

Big Science in the 21st Century

Economic and societal impacts

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Chapter 28

Big Astronomy: large telescopes and the dual narrative of impact

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Astronomy has a long tradition of using ever-larger telescopes to explore the Universe. Today, large telescope projects define the structure of the discipline in terms of institutional organization and funding. But despite the long history of large telescope building, astronomy did not automatically adopt a ‘Big Science’ culture. In this essay, I argue that ‘Big Science’ ways of working were introduced into astronomy from the outside: via radio astronomy and space science. In recent decades, the different instrument cultures of these fields have gradually been integrated in to ‘multi-messenger’ and ‘multi-instrument’ astronomy.

Analyzing this history will help to understand a specific feature of Big Astronomy. Science and engineering are inseparable in big telescopes, but they are presented very differently to the outside world. Astronomy is often presented as the ultimate ‘pure’, curiosity-driven science, but its main instruments are also promoted (and funded) as technological development projects. These narratives are used side-by-side, depending on the context and audience. In this paper, I will analyze this ‘dual narrative’ of the impact of astronomy, and the implications for outreach, education, policy, and funding.

28.1 Introduction

The Very Large Telescope (VLT) in the Chilean Atacama desert has been observing the sky for over two decades. Several ‘Extremely Large Telescopes’ (ELTs) are under construction, and a \$10 billion new space telescope was launched in December 2021. Clearly, astronomers have embraced bigness.

These instruments are used to investigate questions about the origins of the Universe and of the life in it: big scientific questions with strong popular appeal, but also quite abstract questions, with little direct application in daily life.

Astronomy lost most of its practical applications with the improvement of clocks, compasses, and maps. Understanding the cosmos is often presented as the ultimate ‘pure’, curiosity-driven investigation. This endeavor has a strong cultural resonance, contributing in no small measure to the public appeal of astronomy.

Does this mean that the impact of astronomy is purely scientific and cultural? Are those large telescopes really funded only for scientific reasons, even in the current innovation-centered science policy environment? Are there no spin-offs? The scientific and cultural impact is definitely important, but looking at the curiosity-driven uses of telescopes reveals only half the story. Much of the funding for astronomy is not spent on using telescopes for astronomical research, but on building the telescopes and auxiliary instruments and developing the highly advanced technology they need¹. That part of the discipline has a very concrete economic and technological impact. This has led to a ‘dual narrative’ about the impact of astronomy, emphasizing either pure science or technological innovation, depending on the context and audience.

Astronomy has a long tradition of pushing for ever-bigger telescopes to explore the Universe. Today, large instruments shape the structure of the discipline, and the future of astronomy is planned in terms of new telescopes of different kinds (figure 28.1). Astronomers did not automatically adopt a ‘Big Science’ culture, however. Until well into the twentieth century, even the largest telescopes were used mostly by individual researchers. In this paper, I argue that ‘Big Science’ ways of working were introduced

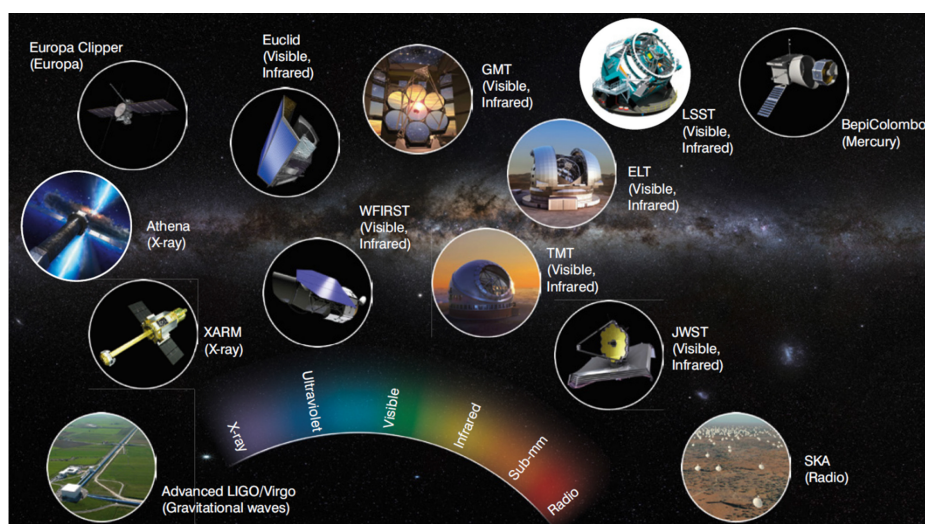


Figure 28.1. The future of astronomy is planned in terms of large instruments that can observe different parts of the electromagnetic spectrum: major instruments planned for the 2020s (International Astronomical Union 2020, p 20, reproduced with permission).

¹ In this chapter, I will mostly use the terms ‘telescopes’ and ‘instruments’ interchangeably; I will specify if I use ‘instruments’ in the more specific sense common in astronomy, for auxiliary instruments attached to telescope systems (for example cameras or spectrographs).

into astronomy from the outside: via radio astronomy and space science, both developed in Cold War contexts. It took time and effort to integrate the different instrument cultures into one discipline of ‘multi-wavelength’ and even ‘multi-messenger’ astronomy, since this always also involved ‘multi-instrument’ astronomy. In the first part of this essay, I will describe and analyze this process.

I will also describe how astronomical instruments gradually were institutionally separated from research. This is relevant for the second part of the essay, in which I analyze the ‘dual narrative’ of Big Astronomy’s simultaneous pursuit of both cultural and technological impact.

I will start with a discussion of the importance of big telescopes for astronomy.

28.2 Why Big Astronomy?

Apart from missions within the Solar System, astronomers cannot investigate their research objects directly. All they can do is theorize, model, and, especially, observe. Astronomers have to work with whatever ‘messengers’ the Universe happens to send to their instruments. These can be cosmic rays, neutrinos, gravitational waves, but above all, light. For this simple reason, astronomers are always looking for ways to capture more light. That can be done by building bigger telescopes, by improving detectors to process the incoming light more efficiently, by improving data processing to filter out noise, and by extending observations to all parts of the electromagnetic spectrum. After the Second World War, new kinds of telescopes have expanded beyond visible light, by observing radio waves, infrared and ultraviolet light, x-rays, and gamma rays (Brandl *et al* 2010). This has radically changed our view of the Universe and the objects within it. The new telescopes revealed quasars, pulsars, interstellar molecules, and other things that had never been seen before, and in some cases not even been thought of before (Longair 2006, Dick 2013).

The idea that progress is strongly technology-driven plays a central role in astronomy (Smith 1997, Dick 2013, Harwit 2019). This started with the very first telescopes, which were such an improvement over the naked eye that Galileo discovered the moons of Jupiter, features on the surface of the Moon and the stellar nature of the Milky Way within months of first turning his instruments to the sky (Heilbron 2012). The argument that new instruments can ‘uncover new phenomena not yet imagined’ remains a strong and much-used argument for constructing ever-larger telescopes (Spitzer 1946, Smith 1989, 1997, cf. chapter 25 in this volume). The idea of ‘Big Astronomy’ is now widely embraced by astronomers, although the cost of some projects can still cause some to worry about consequences for funding of other projects (Smith 1989, McCray 2004, cf. chapter 24 in this volume).

Because of the importance of observation, access to large telescopes is one of the most important resources for any astronomer. Some large telescopes are open for all astronomers, who can apply for observing time. In other cases, some or all of the observing time is reserved for researchers from institutions that contributed funding or were otherwise involved in the development. These are highly coveted privileges (Smith 1997, DeVorkin 2000, McCray 2000, Baneke 2019, Williams and Mauduit 2010).

Large telescopes are not only important for researchers, but also for astronomical institutions. Institutions that develop (parts of) major instruments build up a lot of highly specialized expertise. To maintain that expertise—read ‘staff’, because expertise is embodied in people—after a project is finished, they need a new project that involves their specialty. In other words, they need a ‘pipeline’ of new instruments. Because each project needs a long time before it is approved and funded, astronomers, engineers, and managers are constantly thinking about future projects, in order to secure long-term institutional continuity (McCray 2004, Conway 2015, Baneke 2019). Having access to instruments also is an asset to attract new staff and students. All this explains why instruments are so central in the future planning of astronomy—also since the timescales of major instruments are much longer than the usual timescale of academic research grants.

This also means that new telescopes have an impact on astronomy long before ‘first light’, the start of scientific operations. Robert Smith and Patrick McCray have described beautifully how the run-up to the Hubble Space Telescope and the Gemini Telescopes have shaped telescope technology as well as the American astronomical community over several decades (Smith 1989, McCray 2004). Similarly, the Square Kilometer Array, a giant new radio telescope, to be built by a global consortium in South Africa and Australia, has already been influencing astronomy for several decades, even though construction has only just started (Baneke 2019).

28.3 Sources of instrument culture

The drive to build ever more powerful telescopes is a red thread throughout the history of modern astronomy, but that does not mean that every step was self-evident at the time, or that there was anything ‘natural’ about the evolution of large telescopes into ‘Big Science’². Every major new telescope was a risky project for its proponents and funders (Smith 1997, McCray 2004). In addition, major improvements involved new technologies, which often required new ways of working: how to do observations, how to process the data, and how to organize the operation of the telescopes. New kinds of instruments came with new ‘instrument cultures’.

In this section, I will discuss three major sources of instrument cultures in modern astronomy: the optical tradition, radio astronomy, and space research. I will characterize how elements of all these instrument cultures were integrated into contemporary astronomy. I will also describe how the development of Big Astronomy led to an increasing separation between instruments and research, both in practice and institutionally.

28.3.1 Optical astronomy

Astronomical observatories were among the first institutions that were specifically created for scientific research. Ulugh Beg and Tycho Brahe’s observatories had a significant staff and large instrument collections. Moreover, these observatories were

² Excellent overviews of the historiography of Big Science can be found in Capshaw and Rader (1992) and Hallonsten (2016).

funded by monarchs. Team work, large instrumentation, and government funding are all commonly taken as characteristics of Big Science. But at the same time, these early modern observatories were personal enterprises that did not survive their founder. The funding by monarchs fits more into the pattern of early modern patronage than modern government funding. And while some instruments were large, they were operated by individuals. Collaboration mostly consisted in combining data by multiple observers (see chapter 22 in this volume).

This changed with the founding of national observatories, for example in Greenwich, Paris, and Washington. In the early nineteenth century, Pulkovo Observatory near St Petersburg became the model for a string of new observatories (Dick 1991). The very design of these observatories highlighted the importance of instruments in astronomy. They were literally constructed around the telescopes (especially meridian circles). But still, there was a clear division between designing, building, and maintaining instruments on the one hand, and using them on the other. Astronomers mostly purchased their instruments from specialized (commercial) instrument makers, who were not involved in using the instruments for observations (Smith 1997).

The telescopes were intended for long-term use, in a discipline that valued precision above everything else. So it was worth spending a lot of time on calibrating the instrument, and on getting to know all its remaining imperfections. ‘Know your instrument’ was a key part of every astronomer’s work ethic (McCray 2004).

In the 1880s a large number of observatories agreed to jointly produce a giant photographic survey of the entire sky, the *Carte du Ciel* (Bigg 2000). This mammoth undertaking, which ran until the 1960s and was never completely finished, was certainly one of the most ambitious scientific projects of the era, even if it did not involve large instruments. It was triggered by the emergence of photography, a technology that fundamentally changed the instrument culture of astronomy (Lankford 1984). Instead of making measurements while looking through a telescope, astronomers increasingly took photos which they could investigate at leisure during the day. This made observations much more efficient. In addition, long exposure times brought much fainter objects within reach, and they provided a permanent record of the observations that could be revisited later. However, taking photos still required staying up in the telescope dome all night.

From the turn of the twentieth century, the largest telescopes were operated by privately funded observatories in the United States. The undisputed master of this ‘large telescope era’ was George Ellery Hale, who engineered the construction of the largest telescope in the world four times in a row, each time funded by a private philanthropist: at Yerkes Observatory near Chicago, Mt Wilson Observatory near Los Angeles (twice), and Mt Palomar in Southern California (Van Helden 1984, Wright 1994, Sandage 2004).

Hale did not build his new telescopes at existing observatories. Astronomical observations are not only limited by telescope quality and size, but also by clouds and atmospheric disturbances. Since astronomers could travel while big telescopes could not, it made sense to build telescopes in the places with the best ‘seeing’ conditions, which Hale found in California. This became standard practice in the twentieth century. In this way, telescopes got geographically separated from research

institutions (although Hale made an effort to change a local college near Mt Wilson into a research university: this became Caltech).

Hale's telescopes feature in many publications about Big Science. Impressively large and expensive, they are regarded as direct predecessors of the large scientific instruments after the Second World War. But however big, the telescopes were used by individuals and operated by single institutions with powerful directors (Lankford 1997, cf. Sandage 2004). There was no team work, no government funding, and no 'big management'.

The era of large optical telescopes culminated in 1948 in the opening of Hale's masterpiece, the 200 inch (5 m) Mt Palomar telescope. But at the same time, this marked the start of stagnation. Palomar became the model for a string of 4 m sized telescopes that were built in the next few decades, but it was widely agreed that larger telescopes were impossible without significant technological innovations. The disappointing results of a Soviet 6 m telescope reinforced that idea (Keel 1992).

Apart from technological difficulties, cost was also an issue. No observatory could match the resources of the rich Californian institutes. In 1946 the International Astronomical Union (IAU) proposed to solve this by establishing international observatories (Blaauw 1994, Andersen *et al* 2019). In the next decades, international pooling of resources to develop large telescopes indeed became common practice, although without any central coordination by the IAU.

The Palomar telescope was only surpassed in size in the 1990s, although telescopes improved in the meantime because of more efficient detectors and active optics. In the decades after the Second World War, the main impulse in astronomical observations came from other directions, however: radio and space technology.

28.3.2 Radio astronomy

In the 1930s and 1940s radio and radar engineers noticed radio 'noise' coming out of the sky. This was a nuisance, but some of them realized that it could be scientifically interesting. After the end of the Second World War, groups of engineers and scientists started to investigate the radio noise systematically, using surplus wartime radar equipment as the starting point for their research (Agar 1998, Sullivan 2009, Munns 2012, Elbers 2017).

Radio receivers differed from existing telescopes. The most notable differences were the role of electronic technology and the format of the resulting data. Astronomers were used to look through telescopes themselves or to take photos, but radio observations required detectors which produced an electronic signal. It required a lot of work to translate this data into a visual image of the sky. Initially, it was also difficult to identify radio sources with known astronomical objects. This improved in the course of the 1950s, as more sources were identified. By that time, the receivers were called 'radio telescopes', indicating their gradual integration into astronomy (Sullivan 2009).

The emergence of radio astronomy is often described as the opening of a new 'window' on the Universe. Before, the Universe could only be observed in visible light, which revealed planets, stars, and nebulae. Radio waves revealed the existence

of pulsars, quasars, black holes, and many other things that had never been observed before. Jan Oort, a pioneer of radio astronomy, commented in 1978: ‘Before the advent of radio astronomy, astronomers had not realized at all how many things in the Universe are of an explosive nature’³. This explosive nature even included the Universe itself: the ‘Big Bang’ theory of the origins of the Universe was spectacularly confirmed by the discovery, with a radio telescope, of the cosmic background radiation in 1965. The Universe turned out to be a much more diverse place than anyone had thought.

Because of the differences, the instrument culture of early radio research also differed from traditional (optical) astronomy. Most notably, the boundary between science and technology was much less clear. While in optical astronomy, the instruments were built before they were used for observation, in radio astronomy the instrument kept being modified during observations. Engineers and scientists had to cooperate in every phase. Operating the telescopes, and even processing the data, required intimate knowledge of electronic technology. Radio astronomers were also among the first large-scale users of computers.

For all these reasons, it was not easy to integrate radio observations into astronomy. Another factor was the different background of the people involved: physicists and engineers had to learn the basics of astronomy, while astronomers had to familiarize themselves with electronic technology, and each had to appreciate the other’s role in the process. This took time and effort (Agar 1998, Sullivan 2009, Munns 2012).

Radio astronomy was heavily based on military technology, especially radar, but the link was in the technology, not in the scientific research that was done with the instruments⁴. The ‘dual use’ nature of the technology was an asset: the expertise and experience with radio astronomy could easily be turned to military uses if needed, but until that time, nothing looks more peaceful than an astronomical observatory. Radio telescopes were also used as ‘showcase’ technologies, to display national technological prowess (Agar 1998).

Many radio telescopes were developed outside the institutional structure of astronomical observatories, and with direct government support. They were operated by newly created organizations, in many cases consortia of universities working together, for example the NRAO in the US and SRZM in the Netherlands (DeVorkin 2000, Baneke 2015). In Britain, the large Jodrell Bank radio dish was at the center of discussions about the relation between large instruments and academia (Agar 1998, ch 2).

From the 1950s, this model was also adopted for new large optical telescopes, which had become too expensive for most individual observatories. Several European countries joined the European Southern Observatory (ESO), which aimed to build a large telescope in the Southern hemisphere, while American universities collaborated to develop joint telescopes in both Arizona and Chile (Blaauw 1991, McCray 2004).

³ Interview with W T Sullivan, 1978, NRAO.

⁴ A high-profile exception was the use of the Jodrell Bank telescope to track Sputnik (Agar 1998).

The new organizations were explicitly modeled after the paradigmatic Cold War Big Science projects: high-energy physics. Brookhaven Laboratory was a model for the American National Optical and Radio Observatories, for example; some of the same people were involved in founding these institutions (DeVorkin 2000, McCray 2004). ESO was explicitly modeled after CERN, again with some of the same people involved. ESO even had an instrumentation department located at CERN (Blaauw 1991).

The emergence of ‘facility’ organizations to manage telescopes triggered discussions about access and division of labor. Should they have their own research staff, or should they only provide technical assistance? And who could use the joint instruments: only staff of the institutes or countries who contributed? Or could other researchers also apply? Would there be quota for specific groups? These were sensitive points, because they concerned the most important resource for astronomers: access to high-quality telescopes (DeVorkin 2000, McCray 2000).

By the 1960s, large radio and optical telescopes looked like ‘Big Science’ in the traditional, Cold War era sense. They were large and expensive instruments, funded by governments, operated by dedicated organizations with their own management structure, and used by many different researchers. Operating them required team work of scientists, engineers, and managers in all stages, from first proposal to data processing. Compared to high-energy physics, the teams were still small, however. In that sense, ‘big instruments’ did not automatically lead to a ‘Big Science’ instrument culture.

28.3.3 Space

Visible light and radio waves from outer space can be observed from the ground. Other wavelengths cannot: ultraviolet and infrared light, x-rays, and gamma rays are blocked by the Earth’s atmosphere. Opening these ‘windows’ required going beyond the atmosphere, into space. It also required changing the ways astronomers worked (DeVorkin 2010). Even more than radio astronomy, the development of space research is intertwined with the politics of the Cold War.

From the early twentieth century, scientists used high-altitude balloons to investigate the upper atmosphere and to observe cosmic radiation. After 1945 they could also use ‘sounding rockets’, which left the atmosphere for a few minutes on a ballistic trajectory before falling back to Earth. The short time available, and the difficulty of pointing the instruments at a specific source, meant that they could not be used for most astronomical research, except solar physics and cosmic radiation (DeVorkin 1992).

Apart from the practical difficulties, the instrument culture of early space research also made it difficult for astronomers to participate. They were not used to the ‘tinkering’ style of the rocketeers, who built their own instruments. The fact that the instruments could be used for only a few minutes, after which they were destroyed on landing, was also very foreign to them (DeVorkin 1992, 2010).

The launch of Sputnik in October 1957, during the International Geophysical Year, changed the situation. Earth-orbiting satellites promised stable observing platforms outside the atmosphere. In the following years, space agencies initiated scientific programs that included astronomical projects. A major boost came in

1958, when the newly founded NASA offered to launch foreign scientific experiments. This was a diplomatic gesture, intended to re-gain the initiative after the blow to American prestige of having lost the first satellite launch to the Soviet Union (Krige *et al* 2013). The offer made it possible for scientists in many other countries to develop space instruments (Krige and Russo 2000, Baneke 2014).

Many governments were eager to support space initiatives, for scientific reasons but also to catch up with the technology and to support local high-tech industries. Developing astronomical instruments was an excellent way to do this. (Reinke 2007, Baneke 2014). Even if astronomical observations were not of any practical use, the technology was. Like radio astronomy, space technology is ‘dual use’, so any experience from developing scientific instruments could also be used for commercial and military applications. The ‘arsenal of knowledge’ argument worked in favor of ‘pure science’ (Krige 2010).

One would expect astronomers to jump at the opportunity, but many of them were initially cautious. Nancy Grace Roman, who was hired by NASA to develop its astronomy program, described the ‘technical and social challenges’ she encountered when approaching astronomers (Roman 2001, cf. Smith 1989, 2010). For one thing, satellite observations had to be done electronically, since the photographic technology that most astronomers were used to was not usable in space. Because the data had to be transmitted back to Earth, the amount of data was also very limited. This only changed later with advancing electronic and digital technology.

Astronomers were also not used to develop instruments to use them so briefly. The development of space instruments often took many years, while the actual missions were usually much shorter, especially in the beginning. According to Roman, this problem was solved in part by the influx of experimental physicists, who were more used to this way of working. Many pioneers of space research had a background in cosmic ray research (cf. Tucker and Giaconni 1985, DeVorkin 2019).

The short lifetime of the instruments, in combination with the difficulty of communicating with spacecraft in orbit, also meant that the observing programs of the instruments had to be planned before launch. In contrast to ground-based telescopes, each space instrument had a well-defined mission.

Because of their cost, complexity and political sensitivity, space projects could only be organized by government-supported space agencies. There were always many parties involved, including space agencies, scientific institutions, and industry. Each step, from design and construction to operation and data processing, required large, multidisciplinary teams.

If radio telescopes were big instruments but not necessarily Big Science, space telescopes were Big Science, but not big instruments. Satellites were small, and the astronomical instruments on board were even smaller. But precisely this small size made them even more complex. Each instrument had very tight limits regarding size, weight, energy use, temperature management, etc. Any design change immediately had repercussions for other components of the spacecraft. In addition, the quality requirements were extremely strict, because even the tiniest irregularity could endanger the whole mission, and fixing an instrument in space was impossible. All this required very strict management.

Roman commented that many astronomers were not used to the detailed management culture of space, and ‘in fact tried to rebel against it [...] Part of the problem was that the astronomical community generally had no appreciation of the complexity of satellite projects’. For many space novices, the amount of paperwork was one of the biggest shocks (Roman 2001, p 507, Baneke 2014, cf. Johnson 2002).

A final complicating factor was the sensitive political context, which was new to most astronomers. The high cost of each project ensured political attention, and all technology was closely connected to military and intelligence uses. On the whole, this benefited astronomy though. Missiles were turned into rockets to provide access to space; Cold War diplomacy opened possibilities for scientists from smaller countries to develop space instruments; X-ray and gamma ray detectors developed to monitor nuclear testing proved to be useful for astronomical observations; and military infrared detectors boosted infrared astronomy.

Robert Smith has characterized space research as ‘a gift of the Cold War’ (Smith 2011). Groundbreaking observatories such as Uhuru (x-ray, launched 1970) and IRAS (infrared, launched 1983) really opened new windows on the Universe. They were followed by a string of ever more powerful observatories (Tucker and Tucker 1986, Bleeker *et al* 2001, Rieke 2006, Giacconi 2008).

Access to space has opened many new windows on the Universe. It has revolutionized our knowledge about the life cycle of stars, the origin of planets, the nature of the interstellar medium, and many other aspects of the Universe. But while astronomers could use space infrastructure, the way of working was shaped by space, not astronomy (DeVorkin 2010). This meant that they had to get used to Big Science in all its aspects, including ‘Big Management’, ‘Big Money’, and ‘Big Politics’.

28.4 Merging instrument cultures

The opening of the electromagnetic spectrum created new subdisciplines like radio astronomy and high-energy astrophysics, each of which mostly used its own set of specialized instruments. In the last quarter of the twentieth century, astronomers increasingly started to combine different kinds of observations in their research: astronomy became ‘multi-wavelength’. The bright supernova of 24 February 1987 in the Large Magellanic Cloud was a breakthrough. It was observed with many different kinds of telescopes, vastly increasing our understanding of stellar physics. Apart from light, several neutrinos from the supernova were also detected, the first observed neutrinos from any astronomical object other than the Sun. This was another addition to the astronomers’ observational toolkit: not another wavelength but another kind of ‘messenger’ entirely (Jayawardhana 2014).

Interestingly, we can also see the multi-wavelength integration in the instrument culture. The differences in working with optical, radio, and space instruments diminished. Gradually, a new instrument culture of ‘Big Astronomy’ emerged. For one thing, all new telescopes were operated electronically, and electronic cameras and detectors became standard in all wavelength ranges. The era of chemical photography was over (McCray 2004, 2014). This meant that astronomers did their observations sitting behind a computer screen in a well-lit, well-heated control room,

physically separated from the actual instrument, whether they were using optical, radio, or space instruments.

On the other hand, space observatories also adopted some elements of ground-based instrument culture. The International Ultraviolet Explorer (IEU), launched in 1978, was the first space observatory at which all astronomers could apply for observing time. Guest observers could do their observations together with the staff of the NASA and ESA ground stations. For all practical purposes, this was similar to ground-based telescopes. The IUE really popularized space astronomy: it was used by a significant share of the world's astronomers during its 18-year lifetime (Massey and Robins 1986, Roman 2001). This way of working was later also used at other space observatories.

From 1990, a series of large space observatories was launched to investigate all wavelength ranges, starting with the iconic Hubble Space Telescope, which had been in preparation for many decades (Smith 1989). This multi-billion-dollar instrument became a popular icon, in part because of the dramatic story of the human repair mission to fix its flawed primary mirror, and of course because of the spectacular images that the Space Telescope Science Institute produced based on its observations (Kessler 2012, Launius and DeVorkin 2014). It was followed by European, American, and Japanese space observatories in all wavelength ranges (Russia, and later China and India, focused more on Solar System missions).

The end of the twentieth century also saw a revival of ground-based optical telescopes. In the 1980s, a series of experimental telescopes tested new technologies that paved the way for a new generation of large telescopes⁵. The first to surpass the iconic Palomar telescope was the Keck telescope in 1993, with a 10 m segmented mirror. It was followed by a series of 8 to 10 m telescopes, including ESO's rather unimaginatively named Very Large Telescope (VLT), which consists of four 8 m telescopes (McCray 2004, Woltjer 2006, Madsen 2012, Leverington 2017).

The new telescopes all produced data in electronic (increasingly digital) format, increasingly following international standards (Giacconi 2008, McCray 2014). This made it easier to share data and link different archives. The resulting data archives could also be used as 'virtual observatories' for new research. An important side effect was that this improved research opportunities for people who did not have direct access to expensive facilities.

Another kind of virtual telescope emerged in radio astronomy: observations from different radio telescopes could be combined to reach the resolution of a telescope the size of the distance between them. Eventually this 'very long baseline interferometry' could span the entire Earth and even extend into space. This required communicating and processing extremely large amounts of data, making astronomers pioneers in 'Big Data' science.

Most telescopes have multiple cameras, spectrographs, and other auxiliary instruments attached to them⁶. By the end of the century, these had become as

⁵ Most notably the American Multi-Mirror Telescope in Arizona, the European New Technology Telescope in Chile, and the Australian Advanced Technology Telescope in Australia.

⁶ In fact, the term 'instrument' in astronomy usually refers to these auxiliary instruments, not whole telescopes.

complex and expensive as entire telescope systems of earlier decades. Some ground-based telescope organizations started to treat them as independent projects. The instruments would be proposed and developed by separate consortia of academic institutes and high-tech industry, sometimes with their own funding. This practice resembled the way space agencies such as NASA and ESA recruited instruments for their astronomical satellites. The required level of precision of some ground-based instruments also approached that of space technology. In fact, some ESO managers explicitly talked about importing the ‘space culture’ of management and quality control (Woltjer 2006, Giacconi 2008, Madsen 2012, cf. McCray 2004, p 233).

By the end of the century, the largest telescopes were all operated by specialized organizations, as research ‘facilities’ or ‘infrastructure’ (Cramer and Hallonsten 2020). Some organizations, such as ESO, operated multiple telescopes; others were *ad hoc* consortia for specific instruments, such as the Canada–France–Hawaii Telescope. Most telescopes involve international collaboration. The number of countries involved has grown and diversified beyond the traditional North American and Western European countries. Japan, Spain, and South Africa operate 10 m class telescopes; South Africa, China, India, and other countries also operate leading radio telescopes, while many more have joined international consortia.

Most of the major ground-based optical telescopes are now concentrated in a few places with the best ‘seeing’ conditions, most notably Hawaii, Northern Chile, and the Canary Islands. There, multiple telescopes share basic infrastructure such as roads, water, and energy supply, even while the individual telescopes can be operated by different organizations.

28.5 Megascience

The 1990s saw the start of a veritable ‘telescope boom’, both on the ground and in space. But of course, astronomers being who they are, they were already preparing the next generation of instruments. These would be even bigger, with even ground-based ‘megascience’ instruments costing in the order of a billion dollars (on megascience: Hoddeson *et al* 2008, Jacob and Hallonsten 2012).

The first of the new generation of instruments was ALMA in the Chilean Atacama desert, fully operational since 2013. It is an array of dishes to observe millimeter and submillimeter wavelengths, until then a relatively underexplored part of the electromagnetic spectrum. It combines characteristics of radio telescopes (multiple dishes linked by interferometry) and space science (some technology, and its operation in an environment that is inhospitable for both humans and instruments, in a desert at 5 km altitude). Its European component is managed by ESO, which until then only operated optical telescopes.

ALMA originated as a merger between planned American, European, and Japanese instruments, with other countries joining later (Vandenbout 2004). This is also characteristic of the latest generation of instruments: they are unique and global. The planned Square Kilometer Array, a radio telescope that will be divided over South Africa and Australia, will also be one of a kind (Ekers 2012, Garrett 2013). The James Webb Space Telescope, launched in December 2021 after many

delays and cost overruns, will have unique capabilities. The telescope, which is regarded as the successor to the iconic Hubble Space Telescope, is mostly funded and developed by NASA, with several international partners⁷.

The next generation of optical telescopes will have mirrors of 30–40 m. Three of these ‘extremely large telescopes’ are in preparation, although the timeline of two of them is unclear⁸. Several other large ground-based and space instruments are also in preparation, both general observatories and more specialized instruments such as the Vera C Rubin Observatory, which will survey the entire sky every few nights. It will produce enormous amounts of data, further pushing astronomy’s role as a pathfinder in ‘Big Data’ processing.

In the meantime, other ‘Big Science’ instruments have become more relevant for astronomy as well. Neutrino detectors have increasingly been able to detect neutrinos from astronomical sources. And in 2015, the LIGO gravitational wave detector made the first confirmed observation of a gravitational wave. In 2017, the detection of another gravitational wave by LIGO and VIRGO could be identified with sources that could also be observed with other telescopes, marking a breakthrough in ‘multi-messenger’ astronomy. It has taken many decades to develop gravitational wave detectors; now they could be added to astronomy’s toolkit (Collins 2017, Schilling 2017).

The instrument culture of neutrino and gravitational wave detectors resembles that of high-energy physics, with very large teams of scientists and engineers cooperating on very specific experiments. This is different from the dominant culture in astronomy, where even the largest instruments were still predominantly used by fairly small teams. In 2005, the average number of authors of astronomical papers was about 5 (Abt 2007). But also in astronomy, this was changing. A spectacular example was the creation of a picture of the immediate surrounding of a black hole with the Event Horizon Telescope in 2019. The EHT is not one instrument but a global consortium of many radio telescopes. Its publications had hundreds of authors (The EHT Collaboration *et al* 2019). ‘Big Science’ indeed, albeit not with a single big instrument.

28.6 The impact of astronomy: two narratives

The stream of new telescopes from the last three decades has vastly increased our understanding of the cosmos. Astronomers can look farther into the Universe than ever before, see more details, and investigate more different wavelengths. More giant instruments are in preparation.

But these new telescopes are being developed in a very different context than the ones from the Cold War era. The end of the Cold War not only changed geopolitics, it also changed science policy. Astronomy may have been one of the biggest

⁷ I am looking forward to Robert Smith’s forthcoming book about the James Webb Space Telescope.

⁸ ESO’s Extremely Large Telescope (ELT) is under construction in Chile; two US-led international consortia are working on the Giant Magellan Telescope (GMT) in Chile and the Thirty Meter Telescope (TMT) in Hawaii or possibly the Canary Islands.

beneficiaries of the Cold War, but the new policy context did not favor astronomical research. Research was supposed to stimulate economic growth via ‘innovation’ and connections with private enterprise (Elzinga 2012, Crease and Westfall 2016, Hallonsten 2016, see also chapters 23, 24, and 33 in this volume).

According to some scholars, ‘Big Science’ did not fit easily into the new policy context. Large instruments lost their exceptional status; they were increasingly subjected to ‘normal’ science policy criteria of relevance and accountability (Elzinga 2012, Baneke 2019, chapter 33 in this volume). The ‘persistence of Big Science’ after the Cold War has even been raised to the status of research problem (Jacob and Hallonsten 2012). The case for Big Astronomy would seem especially problematic. Solar physics has some practical value because of the potential impact of solar storms on electrical equipment, and there are high expectations of future Solar System mining, but the commercial value of research time on large telescopes is negligible, apparently leaving only ‘pure science’ arguments to legitimize their funding (Williams and Mauduit 2010).

How, then, to explain the telescope boom of the recent decades? To understand this, it is important to realize that the image of astronomy as a ‘pure science’ with few practical applications, is only one part of the story, albeit a very powerful part. In its Strategic Plan, the International Astronomical Union (IAU) published an image of the impact of astronomy in different fields (figure 28.2). Two of the main sectors relate to research, but the third addresses ‘technology and skills’. These relate not to astronomical science, but to telescope technology and data processing, which

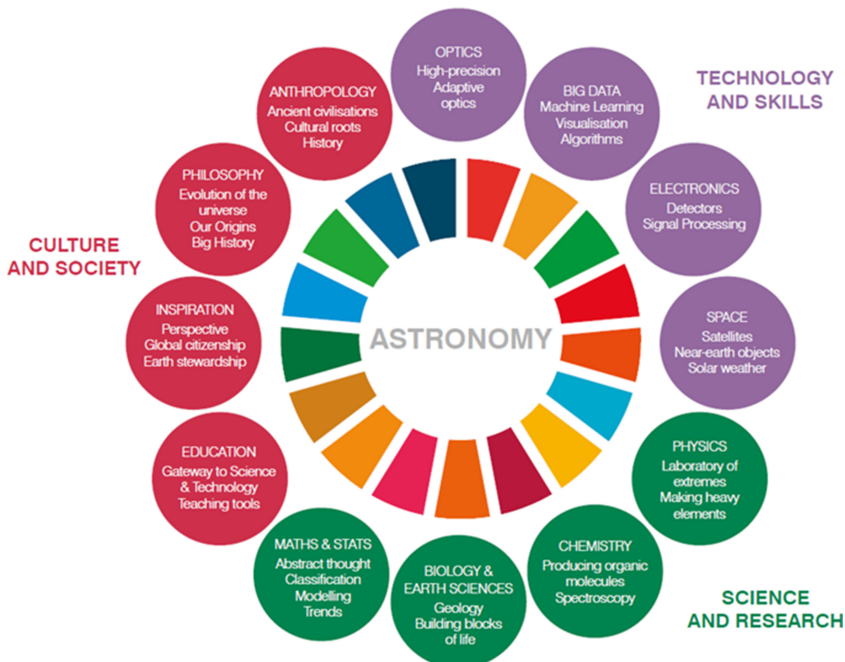


Figure 28.2. The ‘wheel’ image of the impact of astronomy (International Astronomical Union 2020, p 20, reproduced with permission).

have very clear connections to innovation and industry. So there are two complementary narratives about the impact of astronomy: that of pure, curiosity-driven science, and that of advanced applied technology. These two narratives reinforce each other in a unique way.

28.7 Research

The science and culture sections of the IAU's wheel image present the impact of astronomical research as a 'pure science'. It addresses big questions about the nature and origins of the Universe, life, and the fundamental laws of physics. The Universe provides extreme conditions that can never be replicated in any laboratory, revealing aspects of nature that could otherwise never be studied, which is of course interesting for scientists.

Outside academia, astronomy has a very strong cultural resonance, that sometimes borders on the religious ('inspiration' and 'philosophy' in the IAU's wheel). Astronomy is connected to fundamental ideas about humanity ('our origins' and 'cultural roots'), and realizing how small and fragile our Earth is in the vast cosmos ('perspective'). This has strong moral overtones, connecting to the unity of humankind ('global citizenship') and environmental issues ('Earth stewardship').

Astronomy is also connected to understanding the origins of the Universe, and increasingly the origins of life. This last topic has been boosted in recent decades by the study of exoplanets and the discovery of organic molecules in interstellar matter—and of course by the intense study of Mars (Lambright 2014). The cultural resonance of astronomy is also symbolized by iconic images such as the 'Pillars of Creation' and the 'Pale Blue Dot' (Kessler 2012). At the same time, despite the emphasis on 'origins', astronomy seems to have avoided major religious controversies in recent years, for example in comparison to evolutionary biology. The Vatican even operates a fully scientific observatory.

Because it has no obvious use, astronomical research has no ethical, political, commercial, environmental, or privacy-related downsides. While much astronomical technology has military connections, the link has always remained less visible than in the case of high-energy physics, for example. Together with its popular appeal and its universal image, this makes astronomy an appealing topic for international collaboration ('global citizenship' again). Even political opponents can agree on the value of astronomy, making it a great field for scientific diplomacy. The IAU is proud of the fact that North Korea and Syria joined recently (Andersen *et al* 2019). In addition, large telescopes are highly visible and prestigious. We should not underestimate the political importance of public appeal and the 'cool factor'.

All these effects make astronomy a perfect 'poster child' for science. Astronomy has a very strong popular presence in all kinds of popular science, educational activities, and public planetariums. New discoveries are frequently covered by mainstream news media. The International Year of Astronomy in 2008 was one of the largest science outreach events ever (Russo and Christensen 2010). Astronomers actively promote this image in their outreach, in particular

emphasizing how astronomy can stimulate a more general interest in science. This is actually a way to connect to innovation, by arguing that attracting children to science and technology will increase the innovative potential of a community or nation ('gateway to science and technology' in the IAU wheel, cf. the Astronomy for Development initiative, (IAU Office of Astronomy for Development [n.d.](#))).

28.8 Instruments

The third section of the IAU's wheel concerns 'technology and skills', referring to optics, electronics, space technology, and Big Data. These fields are crucial for the development of large telescopes, not least Big Data—modern telescopes produce unprecedented amounts of data, pushing astronomers to become pioneers in data processing on the largest scale, especially in filtering out noise. But these are also all fields of high economic and social value. Astronomers are quick to point out the links between astronomical and medical imaging technology, for example, or between radio astronomy and wifi (Downer *et al* 2019).

The message is that funding a telescope is not just an investment in astronomy, but also in technology and innovation. This of course provides an important legitimization for funding in an innovation-centered policy context. Since much of the funding for astronomy concerns instrument development rather than astronomical research, this is a major addition to the 'pure science' narrative. The technological development does not stop after the telescope starts scientific operations, because the auxiliary instruments can be renewed—most ground-based telescopes have multiple generations of cameras, spectrographs, and other instruments over their lifetime.

Telescope and instrument development and construction are well-defined projects with a clear timeline, matching the project-based structure of modern science funding. Major telescopes also involve major contracts for industry, so there are commercial interests involved as well—again, in contrast to 'pure' astronomical research.

Other than astronomical research, telescopes can be controversial. The Hubble and James Webb Space Telescopes have been the topic of fierce political debates, because of their sheer cost (Smith 1989 and forthcoming). There is also diplomatic competition for hosting large instruments, which are expected to add prestige and (economic and scientific) benefits to the host country.

Some of the controversies about the location of ground-based telescopes are more sensitive. Because they need remote locations, far from any (human) interference, telescopes are often built in protected natural areas. Some locations are also controversial for cultural and religious reasons. The most notable example is Mauna Kea in Hawaii, home to several of the world's largest telescopes, which is held sacred by the Hawaiian population (Swanner 2017).

28.9 The dual narrative of impact

The two complementary narratives of impact make building telescopes appealing projects from a political point of view. Just like the 'dual use' nature of astronomical technology was an advantage during the Cold War, the combination of fundamental

scientific questions with innovative telescope technology is a benefit in current-day science policy.

Either narrative can be emphasized, depending on the audience: funding agencies, politicians, science diplomats, academic boards, or the broader public. Large telescopes can be legitimized as investments in fundamental science, but at the same time most of the funding will go to advanced technology. Or, conversely, telescopes can be ‘sold’ as stimulating innovation without them having to be directly useful as scientific instruments. This differs from the post-Cold War ‘transformed Big Science’ or ‘megascience’ that some authors have described, in which Big Science facilities are expected to provide more direct economic and practical benefits, including via use of the facilities by private parties (Hoddeson *et al* 2008, Hallonsten 2016). The dual narrative of astronomy provides an interesting case study for Hallonsten’s analysis of the simultaneously grand and practical expectations connected to current-day Big Science (chapter 33 of this volume, cf Baneke 2019).

Another interesting example of the possibility provided by the dual narrative can be found in the controversies about telescopes on sacred sites. Leandra Swanner has described how astronomers invoke the universality and spiritual meaning of astronomy in their attempts to reach out to the opponents of the telescopes (Swanner 2017). In other words, they try to switch the debate from the instrument-focused narrative to the universal science one.

An excellent example of the combination of the two narratives can be found in South Africa, where the post-Apartheid regime invested strongly in astronomy. The choice for a ‘pure science’ was explicitly intended to underline that South Africa was not ‘just’ a developing nation that had to prioritize practical needs. But, at the same time, the decision to fund the construction of the 10 m South African Large Telescope (SALT) was also supported by the technological narrative and the benefits for local industry (Whitelock 2004). The IAU’s Office of Astronomy for Development, based in Cape Town, explicitly uses the two narratives in a similar way to argue for investments in astronomy in all countries, regardless of their GDP (IAU Office of Astronomy for Development [n.d.](#)).

28.10 Conclusion

Astronomy is dependent on a constant supply of new large telescopes, both scientifically and institutionally. In the course of the twentieth century, astronomical instruments have become separated from research institutes. Hale famously moved telescopes away from universities, to places where the ‘seeing’ conditions were optimal. This has become common practice, so that most ground-based telescopes are now concentrated in a handful of locations on Earth. Space telescopes are even further away of course, but as I have shown, in practice, the difference in using ground-based and space instruments has all but disappeared. Their instrument cultures have merged into multi-messenger and multi-instrument astronomy. Telescopes have also become separated from research on the institutional level. We have seen how, since 1945, large telescopes have increasingly been built and operated by dedicated international organizations.

In the same period, another separation between instruments and research has emerged on the level of policy, funding, and legitimation. Much of the funding for astronomy is devoted to instrument development and construction, not use. This has given rise to a ‘dual narrative’ about the importance and impact of astronomy: a scientific and cultural narrative on the one hand, and a technological and economic one on the other hand. The two narratives do not contradict or obscure each other; they rather reinforce each other in a unique way. They provide flexibility in different policy contexts and for different audiences. Understanding the dynamics of the dual narrative of impact helps to understand the remarkable public, political, and financial support for Big Astronomy.

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