Quantum Mechanics_Celestial mechanics

Celestial mechanics is the branch ofastronomy that deals with the motions ofcelestial objects. The field applies principles ofphysics, historically Classical mechanics, to astronomical objects such as stars and planetsto produce ephemeris data. Orbital mechanics(astrodynamics) is a subfield which focuses on the orbits of artificial satellites. Lunar theory is another subfield focusing on the orbit of the Moon.

History of celestial mechanics

For early theories of the causes of planetary motion, see Dynamics of the celestial spheres.

Modern analytic celestial mechanics started over 300 years ago with Isaac Newton's Principia of 1687. The name "celestial mechanics" is more recent than that. Newton wrote that the field should be called "rational mechanics." The term "dynamics" came in a little later with Gottfried Leibniz, and over a century after Newton, Pierre-Simon Laplace introduced the term "celestial mechanics." Prior to Kepler there was little connection between exact, quantitative prediction of planetary positions, using geometrical or arithmetical techniques, and contemporary discussions of the physical causes of the planets' motion.

Johannes Kepler

For detailed treatments of how his laws of planetary motion can be used, see Kepler's laws of planetary motion and Keplerian problem.

Johannes Kepler (27 December 1571–15 November 1630) was the first to closely integrate the predictive geometrical astronomy, which had been dominant from Ptolemy to Copernicus, with physical concepts to produce a *New Astronomy, Based upon Causes, or Celestial Physics...*. His work led to the modern laws of planetary orbits, which he developed using his physical principles and theplanetary observations made by Tycho Brahe. Kepler's model greatly improved the accuracy of predictions of planetary motion, years before Isaac Newtondeveloped his law of gravitation.

Isaac Newton

Isaac Newton (4 January 1643–31 March 1727) is credited with introducing the idea that the motion of objects in the heavens, such as planets, the Sun, and theMoon, and the motion of objects on the ground, like cannon balls and falling apples, could be described by the same set of physical laws. In this sense he unified *celestial* and *terrestrial* dynamics. Using Newton's law of universal gravitation, proving Kepler's Laws for the case of a circular orbit is simple. Elliptical orbits involve more complex calculations, which Newton included in hisPrincipia.

Joseph-Louis Lagrange

After Newton, Lagrange (25 January 1736–10 April 1813) attempted to solve the three-body problem, analyzed the stability of planetary orbits, and discovered the existence of the Lagrangian points. Lagrange also reformulated the principles ofClassical mechanics, emphasizing energy more than force and developing amethod to use a single polar coordinate equation to describe any orbit, even those that are parabolic and hyperbolic. This is useful for calculating the behaviour of planets and comets and such. More recently, it has also become useful to calculatespacecraft trajectories.

Simon Newcomb

Simon Newcomb (12 March 1835–11 July 1909) was a Canadian-American astronomer who revised Peter Andreas Hansen's table of lunar positions. In 1877, assisted by George William Hill, he recalculated all the major astronomical constants. After 1884, he conceived with A. M. W. Downing a plan to resolve much international confusion on the subject. By the time he attended a standardisation conference in Paris, France in May 1886, the international consensus was that all ephemerides should be based on Newcomb's calculations. A further conference as late as 1950 confirmed Newcomb's constants as the international standard.

Albert Einstein

Albert Einstein (14 March 1879–18 April 1955) explained the anomalous precession of Mercury's perihelion in his 1916 paper *The Foundation of the General Theory of Relativity*. This led astronomers to recognize that Newtonian mechanics did not provide the highest accuracy. Binary pulsars have been observed, the first in 1974, whose orbits not only require the use of General Relativity for their explanation, but whose evolution proves the existence of gravitational radiation, a discovery that led to the 1993 Nobel Physics Prize.

Examples of problems

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Celestial motion without additional forces such as thrust of a rocket, is governed by gravitational acceleration of masses due to other masses. A simplification is the *n*-body problem, where the problem assumes some number *n* of spherically symmetric masses. In that case, the integration of the accelerations can be well approximated by relatively simple summations.

Examples:

- 4-body problem: spaceflight to Mars (for parts of the flight the influence of one or two bodies is very small, so that there we have a 2- or 3-body problem; see also the patched conic approximation)
- 3-body problem:
    - Quasi-satellite
    - Spaceflight to, and stay at a Lagrangian point

In the case that $n=2$ (two-body problem), the situation is much simpler than for larger n. Various explicit formulas apply, where in the more general case typically only numerical solutions are possible. It is a useful simplification that is often approximately valid.

Examples:

- A binary star, e.g., Alpha Centauri (approx. the same mass)
- A binary asteroid, e.g., 90 Antiope (approx. the same mass)

A further simplification is based on the "standard assumptions in astrodynamics", which include that one body, the orbiting body, is much smaller than the other, the central body. This is also often approximately valid.

Examples:

- Solar system orbiting the center of the Milky Way
- A planet orbiting the Sun
- A moon orbiting a planet
- A spacecraft orbiting Earth, a moon, or a planet (in the latter cases the approximation only applies after arrival at that orbit)

Either instead of, or on top of the previous simplification, we may assume circular orbits, making distance and orbital speeds, and potential and kinetic energies constant in time. This assumption sacrifices accuracy for simplicity, especially for high eccentricity orbits which are by definition non-circular.

Examples:

- The orbit of the dwarf planet Pluto, ecc. = 0.2488
- The orbit of Mercury, ecc. = 0.2056
- Hohmann transfer orbit
- Gemini 11 flight
- Suborbital flights

Perturbation theory

Perturbation theory comprises mathematical methods that are used to find an approximate solution to a problem which cannot be solved exactly. (It is closely related to methods used in numerical analysis, which are ancient.) The earliest use of Perturbation theory was to deal with the otherwise unsolveable mathematical problems of celestial mechanics: Newton's solution for the orbit of the Moon, which moves noticeably differently from a simple Keplerian ellipse because of the competing gravitation of the Earth and the Sun.

Perturbation methods start with a simplified form of the original problem, which is carefully chosen to be exactly solvable. In celestial mechanics, this is usually aKeplerian ellipse, which is correct when there are only two gravitating bodies (say, the Earth and the Moon), or a circular orbit, which is only correct in special cases of two-body motion, but is often close enough for practical use. The solved, but simplified problem is then *"perturbed"* to make its starting conditions closer to the real problem, such as including the gravitational attraction of a third body (the Sun). The slight changes that result, which themselves may have been simplified yet again, are used as corrections. Because of simplifications introduced along every step of the way, the corrections are never perfect, but even one cycle of corrections often provides a remarkably better approximate solution to the real problem.

There is no requirement to stop at only one cycle of corrections. A partially corrected solution can be re-used as the new starting point for yet another cycle of perturbations and corrections. The common difficulty with the method is that usually the corrections progressively make the new solutions very much more complicated, so each cycle is much more difficult to manage than the previous cycle of corrections. Newton is reported to have said, regarding the problem of the Moon's orbit *"It causeth my head to ache."*[1]

This general procedure – starting with a simplified problem and gradually adding corrections that make the starting point of the corrected problem closer to the real situation – is a widely used mathematical tool in advanced sciences and engineering. It is the natural extension of the "guess, check, and fix" method used anciently with numbers.

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