A Companion to Physics in the XXth century. Part 4.

Slide 2 shows the time table of important events in the development of astronomy during the last four centuries. It is worth remembering that Johannes Kepler still held to the view that the stars are fixed to the cristalline sphere; he even tried to estimate the thickness of that sphere to be about 15 km (in modern units).

Christiaan Huygens estimated the distance to Sirius, the brightest star of the sky, by comparing its brightness with that of the Sun. He obtained the result of 27 664 astronomical units. The astronomical unit or the average distance from the Earth to the Sun is defined as 149 600 000 km, or 8.3 light-minutes. Huygens' estimate was therefore about 160 light-days or 0.438 light-years (l.y.), whereas we know now that the distance to Sirius is about 8.8 l.y.

In 1785 William Herschel (Slide 3) whose discoveries have been already discussed in „Physics of the Enlightenment. Part 1.", published the pioneering work *On the constitution of the heavens*, in which he estimated the form and dimensions of our system of stars (Slide 4). He performed counts of the number of stars in different parts of the sky, and then made use of the assumptions (Slide 5) which were not correct. Thus, his general picture of our star system (our Galaxy) was reasonably good, except for the estimates of the distances. The first modern measurement of the distance to a star was performed in 1838 by German astronomer Bessel. He measured the parallax of the star 61 Cygni (the star number 61 in the constellation of Cygnus, the Swan). For the first time humanity learned about the vastness of the universe.

At the end of the XIXth century astronomers were convinced that all the visible stars and different objects (Slides 7-8) seen in the sky belong to a single system, the Milky Way galaxy. The spiral nebulae which we now call galaxies were considered to be made of gases (Slide 9).

At the beginning of the XXth century the source of the energy of the Sun and other stars was not yet known, but the accepted explanation was that proposed by Hermann Helmholtz (Slide 10). The correct solution was found only in 1939 and resulted from the progress in nuclear physics (Slide 11).

The Doppler effect plays a very important rôle in astronomy as documented in the Slides 12-21. It has been mentioned in „Companion to Physics in the XIXth century. Part 1." that the first estimate of the velocity of stars was obtained by William Huggins in 1868. We know now that his result had an uncertainty of about 40%. Since that time the accuracy of measurements of spectral lines has considerably improved thanks to the use of special narrow-band filters (Slides 17-18). The study of periodic changes in the radial velocity of variable stars confirmed the cause of changes in their observed brightness. The eclipsing variable stars (called Algol type - because their variability was first noticed for the star Algol in the constellation of Perseus) are binary systems in which the components periodically eclipse each other. The cepheids (called after the star δ in the constellation of Cepheus) are pulsating stars which periodically change their dimensions. Observations of periodic variations in the position of spectral lines of stars led to detection of planets which are orbiting them (so-called exo-planets). The broadening of spectral lines of the stars serves as an indicator of their rotational velocity. Fast rotating stars have diffuse spectral lines, and slow rotating - narrow lines.

Slide 22 lists some determinations of the size and form of our Milky Way system. In 1917 Shapley still believed that all celestial objects, including spiral nebulae (the galaxies), belong to the same great system. Slide 23 shows a model of our Galaxy from 1930. The first model of our galaxy showing its spiral arms was published in 1900.

In Slide 25 we see the photograph of two dwarf galaxies visible in the southern sky. They have been first described by members of the Magellan expedition which circumnavigated the earth globe, hence the name Magellanic Clouds. These two star systems are quite close to us so that one can easily see and study their stars. In the early years of the XX^{th} century the Small Magellanic Cloud (SMC) was surveyed by Henrietta Leavitt of the Harvard Observatory. She published a list of more than 1700 short period variable stars and was able to determine periods of variations of 25 Cepheids. She noticed that the brightest stars had the longest period. Leavitt rightly concluded that, as the SMC was very distant, its stars were all at similar distances from us. Thus the differences in their apparent magnitude were virtually the same as differences in absolute magnitude (Slide 26). It was a breakthrough in the study of the universe, because Leavitt's period-luminosity relation could be used to determine the distance of any Cepheid from its measured period of variation of brightness. However, one had first to determine the distance to the SMC; it was first achieved by Danish astronomer Ejnar Hertzsprung who used the statistical method (Slides 27-28). A few years later Harlow Shapley recalibrated the absolute magnitude scale of Cepheids using a much larger sample of stars than Hertsprung, and corrected the distance to the SMC.

Measuring the periods of Cepheid variables and their apparent magnitudes had enabled the distances to the globular clusters and the nearest galaxies to be determined (Slides 29-32). In 1924 Edwin Hubble identified cepheid variables in the Andromeda galaxy (M 31) and proved that it was a separate galaxy of stars, beyond the Milky Way. This destroyed the old view that all visible celestial objects form a single star system.

Slides 34-73 present the essence of the general relativity theory and its impact on physics and astronomy. Albert Einstein understood well that his special relativity theory refers to a ideal empty world in which one can define inertial frames. Since 1905 he was trying to modify his theory by including omnipresent gravitation. In 1907 he realized that if a man falls freely, he would not feel his weight. The equivalence principle was „the luckiest thought in my life" - he recollected later. The road to the general relativity theory was still complicated because the theory required elaborated mathematics. In 1908 Hermann Minkowski took an important step when he introduced four-dimensional space-time. Einstein understood that he had to geometrize gravitation by using non-Euclidean geometry. His great idea was to consider gravitation as curvature of space-time. Slides 37 and 38 summarize the difference between special and general relativity.

On 25 November 1915 Einstein presented the final version of his general relativity theory to the Prussian Academy of Sciences in Berlin. It was published in the beginning of 1916 as a small brochure (Slide 39). At that time the capital of Germany remained a quiet place in spite of the world war which raged on all the fronts. The mathematics of general relativity is quite complicated. The „Einstein equation" is shown in Slide 42. It has on the left-hand side so-called Einstein tensor with ten components which describe space warped by matter, whereas the energy-momentum tensor on the right-hand side describes the distribution of matter. The equation is only apparently simple because in fact it is a system of ten nonlinear second order partial differential equations for the ten components of the said tensors. The numerical coefficient linking the two tensors is very small which is the reason why the influence of gravitation on space remained unnoticed for so long. A two-dimensional explanation of space curved by gravitation is shown in Slide 43.

A short chronology of events in the 1920s is presented in Slide 40. German astronomer Karl Schwarzschild found the first two exact solutions of the Einstein's field equations within two months after their publication. The first solution corresponded to an ideal body consisting of a mass point at the origin, the other corresponded to a spherical body of finite extent. Schwarzschild introduced the gravitational radius (or Schwarzschild radius) which defines the radius of a spherically symmetric body at which the escape velocity is equal to the speed of light (so that light emitted from the centre is not able to escape). For a body of the mass of the Sun the Schwarzschild radius is about 3 km, for a body of the mass of the Earth it is about 9 mm.

In 1917 Einstein noticed that his equations predicted that the universe was either expanding or contracting. He was convinced that the universe was static and introduced the term, the „cosmological constant" to secure it (Slide 41). Alternative solutions were found by Dutch astronomer de Sitter and Russian mathematician Aleksandr Friedman.

The three predictions of the general relativity theory are listed in Slide 44. The advancement of Mercury's perihelium has been very precisely determined by astronomical observations and could not be explained by classical physics, while the general relativity theory predicted it exactly (Slides 45-46). Light deflection in the gravitational field was first confirmed by measurements of positions of stars visible during the total solar eclipse in 1919 (Slides 47-51). After that Albert Einstein became the most famous scientist of the world.

Some consequences of the theory of relativity are summarized in Slides 56-73. Slides 56-57 contain the reminder that the effect of time dilation in special relativity is reciprocal because the two systems in motion are equivalent. The general relativity theory predicts that time runs slower in stronger gravitational field (Slide 61). This prediction has been first checked experimentally in 1972 with the use of atomic clocks transported by airplanes around the Earth (Slides 62-63). Nowadays we can observe this effect in the operation of the Global Positioning System (GPS). Without corrections given by general relativity theory the GPS system would stop indicating exact position of the receiver after several seconds! (Slides 64-66). The gravitational dilation of time is very small but it had been measured in 2010 with the use of the most precise atomic clocks (Slides 66-70).

Another prediction of the general relativity theory: gravitational lensing, had been confirmed in beautiful pictures taken by the Hubble Space Telescope (Slides 72-73).

The first measurements of radial speeds of galaxies from the Doppler effect were performed by Slipher in 1911. By 1929 the number of measured speeds was already large enough to allow Edwin Hubble to notice the relation between speed and distance of the galaxy (Slide 75). Two years later Hubble and his assistant Humason had enough good measurements to confirm that the galaxies recede from us with velocities v proportional to their distance r (Slide 76). The coefficient H of proportionality ($v = H \times r$) is called the Hubble constant. It measures the rate of the expansion of the universe. That quantity was initially determined to be about 500 (km/s)/Mpc but elimination of various errors reduced it by a large factor (see Slide 77, where Mpc - megaparsec; 1 parsec equals about 3.26 light-years). In recent years a new problem appeared, because the values of H obtained by two different methods do not agree, the difference being much larger than possible error bars (see Slide 111).

Radioastronomy began by accident. Karl Jansky of the Bell Telephone Laboratories was studying the cause of interference at a frequency of 20.5 MHz on a newly opened transatlantic radio link (Slide 79). In 1932 he discovered that the observed hiss was coming from the sky. Jansky spent a year observing and analysing the signals and identified a possible source near the centre of the Milky Way. Jansky's results were largely ignored by the astronomers who regarded radio technology with suspicion. It took some time before radioastronomy was accepted as a new branch of astronomy operating in a new window beside the visual light. In 1958 spiral structure of our Galaxy was been determined from the observations at the 21 cm line of neutral hydrogen (Slide 80).

In August 1967 Jocelyn Bell, one of the research students in Cambridge, noticed an unusual periodic signal coming from the sky (Slide 81). Originally it was thought that the signals were man-made, or perhaps come from some extraterrestial inteligence. The source was accordingly first designed as LGM 1 (standing for Little Green Men). After further studies it was concluded that the pulses arrive from rapidly rotating neutron stars which were emitting beams of synchrotron radiation. These beams would be picked up by the Earth observers as regular electromagnetic pulses in the same way that the rotating light of a lighthouse is seen to flash by a stationary observer (Slide 82).

Another unexpected discovery took place in 1963. The astronomers were looking for the optical objects correlated with some radio sources. The were puzzled by an apparent correlation of radio source named 3C 273 with a faint blue object looking very much like a star. It appeared that its spectrum was unlike anything that had been seen before. Luckily American astronomer Marteen Schmidt realized that the lines seen in the spectrum of that object were hydrogen lines with a very large red shift of 0.16 (Slide 83). It meant that the object is receding from us at 15% of the speed of light, and that its distance is about 2 billion light years. Soon several other similar objects were found with even larger red shifts. They became known as quasi-stellar objects, or „quasars". They all belong to the most distant objects seen from Earth (Slide 84) and emit enormous amount of energy.

Already in 1928 Belgian astronomer Georges Lemaître suggested that the expanding universe might have originated form the Big Bang. He knew about several galactic red shifts measured by

Slipher and linked this information with Einstein's theory of relativity. His suggestion passed unnoticed. In 1948 the problem was attacked by George Gamow and his collaborators Ralph Alpher and Robert Herman. They had predicted that the Big Bang would have produced radiation at very high temperature which should still be observable in the universe although much cooled down because of its expansion. Several people pretended to have observed such a radiation but their results were nonconclusive. In 1965 Arno Penzias and Robert Wilson of the Bell Laboratories accidentally discovered that the whole sky was radiating at a wavelength of 7.3 cm. They analysed that radiation at other frequencies and showed that it was similar to the black body radiation of about 3.5 K. At the same time Robert Dicke and his collaborators were looking for such a radiation and had the theoretical analysis ready. This major discovery confirmed the Bing Bang theory. Subsequent measurements determined exactly the properties of that microwave radiation. It indeed corresponds to the black body radiation of the temperature 2.726 K (Slides 86-87). In recent years it was possible to measure the relative intensities of spectral lines in the light of distant galaxies and determine their temperature (Slide 88) by making use of the Boltzmann formula for the occupation of atomic energy levels (see explanation in Slide 110). The expansion of the universe causes its cooling. The galaxies observed at $z = 2.4$ have T about 9 K.

The expansion of the universe has been confirmed by observations of Supernovae stars (Slide 89). In the expanding universe each wave of light is emitted from a position farther from the observer than the previous one, so that succesive waves will arrive at the observer with an increasing delay. A pulse of light whose duration is T in the rest frame of the source will have duration $(1 + z)T$ in the rest frame of the observer. The light curves of the Supernovae are affected in proportion to their distance: their light curves are „stretched" by a factor $(1 + z)$

During the last few decades cosmology became an exact science as the result of numerous space missions and observations from high altitude in our atmosphere (Slide 90). The first map of the microwave radiation covering the whole sky was delivered by the Cosmic Background Explorer (Slide 91). Its raw spectrum had to be corrected by removing the dipole component (upper illustration) caused by the motion of the Earth in space, and the contribution from the Milky Way (central illustration); the corrected map is shown in the lower illustration. The red and blue colours indicates deviations of the temperature from the average; the deviations are minute, about one part in 10^5. Thus the background radiation is very uniform. This result has been confirmed by further missions which had much better resolving power (Slides 92-93).

One of the hot topics in astrophysics is the problem of rotation of galaxies. In 1978 Vera Rubin and her collaborators published the results of measurements of rotation speed of several galaxies. They found that the speed of rotation is larger than expected from the amount of their visible mass - if the Newtonian mechanics was used for calculations. The first hint for the existence of invisible mass in galaxies was published in 1933 by Fritz Zwicky who studied the cluster of galaxies in the constellation of Coma (Slide 94). The conventional explanation today is that there exists so-called dark matter in the form of WIMPs - Weakly Interacting Massive Particles. Such particles have not been found yet. Other scenarios are possible, such as e.g. Modified Newtonian

Dynamics (MOND). However, the dark matter hypothesis recently encountered difficulties (see explanatory Slides 112 and 113), so that the problem remains open.

In the early 1960s Raymond Davis decided to attempt measurement of the flux of neutrinos generated in nuclear reactions in the interior of the Sun (Slide 11). It has been known that the cross section of neutrinos for interactons with matter was very small. Davis planned to study the reaction of neutrinos with the isotope chlorine 37 which produces argon 37, to be extracted by radiochemical methods. The experiment was performed deep underground in the Homestake gold mine in South Dakota in ordre to reduce signals from the energetic cosmic rays. The detector consisted of an 380.000 litres tank of ordinary cleaning fluid, perchloroethylene. It was found that the number of detected neutrinos was lower than expected from calculations. This effect was confirmed by another experiment with a different type of detector located in the Japanese Alps (Kamiokande, and later Superkamiokande). It appeared that the neutrinos (so-called electron neutrinos) produced in the Sun change partly into muon neutrinos which escaped detection in the said experiments (Slide 96). Thus, the neutrinos originally regarded to be massless were found to have mass, otherwise the oscillations between their different types could not occur. It was one of the most important discovery in physics and astrophysics in the last decades.

Concluding remarks. The general trend in the evolution of physics is to describe as many problems as possible in one theory (Slide 98). We are still far from having the „theory of everything", but many physicists believe that such a theory is possible. The big unsolved problem is the lack of link between quantum mechanics and theory of relativity.

Richard Feynman wrote in 1963 that the best way to summarize centuries of physics research is to say that „all things are made of atoms". Since that time there had been enormous progress and if he were alive today, his summarizing sentence could well be that „all things are made of quarks and leptons" - because it defines the limits of our present understanding of the physical world (Slide 99).

The development of physics did not always go in an orderly way. There have been frequent unexpected discoveries and many more of these may be expected in the future (Slides 100-101). The normal growth of physics is exponential as shown in Slide 102, with visible disturbing effect of the two world wars. The number of „eminent" physicsts, who are remembered in encyclopedias even after hundred years, also grows exponentially (Slide 103). The percentage of such physicists seems, however, to decrease with time (Slide 104). Physics changes its character and becomes more like an „industry" with still increasing number of „scientific workers" whose presence is essential to secure development and solution of increasingly complex problems (Slides 114-122). This is reflected in establishing new awards for scientific achievements, such as the Breakthrough Prize for Fundamental Physics (Slide 105), which does not have limits of only three laureates (as the Nobel Prize).

The future course of physics has been beautifully expressed by Oppenheimer (Slide 107).