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THE HISTORY AND BACKGROUND OF ASTRODYNAMICS[1]

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Abstract

The history of astrodynamics began with Newton's Principia, 300 years ago. Newton's laws of motion and law of gravitation, with small modifications, are still applicable today and are being used in space research. The orbiting of the first artificial satellite renewed interest in celestial mechanics which applied the Newtonian laws to the motion of natural bodies. The space applications and the study of the dynamics of artificial bodies introduced several changes in the basic requirements and astrodynamics became the basic research tool in space dynamics. The original contributors in the U.S. to this field were Herrick, Herget, Eckert, Clemence and Brouwer whose influence is still strongly felt, mostly through their many valuable publications, associates, and students.

Introduction

It is indeed a great honor to prepare and present this paper at the 39th Congress of the International Astronautical Federation. The invitation of my colleague, Professor J.V. Breakwell, asking me to review the history of our celestial subject is a challenge along several lines. The primary demand to prepare this paper is that our history covers at least three hundred years since one of the first significant and basic contributions, Newton's Principia[1], was published in 1687. To cover 300 years is a difficult assignment, but to discuss the last thirty years requires probably even more care. It was in 1957 that the first space probe was launched[2], and it became clear in a very few days that Newton has not solved all problems in astrodynamics.

In this paper we shall try to balance the 300 years of preparation and the last 30 years of vigorous activity.

The terminology of our field shows a remarkable variety. The field of astronomy which deals with the dynamics and motion of natural celestial bodies is usually called *celestial mechanics*. As applications to the dynamics of artificial bodies (space probes) became increasingly important, the field was renamed by Professor S. Herrick, and today we refer to *astrodynamics*. When stellar dynamics received the attention of analysts, the term *dynamical astronomy* was introduced. We must thank Newton that the theory and applicability of gravitation is sufficiently general to cover all these fields and terminologies. The basic, inverse-square force law of gravitation and the principles of dynamics can take care of the problems of motion of natural and artificial bodies.

A General View of the History of Astrodynamics

Sir Isaac Newton humbled himself by saying, "If I have seen further, it is by standing on the shoulders of giants."

It is, therefore, justified to say a few words concerning those giants, before we give all the credits to Newton and to his contemporaries.

In this way, the history of astrodynamics might be divided in four parts:

(1) The pre-Newtonian period, beginning with Aristoteles and ending with Galileo;
(2) The classical or Newtonian period, beginning with Newton and ending with Hamilton;
(3) The "modern", 19th century contributors, beginning with Hill and ending with Birkhoff;
(4) The 20th century contributors and the participants of the last thirty years ending today.

The previously mentioned three hundred years of preparation include parts (2), (3) and the first half of part (4).

The Pre-Newtonian Period

We probably should start with *Aristotle* (about 384–322 BC), who represented the philosophical approach as opposed to the scientific one, promoting the geocentric universe.

Hipparchus (about 190–125 BC) was probably the first contributor to present-day astrodynamics, combining astronomy with mathematics. He developed spherical trigonometry and clarified several complex properties of the motion of the moon.

Ptolemaeus (about 151–127 AD), with his epicycles, aimed at proving "scientifically" the validity of the geocentric universe.

We conclude this period by mentioning that some of the Greek philosophers in the third century BC already suggested that the sun might be the "center of the universe", initiating in this way the helicentric hypothesis.

Copernicus (1473–1543)[3] and his students proposed the heliocentric idea more as a convenient way to compute planetary orbits than as a physical fact. His circular planetary orbits were improved by *Kepler* (1571–1630), who offered his laws of planetary motions, and the equation named after him which connects the mean anomaly with the eccentric anomaly. Various new methods of solving Kepler's equation are still offered in today's literature of astrodynamics.[4]

It is difficult to resist to make three additional comments about one of the greatest men in our field belonging to the pre-Newtonian period.

(1) If Kepler would have known dynamics, instead of concentrating on geometry and on kinematics, we would have today Kepler's law of gravitation. It is relatively simple to obtain Newton's inverse-square law of gravitation from Kepler's laws.

(2) Kepler admitted that he used Tycho Brahe's (1545–1601) observational results to obtain his laws of planetary motion. Once again, Brahe could have obtained

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himself Kepler's laws if he would not have insisted on the validity of the geocentric system.

(3) Kepler encountered a well known problem of scientists and engineers which still exists today. His sponsor, the Emperor Rudolf II, requested that Kepler should prepare his horoscopes. Kepler considered astrology as a source of income rather than science and became one of the first "principal investigators" satisfying the requests of a sponsor against his own better judgment. He did not believe in astrology, but his sponsor requested "practical and applicable results". It is tempting to contemplate on the negative effect of his sponsor which possibly prevented him from discovering the law of gravity. After all, research in gravity would have been considered a "useless theoretical game-playing" compared to the "importance of astrology".

Galileo Galilei (1564-1642)[5] is another one of our famous ancestors who combined astronomy with dynamics and offered verbal statements of Newton's laws of motion. So, once again, we could have Galileo's laws of dynamics and Kepler's law of gravitation.

He expressed his strong feelings of the importance of mathematical rationalism by stating that the "book of nature is written in mathematical characters".

The Classical Newtonian Period

Sir Isaac Newton's (1642-1727)[1] contributions, for many historians of science, represent the beginning of a completely new dynamics and a new meaning of "science". This is most adequately summarized by the quotation, "Nature and nature's laws lay hid in night. God said, 'let Newton be,' and all was light," by Alexander Pope.

Since many reference books are available concerning the Newtonian period[1,5,7], only those aspects will be mentioned here which are directly related to astrodynamics.

Let us begin with the unverified apple incident which occurred when, in 1665, Newton left Cambridge because of the plague and went back to his birthplace, where he could dedicate his time to undisturbed thinking. The importance of connecting seemingly unrelated phenomena—in this case falling stones (or apples) on one side, and planetary motion on the other—is clearly demonstrated. In fact, Newton describes the idea leading to artificial satellites with the following thought experiment. If stones are thrown from the top of a mountain with small horizontal velocities, they will hit the ground, but as the velocity is increased, circular and elliptic orbits are obtained around the earth.

Newton's laws of motion, forming the basis of dynamics, can be located in all our undergraduate textbooks. When we follow Newton's original formulation, we arrive at the surprising conclusion that he did not connect force with acceleration, but with the change of momentum. This allows the direct application of Newtonian laws to variable mass and to rocket propulsion.

He applied his law of gravity to the lunar problem which later Poincaré[16] found non-integrable. His unlimited and complete dedication resulted in headaches, sleepless nights, irregular eating habits and, finally, a nervous fatigue at 50 years of age; but still he found some important results concerning the Earth-Sun-Moon three-body problem.

The problem of three bodies is still one of our major headaches in astrodynamics. We certainly can integrate numerically not only three but many-body gravitational systems, but such exercises seldom offer complete understanding of the long-time behavior of the system. This idea leads us to Lambert's erroneous statement according to which all problems in astrodynamics and celestial mechanics may be considered solved, once Newton's laws are applied. It should be emphasized that this statement, which is often repeated even today by the uneducated ignorami, is erroneous for several reasons. First, it must be realized that Newtonian mechanics is not associated with complete predictability in dynamics. This was Leibnitz'[6] dogma and was not accepted by Newton. Laplace's demon enters the picture at this point, knowing all initial conditions and all laws of nature, and predicting the future. He takes the side of Leibnitz. The proper conclusion is that, because of the non-integrability principle, because of our uncertainty of the initial conditions and physical laws, and because of the error accumulation during numerical integration, the limits of predictability in our field are finite.

Our short description of Newton's contributions to our field might be ended by Newton's humble description of his work. "I seem to have been only like a boy playing on the seashore and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me." In order to balance his humility, we also must quote Edmund Halley: "Nec fas est propius mortali attingere divos." ("Nearer the gods no mortal may approach.")

Some of the many contributors to our Newtonian period are Descartes, Leibnitz, Halley, Euler, Clairaut, d'Alembert, Lagrange, Laplace, Legendre, Gauss, Poisson, Encke and Hamilton[7]. This list is presented mainly to remind the reader that the company we keep is outstanding, concerning contributions to science. The direct connections of the works of any of the above contributors to astrodynamics can be detailed and could easily fill a book instead of an article. Our selection of *Lagrange* might show prejudice, but it certainly indicates unexpected applicability of theoretical results.

Joseph Louis *Lagrange's* (1736–1813) announcement concerning the triangular libration points in the Sun-Jupiter system and his prediction of the possible existence of asteroids in these regions date from 1772. Observational astronomers could not verify the existence of these bodies for another 134 years. In this case, theory was certainly ahead of observations. His work on the solar system using the method of the variation of parameters (1782) is one of the fundamental contributions in astrodynamics.

The "Modern", 19th Century Contributors

The well known major contributors of this period are Hill, Tisserand, Poincaré, Moulton, Whittaker, and Birkhoff. The name most familiar to astrodynamicists is *F.R. Moulton* (1872–1952) who is the author of the first book published in the United States in our field, in 1902. It served for many years as the basic textbook. The following quotation might show prejudice, but it will please the devotees of our field: "At the present time, Celestial Mechanics is entitled to be regarded as the most perfect science and one of the most splendid achievements of the human mind." (Note that this book was published before S. Herrick introduced the term "astrodynamics".)

Hill and Tisserand are connected with lunar and planetary theories. Poincaré's and Birkhoff's works are strongly mathematically oriented, and Whittaker's book is along analytical dynamics. All these contributions are important, though only indirectly related to astrodynamics.

The Latest, 20th Century Contributors

This period includes our teachers and the present day workers in our field: Arnold, Brouwer, Duboshin, Herget, Herrick, Kolmogorov, Moser, Siegel and Wintner are some of the principal names.

The Yale University group worked under the leadership of Dirk Brouwer (1902–1966) and the University of California group under Samuel Herrick (1911–1974). The west coast group concentrated more on space dynamics, while the east coast group's primary interest was celestial mechanics. The meeting ground of these groups was satellite dynamics, applicable to artificial and natural satellites. Many meetings and workshops were organized where informal exchanges of information took place. The use of Herrick's universal variables was referred to as *regularization* on the east coast. His special perturbation methods often proved to be superior to Brouwer's results obtained by general perturbation techniques, and vice versa, depending on the problem.

The Summer Institutes organized by the Yale group had many well known lecturers such as Brouwer, Clemence, Eckert, Hagihara and Herget, some of whom cooperated intensely with Herrick in 1957, when the first artificial satellite was placed in orbit.

Some of the assistants of Herrick's school are well known today: Baker, Breakwell, Broucke, Bryson, Escobal, Junkins, and Leitmann, just to mention a few. The list of contributors connected with the east coast is also impressive: Danby, Davis, Duncombe, Garfinkel, Hori, Message, Musen, Rabe, and Vinti, would be some of the names.

These lists are not at all complete. The attempts to prepare an all-inclusive list, using the advice of this author's colleagues, shows that over 150 active contributors are involved today in the field of astrodynamics.

It is important to call attention to the strong and highly competent contributors to our field, working in the Soviet Union. One of the leaders was G.N. Duboshin (1904–1986), who made important contributions by applying quantitative and qualitative dynamics to space research as well as to astronomy. He was the Chairman of the Department of Celestial Mechanics at Moscow University for 25 years with an honorary degree from Torun, birthplace of Copernicus. His group in Moscow and the Institute of Theoretical Astronomy in Leningrad made many basic advances in celestial mechanics and astrodynamics. Abhyankar, Aksenov, Alekseev, Anasova, Arnold, Brumberg, Chebotarev, Chetayev, Demin, Dubyago, Egorov, Elyasberg, Faddeev, Fesenkov, Kolmogorov, Krylov, Lyapunov, Merman, Moisseiev, Orlov and Subbotin are some of the principal contributors.

In addition, the names of the authors of some of the important textbooks of astrodynamics and celestial mechanics should be mentioned: Arnold, Baker, Bate, Battin[4], Brouwer, Danby, Deutsch, Duboshin, Dubyago, Ehricke, Finlay-Freundlich, Fitzpatrick, Hagihara, Herget, Herrick, McCuskey, Moser, Pollard, Roy, Siegel, Smart, Sterne, Stiefel, Stumpff, Taff, Thomson and Wintner.

Concluding Remarks

This short outline of the history of our field is closed with two remarks.

First, the author wishes to apologize for the omission of some names, discoveries, and contributions in the past and at the present. In astrodynamics, we usually locate ourselves in a moving coordinate system, the rotation of which often prevents us from viewing the whole picture at any instant of time. If a name is left out which is important to the reader (such as his own or one of his important ancestors'), he should feel very well since the company of the omitted names includes Gauss, Charlier, Delaunay, and Einstein, just to mention a few.

The second concluding remark refers to the future of our field. The beauty of the panorama of astrodynamics shall never be diminished since the dictum of non-integrability and the law of non-existence of generally valid closed form solutions will not change. This is not a negative statement, considering our field, but it represents the most valuable challenge. The general unsolvability of Newtonian problems above the level of two bodies will not be changed, no matter what magic advanced mathematics, topology, Hamiltonian dynamics, or high speed computers will produce. In this respect our field is far superior to others, since the concern of completely solving the basic problems in other fields is replaced by the challenges of working with the spirits of Brouwer and Herrick on unsolvable problems.

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