Stewart Wills

Marvelous MIRI

The Webb Space Telescope's Mid-Infrared Instrument—the coolest optical gadget in space—is getting ready for its close-up.

Engineers and scientists in the cleanroom at NASA Goddard Space Flight Center, USA, uncrate the just-delivered MIRI instrument from its shipping container on 30 May 2012. NASA/C. Gunn 1111

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Left: The assembled MIRI during alignment testing at the RAL Space cleanroom at Rutherford Appleton Laboratory, UK. Right: A schematic showing MIRI's modules. Science and Technology Facilities Council (STFC) / G.S. Wright et al., Pub. Astron. Soc. Pac. 127, 595 (2015); © The Astronomical Society of the Pacific. Reproduced by permission of IOP Publishing Ltd. All rights reserved.

n late January 2022, the fully unfolded and deployed James Webb Space Telescope—decades in the making, at a cost of billions of US dollars—slipped into orbit around the L2 Lagrange point, 1.5 million km from Earth. Since then, much of the observatory's story has been about waiting for things to cool down. Protected from solar heat by a tennis-court-sized sunshield and by the stable L2 orbit, which keeps the Earth between the sun and the spacecraft, the three near-infrared cameras and spectrographs in Webb's Integrated Science Instrument Module (ISIM) must gradually, passively settle to a temperature of 40 K before they can be readied to gaze into the deepest cosmos.

But for the ISIM's other occupant—sorry, that's just not cold enough. Like an imperious opera singer or a pampered rock star, Webb's Mid-Infrared Instrument (MIRI) demands that things be just right before it will do its magic. In MIRI's case, "just right" means additional active chilling to a bit more than 6 degrees above absolute zero, courtesy of an intricate cryo-cooling system distributed across the spacecraft.

But, as in dealing with a prickly human talent, astronomers and engineers are happy to cater to MIRI's whims—because they know an amazing performance lies ahead.

"We have never, ever had a mid-infrared capability like this," says Gillian Wright, a research astronomer with the UK Astronomy Technology Center (UK ATC), Edinburgh, and the European principal investigator for MIRI. In previous missions, she explains, "the image quality in the mid-infrared has always been limited by the fact that it's been, relative to the wavelength, a very small telescope." Webb's giant, 6.5-m primary mirror, coupled with MIRI's precision optics and detectors tuned to wavelengths of 5 to 28.5 μ m, will add up to "a huge difference in sensitivity ... a step change." The sensitivity gain will let MIRI snoop on the atmospheres of extrasolar planets dozens of light years away; solve riddles about how galaxies, stars and planetary systems form; and, in partnership with the spacecraft's near-IR tools, help scientists survey the first stars in the universe.

The two-decade-plus story of the Webb telescope's development, testing, false starts and delays—culminating in a triumphant Christmas Day 2021 launch and early 2022 deployment—has been widely reported. Yet, in many ways, MIRI nicely encapsulates the very best of that long journey: international collaboration, sustained teamwork, engineering wizardry and the opportunity for dramatic advances in our understanding of the universe. Here, we offer a "celebrity profile" of this remarkable piece of optical technology, and what it will enable.

Birth of an idea

In the Webb telescope's founding document—"HST and Beyond," published in 1996 by the Association of Universities for Research in Astronomy—a mid-IR instrument was only in the "nice to have" category. Instead, the report's authors emphasized the need for "a space observatory of aperture 4 m or larger, optimized for imaging and spectroscopy over the wavelength range 1-5 μ m." That near-IR spectral range chimed with some of the envisioned telescope's overriding themes, such as

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understanding the early evolution of galaxies, and finding the first stars in the universe—whose visible light, owing to the expansion of space, would be red-shifted to that wavelength range.

Yet extending the telescope's range to the mid-IR held many tantalizing potential rewards—some related to a branch of study that, in 1996, had only recently burst on the scene.

"In the early mission proposals, [the Webb telescope] was really a first-light mission," says Oliver Krause, a scientist at the Max Planck Institute for Astronomy (MPIA), Germany, who helped build several of MIRI's key mechanisms. But then, he adds, "this fantastic new science field of exoplanets really came into the game." For example, coupled to a suitably large-aperture telescope, a mid-IR instrument might sense a host star's light filtered through the atmosphere of a distant extrasolar planet in transit, and spectrographically analyze it for signatures of molecules hinting at the presence of life on that distant world. A mid-IR instrument could also probe the larger evolution of exoplanetary systems, active galactic nuclei and the early stages of star formation in ways inaccessible to shorter-wavelength instruments.

These and other mid-IR observations effectively required an ultra-cold telescope in space, far from the bright mid-IR background of the Earth's atmosphere, which would swamp any ground-based detector. Thus the "HST and Beyond" committee further recommended "extending the wavelength coverage ... longward to about 20 μ m, as far as is technically possible and cost-effective."

Astronomers on both sides of the Atlantic quickly jumped in to make the case for a mid-IR instrument on Webb. Part of the European contribution to laying the groundwork for what became MIRI, Wright notes, was securing additional funding from European space agencies. "There was a lot of scientific momentum for it," she says. "But it was also [about] bringing in the extra resources to make it happen."

Eventually, by the early 2000s, a 50/50 partnership had emerged between US and European groups. In Europe, a consortium of 24 astronomical institutes from 10 countries—headed up by Wright as European PI and UK ATC colleague Alistair Glasse as lead instrument



One of MIRI's three focal-plane modules, including a 1024-pixel-square arsenic-doped silicon detector. NASA

scientist—would be responsible for all of MIRI's optics, associated mechanisms and structures. The US side would take care of the focal-plane assemblies (including the detector arrays) and the cryo-cooler needed to make MIRI comfortable at below 7 K; that effort would be guided by science team lead George Rieke of the University of Arizona and project scientist Michael Ressler of the Jet Propulsion Laboratory (JPL).

"I have to say, it was a fantastic working relationship with our European collaborators," says Ressler. "We were told by upper management that such a collaboration would never work when [JPL was] awarded the job. But in the end it went very, very well."

Sensitive and cool

The forging of that collaboration kicked off more than ten years of effort to design, build and test MIRI before its early 2012 delivery to NASA's Goddard Space Flight Center. The design targeted a compact, launch-ready instrument that would perform four key scientific functions in the mid-IR: imaging; low-resolution spectroscopy in the 7-to-12-µm wavelength band; medium-resolution integral-field spectroscopy across the full 5-to-28.5-µm spectral range; and coronagraphy, in which specially designed masks block a distant star's light to enable direct imaging of surrounding planets. The need to optimize the detectors' performance and reduce their dark current is one of the main reasons for MIRI's draconian cooling requirements.



The MIRI filter wheel allows selection in the MIRI imaging module between any of 18 narrowband and broadband filters, coronagraph stops and prisms. A ratchet (top of photo) holds the filter wheel in place during an observation. MPIA

Capturing the light from MIRI's optics are three focal-plane arrays, which package together sensitive arsenic-doped silicon detectors with associated control and readout electronics. The detectors—manufactured by Raytheon Vision Systems, overseen by Ressler's JPL team—rely on a technology inherited from the ones on the earlier Spitzer Space Telescope mission. "I wouldn't quite call them grandchildren; maybe second cousins a couple of times removed," says Ressler.

The most important advance from the Spitzer detectors, according to Ressler, is "simply the size"—1024 pixels square for MIRI, versus a maximum of 256 pixels square for Spitzer, in keeping with Webb's much greater aperture. Beyond that, he adds, a big challenge is "keeping alive the technology and the skills necessary to build it," since arsenic-doped silicon arrays don't have a big market on planet Earth. "These are definitely specialty detectors."

The need to optimize the detectors' performance and reduce their dark current is one of the main reasons for MIRI's draconian cooling requirements. Pushing instrument temperatures to near 6 K relies on the other US contribution, the cryo-cooler built by Northrup-Grumman Aerospace in collaboration with JPL. The closed-cycle helium system includes a pulse-tube precooler—driven by two pistons moving in opposite directions, to cancel out vibrations—that takes things down to 18 K. A second, Joule-Thomson cooling module hammers temperatures down the rest of the way.

One big hurdle was the need to have the cooling system's components distributed across the large spacecraft. "Coolers are easier to build when everything is compact," Ressler explains. But on Webb, the compressors, which must be at room temperature, need to sit on the spacecraft bus, roughly 10 meters away from the cold head at the actual MIRI site—with stainless-steel tubes carrying the helium between the two sides.

Having these "widely distributed components that get bolted onto different things," he says, means that the cooling system could never be tested as a single unit on the ground (though its various components were thoroughly vetted). The cooler was switched on at a low operating power soon after launch, and seems to be running well thus far, according to Ressler. The acid test, though, will come in mid-March (after this issue of OPN goes to press), when the chiller is pushed to full throttle, driving MIRI's temperature down from more than 100 K to just over 6 K in about three weeks.

Small package

The super-cold operating environment naturally helped shape the design and building of the optical instruments themselves—the European side of the project. One early decision, according to Martyn Wells at UK ATC, the optics lead for MIRI, was to make virtually everything in MIRI out of aluminum to prevent problems due to different thermal-expansion coefficients for different materials. (The principal exception is a hexapod mount of carbon-fiber legs, which thermally insulates MIRI from the rest of the spacecraft.)

The all-aluminum construction extends to the mirrors, all of which were diamond-turned in aluminum and then, like the Webb primary mirror, coated with a thin layer of gold. "The roughness of the diamond turning still gives you a very good mirror" for MIRI's mid-IR wavelengths, says Wells.

These complications of a frigid environment came on top of the already formidable challenge of cramming

MIRI's versatile toolkit into the smallest possible package—essential, Wells notes, to meet size and weight requirements for launch.

For example, three of the instrument's four core scientific functions—imaging, coronagraphy and low-res spectroscopy—are ingeniously configured into one instrument, the Mid-Infrared Imaging Module (MIRIM). A "filter wheel" holding an array of 18 broadband and narrowband filters, coronagraph stops and prisms lets the instrument be set up for imaging at various wavelength ranges, for coronagraphy or for low-resolution spectroscopy, depending on the observation specs. Both the overall input field of view and the detector's imaging area are neatly partitioned into separate areas to support each of the three functions.

The other main module, the Medium Resolution Spectrometer (MRS), enables diffraction-limited integral-field spectroscopy in four channels spanning the entire wavelength range supported by MIRI's detectors. This device, too, relies on mechanical wheels to select dispersion gratings and wavelength-sorting dichroics for observation of sub-bands within the wavelength channels.

The filter and grating wheels, which have been described as the heart of MIRI science operations, were developed under Oliver Krause's supervision at MPIA, in partnership with the German firm Hensoldt (formerly Carl Zeiss Optronics). Each of the mechanical wheels features a ratchet system that holds the wheel in its designated position. This both ensures positioning precision and minimizes power requirements, since no power is required during actual science operation to hold the wheel in place. The design, Krause says, has a tested useful lifetime of at least 200,000 filter-changing steps.

As with so much else on MIRI, the extreme low temperature required custom solutions, such as the use of dry lubricants to overcome friction, according to Krause. But he believes the versatile wheels, and the space-saving configuration that they enable, hold one key to making the most of the mid-IR opportunities that Webb's 6.5-m mirror will enable. "I think we have to recognize that James Webb is an outstanding facility," says Krause. "And of course, you want to make the best possible use of such a telescope."

Alignment challenges

The MIRI instrument's elegantly compact optical path begins with a pick-off mirror at the base of the instrument that collects light from the telescope and directs it to an input optics unit. There, a portion of the light is shunted by a fold mirror to the imaging module, where it bounces off multiple mirrors, passes through the filter wheel and ends up at the appropriate spot on the



Adapted from JWST Mid-Infrared Instrument User Documentation, https://jwst-docs.stsci.edu/jwst-mid-infrared-instrument / Infographic by Phil Saunders If all goes well, commissioning should be complete by late June, nearly 180 days after launch—and MIRI will be ready for its debut on the scientific stage.



Each of the four spectral channels of the MIRI Medium Resolution Spectrometer includes an integral field unit (left) that uses a special mirror (right) to slice and reformat the input field for presentation to the grating spectrometer. M. Wells et al., Pub. Astron. Soc. Pac. **127**, 646 (2015); © The Astronomical Society of the Pacific. Reproduced by permission of IOP Publishing Ltd. All rights reserved.

detector array. The remaining telescope light moves on to the MRS, where it enters a pre-optics unit that splits the light into four spectrographic channels with three sub-bands, and proceeds to a main optical unit where the channels are dispersed and imaged onto the detector.

Ensuring the precise optical alignment of all of these pieces, constructed by different partners, constituted a task of mind-bending complexity. "A big part of my job," says Martyn Wells at UK ATC, "was making sure that light coming from a Belgian pickoff mirror, entering UK ATC pre-optics, going into a Dutch spectrometer and landing on an American detector—that all of that light arrived in position, in focus." The work involved painstaking analysis of optical tolerances at each interface—along with ground vibration testing at cold operating temperatures, followed by further alignment checks, even before the fully tested instrument was delivered to NASA Goddard.

"Minor idiosyncrasies"

That delivery, which took place in May 2012, made MIRI the first of Webb's four scientific instruments to reach the Goddard cleanroom in the US, which European PI Wright characterizes as "a very nice achievement." But the instrument wouldn't find its way into space until nearly a decade later, owing to Webb's much-reported delays. In the meantime, the development team kept busy on additional testing with the instrument installed on the spacecraft, as well as building the software pipelines and analytical tools key to MIRI's science agenda.

One interesting thread relates to the instrument's super-cold silicon detectors. JPL's Ressler notes that "silicon does not like to be a semicon-

ductor at 6 K," and that in such frigid temperatures, "minor idiosyncrasies in how [the detectors] operate tend to get magnified." Understanding such "nonideal behaviors" has entailed extensive modeling and analysis of instrumental signatures for various observational scenarios, so that they can be corrected in the data-processing pipeline. Even so, "some of those sorts of issues are fairly tough nuts to crack," Ressler admits. "We've got some really oddball effects that we're still trying to figure out how to mitigate."

That is just one part of the commissioning process that's unfolding as MIRI, along with the other Webb instruments, moves toward taking its first scientific observations around June 2022. As of this writing, the instrument temperature is still a relatively balmy 102 K (-171 °C). In mid-March, after the Joule-Thomson chiller is fully engaged, things will cool down rapidly to near 6 K by early April, some 100 days after launch. At that point, the contamination control panel currently covering MIRI's entrance aperture will open, and the first starlight should pass through its optics to its detectors.

After that will come further weeks of testing image quality and operating mechanisms, refining the processing pipeline and otherwise readying MIRI for the business of observation. If all goes well, commissioning should be complete by late June, nearly 180 days after launch—and MIRI will be ready for its debut on the scientific stage. **OPN**

Stewart Wills is the senior editor of OPN.

For references and resources, go online: optica-opn.org/link/miri.

AFTER FIRST LIGHT

nspiring as MIRI's engineering story is, ultimately the payoff is the science that the instrument will accomplish. And the astronomy community has some ideas.

The Space Telescope Science Institute (STScI), which manages the Webb science agenda, has parceled out more than 10,000 telescope observing hours across hundreds of projects in just the first year—"Cycle 1," in STScI jargon. Those first-year hours are divided up into three project groups.

Guaranteed-Time Observations (GTO)

Around 16% of Webb's observing hours for its first three cycles are set aside for the individuals, teams and institutions that made material contributions to the observatory's development.

One such project of the European consortium, led by Thomas Henning of MPIA—the institute behind MIRI's intricate filter- and grating-wheel mechanisms—will use 120 hours of Cycle 1 GTO observing time to conduct a survey of 50 protoplanetary and debris disks. The project will train MIRI's Medium Resolution Spectrometer (MRS) and coronagraph (along with several of Webb's near-IR instruments) on those systems to get at the chemistry, physics and thermal structure of the zones that ultimately coalesce into exoplanetary systems.

Studying these exoplanet nurseries in more detail offers crucial insight, according to Gillian Wright, the MIRI European PI at UK ATC. "These sound like very simple questions, but we haven't got any data at the moment to begin answering them," she says. "It's really exciting, critical science in understanding how exoplanets form."

Director's Discretionary Early Release Science (DD-ERS)

Another 10% or so of Webb's early observing time will go to programs to quickly ramp up the community's understanding of how to use Webb's instruments and capabilities. Sasha Hinkley of the University of Exeter, UK, is the PI on one of the 13 Cycle 1 DD-ERS projects, focused high-contrast imaging of exoplanets and exoplanetary systems using all four of Webb's scientific instruments—including MIRI.

"What I worked to do," Hinkley says, "was to really synthesize from my community" the required observing modes for direct exoplanet imaging. (A separate DD-ERS project involves transiting exoplanets.) "In the end, we were allocated 54 hours to really test drive all four instruments on James Webb" in those observing modes.

As a key project outcome, he says, the team will quickly push out to the community—in the short time window between first light in June 2022 and the Cycle 2 proposal round in early 2023—a set of software tools for handling direct exoplanet imaging data from the telescope. The team will also provide an assessment of performance metrics and best observing practices, to help the community craft proposals for Cycle 2.

General Observers (GO)

The lion's share of Webb's observing time covers a wide range of projects under the GO program. Many of these



Image of protoplanetary disk around HL Tauri, from the Atacama Large Millimeter Array (ALMA) observatory. ALMA (ESO/NAOJ/NRAO); CC-BY 4.0



An artist's view of the exoplanets in the Trappist-1 system, the target of several planned Webb telescope observations. NASA/JPL-Caltech

efforts will rest on MIRI's superb capabilities in the mid-infrared.

Laura Kreidberg of MPIA, for example, is PI on two fascinating projects. One will attempt to determine whether Trappist-1c, one of the worlds in a celebrated system of rocky exoplanets, has an atmosphere. To do so, she'll use MIRI's imager to understand how the planet's thermal emission differs from day to night.

Kreidberg's other project will zero in on a planet she previously observed using the Spitzer Space Telescope—a world that, she says, is known to be a "bare rock" devoid of an atmosphere. But that will allow her team to use MIRI's low-resolution spectrometer to view emission spectra from the planet, to infer its surface geology—and, perhaps, reveal evidence of volcanism and Earth-style plate tectonics on this world more than 48 light years away.

While the few examples here have focused on exoplanets, MIRI lies at the center of a wide span of other projects in Webb's first observational year, in areas ranging from supermassive black holes to the origin of the celebrated Crab nebula to the nature of dark matter. "MIRI is a real game changer," says Kreidberg. "We've never had access to precise spectroscopy redder than five microns ... Webb is really forging into new territory here."

Article References and Resources

MIRI technical papers

A July 2015 special issue of *Publications of the Astronomical Society of the Pacific* (PASP) offers a splendid overview of MIRI's history, capabilities and scientific potential, along with individual papers providing as deep a dive into the instrument's engineering and optics as you could ask for. Access is free.

- ▶ G.H. Rieke et al. "The Mid-Infrared Instrument for the James Webb Space Telescope, I: Introduction," PASP 127, 584 (2015).
- G.S. Wright et al. "The Mid-Infrared Instrument for the James Webb Space Telescope, II: Design and Build," PASP 127, 595 (2015).
- P. Bouchet et al. "The Mid-Infrared Instrument for the James Webb Space Telescope, III: MIRIM, The MIRI Imager," PASP 127, 612 (2015).
- S. Kendrew et al. "The Mid-Infrared Instrument for the James Webb Space Telescope, IV: The Low-Resolution Spectrometer," PASP 127, 623 (2015).
- A. Boccaletti et al. "The Mid-Infrared Instrument for the James Webb Space Telescope, V: Predicted Performance of the MIRI Coronagraphs," PASP 127, 633 (2015).
- ▶ M. Wells et al. "The Mid-Infrared Instrument for the James Webb Space Telescope, VI: The Medium Resolution Spectrometer," PASP **127**, 646 (2015).
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- M.E. Ressler et al. "The Mid-Infrared Instrument for the James Webb Space Telescope, VIII: The MIRI Focal Plane System," PASP 127, 675 (2015).
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- ► K.D. Gordon et al. "The Mid-Infrared Instrument for the James Webb Space Telescope, X: Operations and Data Reduction," PASP 127, 584 (2015).

Other resources

- NASA. Where Is Webb? (provides ongoing information about Webb Space Telescope deployments, instrument temperatures, etc.), https://webb.nasa.gov/content/webbLaunch/whereIsWebb.html?units=metric.
- JWST User Documentation. JWST Mid-Infrared Instrument, https://jwst-docs.stsci.edu/jwst-mid-infrared-instrument.
- NASA. Webb Instruments: Mid-Infrared Instrument, https://webb.nasa.gov/content/observatory/instruments/ miri.html.
- ESA. MIRI—The Mid-Infrared Instrument on JWST, https://sci.esa.int/web/jwst/-/46826-mirithe-mid-infrared-instrument-on-jwst.
- Space Telescope Science Institute. JWST Approved Programs (a list of Cycle 1 programs, many using MIRI's capabilities), https://www.stsci.edu/jwst/science-execution/approved-programs.
- University of Arizona Dept. of Astronomy. MIRI science, http://ircamera.as.arizona.edu/MIRI/science.htm.