth objects, the combined action of long-term resonances (periapsis, ascending node secular resonance, and Kozai resonance) and orbital resonance is the main excitation mechanism for the eccentricity and inclination of main-belt objects, revealing the possibility that near-Earth objects originate from the main belt.

Celestial orbital dynamic models generally correspond to Hamiltonian systems. Due to the complexity of celestial motion, analytical methods for studying orbital evolution have certain limitations, and numerical calculation methods are also commonly used research methods for complex problems. Based on the energy integral characteristics of the system, I proposed an along-track error compensation method based on energy integrals, which effectively improved the numerical calculation accuracy of Hamiltonian systems and has been well applied in high-precision orbit calculations, such as using long-term satellite laser ranging data to determine changes in the main zonal harmonics of the Earth' s gravitational field. The symplectic algorithm for Hamiltonian systems established by Chinese mathematician Mr. Feng Kang and others has been well applied in the long-term evolution of celestial orbits. I and my collaborators studied the existence of formal integrals of symplectic algorithms, provided their solution processes, and numerically verified their convergence under certain conditions. This theoretically explains the dynamic relationship between the symplectic integrator and the original Hamiltonian system. The symplectic integrator still describes a Hamiltonian system, which is an approximation of the original Hamiltonian system, with errors determined by the accuracy of the symplectic algorithm.

While conducting the above research and gaining attention from international peers, I also trained several graduate students, providing necessary reserve talents for the development of celestial mechanics in China.

2.3 Orbital Dynamics of Deep Space Exploration

On the eve of China' s deep space exploration, I led graduate students to be the first to extend artificial Earth satellite dynamics to deep space probes and conducted systematic research.

The dynamic characteristics of planetary libration points are also fundamental problems in celestial mechanics and have important application value for spacecraft orbital motion. I and my graduate students conducted systematic research on the internal dynamic connections and stability characteristic evolution of periodic orbit families near libration points, achieving a series of original discoveries, including finding the last critical value of the evolution of planar periodic orbit families, providing for the first time the global evolution of periodic orbit families at collinear libration points considering collision singularities, pointing out the dynamic root of double lunar swing-by orbits and providing design schemes for more complex multiple swing-by orbits, and constructing practical high-order analytical solutions for motion near collinear libration points in the elliptical restricted three-body problem for the first time. These theoretical works have enriched the theoretical system of this classic model and have important academic value. For this work, my doctoral student also won the National Excellent Doctoral Dissertation Award. On this basis, I and my collaborators extended the idealized restricted three-body problem to the actual restricted system of the solar system, achieving multiple original discoveries. For example, from a resonance perspective, we first pointed out the dynamic root of the unique stability characteristics of the Sun-Saturn system triangular libration points under Jupiter' s perturbation. Combined with the dynamic asymmetry characteristics of the two triangular libration points of the Sun-Jupiter system under Saturn' s perturbation within the resonance timescale and the planetary migration process, we provided a possible explanation for the origin of the currently observed asymmetric distribution of Jupiter Trojan asteroids. In particular, we conducted original research on the motion characteristics near the collinear and triangular libration points of the actual Earth-Moon system under solar perturbation. We first pointed out that the classical double-circular model of the Sun-Earth-Moon system is not suitable for solving the forced orbits at collinear libration points under the ephemeris model, and constructed semi-analytical solutions for small-amplitude forced orbits and two large-amplitude forced orbits at triangular libration points under the ephemeris model, as well as low-order analytical solutions for motion near them. These works have been repeatedly verified and cited by top foreign teams.

Based on the theoretical research of celestial orbital mechanics and combined with the needs of China' s lunar and Mars exploration projects, I also conducted research on some orbital problems encountered in lunar and deep space exploration activities and provided effective solutions, providing theoretical basis for the orbit design and TT&C countermeasures of corresponding detectors. Some representative achievements include: (1) For deep space exploration flying around celestial bodies without atmosphere, we revealed the mechanism that constrains orbital lifetime differently from atmospheric dissipation for Earth satellites. Through comprehensive theoretical analysis, we found that gravitationally excited large-amplitude long-period terms of eccentricity are the main non-dissipative mechanism constraining orbital lifetime, but the specific mechanisms are different for low and high orbits. For low orbits, it mainly depends on the ratio of odd zonal harmonics to oblateness terms, while for high orbits, it is the combined action of oblateness and third-body gravitation. In both mechanisms, the oblateness term of the main celestial body plays a protective role. (2) For lunar exploration, we extended the quasi-mean element method for Earth satellite motion to lunar orbiters and provided analytical extrapolation formulas for lunar satellite orbital motion. (3) We designed free-return trajectories for manned lunar exploration activities, and proposed effective solutions for problems such as limited re-entry angles under specific epoch return and landing site constraints, transfer to Earth-Moon libration points, and mid-course corrections for lunar or Mars transfer orbits.

The above work has important practical value under the background of increasing demand for the application of Earth-Moon space resources and rapid development of solar system deep space exploration. More than 10 special technical reports have been submitted to national important application departments or units, most of which have been directly applied in the demonstration and planning of multiple related space projects in China.

3 Teaching and Education

While conducting scientific research, I also placed talent cultivation in an important position, aiming to improve the overall level of celestial mechanics (mainly) and orbital dynamics in China's astronomy and aerospace fields and to meet the needs of future development. Before retirement, I personally taught university and graduate courses related to celestial orbital motion theory, such as "Spacecraft Orbital Mechanics," at Nanjing University almost every year. I personally supervised more than 40 doctoral and master' s students, most of whom entered related universities or research institutes after graduation and became backbone personnel, some becoming academic leaders in related fields or key members of scientific and technological projects. Among them, some have grown into recipients of the National Science Fund for Distinguished Young Scholars, recipients of the National Science Fund for Excellent Young Scholars, chief designers of core systems for major national science and technology projects, directors of observatories, members of ministerial-level science and technology expert committees, and hosts or undertakers of multiple national major scientific research project tasks. For this, I have received the Excellent Mentor Award for teaching and educating from Nanjing University and Jiangsu Province multiple times.

In addition to teaching in the Mathematics and Astronomy departments of Nanjing University, I have also taught courses or given special lectures on celestial mechanics methods, satellite orbital mechanics, satellite motion theory, satellite precise orbit determination, and deep space probe orbital mechanics at more than 20 related research institutions, engineering units, and universities in China. I have also been responsible for training visiting scholars (including researchers and teachers) sent by the above units to the Astronomy Department of Nanjing University, cultivating a large number of professional talents for the aerospace field, who play the role of academic backbone in various departments in China.

Years of teaching and scientific research have given me my own unique understanding and insights into celestial (including natural and artificial celestial bodies) orbital theory and applications, which are mainly reflected in the two monographs "Orbital Mechanics of Artificial Earth Satellites"and "Spacecraft Orbital Theory." To meet the needs of different departments, I have also published multiple professional textbooks related to satellite orbital motion theory. These monographs and textbooks have been widely cited by various aerospace departments in China (covering overall design, ground TT&C, onboard autonomous prediction and control, and satellite applications), selected as classic textbooks or main reference books by related universities, and have also become main reference tools for overseas Chinese experts and scholars engaged in related work. I am currently responsible for editing a series of books titled "Space Exploration Orbital Dynamics Series," which takes spacecraft orbital dynamics as the core, based on high-precision and high spatiotemporal resolution measurement technology, systematically and deeply introduces key aerospace technology issues involved in today' s spacecraft orbital motion, including theoretical foundations, measurement methods, precise orbit determination, and scientific applications, aiming to provide a knowledge platform needed by scientific and technological workers engaged in spacecraft orbital research. The series consists of 8 volumes and is planned to be completed within the next 2-3 years.

4 Academic Experience and Research Insights

I retired at the age of 75, having engaged in celestial orbital mechanics research and teaching for 52 years. Looking back on my research path, it can be summarized as: facing practical backgrounds, exploring internal laws, adhering to rigorous and realistic approaches, maintaining dedication to teaching, and keeping a healthy body.

My research objects have mainly focused on three categories: artificial Earth satellites, natural small bodies in the solar system, and deep space exploration spacecraft, with very clear practical backgrounds. Their scientific and application values are different, and the corresponding core scientific problems are also different. Currently, artificial Earth satellite orbital motion has penetrated into every moment of people's daily lives, such as satellite navigation and positioning technology. Natural small bodies in the solar system include asteroids, natural satellites, comets, etc., and their orbital motion involves important astronomical issues such as solar system origin, space defense, and planet formation. Deep space probe orbital motion is undoubtedly an essential topic for humans to understand or utilize the solar system.

From the perspective of celestial mechanics, although the above three types of celestial bodies are all "small bodies," their corresponding dynamic laws are very different, while the research methods used are similar, namely perturbation theoretical analysis. Generally speaking, artificial Earth satellite motion corresponds to a perturbed two-body model, while natural solar system bodies and deep space exploration spacecraft may be perturbed two-body problems or restricted three-body problems, mainly determined by their spatial positions. The perturbed two-body problem and the restricted three-body problem are two basic dynamic models in celestial mechanics. The nature of perturbing forces and the initial distribution configuration of celestial orbits determine the dynamic evolution laws of the system. People' s research goals for these small body orbits are diverse, some requiring high precision, some focusing on stability (long-term or short-term), and some requiring maneuvering or type conversion, thus giving rise to various complex scientific and technological problems.

To do a good job in small body orbital research and application, solid basic theoretical knowledge of celestial mechanics is needed. At the same time, for application, a deep understanding of astrometric techniques and methods is required. Only by closely combining celestial mechanics with astrometry can breakthrough progress be made on some satellite orbital theory and application problems. Orbit, observation technology, and data processing are the three pillars for conducting small body orbital research and application, which is also the core direction for training basic astronomy talents in China in the future.

Currently, China' s deep space exploration is in a stage of comprehensive development, requiring a large number of orbital mechanics talents related to basic astronomy. However, the training efforts of relevant universities and research institutes in China are obviously insufficient, which will inevitably have an adverse impact on China' s future deep space exploration development. I sincerely hope that relevant universities and research institutes in China will pay attention to the development of basic astronomy and elevate it to its proper position, which is an urgent need for the current development of deep space exploration.

A healthy body is the most basic requirement for a person' s life. For scientific researchers, they should pay more attention to physical exercise, because the ratio of sitting to standing time is usually not very reasonable. Starting physical exercise from a young age and persisting in it will benefit one for life. This is my sincere advice to scientific researchers and also my personal experience up to now.

Thanks to the editorial department of *Acta Astronomica Sinica* for inviting me to write this "Academic Career Review." The above scientific achievements, academic experience, and research insights are only my personal summary of the work I have carried out. If there are any inappropriate points, please understand!

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Appendix: Representative Academic Publications

I. Major Academic Monographs

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Note: Figure translations are in progress. See original paper for figures.