A HISTORY OF ASTRONOMY, ASTROPHYSICS AND COSMOLOGY

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Contents

Summary

This chapter describes the history of the development of astronomy, astrophysics and cosmology from the earliest times to the first decade of the 21st century. There is a strong emphasis upon the interaction between astronomical technology, developments in physics and related sciences and astronomical discovery. The first eight sections describe the development of these disciplines up to 1939, up till which time astronomy meant optical astronomy. In section 9 the impact of the Second World War in

facilitating new ways of carrying out astronomy throughout the whole of the electromagnetic spectrum is described. The introduction of these new technologies in the post-War years resulted in many unexpected discoveries which have had importance not only for astrophysics and cosmology, but also for fundamental physics. Sections 10 to 17 describe the remarkable growth of astrophysical and cosmological understanding since 1945. The history is brought up to date with such topics as the discovery of extrasolar planets and the results of the WMAP satellite. Throughout the essay, the importance of astronomy, astrophysics and cosmology for many different aspects of physics and related disciplines is emphasised.

1. Introduction

Astronomy is the oldest of the exact physical sciences. This essay is a non-technical account of how astronomy has led to an understanding, not only of the nature of our physical Universe, but also of fundamental physical processes which define and have been derived from the study of astronomical phenomena. I write as a physicist and astrophysicist, not as a historian or philosopher. My aim is to highlight the contributions of astronomy to the understanding of physical phenomena and to deepen our insights into fundamental physics.

I adopt the following terminology: *astronomy*, *astro-nomos* = the laws of the stars or the science of heavenly bodies, is the observation of celestial phenomena and the derivation of empirical laws from these observations. *Astrophysics* is the use of the laws of physics to understand the nature, composition and physical conditions of heavenly bodies. Whereas astronomy's roots are lost in prehistory, astrophysics is a relatively modern science, conventionally being dated to the applications of astronomical spectroscopy to the understanding of astronomical phenomena. A useful benchmark is 1895, the date of the founding of the *Astrophysical Journal*. It is no coincidence that the flowering of astrophysics coincided with the dramatic increase in scientific understanding during the second half of the 19th century. By *cosmology*, I mean astrophysical and geometrical cosmology, in other words, the observation of the large scale properties of the Universe and the use the laws of physics to understand its origin and evolution. This definition excludes mythological cosmology of all persuasions.

2. Prehistoric, Ancient and Mediaeval Astronomy Up To the Time of Copernicus

Astronomical phenomena have been recorded from the earliest times. Plausibly, stellar constellations are present in the astounding paintings of the caves of Lascaux, dating from about 15,000 years BC. Burial mounds and prehistoric monuments, such as Stonehenge in England and Newgrange in Ireland, are unquestionably aligned with the passage of the Sun across the meridian at the summer solstice. Such alignments have been found in surviving monuments in many parts of the world. The association of many of these with places of burial demonstrates the significance of astronomical phenomena for early societies.

Much of early astronomy was associated with the definition of calendars which were needed to predict the dates of religious festivals, the numbers of months in the year and so on. Different calendraic systems were found in many cultures and were of some complexity because of the non-commensurability of the lunar month and the solar year. The determination of the numbers of months in the year was important, for example, in the levying of taxes. The precise definition of these calendraic systems was the task of the astronomers.

The first of the great astronomers of whom we have knowledge is Hipparchus who was born in Nicaea in the second century BC. His catalogue of 850 stars in the northern sky, completed in 127 BC, was a monumental achievement. The catalogue listed the positions of the stars as well as estimates of their brightnesses. By comparing his positions with those of Timocharis made in Alexandria 150 years earlier, a general drift of the stellar positions was observed. In modern terminology, this is referred to as the precession of the equinoxes, the slow change of the direction of the Earth's axis of rotation relative to the frame of reference of the fixed stars due to the gravitational effect of the Sun and Moon upon the slightly non-spherical Earth. In ancient times, the Earth was assumed to be stationary and so the precession of the equinoxes was attributed to the movement of the 'sphere of fixed stars'.

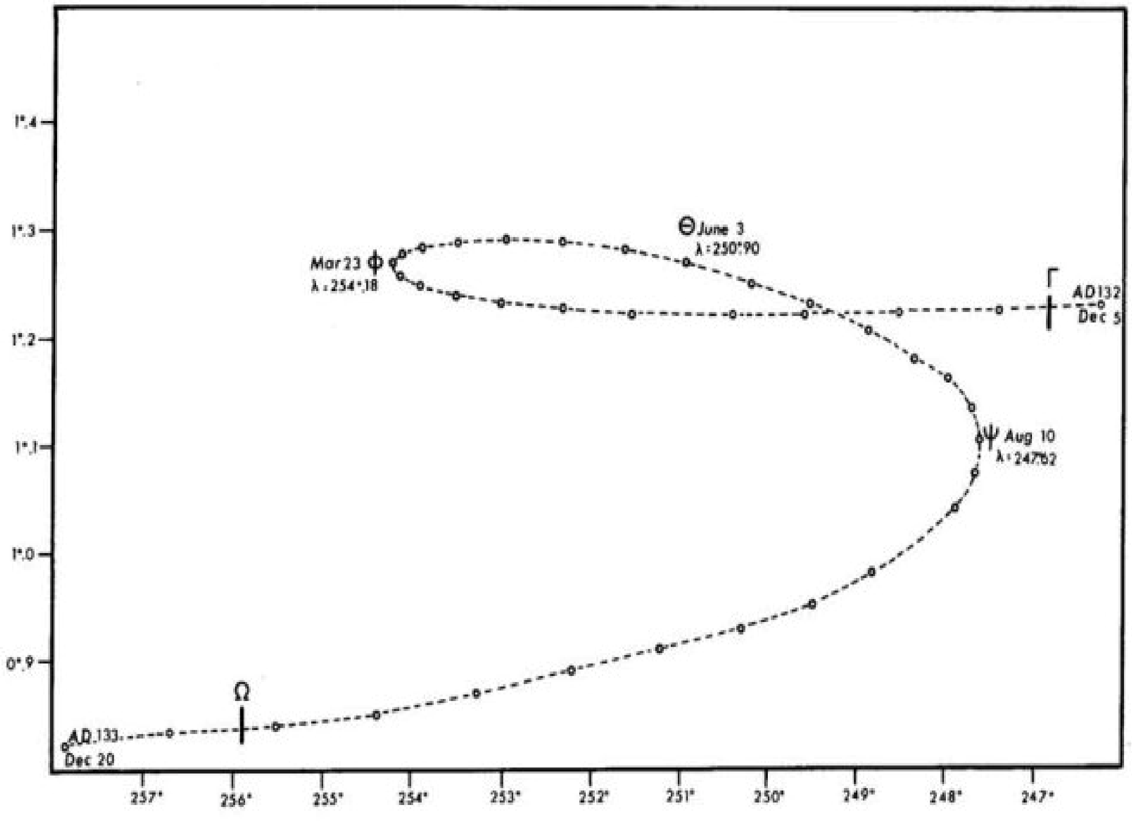

Figure 1. Ptolemy's observations of the motion of Saturn in AD 133 against the background of the fixed stars. (From O. Pedersen, *Early Physics and Astronomy*, 61. Cambridge: Cambridge University Press, reproduced by kind permission.)

The most influential of the ancient astronomical texts was the *Almagest* of Claudius Ptolomeaus or Ptolemy, who lived in the second century AD. The word Almagest is a corruption of the Arabic translation of the title of his book, the *Megelé Syntaxis* or *The*

Great Composition. In Arabic, this became *al-majisti* which was corrupted to become the Almagest. It consisted of 13 volumes and provided a synthesis of all the achievements of the Greek astronomers and, in particular, it leant heavily upon the observations of Hipparchus. Within the Almagest, Ptolemy set out what became known as the *Ptolemaic System of World* which was to dominate astronomical thinking until the 16th century.

How did the Ptolemaic system of the World work? The sphere of the ‘fixed stars’ rotates about the Earth once per day. Against that pattern of stars, the Sun and Moon move in roughly circular paths about the Earth. In addition, the motions of the five planets observable to the naked eye-Mercury, Venus, Mars, Jupiter and Saturn – were the subject of precise measurement. The Greek astronomers knew that the planets did not move in simple circles about the Earth but had somewhat more complex motions. Figure 1 shows Ptolemy’s observations of the motion of Saturn in AD 137 against the background of the fixed stars. Rather than move in a smooth path across the sky, the path of the planet doubles back upon itself.

The challenge to the Greek astronomers was to work out mathematical schemes which could describe these motions. As early as the third century BC, a few astronomers suggested that these phenomena could be explained if the Earth rotates on its axis, and even that the planets orbit the Sun. Heracleides of Pontus described a geo-heliocentric system in which Venus and Mercury orbit the Sun, which itself orbits the fixed Earth. This is a forerunner of Tycho Brahe’s compromise model between the Ptolemaic and Copernican pictures of the structure of the solar system. Even more remarkable was the proposal of Aristarchos that the Earth rotates about is axis and that the planets, including the Earth, move in circular orbits about the Sun. In *The Sun Reckoner*, Archimedes wrote to King Gelon,

You are not unaware that by the universe most astronomers understand a sphere the centre of which is at the centre of the Earth... However, Aristarchos of Samos has published certain writings on the (astronomical) hypotheses. The presuppositions found in these writings imply that the universe is much greater than we mentioned above. Actually, he begins with the hypothesis that the fixed stars and the Sun remain without motion. As for the Earth, it moves around the Sun on the circumference of a circle with centre in the Sun.

These ideas became the inspiration for Copernicus roughly eighteen centuries later. They were rejected at that time for a number of reasons. Probably the most serious was the opposition of the upholders of Greek religious beliefs. According to Pedersen and Pihl (1974),

Aristarchos had sinned against deep-rooted ideas about Hestia’s fire, and the Earth as a Divine Being. Such religious tenets could not be shaken by abstract astronomical theories incomprehensible to the ordinary man.

There were, however, physical arguments against the heliocentric hypothesis according to Aristotelian physics. First, the idea that the Earth rotates about an axis was rejected. If the Earth rotates, then, when an object is thrown up in the air, it should not come down again in the same spot-the Earth would have moved because of its rotation before the object landed. No one had ever observed this to be the case. A second concern was that if objects are not supported, they fall under gravity. Therefore, if the Sun were the centre of the Universe rather than the Earth, everything ought to fall towards that centre. But, if objects are dropped they fall towards the centre of the Earth and not towards the Sun. The Earth must therefore be located at the centre of the Universe. Religious belief was supported by scientific rationale.

The prevailing picture of the structure of the physical Universe was based upon the thinking of Aristotle who held that the sphere is the most perfect solid figure in that, when rotated about any diameter, it remains unchanged. The Universe was composed of layer upon layer of perfect spheres and motions of celestial bodies should be circular. The Earth was composed of the four elements of earth, air, fire and water, but there was a fifth pure element, the aether, which was the substance out of which the celestial bodies were made. This was the background against which the Ptolemaic geocentric system of the world was constructed.

According to the Ptolemaic picture, the Earth is stationary at the centre of the Universe and the principal orbits of the other celestial objects are circles, or spheres, in the order Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn and finally the sphere of the fixed stars. The problem with the simple Ptolemaic system was that it could not account for the details of the motions of the planets, such as the retrograde motion seen in Figure 1. Ptolemy himself stated that uniform circular motion was the only kind of motion 'in agreement with the nature of Divine Beings'. Therefore, it was supposed that, in addition to their circular orbits about the Earth, the planets as well as the Sun and Moon had circular motions about the principal circular orbit, the small circles superimposed upon the main circular orbit being known as *epicycles*. It can be appreciated how it is possible to reproduce the type of orbit shown in Figure 1 by selecting suitable speeds for the motion of the planets on their epicycles.

One of the important features of astrometry, meaning the accurate measurement of the positions and movements of celestial bodies, is that the precision with which their orbits are determined improves the longer the time span over which the observations are made. As a result, the simple epicycle picture became more and more complex, the longer the time-base of the observations. To improve the accuracy of the Ptolemaic model, the centre of the circle of the planet's principal orbit could differ from the position of the Earth but, each compound circular motion had to be uniform. It was then found necessary to assume that the centre of the circle about which the epicycles took place also differed from the position of the Earth. A large vocabulary was developed to describe the details of the orbits. By remarkable geometrical expertise and ingenuity, Ptolemy and later generations of astronomers were able to account for the observed motions of the celestial bodies and make good predictions for the positions of the Sun, Moon and the planets. These models were used in the preparation of almanacs and in determining the dates of religious festivals until after the Copernican revolution.

Until the last half of the 16th century, the predictions of the motions of the celestial bodies were derived from the Ptolemaic system, as refined by the Arabic astronomers. The standard tables, known as the Alphonsine tables, had been prepared by the Rabbi

Isaac ben Sid of Toledo and published in manuscript form in the *Libros del sabre de astronomica* in 1277 under the patronage of Alfonso X, also known as Alfonso the Wise. The tables were copied in manuscript form and were quickly disseminated around Europe. They were only published in the modern sense in 1483, forty years after the death of Copernicus.

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Bibliography

The present chapter is a very condensed version of my book *The Cosmic Century: A History of Astrophysics and Cosmology* (Cambridge: Cambridge University Press 2006), with the addition of material on early astronomy and brought up-to-date since its publication. As a result, a vast amount of material has had to be condensed into modest space. My book contains complete and detailed bibliographic references to all the topics discussed in the present essay (57 pages of literature references, excluding the secondary literature) and readers are referred to the book for more details.

The following volumes particularly helpful:

Bernstein, J. and Feinberg, G. (1986), *Cosmological Constants: Papers in Modern Cosmology*, New York: Columbia University Press. [This volume includes translations of many of the seminal papers in cosmology.]

Bertotti, B., Balbinot, R., Bergia, S. and Messina, A. (eds) (1990), *Modern Cosmology in Retrospect*, Cambridge: Cambridge University Press, Cambridge. [A very useful compilation of essays by many of those involved in the development of modern cosmology.]

Bondi, H. (1960), *Cosmology*, 2nd edition, Cambridge: Cambridge University Press. [A modern classic exposition of basis of cosmological models.]

Clerke, A.M. (1885). A *Popular History of Astronomy during the Nineteenth Century*. Edinburgh: Adam and Charles Black. [This is a classic reference concerning the development of astronomy in the 19th century.]

Gillespie, C.C. (ed) (1981), *Dictionary of Scientific Biography* and Koertge, N. (ed) (2007), *New Dictionary of Scientific Biography*, New York: Charles Scribner's Sons. [Essential resources for authoritative biographies of physicists, astronomers, astrophysicists and cosmologists. These volumes include very extensive bibliographic data and secondary literature.]

Gingerich, O. (ed) (1984) *The General History of Astronomy, Vol. 4. Astrophysics and Twentieth-Century Astronomy to 1950: Part A*, Cambridge: Cambridge University Press. [There are excellent articles in this volume, but the coverage of overall history is partial.]

Harrison, E. (2001), *Cosmology: The Science of the Universe*, Cambridge: Cambridge University Press. [A delightful introduction of cosmology with many interesting historical reflections.]

Harwit, M. (1981). *Cosmic Discovery: the Search, Scope and Heritage of Astronomy*, Brighton: Harvester Press. [A distinctive approach to the development of astronomy, astrophysics and cosmology which provides serious food for thought.]

Hearnshaw, J. B. (1996), The *Measurement of Starlight: Two Centuries of Astronomical Photometry*, Cambridge: Cambridge University Press. [This is an outstanding history of astronomical photometry, a companion to Hearnshaw's history of astronomical spectroscopy.]

Hearnshaw, J.B. (1986) *The Analysis of Starlight: One Hundred and Fifty Years of Astronomical Spectroscopy*, Cambridge: Cambridge University Press. [This is an essential reference book for everyone interested in the development of astronomical spectroscopy and astrophysics.]

Kragh, H. (1996) *Cosmology and Controversy: The Historical Development of Two Theories of the Universe,* Princeton: Princeton University Press. [A very readable survey of a dramatic episode in modern cosmology.]

Lang, K.R. and Gingerich, O. (eds) (1979), *A Source Book in Astronomy and Astrophysics*, *1900-1975*, Cambridge, Massachusetts: Harvard University Press, Cambridge. [This volume contains reprints of and brief historical introductions to many of the important articles published between 1900 and 1975. All the articles are translated into English. Often only excerpts from the complete papers are presented.]

Learner, R. (1981), *Astronomy Through the Telescope*, London: Evans Brothers Limited. [A very readable, illustrated history of the development of the telescope.]

Leverington, D. (1996), *A History of Astronomy from 1890 to the Present*, Berlin: Springer-Verlag. [A useful survey of astronomical discovery in the 20th century.]

Martínez, V.J., Trimble, V. and Pons-Bordeía, M.J. (eds), (2001), *Historical Development of Modern Cosmology*, San Francisco: ASP Conference Series, **252**. [This volume includes many excellent articles about many different aspects of the development of modern cosmology.]

North, J.D. (1965), *The Measure of the Universe,* Oxford: Clarendon Press. [A brilliant discussion of the development of theoretical concepts underlying modern cosmology.]

North, J.D. (2008), *Cosmos: An Illustrated History of Astronomy and Cosmology*, Chicago and London: Chicago University Press. [An excellent survey of the history of astronomy and cosmology, profusely illustrated and containing a large amount of material about non-Western astronomy.]

Pederson, O. and Pihl, M. (1974), *Early Physics and Astronomy*, London: McDonald and Co. [This book provides an excellent introduction to the early work of Ptolemy and others in determining the Ptolemaic system of the world.]

Struve, O and Zebergs, V. (1962). *Astronomy of the 20th Century*, New York: Macmillan Company. [A classic describing the development of 20th century astronomy up till the date of publication. This just predates the explosive development of astronomy from the early 1960s onwards.]

A key resource for all aspects of astrophysics and cosmology is the series entitled *Annual Review of Astronomy and Astrophysics*, which first appeared in 1963. These reviews are authoritative and represent understanding at the year of the review. The more recent volumes include autobiographical essays by a number of the key personalities.

For more details of the terminology and reviews of many areas of astronomy, the following books can be recommended:

Nicholson, I. (1999), *Unfolding our Universe*, Cambridge: Cambridge University Press, Cambridge. [This is an elementary text, but includes a large amount a useful background material on all aspects of astronomy.]

Murdin, P. (ed) (2001). *Encyclopaedia of Astronomy and Astrophysics* (4 Vols.), Bristol and Philadelphia: Institute of Physics Publishing and London, New York and Tokyo: Nature Publishing Group. [Excellent surveys of large areas of astronomy, astrophysics and cosmology.]

Biographical Sketch

Malcolm Longair has held many highly respected positions within the fields of physics and astronomy. He carried out his doctoral research under Martin Ryle and Peter Scheuer in the Radio Astronomy Group of the Cavendish Laboratory. From 1968 to 1969, he worked in Moscow with Academicians V.L. Ginzburg and Ya.B. Zeldovich. He was appointed the ninth Astronomer Royal of Scotland in 1980, as well as the Regius Professor of Astronomy, University of Edinburgh, and the Director of the Royal Observatory, Edinburgh. He returned to the Cavendish Laboratory as Jacksonian Professor of Natural

Philosophy in 1991 and was head of the Laboratory from 1997 to 2005. He has served on and chaired many international committees, boards and panels, working with both NASA and the European Space Agency. He has received much recognition for his work over the years, including a CBE in the millennium honors list for his services to astronomy and cosmology. He is a fellow of the Royal Societies of London and Edinburgh and a foreign member of the Accademia Lincei.

His main research interests are in high energy astrophysics and astrophysical cosmology, and increasingly the history of physics and astrophysics. His recent books include *Theoretical Concepts in Physics* (Cambridge University Press 2003), The *Cosmic Century – A History of Astrophysics and Cosmology* (Cambridge University Press 2006) and *Galaxy Formation* (Springer-Verlag 2008). A current major project is the third edition of his text *High Energy Astrophysics*, to be published in 2010 by Cambridge University Press.