1 Astronomy yesterday, today and tomorrow

1.1 The history of the universe

The echo of the big bang and determination of cosmological parameters

The universe – space, time and all matter – suddenly came into being around 14 billion years ago from an extremely hot and dense state. Ever since this "big bang", space and its embedded matter have been expanding. The reason we are able to reconstruct the history of the universe is related to the finite travel time of light: each look into the depths of space is also a look into the deep past.

A directly observable trace of the earliest phase of the universe is the cosmic microwave background radiation. This remnant also represents the primary pillar of the big bang theory. About 380,000 years after the big bang, matter in its gaseous form had cooled enough to allow atomic nuclei and electrons to combine and form atoms, consisting almost entirely of hydrogen and helium. Matter became transparent to light during this era and released radiation began to fill the universe. It can still be detected today as a radiation field that uniformly fills the sky. Due to the expansion of the cosmos this radiation field has cooled to 2.7 K, which is why we refer to this as the 3K radiation.

The discovery of this homogeneous microwave background in 1965 by Penzias and Wilson was rewarded with the Nobel Prize for Physics. It was not possible to identify any underlying structures, known as anisotropies, until 1992 with the American led COsmic Background Explorer (COBE) telescope. These features are interpreted as overdensities in the primordial gas. Large-scale structures of the universe, such as galaxy clusters, later arose from them (Figure 1.1). Investigations of the structure of the microwave background, together with numerous other studies, provide consistent values for the cosmological parameters, which describe the geometry

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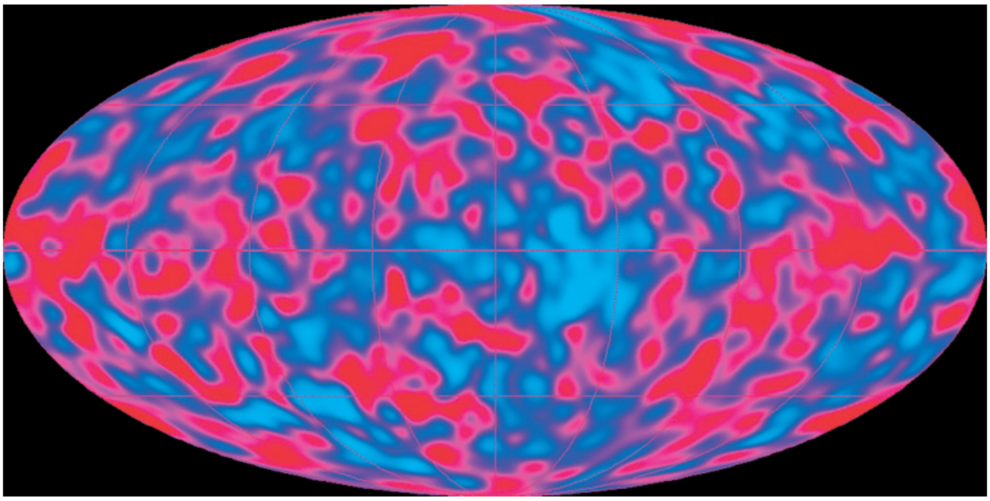

Fig. 1.1: Structures in the cosmic background radiation viewed at an angular resolution of seven degrees. The speckled pattern shows minor fluctuations in temperature, originating from the initial overdensities in the primordial gas. (NASA and the COBE Science Working Group/ESA)

and extent of the universe. They include the Hubble constant, describing the expansion and age of the observable universe, and the density of the various components of matter, thus determining the curvature and expansion history of space.

COBE has an angular resolution of only seven degrees, corresponding to the diameter of 14 full moons, and could therefore only give a rough picture of these "condensation seeds." However, theoretical considerations require that it is precisely these smaller structures which contain further key information about the conditions prevalent during the big bang, and about the creation and further development of the universe. For this reason, one of the central tasks required is the study of the 3K background radiation with far smaller angular resolution and greater sensitivity than was possible with COBE. In the interim, additional measurements were made using high altitude research balloons to proceed further. A breakthrough was achieved by NASA's *Wilkinson Microwave Anisotropy Probe* (WMAP) mission, which confirmed with great precision the projections of the standard big bang model thus determining the cosmological parameters with accuracy. However, comprehensive information on the polarisation and foreground microwave radiation emission will not be recorded until the Planck satellite, developed by the European Space Agency (ESA) to have three times greater resolution, becomes available.

In the distant future, it may yet be possible to identify a cosmic neutrino or even a gravitation wave background, allowing us to view into even earlier epochs of our universe.

Dark matter and dark energy

Probably the most mysterious component of the standard cosmological model is dark matter. It is inferred to exist in many regions of space due to its gravitational effects, but cannot be detected by the emission or absorption of radiation. According to the most recent research results, it represents around one third of the total energy density of the universe. In comparison, the chemical elements of "normal" matter, or what is known as baryonic matter, of which all visible objects are made, contributes only a few percent. Most of the cosmic energy density appears to be composed of this recently discovered and generally mysterious "dark energy". These findings point to a heightened acceleration of cosmic expansion.

From a theoretical point of view, it is assumed that dark matter first formed the overdensities in the early universe, then their gravitational fields collected normal matter that condensed to form galaxies. It therefore played a vital role in the development of structure in the universe. Theoreticians try to simulate this process using powerful computers (Figure 1.2) though the composition of dark matter remains generally unclear. Only a small fraction of it can be made out of faint sky objects. From theoretical considerations, it is probable that we are dealing with an unknown class of elementary particle. This paves the way for a fascinating alliance between cosmology and particle physics.

One promising means of detecting dark matter and determining its mass distribution is provided by the gravity lensing effect. Here, matter, for example in a galaxy cluster, curves the surrounding space so heavily that light is distorted as if in a lens. The image of a galaxy hidden behind such a cluster is then bowed to form a circular arc (Figure 1.3). The mass of the dark matter and its spatial distribution can be determined from these images with the aid of models.

Recent research results come to the conclusion that the remaining cosmic energy density is a form of vacuum energy (corresponding to the cosmological constant of Einstein's Theory of Relativity). This has played a decisive role in the development of the universe. The presence of this mysterious dark energy leads to an accelerated expansion of the universe. While models exist that may clarify the nature of dark matter from the perspective of elementary particle physics, the existence of dark energy comes as a complete surprise. Understanding this type of matter will ultimately lead to

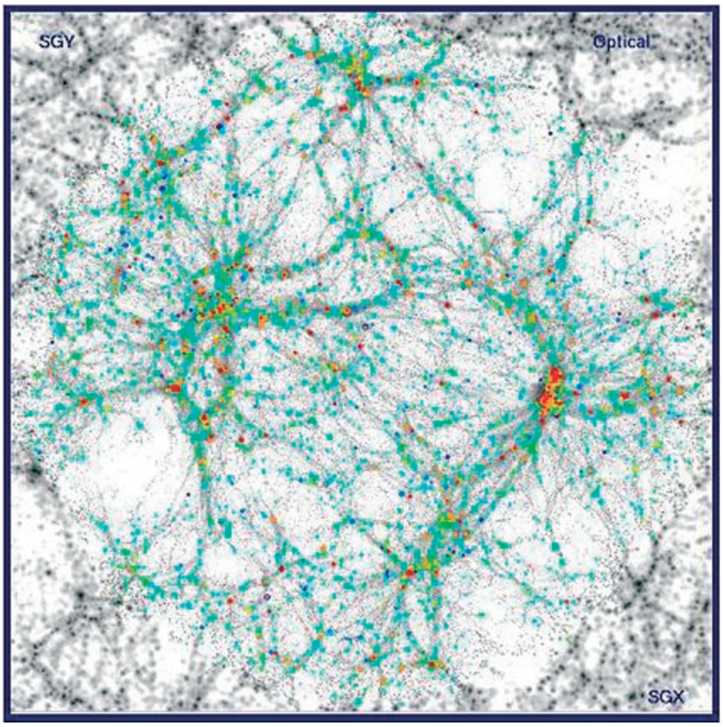

Fig. 1.2: The most powerful computers in the world are required to model the creation of galaxies and galaxy clusters from the primordial gas. The coloured points represent various galaxy types, shown by the colour of their star populations, while the grey background reveals the dark matter. Elliptical galaxies with red, older star components are generally created in galaxy clusters, while in the filaments, spiral galaxies with luminous, young blue stars are primarily formed. (MPA)

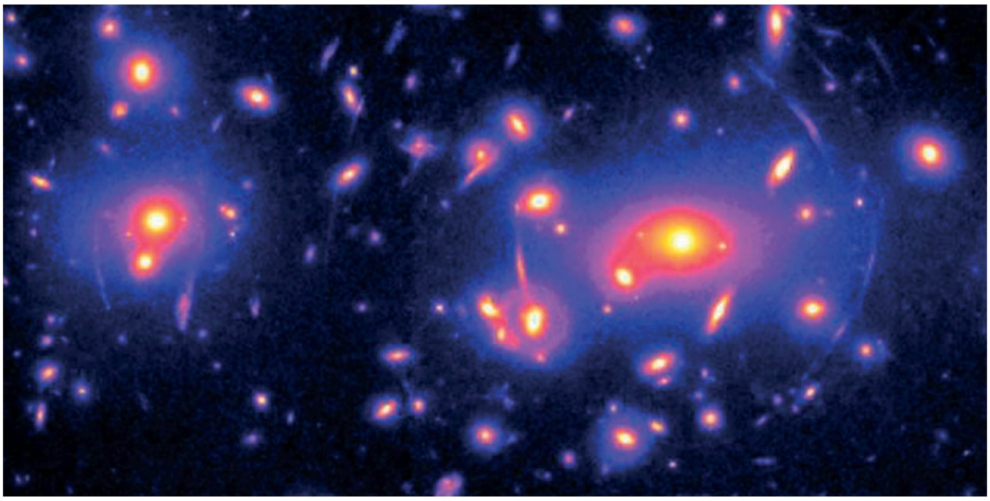

Fig. 1.3: The entire matter in a galaxy cluster acts as a gravitational lens and distorts the image of far-distant galaxies to a circular arc. (ESO)

new, fundamental insights into the microphysics and origin of matter.

The first galaxies and quasars

The first galaxies formed from overdensities (i.e., condensation seeds) in the primordial gas. When exactly this era began and precisely which processes played a role are crucial questions posed by modern research. It is highly probable that the quasars came into being at the same time as the galaxies. They form in extremely compact and luminous central regions of galaxies. As far as we know today, a black hole of several billion solar masses is located at the centre of every quasar. Black holes attract gas and stars in their neighbourhood and devour the matter they contain. During this process, also known as accretion, up to ten thousand times more energy is released in a region the size of our solar system than is radiated by all the stars in the Milky Way thus allowing quasars to be identified at very great distances. The record holders for the most distant objects are quasars that we see as they were when the universe was less than a billion years old.

Quasars have been recently found to play a more important role during the early phase of the universe than was previously suspected. For example, using the German-developed ROSAT X-ray space telescope, astrophysicists discovered that the X-ray background radiation, first identified around 40 years ago, originates from innumerable quasars at early stages of the universe. In 2002, Riccardo Giacconi was awarded the Nobel Prize for Physics due to his pioneering work on the construction of the first X-ray telescopes. These opened the window to the field of X-ray astronomy and to the discovery of background X-ray radiation and its sources.

The existence of massive black holes in the centres of very many, perhaps even all, galaxies is now regarded as fact. The 1990s saw the introduction of an abundance of new data. One important contribution comprises the measurements carried out by German astronomers of the movements of stars within just a few light days of the centre of the Milky Way.

For the first time it was possible to observe with high precision a complete orbit of a star circling the central black hole. The high velocity of this star indicates a dark, central concentration of mass. It is highly probable that this is a black hole of approximately three million solar masses. It has only recently been discovered that the mass of central black holes correlates very well to the velocities of the stars in the mother galaxies. This is indicative of a common creation process for both the black hole and its surrounding galaxy.

The decisive breakthrough, in the search for the most distant and therefore youngest galaxies and quasars, has only been made during the last five years by combining the capabilities of the 10 m Keck telescope and the Hubble Space Telescope. German research groups are now in a position to contribute to this field of research, thanks to the *Very Large Telescope* (VLT) at the European Southern Observatory (ESO).

Formation of galaxies and massive black holes

The most recent data indicates that the early history of young galaxies must have been very turbulent. Observations made using the European Infrared Space Observatory (ISO) verify that the creation of new stars must have been quite explosive in many young galaxies.

The galaxies were also closer together than they are today. Galaxies often collided and merged with one another. Observations of nearby galaxies have shown that these collisions initiated vigorous phases of star production. Massive black holes, observed in many galactic centres, may have also formed during this phase and subsequently been fed by the gases they attract.

Great expectations are linked to observations in the infrared to millimetre range which may facilitate our understanding of the formation and early development of galaxies. For example, the German-American airborne observatory SOFIA *(Stratospheric Observatory for Infrared Astronomy)* is expected to start operations in 2005. The European space telescope Herschel will also create a new benchmark for observations in the submillimetre range. The launch is planned for 2007. From 2010 onwards, even the most remote galaxies will be spatially resolved, and their structures and dynamics studied using ALMA, the interna-tional millimetre and submillimetre interferometer in Chile. Finally, the joint NASA and ESA *James Webb Space Telescope* (JWST) (also from 2009/2010) will be in a position to carry out highly sensitive observations of the first galaxies in the near and mid-infrared.

Active galaxies

Black holes not only played a role in the creation of the galaxies. They are also the root cause of the activity of galactic nuclei. During the past two decades it has been possible to describe the initially very large number of different types of active galaxies using one and the same physical model. This tells us that there is a massive black hole drawing in matter from its surroundings at the centre of every galaxy. Matter first orbits the hole and forms a disk that increases in temperature towards the centre; finally, it falls into the black hole. At this stage the hot gases radiate primarily in the X-ray and UV ranges, as well as emitting visible light.

In many cases, two gas jets are ejected in opposite directions into space at almost light speed and perpendicular to the plane of the disk. The front edges culminate in giant plasma bubbles. They emit bundled radio, gamma, and X-ray radiation. German researchers have contributed substantially to the investigation of these jets and accretionary disks both in theory and in practical observations. For example, it was the Effelsberg radio telescope, a central element of the intercontinental radio interferometric network, that made possible a spatial resolution of these jets up to a few light years distance from black holes. During the last few years gamma ray astronomers have discovered that these jets are also the sources of high-energy photons, whose origin is still not completely clear. In the future, these processes will be studied using special telescopes, such as H.E.S.S. and MAGIC, to identify high-energy photons in the gamma wave range.

1.2 The life cycle of stars and the matter cycle

The Milky Way

Our solar system forms part of the Milky Way, a spiral galaxy with a diameter of around 100,000 light years. Studies of our galaxy, its creation and development, represent one of the primary responsibilities of astrophysics. The essential areas of this field include calibration of the absolute distance scale and identification of the fundamental physical stellar parameters.

Astrometry – calibration of the distance scale and the stellar parameters

Hipparcos, the European astrometric satellite, which finally started in 1989 with the active participation of German astronomers, provided essential contributions in this field. It pinpointed the positions and intrinsic movements of more than 100,000 stars with a precision of up to 0.001 arc seconds. This enables the distances of stars within several thousand light years of us to be determined very precisely. In addition, more than a million stars were astrometrically surveyed with lower precision and their luminosities and colours were determined. Among other advantages, these measurements are critical for determining the distance scale. The precision achieved by Hipparcos will be substantially improved by GAIA, a future follow-up mission.

From interstellar clouds to protostars

The second component after stars is the interstellar medium (i.e., the gas and dust between the stars). New stars are still created today within the interstellar medium. Here gas condenses to form large clouds of up to one million solar masses. Smaller parts of these clouds can collapse under their own gravity and, in the course of this collapse, flatten to rapidly rotating protostellar disks. The matter at the centre of these disks then condenses to form stars.

Protostars identified

One of the problems that arise when studying the initial phase of the creation of stars is that it takes place hidden inside dense clouds. These clouds only becomes translucent at longer wavelengths that include the far infrared, submillimetre, millimetre and radio ranges. Using the German-French-Spanish millimetre-range observatory IRAM and the ISO satellite, it was possible for the first time to detect protostars, the extremely cold and dense zones in the interior of dust clouds. These "star cradles" will be studied in detail in the future using observatories such as SOFIA, Herschel and ALMA.

Protoplanetary disks

One very important advance was the first identification of protostellar dust disks using the IRAM telescope and the Hubble Space Telescope (Figure 1.4). These young stars are now in a similar phase to our sun 4.6 billion years ago. Further research must clarify how these disks formed and under what conditions planets were created within them. To pursue these questions, observations over all wavelength ranges, measurements from a variety of astrophysical laboratories, and numerical simulations are necessary. Infrared interferometry, which is to be carried out using the *Very Large Telescope* (VLT), the *Large Binocular Telescope* (LBT) and DARWIN, a European satellite project, will be of particular importance for future research of stellar and planetary genesis. Using the *James Webb Space Telescope* (JWST) it will be possible for the first time to resolve and optically observe young solar systems.

Jets from young stars

In the mid-1980s, it was also surprisingly realised that many young stars eject tightly bundled particle beams into space and perpendicular to the disk plane (Figure 1.5). These jets are similar in their morphology to the relativistic particle beams observed in active galaxies (see above), but are only up to ten light years long and have much slower particles. The details of their genesis remain unclear. The cause and energy source may lie within the accretion disk surrounding these young stars, similar to the gas jets of active galaxies. Another subject of current research is the question of how the approximately

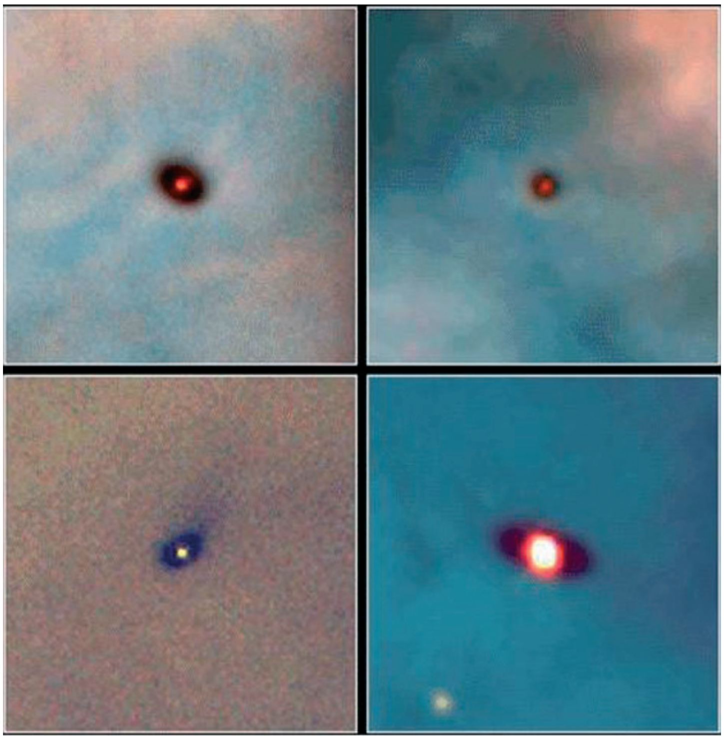

Fig. 1.4: Dark dust disks around young stars, discovered by the Hubble Space Telescope, made visible by absorption of the radiation from the lighter background. (NASA/ESA/MPIA/AIP)

ten-thousand year long jet phase affects the development of the star and the disk.

Extrasolar planets

The pioneering discovery in 1995 of planets orbiting nearby stars opened up a whole new field of astronomical research. More than a hundred of these extrasolar planets were known by early 2003. Currently, almost all of these bodies can only be indirectly detected by way of the gravitational effects on their stars. One of our foremost aims is to directly observe these objects within the next 10 to 15 years using imaging and astrometric techniques. The direct detection of massive, Jovian, extrasolar planets and the spectroscopic investigation of their atmospheres could soon be possible thanks to the improved adaptive optics on new large telescopes. Advances are also expected from GAIA, the astrometric space telescope.

Only planets at least as massive as Saturn can be detected using today's resources. Detection of earth-like planets and the identification of their chemical properties would represent

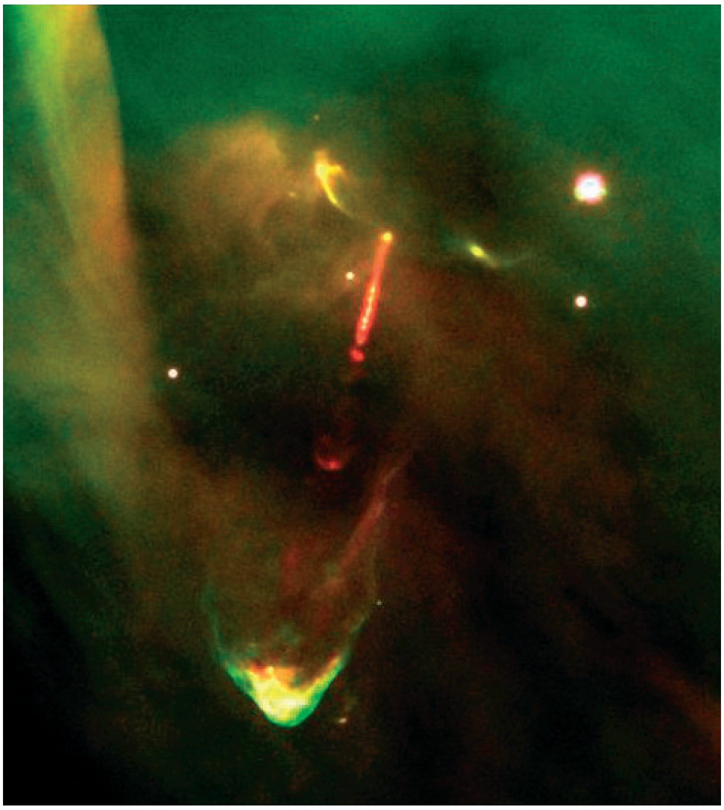

Fig. 1.5: A jet is emitted from a young star in the star formation region in Orion and ends in a frontal wave. (ESO/LSW Heidelberg)

an enormous move forwards. Extremely precise photometric methods (observations of occultation of the star by the planet) and direct imaging techniques (infrared or optical interferometry) using space observatories are necessary to achieve this very demanding objective. The requisite instruments, such as DARWIN, are currently being planned by researchers in Europe and the USA.

Our solar system as a model

At this point it is worth mentioning solar system research, which is, however, not the subject of this memorandum. A profusion of what are presumably generic characteristics of planetary genesis can be derived from new discoveries made in the field of cosmochemistry, in terms of the chemical and physical properties of "primordial matter" in our solar system. This information can be useful when searching for extrasolar planets. It is also necessary in order to understand whether or not our solar system is typical or occupies a special position among the planetary systems. Researchers at German institutes have also made vital contributions in this field over the last 15 years. These include a theoretical link between the development of protostellar disks and measured cosmochemical variables, and the dating of primitive meteorites. Direct analyses of the composition of cometary material by the ESA probe Giotto was, without question, one of the highlights.

Final stages of stellar development

A star is illuminated by the nuclear reactions within its interior, which thereby release energy. It remains stable until it has consumed a considerable amount of its fuel reserves. The way in which it ends its existence depends on its mass. Our sun will expand to a red giant in about five billion years and then eject its outer gas shell. It then collapses to form a white dwarf the size of the Earth. The temperature increases to several ten-thousands of degrees and illuminates the previously ejected gas shell. These shells, known as planetary nebulae, are observed in numerous forms throughout the Milky Way and nearby galaxies (Figure 1.6).

Neutron stars and pulsars

Very massive stars, around 8 to 30 times more massive than the sun, first expand to supergiants and lose a great deal of their matter, before they explode as supernovae. While the outer shell is ejected, the innermost region of the star collapses upon itself forming a neutron star with a diameter of only around 20 kilometres. Neutron stars are objects with fascinating properties. The temperature of a young neutron star is approximately 100,000 degrees, as demonstrated by ROSAT. In the interior, matter is as heavily compressed as in an atomic nucleus. A piece of this matter the size of a sugar cube would weigh ten billion tonnes on Earth.

If a star collapses to form a neutron star, it also rotates extremely fast around its own axis. The neutron star in the Crab Nebula (Figure 1.7), for example, rotates around its axis 33 times per second. At the same time, the magnetic field at the surface becomes enormously dense and is finally a trillion times stronger than Earth's magnetic field. Electrically charged particles are accelerated almost to light speed along the axis of the magnetic field and discharged into space. They emit (synchrotron) radiation in the direction of discharge and the particle swarm generates two cones of light, which project into space from the magnetic north and south poles respectively. This radiation encompasses the radio range up to the highest gamma energies

In many neutron stars the axis of the magnetic field is inclined with regard to the axis of rotation. This causes the two

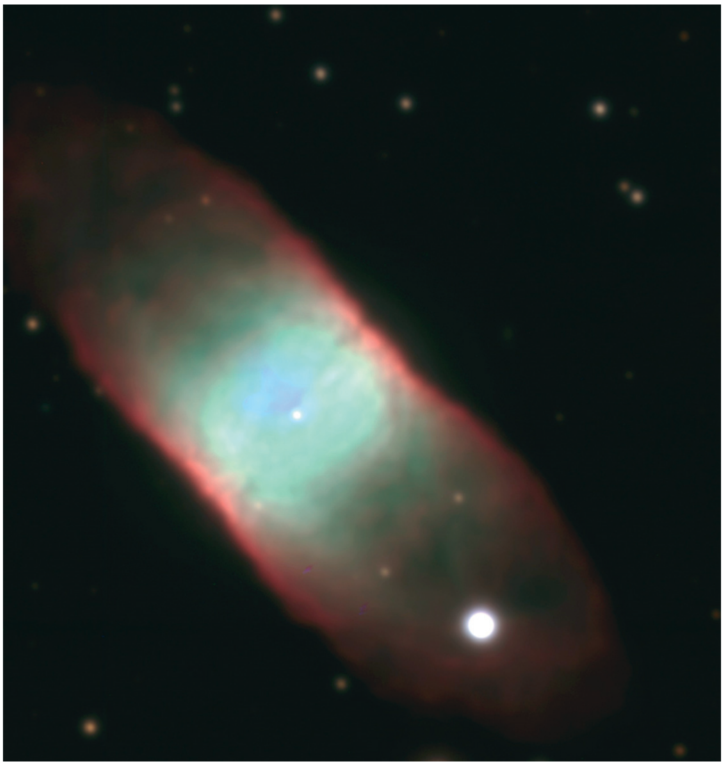

Fig. 1.6: The brightest planetary nebula in the northern sky: the Dumbbell Nebula, 650 light years away. (ESO)

light cones to rotate through space. If they by chance pass over the Earth, they can be detected by their lighthouse-like flashing pulse. These flashing neutron stars are called pulsars.

Pulsars have also become important because they represent extremely precise "clocks" due to their practically constant pulse rate. The American astrophysicists Taylor and Hülse utilised this property to measure the mutual orbits of two neutron stars. Over a number of years they realised that the orbital period was gradually slowing. It was possible to explain this effect by the emission of gravitation waves. Bodies lose energy in this way and slowly approach each other. The measured reduction corresponded to less than one percent, with the energy loss predicted by the General Theory of Relativity. The two researchers were awarded the Nobel Prize for Physics in 1993 for this first indirect proof of gravitational waves.

Stellar black holes

An extremely massive star with more than 30 solar masses can probably not avoid collapse. In theory, the burned out

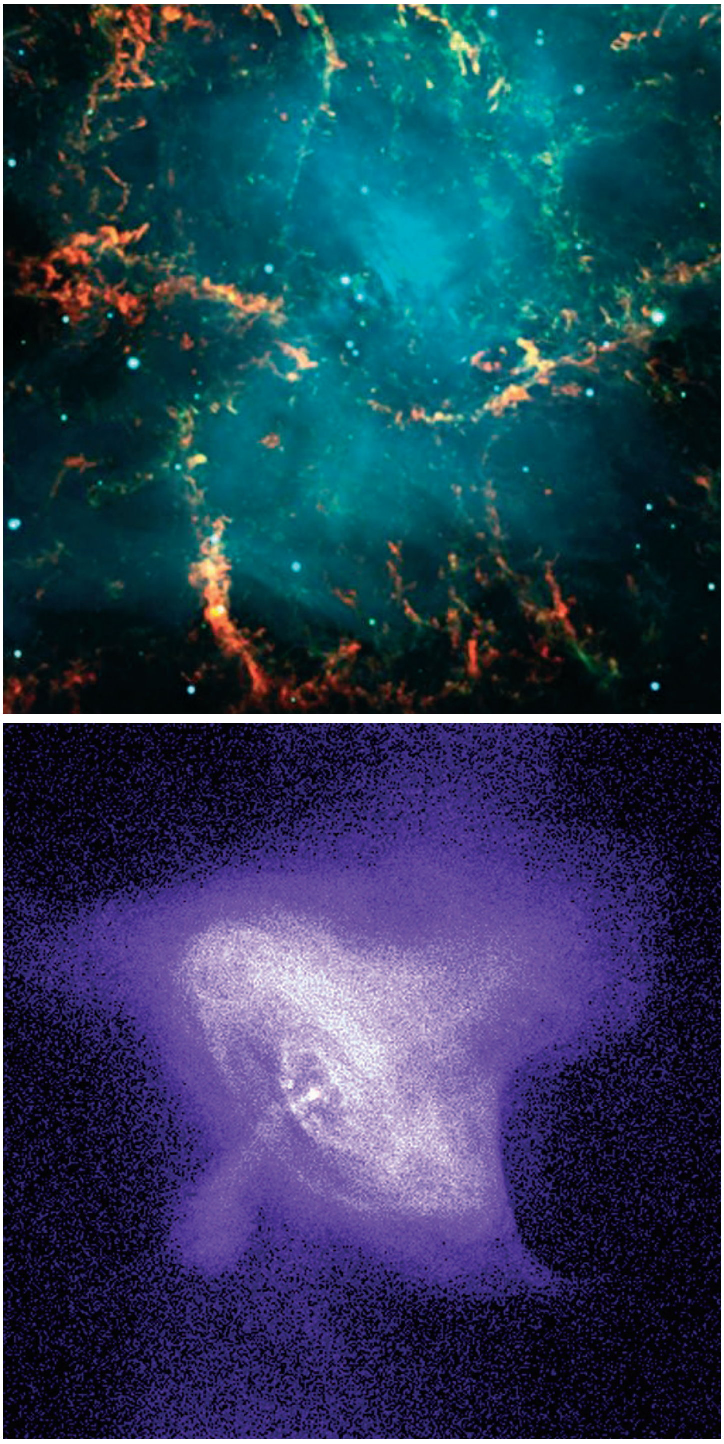

Fig. 1.7: The crab supernova remnant in the constellation Taurus. The supernova was observed by Asian astronomers in 1054. Top, image in the visible band (ESO), below, the X-ray image taken by Chandra (NASA/ CXC/ SAO), showing details of the inner, active region around the quickly rotating neutron star.

star collapses completely and disappears in a (stellar) black hole. The gravity is now so strong within a certain region that neither matter nor light can escape. The radius of this region in a black hole of eight solar masses, for example, is about 25 kilometres.

Black holes can only be detected indirectly due to the effects they have on their environment, as exemplified in double star systems, where two stars orbit one another in gravitationally mutual orbits. Astrophysicists today are aware of several systems in which one component is invisible and very massive, therefore probably being a black hole. X-ray observatories, such as the European XMM-Newton space telescope and future XEUS, are extremely important in this field. Interferometers on the VLT and LBT, currently under construction, will also provide more information on these mysterious heavenly bodies.

The matter cycle

In around five billion years from now, our sun will expand to form what is known as a red giant. Internal processes initiate an expansion of the outermost gas shell, simultaneously leading to its cooling and forcing the radiation peak into the long-wave, red range. A cycle, or matter "recycling," is associated with the birth and demise of the stars; stars are re-created from the interstellar medium. During their stable combustion phase they generate by nuclear fusion heavy elements in their interiors. As red giants or supernovae they then give back some of this processed matter to the surrounding interstellar gas, where it serves as the raw material for the next generation of stars. In this way the stars gradually enrich the interstellar medium and subsequent star populations with heavy elements.

Cosmic evolution of the elements

This process represents one of the prerequisites for the emergence of the planets and, ultimately, life itself. This is because, as far as we know today, only the light elements hydrogen and helium were created during the big bang. The diversity of chemical elements and all life on our planet is therefore a result of a cosmic chemical process that took place long before the Earth existed. Every carbon or oxygen atom in our bodies was generated billions of years ago in the interior of a star.

Supernova remnants

Understanding of these complex nucleosynthetic processes (i.e. the formation of heavy elements), is crucial and possible by observing planetary nebulae and the remnants of supernova explosions. The latter are generally extremely hot and must therefore be investigated in the X-ray range (or in the nonthermal radio or gamma ray range). Many new supernova explosive clouds have been discovered with the help of ROSAT. However, spectral investigations of the requisite sensitivity and resolution have only now been made possible thanks to the ESA XMM-Newton mission and the American X-ray observatory Chandra.

Supernova remnants are also seen as the principal source of high-energy charged particles, known as cosmic rays. They fill the entire Milky Way, and probably intergalactic space, and bombard the Earth constantly. They are considered one of the motors of the natural gene mutations that life is subjected to on our planet. The discovery and development of what is probably the most important process for the generation of cosmic rays is based on the research results acquired by German institutes.

The numerical simulations of supernovae also need to progress in parallel with observations. The explosive mechanism is still not completely understood. Neutrinos and chaotic mixing processes during detonation presumably play

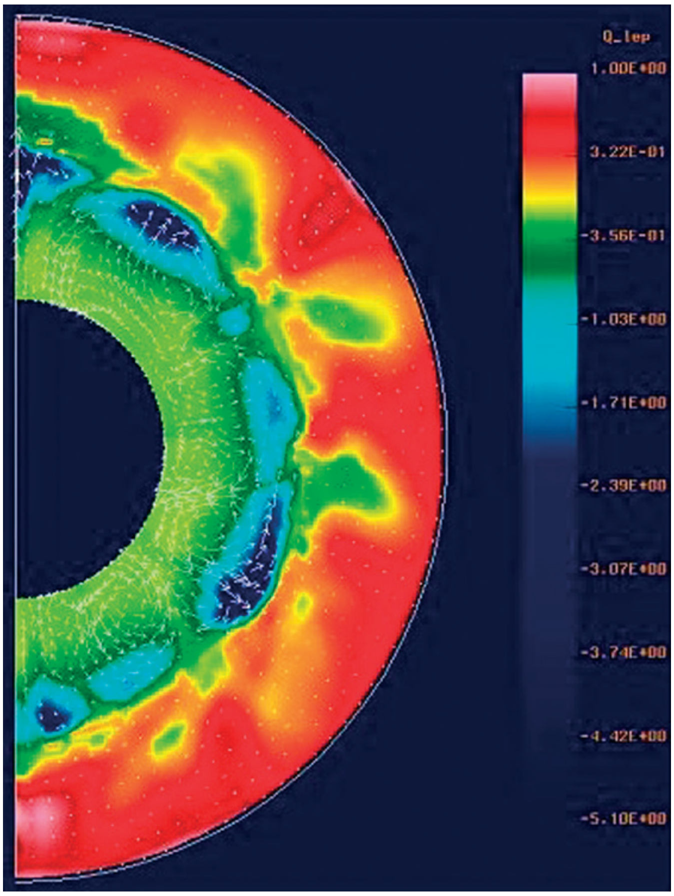

Fig. 1.8: The explosion of massive stars can be simulated on the computer. The turbulent mixing of matter can be seen: oxygen, blue; silicon, green; nickel, red. (MPA)

a decisive role. One of the objectives of such investigations is to identify the frequency with which the various chemical elements, up to and including uranium, are generated (Figure 1.8).

Our sun

Our nearest star is the sun. Due to its proximity, it allows plasma physics processes of fundamental astrophysical importance to be investigated with the necessary spatial resolution. The magnetic activity of the sun leads to fluctuations in its radiation and in the solar wind. They both influence satellites, communications systems and probably our climate. In past years, space telescopes such as SOHO and terrestrial telescopes such as the observatory on Tenerife have analysed the sun with increasing precision (Figure 1.9). One of the highlights of this research was the precise analysis of the inner structure of the sun with the help of the relatively new method of helioseismology. Huge advances have also been possible in high-resolution imaging and spectroscopy (plasmadiagnostics) of the solar atmosphere, including the corona, using instruments in the visible, ultraviolet and X-ray radiation ranges. Two highlights of German solar research include the precise identification of the sources of solar wind using SOHO and the discovery that the solar magnetic field has strengthened manifold, apace with global warming, since the Little Ice Age of the seventeenth century.

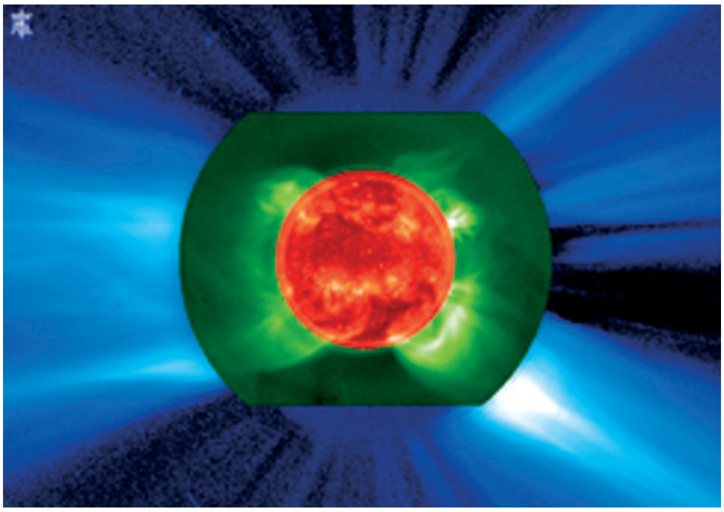

Fig. 1.9: Solar observations using various instruments on the SOHO satellite. This image shows areas of magnetic activity on the red surface of the sun, the hot solar corona (green) and the solar wind (blue). (ESA/NASA/MPAe)

Holistic studies of the sun and its atmosphere, extending into interplanetary space, will form a focal point of future research. This "holistic" view is the key to understanding magnetic activity and the influence of the sun on the Earth's climate. The necessary wavelength coverage and spatial and temporal resolution will be achieved by the next generation of telescopes, including GREGOR on Tenerife and the balloon-based SUNRISE, through possible participation in the American solar telescope project, ATST, and with the instruments on the ESA space probe SOLAR ORBITER.

1.3 New windows into space

Progress in astronomy and astrophysics has most often been associated with the development of new instruments, detectors and telescopes, both in terms of the increased performance of the instruments in the "classical" wavelength ranges and in opening up new fields. In addition, this often leads to very fruitful synergies with developments in totally different fields of physics and technology, such as semiconductor and laser physics, electronics and computer technology. Technological progress provides new information by achieving better spatial resolution and more detailed analyses of the spectrum of electromagnetic waves.

Pioneering work in opening new windows into space was recognised by the Nobel Prize for Physics in 2002. It was awarded jointly to Riccardo Giacconi (1962, 50%) for the discovery of cosmic X-ray radiation, Raymond Davis Jr. (1971, 25%) for the solution of the solar neutrino problem, and Masatoshi Koshiba (1987, 25%) for the discovery of the first astrophysical neutrinos from supernova 1987A. During the next 15 years, astrono-mers want to further open windows to the neutrino universe and also a new window to gravitational waves.

"Moore's Law" applied to the sensitivity of telescopes

For example, the sensitivity of radio telescopes has doubled on average every two to three years since the nineteen-thirties (Figure 1.10). This rapid development is easily comparable to Moore's (semiconductor) Law, stating that the storage capacity of chips doubles every 1½ years. Today's radio telescopes equipped with the newest receivers are around one hundred million times more sensitive than 50 years ago. More technical advances should lead to sensitivity increases of between 10 and 50 times within the next 10 to 15 years. These improvements, already demonstrable today, open up fantastic oppor-

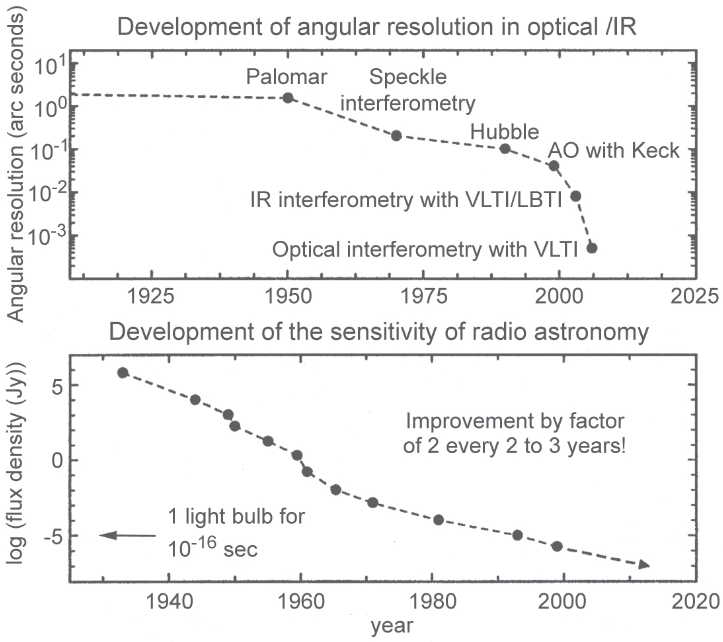

Fig. 1.10: Development of the measuring sensitivity in radio astronomy (bottom) and angular resolution (top) of telescopes in the infrared and visible light ranges. (MPIfR)

tunities for astronomy in the submillimetre and millimetre ranges. In the future, increases in the speed of digital signal processing will also set in motion a completely new class of digital radio telescope in the centimetre range.

Increase in angular resolution

Angular resolution (the capacity to discern two close objects as separate entities) has also improved considerably in the past (Figure 1.11). Here, radio astronomy occupies a special position inasmuch as the idea of coupling two or more antennas (synthetic aperture) had already been developed by the mid 1950s. From the end of the 1960s this resulted first in intercontinental interferometry and then in space-based interferometry, which was successfully demonstrated at the end of the 1990s. It allows an angular resolution of up to 50 millionths of an arc second, corresponding to a width of around 10 centimetres at the distance of the moon!

Optical and infrared interferometry: a promising field

Building interferometers in the infrared and visible light ranges is a much more difficult undertaking. Initial successes with the Keck Observatory in Hawaii and the Very Large Telescope at the European Southern Observatory, ESO, in Chile, promise great leaps in angular resolution in the near future.

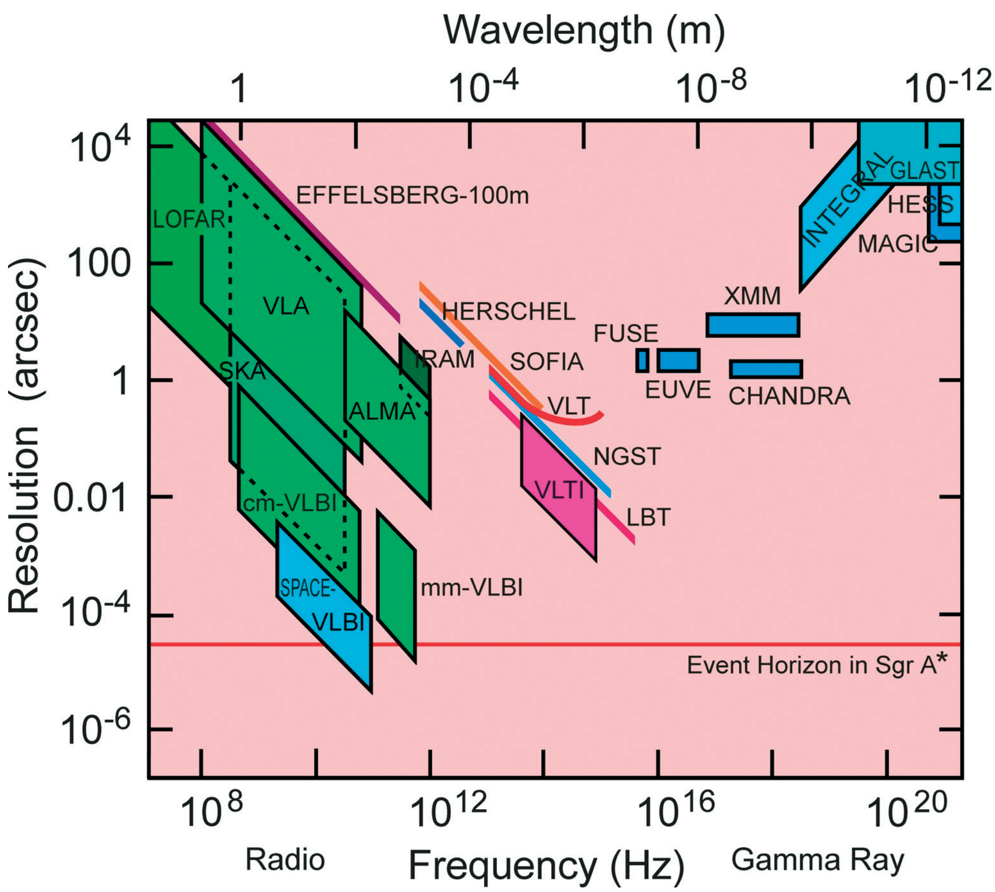

Fig. 1.11: The entire electromagnetic spectrum can be covered by modern telescopes. The angular resolution and sensitivity range of the most important instruments mentioned in this memorandum are shown here.

Adaptive optics

Adaptive optics technology plays a vital role in the implementation of these projects. It allows natural air turbulence, which leads to blurring in astronomical exposures, to be compensated for during observation. Adaptive optics, as also developed by German groups for Calar Alto and for Tenerife, operate very well in the infrared. However, in order to extend the technology into the visible light range, additional effort is still required. Interferometers, equipped with adaptive optics, will improve angular resolution more than one hundredfold in the coming 10 to 15 years. In other wavelengths, as well, new technologies and telescopes will lead to improvements in angular resolution.

Neutrino astrophysics

Neutrinos are elementary particles that only interact weakly with normal matter, making them very difficult to detect. They are created during nuclear fusion in the interiors of stars or in supernova explosions. These particles are therefore very important to astrophysics, because they contain unique information on the processes discussed here and allow us, for example, to take a look into the interiors of stars, a view that would otherwise remain hidden.

Solar neutrinos

Since the end of the 1960s, several experiments have been carried out in an attempt to locate solar neutrinos. The detection of solar neutrinos and the discovery of neutrinos from supernova 1987A were honoured with shares of the 2002 Nobel Prize for Physics. At the beginning of the 1990s several experiments, including the German-led GALLEX, caused sensations when they managed to detect neutrinos in the main branch of the hydrogen fusion cycle. Strictly speaking, it was the first direct evidence that the sun – and therefore all other stars – generates its energy by nuclear fusion. However, the detectors registered significantly fewer neutrinos than theory had led us to expect, which was explained by the fact that neutrinos possess an at-rest mass. This contradicts the standard particle physics model, which states that neutrinos are massless. These observations are merely one example of the many interactions of astrophysics with other sub-disciplines of physics.

Neutrino research in ice

Another success was the detection of a dozen neutrinos from supernova 1987A, located in the Large Magellanic Cloud. Here, the Japanese detector Super-Kamiokande enjoyed particular success. Encouraged by these initial successes, new "neutrino observatories" were planned and built. The most progress so far has been made by the AMANDA project, in which German researchers play a decisive role. Light-sensitive detectors are sunken into the ice near the Amundsen-Scott Station at the south pole. Similar to Super-Kamiokande, they register energetic neutrinos, which emit Cherenkov radiation inside the detector. Researchers hope to actually detect neutrinos from supernovae or from the centres of distant galaxies using AMANDA. Even higher sensitivity will be achieved by the international follow-up experiment IceCube; similar to AMANDA, it will be built below the south polar station.

Gravitation waves

Astrophysicists around the world broke new technological and scientific ground with the construction of gravitational wave detectors. They will make it possible to directly detect temporally variable ripples in space, as predicted by the General

Theory of Relativity. The challenge lies in the fact that the expected change in spacing amounts to a mere tiny fraction of an atomic nucleus. It is hoped to detect this by using laser interferometers. These instruments have been made possible by advances in the field of laser and precision metrology. German researchers are in charge of the construction of the GEO600 interferometer near Hanover in northern Germany.

Proof of this phenomenon would represent a further brilliant confirmation of Einstein's General Theory of Relativity. On the other hand, the waves would provide information on the most energetic processes in the cosmos. These include supernovae, binary star systems following close orbits, colliding and merging neutron stars, and black holes. It is even hoped to obtain gravitation signals from the big bang in the long term. But this will require laser interferometers in space, such as LISA, as currently planned by ESA and NASA.

Advances in numerical astrophysics

Besides classical theoretical astrophysics, during the last few years numerical simulations have become an important aid for describing complex phenomena in our universe. The performance of computers has increased to the same degree that telescopes and detectors have advanced. During the last 15 years the speed of computers has increased by a factor of around one thousand. In conjunction with the development of increasingly efficient algorithms and the use of specific hardware components, this has resulted in enormous advances in numerical simulations for many astrophysical processes. These include the genesis of stars and planets in dust clouds, supernovae explosions, the genesis of galaxy clusters, or the processes in the disks around black holes, to name but a few examples.

Realistic results are only obtained from numerical simulations if, on one hand, as many physical processes as possible are taken into consideration and, on the other, good spatial and temporal resolution is achieved. In order to interpret the ever more detailed observation data, increasingly powerful computers must be employed and the numerical methods must be continuously improved.

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Box 1.1: Multi-wavelength ground- and space-based astronomy

The use of telescopes in all wavelength ranges, from radio to gamma waves, which correspond to ten to the power of minus 15, is increasingly important to modern observational astronomy. There are a number of objects whose nature only becomes obvious when seen in all wavelengths, active galaxies being one very good example. Analysis and interpretation of the data requires increasingly complex software, which will be made available to all users within the framework of the "Virtual Observatory" project.

Since the beginning of the 1980s, multi-wavelength astronomy has been subject to rapid development and German groups have played a leading role (Figure 1.11). The German-French-Spanish institute IRAM (Institute for Radio Astronomy in the Millimetre Range) has provided German researchers with access to the world's best telescopes in the millimetre wavelength range for more than 10 years. During the 1990s the European Space Agency's (ESA) *Infrared Space Observatory* (ISO) represented a further highlight. It was the world's most successful infrared mission of the 1990s. German institutes and industry were crucially involved in building the detector, contributing to the astronomical yield and to the data archive.

The X-ray space telescope ROSAT was also a great success. It carried out the first complete survey of the sky using an imaging X-ray telescope and discovered more than 100,000 individual sources. To date, approximately 5,000 scientific publications have been made based on ROSAT data. This makes this telescope almost as successful, in terms of data yield, as the Hubble space telescope. In the meantime, the follow-up missions XMM-Newton and CHANDRA provide considerably more detailed information on the X-ray universe. A milestone of gamma ray astronomy was NASA's *Compton Gamma Ray Observatory* (CGRO). It carried four scientific instruments, one of them designed under German leadership. Compton allowed the observation of particularly hot heavenly bodies such as neutron stars or supernovae explosion clouds with previously unachievable sensitivity.