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Astronomical technology – the past and the future

Karl Schwarzschild Award Lecture 2015

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The past fifty years have been an epoch of impressive progress in the field of astronomical technology. Practically all the technical tools, which we use today, have been developed during that time span. While the first half of this period has been dominated by advances in the detector technologies, during the past two decades innovative telescope concepts have been developed for practically all wavelength ranges where astronomical observations are possible. Further important advances can be expected in the next few decades. Based on the experience of the past, some of the main sources of technological progress can be identified.

1 Introduction

The topic of this lecture has been chosen for the following reasons: Firstly, technology is extremely important in astronomy. New scientific results quite often result directly from technical advances. Innovative technologies have also been among my personal research interests. Finally, this topic is rather appropriate for a Karl Schwarzschild lecture, as Schwarzschild, apart from his fundamental work in astrophysics, contributed much to the astronomical technology of his time, in particular in the fields photographic photometry, the understanding of the photographic process, new observational techniques, telescope optics, and even interferometry. A testimony to Schwarzschild's awareness of the important role of technology is a lecture on "Präzisionstechnik und wissenschaftliche Forschung" (Precision Technology and Scientific Research), which he presented in 1914 at the annual meeting of the German Society for Mechanics and Optics (Schwarzschild 1914). In this talk he stated that "precision technology is the basis of measuring in time and space, and on measuring depends, together with the sciences, a major part of our whole culture"[1].

For this lecture I will not go back to the time of Karl Schwarzschild. Instead, I will concentrate on the past fifty years, as this is the time span where practically all the tools have been developed, which we use today. It is also the period which I could follow personally. Because of the scale and diversity of astronomical technologies, this report cannot be complete. The emphasis will be on evolutionary landmarks, and there will be a bias towards optical astronomy. To provide an idea of the situation fifty years ago, I will start with a recollections of my own first encounter with astronomy and astronomical technology.

2 Becoming an astronomer in the 1960s

I got involved in astronomy almost by chance while studying physics. In the 1960s nuclear physics was most fashionable. Therefore, after obtaining a degree of "Vordiplom" at the University of Tübingen in 1961, I moved to Göttingen in order to do a diploma thesis in the nuclear physics group of Arnold Flammersfeld. Unfortunately – or, in hindsight, I would say fortunately – too many of my fellow students had the same idea. All diploma positions at Flammersfeld's institute were filled, and there was a waiting period of several months. Looking for alternatives, I found that in astrophysics one could start a thesis immediately. Thus, instead of working in Flammersfeld's accelerator lab, I ended up in Göttingen's historic astronomical observatory, where Carl Friedrich Gauß and Karl Schwarzschild once had worked.

The topic of my thesis was a study of the the local interstellar magnetic field by measuring the interstellar polarization of starlight. My adviser was Alfred Behr (1913–2008), who was known for work on astronomical instrumentation, polarimetry, and cosmology. For my observations I was using the historic 34-cm Hainberg refractor at the outskirts of Göttingen and a polarimeter which Behr had built, and which at the beginning of the 1960s was the most accurate instrument of its kind. It could measure stellar linear polarization down to about 10^{-4}. I used Behr's instrument without changes, but I replaced the mechanical calculators,

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[1] "Die Präzisionstechnik ist ja die Grundlage aller Kunst des Messens in Zeit und Raum, und an Maß und Messen hängt mit der Wissenschaft zugleich ein großer Teil unserer ganzen Kultur."

Fig. 1 Aerial view of Yerkes Observatory. (Image credit: University of Chicago Photographic Archive, Special Collections Research Center, University of Chicago Library).

which at that time were used for the data eduction, by a computer program. This made it possible to include additional terms in the reduction algorithm, which further increased the accuracy and reliability of the results. The computer, an IBM 650, was owned by one of the local Max Planck Institutes, but was available to university staff when not used by the MPI. It was still based on vacuum tubes and (compared to modern hardware) it was incredibly slow. But it was much faster and very much more convenient than mechanical calculators.

Thanks to Behr's excellent instrument the observations produced interesting data. But due to the often overcast sky of Göttingen, progress was slow. (According to our national meteorological service, of all stations with long-term records, Göttingen is one of the three places with the lowest percentage of clear sky hours in Germany). After watching the clouds above Göttingen for about a year, I started looking for possibilities to move Behr's polarimeter temporarily to a better location, and I received a positive response from the Haute Provence Observatory in Southern France. Behr, my boss, was in the US at that time. So I wrote him a letter explaining my plans. He replied that he had an even better idea: He had met William Albert Hiltner (1914–1991) who had been one of the discoverers of the interstellar polarization, and who at that time was the director of the Yerkes Observatory of the University of Chicago. Hiltner had just installed a new telescope dedicated specifically for polarimetric observations, and he was looking for somebody helping him to get the new instrument to work. In compensation for functional work for his institute, Hiltner offered me a temporary technical position and all the observing time I would need to complete my program. Thus, thanks to the clouds of the Göttingen sky I got the chance to join – already as a student – one of the major astronomy departments in the US. As I learned later, one reason for Hiltner's generous offer was that Behr had told him about my computer program. Obviously, as soon as astronomers started using computers, instrument-related software became a valuable asset.

In the early 1960s, Yerkes Observatory (Fig. 1) was still the home of the complete astronomy department of the University of Chicago. The observatory has been named for the rich Chicago businessman Charles Yerkes (1837–1905), who had a criminal past and a rather poor reputation. (More about the interesting CV of Mr. Yerkes can be found in a history blog by Bruce Ware Allen, http://ahistoryblog.com/2012/08/). It was another Chicago citizen, George Ellery Hale (1868–1938), who converted the poor reputation of Mr. Yerkes into a windfall for science. Hale, the first professor of astronomy at the University of Chicago, convinced Mr. Yerkes that he could improve his reputation by financing an astronomical observatory for the just founded university. Yerkes agreed and told Hale to "build the largest and best telescope in the world, and send the bill to me". Hale did both, with enthusiasm. When the observatory opened in 1897, it included the famous 40-inch refractor which is still the world's largest lens telescope.[2] Hale later moved to California, where he founded Mount Wilson Observatory with a 60-inch reflector, to which he later added the 100-inch Hooker Telescope. With these instruments completed, he initiated the construction of the 200-inch Mount Palomar telescope, but he died ten years before that telescope could be completed. At the time of their commissioning, all these telescopes were the largest functioning instruments in the world. Hale also founded or initiated the Astrophysical Journal, the American Astronomical Society, the US National Research Council, and many other important organizations. He was arguably the personality most responsible for the pre-eminence of the US in astronomy during the following decades.

During much of the 20th century, Yerkes Observatory remained an important center of astronomical research. While Otto Struve was its director or department chair between 1932 and 1950, he managed to attract outstanding scientist from all over the world to Yerkes. Many of the staff members of that time later held leading positions in the US and European astronomy, and some played decisive roles in the development of modern astronomical techniques. By the time when I joined the institute in summer 1964, Yerkes Observatory had already passed its apogee, but its staff still included first-class scientists such as Subrahmanyan Chandrasekhar, W. W. Morgan, and W. A. Hiltner. And Yerkes was still connected with the McDonald Observatory in West Texas which belonged to the University of Texas, but which was founded by Otto Struve and initially operated by Yerkes staff until the University of Texas could establish an astronomy department of its own.

Hiltner's new polarimeter followed the same principle as Behr's instrument in Göttingen. In both cases, a Wollaston prism was used to split the incoming light into two perpendicularly polarized beams which were directed to two photomultiplier tubes (PMTs). The amount and position angle of the linear polarization of the incident light was de-

[2] A detailed account of the beginning and the remarkable history of Yerkes Observatory has been given by Donald Osterbrock (1997).

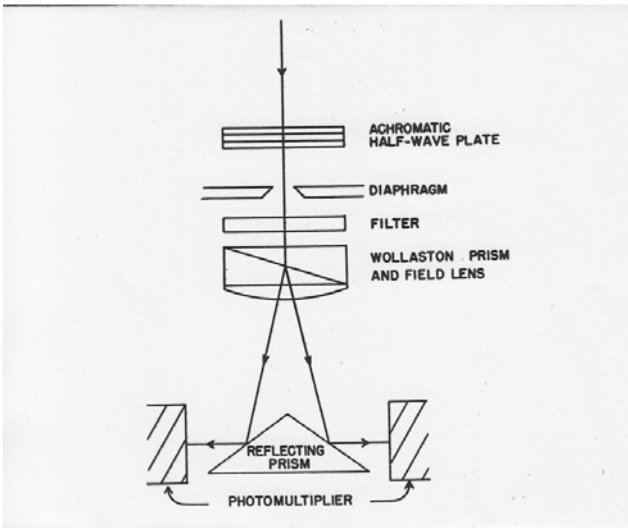

Fig. 2 Optical layout of the half-wave-plate polarimeter built for Yerkes Observatory. Details see Appenzeller (1967).

rived by rotating the Wollaston prism together with the detectors (in steps) around the optical axis. For linearly polarized light, this results in a periodic variation of the difference (and ratio) of the two output beams. Fourier-analyzing this difference signal gave the amount and position angle of the polarization. In Göttingen the polarimeter was rotated behind the telescope. In this case the measured polarization is a superposition of the stellar polarization and any polarization produced by the telescope optics. Unfortunately, telescopes tend to produce instrumental polarization, which often is variable. Therefore, at Yerkes the the polarimeter was rigidly attached to the telescope and the whole telescope tube, including the optics, was rotated together with the polarimeter. In this case, the instrumental polarization produces a constant intensity difference between the two beams only, which does not affect on the measured polarization. Together with a similar telescope which was installed at the Siding Spring Observatory in Australia, the Yerkes instrument was used to set up a system of polarimetric standard stars with well established polarization parameters that were free of instrumental polarization.

A disadvantage of Hiltner's new instrument was that the rotation of the telescope and the need to re-center the target at each rotation step resulted in a relatively low ratio between the on-target integration time and the total time required for each observation. In order to reduce the overhead, I suggested to Hiltner to keep the telescope and polarimeter fixed and to rotate the plane of vibration of the incident polarized light. As described in the textbooks of optics, this can be done by means of a half-wave plate. For broad-band applications an achromatic half-wave plate is required, which can be constructed by combining three normal wave plates with different orientations of their optic axes, as had been shown by the Indian optician Shivaramakrishnan Pancharatnam (1955). Hiltner liked the idea and asked me whether I could build a half-wave-plate polarimeter for his institute. That request was the beginning of my career in building astronomical instruments.

Being still a student at Göttingen, I could not start the new instrument immediately, as I first had to go back to Germany for about a year to finish my studies. But in the spring of 1966 I was back in Chicago and started constructing the half-wave-plate polarimeter (Fig. 2).

During the year in Göttingen, I visited the 1965 fall meeting of the Astronomische Gesellschaft in Eisenach, Thüringen, where I gave my first (short) talk at an AG meeting. That meeting took place almost exactly 50 years ago. Thus, for me the talk today, is, in a sense, a semi-centennial. With this remark I conclude the personal part of this talk, passing on now to a more general overview of the last fifty years.

3 The 1960s: Big discoveries, small technical advances

Scientifically, the period 1960–1969 was an exceptionally exciting time. During that decade probably more new types of astronomical objects were discovered than in any ten-year period before or after. Up until 1960 astronomy was essentially restricted to studies of the solar system, the stars, galaxies (including our own), and the interstellar matter. The existence of dark matter had already been shown, but was largely ignored. By 1970 we knew more than twice as many types of astronomical sources. Among the newly discovered species were the stellar X-ray sources (found in 1962), the quasars (1963), the pulsars (1967), the cosmic microwave background (1965), and the gamma-ray bursters (first observed in 1967). Moreover, during that decade the first FUV radiation, X-rays, and γ-rays from the Milky Way and from other galaxies were recorded (1967, 1968), and man landed on the Moon (1969). These discoveries greatly influenced astronomy, but most were based on conventional technologies. The landmark spectroscopic observations still used photographic plates. The X-ray observations were made with old-fashioned Geiger counters, and the CMB was discovered with an antenna that had been built years earlier for communication purposes.

There was some progress in the detector field. For the first time image intensifier tubes were used with photographic plates, and Frank Low (1933–2009), who worked at Texas Instruments at that time, invented the germanium bolometer (Low 1961), which was much more sensitive and covered a much broader wavelength range than earlier IR detectors. Starting 1965, he used his new detector to carry out the first infrared observations from above the atmospheric H_2O (first on a military airplane operated by the US Navy, then with a Lear Jet of NASA), setting the stage for the later Kuiper and SOFIA stratospheric observatories (see, e.g., Aumann, Gillespie & Low 1969). First steps towards space astronomy were the launches of the solar observatories OSO 1 to 6, and the UV satellite OAO 2 which included UV-sensitive TV cameras and PMT-based UV-band photometers. Among the results of OSO 3 was the first detection of γ-photons from space.

An important step for optical photometry was the introduction of photon counting with photomultipliers. Counting individual visual-light photons was, in principle, possible since photomultipliers had been invented. The internal amplification of the PMTs (of the order 10^7) produces charge pulses that could be individually detected, even with the noisy vacuum-tube electronics of the 1960s. Photon counting was well known to give the maximal attainable photometric accuracy, limited only by the statistical variation of the number of photons received per unit of time. Several astronomers, including Hiltner, had been experimenting with the photon-counting technique in the 1950s, but had given up because of non-linearities. While all counting methods become nonlinear due to dead-time effects at some rate, in the case of photomultipliers nonlinearities connected with the peculiar pulse shape of PMTs set in already at relatively low light fluxes. Therefore, in the early 1960s photometry (and polarimetry) was done by measuring the DC current produced by PMTs. However, this results in an additional statistical error due to the varying charge multiplication factors of the individual photo electrons. Therefore, in the DC mode the *detective* quantum efficiency of PMTs is much lower than the *responsive* QE of the cathode.

Among the work which I did at Yerkes was the developing of an electronic circuit which avoided the nonlinearities in photon counting, and the half-wave-plate polarimeter which I built there used such an improved photon counting system. As we had the DC amplifiers still at the telescope, we could carry out a direct comparison of the two methods under identical conditions. As expected from the theory, photon counting reduced the statistical errors by factors of about 2 to 3 and made it possible to observe faint objects where the DC method produced noise only.

Another innovation of the new polarimeter was a programmable controller (a small custom-built process computer) which operated the half-wave plate, started and stopped the integrations, and initiated the data readout and storage. The automatic control, the facts that a target recentering was no longer required, and that the sky background observations could be carried out in a more flexible way, reduced the the observing time for a given object by factors between 5 and 10. A program which before required about one week could now be done in one night.

As seen from today, the Yerkes polarimeter was an example of the minor technological improvement of existing technologies in the 1960s, which nevertheless resulted in a significantly better performance and in a much more efficient use of the valuable observing time.

4 The 1970s: Photocathodes replace photography, Einstein, COS-B, and the MMT

While the technological advances of the 1960s were moderate, the pace of technological progress increased dramatically after 1970. Most important was the replacement of the photographic plates by photocathode-based 2D detectors. Among the first and most successful examples of these new detectors was the image-dissector scanner developed at the Lick Observatory (Robinson & Wampler 1972). But similar devices were built simultaneously at many other places in the US and in Europe. Their use in space begun with the International Ultraviolet Explorer (IUE) satellite which was launched in 1978. Due to their higher quantum efficiency, photocathode detectors were faster and reached fainter sources. But more important was their linearity, which (in contrast to photography) made it possible to subtract sky backgrounds. This allowed us for the first time to obtain quantitative images and spectra of targets whose surface brightness was well below that of the night sky.

Fig. 3 The original Multiple Mirror Telescope on Mount Hopkins, Arizona, consisting of six 1.8-m mirrors in a common mount and with a common focus. Photo: Smithsonian Institution Archives.

A highly important event of the 1970s was the completion of the Multiple Mirror Telescope (MMT, Fig. 3) on Mount Hopkins in Arizona in 1979 (Beckers et al. 1981). Its concept had been developed by Aden Meinel (1922–2011) with support by Frank Low and Fred Whipple (Meinel et al. 1972). While Hale clearly was the leading personality for the development of astronomical telescopes in the first half of the 20th century, Aden Meinel arguably played this role after 1950. He was born in Pasadena, and, before studying optics and astronomy at Pasadena and Berkeley, he worked as an apprentice in the optical lab of the Mount Wilson Observatory. During the Second World War he was involved in developing rockets for the US Navy. Between 1949 and 1956 he worked at Yerkes Observatory (after 1953 as its deputy director), before being appointed the first director of the National Optical Astronomy Observatory (NOAO), which became Kitt Peak National Observatory. Meinel later headed the Steward Observatory of the University of Arizona, and then founded the Optical Science Center of the UoA which developed into today's prestigious College of

Optical Sciences. After retiring from the UoA he worked at the Jet Propulsion Laboratory in his home town Pasadena on the "Large Deployable Reflector" project which developed into the James Webb Space Telescope.

Meinel realized that with the Palomar telescope the large rigid mirrors and the equatorial mounts had reached a dead end. Already at Yerkes Observatory Meinel developed concepts for innovative new telescopes, including a 400-inch Arecibo-type optical instrument (see Meinel 1978). At NOAO he initiated the "Next Generation Telescope" study program, which discussed the possible (and impossible) telescope concepts promoted at that time. At the same time, he established at NOAO a working group to plan a large optical space telescope. Together with the work of a similar study group initiated by Lyman Spitzer (1914–1997) at Princeton University, Meinel's group was later merged into a NASA project, which eventually resulted in the Hubble Space Telescope. Although after 1946 he worked at civilian institutions, Meinel never completely cut his relations with the US military. In this context he learned about six high-quality 1.8-m mirror blanks, made by Corning, which had been ordered, but never been called for, by the US Air Force. Meinel acquired these blanks for a symbolic price and constructed a telescope with the six mirrors in a common mount and with a common focus (Fig. 3). After some initial difficulties, the Multi-Mirror Telescope (with the light collecting power of a single 4.5-m aperture) worked quite well. It was the first segmented reflecting telescope and the first telescope depending entirely on active optics, and it demonstrated that instruments with large effective apertures could be realized in this way. Thus, the MMT formed the basis of the new-generation large optical/IR telescopes of the 1990s and beyond.

In the field of X-ray astronomy a major milestone was the first (still modest) X-ray sky survey by Riccardo Giacconi and his group using the Explorer 47 (Uhuru) satellite, launched in 1970. Technologically more important was the HEAO-2 (Einstein) X-ray observatory, launched in 1978. Its payload included the first large grazing-incidence telescope, as well as imaging X-ray detectors which produced first high-resolution X-ray images of astronomical objects. An example is shown in Fig. 4. A big step forward in our knowledge of the γ-ray sky was the launch of the COS-B survey satellite in 1975.

In addition to the MMT, the 1970s witnessed the construction of seven new optical telescopes with apertures larger than 3 meters. But, apart from the altazimuth mounting of the Russian 6-m telescope, these instruments were still essentially based on concepts and technologies developed before 1960. The same was true for the (scientifically highly successful) OAO 3 (Copernicus) FUV space mission.

More innovative was the new 100-m telescope of the Max Planck Institute for Radio Astronomy at Effelsberg which was completed in 1971. Its overall design followed the conventional "dish" concept, pioneered by Grote Reber in 1937. But, as an important new feature, the mechanical structure of the Effelsberg dish was designed to always retain a paraboloid surface in spite of the unavoidable deformation during altitude changes. This "homologous" design concept made it eventually possible to use the 100-m dish at wavelength as small as a few millimeters.

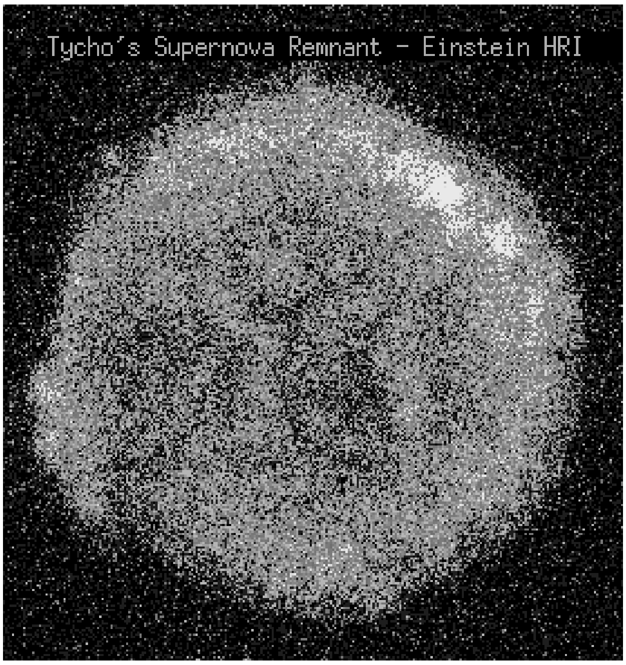

Fig. 4 X-ray image of the Tycho supernova remnant obtained with the HEAO-2 (Einstein) observatory. With an angular resolution reaching about 2″, HEAO-2 was the first mission capable of high-resolution X-ray imaging. (Credit: NASA).

5 Between 1980 and 1992: CCDs, the VLA, space observatories, and VHE gamma photons

Although they had been developed with much effort only in the decade before, 2-D photocathode devices became obsolete when CCDs and other solid-state array detectors became available during the 1980s. The CCD detector was invented at the Bell Labs in 1969 as an imaging device for "picture phones". The first ones were rather noisy, and by 1975 their usefulness for astronomy was still disputed. But, in the following years low-noise CCDs were developed, and already in 1976 a first astronomical application was reported at an AAS meeting (Loh 1976). At the 1981 SPIE meeting on "Solid State Imagers for Astronomy" (Geary & Latham 1981) various US and European groups reported their positive experience with the new detectors, and during the following years CCDs and NIR array detectors were installed at all major observatories while the photocathode detectors disappeared, except for some UV and soft X-ray applications.

What made the semiconductor array detectors so attractive, was their high quantum efficiency (reaching close to 100 %), their mechanical robustness, their lower sensitivity

Fig. 5 Radio image of the Quasar 3C175 with a resolution of about 350 mas, obtained with the Very Large Array. The field is about $1'.2 \times 0'.6$. (Credit: NRAO).

Fig. 6 The Very Large Telescope (VLT) of the European Southern Observatory at Paranal, Chile. The light from the four large (8.2-m) telescopes and the four smaller (1.8-m) telescopes can be combined coherently to reach an angular resolution at visual/NIR wavelengths of about one milliarcsecond. (Credit: ESO).

to overexposure, and the fact that (in contrast to photocathode devices) no high voltage was required.

Another landmark in the development of astronomical imaging was the completion of the VLA in 1980. A directional antenna system had already been used by Jansky in his discovery of radio radiation from space, and first radio interferometers had been constructed during WW2 for military purposes. In the years after the war, large astronomical interferometers had been installed in England, Australia, and the Netherlands. But it was the size and the non-redundant design of the VLA that made it possible for the first time to produce routinely complete and well resolved radio images of complex astronomical sources, as illustrated in Fig. 5. These observations demonstrated convincingly the imaging capabilities of aperture synthesis which had a major influence on the telescope design at radio, IR, and visual wavelengths during the following decades.

Among the advances in space astronomy was the 1983 launch of the IRAS satellite. This instrument, which had been proposed by Frank Low and realized by a US-European cooperation, opened up the FIR sky.

Even more important was the Hubble Space Telescope, launched in 1990, which was scientifically particularly successful and which became the most popular NASA mission to date. Among other results, the HST dramatically extended the redshift range at which galaxies and QSOs could be observed.

During the same year the launch of the ROSAT satellite resulted in a first inventory of the cosmic X-ray sources.

Less widely known, but not less important, was the Compton Gamma Ray Observatory (launched in 1991) which produced (among other results) the first sky map for photon energies above 100 MeV and provided critical new information on the gamma-burst sources.

A smaller, but technically highly innovative space mission was the Hipparcos satellite (launched in 1989) which revolutionized the field of astrometry.

At the early space observatories (such as the highly successful IUE satellite) the observations were carried out in the same way as the work in ground-based observatories of that time, with a single scheduled observer operating the telescope and the instrumentation. The only difference was that the individual steps were carried out by remote control. The Hubble Space Telescope was the first observatory which was fully based on computer-controlled automated instruments and queue scheduling. The advantages and economy of this operating mode soon became evident, and within a few years these techniques became routine at practically all major ground-based facilities as well.

Other technical breakthroughs of the 1980s was the first astronomical use of adaptive optics (originally developed for military applications) and the first detection (in 1989) of TeV photons (from the Crab nebula) with the air-shower Cherenkov telescope of the Whipple Observatory on Mount Hopkins in Arizona. With this addition, the wavelength range of electromagnetic radiation available for astronomers reached the present-day interval of about 10^{-20} m to about 20 m (a frequency range of about 70 octaves!).

6 Starting 1993: A new generation of large telescopes

While the period 1960–1990 was dominated by advances in detector technologies, the last two decades were marked by the completion of innovative new telescopes.

The construction of these new large facilities extended to all astronomically useful wavelength ranges and involved institutions in many different countries from all inhabited continents.

At optical/IR wavelengths the important first example was the Keck-1 telescope with its 10-m segmented mirror, completed in 1993 (Nelson & Gillingham 1994). During the following years, 15 more telescopes with apertures above

Fig. 7 The Atacama Large Millimeter/submillimeter Array (ALMA) on the Chajnantor plateau, Chile. (Credit: ESO).

6 meters and actively controlled and/or segmented mirrors were installed in different parts of the world. Apart from a superior light collecting power of these large facilities, their actively controlled optics resulted in a significantly better image quality, even for seeing-limited observations. Some of these new instruments, such as the ESO-VLT (Fig. 6), LBT, and Keck 1+2) were designed to include interferometric and aperture synthesis capabilities. Although less big, the astrometric satellite GAIA (launched in 2013) has also to be mentioned, as its will a have a big impact on several subfields of astronomy.

For shorter wavelengths a new generation of advanced X-ray telescopes, such as ASCA (1993), Chandra, and XMM-Newton (both launched in 1999) became operational. Using large grazing-incidence optics, X-ray CCDs with a spectral resolution of about $R = 50$, and grating spectrometers for higher spectral resolutions, the data produced by these X-ray observatories were for the first time fully comparable to high-quality optical data.

FIR observatories with actively or passively cooled space telescopes, such as ISO (1995), *Spitzer* (2003), and *Herschel* (2009) resulted in a significant improvement of the sensitivity limit at these wavelengths. A similar role was played for the EUV by the FUSE observatory (1999), for the gamma-ray astronomy by the INTEGRAL (2002) and Fermi (2008) space missions, and for the VHE gamma range by the new large Cherenkov air shower telescope systems HEGRA, H.E.S.S., and VERITAS. Finally, the completion of the ALMA array in Chile in 2013 (Fig. 7) resulted in a major improvement of the the sensitivity, resolution, and imaging capabilities at millimeter and sub-mm wavelengths.

In addition to the multi-purpose instruments listed above, some important “single-target” telescopes were realized. Those included the WMAP and PLANCK space missions (for studying the CMB) and new large solar telescopes, such as the NST, installed at the Big Bear Lake Observatory, California, and the GREGOR telescope, constructed on the Spanish island of Tenerife.

7 The future

Many of the facilities listed in the last section are still in operation. Thus, this overview has reached the present-day status, and we may now ask what kind of technological progress the future may have in store. Such an outlook is necessarily speculative. However, there are at least three fields where predictions appear reasonably safe:

7.1 Projects in progress

At present, several large projects are already under construction or in an advanced planning stage. These will almost certainly dominate the technological efforts for at least another decade. They again cover the whole wavelength range between the radio and the VHE-gamma energies. Although their realization is not yet in all cases assured, at least most of these projects will probably become reality.

Closest to completion are the Astro-H X-ray facility and the James Web Space Telescope for very deep NIR observations. Both are expected to be launched before the end of the present decade. During the following decade, three big ground-based optical telescopes (the Thirty Meter Telescope, the 39-m ESO E-ELT, and the 21.4-m equivalent Giant Magellanic Telescope), the radio-frequency Square Kilometre Array, the Cherenkov Telescope Array for the VHE gamma astronomy, and (possibly) ESA’s X-ray telescope ATHENA may receive their first photons. Although all the new instruments promise great scientific progress, from the standpoint of technology they are in most cases less exciting, as they are mainly extrapolations of existing facilities to much larger sizes. Exceptions are ATHENA with its innovative silicon pore optics and Astro-H with new superconducting detectors.

A smaller, but scientifically not less important project, is the Large Synoptic Survey Telescope (LSST). Apart from tracing all types of variable sources, the very deep new map of the sky, which the LSST will produce over the years by coadding frames, will be a most valuable data base for many future scientific studies. Among the challenges connected with the LSST will be the software tools needed to extract information from such large data bases efficiently.

The new instruments mentioned above will bind much of the financial and personal resources available in the near future. Thus, it may be prudent to wait for the experience with these projects before planning an even more advanced generation of telescopes. On the other hand, one should not stop thinking about the distant future, although it may take some time before dreams such as observatories on the moon may become a reality.

7.2 New photon detectors

On shorter timescales we may well experience important progress in the fields of focal plane instrumentation and, in particular, energy-resolving photon detectors. For any individual photon the frequency ν and wavelength λ are well determined by the relation $E = h\nu = h\lambda^{-1}c$, where E is the photon energy. However, at present only at gamma and X-ray wavelengths the photon energies (or wavelengths) are determined directly by the detectors, while at longer wavelengths more or less complex spectrometers are used to sort the photons before they are detected. Obviously this not very satisfactory situation is due to the use of semiconductor detectors and the fact that the most common semiconductors (such as silicon) have intrinsic band gaps corresponding to about the energy of visible photons. Hence, visible photons can produce single photo electrons only, while the more energetic photons can produce multiple conduction electrons, where the number (or total charge) can be used to derive the energies of the individual detected photons.

It has been known since many years that in superconducting metals below a critical temperature band gaps are formed which are much narrower (typically 0.1–1 meV). Thus, superconducting detectors can measure photon energies with an energy resolution for visible light, which is comparable to that of Si-based CCDs for X-rays. In a similar way superconducting (micro-) bolometers can be used as photon-energy recording detectors. Bolometers (where photon energies are determined indirectly by measuring the resulting heat input), can be used at all wavelengths, where photon absorption is possible, including the UV, visual, IR, and sub-millimeter ranges. Single-pixel superconducting photon detectors and small arrays based on these principles have been constructed and tested since more than 15 years (e.g. Jakobsen 1999). But, most of these devices are limited to pixel formats which are not competitive with modern CCDs.

A possible breakthrough could be the Microwave Kinetic Induction Detector (MKID) read-out principle. MKIDs are already used at mm- and sub-mm observatories, and first scientific results obtained in the visual have been published. The presently existing visual-wavelength MKID arrays still have a few thousand pixels and a visual-light spectral resolution of $R = \lambda/\delta\lambda \approx 10$ only, but megapixel arrays and spectral resolutions of the order 10^2 appear to be technically feasible (Mazin et al. 2013, 2014). If this can be achieved, MKID-based photon detectors may soon replace the CCDs for low-resolution imaging spectroscopy and many other applications. The low operating temperature (of the order 100 mK) of the superconducting devices results in a more complex operation, but advances in the low-temperature technologies make such systems increasingly feasible and affordable.

Energy-resolved photon counting and imaging using microbolometers (also known as microcalorimeters) have also been introduced in X-ray astronomy, where they reach a significantly better spectral resolution than is possible with silicon CCDs. However, as X-ray observatories have to be operated in space, the low detector temperatures are even more challenging.

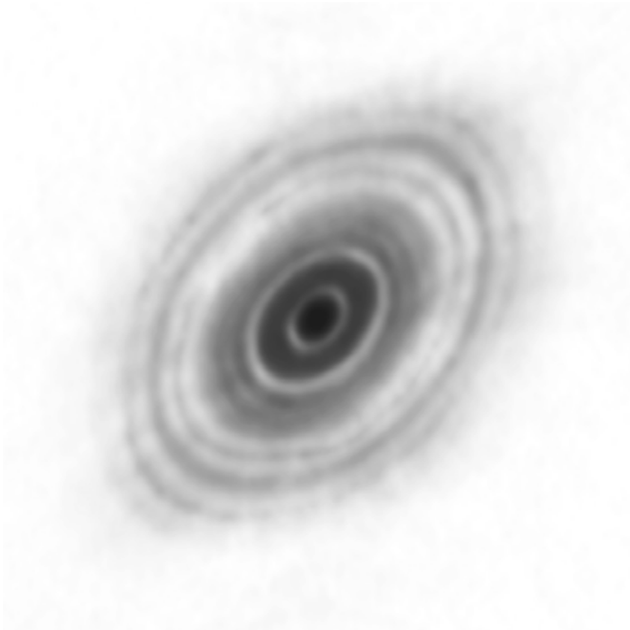

Fig. 8 Millimeter-wave image with a resolution of about 50 mas of the circumstellar disk around the very young (T Tau type) star HL Tauri obtained with the Atacama Large Millimeter/submillimeter Array. (Image credit: ESO.)

7.3 Aperture synthesis

Another technique where important further progress can be safely predicted, is the field of interferometry and aperture synthesis. The big success with radio interferometers has already been mentioned. More recently ALMA has demonstrated the great potential of such techniques at mm and sub-mm wavelengths. Circumstellar disks around young stars, which 30 years ago could be inferred only indirectly, can now be imaged and studied in significant detail (Fig. 8). At NIR wavelengths observations with the VLT and the Keck interferometers already resulted in very valuable scientific data, and the LBT promises new possibilities in the interferometric imaging of complex objects. As an example I note the imaging of the symbiotic binary system SS Lep, obtained in the *H*-band by Blind et al. (2011) with the VLTI/PIONIER instrument. In view of the ongoing technical developments, we can expect that this type of work will soon be expanded to a wider wavelength range and to sources with more complex geometries.

8 The sources of technological progress

Looking back on the history of the past five decades, it appears to me that the main sources of major advances are

(1) a steady improvements of existing technologies,

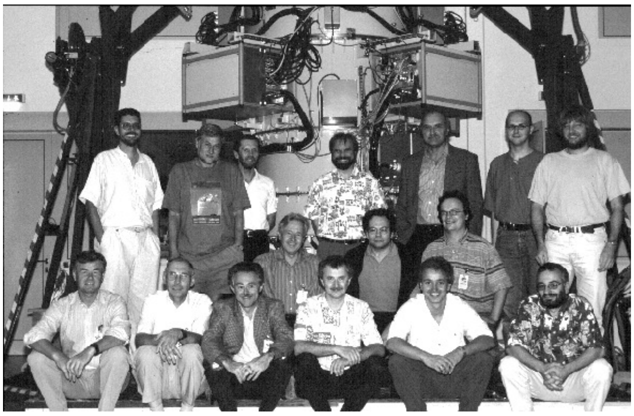

Fig. 9 Part of the team which developed the FORS instruments for ESO's Very Large Telescope. The photo was taken during the acceptance tests of FORS1 in Europe. FORS1, which was the first science instrument at the VLT, is visible in the background.

(2) the adaption of new technologies developed in other fields,
(3) outstanding personalities with a bold vision and the political skills to realize new big projects, and
(4) competent and motivated teams of scientists, engineers, and technicians, who are dedicated to their work, and who enjoy technological challenges.

Steady improvements of existing technologies by new ideas and the adoption of new techniques developed elsewhere does not sound very exciting. But much of the past progress was actually based on such gradual improvements. Examples are Schwarzschild's diligent work on the photographic methods, but also the improvements of the existing techniques in the 1960s described above. Among the important technologies adopted from other fields are the telescope, photography, photomultipliers, computers, CCDs, and adaptive optics.

Large projects, such as innovative new telescopes, new wavelength ranges, and completely new methods, can often be traced to the vision, the tenacity, and the political skill of outstanding personalities. Examples which I mentioned already are George Ellery Hale, Otto Struve, Aden Meinel, Frank Low, and Lyman Spitzer. Other examples are Riccardo Giacconi who initiated and dominated the development of X-ray astronomy, David Heeschen who was the main driver for the VLA project, and Yasuo Tanaka who pioneered the use of energy-resolving CCDs in X-ray astronomy. European colleagues, who played such roles, are, e.g., Martin Ryle, the founding fathers of ESO (including Jan Oort, Otto Heckman, and André Danjon), Lodewijk Woltjer, who initiated ESO's Very Large Telescope. Examples in Germany are Karl-Otto Kiepenheuer, Otto Hachenberg, Joachim Trümper, and Hans Elsässer.

An interesting document in this context is a staff photo taken at Yerkes Observatory in 1950. This historic photo includes a sizable fraction of the (US and European) "visionaries" which I mentioned above. (The Photo can be found in the photographic archive of the University of Chicago, which is accessible in the internet through the UoC web page.)

Finally, no major technological project can be successful without the cooperative work of motivated teams of scientists, engineers, and technicians, who are dedicated to their work and who enjoy technological challenges. Figure 9 shows part of such a team with which I had the pleasure of realizing a successful astronomical instrument. The group includes scientists as well as technical experts of various fields. That highly motivated teams of scientists *and* technicians are indispensable for such work was again stressed already by Karl Schwarzschild in his lecture to the German Society for Mechanics and Optics. There he characterized the "right" scientists *and* the "right" technicians (required to achieve progress) as those who would be as happy in heaven as in hell, as long as they have the tools to reach their objectives.[3] These words of Karl Schwarzschild, sound as true today, as they were one hundred years ago.

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[3] "Mit Fernrohr und Logarithmentafel wäre der rechte Astronom in Himmel und Hölle gleich zufrieden, und ebenso der rechte Mechaniker mit Reißbrett und Drehbank."

