Theme 1: Astronomy in History

1.1 The Uses of Astronomy

Astronomy is generally reckoned to be the oldest of the sciences. Most ancient civilisations practised something that we would recognise as astronomy; the first applications of mathematics to the understanding of the natural world involved astronomy; the mediaeval university syllabus included astronomy (the *trivium* of grammar, rhetoric and logic was followed by the more advanced *quadrivium* of arithmetic, astronomy, geometry and music). Astronomy also played a very large part in the foundation of "modern science" in the 17th century—the so-called "Scientific Revolution" is often considered to have begun with the publication of Copernicus' *De Revolutionibus* in 1543. Why is this? Why did such an apparently abstract discipline—the study of the night sky—play such an important role in ancient societies?

There are two—perhaps three—principal reasons for the importance of astronomy in pre-modern eras. All require a certain level of observational precision and mathematical sophistication: this is why astronomy quickly became recognisable as a science, whereas other equally important disciplines—such as engineering and medicine—remained more in the nature of "crafts".

1.1.1 Calendrics

Knowing the time of year is key to a successful agrarian society: you need to know when to plant crops, when to expect rains or river floods, how long the stored grain has to last, and so on. The time of year can be estimated quite accurately from natural phenomena such as the return of migratory animals, but one might reasonably suspect that a certain amount of prestige would be acquired by anyone who could predict such events in advance. A regular, calculable, observable phenomenon would be very useful for this purpose—and the night sky offers precisely that. In an era before street lighting, the phases of the Moon and the shifting positions of the naked-eye planets (most of which are very bright compared to most stars) would be very dramatic. The regularity of these motions is clear enough to be perceptible, but complicated enough to require careful study to be useful: for example, the year does not contain an exact number of full moons, so a lunar calendar quickly gets out of step with the seasons. Therefore there is an incentive to keep good records, and to develop mathematical models of the motion of those celestial bodies which are seen to move (this is the origin of the Greek term *planetes*, "wanderer", which gives us our word "planet").

1.1.2 Navigation

The positions of celestial bodies can provide useful markers for navigation. The height of the Sun at noon can easily be used to calculate latitude, and the constellations can provide the same service at night (though the use of the Pole Star to determine north is only temporary, because of precession). Navigation was not a major use of astronomy for most ancient societies—most sea-faring was done within sight of land. However, with the advent of transatlantic voyages in the 16th century navigation became a preoccupation of many European governments, and considerable effort was put into developing the necessary techniques and instrumentation (leading eventually to the development of the sextant, which remained an important nautical instrument up to modern times).

The most challenging problem for astronomical observations is the determination of longitude; the development of practical methods of longitude determination took up a great deal of astronomical manpower in the 17th and 18th centuries, but the problem was eventually solved by the development of reliable chronometers.

1.1.3 Astrology/Religion

To anyone living near the sea, it is obvious that the phases of the Moon are linked with the height of the tide. The changing day length over the seasons is equally obviously linked to the position of sunrise and sunset. We accept these relations as causal—the Earth-Sun-Moon geometry does affect the height of tides; the angle of the Sun does determine the warmth of the season, and its declination does determine the length of the day. It is not surprising that ancient peoples were prepared to accept other associations as causal, and to assume that the motion of the planets might affect human actions as well as natural phenomena. Thus astrology was, from earliest times to the 17th century, a major driver for astronomical observations (Tycho Brahe is remembered as the preeminent naked-eye astronomer and the man who bequeathed Kepler the data he needed to construct his three laws; but Tycho also cast horoscopes). This can be clearly seen in the nature of the observations that were made: the European tradition viewed the heavens as basically unchanging and focused on the motions of the planets, whereas the Chinese thought transient celestial phenomena were astrologically important; therefore we have superb records of comets and supernovae from the Chinese records, but very little from the Europeans.

Even when astrology became detached from mainstream religion, astronomical observations were still of importance for the timing of religious festivals. This ties in with the calendric function of astronomy: lunar calendars require intercalation of additional months if they are to remain in step with the seasons, and even purely solar calendars require the occasional extra day to account for the fact that the year is not precisely 365 days. Thus, from very early times there were incentives to observe the night sky and to attempt to predict the motions of celestial bodies. Since the making of precise, testable predictions is now regarded as one of the hallmarks of science, astronomy was “scientific” from its earliest days. However, note that most of the early incentives for studying astronomy relate primarily to the motion of the “planets” (in this sense including the Sun and Moon); the stars are simply useful signposts to assist in defining the locations of the planets. This is reflected in the history of astronomy: despite the name, which means “star-reckoning”, the stars do not really attract much attention until the 19th century.

Note that none of these early motivations for the study of astronomy has really persisted to the present time. Our current standards for time measurement and navigation do not rely on astronomy, and of all the major religions only Islam still ties its calendar directly to astronomical observations (of the “new moon”, which in Islam means the first visible crescent, rather than the astronomical meaning of lunar conjunction, which produces no visible Moon at all). The modern reasons for studying astronomy can be divided into two (overlapping) categories:

1.1.4 Astronomy as a laboratory for extreme physics

From the birth of modern science to the present day, astronomy has provided insights into physics which, because of the extreme conditions required, were not (at the time) deducible from conventional experimental physics. Some examples of this include:

- evidence for the "universality" of Newton's laws of motion and of gravity, as set out in the *Principia* (the same laws can describe falling bodies on Earth and the motion of the planets as codified by Kepler);
- the finite speed of light, as deduced by Römer from the timing of the occultations of Jupiter's moons;
- evidence in favour of General Relativity, initially from the advance of the perihelion of Mercury (a "postdiction", in that this was a known problem before 1915, but persuasive because GR could account for the discrepancy with good quantitative precision) and the observation of gravitational bending of starlight by Eddington and colleagues in 1919; in more modern epochs by studies of binary pulsars (which won Hulse and Taylor a Nobel Prize in 1993);
- evidence for non-zero neutrino masses (from the solar neutrino deficit; the best current upper limit on what those masses actually are is also astronomical, deduced from the WMAP and *Planck* studies of the cosmic microwave background).

This motivation has decreased somewhat in modern times, because modern experimental techniques can often probe extreme conditions in the laboratory. The most notable exception is the increasingly tight linkage between theoretical particle physics and theoretical cosmology, caused by the fact that energy scales in the very early universe exceed any that could be produced in terrestrial accelerators.

1.1.5 Addressing Big Questions

The primary motivation for modern astronomy is undoubtedly human curiosity. Astronomy addresses the "big questions" (Where do we come from? How did the world begin?) which have always attracted the attention of humanity, albeit usually in the guise of religion. This is the motivation usually expressed by students wishing to study astronomy at university, and probably also explains the success of popular expositions of astronomy, and particularly cosmology—e.g. Hawking's *A Brief History of Time* and Bill Bryson's *A Short History of Nearly Everything*. Similar "big questions" (What is the world made of? Why do things behave in the way that they do?) are also the primary rationale behind the study of particle physics—but particle physics is more abstruse and more difficult to explain than astronomy, and hence does not usually manage to resonate with nonscientists as astronomy does, though the new discipline of "particle cosmology" is challenging this, with books such as Brian Greene's *The Elegant Universe* achieving popular success. In terms of popular support, it surely helps that astronomy produces arresting visual imagery—consider the number of HST images that make their way on to the front pages of newspapers, despite their lack of obvious relevance to the lives of the papers' readers—but this is clearly not a dominant motivation in the persistence of the subject as a scientific discipline!

Thus, the history of astronomy spans not only a vast amount of time, but also a vast change in the attitudes of practitioners and the general public. Initially, astronomy was very much an applied science, in the service of religion and the calendar; later, it became an inspiration and a test-bed for the application of mathematical techniques to natural phenomena, and subsequently for the development of empirically supported "laws of nature" which gave birth to modern science; finally, it has become established as a "pure", curiosity-driven, science aiming to shed light on fundamental questions about humanity and the universe. A study of the history of astronomy therefore touches on many aspects of history, culture, society and philosophy, as well as documenting our progress in understanding the cosmos. Some (by no means all) of these issues will be considered in this course; for more details on any given aspect, consult the extensive specialist literature.

1.2 A Timeline for the History of Astronomy

In this course, we shall take a thematic (albeit broadly chronological) approach to the history of astronomy, as summarised in the course outline. This has the disadvantage that it may sometimes obscure the overall picture of what is happening at any given time. Therefore, we start the course with a brief chronological account of the history of astronomy, together with relevant events in the wider history of science and in the socio-political context. This timeline focuses primarily on Western Europe and the Near East, because this is the tradition that ultimately led to modern astronomy; it should be noted that from ~1000 BC much excellent observational work was carried out in China and neighbours (Japan, Korea, Vietnam, Cambodia). This is of particular interest because, owing to a different astrological system, the Chinese recorded transient phenomena ignored by Western observers; the Chinese records are thus our main source for information on phenomena such as supernovae and comets. However, the Chinese understanding of astronomy as a system did not really influence the development of modern scientific astronomy, because of the lack of real contact between Europe and China in the relevant period. (This contrasts with the situation with Islamic astronomy, which inherited much of the Greek and Mesopotamian tradition through the Islamic conquest of the eastern Mediterranean and then transmitted it—augmented by additional work and greatly improved mathematical techniques and notation—to Renaissance Europe, particularly via Spain.)

Date	Astronomy	Other Sciences	Social/Political
~30000 BC	Records of lunar phases in cave paintings and bone carvings		Nothing known.
3500 – 2500 BC	Astronomically aligned monuments, e.g. Stonehenge, Newgrange. Early calendars, e.g. Egyptian, Sumerian Probable astronomical record-keeping, in many cultures.		Little known of the society that built megalithic monuments. Writing developed (Sumerian cuneiform, then Egyptian hieroglyphic) Egyptian 1st Dynasty, ~3150 Sumerian dynastic period, ~2900 Pyramids of Giza, 26th century.
2500 – 1500 BC	Definite evidence of astronomical record-keeping, e.g. record of lunar eclipse in Ur (Sumeria), 2094 BC Lunisolar calendars.	Place-value mathematical notation introduced in Mesopotamia. Geometry texts in Egypt and Babylonia.	Akkad conquers Sumer. Egyptian Middle Kingdom, ~2160-1780. Chinese dynastic period begins, ~2100. Minoan civilisation in Crete.
1500 – 1000 BC	Start of eclipse records in China. Records of planetary ephemerides and heliacal risings of stars in Babylonia.		Egyptian New Kingdom (Tutankhamun, ~1330) Mycenaean period in Greece Olmec civilisation in Mesoamerica, from ~1400 (first of the Mesoamerican pre-Columbian civilisations)

1000 – 600 BC	Systematic records of astronomical phenomena in Babylonia. Prediction of lunar eclipses. Establishment of zodiacal constellations. ~700 BC, Hesiod's *Works and Days* sets out solar calendar defined by heliacal risings.	Indian mathematics develops.	Foundation of Rome, ~750. Neo-Babylonian Empire, 626 – 539. Development of Greek city-states.
600 – 350 BC	585 BC, Thales of Miletus predicts solar eclipse. 5th century: both Meton of Athens and Babylonia know the 19-year Metonic cycle—it's not clear if the discoveries were independent or, if not, who got it from whom. Eudoxus (408-355) developed the first model of the planetary system using combinations of spheres to account for retrograde motion.	Pythagoras, ~580–500, various topics in mathematics and astronomy. Democritus, ~460–370, proposes that matter consists of atoms. Plato's Academy founded, 387. Eudoxus develops more abstract mathematical and geometrical principles, later built on by Euclid.	Classical Greece. Athenians and allies defeat Persia at Marathon and Salamis, 480s
340- 323 BC	Aristotle (384-322): empirical evidence for spherical shape of Earth; distinction between "terrestrial" and "celestial" phenomena; Earth as natural centre of cosmos. Heraclides (~390-310) suggests that the Earth rotates on its axis.	Aristotle works extensively in various sciences, developing highly influential body of work.	Reign of Alexander the Great. Alexandrian empire unites Greece and Persia: fruitful contact between Greek model-builders and Babylonian calculators.
323- 100 BC	*Hellenistic astronomy*: Aristarchos (310-230): distances of Sun and Moon; heliocentric model of planetary system. Eratosthenes (276-195): size of the Earth. Apollonius (262-190): eccentric orbits, epicycles. Hipparchos (~190-120): star catalogue, accurate length of year, precession of equinoxes, theory of lunar and planetary orbits. Antikythera mechanism, embodying Hipparchos' model of the planetary system, ~100.	Euclid (325-265): development of formal geometry, especially his book *The Elements* (of mathematics—no connection with Aristotle's theories of chemistry). Archimedes (287-212): mathematics, mechanics (e.g. Archimedes' Principle), machines (e.g. Archimedes' screw). Apollonius of Perga publishes work on conic sections, ~210	Alexander's empire fragments into a number of Greek-ruled successor states. Under the Ptolemies, Alexandria develops as centre of scientific learning. Rise of the Roman Republic. Wars with Carthage, 264-146. First Emperor of China (terracotta warriors), 258-210.
100 BC- AD 14	Julian calendar developed, 46 BC (replacing lunisolar calendar with pure solar calendar). Chinese astronomy text *Zhoubi suanjing*, covering positional astronomy and surveying.	Lucretius' *De rerum natura* summarises current understanding of science	Establishment of Imperial Rome (Augustus, 63 BC – AD 14). Jesus of Nazareth, ~4 BC – ~AD 30. First "long count" date stelae in Mesoamerica.
AD 14- AD 200	Ptolemy (~100–170) produces the most developed version of the Greek geocentric planetary model, which continues to be used until the 16th century. Chinese record SN 185, the	Hero of Alexandria (~10-70) builds machines powered by steam and by wind. Zhang Heng (78-139) invents the seismograph. Galen (129-200 or 216) writes	Roman empire at peak. Hadrian's Wall built, AD 122–128.

	earliest probable supernova record.	highly influential treatises on medicine, anatomy and pharmacology.	
AD 200-600	Āryabhaṭa (476-550) writes the *Āryabhaṭiya* (499), a work on astronomy and mathematics which includes a geocentric model of the solar system, based on earlier Greek work but independent of and in some respects better then Ptolemy's (incorporates rotation of the Earth). Also includes good algorithms for eclipse prediction. Maya civilisation developed accurate understanding of motions of Venus, Jupiter and Mars, and probably eclipse predictions, but no model building.	*Āryabhaṭiya* also includes an excellent approximation to π (62832/20000 = 3.1416) and tables of trigonometric functions, introducing modern sine function in place of Greek chord. Although it does not use place-value notation, the nature of some of the calculations suggests that Āryabhaṭa knew this system.	Classic Maya period, ~250-950. Decline of Roman empire, especially in west. Foundation of Constantinople and adoption of Christianity under Constantine (reigned 306-337). Western Roman empire ends, 476.
AD 600-1000	Islamic scholars translate and thus preserve much Greek science, refine and develop Ptolemy's model, invent modern spherical trigonometry, and improve instruments, e.g. astrolabe. Astronomical tables or *zīj* produced by Islamic scholars: not only tables of planetary positions (from Indian or Ptolemaic models) but also mathematical tables.	Indians develop first real understanding of zero as a number (instead of just a placeholder for a missing digit in place-value notation). Indian numerals come into use in Islamic world. Islamic mathematics: al-Khwārizmi writes treatise on algebra, 830 (his name gives us the word *algorithm*; the title of his book gives us *algebra*).	Mohammed, 570–632. Meteoric rise of Islam; conquest of much of North Africa and Asia Minor. Conquest of most of Spain, 711-719. Modern European states beginning to emerge. Æthelstan (894-939), grandson of Alfred the Great, is first king of England (recognisably the modern country), unifying the various Anglo-Saxon and Danish kingdoms.
AD 1000-1200	Astronomical ephemerides spread to Europe, particularly Toledo Tables by al-Zarqālī (1027-1087). These were translated into Latin in the 12th century and were highly influential. Astronomers in Far East observe SN 1006 (the brightest naked-eye supernova ever recorded) and SN 1054 (which formed the Crab Nebula).	University of Bologna founded, 1088 (first university in modern sense; Oxford University, ~1096, is the second). Greek and Islamic science texts begin to be translated into Latin, 12th century, largely as consequence of reconquest of Spain. Movable type invented in China, 1040.	Norman conquest, 1066. First Crusade, 1099. Moorish rule in Spain recedes: kingdoms of Castile, Aragon and Portugal established.
AD 1200-1500	Astronomy taught in universities as part of standard curriculum, and textbooks written/translated. Alfonsine Tables of planetary positions, 1252. More developments in instrumentation: cross-staff, quadrant. Regiomontanus (1436-76): systematic programme of	More universities established, including Cambridge in England and St Andrews, Glasgow and Aberdeen in Scotland (yes, more in Scotland than in England, from 1495 till 1832!). Beginnings of a concept of experimental science (Robert Grosseteste, Roger Bacon). Printing press developed in Europe, (Gutenberg, 1439, then	Greater stability in Europe and rise of merchant class. More education and greater levels of literacy among laypeople. Black Death (1346-53) devastates Europe, killing ~half the population. Artillery (cannon) being used in warfare, 15th cent.

	observations, of very good accuracy, and ambitious textbook printing programme (sadly terminated by his early death).	very rapid spread: ~1000 presses in operation in Europe by 1500). This is critically important for the dissemination of new ideas. Islamic mathematical methods spread to Europe.	Fall of Constantinople (1453): end of last vestiges of Roman Empire. Contact with New World (1492) emphasises need for navigational instruments—ships now undertaking long voyages out of sight of land.
AD 1500-1600	Copernicus (1473-1543) writes *De Revolutionibus* (1453): reintroduction of heliocentric model. Basis of *Prutenic Tables*, 1551. Giordano Bruno (1548-1600) espouses Copernican theory and concludes that there must be many life-bearing worlds. Burned at stake for heresy, 1600. Tycho Brahe (1546-1601) shows that the "new star" of 1572 (a supernova) and the comet of 1577 are not sublunary; constructs star catalogue; makes extensive observations of Mars in unsuccessful attempt to measure parallax. Gregorian calendar developed, 1582.	Paracelsus (1493-1541) revives study of chemistry, toxicology and medicine in Europe. Mathematical sophistication increases: Tartaglia (1499-1557) translates Euclid and devises a method for solving cubic equations. Significant progress in anatomy and zoology. Galileo discovers constancy of period of pendulum, 1583. Invention of telescope in Netherlands, ~1590. William Gilbert, *De Magnete* (1600), describes Earth's magnetic field and distinguishes electricity from magnetism.	Protestant Reformation (Martin Luther, 1483-1546; his "95 Theses", 1517; Ulrich Zwingli, 1484-1531; Jean Calvin, 1509-1564). Henry VIII establishes Church of England, 1534. Increasing levels of education and intellectual independence. Higher education no longer confined to clerics. Destruction of Meso-american civilisations by Spanish conquistadors. Foundation of Spanish Empire. 1588 Spanish Armada defeated
AD 1600-1700	1602 Tycho's star catalogue published. 1604 Kepler's supernova 1608 Galileo begins telescopic observations 1609 Kepler's *Astronomia Nova* (Kepler's 1st & 2nd laws) 1610 Galileo, *Sidereus Nuncius* 1610 Galileo discovers satellites of Jupiter. 1611 Kepler publishes improved telescope design 1613 Galileo writes letter on sunspots 1619 *Harmonice Mundi*, Kepler's 3rd law 1632 Galileo, *Dialogue of the Two Chief World Systems* 1639 Huygens recognises Saturn's rings 1655 Huygens discovers Titan 1663 James Gregory publishes design for reflecting telescope	Many foundations of modern science laid, e.g. gas laws (Boyle, Hooke), mechanics (Galileo, Hooke, Newton), calculus (Newton, Leibniz). Rise of properly designed controlled experiments and predictive mathematical models. Concept of universal physical laws. Final demise of Aristotelian physics. 1614 John Napier invents logarithms 1621 Snell discovers his law of refraction. Galileo shows that acceleration under gravity is independent of mass of body 1636 Harvard University founded 1644 Descartes, *Principles of Philosophy* 1662 Royal Society founded 1665 *Phil. Trans.* started	1603 Death of Elizabeth. Union of Crowns of England and Scotland. 1605 Foundation of East India Company. Danish, Dutch, English and Portuguese all establish presence in India for trading purposes. 1607 Foundation of English Colony of Virginia Increasing importance of long-distance travel makes navigation and accurate maps a critical issue. 1639-1651 Wars of the Three Kingdoms (English Civil War). Execution of Charles I. Protectorate of Oliver Cromwell, 1653-8. 1660 Restoration of Charles II.

	1665 Cassini discovers Great Red Spot 1667 Paris Observatory founded 1668 Newton builds reflecting telescope 1672 Cassegrain publishes design for reflecting telescope 1675 Greenwich Observatory founded 1676 Römer deduces finite speed of light 1677-8 Halley catalogues southern stars 1687 Newton publishes *Principia* 1695 Halley predicts return of comet in 1758/9	1665 Hooke publishes *Micrographia*, first discussion of microscopic sctructures 1666 Paris Académie des Sciences founded 1672 Newton uses prism to decompose white light 1693 Halley works out the lens equation, $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$.	
AD 1700-1800	Rapid development of astronomical instrumentation. Numerous star catalogues. Early studies of "nebulae", and first attempts to understand the Galaxy. Many detailed Newtonian calculations of planetary and satellite orbits. 1729 Bradley discovers stellar aberration 1750 Wright: early speculations on structure of Galaxy 1758 Dollond builds the first achromatic lenses 1759 Halley's Comet duly returns, and acquires its name 1761, 1769 Transits of Venus 1767 Michell deduces, by statistical arguments, existence of binary stars and star clusters 1781 Messier's catalogue of "fuzzy things that aren't comets" 1781 William Herschel discovers Uranus 1783 Goodricke studies variable stars (Algol and δ Cephei) 1796 Laplace proposes the nebular hypothesis for the	Emergence of modern chemistry (Priestley, Lavoisier, Dalton). Advances in Newtonian mechanics by Laplace, Lagrange, Euler, etc. First systematic studies of heat and electricity. 1738 Daniel Bernoulli invents kinetic theory of gases 1742 Celsius invents Celsius temperature scale 1751 Franklin publishes book on electricity 1753 Linnaeus invents modern biological naming convention 1761 Joseph Black introduces concept of latent heat 1761 Longitude problem solved by development of reliable chronometers (Harrison's H4) 1783 Carnot describes operation of heat engines 1788 Hutton, *Theory of the Earth*, introduces doctrine of uniformitarianism in geology and very great age of the Earth ("no vestige of a beginning, no	Much social upheaval (Jacobite rebellions in Scotland, 1715, 1745; American independence, 1776; French Revolution, 1789). Beginnings of modern parliamentary democracies. United Kingdom formed by Act of Union, 1707. Beginning of Industrial Revolution: 1712 Newcomen's steam engine; 1776 Watt's (much improved) steam engine; 1761 onwards development of canal system; mechanisation of textile production; industrial iron production and bulk production of chemicals; mechanisation of agriculture (1701 Tull, seed drill; 1730 Foljambe, iron plough; 1784 Meikle, threshing machine), which freed up labour for heavy industry and accelerated urbanisation. 1776 Adam Smith publishes *The Wealth of Nations* (origin of capitalism as economic theory)

	formation of the solar system	prospect of an end")	
AD 1800-1900	Major advances in instrumentation: improved refractors, then silver-on-glass reflectors; photography; spectroscopy. 1801 Piazzi discovers 1 Ceres 1802 Olbers discovers 2 Pallas. Herschel first uses the word "asteroid" for these small planetary bodies (most people just call them planets) 1803 Herschel confirms binary stars by observing orbital motion 1804 3 Juno discovered 1807 4 Vesta discovered 1814-15 Fraunhofer maps solar spectrum 1826 Olbers propounds his paradox 1838 Bessel makes first reliable parallax measurement, of 61 Cygni. (Struve and Henderson make less reliable measurements, of Vega and α Cen respectively) 1843 11-year solar cycle discovered 1845 onwards: many further main belt asteroids discovered—no longer regarded as full-status planets (term "asteroid" becomes commonly used) 1846 Existence of Neptune deduced by Adams and Leverrier by analysis of perturbations of Uranus' orbit; Neptune consequently discovered by Galle 1857 Maxwell analyses dynamics of Saturn's rings	"Classical physics" perfected: wave theory of light (Young, 1801; Fresnel, 1830); thermodynamics (Carnot, Meyer, Joule, Kelvin, Helmholtz, Maxwell, etc.); classical electrodynamics (Oersted, Faraday, Ampère, Maxwell, etc.) 1800 Herschel discovers infrared radiation 1801 Young's two-slit experiment 1807-12 Davy presents a series of lectures developing modern chemistry 1807 Young coins the term "energy" 1808 Dalton presents modern atomic theory 1811 Fourier develops theory of Fourier series 1824 Carnot devises Carnot cycle 1820s studies of emission spectra of salts via flame spectroscopy 1830 Lyell's *Principles of Geology* establishes modern geological science. 1831 Faraday uses a moving magnetic field to generate electricity 1839 Daguerre introduces the daguerreotype process—first practical photography 1851 Frederick Scott Archer invents wet collodion process 1854 Lord Kelvin coins the word *thermodynamics* 1859 Darwin, *Origin of Species* 1859 Kirchhoff-Bunsen laws of spectroscopy	Continuing advance of industrialisation and development of new technologies. Machine tools. Strong emphasis on science and engineering in support of this. Heyday of British Empire. 1801 Jacquard invents punched-card loom (arguably first programmable machine) 1829 Stephenson's *Rocket* wins Rainhill Trails. Start of railway era. 1832 Durham University founded (first new university in UK for ~300 years) 1840s Domestic gas lighting introduced

	1864 Huggins observes emission line spectra from planetary nebulae and concludes that they are gaseous 1868 Secchi develops first spectral classification system for stars 1872 Draper photographs spectrum of Vega 1880 Silver-on-glass mirror technology introduced 1888 Lick refractor (36")—with Yerkes 40" refractor (1897), last of the great research refractors 1890 First version of Harvard classification system (Pickering and Fleming) 1897 Maury's (short-lived) classification system, including first spectral identification of giant stars 1898 Keeler refurbishes Crossley reflector—first major reflector in a professional observatory (Lick)	1859 Maxwell derives the Maxwellian distribution 1861 Maxwell interprets light as an electromagnetic wave 1861 Maxwell (again!) and Sutton take first colour photo 1865 Maxwell publishes his electromagnetic theory 1871 Richard Leach Maddox invents dry plate process 1870s Maxwell, Boltzmann, Clausius and Gibbs develop the theory of thermodynamics 1880s Hertz produces radio waves and proves that they are electromagnetic waves as predicted by Maxwell 1890s development of Diesel engine 1895 Röntgen discovers X-rays 1896 Becquerel discovers radioactivity 1897 JJ Thomson discovers the electron	
AD 1900-1950	Advances in physics (quantum mechanics and general relativity) lead to the development of two new branches of astronomy: astrophysics and cosmology. 1905 Hertzsprung introduces the idea of red giants 1906 Kapteyn's model of the Galaxy 1908 Mt Wilson 60" reflector—first of the purpose-built research reflectors 1911 Hertzsprung constructs colour-magnitude diagrams for the Pleiades and Hyades 1912 Leavitt discovers Cepheid period-luminosity relation 1913 Russell draws first modern-style HR diagram 1913 Hertzsprung uses period-luminosity relation to infer distance of Magellanic Clouds	Dramatic shift from ~1900 view of physics as essentially a finished article. 1900 Planck's formula for blackbody radiation, introducing $E = h\nu$ 1905 Einstein's "annus mirabilis"—special relativity, the photoelectric effect, Brownian motion 1909 Geiger and Marsden (working for Rutherford) conduct α particle scattering experiments leading to discovery of atomic nucleus 1911 Development of metal filament lightbulb 1913 Bohr's semiclassical theory of the hydrogen atom	Two world wars: emergence of USA (and, after 1945, USSR) as global superpower. Decline of British Empire. Increasing levels of Government funding for universities and "pure research"—previously Government funding tended to be for applied work, e.g. (for astronomy) navigation and timekeeping. Widespread car ownership: beginning of decline of railway system. Electricity becomes ubiquitous for domestic power and lighting 1914-18 World War I

	1914 Shapley interprets Cepheids as pulsating variables 1915 Slipher publishes first Doppler shifts of “spiral nebulae”—11/15 are redshifts 1917 100" Hooker telescope on Mt Wilson 1918 Shapley’s model of Galaxy 1918-24 Cannon and Pickering: final version of Henry Draper catalogue and Harvard spectral classification 1919 Eddington expedition measures gravitational bending of starlight 1920 Great Debate over status of spiral nebulae 1920 Eddington proposes stars fuelled by hydrogen fusion 1920 Saha equation for ionisation states of atoms in stellar atmospheres 1922-24 Friedmann’s expanding universe solutions of GR 1923 Hubble finds Cepheids in nearby spirals, establishes existence of external galaxies 1924 Payne determines solar composition 1924 Eddington, mass-luminosity relation 1926 Eddington, *Internal Constitution of the Stars* 1927 Lemaître rediscovers Friedmann’s solutions to GR 1929, 1931 Hubble (& Humason), redshift-distance relation 1929 Atkinson and Houtermans apply quantum tunnelling to problem of fusion in stars 1931 Chandrasekhar, theory of white dwarfs 1932 Jansky detects radio emission from Milky Way 1934 Baade and Zwicky distinguish novae and supernovae, and postulate that latter arise when massive star collapses to form neutron star 1938-39 Bethe and colleagues work out theory of hydrogen fusion (pp chain and CNO cycle) 1944 Baade resolves bulge of M31 and introduces concept of stellar	1915 Einstein’s general theory of relativity 1916 Karl Schwarzschild solves Einstein’s field equations for a non-rotating black hole 1920s: development of quantum mechanics (1923 de Broglie, $\lambda = h/p$; 1925 Schrödinger equation, matrix mechanics; 1927 Heisenberg’s uncertainty principle, Dirac equation, origins of quantum field theory) 1928 Gamow explains α decay by quantum tunnelling 1930 Pauli postulates neutrino 1931 Urey discovers deuterium 1932 Anderson discovers positron; Chadwick discovers neutron 1934 Oliphant postulates existence of ^{3}He	1915 UK Department of Scientific and Industrial Research set up to fund university research (replaced by system of Research Councils in 1965) 1926 Central Electricity Board set up in UK to construct the National Grid 1933 Hitler appointed Chancellor of Germany after Nazi party wins election 1939-45 World War II Radar development in WWII paves way for radio

	populations 1944 van der Hulst predicts existence of 21 cm line of neutral hydrogen (first observed 1951) 1945 Jodrell Bank established; also around this time, radio astronomy facilities in Cambridge and Sydney 1946 V2 rockets used for astronomy 1948 Palomar Observatory (200" reflector, 48" Schmidt) 1948 Birth of modern cosmology: αβγ paper on hot dense early universe, Bondi, Gold and Hoyle on steady state model		astronomy

From 1950 to the present day, the line between "astronomy" and "history of astronomy" becomes increasingly blurred, and the expansion of the subject and its increasingly rapid development make constructing a timeline very difficult (multiple lines of enquiry are progressing in parallel). The difference between astronomy ~1900 and ~1950 is almost as striking as between ~1600 and ~1700: in 1900, only the dynamics of the solar system had a strong theoretical basis, there were no distances for anything beyond the nearest stars, the physical basis of stellar energy generation had yet to be understood, and the question of the origin and evolution of the universe as a whole was basically ignored; whereas in 1950 the theoretical framework is more or less in place, with only particle physics still to be understood, and the research programme is recognisably modern (though it will be greatly expanded over the next couple of decades by the advent of space-based instrumentation, foreshadowed by the use of V2 rockets in 1946). This drives home the idea that astronomy is at once the oldest and one of the youngest of the sciences—with the exception of orbital mechanics and spherical trigonometry, very little of the undergraduate astronomy curriculum dates from before the 20th century (in contrast to physics, where the 19th-century edifice of classical physics is still very relevant despite the complete restructuring of its basic theoretical framework in the early 20th century).