T. TSCHIDA/NASA

Ready for boarding — finally

NASA and Germany have spent 15 years and billions of dollars on SOFIA, an airborne telescope that is about to produce its first results. **Eric Hand** asks whether the science will justify the cost.

The hangar is so big that it once held a fleet of pirate ships. That was back when this 20,000 square-metre NASA facility in the desert town of Palmdale, California, was being used as a soundstage for the 2007 film *Pirates of the Caribbean: At World's End*.

Today, the film crews have long since packed up and gone. But the NASA mechanics pedalling around the squeaky-smooth concrete floor on bicycles are still tending to a diva as high-maintenance as any in Hollywood — a Boeing 747 that fits into one corner with room to spare. Like many a Tinseltown star, the jumbo jet is ageing: its fresh coat of paint covers an airframe that first carried passengers in 1977. And it has clearly undergone plastic surgery. There is the telltale swelling of the fuselage just behind the wings, for example, where incisions outline a retractable door. There are also a multitude of less visible fixes on the inside, all focused on what lies behind the door: a 2.5-metre telescope that has turned this formerly plain jet into the much heralded Stratospheric Observatory for Infrared Astronomy (SOFIA).

SOFIA's interior is a beehive of activity on this evening of 17 May. Some scientists are tinkering in the combined cabin and control deck. Others are pouring liquid nitrogen into one of the telescope's instruments. Still others are frantically trying to fix a broken cooling system. Their sense of urgency is palpable. Only when everything is working can SOFIA roll out of the hangar onto the tarmac, where it will open its telescope door, point its mirror at Polaris, and begin taking 'first-light' data from the ground. And only when this final 'ground ops' test is completed can SOFIA embark on its first science flight, scheduled for a week afterwards.

SOFIA's long-suffering science team has a lot to prove. Inaugurated in 1996 as a joint project between NASA, which modified the 747, and the German Space Agency (DLR), which built the telescope and pays 20% of the costs, SOFIA is designed to give astronomers a clear view of the Universe at infrared wavelengths — a part of the spectrum rich with information about galaxies, planets and newborn stars. But to accomplish that mission, the plane will have to lift the 20-tonne telescope at least 12 kilometres into the air, and then fly through the stratosphere at some 1,000 kilometres an hour with the open door forming a 3-metre-wide hole in its fuselage.

The technical challenges of engineering such a radically modified plane, combined with management failures, have already put SOFIA almost a decade behind schedule — the original completion date was supposed to be 2001 — and roughly tripled its development costs. Its estimated total cost, including 20 years of operation, now comes to about US$3.75 billion — a price tag that by one measure, dollars per hour of observation, would make SOFIA as costly as the Hubble Space Telescope, NASA's most expensive astronomy mission ever (see 'Money per mission'). The delays have also meant that competing infrared astronomy missions such as the European Space Agency's Herschel Space Observatory— which was supposed to launch well after SOFIA — have instead gone up first and scooped some of the creamiest science. The result is that any mention of SOFIA now leads many astronomers to respond with eye-rolling and shoulder shrugs.

"We would like to have some proof — proof that we have something flying and taking data."

"I'm worried about this," says Garth Illingworth, an astronomer at the University of California, Santa Cruz, and the former chair of an astronomy advisory committee to the National Science Foundation. "The science missions we do should have very high science return and be cost effective. In my view, SOFIA meets neither of those criteria."

Hence the urgency in Palmdale, where the first science flight is seen as a chance to rebut SOFIA's many critics. "It's a lot of pressure for us," says Pasquale Temi, a SOFIA facility scientist.

"We would like to have some proof — proof that we have something flying and taking data." The plan is to follow the initial science flight with limited science operations starting in November. From there, the project will gear up step by step to full operations, reaching 800 hours of night-time observations a year with all eight of the telescope's instruments in 2014.

But tonight, no one dares summon the diva from its dressing room. The cooling system is finally fixed, but towering clouds are tumbling over the mountains that stand between Palmdale and Los Angeles. Opening the telescope door on the tarmac is out of the question: raindrops could fall on the mirror. "There's nothing we can do," says Temi, shaking his head mournfully.

Chasing eclipses

For all the contention surrounding this latest (and probably last) of NASA's flying observatories, airborne astronomy has a rich history. Astronomers used biplanes to chase solar eclipses as early as the 1920s. And in 1968, when NASA started flying a Learjet equipped with a 30-centimetre telescope stuck through a passenger window, they began to stare beyond the Sun at stars, galaxies and planets. The next year, the agency approved work on what would become the Kuiper Airborne Observatory (KAO), which featured a 0.9-metre telescope staring through a hole in the roof of a converted Lockheed C-141 Starlifter, once a military transport aircraft.

By 1974, the KAO was taking data at altitudes of 12 kilometres and above — and in the process, demonstrating the advantages of astronomy from the stratosphere. Because atmospheric water vapour at lower altitudes absorbs most of the infrared light at wavelengths longer than a micrometre or so, an airborne telescope can gather infrared photons far faster than any ground-based counterpart, and thus increase its sensitivity to faint objects.

T. TSCHIDA/NASA

Scientists test SOFIA's 2.5-metre telescope inside the Boeing 747.

MONEY PER MISSION

Mission	Lifetime cost (US$ billion)	Start of operation	End of operation	Hours of observation	Cost per hour ($ thousand)
Herschel Space Observatory	1.4	2009	2012	20,000	**70**
Spitzer Space Telescope	1.7	2003	2012	54,000	**31**
SOFIA	3.75	2014	2034	16,000	**234**
Chandra X-Ray Observatory	4.4	1999	2014	90,000	**49**
James Webb Space Telescope	5.2	2014	2024	60,000	**87**
Hubble Space Telescope	14.1	1990	2015	60,000	**235**

The KAO's mobility proved to be helpful, too. Just as the early airborne astronomers chased solar eclipses, the KAO could seek the best paths across the globe for observing occultations: eclipses in which comets, asteroids or planets pass in front of distant stars that backlight the object and create a faint shadow across Earth. Occultations are a chance to measure the size, shape and even the atmospheric chemistry of the passing object. It was in this way that the KAO made some of its most famous observations: the rings around Uranus[1] and an atmosphere on Pluto[2]. SOFIA scientists are hoping that the new mobile observatory will extend such studies to the thousands of poorly understood icy bodies in the Kuiper belt beyond Neptune's orbit.

"I didn't think it was ever going to fly."

Even more helpful was that astronomers were able to refurbish and upgrade the KAO's instruments 50 times over the years, says Allan Meyer, a SOFIA scientist who flew on hundreds of KAO flights. This allowed the KAO to stay *au courant* as the efficiency of infrared detectors improved. And that, in turn, gave it a distinct advantage over space telescopes, despite the orbital instruments' much clearer vision at every wavelength: their instruments become outdated very quickly. (The one exception is Hubble, the only space telescope designed to be upgraded.)

By the early 1990s, however, airborne astronomers were looking past the ageing KAO towards SOFIA. The bigger plane wouldn't fly higher than the C-141. But with a telescope almost three times the diameter of the KAO's, it would provide astronomers with about eight times the light-gathering power, thus allowing them to study much fainter objects.

Dan Lester, an astronomer at the University of Texas at Austin who helped to develop conceptual designs for SOFIA, recalls laying out this rationale when he met with members of the US Congress in the early 1990s. They loved it, he says. They wouldn't have to go to some frigid, forbidding mountain top to see astronomy in action. SOFIA could land in any congressional district with a big enough airport, and carry aloft politicians — along with teachers, journalists and other interested parties — in the first-class seats. "The taxpayers could see their investment in the flesh," says Lester. "People on the Hill liked this."

NASA accordingly got the go-ahead for SOFIA, but at a price: the KAO had to be retired in 1995 so that its operations money could be shifted over to SOFIA construction. In 1996, NASA awarded a management contract to the Universities Space Research Association (USRA) of Columbia, Maryland. It was a grand experiment in privatization, and supposedly more efficient than having NASA manage the project directly. Lester recalls how disappointed the University of Texas was to lose its bid for the contract. But in retrospect, he says, "we took a deep breath and said, 'We were sure lucky we didn't get that'".

Dynamic problems

It turned out that cutting a 3-metre square out of the side of a 747 and making it fly smoothly with a 20-tonne telescope in its rear was a far tougher problem than modifying the KAO. Engineers spent years finding ways to stiffen the fuselage and direct airflow around the hole, lest the slipstream create the 1,000-kilometres-per-hour equivalent of blowing across the lip of a bottle; the resulting resonance in the cavity would have shaken the telescope uncontrollably. Meanwhile, two subcontractors, responsible for building the retractable door, went bankrupt.

By 2003, development costs had risen to $373 million, and the projected completion date was receding farther and farther into the future; the USRA knew astronomy, but not aeronautics. By 2006, fed-up agency officials were plotting to kill SOFIA.

"It was me," says Mary Cleave, tapping her nose. "I didn't think it was ever going to fly." In 2005, Cleave, now retired, found herself in the

J. ROSS/NASA

With its sliding door wide open, SOFIA flies above the Sierra Nevada in California on a test flight in April.

unenviable position of being NASA's science chief at a time when the science budget was being cut. Her boss, former administrator Michael Griffin, was championing the new NASA policy of returning astronauts to the Moon, but Congress wasn't giving him any extra money to get them there. Cleave was told to siphon off a few billion dollars from her budget to the human spaceflight programme. And an obvious source was the chronically over-budget SOFIA. "USRA had no background in managing a project like that," says Cleave. "None. That's why it fundamentally got into trouble."

But when SOFIA was cancelled in the presidential budget request of February 2006, the uproar came quickly — much of it from Germany. "It would have been a disaster," says Sigmar Wittig, who was DLR director at the time. Wittig immediately went to see Griffin, and explained the political embarrassment that a cancellation would cause for the DLR, which had already sunk millions into building the telescope. Congress, too, protested the loss of contracts in so many members' districts, and hauled Griffin and Cleave into hearings where they were grilled about SOFIA's future.

Under review

Cleave was beginning to realize that it was nearly impossible to cancel an international partnership. But she could still reshape it. She set up a review team, which later in 2006 recommended transferring management of SOFIA aircraft operations from the KAO's former base, the Ames Research Center in Mountain View, California, to the Dryden Flight Research Center near Palmdale, long the home of NASA's aeronautics experts. The only thing left to be managed by the USRA and Ames was SOFIA's science programme.

Dryden, with its extensive flight-test experience, did succeed in getting SOFIA up in the air — albeit with extreme caution, opening the retractable door bit by bit and incrementally flying at higher and higher altitudes. And that step-by-step approach paid off: today, test pilot Timothy Williams says he doesn't even notice when SOFIA's door opens. "It's amazingly benign," he says. "It's almost imperceptible."

But adding Dryden to the mix increased development costs, says Xander Tielens of Leiden University in the Netherlands, a former SOFIA project scientist who is also principal investigator for an instrument on Herschel. "There's enough guilt to go around for everybody," he says.

Dryden's incremental approach also meant that other infrared science experiments have beaten SOFIA out of the gate. SOFIA does cover a huge swathe of infrared wavelengths, from less than a micrometre up to a millimetre (see 'Common ground'). Yet the Herschel satellite, launched in 2009, uses its 3.5-metre-wide telescope and deep space location to cover a large part of SOFIA's spectrum with far greater sensitivity. "Herschel has indeed scooped the area they were optimized for," says John Mather, a Nobel laureate in physics at Goddard Space Flight Center in Greenbelt, Maryland. That includes studying the Universe's earliest galaxies — shrouded in glowing dust that is dark to optical telescopes — in an attempt to understand the timing and mechanics of the starbursts that contributed to their formation.

Mather is also the project scientist for the James Webb Space Telescope (JWST), which, after its launch in 2014 will use its finely honed, 6.5-metre mirror to encroach on SOFIA's turf from the shorter wavelength side of the infrared spectrum.

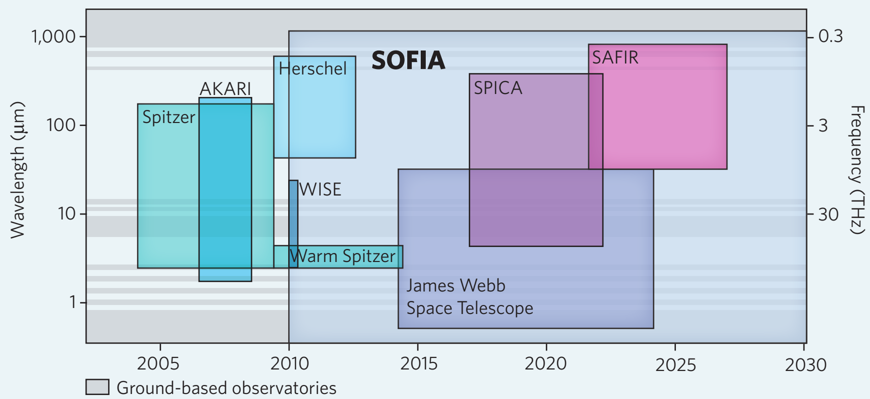
Given that competition, and its comparatively limited sensitivity to targets beyond the Milky Way, SOFIA will probably stick to studying objects slightly closer to home, such as the disks of dust and gas around young stars that eventually coalesce into planets. But within that domain, says Mather, it will have some undeniable advantages. SOFIA has a superior ability to perform spectroscopy, which doesn't require objects to be as bright. So a natural role for SOFIA would be measuring the chemistry and velocity of these gases and dusts, which would help astronomers understand how planetary building blocks take shape. Tielens adds that there is a vast need for spectroscopic follow-up to the many objects that Herschel won't have time to completely understand before its 3-year supply of liquid helium is exhausted.

A niche of one's own

But SOFIA's uses go beyond follow-up, emphasizes Eric 'the Infrared' Becklin, an astronomer who served as a principal investigator on the KAO, and then as 'director designate' of SOFIA from 1996 until he stepped down last year to

COMMON GROUND

The spectral coverage of SOFIA overlaps with other existing and planned infrared observatories.



THE CASE FOR SOFIA NASA AMES RESEARCH CENTER; 2009 make way for someone younger. Now an emeritus professor at the University of California, Los Angeles, Becklin says that SOFIA will have the 30–60-micrometres wavelength region all to itself — at least until the 2018 launch of a proposed Japanese mission called SPICA (Space Infrared Telescope for Cosmology and Astrophysics). This wavelength band is where Solar System planets emit some of their brightest infrared light, which in turn should carry crucial information about their still unresolved atmospheric chemistries.

Even as SOFIA astronomers look for their niche, others wonder if it will ever be worth the cost. "It's shockingly expensive," says Barth Netterfield, an astrophysicist at the University of Toronto in Canada. As a scientist on the Balloon-borne Large-Aperture Sub-millimeter Telescope (BLAST), Netterfield in 2006 made pioneering observations of cosmic infrared background radiation from a 2-metre telescope that was carried to the edge of space by a balloon, and then circled the South Pole for 11 days[3]. Total project cost, including another planned flight this winter: $7 million.

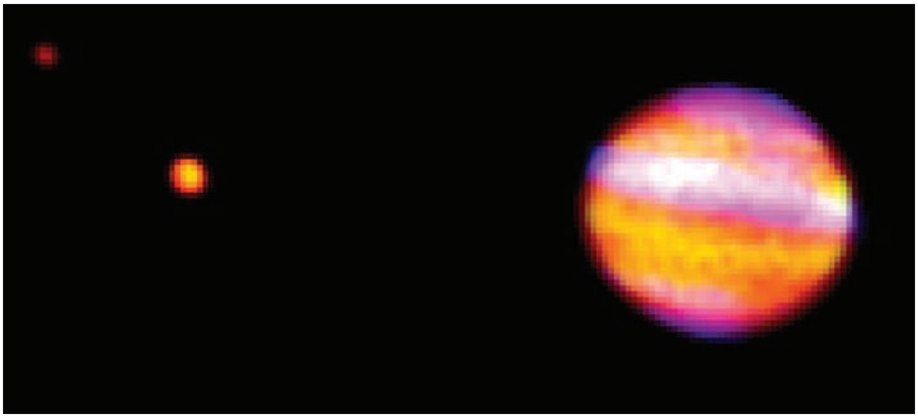
SOFIA's far heftier price tag has consequences for the rest of the astrophysics programme at NASA. Cleave says that by cancelling SOFIA, she was trying to save competitive mission lines such as the 'explorer' programme, which awards small satellites to principal investigator-led teams, often from universities. For many years, the explorer programme funded the launch of one relatively inexpensive mission nearly every year. Some of these missions, such as Swift, a γ-ray telescope, and the Wilkinson Microwave Anisotropy Probe, which mapped the cosmic microwave background, have had a major scientific impact[4]. But now, 57% of the NASA astrophysics budget goes to just three missions: Hubble, the JWST and SOFIA. The launch rate of small explorers has dropped considerably. SOFIA, says Cleave, will be a weight on the future astrophysics programme for a long time.

"There's enough guilt to go around for everybody."

Becklin acknowledges SOFIA's high costs. But he says it shouldn't be judged in terms of dollars per hour of observation, but by the science per dollar. "It's the unique science that we produce," he says.

Unfortunately, it is hard to say what the 'science per dollar' is for SOFIA until it actually does some science. Without that, NASA and the astronomical community have both had to proceed by guesswork. In 1990, in the regular prioritization exercise dubbed the 'decadal survey', American astronomers ranked SOFIA as their third most important medium-sized project for the coming ten years. But that was when SOFIA was supposed to be flying by 1998 for $230 million. The airborne observatory wasn't ranked at all in the 2000 decadal survey, because it was already under development, nor will it be ranked in the 2010 survey, due out later this year.

Meanwhile, because SOFIA won't be fully operational until 2014, it has also been exempt from the 'senior reviews' that NASA carries out on it operational missions every two years — reviews that evaluate and rank the missions in the science-per-dollar terms that Becklin wants. So in effect, the broader research community hasn't had a chance to critically reassess the scientific case for SOFIA for 20 years — a situation that Netterfield, like many other critics, finds inexcusable. "Put me on a review panel," he says.



NASA

First-light images of Jupiter and its moons verified that SOFIA's telescope was stable in flight.

First light

On 25 May, a week after the failed dress rehearsal, a noisy tug pushes SOFIA out of its hangar in Palmdale as the Sun goes down. Little birds in the roof scatter as the big bird backs out, its tail slipping through the door with just a metre of clearance. Crewmen, airhorns in hand, watch the wing tips as the jumbo jet rolls out, pivots and heads to the runway.

Williams, the test pilot, has been given control of the throttle for this first-light flight. He sends the plane hurtling down the runway, then eases it up into the moonlit night above a bank of clouds that have piled up sluggishly against the California coast. He points SOFIA southwest, guiding it past the Los Angeles airport, past Santa Catalina Island off the coast, and into Whisky two-niner-one: Warning Area 291, a huge swathe of the Pacific Ocean sometimes used for military training exercises. Williams and the other pilots then take turns guiding SOFIA along straight bearings while the scientists in the cabin gather their first science images from a few bright test targets: Jupiter and the galaxy Messier 82.

Back at the hangar in Palmdale, Eric Becklin follows SOFIA for a little while on a public tracking website before heading to bed at midnight. Still involved in the project as an adviser, Becklin no longer has a special line to communicate with the plane. That's for the new Erick the Infrared: Erick Young, who took over as director designate last year.

Yet both scientists are back by the runway before dawn to watch as Williams gently guides SOFIA back to a 5:35 a.m. touchdown. Soon enough, the aircraft is parked again inside its hangar.

"Spectacular!" enthuses Becklin as he recalls the landing. "Then the most important thing: we got those beautiful images that were way beyond our expectations."

Young is equally ecstatic. "It's the first time that we can really say we have an observatory," he says.

Even Cleave says she's happy to hear that SOFIA is flying (although she is a bit incredulous). And that's not an uncommon feeling among critics, says Lester, whose involvement in the SOFIA project has waxed and waned over the years. He says he has had to detach himself from the mission, in the same way that parents have to avoid projecting too many of their dreams and desires onto their children. "They grow up — and they don't end up achieving your dreams. But you love them anyway. That's the way I feel about SOFIA." Lester pauses. "And that's the way a lot of the community feels about SOFIA." ■

Eric Hand is a reporter for *Nature* in Washington DC.

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2. Elliot, J. L. *et al. Icarus* **77,** 148–170 (1989).
3. Devlin, M. J. *et al. Nature* **458,** 737–739 (2009).
4. Hand, E. *Nature* doi:10.1038/news.2009.81 (2009).

See Editorial, page 413.

Protein mapping gains a human focus

Next phase of the US Protein Structure Initiative enlists biologists to help crack tough human receptors.

About one-quarter of approved drugs target members of a single protein family: the G protein-coupled receptors. Members of this clan — the largest protein family in the human genome — control everything from hormone signalling to the perception of light and scent.

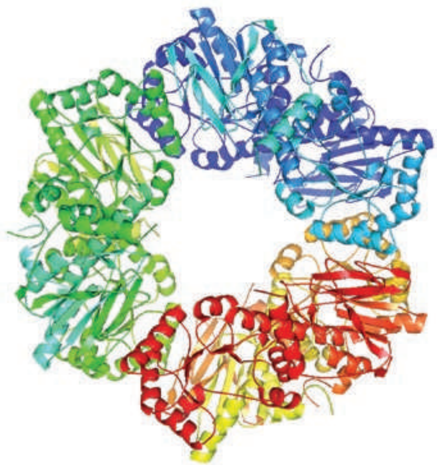
Although the receptors are a drug developer's dream, they are a structural biologist's nightmare — difficult to make in the lab and unstable when snatched from their natural home in cell membranes. The human genome encodes more than 800 of these unwieldy proteins, but after decades of work, researchers have determined the three-dimensional structures of only five from humans, leaving many efforts to develop receptor-targeted drugs shooting in the dark.

The latest phase of an ongoing US assault on protein structures — launched last week by the US National Institute of General Medical Sciences in Bethesda, Maryland — aims to improve that record. The Protein Structure Initiative (PSI) has been churning out protein structures since 2000, but its next five-year, US$290-million programme will move away from its goal of the past decade, which was to achieve a complete understanding of the elaborate amino-acid folds that comprise a protein and determine its function. Instead, the initiative will pair its 13 protein-structure research centres with a network of biologists in universities and industry in the hope of solving some of the world's most troublesome and medically relevant proteins — including the G protein-coupled receptors.

In the past decade, PSI investigators have been ploughing through a list of human and non-human proteins selected mainly for their diversity. Using techniques including X-ray crystallography and nuclear magnetic resonance spectroscopy, the centres aimed to map the protein 'universe' — a compendium of all the possible ways a protein could fold. Such a map could help researchers to predict a protein's structure from its amino-acid sequence.

Cash concerns

But the PSI soon faced charges from structural biologists that too much money had been wasted on proteins of little biological interest. Of the roughly 5,000 protein structures solved by the PSI to date, only 128 are human proteins. In 2007, a PSI advisory committee agreed with the criticisms, noting that the PSI's mapping attempts were unlikely to bear fruit: at the time, structure initiatives worldwide had determined the folds for only about 1% of protein families.



Almost 5,000 protein structures have been solved by a US effort — but only 128 are human proteins.

BERKELEY STRUCTURAL GENOMICS CENTER

Even so, that was enough to improve protein modelling, says Johan Weigelt, a structural biologist at the Karolinska Institute in Stockholm. "A lot more structures can be modelled now than could be modelled five years ago, and that's thanks to the PSI," he says. "But for the majority of the biological community, it just wasn't that interesting."

Other projects have tackled protein-structure determination on a grand scale while keeping biology at the centre. The Structural Genomics Consortium, for example, links scientists in the United Kingdom, Canada and Sweden. Funded by a mixture of public and private funds, the consortium specifically targets proteins that are important for human health. Similarly, Japan's Targeted Proteins Research Program, which receives about 4 billion yen (US$46 million) a year, focuses on proteins that are crucial in human health, food production and fundamental biology questions.

The PSI will now adopt a similar approach: its next five-year phase has been named PSI:Biology and will fund ten collaborations with biologists. For example, one of the PSI's 13 centres, the Northeast Structural Genomics Consortium, based at Rutgers University in New Jersey, will team up with outside researchers to tackle proteins that are made in mitochondria — the cell's energy factories — as well as proteins that regulate gene expression. Nine of the centres will focus entirely on challenging membrane proteins such as the G protein-coupled receptors. And the programme overall will take on more human proteins, which are typically larger and more difficult to work with than their bacterial counterparts.

The new emphasis comes as budgets for the PSI centres are tightening. With more biologists to support outside the centres, some of the 13 research hubs are receiving a smaller slice of this year's $58-million PSI budget. The cuts could pose a problem for the oldest centres, whose equipment has now been in use for a decade, says Gaetano Montelione, director of the Northeast Structural Genomics Consortium, where the budget has been cut by about 30%.

Cheryl Arrowsmith, a structural biologist at the University of Toronto in Ontario, Canada, and principal investigator in the Structural Genomics Consortium, wonders whether PSI:Biology will foster enough interaction with biologists. She notes that, unlike the international consortium, the PSI's major research centres will not employ biologists on site, which she says is useful because solving structures often requires detailed knowledge of a protein's unique biochemistry. For example, some proteins are more stable and thus more amenable to crystallography when bound to a natural partner they might normally encounter in a cell.

Meanwhile, one member of the PSI advisory committee, structural biologist Michael Levitt of Stanford University in California, has recanted his criticism that the programme's earlier focus on folds was quixotic. After the committee met, Levitt performed his own calculations of how large the protein universe is. He found that seemingly unique folds are often merely intricate combinations of previously known folds (M. Levitt *Proc. Natl Acad. Sci. USA* **106,** 11079–11084; 2009). He now says that worldwide programmes have mapped about 6% of the protein universe, not 1%. "And that's actually quite impressive." ■

Heidi Ledford

Corrections

The News story 'Animal rights "terror" law challenged' (*Nature* **466,** 424; 2010) incorrectly implied that the targets of harassment by animal-rights activists were all researchers at the University of California, Berkeley. Researchers at the University of California, Santa Cruz, were also targeted.

The News Feature 'Ready for boarding — finally' (*Nature* **466,** 428–431; 2010) wrongly stated that spectroscopy performed by an airborne astronomical observatory doesn't require objects to be as bright as for imaging. In fact, spectroscopy requires more light than does imaging.