Chapter 2
Beyond the Hubble Space Telescope: Early Development of the Next Generation Space Telescope

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Abstract In this paper we investigate the early history of what was at first called the Next Generation Space Telescope, later to be renamed the James Webb Space Telescope. We argue that the initial ideas for such a Next Generation Space Telescope were developed in the context of the planning for a successor to the Hubble Space Telescope. Much the most important group of astronomers and engineers examining such a successor was based at the Space Telescope Science Institute in Baltimore. By the late 1980s, they had fashioned concepts for a successor that would work in optical, ultraviolet and infrared wavelengths, concepts that would later be regarded as politically unrealistic given the costs associated with them. We also explore how the fortunes of the planned Next Generation Space Telescope were intimately linked to that of its "parent," the Hubble Space Telescope.

2.1 Introduction

Very large-scale machine-centered projects have been a central element in the physical sciences since World War II, especially in North America, Europe, and Japan. Built with the support of national governments, often working together in international partnerships, these endeavors cost hundreds of millions or even billions of dollars and engage the efforts of armies of scientists and engineers. The biggest of these projects have typically taken decades to bring to fruition. For scientists, their construction has been in large part an act of faith that new and powerful new scientific instruments will surely lead to novel and exciting scientific results.[1]

The journey from conception to completion for such endeavors has usually been fraught with assorted challenges and difficulties, and in some cases these have led to a project's demise years after detailed work has begun. A striking example of this is the 1993 cancellation of the Superconducting Super Collider, a high-energy physics accelerator, after the Department of Energy spent over $4 billion on its design and construction.[2] In general, however, scientists and scientific communities have

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become increasingly adept at enlisting broad involvement in proposed programs, thereby building stronger bases of support that enable advocates to better resist threats of cancellation. Such very large-scale efforts have also resulted in unique and extremely powerful tools that have greatly expanded as well as helped to intellectually reconstitute scientific disciplines. A leading example of this phenomenon is the Hubble Space Telescope.

The space and scientific agencies, as well as the scientific and engineering communities, engaged in such enterprises have often faced a number of critical and sensitive issues. One is when to initiate serious design work on new machines that will replace those in operation, being built, or being planned. Another is the question of when to decommission instruments already doing productive research. Given the very long lead times from conception to operation, engineers and scientists have often wanted (or been forced) to begin planning the next big machine years or decades before securing any scientific results from the one under construction, results that of course might well have the potential to shape or revise design decisions.

In this paper we will examine how a scientific community and its constituent sub-communities took the first steps towards the construction of what was initially called the Next Generation Space Telescope (renamed by NASA in 2002 as the James Webb Space Telescope in honor of NASA's administrator between 1961 and 1968). Scientists and engineers initially conceived the NGST in the mid-1980s as a successor to the Hubble Space Telescope (HST), some years before this observatory began scientific operations in orbit around the Earth in 1990.

There were initially two parallel tracks to the NGST's early history. In one there were a range of developments in infrared astronomy that would prove later to be crucial for NGST planning. In the second track, advocates explored a successor to the Hubble Space Telescope that would operate in ultraviolet, optical, and infrared wavelengths, just as the Hubble was supposed to do. These two tracks would ultimately come together in the mid-1990s and prompt NASA to issue a study contract in October 1995 for feasibility studies for a Next Generation Space Telescope. In this paper, our focus is on the second of these two tracks, and our main narrative thread is provided by the way in which scientists and engineers examined a wide range of design options for the NGST early in its life.

The largest of large-scale scientific tools require not just the enthusiastic endorsement of small groups of scientists and engineers, but the whole-hearted support of entire scientific communities, generally in more than one country because projects of the largest scale typically involve international collaborations. We therefore ask how advocates worked to form a consensus around some basics of the design of the NGST. This effort helped to create a favorable climate of opinion, a key step towards winning broad approval for an NGST by persuading colleagues it might be not just technically feasible but also perhaps politically feasible. As we will see, space astronomy has been in one respect a remarkable adventure of the human spirit, but in the U.S. it has also been pursued in a highly competitive environment with often intense debates and conflicts over resources and priorities. That is, the resultant mission is rarely a consensus design, but rather the "winner" of a contentious process.

2.2 A Successor to the Hubble Space Telescope

In its early years, NASA supported space astronomy in various wavelength regions, although the agency gave the edge to UV and optical astronomy from the start. Studies in the different wavelength regions nevertheless ran a similar course in that research generally started with survey missions, leading in time to very versatile but complex and costly spacecraft. The pace at which a particular wavelength region reached the stage of what would later be called "Great Observatories" or "Flagship" missions differed. As UV and optical investigations had gained an early lead, the large-scale observatory in this region came first in the shape of the Hubble Space Telescope (HST).

From the early 1970s on, the HST was the key space telescope in NASA's planning.[3] By 1974, this was a joint effort of NASA and the European Space Agency, although NASA was the dominant partner. NASA, of course, has been primarily a technical management agency. When it comes to pursuing astronomy, NASA has mostly provided money, facilities and management expertise. The design and construction of hardware and software themselves has come very largely from industrial contractors that NASA oversees and coordinates. NASA, of course, has its own institutional interests, of which astronomers outside the agency must be mindful to get built the tools they desire. NASA, however, is not a monolithic agency. Different groups within the space agency often have somewhat different or even contradictory interests. NASA's history is replete with many examples of the tensions, for example, between its different several field centers as well as between the field centers and NASA Headquarters in Washington D.C.[4]

The idea of building a successor to HST also seemed obvious to some, but by no means all, astronomers almost from the start of serious planning for Hubble. Detailed design and construction of HST began in 1978 following White House and Congressional approval of the project, by which time astronomers had generally accepted the view that "the whole history of science, and particularly of Astronomy in recent years, tells us that progress depends on the development of new instruments which give us new ways of looking at the world."[5] The main advocates in the 1980s of a successor to the Hubble Space Telescope, as we shall see, were based at the AURA-managed Space Telescope Science Institute (STScI) in Baltimore. There was therefore an aspect of "institutional maintenance" too to this effort. Once the HST's mission was over, so was the Institute's, unless new business, perhaps in the form of a successor to the HST, was in the offing. Thus, long range scientific planning meshed nicely with institutional maintenance.

Even before the Hubble Space Telescope was launched, the central question for many astronomers was *not* "Should a successor to the Space Telescope be built?", but rather how much the successor to the Hubble Space Telescope should differ from the HST itself. Of special importance was whether they should simply scale up Hubble to what seemed likely to be a "do-able" size, given whatever technology would be available at that future time. By the mid-1980s, Hubble's mirror, 2.4 m in diameter, was quite small by the standards of state-of-the-art ground-based telescopes, either under construction or in planning. Scaling up to a bigger mirror size and fashioning a generally larger version of Hubble was therefore an attractive option to at least explore. The limit to how big a mirror they might reasonably argue for would likely be set by the perceptions of what cost its patrons in the White House and Congress would support. On the other hand, instead of a simple scaling-up, supporters of the new space telescope could be even bolder and press for radical, and therefore quite probably more risky, technological choices. This could also include a major mission that would operate at different wavelengths than Hubble, thus opening a new "window" in exploring the Universe. Addressing the question of how far to push the technological boundaries as well as simply determining what they were and what the "political system" would support demanded in part that astronomers and engineers integrate various elements from existing state-of-the-art telescope designs into their planning. It also required that eventually they take the expertise of industrial contractors and the military into account as they had very extensive experience in both planning and building complex satellites for a variety of national security purposes.[6]

The various contractors who might be involved in planning for, managing or building such a machine also had self-interest in proposing some sort of successor to the Hubble Space Telescope. For example, in 1980, NASA's Marshall Space Flight Center considered a plan to launch an 8 m space telescope into low-Earth orbit in the external tank of the space shuttle. In the following year, the company responsible for the optical elements of the HST, Perkin-Elmer, published an article on "Space Astronomy." Included here was a concept for an optical-ultraviolet telescope in space with a mirror 8 m in diameter (a very big step up from the 2.4 m diameter mirror for the HST). Malcolm Longair, one of the leading European astronomers working closely on the HST and at the time Astronomer Royal for Scotland, carried this idea further when in 1983 he argued that many "exciting projects are being converted from gleams in the eye of the astronomer into feasible astronomical projects, the only limits being those of the imagination of the astronomer and the more important limits of funding and manpower. Examples of these types of project include a very large space telescope for optical and ultraviolet observations. An aperture of up to 10 m . . . would represent a huge increase in scientific capability over even the Space Telescope."[7]

During the 1980s, the idea of such a successor to the HST was pressed most enthusiastically by a group of staff members at the Space Telescope Science Institute. Key in this respect was the Institute's director, Riccardo Giacconi. Giacconi, arguably the leading figure in the establishment of x-ray astronomy, shared the Nobel Prize for Physics in 2002 for this work. From hard experience of flying and planning x-ray satellites, Giacconi knew that the lead times for large-scale space observatories could be counted in decades. If there was not to be big gap between the end of the life of the Hubble Space Telescope and its successor, it was essential to get planning underway well before HST was launched.

By 1986, a small group at the Institute was thinking hard about such a successor. The group included astronomers Garth Illingworth and Peter Stockman, as well as Pierre Bely, an engineer with experience of large ground-based telescopes as well as space astronomy. In that year, Bely wrote a paper that laid out some of the details for a 10 m optical telescope in space. He considered, among other things, the size, cost, and location of such a telescope. In line with Giacconi's own thinking, Bely contended that although the Hubble Space Telescope was not yet launched, its limited operational life of 15 years and experience that it takes from ten to fifteen years to complete a large astronomical telescope, meant "it soon will be time to start making serious plans for its successor."[8] Bely reported that several designs had already been advanced. He promoted a general purpose observatory in space that would be as "unspecialized"[9] as HST. By "unspecialized," Bely meant that the new observatory, like HST, should have a wide, rather than a narrow, range of capabilities – a general-purpose observatory, which would also have political appeal to a broad range of astronomical communities.

The new telescope, however, should be a much more powerful scientific tool than the HST: among other things, it should have a bigger mirror and greater resolving power, and cover the wavelength range from the ultraviolet through the optical to the infrared. Bely considered costs, where such a telescope should operate from, whether or not it should be an international venture, the options for the size and type of main mirror, and a number of other issues. In the end, he advocated further studies of a telescope with a primary 10 m in diameter placed into geosynchronous orbit; that is, an orbit some 22,000 miles or so above the Earth, so that it would always be above one part of the planet. This location was sufficiently far from the Earth that the Earth would not block out large sections of the sky, a serious handicap for the Hubble Space Telescope designed to orbit only a few hundred miles above the Earth, which was at the time the limit to the altitude to which a larger optical system could be launched by the system – the Space Shuttle – that was available to the astronomers. Bely's initial design criteria proved to have significant longevity as the NGST began to take shape.

2.3 The Space Studies Board

Since the American government established NASA in 1958, the agency has maintained important links with the National Academy of Sciences. Charged, among other things, with providing advice to the government, the National Academy of Sciences had formed the Space Sciences Board (later renamed as the Space Studies Board [SSB]) at the dawn of the Space Age with the specific intent of using the Board to provide advice to NASA. Although the relationship between the SSB and NASA has sometimes been fraught, in the opinion of some critics, the National Academy quickly became a form of "shadow government" whose backing was often reckoned to be critical if a new project was to proceed. The Space Studies Board's recommendations therefore generally carried clout, and its reports can become crucial political resources. If a successor to the HST was to come into being, it would surely need the strong backing of the National Academy.

In 1988, the Space Studies Board released a report that detailed key scientific issues they anticipated that space scientists would tackle from roughly 1995 to 2015.

Space Science in the Twenty-First Century: Imperatives for the Decades 1995–2015, outlined three main areas for astronomy and astrophysics, one being "large area and high-throughput telescopes."[10] The SSB also recommended NASA consider an optical telescope with a mirror 8–16 m in diameter: "A large aperture space telescope for the ultraviolet, optical, and infrared regions has immense scientific potential. The need for such a telescope will be very high after 10 to 20 years use of HST and ground-based 8-to 10 m-class telescopes," the report contended. "Even now we see that some of the most fundamental of all astronomical questions will require the power of a filled-aperture telescope of 8- to 16-m diameter designed to cover a wavelength range of 912 Å to 30 μm [that is, from the ultraviolet to the mid-infrared] with ambient cooling to 100 K to maximize the infrared performance."

The report also noted that both the Hubble Space Telescope and SIRTF (the Space Infrared Telescope Facility, a medium-aperture infrared telescope at this time slated to be carried into space intermittently by the Space Shuttle), which had yet to be launched, with the expected wealth of date yet to be analyzed so "it is difficult but not premature to formulate a detailed concept of such a large-scale telescope for the ultraviolet, optical and infrared regions." The report's authors nevertheless extolled the increased performance of such an instrument compared to the Hubble Space Telescope. In their opinion, there was a wide range of scientific problems that could be tackled only by a telescope of this type. The extra light-gathering power and resolution, combined with advanced instruments and detectors, "would lead to a quantum leap in our understanding of some of the most fundamental questions in astronomy."[11] But they stressed it would "not simply be a scaled-up HST." Unlike the HST, the new telescope's optics could be cooled to "at least the lower limit of passive radiation methods, about 100 K[12]", and so its infrared performance optimized. [The great challenge with infrared observations is to ensure that the thermal emission from the telescope itself does not swamp the radiation the telescope is detecting from astronomical objects.] For an 8 m class telescope, a large launch vehicle could carry it to orbit, while a 16 m telescope would require the segments of its mirror to be lofted into space and then assembled onto a structure. Also, the group reckoned that an 8–16 m telescope was "within closer reach than a simple extrapolation form HST would suggest."[13]

2.4 Beyond the Hubble Space Telescope

In 1988 STScI scientist Garth Illingworth gave a presentation on "The Next Generation: An 8–16 m Space Telescope" as part of the International Astronomical Union's General Assembly in Baltimore in 1988. He posed the basic question "*What is the UV-Visible-Optical Observatory that will follow HST*?" First, he made the case for a successor, what he referred to as "Son of HST" or maybe "Daughter of HST." He presented two arguments in making his case: continuity and discoveries. HST offered broad capabilities and the scientific case for such an observatory would be as true in the future as it had been for HST back in the 1970s, both to carry out major observing programs and to support other missions. New facilities, such as a next generation telescope, would "open up new 'discovery space' by a significant amount." About the same time, a popular book and accompanying articles on *Cosmic Discovery* by Cornell astronomer Martin Harwit was widely quoted among astronomers. According to Harwit, an increase in instrument sensitivity of 2–3 orders of magnitude were typically required to achieve major "discoveries;" that is, an increase in telescope diameter of 3–5 along with new generations of instruments. In line with the 1988 Space Studies Board report, Illingworth described the observatory he would prefer to study, one with a 16 m primary (perhaps with a segmented design made up of four 8 m parts) that would be passively cooled to around 100 K, be in geosynchronous orbit, and operate in the wavelength range from 0.1 μm to longer than 10 μm, thereby providing an extremely powerful telescope that could operate from the ultraviolet well into the infrared. As to timing, he noted that in 1962, the National Academy of Sciences had held a workshop that produced "A Review of Space Science," and recommended a large diffraction-limited space telescope, in effect a recommendation for what became HST. This meant there had been more than 25 years from a major recommendation to launching HST (he was speaking about a year before its launch). Hence, to ensure a successor to the HST in 15–20 years – that is, around 2005–2010 – "now is clearly the time to move."[14] Even more sobering, what would become the Space Infrared Telescope Facility (SIRTF) and today the Spitzer infrared "Great Observatory" was first proposed to NASA in the summer of 1971 and launched slightly more than 30 years later.

A year after Illingworth gave his presentation at the International Astronomical Union, over 130 astronomers, engineers, and science managers met in Baltimore at the Space Telescope Science Institute to plan what was now called "The Next Generation Space Telescope." This gathering proved a key step in moving beyond the Hubble Space Telescope to the 'Next Big Machine' for space astronomy. The Baltimore meeting was of a kind that astronomers frequently held. Such meetings offer a convenient forum for members of the science and engineering communities to acquaint themselves with what their colleagues are doing, exchange ideas, advocate particular choices, impress potential patrons and possible partners, build a base of support among scientists, and generally move a project forward. As one participant explained, "No one goes away from these meetings and says 'I've seen the Holy Grail and so-and-so has it.' They are to inform people and get everyone up to the same level before they can move on to the next level."[15] Attendees at the 1989 workshop learned of several diverse designs already vying to become the Next Generation Space Telescope. Some were relatively new while versions of others had circulated throughout the astronomy community for years, again a common practice in astronomy by this date.

Garth Illingworth chaired the meeting's science committee. He described his colleagues' goals as "very ambitious and challenging, but realistic extrapolations of current technology."[16] The organizers of the Baltimore meeting presented their colleagues with two "straw man" designs to focus their discussion – one was a space telescope with a 10 m mirror orbiting the Earth. The second was even more exotic: a 16 m telescope on the lunar surface, its proposed location reflecting NASA's very short-lived commitment to a new policy announced just weeks earlier by President George H.W. Bush on 20 July 1989, the twentieth anniversary of astronauts landing on the Moon. This proposed program, known as the Space Exploration Initiative (SEI), envisaged a relatively swift return by the United States to the surface of the Moon and the start of planning for a human expedition to Mars.[17]

NASA and the astronomy community responded to Bush's proposal (and the hope of massive funding that might become available) by rapidly developing optimistic plans for Moon-based astronomy facilities. One idea suggested by NASA's Marshall Space Flight Center (at the time the lead NASA center for the development of the Hubble Space Telescope) was a Large Lunar Telescope. These schemes pictured a 16 m telescope (with a segmented mirror) that would be assembled robotically or perhaps by teams of astronauts. In the planning for the Hubble Space Telescope some two decades earlier, the option of a large Moon-based telescope had also been raised. For a time the name of the proposed telescope was the Large Orbital Telescope, but this was changed to the more neutral Large Space Telescope so as to leave open the possibility of basing it on the Moon. Bush's ambitious, but politically unrealistic, plan faded swiftly away and carried off with it the idea of a lunar telescope. Marshall's planning initiatives nevertheless underlined the space center's interest in some sort of role in the NGST project.

Astronomers considered other locations for the proposed Next Generation Space Telescope. One option that engineers advanced was a low-Earth orbit achieved via the Space Shuttle, which is where the HST would be located. Another involved flying the telescope to one of the Lagrangian points. Located about a million miles from Earth, this piece of cosmic real estate was reckoned by many advocates of NGST as having excellent qualities for a space observatory: it is very cold and dark and a long way from the Earth. But placing a telescope at a Lagrangian point would also eliminate the option of having visiting astronauts service and upgrade it, at least so long as the Shuttle was the only means to flying U.S. astronauts into space. The proposed location for an NGST was, as we shall see, a critical element in the efforts to develop a telescope that would be far less expensive than a scaled-up version of the Hubble Space Telescope.

The debate and negotiations that ensued on the possible location of an NGST as well as other issues revealed several critical problems that astronomers and engineers reckoned they needed to resolve if they were to make serious progress towards a Next Generation Space Telescope. One pressing issue was the design and size of the telescope's primary mirror. Astronomers generally regard the primary mirror as the single most important component of any telescope. Its size and quality determine how much light the telescope can collect and the worth of the data it produces. At the Baltimore meeting engineers and industrial contractors touted the optical quality of Hubble's 2.4 m mirror, which at the time was generally reckoned to be superb (which of course was not in fact the case). A 10 m mirror would collect twenty times as much light as HST and, other things being equal, yield much superior images and even more exciting data.

Even a 16 m mirror was discussed. Not widely appreciated at the time was a prescient design by a Swales engineer, Philip J. Tulkoff, that proposed a 10 m space

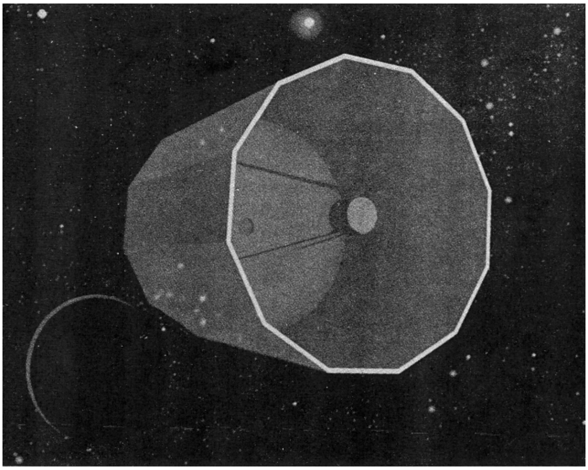

Fig. 2.1 Artist's concept of a 10 m next generation space telescope as envisaged in 1989

aperture telescope that could be passively cooled to between 70 and 100 K, permitting very sensitive observations well into long infrared wavelengths and a modest step in breaking the engineering paradigm of the time that infrared space telescopes required complex and heavy liquid cryogen systems.

As already noted, by 1989 the size of Hubble's mirror was decidedly modest by comparison with ground-based telescope. By the 1980s, the standard size of telescope mirrors for ground based instruments was in the 4 m range while astronomers and engineers were already well-along in building telescopes with mirrors that sported mirrors as large as 10 m (Fig. 2.1). Astronomers reckoned, however, that HST's location far above the turbulent atmosphere would allow it to collect images of exquisite detail while working 24 hours a day and these factors would more than offset the fact that in terms of size its mirror was far from the state-of-the-art in 1989. HST's mirror was also relatively heavy in comparison to the new lightweight technologies NASA and the military desired. Putting objects into orbit in the era of the Space Shuttle was – and remains – extremely expensive, and designers of scientific spacecraft in the 1980s and 1990s, therefore, saw reducing weight wherever possible as a crucial problem. Designers also knew that the heavier a scientific satellite generally the more it would cost. Developing the capability to make very big lightweight mirrors, sometimes called "gossamer optics,"[18] was clearly generally reckoned by the participants at the Baltimore meeting to be the most significant technical obstacle to building the NGST.

The design of NGST's primary mirror certainly became one of the project's so-called tall poles,[19] just as it had been for the Hubble Space Telescope. That is to say, designing and fashioning the primary mirror to the required specifications might entail such difficulties that it would hold up the project (aka, the "tent") and other problems would tend to get lost beneath the canvas – problems that would be present, certainly, but not so pressing or so visible. If astronomers were going to launch any Next Generation Space Telescope, it was already clear to its advocates in 1989 that they needed to reduce radically the weight of the mirror from what they could expect if they simply scaled-up the HST mirror design. Such a procedure would lead to a hugely expensive telescope, and a key concern at the meeting was the overall cost of an NGST. Hanging over the proceedings was the need to "break" the cost curve of the HST as an extrapolation of this curve would mean, unless the political context changed radically, an impossibly expensive telescope that would never be built.

George Field, a prominent astronomer who had been a champion of the Hubble Space Telescope in the 1970s, suggested at the Baltimore meeting that the price of a telescope in low Earth orbit with a mirror of diameter D (meters) would be about $\$3.8(D/10)^{1.7}$ billion in 1986 dollars.[20] If a 16 m telescope were placed on the Moon, the new estimate for the telescope alone would be $8.4 billion in 1986 dollars. As Garth Illingworth noted in his presentation, one scaling law used for the cost of telescopes reckoned that the cost rose as the 2.7th power of the diameter. HST's cost for design and development was around $2 billion, so applying "such a factor for a 10–16 m class telescope based on HST's cost leaves one gasping." But Illingworth contended that recent large ground-based telescopes had "broken" this "cost curve," which had been established by telescopes built in the 1950s to the 1970s, by a factor of 4, with more gains in the "pipeline." Critical was savings in weight, which translated into cost savings. Illingworth judged that as "we can see from the discussion at this meeting, this is an area where major improvements in fabrication and polishing techniques are occurring. The combination of improved performance and lower weight for the optical segments will directly and dramatically affect the final cost of the NGST."[21]

In the published report of the Workshop, five statements and recommendations were presented as representing the spirit of the collective opinion of the participants and are worth quoting here at length. There were:

1. Scientific Objectives:

There will be a definitive need to continue and extend the observational capability offered by HST beyond its predicted lifetime. A gap of more than 5 years would be a blow to the vitality of forefront astronomical research.

The scientific potential of an HST follow-up mission with enhanced flux collecting power and spatial resolution, and with spectral coverage extended through the near-infrared is enormous.... An observatory providing high sensitivity and high-throughput spectroscopic capability at diffraction-limited spatial resolution from the UV to beyond 10 microns is vital for the study of the most fundamental questions of astrophysics. These include the formation and evolution of galaxies, stars and planets, and the nature of the young universe.

2. Technological Readiness:

A telescope in the 10–16 m class is not an unrealistically large step beyond the current state of technological development. While development and demonstration programs are clearly needed, many of the core technologies are maturing to the point where the required goals appear to be within a very reasonable extrapolation of the current state-of-the-art. In particular, advances in the fabrication of lightweight optics and new techniques for polishing have the potential for very substantial weight savings and hence cost savings, while offering optical performance beyond what was possible in the past.

3. Siting:

Both the Moon and high Earth orbits are suitable sites for [the] next generation space telescope. Low Earth orbits are undesirable because of high disturbance levels, insufficient passive cooling and low observing efficiency.... Space-based and lunar-based designs should be pursued in parallel for the next few years to clarify the observational, technical, space logistical and cost tradeoffs.

4. Programmatic approach:

A 10–16 m (space-based) to 16 m (lunar-based) aperture is considered a realistic goal. Future workshops should concentrate on further definition of the scientific objectives, review of preliminary studies and the identification of critical technologies. Strawman designs should be prepared to refine the various concepts and ideas and to focus discussion.... In projects of this complexity, efficient design is the result of many compromises that can only be developed by successive iterations and by system-level analyses. The importance of this iterative process involving astronomers, physicists and engineers in the science-engineering tradeoffs and in defining the requirements was emphasized by many participants. The involvement of these different groups needs to occur during all phases of the project, from concept to development, through technology development and fabrication, and finally during system-level testing.

Once clearly identified by the preliminary design process, the development of the key enabling technologies should be integrated with the appropriate long-term program of the national and international Space Agencies....

5. International cooperation:

Like HST, the next generation space telescope project should be carried out cooperatively as an international program. Cost sharing renders such major missions more affordable for each participating country, and international collaboration often enhances quality and performance. Complex and pioneering space missions also benefit from the exchange of ideas and variety of approaches afforded by multicultural associations.[22]

Co-operation between NASA and the European Space Agency was very much "in the air" at the Workshop. Duccio Machetto, an ESA astronomer based at the Space Telescope Science Institute, spoke on "ESA['s]" Long Term Plans and Status. He noted that "There is a large interest in the astronomical community in Europe for HST and also in a future HST. It is therefore important to include the European astronomical scientific community in a possible joint venture in a 10–16 m next generation space telescope."[23] Further, one page of the published report of the Workshop also carried a section headed "Sage Advice." Here John Bahcall, a leading and very influential astronomer who had played a pivotal role in winning Congressional approval for the Hubble Space Telescope in the 1970s and so making the HST politically feasible, was quoted as arguing that "International cooperation may be critical for such a major project."[24] Ultimately, the James Webb Space Telescope would be a cooperative venture of NASA, the European Space Agency, and the Canadian Space Agency. At this stage, however, none of the astronomers and engineers who attended the workshop was based at Canadian institutions, although there was already strong European interest. Indeed, as we shall see in subsequent work, the European space agencies were in many cases offering the astronomy communities more frequent opportunities at this time to fund advanced post-HST concepts than NASA.

2.5 The Decade of the Infrared

As astronomers and engineers met in Baltimore to discuss an NGST, work was already proceeding on what became known as the Bahcall Committee report, as this very large scale effort at planning was chaired by John Bahcall. We have already discussed the importance of advice from the National Academy of Sciences in shaping NASA's priorities. Hence a significant hurdle came for the NGST when in early 1989 the National Research Council commissioned the Astronomy and Astrophysics Survey Committee to review the field and produce a series of recommendations on new ground-based and space-based programs and observatories. The Bahcall Committee's recommendations were based on studies by fifteen advisory panels that represented various wavelength regions and particular areas of astrophysics. In all, advice came from over 300 astronomers who served on these panels, and another 600 or so wrote letters, essays, or delivered oral presentations at various open meetings.

In line with the usual thinking of astronomers by this point, the Committee argued in its final report that "Progress in astronomy often comes from technological advances that open new windows on the universe or make possible large increases in sensitivity or resolution. During the 1990s, arrays of infrared detectors, the ability to build large optical telescopes, improved angular resolution at a variety of wavelengths, new electronic detectors, and the ability of computers to process large amounts of date will make possible an improved view of the universe."[25] The Committee went on to package their conclusions by proclaiming the 1990s as "The Decade of the Infrared" and expected that the "technological revolution in detectors at infrared wavelengths will increase the power of telescopes by factors of thousands."[26]

The panel on ultraviolet and optical astronomy, which was chaired by Garth Illingworth, who we have seen was an active champion of a successor to the HST, strongly recommended building what the panel termed the "Large Space Telescope." This would be a 6 m telescope operating in the ultraviolet, the infrared, and the optical, and the panel urged that it be flown within a few years of the end of the expected 15 year life of the HST (then assumed to be 2005). The panel therefore proposed starting the Large Space Telescope in 1998 so that it could be completed by 2009. The Large Space Telescope would later be followed by "a telescope of astonishing power," the 16 m Next Generation Space Telescope, which the panel judged should naturally be located at a lunar outpost,[27] again assuming a major NASA program capable of placing and operating complex facilities on the lunar surface at a cost and timeframe acceptable to the astronomy community.

With the Bahcall Committee charged to recommend the most important new initiatives for the decade 1990 to 2000, it in fact advocated neither the Large Space Telescope nor the Next Generation Space Telescope. Even the Large Space Telescope was costed at $2 billion and in 1991 very large scale astronomy projects were standing in the shadow of the Hubble Space Telescope, which had been launched in 1990 but, as we shall see later, its early performance had failed badly to live up to its advance billing. While the Bahcall Committee did not give explicit reasons why it chose not to back the Large Space Telescope, they certainly judged it premature to give it a top priority. In particular, the Bahcall Committee assessed what it reckoned to be the critical technological initiatives for the 1990s so as to “form the basis for frontier science in the decade 2000–2010.” $50 million, the Committee argued, should be spent developing technologies for large space telescopes.[28] Contending that “we must begin now the conceptual planning and technological development for the next generation of astronomy missions to follow the Great Observatories,” they cited as one example the 6 m Large Space Telescope operating in the ultraviolet to the infrared. They discussed other possible missions too, including a very large x-ray telescope and a submillimeter observatory consisting of a deployable 10 m telescope. It did not, however, make a choice between the different options, judging that the “scientific imperatives and the infrastructure available at the time of selection will influence which missions are chosen.”

Among the technical issues, they reckoned, would be the construction and control of lightweight systems, the capability of launch vehicles, advances in robotic constructions techniques, as well as the possible availability of facilities on the Moon. “The technology development programs listed [in this report],” the Bahcall Committee claimed, “will provide part of the factual basis required for decisions about future astronomical missions.”[29]

2.6 A Road Not Traveled

By 1991, as Bahcall’s committee deliberated its recommendations for astronomy’s next decade, the advocates for some sort of Next Generation Space Telescope (what had also been called the Large Space Telescope in the Bahcall Committee deliberations) had made considerable progress in nursing their project along. But they were still a very long way from a go-ahead to start detailed feasibility studies, let alone serious design work or actual construction. The kind of issues that could derail plans for a big space telescope are provided by the story of another of the large space telescopes touched on by the Bahcall Committee, the Large Deployable Reflector (LDR).[30] Far from being a side story, the LDR offers an example of NASA sets about developing new missions and its fate was a warning at the time to NGST advocates.

In the late 1970s, engineers and scientists from two NASA field centers, the Jet Propulsion Laboratory and Ames Research Center, both in California, had proposed the LDR. This mission sprang from JPL’s studies that began in 1976 of a space observatory to make observations in the submillimeter wavelength range. These studies led to a series of workshops in 1977 involving American and European astronomers. They recommended pursuing a 10 m space telescope to operate in the infrared and sub-millimeter regions of the spectrum. As the possible designs matured, they suggested one path to bigger yet lighter mirrors. Rather than using a single, massive piece of material for the primary mirror, engineers by the early 1980s proposed a Large Deployable Reflector with a 20 m mirror (Fig. 2.2).

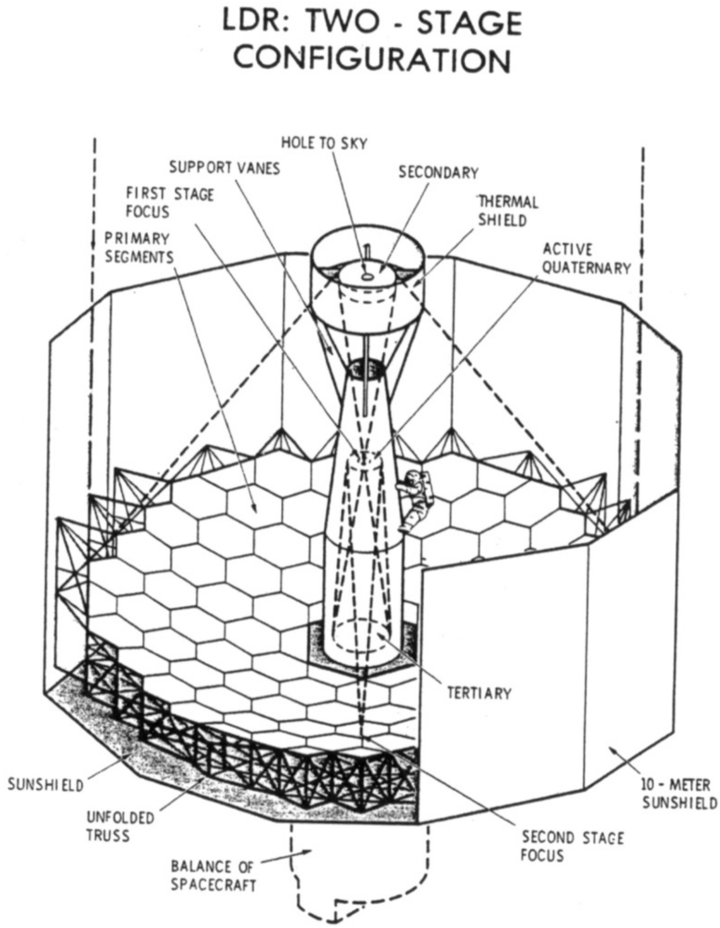

Fig. 2.2 A concept that never was. The planned large deployable reflector with a 20 m primary

Assembled from small lightweight hexagonal segments, this would fit together to make one giant light collector. The mirror could be collapsed to a smaller size to fit inside a rocket or into a spacecraft that would fit into the Space Shuttle's cargo bay (the first flight of which was in 1981), and then, once in space, open like the petals of a flower. In later studies engineers examined assembling the LDR in space using the space station, NASA's flagship program, which had been approved for construction by President Reagan in 1983, illustrating the often *ad hoc* nature of plans for new missions as advocates borrow from existing projects or other planned missions and work within the overall context of NASA's broader institutional goals.

The idea of a segmented primary mirror was attractive to many managers, engineers and scientists, one major reason being the advances astronomers were making in designing ground-based telescopes that exploited segmented mirrors.[31]

Designs for segmented primary mirrors for space projects were based, in part, on new schemes astronomers were proposing for ground-based telescopes. During the 1980s, for example, engineers and astronomers at Caltech and University of California developed segmented mirror technologies for the 10 m Keck Telescope project in Hawaii. The first Keck telescope went into operation in 1991 and a second one soon followed. Other telescope projects were also demonstrating how computers linked with mechanical systems could accurately control lightweight mirrors. This knowledge helped boost the confidence of NASA staffers that segmented mirror technologies could be developed for space telescopes.[32]

The Jet Propulsion Laboratory and Ames sustained the Large Deployable Reflector program with modest funding throughout the 1980s. The two NASA centers held conferences on it every two years which drew dozens of participants. In 1982, for example, a week-long workshop in California, similar in many respects to the Baltimore NGST workshop that was to be held in 1989, attracted around one hundred scientists and engineers to develop the science rationale for the LDR and to formulate what its observational capabilities should be.[33] The National Academy of Sciences twice recommended the Large Deployable Reflector as a high priority.[34] While it existed only on paper, the Large Deployable Reflector was a serious project whose advocates initially had high hopes of advancing it through the NASA bureaucracy and the White House and Congress to the stage where it would indeed be built. Reflecting their seriousness, NASA supported Lockheed Martin and Kodak to perform studies of the Large Deployable Reflector concept.

Although the Bahcall Committee had declared the 1990s as the decade of the infrared, in the end it did not support the LDR. Instead the Committee gave its strong backing to three other infrared projects instead,[35] although none were missions considered capable enough to be considered the successor to Hubble. Hence after several years of funding, NASA's upper management decided not to pursue the Large Deployable Reflector past the initial design stage. Advances in ground-based telescopes, its anticipated very high cost, plus the fact that somewhat similar missions were being pursued by the European Space Agency, kept it limited to the drawing board.

One common pattern in NASA's strategy in the 1980s and 1990s for developing new missions is clear here. The agency sponsored studies of various depths for many possible projects. Relatively few survived to be built, but elements of them lived on in various ways in other programs. In the case of the Large Deployable Reflector, the deployable primary mirror concept became a central feature in NASA's later plans for Next Generation Space Telescope,[36] although the *direct* influence on the designs of the NGST was probably negligible.

2.7 Spherical Aberration

In April 1990, before the results of the deliberations of the Bahcall Committee were complete, the Hubble Space Telescope was launched amid an enormous blaze of publicity. Expectations of the quality of the images it would return were extremely high, among astronomers and the general public. When NASA released the first images to the public, however, its spokesmen had the grim job of announcing that the telescope suffered from an optical defect known as spherical aberration. This meant that its images were not nearly as good as expected and that HST's scientific performance would be crippled, at least until some kind of repair or technological fix could be put into place. Derided by late night comedians and in editorial cartoons, proclaimed to be a "technoturkey" by one U.S. Senator, Hubble swiftly became a national symbol of technological failure.[37]

The space agency put into place a team to locate and review what had gone wrong. It soon concluded that the primary mirror was the culprit. Due to a mistake that had not been caught in assembling a test device, the primary mirror had been polished too flat at its edges.[38] Cast in the now dubious role of successor to the flawed and for a time publicly ridiculed Hubble Space Telescope, the consequences for the Next Generation Space Telescope were severe. Progress on its planning slowed to a crawl. It was not, however, brought to a halt.

In early 1991, there was a two-day workshop with 79 participants at the Jet Propulsion Laboratory on "Technologies for Large Filled-Aperture Telescopes in Space," one result of funding by NASA Headquarters to advance the technologies engineers and scientists reckoned to be needed for new astrophysics missions between 1995 and 2015. A number of the presentations centered on possible successors to the Hubble Space Telescope but, to judge from the conference proceedings, the likely cost of such a Next Big Machine was even more of a concern for the participants than they had they had been two years earlier in Baltimore.

In the executive summary of the two-day workshop, Garth Illingworth described the main conclusions drawn by the participants. As he put it, an 8 m class telescope "in high Earth orbit would have unprecedented power for problems as diverse as planet searches around nearby stars to the way in which galaxies formed in the young universe. It will build upon the discoveries and astronomical understanding of many decades of research with astronomical observatories, and is the natural successor to the Hubble Space Telescope (HST) and the new generation of large 10 m class ground-based telescopes."[39] He reckoned that while the gains with the HST are "impressive," those with the NGST would be "truly astonishing."[40]

Illingworth also claimed that operating an NGST in high Earth orbit would lead to savings in weight, size, power, and the complexity of its operations. These savings would in turn mean an 8 m NGST would be comparable in weight to the HST (12 tons), thereby "breaking away" from the HST cost curve; that is, securing a telescope considerably less expensive than might be anticipated just from the HST experience. But there was also now a key development. In the discussion of one of the papers, Rodger Thompson of the University of Arizona and a Principal Investigator for one of the instruments slated to fly aboard the HST later in the 1990s, challenged the assumptions underlying the planning directed towards a single, multipurpose and multiwavelength telescope that would cost a great deal of money, but not be serviced on orbit. He asked if "maybe a series of identical, let's say 6 m telescopes with individual instrumentation, all sort of lined up to go for specific purposes, might be better. One might be cryogenic, one might be just for spectroscopy or something else. This might be a better way to save money. These are production line types of telescopes."[41]

Illingworth protested that while there was "a significant level of rationality in that argument," politically it would be one that "you'd never be able to sell. Having one of something that was closely similar to the rest of them would essentially kill off the rest, given the cost. In the minds of the folks that are funding these things – and I think Congress in a sense – they're looking at this and saying: Here's astronomers out there wanting the world. We'll give them one and that's it."[42] Thompson replied that HST's fate had changed attitudes.

Other participants also spoke in favor of Thompson's idea. Although various concerns were expressed, in the panel discussion of the chairs of the various working groups, the debate had now shifted the consensus to planning for two telescopes. But the discussants also accepted that no studies had been done on this concept. Basic information was lacking so serious studies were needed. As Illingworth put it, "If it turns out it's do-able, the cost to do two of them, then you know you're not in a position of really selling it. If there are some cost savings to be made, we may be in a much more advantageous position."

One of the possible telescopes now being mentioned was what one speaker referred to as a "super Edison;" that is, a larger and more powerful version of a concept for an ambitious passively cooled "next generation" infrared telescope developed by a team led by University of Wyoming astronomer Harley Thronson in collaboration with a group at the Royal Observatory, Edinburgh.[43] Thronson was in attendance at the workshop. But only later, as we shall discuss elsewhere, would schemes for infrared telescopes mesh with the planning for the NGST.

Hence in the executive summary of the workshop, the conclusion now was that "While we have discussed NGST as being a single all-purpose UV to mid-IR telescope, it has been suggested that it may well be cheaper to design and configure two spacecraft, one for UV-Visible and the other for the Visible-IR. This is not obviously the case. Technical feasibility studies need to be combined with cost trade-off analyses to establish the most cost-effective and timely route to fruition of the program. The current baseline is to consider NGST as a single [high Earth orbit] telescope"[44] operating in the uv-visible and infrared.

2.8 Conclusions

Years before the Hubble Space Telescope was launched in 1990 a number of astronomers and engineers in the US and Europe were thinking hard about a possible successor to the HST as well as working to engage a broad community of researchers in the design of such a new observatory. That the launch of any such successor was likely to be many years away was also widely accepted. However, the fiasco of Hubble's spherical aberration had a serious effect on the pace at which plans were advancing for the Next Generation Space Telescope. Thus crucially for the dynamics of building the "Next Big Machine," the fate of the offspring was intimately tied to that of the parent. In fact, as we will describe in later papers, it was only when in the mid-1990s that the NGST planning was remade by the incorporation of a series of technology developments in infrared astronomy that NASA threw its institutional weight and money behind the development of a Next Generation Space Telescope: until that time, the American space agency had been generally standing on the sidelines as the major astronomical space telescope of the early 21st Century was being debated. The efforts between the mid 1980s and the early 1990s were nevertheless critical to the establishment and success of the later endeavor.

Without a set of committed advocates in these years willing to work away often as individuals or small groups to raise the consciousness of their colleagues about the possibilities of a successor to the HST even before its launch and eventual success, those later efforts would surely have been postponed, if pursued at all.

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Notes

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Michael Shull, Matthew Greenhouse, and Chick Woodward embarrass Harley Thronson, who obviously dressed inappropriately for a meeting in Arizona