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'.

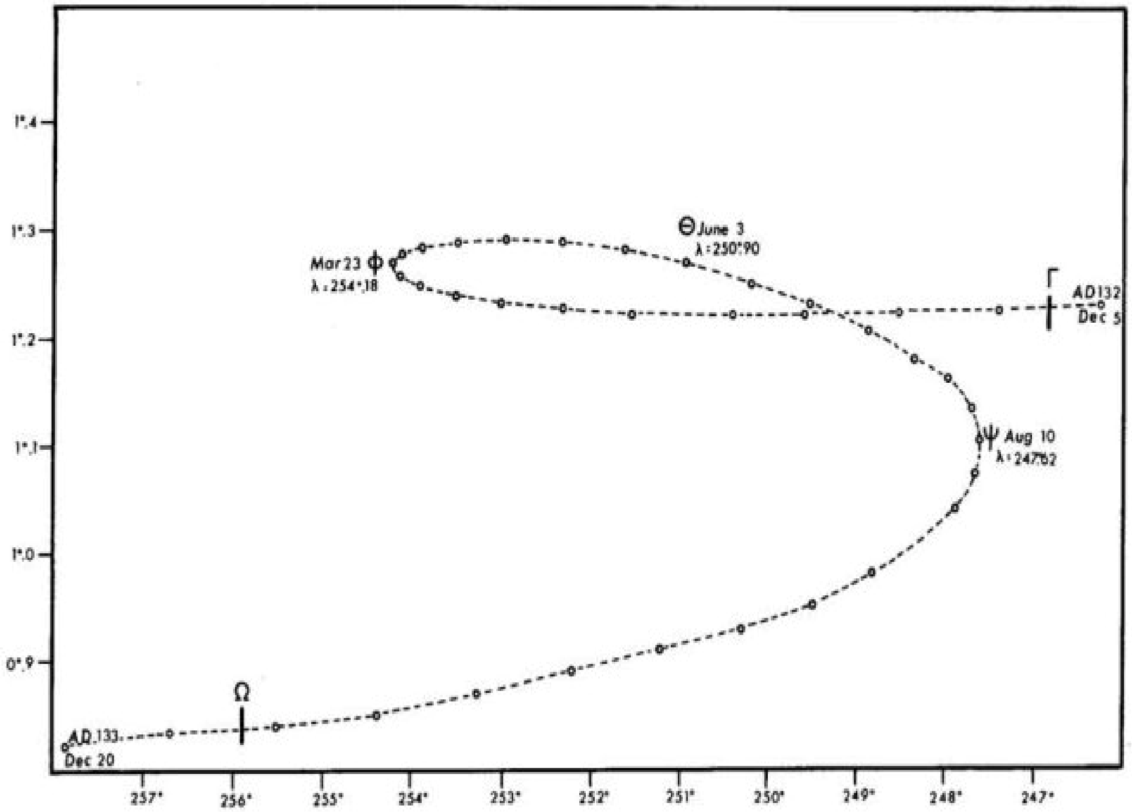


Figure 1. Ptolemy's observations of the motion of Saturn in AD 133 against the background of the fixed stars. (From O. Pedersen, *Early Physics and Astronomy*, 61. Cambridge: Cambridge University Press, reproduced by kind permission.)

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.

3. The Copernican, Galilean and Newtonian Revolutions

By the early 16th century, the continued refinement of the Ptolemaic system made it a more and more complicated tool for predicting the positions of the celestial bodies. Nicolaus Copernicus (1473-1543) revived the idea of Aristarchus that a simpler model, in which the Sun is at the centre of the Universe, might provide a simpler description of the motions of the planets. Taking his inspiration for Aristarchus, he investigated whether or not a heliocentric Universe might not provide a simpler description of the motions of the planets. The Copernican, or heliocentric, picture worked remarkably well. In 1514 he circulated his ideas privately in a short manuscript called De *hypothesibus motuum coelestium a se constitutis commentariolus* (A commentary on the Theory of the Motion of the Heavenly Objects from their Arrangements). The ideas were presented to Pope Clement VII in 1533 who approved of them and in 1536 made a formal request that the work be published. Copernicus still hesitated, but eventually wrote his great treatise summarising what is now known as the Copernican model of the Universe in *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Celestial Spheres). The work was eventually published by Osiander in 1543, the first copy reputedly being brought to Copernicus on his death-bed. In his foreword to the treatise, Osiander stated that the Copernican model was only a calculating device for simplifying the prediction of planetary motions, but it is clear from the text that Copernicus was in no doubt that the Sun really is the centre of the Universe, and not the Earth.

Figure 2 shows the famous picture which appears opposite page 10 of Copernicus' treatise, showing the planets in their familiar order with the Moon orbiting the Earth and the six planets orbiting the Sun. Beyond these lies the sphere of the fixed stars. The implications of this picture were profound. Firstly, the size of the Universe was vastly increased as compared with the Ptolemaic model. Because the fixed stars showed no parallax, they had to be very distant indeed. In the version of the Copernican model by Thomas Digges (1546 – 1595), the Universe is of infinite extent and the stars are scattered throughout space. The second fundamental insight was that something was wrong with the Aristotelian concept that all objects fall towards the centre of the Universe which is now occupied by the Sun.


NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono menſe reducitur. Sextum deniq; locum Mercurius tenet, octuaginta dierum ſpacio circũ currens. In medio uero omnium reſidet Sol. Quis enim in hoc

pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum ſimul poſsit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uo-

Figure 2. The Copernican Universe from Copernicus’ treatise *De Revolutionius Orbium Celestium,* 1543. Opposite page 10, Nurnberg (Courtesy of Royal Observatory, Edinburgh).

Copies of Copernicus’ *De Revolutionibus* circulated rapidly throughout Europe. One of the motivations behind Copernicus’ researches was to produce a better mathematical description of the motions of the Sun, Moon and the planets. In fact, the predictions of the Copernican model were not much more accurate than Ptolemy’s predictions.

Erasmus Reinhold (1511 – 1553) used the data in *De Revolutionibus* to produce what were known as the *Prutenic Tables*, or Prussian tables, of the positions of the stars and planets. These were published in 1551, no more than eight years after the first publication of *De Revolutionibus*.

Tycho Brahe (1546-1601) acquired his own copies of the Alphonsine and Prutenic Tables while a student in Leipzig. In 1563, he found that the predictions of these tables were in error by about a month according to the Alphonsine tables and by a few days if he used the Prutenic Tables. The need to improve the accuracy with which the planetary orbits were known was one of the prime motivations for the monumental series of observations which he began in the late 1570s. With the strong financial support of Frederick II of Denmark, Tycho created one of the great astronomical observatories. In fact, he built two observatories, the main observatory *Uraniborg* and a second observatory with firmer foundations, known as *Stjerneborg*. The glories of the observatory were the scientific instruments, which were specially constructed to Tycho's specifications. Tycho's observations were carried out systematically over the period 1576 to 1597 and his final catalogue contained the positions of 777 stars measured with an accuracy of about 1 to 2 minutes of arc. After Frederick II's death in 1588, the support for pure science waned under his successor, Christian IV, and Tycho left for exile in 1597, taking with him his observations, instruments and printing press. He eventually settled outside Prague under the patronage of Emperor Rudolf II. One of his last acts in 1600 was to employ Johannes Kepler (1571–1630) to reduce his observations of the planet Mars.

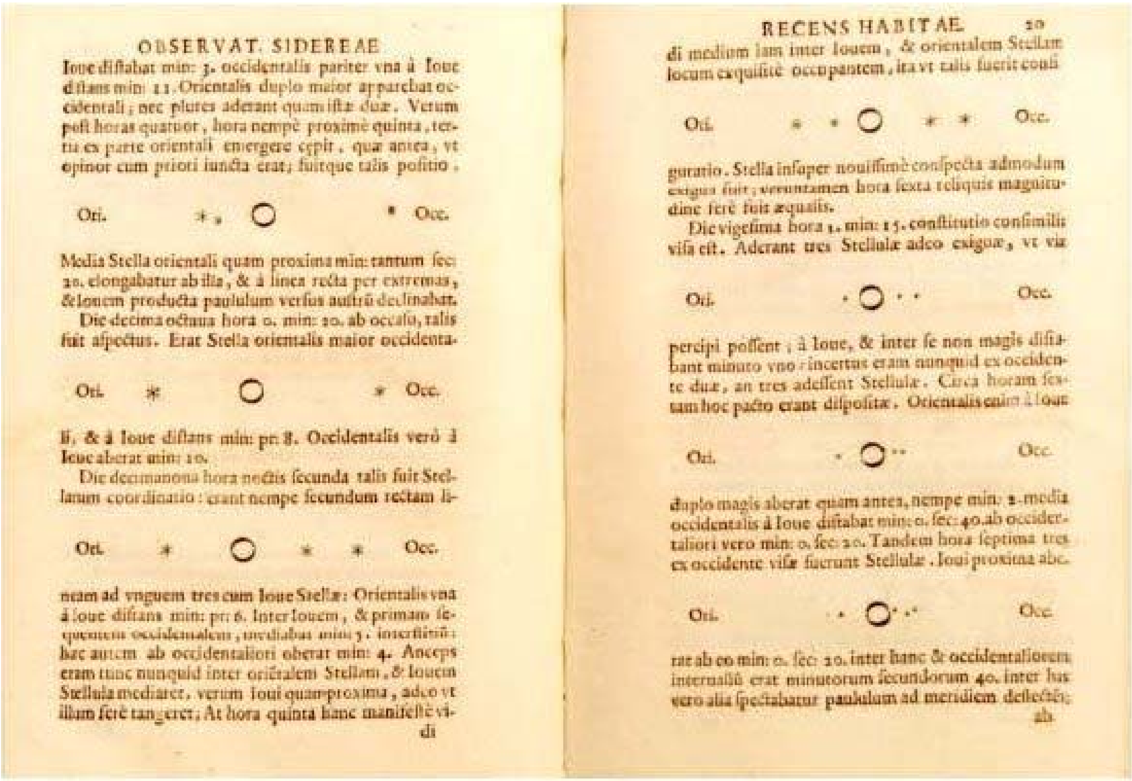
Kepler was a passionate and convinced Copernican and well known astronomer who in 1597 had published his ideas about the structure of the Solar System in his *Mysterium Cosmographicum* (The Mystery of the Universe). On his deathbed, Tycho urged Kepler to complete a new set of astronomical tables to replace the Prutenic tables. These were to be known as the *Rudolphine Tables* in honour of the emperor Rudolph II.

Kepler carried out an enormous number of calculations to try to fit the observed orbit of Mars to circular orbits, following the percept that only circular motions should be used to describe the orbits of the planets. After a great deal of trial and error, the best orbits he could find still disagreed with Tycho's observations by an error of 8 minutes of arc. In the course of studying non-circular orbits, he found that the area swept out by the line from the Sun to the planet is the same in equal time intervals, Kepler's *second law of planetary motion*. After many geometric experiments, he found that the orbits of the planets were ellipses, with the Sun in one focus. In 1609, he published this key result in *The New Astronomy*, four years after he had discovered of this law, which is now known as *Kepler's first law of planetary motion*. Kepler's third law was deeply buried in his crowning achievement, the *Harmonices Mundi* or the Harmony of the World in which he synthesized all his ideas into one harmonious picture of the Universe, encompassing geometry, music, architecture, metaphysics, psychology, astrology and astronomy. By 1619, he had much more accurate mean radii for the orbits of the planets and, by the time he had reached the writing of Book V, Chapter III, 8th Division of the Harmony of the World, he discovered suddenly what is now known as *Kepler's third law of planetary motion*, the period of a planetary orbit is proportional to the three-halves power of the mean distance of the planet from the Sun. Eventually Kepler completed the *Rudolphine Tables* and they were published in September 1627. These set a new standard in the accuracy of the predictions of solar, lunar and planetary positions. Kepler's three great laws were to be the springboard for Newton's great synthesis of the laws of gravity and motion, but he also built upon the pioneering insights of Galileo Galilei (1564–1642).

Galileo was strongly opposed to Aristotelian physics, which was not in accord with the way in which matter actually behaves. In the first years of the 17th century, he began a series of brilliant experiments which established the law of acceleration $x = (½)at^2$. By dropping objects from different heights, he established that falling objects obey this times-squared, what is now called the *acceleration due to gravity*. Next he established *Galileo's theorem*-the time it takes a ball to roll down the slope from A to the point C, where the slope cuts the circle, is equal to the time it takes the ball to fall freely from down the diameter of the circle. Finally, he used these results to show that the period of a pendulum is independent of the amplitude of its swing. Galileo had succeeded in putting into mathematical form the nature of acceleration under gravity.

The invention of the telescope is attributed to the Dutch lens-grinder Hans Lipperhey (1570-1619) who in October 1608 applied to Count Maurice of Nassau for a patent for a device which could make distant objects appear closer. His application was turned down on the grounds that the device was already too well-known to merit a patent. Galileo heard of this invention in July 1609 and by August, he had succeeded in constructing a telescope which magnified 9 times, three times better than that of Lipperhey. By the end of 1609, he had made a number of telescopes of increasing magnifying power, culminating in a telescope with a magnifying power of 30.

In January 1610, he first turned his telescopes on the skies and immediately there came a flood of remarkable discoveries which were quickly published in March 1610 in his *Sidereus Nuncius* or The Sidereal Messenger. The three outstanding discoveries were: (i) the Moon is mountainous rather than a perfectly smooth sphere, (ii) the Milky Way was shown to consist of vast numbers of stars rather than being a uniform distribution of light, and (iii) Jupiter had four satellites, the motion of which he followed over a period of several weeks (Figure 3). The book caused a sensation throughout Europe and Galileo won immediate international fame. These discoveries demolished a number of Aristotelian precepts. For example, the resolution of the Milky Way into individual stars was quite contrary to the Aristotelean view. In the satellites of Jupiter he had discovered a prototype for the Copernican picture of the Solar System.



OBSERVAT. SIDEREAE

Ioue diſtabat min: 3. occidentalis pariter vna à Ioue diſtans min: 11. Orientalis duplo maior apparebat occidentali; nec plures aderant quàm iſtæ duæ. Verum poſt horas quatuor, hora nempè proximè quinta, tertia ex parte orientali emergere cœpit, quæ antea, vt opinor cum priori iuncta erat; fuitque talis poſitio.

Ori. * * ○ * Occ.

Media Stella orientali quam proxima min: tantum ſec: 20. elongabatur ab illa, & à linea recta per extremas, & Iouem producta paululum verſus auſtrū declinabat.

Die decima octaua hora 0. min: 20. ab occaſu, talis fuit aſpectus. Erat Stella orientalis maior occidentali, & à Ioue diſtans min: pr. 8. Occidentalis verò à Ioue aberat min: 10.

Ori. * ○ * Occ.

Die decimanona hora noctis ſecunda talis fuit Stellarum coordinatio: erant nempe ſecundum rectam lineam ad vnguem tres cum Ioue Stellæ: Orientalis vna à Ioue diſtans min: pr: 6. Inter Iouem, & primam ſequentem occidentalem, mediabat min: 5. interſtitiū: hæc autem ab occidentaliori aberat min: 4. Anceps eram tunc nunquid inter orientalem Stellam, & Iouem Stellula mediaret, verum Ioui quamproxima, adeo vt illum ferè tangeret; At hora quinta hanc manifeſtè vidi

Ori. * ○ * * Occ.

RECENS HABITAE. 20

di medium iam inter Iouem, & orientalem Stellam locum exquiſitè occupantem, ita vt talis fuerit configuratio. Stella inſuper nouiſſimè conſpecta admodum exigua fuit; veruntamen hora ſexta reliquis magnitudine ferè fuit æqualis.

Ori. * * ○ * * Occ.

Die vigeſima hora 1. min: 15. conſtitutio conſimilis viſa eſt. Aderant tres Stellulæ adeo exiguæ, vt vix percipi poſſent; à Ioue, & inter ſe non magis diſtabant minuto vno: incertus eram nunquid ex occidente duæ, an tres adeſſent Stellulæ. Circa horam ſextam hoc pacto erant diſpoſitæ. Orientalis enim à Ioue duplo magis aberat quam antea, nempe min: 2. media occidentalis à Ioue diſtabat min: 0. ſec: 40. ab occidentaliori vero min: 0. ſec: 20. Tandem hora ſeptima tres ex occidente viſæ fuerunt Stellulæ. Ioui proxima aberat ab eo min: 0. ſec: 20. inter hanc & occidentaliorem interuallū erat minutorum ſecundorum 40. inter has vero alia ſpectabatur paululum ad meridiem deflectēs; ab

Ori. * ○ * * Occ.

Ori. * ○ * * Occ.

Ori. * ○ * * Occ.

Figure 3. Two pages from Galileo’s *Sidereus Nuncius* of 1610, showing his drawings of the movements of the four Galilean satellites (Courtesy of Royal Observatory, Edinburgh).

Later in 1610, he made two other crucial telescopic discoveries, (iv) the rings of Saturn, which he interpreted as close satellites of the planet, and (v) the phases of the planet Venus. When Venus was on the far side of its orbit with respect to the Earth, it appears circular but when it is on the same side of the Sun as the Earth, it looks like a crescent Moon. This was interpreted as evidence in favor of the Copernican picture.

Prior to his telescopic discoveries of 1610-11, Galileo was at best a cautious Copernican but it gradually became apparent to him that his new understanding of the nature of motion eliminated all the specific *physical problems*. His great telescopic discoveries provided powerful evidence which was consistent with the Copernican picture. He had discovered that there are mountains on the Moon, just as there are on Earth, suggesting that the Earth and the Moon are similar bodies. The phases of Venus turned out to be exactly what was expected according to the Copernican picture. Thus, both the physical and astronomical objections to Copernicanism were removed, leaving only the theological and logical problems to be debated.

In December 1613, the Grand Duchess Dowager Christina asked Castelli, one of Galileo’s colleagues, about the religious objections to the motion of the Earth. Castelli responded to the satisfaction of both the Duchess and Galileo, but Galileo felt the need to set out the arguments in more detail. Galileo’s letter came into the hands of the conservatives. In March 1615, the Dominican Friar Tommaso Caccini laid a formal charge of *suspicion of heresy* against Galileo before the Roman Inquisition. The findings of the Inquisition were favorable to Galileo personally and he was acquitted of the charge. However, the Inquisition also asked a committee of eleven consultants for an opinion on the status of Copernicanism. On 16 February 1616, it reported unanimously that Copernicanism was philosophically and scientifically untenable and theologically heretical. Galileo was given a private warning by Cardinal Bellarmine to stop defending the Copernican world picture. Furthermore a public decree by the Congregation of the Index reaffirmed that the doctrine of the Earth's motion was heretical and that Copernicus' *De Revolutionibus* was suspended until a few offending passages were amended. Although personally exonerated, the result was a defeat for Galileo.

In 1623, Gregory XV died. His successor, Cardinal Maffeo Barbarini, was elected Pope Urban VIII and he took a more relaxed view of the interpretation of the scriptures than his predecessor. Galileo had six conversations with Urban VIII in Spring 1624 and came to the conclusion that Copernicanism could be discussed, provided it was only considered hypothetically. Galileo returned to Florence and immediately set about writing the *Dialogue on the Two Chief World Systems, Ptolemaic and Copernican*. He made every effort to comply with the wishes of the censors. The preface was written jointly by Galileo and the censors and, after some delay, the great treatise was published in 1632. *The Two Chief World Systems* was well received in scientific circles, but very soon complaints and rumours began to circulate in Rome. In fact, Galileo had not treated the Copernican model hypothetically at all. The Copernican system was portrayed in a much more favorable light than the Ptolemaic picture, contradicting Urban VIII's conditions for discussion of the two systems of the world.

Galileo, now sixty-eight years old and in poor health, was forced to come to Rome under the threat of arrest. The result of the trial was a foregone conclusion. On 22 June 1633, Galileo was found guilty of 'vehement suspicion of heresy' and publicly admitted his errors. He returned to Florence where he remained under house arrest for the rest of his life. With indomitable spirit, Galileo set about writing his greatest work, *Discourses and Mathematical Demonstrations on Two New Sciences Pertaining to Mechanics and to Local Motion*. In this treatise, he brought together the understanding of physics which he had gained over a lifetime. These insights were fundamental to Isaac Newton's revolutionary works on the laws of gravity and motion.

Newton (1642-1727) was born on Christmas Day, 1642, the same year that Galileo died. He went up to Trinity College, Cambridge in 1661 and took his BA degree in 1665. In the same year, the Great Plague began to spread north to Cambridge. The University was closed and Newton returned to his home at Woolsthorpe. The next two years were one of the most remarkable creative periods of anyone who ever lived. In mathematics, he discovered the binomial theorem and the differential and integral calculus. In optics, he discovered the decomposition of light into its separate colors. In physics and celestial mechanics, he began the unification of celestial mechanics with the theory of gravity, which was to lead to his laws of motion and the universal theory of gravity.

Newton was a very skilled experimenter and he undertook a number of optical experiments using lens and prisms while he was at Trinity College and at Woolsthorpe.

In 1666, he carried out his *experimentum crucis* in which he demonstrated experimentally that white light is a superposition of all the colors of the spectrum and that different colored rays on passing through a prism are bent by different amounts. He concluded that it is not possible to build a large refracting telescope of the type pioneered by Galileo because different colors would be focused at different positions on the optical axis of the telescope, the phenomenon of 'chromatic aberration'. Because of this problem, Newton designed and built himself a new type of all-reflecting telescope, what is now called a 'Newtonian' telescope, which was demonstrated to acclaim to the Royal Society of London in 1672 (Figure 4).

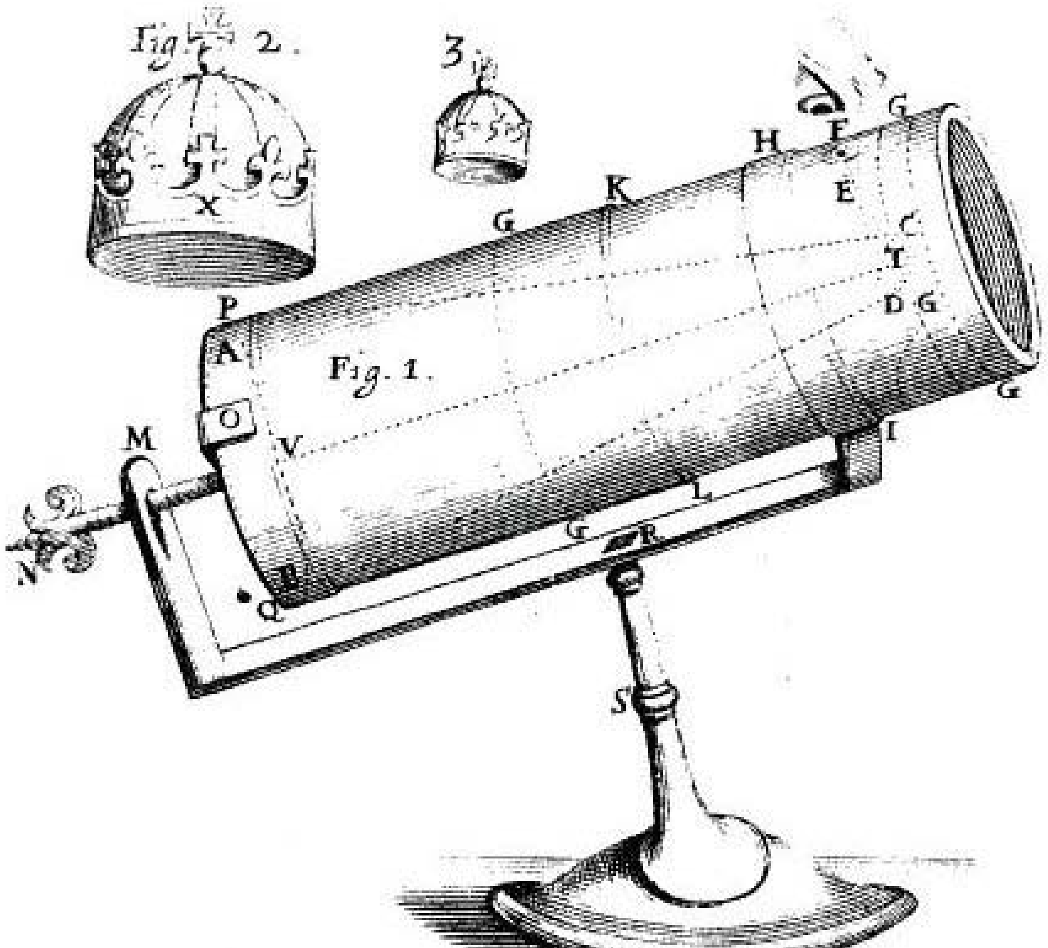


Figure 4. Newton's reflecting telescope, as illustrated in the *Philosophical Transactions of the Royal Society*, 1672. The two crowns show the improvement in magnification of Newton's telescope over the traditional refracting telescope, such as that used by Galileo.

The most famous of his achievement of his years at Woolsthorpe was the discovery of the law of gravity. Newton was aware of Kepler's third law of planetary motion, since the *Harmony of the World* was in the Trinity College library. In Newton's own words, "the notion of gravitation [came to my mind] as I sat in contemplative mood [and] was occasioned by the fall of an apple." Newton realized that the force of gravity which makes apples fall to the ground is the same force which holds the Moon in its orbit about the Earth and the planets in their orbits about the Sun. To quantify this insight, he needed to know how the force of gravity varies with distance. He derived this law from Kepler's Third Law by assuming that the orbits of the planets are circular and that the centrifugal force acting on the planet is balanced by the force of gravity between the Sun and the planets. This immediately led to the primitive form of Newton's *inverse square law of gravity*, $f \propto r^{-2}$. As a result, the acceleration of the apple should be greater than that of the Moon because the Moon is 60 times further away from the centre of the Earth than the apple is. This agreed precisely with the observed centrifugal acceleration of the Moon.

There were a number of problems with the analysis. For example, Kepler had shown that the orbits of the planets are ellipses and not circles. Newton was also unsure of the influence of the other bodies in the solar system upon each others' orbits. Furthermore, he was unable to explain all the details of the Moon's orbit which is influenced by the fact that the Earth is not spherical. Finally, he may have been concerned about the step in the calculation in which all the mass of the Earth is located at its centre in order to work out the local acceleration due to gravity and its influence upon the Moon.

Newton laid this work aside until 1679 when he was prompted to return to it by an interchange of letters with Robert Hooke (1635-1703). Hooke challenged Newton to work out the curve followed by a particle falling in an inverse-square law field of force. During the correspondence, Newton showed that it is indeed permissible to locate all the mass of Earth at its centre, provided the Earth is spherically symmetric. He also worked out that, in general, the orbit of a particle in an inverse-square law field must be one of the conic sections. In particular, the paths of the planets under the influence of the attractive inverse-square law of gravity are ellipses. In 1684, Edmund Halley (1656-1742) traveled to Cambridge to ask Newton precisely the same question which had been posed by Hooke. With a great deal of persuasion, Newton agreed to set about systematising all his researches on motion, mechanics, dynamics and gravity in what became his great treatise *Philosophiae Naturalis Principia Mathematica* or the *Principia* for short. This treatise is one of the greatest intellectual achievements of all time. In the very beginning, *Newton's Laws of Motion* were set out in their definitive form.

The Principia was written in terms of geometrical arguments and demonstrated that the orbits of planets, comets and other celestial bodies about the Sun should be conic sections. Although Newton had invented his version of the differential calculus, the method of fluxions, the more compact methods of Gottfried Leibniz (1646-1716) rapidly became the preferred mathematical tool for addressing dynamical problems. The application of the differential calculus to the motions of astronomical bodies culminated in Pierre-Simon Laplace's (1749–1827) great five volume work, *Mécanique Celeste*, published between 1799 and 1825.

4. From Astronomy to Astrophysics – the Development of Astronomical Techniques in the 19th Century

The precise determination of the positions and motions of celestial bodies and accurate time-keeping found practical application in navigation and national observatories were established in many countries dedicated to the production of tables of the predicted positions and motions of astronomical objects. One of the early by-products of accurate time keeping was the first reasonably accurate measurement of the speed of light in 1676 by the Danish astronomer Ole Rømer (1644-1710) who observed that the interval between eclipses of Jupiter's innermost satellite Io by the planet was greater when the Earth moved away from the planet and was shorter when the Earth moved towards it. Interpreting these differences as resulting from the changing distance between the Earth and Jupiter, Rømer found a value for the speed of light of $c = 225{,}000 \text{ km s}^{-1}$.

Accompanying the need to measure accurate positions for the stars was the need to determine time precisely and this led to the development of precise clocks, such as those produced by John Harrison (1693-1776) in the 18th century. Thus, the primary role of the national observatories was the precise determination of what was to become universal time through a detailed understanding of the irregularities in the Earth's motion and rotation due to the gravitational influence of the Moon and planets upon the aspherical Earth.

A gradual shift of emphasis from astronomy to astrophysics took place through the 19th century and can be attributed to three key technical breakthroughs-the measurement of reliable distances for the stars by the method of geometric parallax, the development of spectroscopy as a tool for astrophysics and the invention of photography. These developments in turn necessitated improvements in the design and construction of telescopes. The combination of these technical developments and advances in the understanding of basic physical processes were to lead to the extraordinary development of astrophysics and cosmology in the 20th century.

Astronomical distances

From the seventeenth century onwards, most astronomers assumed that the stars are objects similar to the Sun, but at vastly greater distances. The method of distance determination used by Newton and others involved assuming that the Sun and stars have the same intrinsic luminosities, the method of *photometric parallaxes*. The technical problem was that the Sun is so much brighter than the brightest stars that it was difficult to make good estimates of the ratio of their observed intensities. An ingenious solution was discovered in 1668 by James Gregory (1638-1675), who used Jupiter as an intermediate luminosity calibrator, assuming that its light was entirely sunlight reflected from the disc of the planet and that its surface was a perfect reflector. The distance of the bright star Sirius found to be 83,190 astronomical units. The same method was used by John Michell (1724-93) in 1767 to estimate of a distance of 460,000 astronomical units for Vega, or α Lyrae, about a factor of four smaller than that found in 1838 by Wilhelm Struve using trigonometric parallaxes.

Since the time of Copernicus, it had been realized that a test of the hypothesis that the

Earth moved about the Sun would be the observation of the annual parallax of the stars. Attempts to measure these small movements of the stars had been subject to a variety of insidious systematic errors. In 1728, instead of the expected effect, Bradley (1693-1762) discovered the phenomenon of the aberration of light due to the motion of the Earth, the effect amounting to about ± 20 arcsec for the star γ Draconis. An upper limit could be derived for the annual parallax of γ Draconis and hence a lower limit to its distance of 400,000 astronomical units, consistent with Newton's estimate using the method of photometric parallax published in the same year.

The first definitive distance measurements were made in the 1830s by the method of *trigonometric parallax*, the apparent motion of nearby stars against the background of the distant stars due to the Earth's motion about the Sun. At Koenigsberg, Friedrich Bessel (1784-1846) used the 16-cm heliometer built by Fraunhofer to measure the movement of the high proper motion star 61 Cygni relative to distant background stars and published its parallax of about one third of an arcsec, corresponding to a distance of 10.3 light-years, in 1838. In the same year, Thomas Henderson (1798-1844) published a parallax of 1.16 arcsec for the southern star α Centauri and almost contemporaneously Wilhelm Struve (1793-1864) measured the parallax of α Lyrae to be 0.12 arcsec. These observations set the scale of the Universe of stars and showed unambiguously that the stars are objects similar to our Sun.

One of the key programmes for the development of astrophysics in the late 19th century and the early years of the 20th century was the gradual accumulation of trigonometric parallaxes for nearby stars, but it was a difficult and demanding task. By 1900, less than 100 parallaxes for nearby stars had been measured with any accuracy.

Astronomical spectroscopy

The first decades of the 19th century marked the beginnings of quantitative experimental spectroscopy. The breakthrough resulted from the pioneering experiments and theoretical understanding of the laws of interference and diffraction of waves by Thomas Young (1773-1829). In 1801, he used the wave theory of light of Christian Huyghens (1629-1695) to account for the results of his famous double-slit experiment.

In 1802, William Wollaston (1766-1828) made spectroscopic observations of sunlight and discovered five strong dark lines, as well as two fainter lines. The full significance of these observations was only appreciated following the spectroscopic experiments of Joseph Fraunhofer (1787-1826) who placed a prism in front of a 25 mm aperture telescope and rediscovered the narrow dark lines which would provide precisely defined wavelengths standards. He labeled the ten strongest lines in the solar spectrum A, a, B, C, D, E, b, F, G and H and recorded 574 fainter lines between the B and H lines (Figure 5). A major advance was the invention of the spectroscope made by placing a theodolite on its side and observing the spectrum through a telescope mounted on the rotating ring. Fraunhofer also made the first spectroscopic observations of the planets and the stars. In 1817, he reported the observation of Fraunhofer lines in the spectrum of Venus, inferring that the spectrum was the same as sunlight. In first magnitude star Sirius, he found "... three broad bands which appear to have no connection with those of sunlight." In 1823, he made further observations of the spectra of the planets and the brightest stars, anticipating by about 40 years the next serious attempts to measure the spectra of the stars.

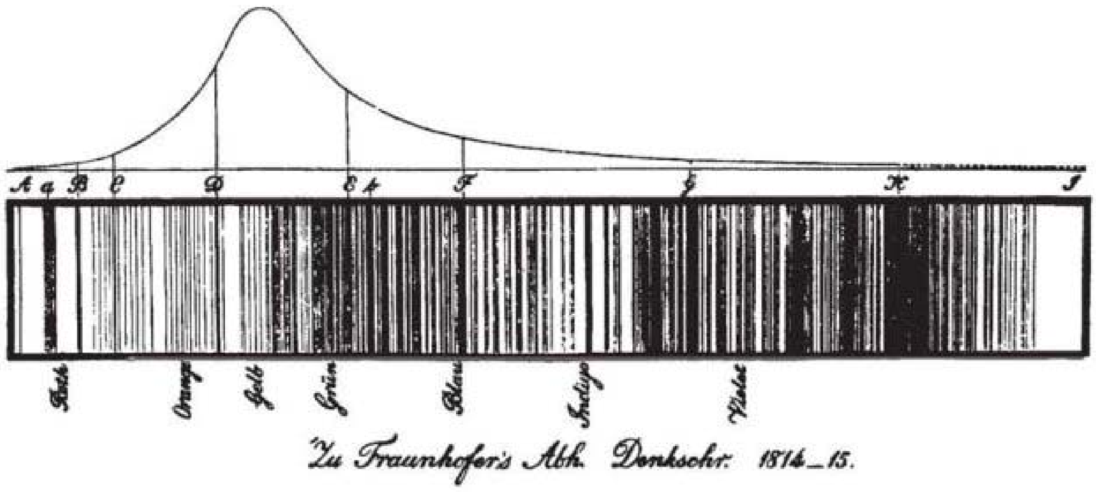


Figure 5. Fraunhofer’s solar spectrum of 1814 showing the vast numbers of dark absorption lines. The colors of the various regions of the spectrum are labeled, as well as the letters A, a, B, C, D, E, b, F, G and H, indicating the most prominent absorption lines. The continuous line above the spectrum shows the approximate solar continuum intensity, as estimated by Fraunhofer. (J. Fraunhofer, 1817. On the Refractive and Dispersive Power of Different Species of Glass in Reference to the Improvement of Achromatic Telescopes, with an Account of the Lines or Streaks which Cross the Spectrum, Denkschriften der königlichen Akademie der Wissenschaften zu München, 5, 193-226).

Using the lines in the Sun as wavelength standards, Fraunhofer was able to characterise the chromatic properties of glasses and lenses quantitatively and precisely, leading to much superior glasses, as well as to much improved polishing and testing methods for glasses and lenses. These technical improvements also resulted in the best astronomical telescopes then available, including the 24-cm Dorpat Telescope at the Dorpat, now Tartu, Observatory in Estonia and the heliometer for Friedrich Bessel.

Fraunhofer had noted that the dark D lines coincided with the bright double line seen in lamplight. In 1849, Léon Foucault (1819-1868) performed passed sunlight through a sodium arc so that the two spectra could be compared precisely. To his surprise, the solar spectrum displayed even darker D lines when passed though the arc than without the arc present. He followed up this observation with an experiment in which the continuum spectrum of light from glowing charcoal was passed through the arc and the dark D lines of sodium were found to be imprinted on the transmitted spectrum. Ten years later, Gustav Kirchhoff (1824-1887) made the crucial observation that, to observe an absorption feature, the source of the light had to be hotter than the absorbing flame. From these considerations, Kirchhoff concluded that sodium was present in the solar atmosphere. These results led to the understanding of the relation between the emissive and absorptive properties of any substance, now known as Kirchhoff’s *Laws of Emission and Absorption of Radiation*.

Throughout the 1850s, there was considerable effort in Europe and in the USA aimed at identifying the emission lines produced by different substances in flame, spark and arc spectra. In 1859, Julius Plücker (1801-1868) identified the Fraunhofer F line with the bright Hβ line of hydrogen and the C line was more or less coincident with Hα, demonstrating the presence of hydrogen in the solar atmosphere. The most important work, resulted from the studies of Robert Bunsen (1811-1899) and Kirchhoff. In his great papers of 1861 to 1863 entitled *Investigations of the Solar Spectrum and the Spectra of the Chemical Elements*, Kirchhoff concluded that the cool, outer regions of the solar atmosphere contained iron, calcium, magnesium, sodium, nickel and chromium and probably cobalt, barium, copper and zinc as well.

The Invention of Photography

The photographic process was invented by Louis-Jacques-Mandé Daguerre (1789-1851) and William Henry Fox Talbot (1800-1877). The search for methods of recording images began with the discovery that some natural compounds are rendered insoluble when they are exposed to light. In the course of his experiments, Daguerre discovered that iodine-treated silver paper was also sensitive to light. By 1835, he had made the important discovery of the *latent image* which was recorded on sensitised paper, even if the light was not intense enough to darken the paper. The latent image could then be developed by exposure to mercury vapour and fixed by a strong salt solution. The exposures were about 20 to 30 minutes. The *Daguerreotype process* was announced by François Arago (1786-1853), the director of the Paris Observatory, on 7 January 1839. A similar announcement was made almost simultaneously by Fox Talbot in England.

Isolated examples of successful daguerreotype images of astronomical objects were reported over the following decade, including the Moon and a solar eclipse. The first daguerreotype spectrum of the Sun was obtained by Edmond Becquerel (1820-1891), showed the complete Fraunhofer spectrum as well as many lines in the ultraviolet region of the spectrum. In 1851, exposure times were greatly reduced by the invention by Frederick Scott Archer (1813-1857) of the wet collodion process which produced finely detailed negatives. The faster, fine-grained plates quickly superseded the daguerreotype process. The first photographic spectrum using this process was obtained of the bright star Vega by Henry Draper (1837-1882) in 1872. The spectrum showed the Hγ and Hδ lines of hydrogen, as well as the first detections of the next seven ultraviolet lines in this hydrogen series, seven years before they were measured in the laboratory. These observations were used by Johann Jakob Balmer (1825-1898) in his papers of 1885 on the Balmer formula, describing the wavelengths of the lines in the spectrum of hydrogen.

The search for improved materials continued and culminated in the discovery of emulsions consisting of silver salts suspended in gelatin by Richard L. Maddox (1816-1902) and Charles Bennett (1840-1927) in 1879. The speed of the gelatin emulsions could be vastly increased by prolonged exposure to heat, or by the addition of ammonia, the beginning of the dark art of hypersensitising photographic. Over the next few years, some superb astronomical images were taken of star clusters and nebulae.

The New Generation of Telescopes

The need to be able to track and guide the telescope accurately for long exposures required major improvements in telescope design. Lewis Morris Rutherfurd (1816-92) invented a clockwork drive for his photographic telescope and, during the 1850s and 1860s, produced some excellent astronomical images. Rutherfurd also obtained photographic spectra of Sun, that taken in the 1870s consisting of twenty eight overlapping plates and totalling about 3 meters in length. John Draper (1811-1882) devoted huge efforts to optimising telescopes for photographic purposes. Over a three year period, he devised a series of seven grinding and polishing machines and produced over one hundred mirrors ranging up to 19 inches in diameter. In the last year of his life, 1882, he succeeded in obtaining the spectra of 10th magnitude stars in the region of M42.

Refracting telescopes were the preferred choice for astrometric applications but this development reached the end of the line with the completion of the 1-meter (40-inch) refractor at the Yerkes Observatory. Several large reflecting telescopes were constructed earlier in the century, the largest of these, known as the 'Leviathan', being built by William Parsons, the third Earl of Rosse, a 1.8-meter (72-inch) reflector at his home at Birr Castle in Ireland. Despite almost insuperable problems, Rosse (1800-1867) made good visual observations of diffuse nebulae, his greatest achievement being the observation of spiral arms in nebulae such as M51.

The biggest problem with the large reflectors was the primary mirror. In Lord Rosse's telescope, the mirror was made of speculum metal, an alloy of tin and copper with a pinch of arsenic, which is 50% reflective but which is a very brittle and difficult to work with. The solution to the problem of producing large silvered telescope mirrors was discovered by Justus von Liebig (1803-1873) who in 1835 showed how metallic silver could be deposited by reducing silver nitrate chemically. The first reflecting telescopes using silvered mirrors were built by Karl Steinheil (1801-1870) in 1856, a 10-cm reflector, and by Léon Foucault (1819-1868), who constructed successively larger telescopes, culminating in his 80-cm reflector for the Marseilles Observatory in 1864.

Large fully-steerable reflectors were much more susceptible to flexure and to vibrational and temperature effects than refractors. During the 1870s, Andrew A. Common (1841-1903) and George Calver (1834-1927) made a major effort to overcome the inherent problems in the design of reflecting telescopes. The principal innovations involved in constructing their 91-cm reflector were to relieve the weight on the bearings by submerging a hollow steel float in mercury, and the introduction of an adjustable plate-holder. The result was that the tracking and guiding of the telescope were very smooth. Their 90-minute exposure of the Orion Nebula won the Gold Medal of the Royal Astronomical Society in 1884.

In 1895, Edward Crossley (1841-1905) presented his 91-inch reflector, built to the Common-Calver design, to the Lick Observatory of the University of California at Santa Cruz. An important innovation was that the observatory was located on an excellent Californian mountain site at Mount Hamilton, where the transparency and stability of the atmosphere were known to be very good and there was a large percentage of clear nights. The mirror was repolished by Howard Grubb (1849-1931) and the mounting of the telescope stiffened by James E. Keeler (1857-1900). By 1900, Keeler had obtained spectacular images of spiral nebulae, including his famous image of M51. Not only were the details of its spiral structure observed in unprecedented detail, but there were also large numbers of much fainter spiral nebulae of smaller angular size.

The next step in increased aperture followed the appointment of George Ellery Hale (1868-1938) as founding Director of the Mount Wilson Observatory in 1904. He persuaded his father to buy the 1.5-meter blank for a 60-inch reflecting telescope for an enlarged version of a Calver-Common telescope. Before the 60-inch telescope was completed, however, he persuaded J.D. Hooker to fund an even bigger telescope, the 100-inch telescope to be built on Mount Wilson. In 1906, the American philanthropist Andrew Carnegie (1835-1919) visited the fledgling Mount Wilson Observatory and pledged an additional $10M to the endowment of the Carnegie Institution requesting that the benefaction be used to enable the work to proceed as rapidly as possible. The technological challenges presented by the 100-inch were proportionally greater, the mass of the telescope being 100 tonnes. The telescope was to be at the heart of observational cosmology through the key years from 1918 until 1950 when the 200-inch telescope was commissioned.

The Funding of Astronomy

Before the 1880s, astronomy was supported by National Observatories, the principal functions of which were the accurate measurement of time and latitude. Otherwise, astronomy was carried out by dedicated enthusiasts, or as a rich man's hobby. After the American Civil War, a number of individuals became fabulously wealthy and proved to be remarkably generous patrons of astronomy. The organisation and management of the vast Harvard Observatory by Edward Pickering provide good examples of the generosity of private patrons in supporting astronomy. Over the years when the great surveys were undertaken, Pickering obtained several $100,000 from the Henry Draper Fund, $400,000 from the Paine Fund in 1886, $230,000 from the Boyden Fund in 1887 and $50,000 from the Bruce Fund. Pickering's personal contribution to the project amounted to about $100,000. Another example is James Lick who, on his death in 1876, he left a bequest of $700,000 to build 'a powerful telescope, superior to and more powerful than any telescope ever yet made... and also a suitable observatory connected therewith.' The generosity of Andrew Carnegie has already been mentioned. Thus, even in the early 20th century, astronomy was 'big science' and relied upon the infusion of resources on a considerable scale to maintain progress.

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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:

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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.

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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.