Is the next big thing too big?

The cost of the James Webb Space Telescope could cripple US astronomy. **Tony Reichhardt** takes a closer look.

Every ten years, US astronomers get together to list the things they want most in all the world — and outside it. This may sound like a grown up version of writing to Santa Claus, but these Decadal Surveys are taken very seriously. Presenting a united front on what matters most to one's profession is a powerful bargaining tool when projects come up for political approval.

On astronomers' most recent wish list, put together in 2000, pride of place was given to what was then known as the Next Generation Space Telescope, an observatory that would take up the mantle of the Hubble Space Telescope as Earth's orbiting eye on the cosmos. Half a decade on, that telescope, now named after former NASA administrator James Webb, is well under way. But, as always, there's a catch. At the beginning of the millennium, US astronomers thought that their most-wanted project would cost \$1 billion. Its projected cost is now nearly five times that.

Price tags that mimic the Big Bang's inflation are nothing new to astronomy. The problem for the James Webb Space Telescope (JWST) is that the budgetary space in which it's expanding is shrinking. Money once slated for science is being diverted to the space shuttle, the International Space Station and plans for future

manned exploration (see *Nature* 439, 768–769; 2006). So the costs of the Webb telescope are leading to cancellations — or 'indefinite deferrals', as NASA prefers to call them. For those whose dreams are crushed in this process, the Webb telescope is looking less like the future of their field and more like its foreclosure. One critic of the process is Shri Kulkarni, an astronomer at the California Institute of Technology in Pasadena. "My worry," he says, "is that we are starting on a project whose cost we don't understand, and which is now devouring space-based astronomy. I doubt there's any project that is worth abandoning the rest of the field."

"We are starting on a project whose cost we don't understand, which is devouring astronomy."
— Shri Kulkarni

Sterl Phinney is an astrophysicist, also at the California Institute of Technology, whose favoured project, the LISA gravitational wave telescope, has just been deferred indefinitely by NASA. He says that even before the recent cuts, the Webb telescope was "basically sucking up all the other money" astronomers hoped to use. The community is now split between those who view the situation with growing alarm and those who, according to Phinney, "really like the JWST and think it's OK that it eats everything else — although even some of those are worried about the balance and health of astronomy." Kulkarni thinks some in this second camp are still in "stunned shock"

over the most recent shift of funds away from science at NASA, and just haven't reached a consensus on what to say, let alone do, about it.

One thing on which everyone agrees is that, if it works as advertised, the Webb telescope will be one fantastic machine. The telescope's 25-square-metre mirror is not just much bigger than Hubble's; it is bigger than any you would have found at any observatory in the world when Hubble launched.

The long view

Hubble's design is optimized for visible and ultraviolet light, but the Webb telescope will see in the infrared. Sitting above the atmosphere, it will have an unfiltered view of a swathe of wavelengths from 0.6 μm (at the red end of the visible spectrum) all the way to the first fringes of the far infrared at 28 μm . At longer wavelengths, images of a given resolution require a larger mirror; the Webb telescope's honeycomb of burnished beryllium will give it a resolution in the infrared that is as sharp as Hubble's is in the visible. The mirror's size also makes the telescope particularly sensitive: its instruments should see objects 10 to 100 times fainter than Hubble can.

Going into the infrared means the telescope has to have a big mirror and has to be stationed far from Earth (the heat from which would otherwise be a problem). It also has to be thoroughly shielded from the Sun, with a structure that somewhat resembles a multi-

NORTHROP GRUMMAN

storey trampoline. These requirements have all driven up the telescope's cost. But seeing in the infrared is not an optional extra; it's a necessity. If you want to look at the early Universe, the infrared is where the action is.

Theory holds that after the glow of the Big Bang faded, the Universe entered a long, lightless 'dark age'. Eventually, knots in the cold dark material condensed, collapsed and began to shine — the first stars. These earliest stars are receding from us at a great rate, which stretches out the light that reaches us and extends its wavelength towards the red end of the spectrum. The first stars are thought to have started shining less than a billion years after the Big Bang, giving them 'redshifts' in which the change in the light's wavelength relative to its original value is 20 or more — moving visible wavelengths well into the infrared. This is a large part of the reason why even far-sighted Hubble has never seen objects with a redshift of more than 7. The Webb telescope should solve this: young stars characteristically give off ultraviolet light that, after a redshift of 15, shines at $1.9 \mu\text{m}$ — "smack in the middle of our best band", enthuses John Mather, the JWST senior project scientist.

First light

Recently, Mather was part of a team led by Alexander Kashlinsky, now of Goddard Space Flight Center near Washington DC, that used the much smaller Spitzer infrared space telescope to detect a diffuse glow from 'first light' stars (A. Kashlinsky *et al.* *Nature* 438, 45–50; 2005). No current or planned telescope, not even the Webb telescope, can resolve individual first-light stars. But the Webb telescope should be able to see the supernovae that resulted when these massive but short-lived bodies exploded, providing the Universe with its first heavy elements.

It should also see the first galaxies that formed. One of the key observations for the Webb telescope will be 'deep field' pictures similar to those taken by Hubble. In these, a telescope points at a small patch of sky, taking a long, deep exposure that is designed to reveal extremely faint, distant objects. Astronomers hope the Webb telescope's near-infrared deep field (where contrast and resolution are best) will provide them with images of the very first galaxies and proto-galaxies.

For all this, advocates of the Webb telescope are eager to point out that it is more than just a 'first light' machine. They argue — especially to scientists whose projects are being sacrificed — that although the Webb telescope was inspired by cosmologists' interest in the earliest stars, it has much to offer other fields.

Take, for example, the search for planets around other stars. One of the casualties of this year's NASA budget was the Terrestrial Planet Finder, a mission designed to look for objects the size of Earth; its budget fell to zero. The Webb telescope cannot do what the Terrestrial Planet Finder was meant to do. But

planetary scientist Jonathan Lunine of the University of Arizona, Tucson, points out that it should still deliver relevant science that no current telescope can. An interdisciplinary investigator on the telescope's science working group, Lunine says it will return images and spectra for planets not all that much bigger than Jupiter, and may in special circumstances produce spectra for the atmospheres of planets as small as Uranus. Its high-resolution pictures of dusty circumstellar disks will be the sharpest ever, providing insight into planet formation. It even has applications within our own Solar System, for studying the thermal properties of the Kuiper-belt objects that orbit beyond Neptune.

And these are just the planned observations. Heidi Hammel, a planetary astronomer at the Space Science Institute in Boulder, Colorado, and another member of the JWST science working group, says some of the telescope's most important results may well be unforeseen. Some of Hubble's best findings, including the deep-field observations, "came from things

we hadn't even thought of, because it opened up new discovery space", she says.

Cash register

So no one is denying that the JWST will be a first-rate telescope, perhaps even a revolutionary one. Just last August an independent assessment team charged by the project to review the telescope's science potential reported that "the scientific case for the JWST mission has become even stronger" since the Decadal Survey's endorsement in 2000. But what of its expense? NASA's latest budget puts the project's price tag, including \$1 billion for a decade's worth of operations, at \$4.5 billion. That's more than the entire annual research and development budget of the National Science Foundation; it represents more than \$1 million for each full member of the American Astronomical Society.

On top of that there are the contributions by Europe and Canada, junior partners on this telescope just as they were on Hubble. Europe will contribute one of the telescope's four

Sun screen: this half-scale model shows how the Webb telescope will be shielded from solar heat.

NORTHROP GRUMMAN

instruments, the Near Infrared Spectrograph, and the launch on an Ariane 5 rocket. For an investment that approaches half a billion dollars, it will get 15% of the viewing time. Canada's \$57 million will provide a fine guidance sensor and other hardware, for which it gets about 5% of the science use.

The total cost is more than 30 times greater than that of the Keck telescopes on Hawaii, which boast two of the largest mirrors on Earth. One reason for this extraordinary expense is that the JWST is a challenging spacecraft to build. The segmented structure of the mirror, made from 18 hexagonal pieces of beryllium, is unlike anything built before; so is the multilayer sunshade and the system that will deploy them both. Robert O'Dell, who as project scientist for Hubble was in Mather's position 30 years ago, points out that Hubble was able to borrow much of its technology from spy satellites. The Webb telescope has no such heritage on which to draw.

Astronomical costs

NASA tried to head off difficulties by tackling some key technology issues early in the project's life. Although that helped to identify potential trouble spots, it didn't always reduce costs, says Eric Smith, programme scientist for the Webb telescope at NASA headquarters in Washington DC. For example, the engineers found they could build lightweight mirror segments, but not as fast as some had hoped — the job will end up taking six years instead of four. The early development work led to the mirror losing a third of its originally envisaged surface area in 2001. Other proposed cuts in capability — the dropping of the telescope's mid-infrared instrument, a possible further shrinkage to the mirror — were deemed scientifically unacceptable.

Some savings have been found. In 2005, project managers decided to forgo the extra mirror polishing needed to make the telescope's images utterly crisp in wavelengths shorter than

1.7 μm , on the basis that future large ground-based telescopes equipped with adaptive optics would be able to deal with these wavelengths more-or-less as well. And switching from a vacuum test chamber in Ohio to one at the Johnson Space Center in Houston, Texas, should save more than \$100 million.

Despite this, the cost has continued to climb, alarmingly jumping almost \$1 billion in 2005 alone (see graph). NASA's requirement that the programme beef up its contingency fund added a little over \$200 million. A delay in the government's decision to move from a US launcher to the Ariane added an estimated \$300 million as highly paid engineers were unable to move forward until they knew which rocket they were designing for. The situation is particularly embarrassing given that the cost of delaying the decision ended up being greater than the cost of the launch. That delay, and a NASA decision to rearrange the project's long-term budget yet again, saw the launch slip from 2011 to its current date of 2013. Every slip increases the total cost.

By the standards of ground-based astronomy, just a year's worth of Webb telescope overrun looks vast. Even the most expensive proposed instruments, such as the Atacama Large Millimeter Array (see *Nature* 439, 526–528; 2006) or the various Keck-dwarfing 30-metre telescopes that are under discussion, should leave ample change from \$1 billion. But O'Dell offers some perspective. Space telescopes are more expensive not just because the technology is more challenging, but because every problem and every contingency has to be thought through and solved before launch. This typically requires a large team of engineers to remain in place for years. What seem to be additional costs have also come from NASA's long and painful switch to 'full-cost accounting'. In this system, all of a mission's expenses — every paper clip and every guard at the front gate — are included in the total

bill. This makes NASA overheads smaller, and the prices of individual missions greater.

For all this, the growth in cost of the Webb telescope is not unprecedented. O'Dell recalls that in 1972, Hubble's total price including its first year of operation was projected to be \$300 million (\$1 billion in today's prices). According to Robert Smith, a historian at Canada's University of Alberta who wrote a political history of the telescope, Hubble ended up costing a lot more by the time it reached the launch pad in 1990 (several years late owing to the Challenger shuttle

accident). He says that if the budgets were calculated according to NASA's current full-cost accounting standards, "the development cost of Hubble to date is certainly more than \$4 billion in today's dollars".

NASA's Eric Smith adds that when new instruments and operating expenses are added, that comes to \$9 billion. This doesn't include the cost of four space-shuttle servicing missions to Hubble, and a fifth being planned — the cost of a shuttle launch can be put at about \$500 million. All in all, building, launching, using and refurbishing Hubble has probably been the most expensive undertaking ever made in the name of pure science; the mission is still, remarkably, costing more than \$300 million a year.

In that context, you begin to understand how Lunine can claim with a straight face that the Webb telescope — which will outperform Hubble in almost every way — is in fact "a bargain" at \$4.5 billion. Still, the discipline as a whole has to wonder whether it can afford a

PROJECTED COST OF THE JAMES WEBB SPACE TELESCOPE

Far out: the Webb telescope will have an array of hexagonal mirrors (left) that work to find the most distant galaxies yet.

bargain quite this big in straitened times. Between them, Hubble and the Webb telescope will soon consume half of NASA's astrophysics budget (see chart).

Some critics have concluded that the carefully crafted recommendations of the most recent Decadal Survey are no longer viable: if the costs had been clear, the priorities might well have been different. Kulkarni was on the review panel for ultraviolet, optical and infrared astronomy from space. He says, "I now regret that we were not clear thinkers" about what was affordable, and he believes that the plan was "fiscally unrealistic" even before NASA cut its science budget last month.

If it was unrealistic, says David Black, president of the Universities Space Research Association, scientists should share in the blame. "Astronomers pushed NASA to have all these missions. NASA bought into that. And all it

takes is one hiccup like the JWST overrun. It's like rush hour traffic. One incident, and suddenly everybody's piled up, there are schedule delays, and it becomes unstable very quickly."

The problems that come with sending mission after mission into this crowded traffic are exacerbated when the costs of the missions are set artificially low at the beginning. When NASA administrator Mike Griffin told a January meeting of the American Astronomical Society that the Webb telescope wasn't so much overbudget today as it was "undercosted" at its inception, he wasn't just putting a good spin on things.

The Decadal Survey guessed the cost as \$1 billion. Studies in the mid-1990s had pegged the price at between \$500 million and \$1 billion. These were based partly on the hope — unfulfilled, as it happened — that the Webb telescope might take advantage of advances in building low-cost spacecraft developed by the military. Oddly, earlier cost estimates for a large infrared space telescope were closer to the mark. A 1984 Space Science Board panel predicted the cost including operations to be \$4 billion (roughly \$7 billion today), and a subpanel of the 1990 Decadal Survey thought it would run to about \$2 billion not counting operations, which, when adjusted for inflation, closely matches NASA's current projections.

Political plays

Garth Illingworth of the University of California, Santa Cruz, who chaired the 1990 panel, chalks the anomalously low estimates from the 1990s up to a "lack of reality" inherent in the 'faster, better, cheaper' philosophy of Dan Goldin, NASA's administrator at the time. Goldin focused on accelerating the development of spacecraft, and increasing innovation, while accepting a moderate rise in the risk of failure. Some projects conceived under this tag, in particular two Mars missions lost in quick succession, brought it a certain disrepute. "It was a horrible, political circumstance framing all the discussion in that decade," says Illingworth.

Reinhard Genzel of Germany's Max Planck Institute for Extraterrestrial Physics in Garching says it was clear at the time that a \$500-million estimate for the Webb telescope was a "political price". Yet such was the climate of the 1990s that when estimates for the European Space Agency's smaller Herschel infrared observatory came in at \$1 billion, he says, "I was approached by many colleagues saying, 'You

guys are so stupid. Why can't you do this for less?' That's now haunting NASA, of course."

Today, Illingworth inveighs against the "extraordinarily bad, artificial cost estimates" of the Goldin era. But the 2000 Decadal Survey seems to have been happy to accept them. The world of big science is well used to projects being lowballed — a process that gets schemes started on the basis of a low cost estimate, with the implicit hope that by the time the true costs are known inertia and vested interests will make it impossible to pull out. Lowballing is not a practice anyone would defend on principle, but histories like the Hubble's show it can work (see page 127).

Past the disquiet

Craig Wheeler, a University of Texas astrophysicist and president-elect of the American Astronomical Society, takes the lessons of Hubble to heart: "I remember when we were building the Hubble Space Telescope, which has been spectacularly successful, there were an awful lot of eggs put in that basket. And other smaller, faster, university-based projects suffered. I think we got through it." Wheeler accepts the disquiet over the Webb telescope's costs, but he doesn't think astronomers have yet reached "the point we collectively would say 'enough'".

And he warns against revisiting the results of the Decadal Survey on the basis of the current crisis: "You alter those priorities at great risk."

"I remember when we were building Hubble, other projects suffered. I think we got through it."
— Craig Wheeler

Kulkarni is more pessimistic. He thinks that NASA's "laserlike focus" on the Webb telescope short-changes missions that would hunt for planets, probe the nature of dark matter, search for gravitational waves, and tackle other topics that might ultimately prove more popular with young scientists and with the public.

His concern is shared by Charles Beichman of the Jet Propulsion Laboratory in Pasadena, a leading light of the cancelled Terrestrial Planet Finder mission. Beichman thinks the Webb telescope will be "a fine machine. It will do fantastic science". In fact, he is on one of the instrument teams. But when he goes to professional meetings, he sees more young astronomers attending sessions on planet-finding than on Hubble or the Webb telescope.

Lunine thinks the critics are fighting the wrong battle (and that anyone who doesn't realize that the Terrestrial Planet Finder would be costlier than the Webb telescope is dreaming). It is not the JWST that is to blame, he says. The real problem is that "NASA's science budget is not adequate", and science is "taking the hit" as the agency shifts its focus to returning astronauts to the Moon. That may be the case. But for now, the Webb telescope is left in the awkward position of being the only one eating in a room full of hungry people. ■
Tony Reichardt writes for *Nature* from Washington DC.

NASA'S ASTROPHYSICS BUDGET
US\$1.5 billion in 2008