The development of Astronomy during the 20th century

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In 1900 Astronomy was largely a descriptive science, with the exception of celestial mechanics - the study of the motions of planets and other solar system bodies. Here an extensive body of observations of their positions had been accumulated, while detailed "theories" - applications of Newtonian mechanics provided opportunities for a comparison with observation and the determination of the masses of planets. The necessary computations required a massive effort, and it was not unusual in the larger observatories to see several dozens of persons engaged in adding and subtracting logarithms or using simple manual calculating machines. Later in the century, electrical computers and thereafter electronic ones of increasing sophistication led to improvements of the accuracy which in the sixties allowed spacecraft to be sent to specific targets in the solar system.

While the results obtained indicated a remarkable agreement between theory and observation, one minuscule deviation in the orbit of Mercury could not be removed: the computed and observed precession of the perihelion differed by 43 arcseconds per century. The problem was unexpectedly resolved on the basis of Einstein's general theory of gravity, which predicted exactly this.

The other major branch of Astronomy in 1900 was concerned with the determination of the precise positions and motions of the stars. In 1906, J.C. Kapteyn discovered that these were not random, but that it looked as if there were two star streams moving in opposite directions, a phenomenon later described in more physical terms as an ellipsoidal distribution of random velocities. The explanation of the distribution of stars of different apparent brightness and of their motions remained in doubt since the distances of the stars were uncertain. In the twenties, it became finally clear that the stars all belong to a large flattened system - the Milky Way Galaxy - with in the Universe many other such systems - the galaxies. B. Lindblad and J.H. Oort then found that our Galaxy is rotating - not like a wheel, but differentially - and that this could explain the observed motions. Much uncertainty remained because of the light absorbing interstellar dust which caused much of the galactic disk to be hidden from view. Much later with radio waves from interstellar hydrogen and infrared radiation from stars did it become possible to look through the dust layer and to explore the furthest regions of the Galaxy. In the mean time, it had been found that there were many other galaxies containing stars, gas and dust in differential rotation with the linear rotation velocity nearly independent of the distance to the center over most of the galactic disk.

The Ancients already knew that different stars may have very different colors, and by 1900 spectroscopic analysis of starlight had shown associated spectral differences. The interpretation of these remained unclear until developments in atomic physics had made sufficient progress. With photographic spectra the wavelengths of many absorption lines could be determined with sufficient accuracy to identify these as due to hydrogen, helium and other elements like calcium and iron. The presence of helium lines was found to be associated with blue colors, while stars with strong calcium lines tended to be redder. The decisive step in interpreting the spectra was made in 1920 by M.D. Saha, who showed that the spectra were mainly determined by the atmospheric temperature of the stars through the ionization equilibrium and through the excitation energy: In cool stars there is not enough energy to populate the higher levels of helium, while in hot stars the resonance lines of calcium are no longer seen because most of it is in higher states of ionization.

Already in 1905 E. Hertzsprung had found that in a diagram of intrinsic luminosity versus color most stars scattered around a line (the "main sequence") going from blue, luminous to red, faint. Some 10 % were found as red, luminous or faint, blue. Red means cool and cool, luminous indicates a large surface area -hence, the name "red giants". Similarly faint, blue means hot and faint and, hence, small: the "white dwarfs". When the mass of the latter was determined, it became clear that the density had to be very high and that their structure was, determined by degenerate electron pressure. S. Chandrasekhar (1931) then demonstrated the fundamental result that degenerate configurations can only be in equilibrium if the mass is less than a critical mass.

While some progress was made in understanding normal stars, the essential aspect of the energy generation remained unclear. With the progress of nuclear physics it became apparent around 1940 that conditions in stellar interiors were such that nuclear reactions leading to the transformation of hydrogen into helium were possible. In massive stars this happens through a set of reactions in which carbon plays the role of catalyst, while in low mass stars protons fuse directly to deuterons and from there finally to helium nuclei (H. Bethe and C.F. von Weizsäcker). Since in the outer parts of a star the temperature is too low for nuclear reactions to occur, a compositional gradient is established, which has profound implications for the structure of the star. It causes the envelope to inflate producing thereby the red giants.

In the mean time another development in physics allowed some aspects of the Universe to be analyzed. Einstein had already considered the possibility to describe the Universe as a solution to the equations of General Relativity. He looked for static solutions - in a way rather remarkable at a time when change and evolution were becoming accepted in biology, geology and the stellar world. W. de Sitter then found a solution of an empty expanding Universe, and the meteorologist A. Friedman found a general set of evolving solutions also with matter in it. In 1924 C.W. Wirtz showed that the data on galaxies were consistent with a de Sitter Universe, and soon thereafter E. Hubble with improved data from the new 100-inch telescope moderately convincingly showed that the redshifts of galaxies tend to be proportional to their distances - which fact indicates that the Universe is expanding. G. Lemaître in 1931 developed a cosmology with as an initial state "l'atome primitif", a clear predecessor of the Big Bang Cosmology, and G. Gamov in 1942 explored the element synthesis in a hot Big Bang and predicted the cosmic microwave background. Late in the fifties as nuclear physics progressed, it became clear that most elements do not have a cosmological origin but result from processes in evolved stars, especially in supernova explosions.

Technology made slow progress. Observations with the new telescopes were made with gradually improving photographic plates, though quantum. efficiencies of these were no more than one percent and much less in the red part of the spectrum. Photomultipliers followed with better efficiency but without imaging capability.

In the mean time physicists had been detecting the mysterious cosmic rays. Their extraterrestrial origin and positive charge had been established, but their connection with the astronomical universe remained largely unexplored. Their principal interest had been that high energy particle collisions could be studied, though the beam intensity was very low.

Thus, around the half way point in the century the nature of normal stars and white dwarfs had been established, the galaxies were seen to be the building blocks of the Universe, and the expansion of the Universe had been demonstrated. All information about the Universe and its contents came from photons collected with 1-m class telescopes, and most of the collected photons were never detected.

During the second half of the century new developments in physics and perhaps even more in technology led to a major increase in information about the Universe and its contents. Advances were mainly due to improved optical detectors and telescopes, to developments in radio, X- and □-ray detection, to the placement of detectors on spacecraft above the earth's atmosphere and to vastly increased computing power, which was required to manage the large streams of data and to construct models for comparison with observation.

Immediately after the second war several radar engineers began to develop instruments to receive cosmic radio waves which had been briefly glimpsed in the thirties by K. Jansky. As a result, a whole new universe was revealed in which relativistic electrons gyrating in interstellar magnetic fields generated synchrotron radiation. Prodigious amounts of energy up to a million solar rest masses equivalent in some galaxies - appeared to be required in such nonthermal modes. Also radio spectral lines were observed, in particular the 21-cm spin flip line of atomic hydrogen, predicted by H.C. van de Hulst in the mid-forties. From the Doppler shifts in this line the kinematics of our and other galaxies could be derived. This allowed the mass distribution in the galaxies to be inferred and led later to the conclusion that only, part of the mass is in stars and gas, with a large remainder in "dark matter", the nature of which is still unknown. As technology improved molecular lines were detected, and by now molecules with more than a dozen atoms have been found in interstellar space.

With new very accurate atomic clocks radio telescopes in different parts of the world could be synchronized to perform interferometry with angular resolutions of better than a milliarcsec. This has permitted to study very small features in galactic nuclei - in the case of our Galaxy with size not much larger than that corresponding to the radius of the orbit of the earth around the sun.

Celestial X-rays were discovered in the sixties. Most X-ray sources are due to emission from a hot gas or to synchrotron radiation and, thus, give information complementary to that from radio data. Since the earth's atmosphere is opaque to X-rays, these could be studied only once appropriate space vehicles became available. The first X-ray detectors were proportional counters with very poor angular resolution. Later focussing optics for soft X-rays were developed and the situation much improved, while by the end of the century the gas-filled proportional counters began to be replaced by solid state detectors with superior energy resolution.

In 1933 W. Baade and F. Zwicky had predicted that in the powerful stellar explosions manifested as supernovae a neutron star may remain, composed of dense nuclear matter, and that in this process also cosmic rays might be created. Many of the X-ray sources in our Galaxy appear to be double stars with mass being accreted by one of the components which is, in fact, a neutron star. While being accreted, the gas becomes very hot and emits Bremsstrahlung X-rays. Neutron stars have a mass limit not very different from that of the Chandrasekhar mass for white dwarfs. The masses of some of the X-ray sources were found to exceed this limit and therefore should represent more highly collapsed configurations - i.e. black holes.

K. Schwarzschild, in 1916, had shown that such entities represent solutions to the equations of General Relativity, but this had been more an intellectual curiosity. The discovery of X-ray emitting black holes in objects with stellar mass, but also of more massive ones in the nuclei of galaxies, brought General Relativity very much into the main stream. Emission lines from gas close to the black hole are giving information on the kinematics of the gas and thereby allow inferences to be made about the gravitational field - i.e. the metric around the hole.

With radio techniques the pulsars were discovered - rotating neutron stars with strong magnetic fields which are capable of accelerating the relativistic electrons seen in some supernova remnants. The matter ejected during the supernova process shocks the surrounding interstellar gas which is heated to X-ray temperatures and also leads to the acceleration of relativistic electrons emitting synchrotron radiation. While only the electrons are "visible", ions undoubtedly are also present. These may be observed by the gamma-rays generated in their collisions with interstellar gas. As a result, the cosmic rays observed on earth have become integrated into the astrophysical scenarios.

During the last three decades the development of solid state devices - the CCDs - has changed optical astronomy. With their high quantum efficiency of up to 70% or more, they have completely replaced the photographic plates used during most of the century. Computer technology has allowed the construction of 8-10 m class telescopes at affordable cost. As a result, the faint galaxies in the high redshift Universe have become observable, and the evolution of galaxies at times when the Universe was ten times younger than now may be studied.

Optical astronomy has been much hindered by turbulence in the earth's atmosphere. The Hubble Space Telescope was launched to improve the situation and also to gain access to the ultraviolet part of the spectrum. In the mean time a better understanding of atmosphericc turbulence, combined with the capabilities of fast computers, has allowed to overcome part of the atmospheric problems also on the ground. The increased angular resolution resulting from these developments has allowed the study of the inner regions of galaxies and in the future should permit the direct detection of Jupiter-like planets around other stars.

Night vision devices and other military "needs" have stimulated the development of infrared detectors. During the last decade these have found much application in astronomy on the ground and especially in space. The exploration of the "cool universe" of cold gas and dust in which stars and planets are forming is currently in full swing.

Somewhat schematically we conclude that during the first half of this century the development of astronomy has been driven, by the development of physics. In the second half, the strongest impulses have come from new technology. As a result, the narrow spectral window from 3000 - 10000 A has been expanded to the domain from long wavelength radio waves (10 MHz) to hard gamma rays up to several TeV - a range of some twenty powers of ten in photon energy.

Viewing the future we are looking forward to expanding our horizons into the areas of gravitational waves and neutrinos, the latter having already been observed from. the sun. And a large amount of theoretical and observational work at all accessible wavelengths will be needed to arrive at a full understanding of the constituents of our Universe and their interactions.

Much, though far from all, of the basic physics seems to be understood. The same may be said of the earth's climate. But knowing the Navier-Stokes equations has not done much to a full understanding of the climate and its prediction from first principles. The situation is not very different in Astronomy. It is unlikely that fundamentally new physics is needed to describe the interstellar gas. Nevertheless, we are incapable of predicting things like star formation, a process fundamental in galaxy evolution. The world of hydrodynamics has an incredible richness and we are only at the beginning of understanding complex systems like our Universe.