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# The Spitzer Space Telescope

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**Abstract.** The Spitzer Space Telescope, which has operated very successfully since 2003 in its unique Earth-trailing solar orbit, is NASA's Great Observatory for infrared astronomy. We provide a quick overview of the optical characteristics of Spitzer and review the observatory design. The main emphasis is on two unique on-orbit activities used to optimize the scientific return from Spitzer: 1. an unusual approach to focusing the telescope that minimized the use of the cryogenic focus mechanism, and 2. a methodology for extending the cryogenic lifetime of Spitzer by actively controlling the telescope temperature.  [DOI: 10.1117/1.OE.51.1.011008]

Subject terms: cryogenic systems; infrared; space telescope; Spitzer; telescope focus; thermal control.

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## 1 Introduction

The launch of the National Aeronautics and Space Administration's Spitzer Space Telescope (Spitzer) in August 2003 provided the scientific community the most powerful tool yet available for astronomical explorations between 3.6 and 160 μm. Spitzer combines the intrinsic sensitivity of a cryogenic telescope in space with the tremendous imaging and spectroscopic capabilities of the new generation of infrared detector arrays. Spitzer's unique cryothermal architecture and Earth-trailing solar orbit have enabled the spacecraft to continue operating in a totally passively cooled configuration for more than two years after the depletion of the 350 L of liquid helium carried at launch. Well over 2000 papers based on Spitzer studies of objects from near-Earth asteroids to the most distant known galaxies have appeared in the refereed literature since launch, and the observatory remains as robust and productive as ever.

The Spitzer telescope is not remarkable in comparison to contemporaneous and future space-optical systems. In this contribution, we provide a quick overview of the Spitzer telescope but concentrate principally on two activities carried out during the mission that are of particular technical interest—the process by which the telescope was focused on orbit and the approach used to extend the liquid helium lifetime by matching the telescope temperature to the needs of each scientific instrument in turn. Readers seeking a more complete end-to-end technical description of Spitzer, including the instruments and the operations, are referred to Gehrz et al.[1] Werner[2] and Rieke[3] have presented historical accounts of the development of Spitzer. Summaries of the scientific bounty of Spitzer are presented by Werner et al.[4] and Soifer et al.,[5] and in the proceedings of the 2009 Spitzer Science Conference.[6]

## 2 The Spitzer Telescope

The Spitzer optical design is a conventional Ritchey–Chretien two-mirror system. The primary and secondary mirrors and the metering tower that connects them are all fabricated from hot isostatically pressed (HIP) beryllium to maintain alignment and minimize stresses on cooling from room temperature to the operating temperature of 5 K. Beryllium was the material of choice because of its lightweight, good thermal properties, and high strength-to-mass ratio. The telescope has a ~90-cm-diameter mirror, figured and stopped down to produce an 85-cm $f/1.2$-diameter primary aperture, and a 12-cm-diameter secondary mirror. The secondary mirror is mounted on a cryogenic focus mechanism, which provides high-precision motion in the axial direction and was used to focus the telescope on-orbit. The assembled optical system (Fig. 1) has a length of about 90 cm. The mass of the fully assembled telescope, including mirrors, metering tower, focus mechanism, barrel baffle, and the hardware required to mount it to the Spitzer cryostat, is 55 kg. The focal length is 10.2 m and the plate scale is 20 arcsec/mm. Fabrication of the telescope was begun at Hughes-Danbury (now Goodrich) and finished at Ball Aerospace. The mirrors were figured by Tinsley Laboratories, and much of the cryogenic testing was done at the Jet Propulsion Laboratory (JPL).

The telescope was required to provide diffraction-limited images at a wavelength of 6.5 μm over a 30-arcmin field of view. This corresponds to a wavefront error of 0.46 μm at the focal plane; when this was flowed down to and through the telescope, the corresponding requirement on the primary mirror surface error was 0.075 μm rms at the operating temperature of 5 K. Because the primary was figured at room temperature, the process of guaranteeing satisfactory cryogenic performance was neither trivial nor straightforward. Careful initial preparation of the material and annealing/stress relief during the figuring allowed the optics team to establish by test that the mirror deformed predictably (i.e., without hysteresis) on successive cooldowns. The final figure was thus achieved by measuring the mirror figure at operating temperature in a cryogenic test facility at JPL, comparing the cryogenic figure with the room-temperature figure, and taking the difference. This defined a "hit map" specifying the changes to be polished into the mirror at room temperature so that the mirror would distort into the required optical configuration upon cooldown. Two cycles of this process, referred to by the ungainly name of "cryonull figuring," brought the primary mirror to a surface error of

**Fig. 1** Spitzer telescope. This picture shows the assembled optical system—primary mirror, metering tower, secondary mirror (not visible), and focus mechanism atop the tower.

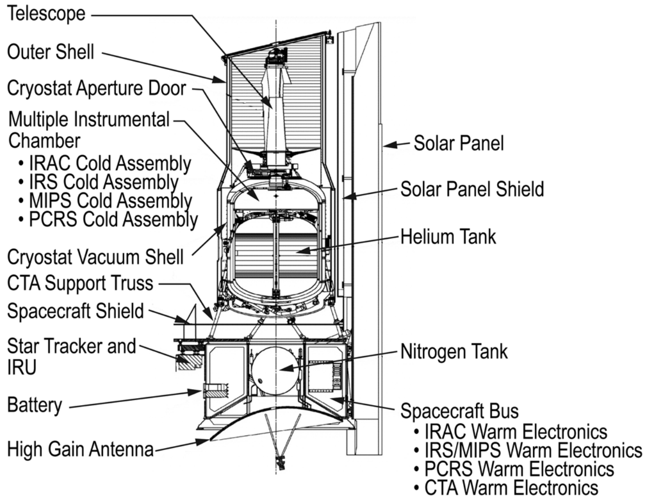


**Fig. 2** Cut-away view of the Spitzer Observatory. The observatory is about 4 m tall and has a launch mass of ~870 kg. The dust cover atop the telescope outer shell in this drawing was jettisoned a few days after launch; the cryostat aperture door was opened shortly thereafter.

0.067 μm rms, exceeding the requirement established in the error budget.

The assembled telescope, the instruments, and the Spitzer cryogenic system (also provided by Ball) underwent end-to-end optical and cryogenic testing in the BRUTUS chamber at Ball Aerospace. The optical tests used an autocollimating flat illuminated by a thermal source in the Spitzer focal plane that was reimaged by the telescope and detected by the shorter wavelength instruments. This test, described in detail by Gehrz et al.,[1,7] established that the system optical quality met predictions and requirements, and also allowed the secondary mirror to be set to place the telescope focus at the optimum prelaunch position.

The Spitzer observatory, shown in Fig. 2, includes the telescope, scientific instruments, the cryothermal system that maintains the instruments and the telescope at appropriate low temperatures for sensitive infrared studies, and the spacecraft. Lockheed-Martin provided the spacecraft and the solar panel and its shields.

## 3 Focusing the Telescope

### 3.1 *Overview of the Focal Plane Instruments*

Spitzer has three focal plane instruments:

- Infrared Array Camera (IRAC; principal investigator Giovanni Fazio, Smithsonian Astrophysical Observatory), which operates in four bands from 3.6 to 8 μm. A 256 × 256 pixels array operated in each of the four bands. The IRAC observed two almost adjacent 5 × 5 arcmin fields of view. Each was viewed by two of the four arrays, by using a dichroic to separate the incoming light into two bands. Thus, one IRAC field of view was imaged simultaneously at 3.6 and 5.8 μm, and the other at 4.5 and 8 μm.
- Infrared Spectrometer (IRS; principal investigator James Houck, Cornell University) with four modules covering wavelengths from 5.5 to 38 μm. The IRS provided long-slit, low-resolving power (R 100) from 5.5 to 38 μm and higher resolution (R 600) spectroscopy in echelle mode from 10 to 35 μm. All four modules were instrumented with 128 × 128 pixels arrays. A small section of one of the spectroscopic arrays could be used as a camera. This permitted the observatory to obtain an infrared image, autonomously locate an infrared source, and offset the observatory to place it on a spectrometer slit. This "peak-up" array could also be used for photometry at 15 μm.
- Multiband Imaging Photometer for Spitzer (MIPS; principal investigator George Rieke, Arizona) imaged in three bands from 24 to 160 μm. Its 24-μm array—also with 128 × 128 pixels—had a 5 × 5 arcmin field of view. The 70- and 160-μm arrays had fewer pixels and somewhat smaller fields of view but nevertheless provided excellent sampling of the telescope PSF. MIPS also had a low-resolution spectroscopic mode (R~20) for spectrophotometry from 50 to 100 μm. MIPS incorporated the only mechanism in the payload—a scan mirror that enabled efficient mapping of large areas.

The three instruments (Fig. 3) shared the 30-arcmin field of view; each was illuminated by mirrors that picked off portions of the focal plane and reflected them into the instrument apertures. The mirrors and the instrument apertures were fixed; the secondary mirror was the only optical element affecting the telescope focus that could be moved on orbit. In addition, the focal plane contained several visible

**Fig. 3** Three Spitzer instruments installed on the base plate of the instrument chamber. The four modules of the IRS are seen in the background. In the foreground, the IRAC, with its black exterior, is to the right, and the MIPS to the left. The black area at the center of the base plate is the telescope focal plane into which the instrument pick-off mirrors protrude.

light sensors, small PIN diode arrays referred to as the pointing calibration reference sensor (PCRS). The PCRS was used to observe visible stars that were observed at the same time by the external star tracker mounted to the spacecraft bus. This established and maintained the registration of the cryogenic field of view with the reference frame of the star tracker, which was used for target acquisition.

As the shortest wavelength instrument, the IRAC levied the most severe requirements on the telescope image quality. To minimize the image degradation due to design residuals, the IRAC fields of view were placed as close as possible to the center of the focal plane.

### 3.2 *Focusing Methodology*

The nominal method for focusing an astronomical telescope is to carry out a "focus sweep" in which the secondary mirror is stepped through a range of positions intended to move the focal point through the optimum position. Images are taken at each secondary mirror position and the optimum focus setting is established. This method was considered highly undesirable for Spitzer because of the unknown risk inherent in repeated and lengthy actuation of the cryogenic focus mechanism. An alternate methodology was developed, consisting of the following elements:

1. Careful design and subsequent metrology of all three instruments and the PCRS made it possible to place each module and its pick-off mirrors so that the modules were confocal to well within the depth of focus for each. This would make it possible to have acceptable image quality at each instrument aperture at a single setting of the secondary mirror's focus mechanism. Specially designed and installed fiducials placed on the outside of each instrument made it possible to check this confocality even after the focal plane was entirely assembled within the cryostat, prior to cooldown on the ground. This confocality ensured that if the IRAC were in focus, as verified by observations of stars on orbit, then all of the instruments would be in focus. Note that with a system $f$-ratio of $f/1.2$, the depth of focus at even the shortest Spitzer wavelength of 3.6 μm was about 0.4 mm, so fabrication and assembly to normal machining tolerances sufficed to ensure confocality.
2. Several software tools were developed by Spitzer scientist William Hoffmann and others[8,9] that could be used, in conjunction with an optical model of the telescope, to determine from astronomical observations at a single position of the secondary mirror how far (if at all) and in what direction the secondary mirror had to be moved to achieve optimum focus. The optical model was built up from the measured characteristics of the primary and secondary mirrors and then refined iteratively during the sequence of tests described below. One of these tools, called Simfit, was based on matching the measured images to a catalog of predicted images versus focal position for all four of the IRAC modules. The second tool, called focus diversity, made use of the fact that the flat IRAC arrays only approximated the curved focal plane of the telescope. The $5 \times 5$ arcmin IRAC arrays are large enough that the final image quality varied considerably and systematically across the arrays. This variation was more marked when the telescope was further away from its optimum focus, so a $3 \times 3$ or $5 \times 5$ sampling of images across the arrays could be used—in comparison with the predicted image quality as a function of defocus—to assess the state of the focus and determine the adjustment that had to be made. In using the focus diversity method, the metric used to determine the image quality was the noise pixel statistic developed by Wright,[10] which can be directly related to the amount of time required for observation to a fixed sensitivity level.
3. Both the Simfit and focus diversity methods were used on test data of image quality as a function of secondary mirror position obtained during the BRUTUS test of the cryogenic optical performance for Spitzer. The two methods gave results that were in agreement with each other and also with the secondary mirror position as established mechanically. This made it possible to set the secondary mirror prior to launch at a position that would give optimum focus following gravity release and on-orbit cooldown. Note that the greatest uncertainty in setting the focus prelaunch was the uncertainty in the radius of curvature of the optical "flat" used in autocollimation in the BRUTUS test. This flat had been found to become slightly concave when cooled to cryogenic temperature and measurement of its cryogenic figure was possible with only limited precision.

### 3.3 *On-Orbit Activities*

An on-orbit focus procedure, optimum focal-plane position, and success criteria were established. We describe the position of the telescope focal plane in millimeters of deviation from the optimum position. The secondary magnification of the Spitzer telescope is 100, and the secondary mirror actuator had a step size of a fraction of 1 μm. Thus it was possible to adjust the position of the focal plane in steps smaller than 0.1 mm, much less than the depth of focus for the shortest wavelength instrument. Similarly, the numerical methods of Hoffmann et al. had been shown to be capable of determining the position of the focal plane to better than 0.1 mm. The on-orbit procedure was rehearsed prior to launch with a double-blind test in which simulated images for a known focal-plane position were input to the system, and the analysis team properly retrieved and determined the offset. A level of initial on-orbit defocus was established that would trigger an anomaly response. Following initial cooldown, the estimated defocus did not exceed this limit (which was about 1.8 mm away from the target best focus) and the focus procedure was initiated. Details of the on-orbit focus activities and the resultant image quality are presented by Gehrz et al.[7]

The focus procedure was actually initiated on the 38th day after launch, when the telescope had cooled down to about 20 K (as discussed below, the Spitzer telescope was launched at ambient temperature and cooled down on orbit). As planned, a small exploratory move was made of the secondary mirror that shifted the focus position by a little more than 0.1 mm, which successfully verified operability and directionality of the focus mechanism (Fig. 4). This was followed by a much larger move that brought the focus position into the previously defined acceptable range. At this point, the image quality was demonstrated to meet the level 1 requirement of diffraction limited at 6.5 μm, so further moves of the focus mechanism were not required. Further measurements showed that the IRS and MIPS instruments also had acceptable image quality at the adopted focus position.

Figure 5 shows directly the image quality measured in all four IRAC bands on orbit, before and after the telescope was focused. The in-focus image is appreciably sharper than that taken before focus, and the wings of the PSF are greatly reduced. As a result, the raw sensitivity—as determined by the noise pixel metric—has been optimized, while the susceptibility of the IRAC 3.6-μm band to neighboring sources (an effect called "confusion") has been reduced. Both of these factors have contributed greatly to IRAC's ability to look far back in time and space to study galaxies as they appeared not long after the Big Bang.

### 3.4 *Warm Spitzer and Its Image Quality*

By design, images that permitted a focus position assessment had been collected periodically as the telescope cooled. As Fig. 4 shows, the focus position did not move by more than ±0.1 mm starting at day 22 when the telescope was at a temperature of 57 K. This temperature independence of the focus position was expected, based on the thermal properties of beryllium, which remains very stable dimensionally at temperatures below ~60 K. This temperature independence of the focal position proved important when Spitzer's liquid helium supply was depleted in May 2009. As expected, the telescope then warmed up to close to 30 K—a temperature at which the two short-wavelength IRAC arrays at 3.6 and 4.5 μm remain as sensitive as during the cryogenic mission. Our knowledge that the system image quality would be unchanged at the higher temperature (which was then verified) allowed us to plan for and execute the Spitzer Warm Mission; the IRAC 3.6- and 4.5-μm arrays have been operated continuously since July 2009 and continue to return excellent scientific data.[11]

## 4 Extending Spitzer's Cryogenic Lifetime

### 4.1 *Defining the Opportunity*

One of Spitzer's most important driving requirements was to achieve natural-background-limited performance over the wide range of wavelengths from 3.6 to 160 μm. This means that instrumental background—due principally to emission from the telescope itself—has to be driven below the level of the diffuse emission from the zodiacal dust cloud and from the cooler interstellar dust. Spitzer is cooled—radiatively and cryogenically—precisely to realize these low backgrounds, which, together with the excellent performance of Spitzer's

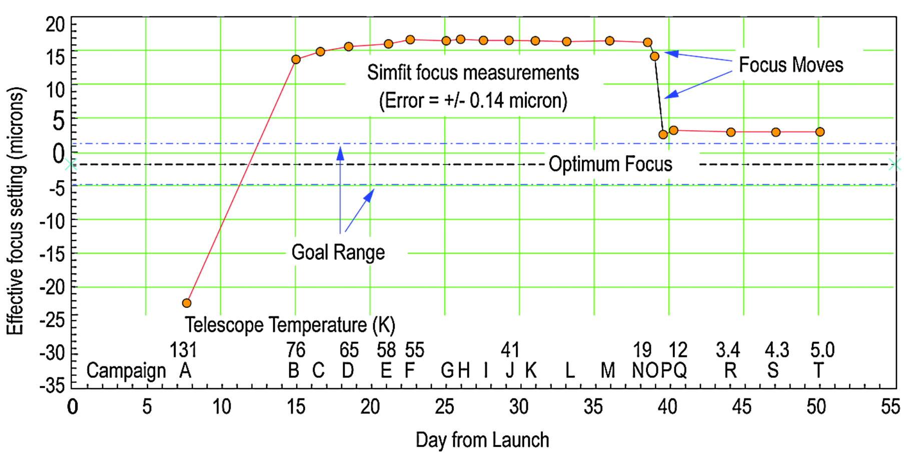


**Fig. 4** Time history of Spitzer focus on-orbit.[7] (Note that this figure describes the focus position in micrometers of the secondary mirror position, in contrast to the millimeters of the focal plane position used in the text. For Spitzer, 1 μm of secondary mirror movement produces a 0.1-mm motion of the focal plane position.) The filled circles plot the effective telescope secondary focus settings relative to the model zero versus the day from launch; these are the average for IRAC bands 1 and 2 determined by the Simfit method. Letters A through T refer to a series of on-orbit measurements of the IRAC images, from which the focus setting was derived. The two focus moves described in the text were made around day 38. At that point, it was determined that the level 1 image-quality requirements had been met, so no further moves were needed.

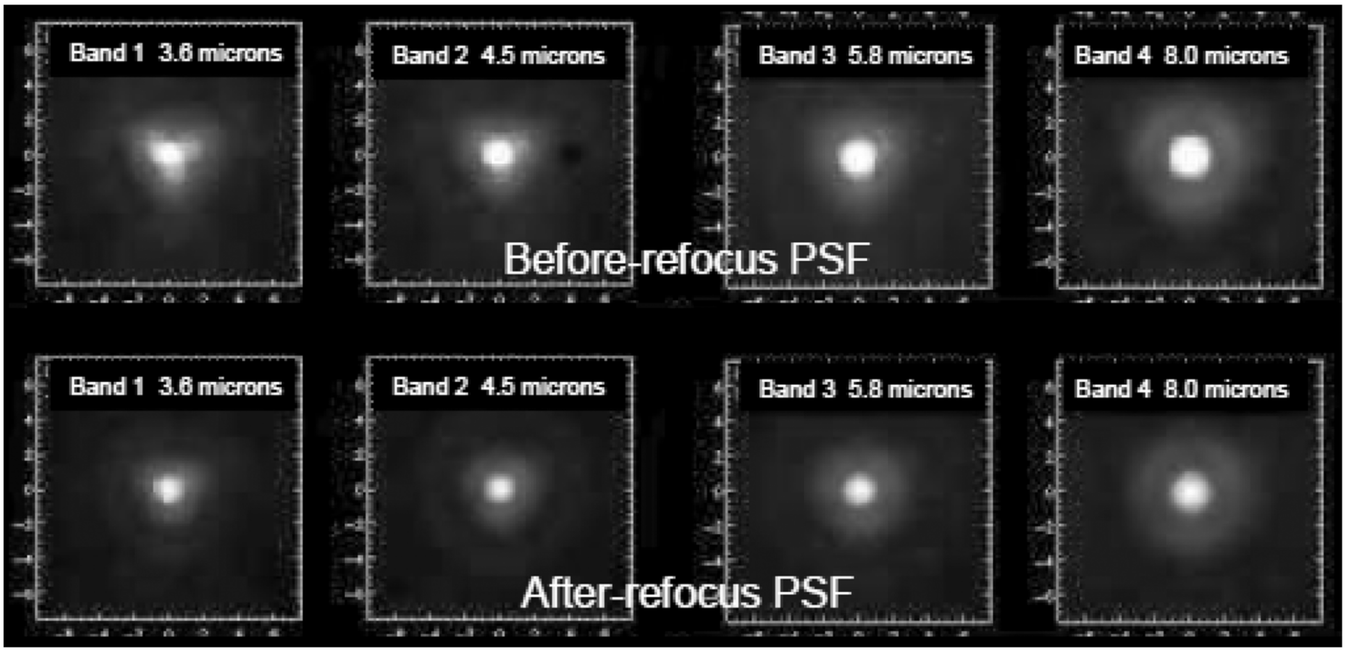


**Fig. 5** Images in all four bands of the IRAC, before and after Spitzer was focused on orbit.[7] The box size is 15 IRAC pixels (18.3 arcsec).The images are displayed with square root scaling to bring out the low-level extended structure. The improvement in PSF sharpness after refocus is clear in all four bands, with the biggest improvement in bands 1 and 2.

detector arrays, lead to the high sensitivity of Spitzer's observations.

The telescope temperature—and its resultant thermal emission—is the major factor that determines the background radiation at the Spitzer focal plane. Because of the laws of blackbody radiation, the required temperature for background-limited conditions varies greatly across the Spitzer wavelength range and thus from one instrument to the next. Specifically, natural-background-limited operation of MIPS at 160 K requires a telescope temperature below 5.5 K, while the shortest-wavelength IRAC band would be natural background limited at a telescope temperature as high as 75 K (although in practice, of course, the temperature never rises to anything like this value). Because of the fact that Spitzer is designed for operation of only one instrument at a time, it is possible to consider tuning the telescope temperature to the specific needs of the instrument that is in use.

Spitzer scientist Charles Lawrence led a group that analyzed this problem and came up with an approach to management of the telescope temperature which also extended the cryogenic lifetime of Spitzer by about nine months. Explanation of this ingenious scheme requires a quick overview of the cryothermal architecture, which is itself an integral part of the success of Spitzer.

### 4.2 *Cryothermal Tutorial*

As mentioned earlier, Spitzer was launched with the telescope at ambient temperature. Once on orbit, the telescope cooled down rapidly by radiating heat to the cold blackness of space. Further cooling was provided by conduction to the cryostat outer shell, which, in turn, was cooled by helium vapor boiled off within the helium tank inside the cryostat (Fig. 2). The instruments, located in a chamber interior to the cryostat, were cooled conductively by contact with the helium tank. This cooling scheme relies on two design features:

1. A system of thermal shields and shells, including the solar panel, shades the telescope and its shields and shells from the light and heat of the Sun. The shields and shells are designed and coated so as to reject any stray heat that leaks in through the solar panel, or up from the spacecraft, and the back half-cylinder of the telescope outer shell is covered with a high-emissivity black coating that radiates to cold space any heat that does get through. The warm-launch architecture was devised by the late Frank Low, who served as Spitzer facility scientist.
2. The use of an Earth-trailing heliocentric orbit for Spitzer, which keeps the observatory far from the heat of the Earth, enables this cooling scheme. In this orbit, the shading solar panel is always oriented toward the Sun, while the back half of the telescope outer shell always views cold space and is able to radiate efficiently. These constraints would be difficult or impossible to sustain in an Earth-orbiting satellite because of the need to have some pointing flexibility to study different astronomical targets. The many benefits of this orbit, which extend far beyond these cryothermal considerations, are described by JPL engineer Johnny Kwok,[12] who proposed that it be adopted for Spitzer. Its advantages are similar to those of the L2 Lagrange point orbit adopted by many current and planned astrophysical observatories.

With this unique configuration, the telescope outer shell cools, entirely passively, to around 34 K. As a result, there was less than 1 mW of parasitic heat diffusing inwards and reaching the helium tank. The main heat load on the helium

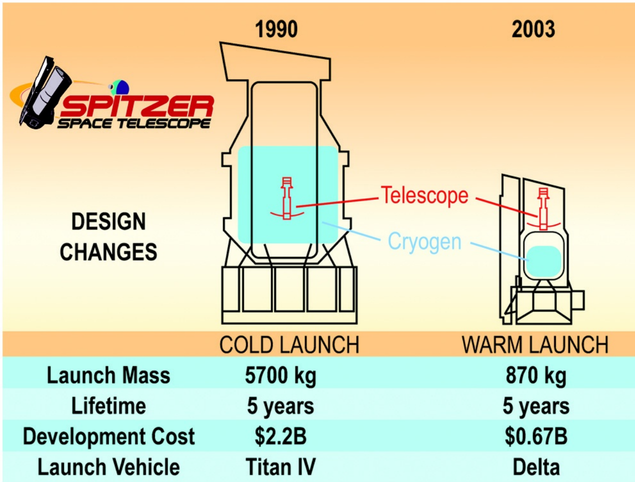


**Fig. 6** Cold-launch (1990) and warm-launch configurations for Spitzer. Note that the telescope size and cryogenic lifetime are the same for each configuration, but the mass, observatory cost, and launch vehicle costs are much smaller for the warm-launch configuration.

was therefore the 2 to 4 mW that the array electronics and heater circuits dissipated while taking data. Because the helium usage was dominated by the instruments, there was no penalty in choosing to operate only one instrument at a time, which in turn enabled the optimization described below. Note the sharp contrast between the Spitzer warm-launch architecture and the cold-launch architecture adopted for the precursor missions, Infrared Astronomical Satellite (IRAS)[13] and Infrared Space Observatory (ISO).[14] This geometry was also the baseline for Spitzer until 1993 (Fig. 6). In these cases, the telescope was launched cold with a large cryostat containing much larger amounts of liquid helium than Spitzer carried. The telescope was thermally anchored to the cryostat, and the warm outer shell resulting from low-Earth operations meant that the helium boil-off was dominated by parasitic rather than instrument loads. (Cryogenic refinements aside, however, IRAS and ISO were tremendously exciting and successful scientifically and helped to pave the way for Spitzer.)

## 4.3 *Exploiting the Opportunity*

Returning to Spitzer, Lawrence et al.[15,16] realized that the original scenario in which the telescope was maintained continually at $T \sim 5.5$ K as required for MIPS observations was overly conservative and wasteful of helium. It turned out that when either IRAC or IRS was operating, the power dissipated by the instrument sufficed to cool the telescope to the operating temperature required by both instruments. On the other hand, MIPS did not dissipate enough power to drive the telescope temperature to 5.5 K, but a make-up heater had been installed on the helium tank for just this contingency. After a few weeks of on-orbit data taking and calibration, a scheme was devised in which the instruments were operated serially for periods of about 10 days. A few days before the MIPS was to turn on, the make-up heater was turned on to a predetermined level. This increased the liquid helium temperature, increasing the boil-off rate and driving the telescope temperature down. As is shown in Fig. 7, the size and duration of the make-up heater pulse were timed to drive

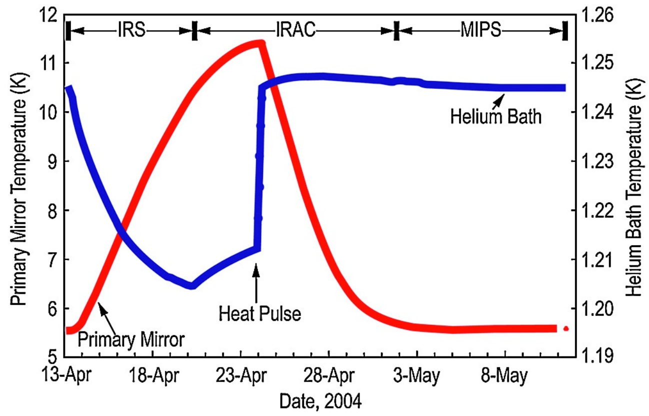


**Fig. 7** One cycle of on-orbit telescope temperature management for Spitzer. The cycle start with the changeover from MIPS to IRS. At this point, the telescope and helium bath temperatures have equilibrated at 5.6 K and 1.245 K, respectively. The MIPS and the make-up heater, which together had supplied 5.17 mW during the MIPS observations, are turned off, and the IRS turned on. The bath temperature (blue) drops, reducing the helium pressure and hence the boil-off rate, so the telescope temperature (red) starts to rise. When IRAC—which dissipates 2.93 mW as opposed to IRS's 2.36 mW—is turned on around April 21, the bath temperature starts to rise but the telescope continues to warm, albeit more slowly. About 7.5 days before the previously scheduled start of the next MIPS run, the make-up heater is turned up to 26 mW for 18,845 s, adding 493 J to the helium and raising its temperature to 1.245 K as needed for MIPS. The telescope starts to cool. Following the heat pulse, the make-up heater is turned down to the level where its contribution plus IRAC's sum to the 5.17 mW is required to maintain the bath at 1.245 K, and the telescope cools to the needed 5.6 K. This entire process is deterministic, so the duration of the heat pulse could be decreased as the mission continued and the helium boiled away.

the helium temperature up to the point required to keep the telescope at 5.5 K. The heater was left on at a lower level so that when the MIPS turned on a few days later, its power, plus that provided by the heater, sufficed to keep the telescope at the desired temperature. As shown in Fig. 7, the thermal time constant of the system was a few days, but that was consistent with the block scheduling approach that had always been planned for Spitzer.

Following the MIPS observing period, the make-up heater was turned off, the IRS was turned on, and the telescope temperature drifted upwards, only to be driven down a few weeks later when the cycle described above was repeated. This scheme relies on the rather paradoxical circumstance that warming the helium cools the telescope, and vice versa; however, it worked remarkably well and the result was to extend the helium lifetime by nine months (of a total of almost six years) compared to the approach in which the telescope temperature was constant. The relatively small swing in telescope temperature, from 5 to 20 K, which resulted from this procedure, did not risk defocusing the telescope (Fig. 4) or induce any mechanical stress to the hardware.

## 4.4 *Enabling the Warm Mission*

The cryothermal architecture had one substantial additional benefit. Although Spitzer's cryogenic system was remarkably efficient, in May 2009 the last drops of helium boiled away and the telescope and instruments began to warm up. At this point, however, the telescope outer shell temperature was still maintained at 34 K, as described above. The telescope itself and the instruments thus warmed up to only about 30 K, as they cooled even below the outer shell temperature by radiating through the open end of the telescope tube. At this temperature, the two shortest wavelength bands of IRAC, at 3.6 and 4.5 μm, continue to operate with unmodified sensitivity, so the Spitzer warm mission—which uses only these two arrays—began in July 2009. Scientifically, Spitzer hardly skipped a beat, and the scientific return from the warm mission continues to advance our understanding of objects ranging from near-Earth asteroids to the most distant galaxies.

## 5 Conclusions

The scientific progression of infrared space observatories, from IRAS to ISO to Spitzer, is self-evident. Less obvious and equally important is the progression in technology, including cryogenics, optics, and detectors. The successor mission to Spitzer will be the James Webb Space Telescope (JWST),[17] to be launched toward the end of this decade. JWST will inherit from Spitzer a rich inventory of newly posed scientific questions. JWST's ability to go beyond Spitzer in addressing these questions reflects the fact that it has leveraged Spitzer's accomplishments in beryllium optics, radiative cooling, and detector arrays, and advanced the state of the art in these and other essential technologies.

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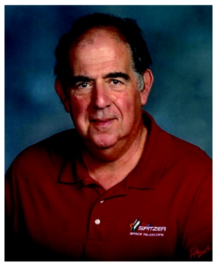

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