GALILEO- the REVOLUTION BEGINS

Galileo is often called the father of modern physics. This is not so much because of his celebrated argument with the church about the Copernican system, but rather because of his extensive use of experiments, coupled with deductive argument and mathematical analysis, to establish general truths about the dynamics and physical properties of a large variety of physical systems. This was a decisive break with 2000 years of history, and showed future generations of scientists how to couple carefully designed experiments with theoretical analysis, to arrive at general conclusions.

(1) GALILEO: LIFE and TIMES

Galileo Galilei was born in Pisa, Italy on February 15, 1564, the first of 6 children. His father, Vincenzo Galilei, was a teacher of music and played the lute; he also carried out experiments on strings to support his musical theories. Galileo's mother was Giulia degli Ammannati. In the early 1570's, he and his family moved to Florence.

Once he was old enough to be educated in a monastery, his parents sent him to the Camaldolese Monastery at Vallombrosa, 33 km southeast of Florence. Galileo became a novice in the Camoldese order, intending to join, but his father wanted him to become a doctor. In 1581 Vincenzo sent Galileo back to Pisa to enrol for a medical degree at the University of Pisa. Galileo apparently did not take his medical studies seriously, instead attending courses on mathematics and natural philosophy. In the year 1582-83 Galileo attended a course on given by Ricci on Euclid's Elements; and that summer Galileo invited Ricci to his home to meet his father. Ricci tried to persuade Vincenzo to allow Galileo to study mathematics, and eventually in 1585 Galileo gave up his medical studies and left the university without completing his degree.

Galileo then began teaching mathematics, first privately in Florence and then, during 1585-86 at Sienna where he held a public appointment, and in the summer of 1586 at Vallombrosa. In this year he also wrote his first book *la balancitta* (the little balance), which described Archimedes' method of finding the densities of substances using a balance. In 1587 he travelled to Rome to visit Clavius who was professor of mathematics at the Jesuit Collegio Romano, taking with him some results which he had discovered on centres of gravity of solids. Thus began a relationship which continued by correspondence for many years. In 1589 Fantoni vacated the chair of mathematics at the University of Pisa, and with the support of Clavius, Galileo was appointed to fill the post (although this was only a nominal position to provide financial support for Galileo). Galileo spent 3 years in this position at the University of Pisa and during this time he wrote a series of essays on the theory of motion, now referred to as *De Motu*, which he never published. In *De Motu* one finds already the idea that one can test theories by conducting experiments- in particular, he discusses how one could test theories about falling bodies using an inclined plane to slow down the rate of descent.

In 1591 Vincenzo died and Galileo had to provide financial support for the rest of the family. Professors at Pisa were not well paid, so in 1592 Galileo obtained an appointment as professor of mathematics at the University of Padua (then the university of the Republic of Venice) with a salary 3 times higher than at Pisa. His main initial duties were to teach Euclidean geometry and Aristotelian/Ptolemaic astronomy to medical students. Galileo spent 18 years at Padua- in many ways these were his most productive years. He also began a long term relationship with Maria Gamba, from Venice. Although they did not marry, in 1600 their first child Virginia was born, followed in 1601 by a second daughter Livia; and in 1606 their son Vincenzo was born.

Although Galileo did little in public to excite interest during these 18 years, they were crucial for the development of his ideas. In 1602 he returned to work on the theory of motion he had begun with *de Motu*, and over the following two years, through his study of inclined planes and the pendulum, he formulated the correct law of falling bodies and worked out the parabolic motion of moving projectiles. These famous results would not be published for another 35 years, after his denunciation by the Inquisition.

It is possible that Galileo might never have acquired the pivotal position he now occupies in the history of science, were it not that in the late spring of 1609, fate took a hand. Galileo describes the crucial event in "the Starry Messenger" (Sidereus Nuncius), published in March 1610:

About 10 months ago I received a report that a certain Dutchman had constructed a spyglass by means of which visible objects, though very distant, were distinctly seen as if nearby. Of this truly remarkable effect several experiments were related, which some persons believed while others denied them. A few days later the report was confirmed by a letter I received from a Frenchman in Paris, Jacques Badovere, which caused me to apply myself wholeheartedly to investigate how I might arrive at the construction of a similar instrument. This I soon did, my basis being the doctrine of refraction.

Galileo began to design and make a series of telescopes whose performance was much better than the Dutch originals. His first telescope gave a $\times 4$ magnification- to improve on this Galileo learned how to grind and polish his own lenses and by August 1609 he had $\times 9$ magnification. Galileo immediately saw the commercial and military applications for ships at sea. His friend Sarpi arranged a demonstration for the Venetian Senate- in return for a large increase in his salary, Galileo gave them the rights to his telescopes.

By the end of 1609 Galileo had turned his telescope on the night sky. His astronomical discoveries were described 6 months later in "the Starry Messenger". This work caused something of a sensation at the time. Galileo claimed to see mountains and craters on the Moon, and that the Milky Way was made up of thousands of faint stars. Most importantly, he claimed to have found 4 small bodies orbiting Jupiter- which he called 'the Medicean stars', in honour of Cosimo de Medici, the Grand Duke of Tuscany. He succeeded in impressing Cosimo enough that in June 1610 Galileo was able to resign his post at Padua to became Chief Mathematician at the University of Pisa (without teaching duties) and 'Mathematician and Philosopher' to the Grand Duke. In 1611 he visited Rome where he received considerable honours, notably from the Collegio Romano, and from the Accademia dei Lincei (of which he was made the 6th member).

While in Rome, and after his return to Florence, Galileo continued to make observations with his telescope, observing Saturn, the phases of Venus, and sunspots- for a detailed discussion of this see below. His observations were published in the 'Discourse on floating bodies' in 1612, and more fully in 'Letters on the sunspots' which appeared in 1613. Again, these publications created a stir- in particular, the existence of sunspots contradicted the Aristotelian idea of the perfection of the sun. His interpretations were not always correct. When 3 comets appeared in the sky in 1618 he became involved in a general debate on the nature of comets, arguing that they were close to the Earth and caused by optical refraction.

Despite his private support for Copernicanism, Galileo tried to avoid controversy by not making public statements on the issue (however, he is on record as having argued against Aristotle's views in 3 public lectures he gave in connection with the appearance of 'Kepler's star' in 1604- using parallax arguments to prove that Kepler's Star could not be close to the Earth). This reticince changed after a meeting in the Medici palace in Florence in December 1613 between Galileo's former student Castelli and the Grand Duke Cosimo II and his mother the Grand Duchess Christina of Lorraine. Castelli defended the Copernican position vigorously and wrote to Galileo afterwards of the debate. Galileo responded by arguing that the Bible had to be interpreted in the light of what science had shown to be true. Galileo had several opponents in Florence who sent a copy of this letter to the Inquisition in Rome. At this time the Catholic Church's most important figure dealing with questions of this kind was Cardinal Roberto Bellarmine, who then saw little reason to be concerned about the Copernican theory. He viewed it as an elegant mathematical construction, rather than a new theory about the nature of the universe- thus it did not threaten the established Christian belief regarding the universe's structure. Galileo therefore escaped censure at this time- however, his remarks concerning the way in which biblical interpretation had to be subordinated to scientific results were not forgotten.

In 1616 Galileo returned to the subject, writing a letter to the Grand Duchess Christina which vigorously attacked the followers of Aristotle, and argued for a non-literal interpretation of Holy Scripture when the literal interpretation contradicted observations. He then argued:

I maintain that the Sun is at the centre of the revolutions of the heavenly orbs and does not move, and that the Earth spins on itself and moves around the sun. Moreover ... I confirm this view not only by rejecting Ptolemy's and Aristotle's arguments, but also by producing many counter-arguments, especially some pertaining to physical effects whose causes cannot be determined in any other way, and also other astronomical discoveries; these discoveries clearly contradict the Ptolemaic system, and they agree admirably with this alternative position and confirm it.

At roughly this time Pope Paul V ordered the Sacred Congregation of the Index to decide on the Copernican theory. The cardinals of the Inquisition met on 24 February 1616 and condemned the teachings of Copernicus. Bellarmine relayed their decision to Galileo (who had not been personally involved in the trial); nevertheless Galileo was forbidden to hold Copernican views. So matters lay until 1623, when Maffeo Barberini, who had been an admirer of Galileo since 1611, was elected as Pope Urban VIII. This happened just as Galileo's book '*Il Saggiatore* (The Assayer) was about to be published by the Accademia dei Lincei in 1623; Galileo was quick to dedicate this work to the new Pope. This work described Galileo's scientific method in some detail, without mentioning the controversy over the Copernican theory. Urban VIII invited Galileo to papal audiences on 6 occasions in 1623 and he was given permission to write on the Copernican theory provided he treated it only as a hypothesis. Galileo, therefore, decided to finally publish his complete views on the question. Galileo's health was uncertain by this time (he was already 59 years old in 1923) and so it took him six years to complete the work.

Obtaining permission to publish his famous 'it Dialogue Concerning the 2 chief World systems' in 1630 was not easy. Eventually he received permission from Florence, not Rome, and in February 1632 the book appeared. It takes the form of a discussion between Salviati, arguing for the Copernican system, and Simplicio who upholds Aristotelian orthodoxy; Sagredo (based on his friend Gianfrancesco Sagredo of Venice) acts as an intelligent 3rd party. This book was clearly polemical, and it was not easily ignored- in fact it rapidly sold out. Shortly after publication the Inquisition banned its sale and ordered Galileo to appear in Rome before them. Illness prevented him from travelling until 1633.

The accusation at the trial which followed was that he had breached the conditions laid down by the Inquisition in 1616. However a different version of the 1616 decision was produced at the 1633 trial, rather than the one Galileo had been given in 1616. The truth of the Copernican theory was assumed now to be not at issue; it was taken as given in 1933 that this theory was false.

Galileo was found guilty as charged, and had to recant in full. He was then condemned to lifetime imprisonment, which eventually became a sentence of house arrest. He was able to live first with the Archbishop of Siena, then later to return to his home in Arcetri, near Florence, but had to spend the rest of his life under supervision by the Inquisition. He was however able to work with his assistant Viviani, which turned out to be extremely important, since Galileo had no intention of being silent. After a severe setback in 1634, when his daughter Virginia, Sister Maria Celeste, died, Galileo managed to restart work and with the help of Viviani he completed in 1638 his "*Discourses and Demonstrations concerning the 2 New Sciences*". This was smuggled out of Italy to Leiden in Holland, where it was published by Louis Elsevier (the founder of the modern publishing house). It was his most rigorous mathematical work which treated a large variety of problems in physics. Much of this work went back to the unpublished ideas in '*De Motu*' from 1590, and the improvements which he had worked out during 1602-1604

Galileo died in early 1642, having gone blind 4 years previously. His will requested a burial in the family tomb in the Basilica of Santa Croce, but his relatives feared this would provoke opposition from the Church. His body was therefore concealed and only placed in the church in 1737 by the civil authorities, against the wishes of many in the Church. On 31 October 1992, 350 years after Galileo's death, Pope John Paul II gave an address in which he admitted that errors had been made by the theological advisors in the case of Galileo. He declared the Galileo case closed, but he did not admit that the Church was wrong to convict Galileo on a charge of heresy, simply because of his belief that the earth and other planets revolve around the sun.