also sees evidence of global increases in CFC-22, methylchloroform, and carbon tetrachloride, all less radiatively active, man-made chemicals.

Additions of radiatively active trace gases to the atmosphere are only part of the trace gas problem. A web of subtle and often poorly understood processes links radiatively active trace gases, inactive trace gases, atmospheric temperature, and the biosphere so that a disturbance in one part of the web will be felt in the others. For example, fossil fuel burning produces carbon monoxide and nitric oxide, neither of which is radiatively active but both of which can react through the classic smog reactions to produce ozone, which is radiatively active. CFC's and nitrous oxide can produce the opposite effect by destroying ozone in the stratosphere. A greenhouse-related warming could increase the rates of chemical reactions that destroy methane in the atmosphere (another participant in the smog reactions), while it could accelerate the biological processes that produce methane.

The effort to account for the trace gases' bewildering array of direct and indirect climate effects is still in its infancy. Most calculations are in the form of simple, one-dimensional climate models, which include only atmospheric processes acting along a vertical column. To produce some of the latest results, Wei-Chyung Wang of Atmospheric and Environmental Research in Cambridge, Massachusetts, included in his model 20 gases, 48 reacting chemical species, 100 chemical reactions induced by solar radiation, and some effects of atmospheric aerosols and clouds. For the purposes of the model, he assumed increases after 1980 in carbon dioxide (0.5 percent per year), methane (1.2 percent per year), and nitrous oxide (0.2 percent per year). Emissions of CFC's and other nitrogen oxides remained unchanged.

Wang's model predicts equal roles for carbon dioxide and trace gases in raising the average global surface temperature 0.8°C by 2010. (This model predicts a 2.0°C warming for a doubling of carbon dioxide.) By the turn of the century, the climate would be warmer than it has been in several centuries or even the past 1000 years. The warming due to increased carbon dioxide would be 48 percent of the total, and that due to the direct radiative effects of the trace gases other than ozone would be 26 percent of the total. The total amount of ozone would not change, but its redistribution, especially around the sensitive altitudes of the tropopause, would contribute the remaining 26 percent of the warming.

Although models have differed widely in the assumed trace gas changes, chemical reaction rates, and other crucial details, all the models indicate a significant role for trace gases. In a model constructed by Andrew Lacis and his colleagues at the Goddard Institute for Space Sciences, New York, doubling carbon dioxide produced a 2.9°C warming, and assumed changes in trace gas concentrations that might occur over the next century produced a 1.0°C warming. At the National Center for Atmospheric Research in Boulder, V. Ramanathan's model indicates a 2.0°C temperature increase in response to the doubling of carbon dioxide and an additional 1.6°C warming when changes in trace gases are included. The actual uncertainties in such calculations are probably greater than these broadly consistent results might suggest, but researchers want very much to reduce those uncertainties. When policy-makers ask what is causing an apparent global warming, researchers want to have some answers.

—RICHARD A. KERR

The Infrared Astronomy Satellite (I)

Our tale begins with the engineers who got an enormously complex mission into orbit—working perfectly; next, IRAS science

The Infrared Astronomy Satellite (IRAS) was launched into polar orbit from Vandenberg Air Force Base, California, at precisely 6:17.375 p.m. PST on 25 January 1983. Lift-off was right on schedule—or 2 years late, depending on how one looked at it. In fact, getting IRAS to that point had been one of the most frustrating and difficult space projects ever attempted. Yet on 25 January that hardly mattered. Because when IRAS was finally in orbit, it performed almost perfectly.

The scientists were ecstatic. "[IRAS] marks the beginning of a new era in infrared astronomy," proclaimed the exultant science and engineering team in a recent review article.* The $180-million IRAS, a joint endeavor of the United States, the Netherlands, and the United Kingdom, is making the first comprehensive survey of the sky at infrared wavelengths between 8 and 119 micrometers. This particular band contains some of the most important emissions from planets, asteroids, comets, interstellar molecules, and the cold gas and dust of the galaxy's star-forming regions. Moreover, infrared photons are able to penetrate the interstellar clouds that obscure so much of the galaxy from optical astronomers. (These same photons are strongly absorbed in the atmosphere of the earth, unfortunately, which is why the all-sky survey had to wait for a satellite.) IRAS's early discoveries include, for example, two new comets and a ring of dust around the Andromeda galaxy.

IRAS is a milestone in an engineering sense as well. The telescope has to be cooled with superfluid helium lest its own thermal emissions overwhelm the signal it is looking for. Thus, IRAS contains by far the largest cryogenic system ever flown in space (475 liters of liquid helium). Moreover, the system is working even better than expected: helium is boiling off inexorably, but so slowly that the estimated lifetime of IRAS is now 340 days instead of the prelaunch estimate of 220 days. IRAS's success has encouraged NASA headquarters to move forward on such long-delayed cryogenic projects as the Cosmic Background Explorer, which will look for subtle, cosmologically significant variations in the 2.7 K microwave radiation; and the Shuttle Infrared Telescope Facility (SIRTF), a more powerful successor to IRAS that will be operated from the shuttle payload bay.

For all of that, the smiles are still a bit strained at times. The institutional scars left by the IRAS development effort are only just now beginning to heal. Indeed, the IRAS story is strikingly reminiscent of the managerial confusion and technical hang-ups that have recently come to light on the Space Telescope project (*Science*, 8 April, p. 172).

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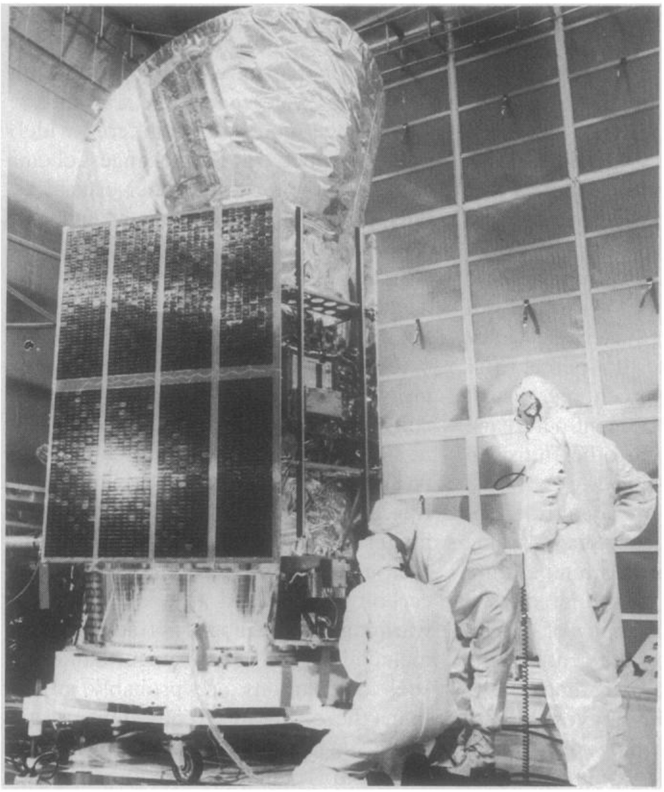

IRAS is readied for launch.

NASA first began planning IRAS in 1974, inspired by a short-lived, cryogenically cooled satellite that the Air Force had launched not long before to look at the infrared background of the sky. The problem, of course, was money. A new cryogenic observatory would not be cheap, and NASA was already beginning to feel the financial pinch of space shuttle development.

Independently, however, and at almost the same time, the Netherlands' aerospace agency, NIVR, was thinking along similar lines. The agency had just finished its first solo mission, a small cosmic-ray/ultraviolet observatory known as the Astronomical Netherlands Satellite. Building an infrared satellite, with its tremendous potential for scientific payoff, seemed a good way to maintain the momentum. Moreover, the timing was right. Surging oil prices in the wake of the 1973–1974 oil embargo were proving a boon to the national economy—most of Europe's imported oil passes through Dutch refineries—and the government was eager to invest some of that windfall in building up the country's strength in high technology. The electronics and aerospace industries were prime candidates.

On the other hand, it was NASA that had the state-of-the-art expertise in such key technologies as infrared detectors. The idea of a collaborative effort thus followed naturally. A joint working group, which met at the Goddard Space Flight Center outside of Washington, D.C., began drawing up conceptual designs for IRAS in 1975.

Shortly thereafter the United Kingdom joined in, adding its strong community of infrared astronomers to the project. In the final division of labor, the Dutch took charge of building the spacecraft itself, with its associated systems for communications, pointing, and power; the British agreed to build the IRAS ground station (at Chilton, south of Oxford), from which they would operate the satellite and collect its data once it was in orbit; and the Americans took on the telescope, the detectors, the cryogen system, the scientific data processing, and provision of the launch vehicle.

Now, at this level things have remained reasonably amicable ever since. Lower down within NASA, however, the project was not so lucky. The original work on IRAS had been done at Goddard. But in the painful retrenchments of the post-Apollo years, NASA was trying to preserve as much capability in its research centers as possible. In practice, this often meant defining and policing the centers' turf.

The responsibility for infrared astronomy, as it happened, had already been given to the Ames Research Center in Mountain View, California. In fact, Ames was at work even then on conceptual designs for SIRTF. Accordingly, shortly before funding for IRAS was officially approved in 1977, responsibility for the telescope was passed across the country to Mountain View.

"It seemed like a logical stepping stone towards SIRTF," says Franklin Martin, who was then head of NASA's advanced projects division. (He has recently gone to work at Goddard.) On the other hand, he says, there were concerns that Ames might not have the technical and managerial skills needed to handle the IRAS project as a whole. Thus, the overall responsibility for IRAS was given to the Jet Propulsion Laboratory (JPL) in Pasadena, California.

"That arrangement," sighs Martin, "is the one thing we would do differently. When you take a complicated interface like that and add in technical and financial problems, you get trouble."

"The friction goes up exponentially," agrees Palmer Dyal, head of advanced project development at Ames. Understandably, neither Dyal nor his counterparts at JPL are eager to resurrect specific grievences now. But in general, it seems to have been a matter of too many people with overlapping responsibilities. A technical glitch would arise; the JPL managers would start nosing in at the working level; headquarters would want something completely different; Ames would feel harassed and uncooperative; JPL would grit its institutional teeth, convinced it could handle the problem better without Ames in the way; and relations would go from bad to worse. It was too bad, says Dyal, because on projects such as the Pioneers and the Galileo orbiter/probe mission to Jupiter, Ames and JPL have worked together well.

In essence, says IRAS project manager Gerald Smith of JPL, the lesson is one of common sense: make the management organization an important consideration in the beginning. "It's all very nice to emphasize international participation and spreading the work around," he says. "But as you get downstream, you may find that the organization you created for these reasons is not very effective at getting the job done."

Be that as it may, the management concerns were a small perturbation compared to the technical problems faced by IRAS. It was the old story: in a project that called for pushing the state of the art, people underestimated the complexity in the beginning. "So there were surprises," says Smith. "Then, once we were in that situation, there was the inevitable pressure to keep the costs down. NASA was undergoing significant belt-tightening at the time, and IRAS *was* supposed to be a low-cost Explorer-class satellite. There was a tremendous reluctance to acknowledge that it was more complex than that."

The technological challenges were there in plenty—the 60-centimeter beryllium primary mirror, for example, cast and polished by the Perkin-Elmer company of Danbury, Connecticut; or the porous steel plug that would vent evaporating helium into space and simultaneously keep the remainder of the superfluid helium from creeping out after it. But for sheer aggravation and headache, there was little to rival the electronics of the infrared detector array that was to sit at the telescope's focal plane.

There are 62 detectors in the array, each a little rectangle of semiconductor less than a centimeter across. The original design—agreed to by Ames, the IRAS science team, and the focal plane subcontractor, Rockwell International—called for backing the detectors with preamplifiers based on MOSFET's, metal oxide semiconductor field effect transistors. However, in the course of development it became apparent that the MOSFET design would not reach the hoped-for sensitivity.

This was a disappointment. But the program was already far behind schedule and, grumbling from the science team aside, Ames thought it might still be possible to have a satisfactory mission with only slightly reduced performance. So in the summer of 1980, Ames took delivery of the completed array from Rockwell (with a lien on performance), cooled it down, and started its own check-out.

Twenty-three MOSFET's promptly destroyed themselves by static discharge.

There ensued a great pointing of fingers. But at this stage it hardly mattered who was to blame. JPL took charge of the focal plane directly and scrapped the MOSFET's. Smith then appointed a JPL Tiger Team to come up with a new preamplifier design, based on a concept by science team member Frank Low of the University of Arizona.

Meanwhile, however, the Dutch were finishing the IRAS spacecraft and were anxious to begin integrating it with the telescope. "We had much preferred to do the integration *here*," says Smith. "But it was a highly visible activity, and very important to the Dutch." The telescope contractor, Ball Aerospace of Boulder, Colorado, delivered the finished telescope to NASA in the spring of 1981; in May, therefore, NASA dutifully placed it aboard a C5-A transport bound for the Netherlands. In place of the completed focal plane was a portion of the original array, which had been retained for testing purposes.

The telescope was received in style, attended by Dutch government officials, NASA officials, television cameras, and speeches. There followed 5 months of spacecraft integration and vibration testing; then in October, with renewed fanfare, the now-assembled IRAS was returned to JPL. (Ames's responsibility had ended with the delivery of the telescope.)

At JPL, the telescope and the spacecraft were quietly separated again.

"The array was still missing," explains Smith. In fact, the new array was not even finished until Christmas of 1981, and the spacecraft was not reassembled with the now-completed telescope until February 1982.

"It was the first time we had a telescope complete enough to test thoroughly," says Smith. Indeed, in a sense the next step would be the final test: IRAS would be cooled down to liquid helium temperatures and kept there until launch, now scheduled for August 1982. The passage from room temperature to 2 K would be an enormous thermal stress on the system, and no one wanted to do it more often than necessary. The cooldown was completed by the end of February, and the engineers began their first full-blown electrical tests.

> "We thought there'd be no end to it. The problems were just continuous."

The system was a mess.

One whole bank of detectors was out, and there were two isolated detector failures elsewhere in the array. Moreover, of the roughly 700 wires that penetrated the Dewar and made the transition from room temperature to 2 K, some were dead, some were "cross-talking" with their neighbors, and some were just plain noisy.

"That was a bum time in our life," says IRAS telescope system manager Allan Conrad. "There were so many different problems that it took us a long while to sort out the pieces enough that we could begin to fix them. Then all through it there was this debate: Do we warm [the telescope] up and fix the known problems, and maybe risk more problems when we cool it back down again? Or do we guts it out and try to fix it from the outside?"

"We decided," he says, "to guts it out."

So they separated the telescope and spacecraft again and started troubleshooting. A turning point came when science team member James Houck of Cornell had a clever idea over an ale one night in England: simply reverse the voltage bias on the failed bank of detectors. "He told us, we tried it, and it worked!" says Conrad, "And that was a big deal, because the two failed detectors were in the same wavelength band."

It took 4 months, but in the end the decision to keep the telescope cold paid off. In early July, with virtually all the problems resolved, the telescope and spacecraft were reassembled for the last time and IRAS was put on track for a November launch.

"Of course," says Smith, "that required keeping to a perfect schedule—which never happens."

IRAS was subjected to new vibration tests. Parts failed and had to be fixed. IRAS went into a mammoth vacuum chamber to verify its readiness for space. Its thermal control was off. A microprocessor failed. Launch slipped into January 1983. "For a time," says Smith, "we thought there'd be no end to it. The problems were just continuous."

There were concerns over a possible leak in the Dewar that, if real, could contaminate the optics. With feelings running high, Smith decreed that the evidence did not justify the risk of trying to fix it. In November, IRAS was shipped to the Western Space and Missile Center at Vandenberg and placed atop its Delta launch vehicle.

Tuesday, 25 January, proved to be one of the few clear days in an exceptionally rainy West Coast winter. Indeed, a storm was due in the next day. At T-4 hours, the wind shear aloft was prohibitive; at T-2 hours it was just barely acceptable. At T-10 minutes, well after sunset, Conrad left the blockhouse and drove down the dark beach to a spot that would give him a clear view.

The ignition of the Delta lit up the night. Conrad could follow the trajectory for something over a minute; the first of the Delta's solid rocket boosters were just burning out as it vanished into a low cloud layer.

"It was fearful," says Conrad. "I just wanted to get IRAS off that rocket and into space."

The Delta arced southward over the Pacific. It was visible from Pasadena. From San Diego. First stage separation and second stage ignition at 4 minutes. Cutoff at 8 minutes, 54 seconds. Coast to 900 kilometers altitude, reignition at 58 minutes 20 seconds. Seven seconds later, cutoff.

IRAS was in orbit.

—M. MITCHELL WALDROP