The Development and Mission of the Space Infrared Telescope Facility (SIRTF)

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ABSTRACT

The Space Infrared Telescope Facility (SIRTF) was successfully launched on August 25, 2003. SIRTF is an observatory for infrared astronomy from space. It has an 85cm diameter beryllium telescope operating at 5.5 K and a projected cryogenic lifetime of 4 to 6 years based on early flight performance. SIRTF has completed its in-orbit checkout and has become the first mission to execute astronomical observations from a solar orbit. SIRTF's three instruments with state of the art detector arrays provide imaging, photometry, and spectroscopy over the 3-180 micron wavelength range. SIRTF is achieving major advances in the study of astrophysical phenomena from the solar system to the edge of the Universe. SIRTF completes NASA's family of Great Observatories and serves as a cornerstone of the Origins program. Over 75% of the observing time will be awarded to the general scientific community through the usual proposal and peer review cycle. SIRTF has demonstrated major advances in technology areas critical to future infrared missions. These include lightweight cryogenic optics, sensitive detector arrays, and a high performance thermal system, combining radiative and cryogenic cooling, which allows a telescope to be launched warm and to be cooled in space. These thermal advances are enabled by the use of an Earth-trailing solar orbit which will carry SIRTF to a distance of ~0.6 AU from Earth in 5 years. The SIRTF project is managed for NASA by the Jet Propulsion Laboratory which employs a novel JPL-industry team management approach. This paper provides an overview of the SIRTF mission, telescope, cryostat, instruments, spacecraft, orbit, operations and project management approach; and this paper serves as an introduction to the accompanying set of detailed papers about specific aspects of SIRTF.

Following its successful launch and commissioning, SIRTF was renamed the Spitzer Space Telescope in honor of Dr. Lyman Spitzer. Lyman Spitzer, renowned Princeton Astrophysicist, is also widely viewed as the father of the concept of placing telescopes in space.

1. MISSION DESCRIPTION

The Spitzer Space Telescope is the fourth and final component of NASA's Great Observatories program. In addition, Spitzer is a key component of the NASA Search for Origins program. The observatory was successfully launched from Kennedy Space Center on August 25, 2003 aboard a Delta II Heavy launch vehicle. Figures 1 and 2 below show the completed observatory as well as Launch vehicle on the pad, hours before launch.

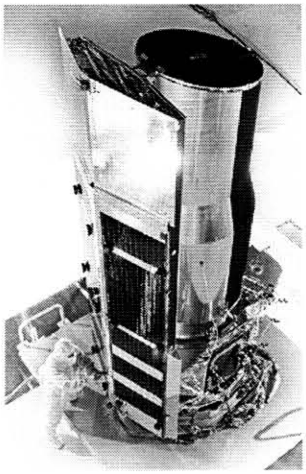

Figure 1. Completed Observatory

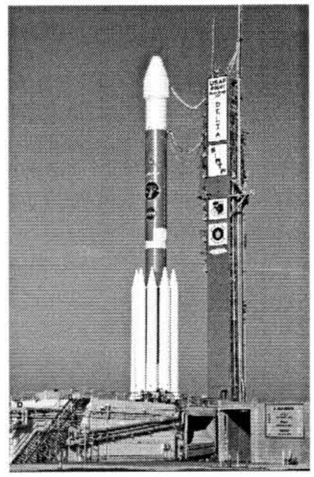

Figure 2. Spitzer Ready to Launch

Spitzer is an infrared space telescope, which utilizes a combination of active and passive cooling to unlock the infrared secrets of the universe. The mission requirement of a 2.5-year lifetime now appears to be easily reachable with a likely lifetime in excess of five years. The timely launch has enabled concurrent observations with both the Hubble Space Telescope and the Chandra X-ray Observatory. Spitzer is the first NASA program to exploit the simplicity and elegance of the solar orbit. This orbit, in which the observatory drifts away from the earth about 0.1 AU per year, allows for excellent observing efficiency and removes the earth as a heat source for the telescope.

The observatory is oriented such that the sun shield is always shading the telescope from the sun. This is crucial to Spitzer's thermal performance and allows a flexible operational pointing zone. This pointing strategy, shown in figure 3, permits any target in the celestial sphere to be visible for at least two forty-day periods per year. Commanding and telemetry retrieval (science and engineering) are accomplished during twice-a-day 45-minute communications passes with the Deep Space Network (DSN). The three scientific instruments are operated one at a time during campaigns varying from 3 to 7 days. Stored command sequences which contain the commanding for the next week are uplinked during the communications passes as needed.

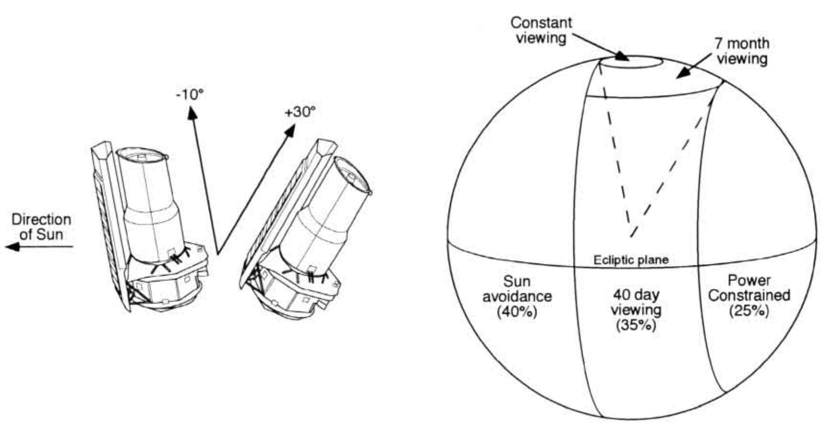

Figure 3. Operational Pointing Zone

The detailed observing plan is dictated by target priority and availability as well as cryogen utilization efficiency. The observatory was commissioned for scientific use during a 60 day in-orbit checkout period followed by a 30 day science verification period.

2. SCIENCE

Basic Principles

Spitzer's scientific potential derives from the combination of the intrinsic sensitivity of a cryogenic space telescope with the tremendous imaging and spectroscopic power of state-of-the art infrared detector arrays. This combination gives Spitzer a 100-to-10,000 gain in capability over previous infrared space missions and also makes Spitzer by far the most sensitive instrument for infrared astronomy to be available to the scientific community.

Almost ten years ago, the Spitzer Science Working Group chose four major scientific themes to define the measurement and performance requirements for Spitzer. These are:

<u>Protoplanetary and Planetary Debris Disks</u>

The study of material around nearby stars which is indicative either of a planetary system in formation or of a more mature planetary system which replenishes the circumstellar matter.

<u>Brown Dwarfs and Super Planets</u>

Understanding the formation, composition, and structure of objects with masses between 0.001 and 0.1 times that of the sun, objects which are too low in mass to have star-like brightness but which glow faintly in the infrared due to the heat generated as they form.

<u>Ultraluminous Galaxies and Active Galactic Nuclei</u>

The exploration of the most luminous objects in the nearby and distant Universe, objects which may radiate predominantly at infrared wavelengths and have thousands of times the power output of our own Milky Way galaxy.

<u>The Early Universe</u>

The study of the formation and evolution of galaxies, looking back to an epoch when the Universe was no more than one-fifth of its current size and age.

These themes have been of ongoing scientific importance and are heavily featured in the selected Legacy Science programs (see below) and in the scientific plans of the Spitzer Guaranteed Time Observers.

Although only the requirements of these four themes were allowed to drive the Spitzer design, it was anticipated that the resulting facility would be used for a very wide variety of scientific investigations. Both a focus on these themes and the expected wider variety of applications are apparent in the initial scientific results from Spitzer discussed below.

Utilization

<u>The Spitzer Legacy Program</u>

Legacy Science projects are large investigations aimed at exploiting Spitzer unique capabilities, at creating a significant scientific legacy in the form of scientific publications and archival data products, and at encouraging follow-on observations with Spitzer during the mission's limited lifetime. Consistent with this latter objective, the pipeline-processed data from Legacy Science observations are to be released publicly via the Spitzer archive at the same time they are passed on to the team executing the program. Upward of 3000 total hours have been awarded to the six Legacy teams selected by a peer-reviewed competition in 2000. The six selected projects include deep and wide area extragalactic surveys, detailed infrared investigations of many nearby galaxies, a galactic plane survey, and extensive studies of planetary systems at all stages of evolution around both young and mature stars in the solar neighborhood.

<u>General Observers</u>

The community will be given multiple opportunities to propose General Observer projects and/or Archival Research with Spitzer. On our current schedule, the first call for General Observer proposals was issued in November, 2003, with proposals due in February 2004. The first General Observer observations will take place in July 2004, on this schedule. Subsequent opportunities for General Observer and Archival Research proposals will occur on approximately one-year centers. Over 75% of the observing time on Spitzer will be allocated to the community through the combined General Observer and Legacy programs, and the community may also apply for Director's Discretionary Time.

Guaranteed Time Observers
About 20% of the observing time is reserved for the three instrument teams and the other members of the Spitzer Science Working Group who have guided the development of Spitzer over the past two decades. The Guaranteed Time Observers have largely defined their scientific programs and selected and prioritized targets for the first 2.5 years of the Spitzer mission. Interested scientists can learn more about the plans of the Legacy Science teams and the Guaranteed Time Observers from the information posted on the SSC website (http://ssc.spitzer.caltech.edu).

Discovery and Follow-up
An important subtheme of the Spitzer scientific planning has been exploitation of the discovery potential inherent in Spitzer large arrays and great sensitivity gain. The execution of the large survey programs which will produce these discoveries began only shortly before the deadline for the first round of Spitzer GO proposals in 2004 February. Thus the first real discovery "follow-up" will start with the second cycle of GO proposals, scheduled to begin execution on the spacecraft in mid-2005. With the anticipated cryogenic lifetime of 5+ years, there will be ample opportunities – not only for follow-up of the initial discoveries, but for follow-up of the follow-up!

3. OBSERVATORY DESCRIPTION

The Spitzer Space Telescope is comprised of three major subsystems: the spacecraft, the cryogenic telescope assembly (CTA), and the science instruments. Care was taken in the observatory design to maintain simplicity and minimize moving parts. Figure 4 below shows key components of the observatory.

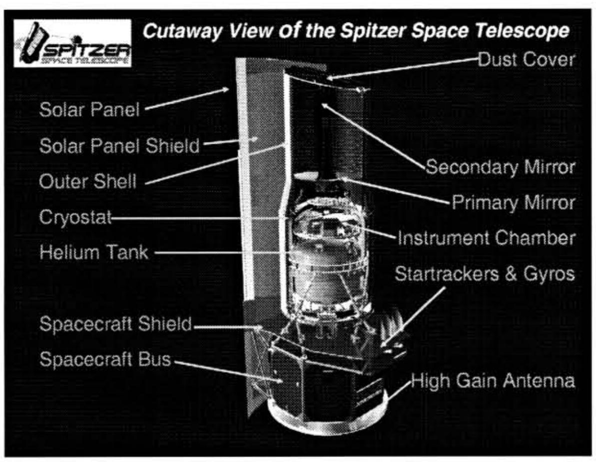

Figure 4. Cutaway View of the Spitzer Space Telescope

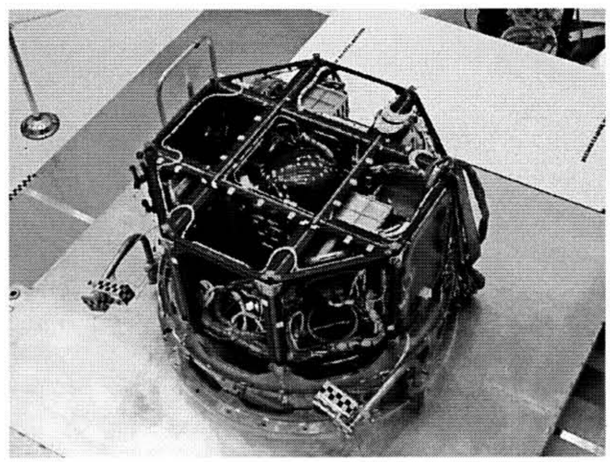

Figure 5. Spitzer Spacecraft without Sun Shield/Solar Panel

Spacecraft
The spacecraft provides the structure to which the CTA is mounted, thermal control, pointing control, command and data handling, and communications with the ground. On board fault protection allows the spacecraft to operate autonomously for up to a week as needed. The data storage capability (mass memory card) is sized such that any single missed DSN pass will not result in any lost data. The spacecraft is block redundant and includes cross-strapping in most areas. A small cold-gas (N2) system is used to unload momentum buildup in the reaction wheels as needed. The Spitzer pointing requirement is for 5 arc sec of absolute pointing with a stability requirement of 0.2 arc sec. On orbit performance against these requirements is excellent and will be discussed in an upcoming section of the paper. Communications are accomplished via the fixed high gain antenna mounted on the bottom of the spacecraft. The spacecraft also includes twin low-gain antennae as well. Another sensor, the Pointing Calibration Reference Sensor (PCRS) is mounted alongside the science instruments on the focal plane to provide for handover between the star trackers and telescope boresite. Figure 5 above shows the key components of the spacecraft.

Cryogenic Telescope Assembly (CTA)
Figure 6 below shows the completed CTA. At the heart of the CTA is an 85 cm aperture beryllium telescope, which operates at 5.5K. The telescope has exceeded its performance goal of being diffraction limited at 6.5 um. Other key components of the CTA are the Multi-Instrument Chamber (MIC), which houses the three science instruments; the superfluid helium cryostat, and the outer shell group. The telescope assembly is mounted and thermally connected to the cryostat vacuum shell via bipod flexures. The helium tank volume is 360 liters. Details of these systems and resulting performance are described in Finley et al. [9]

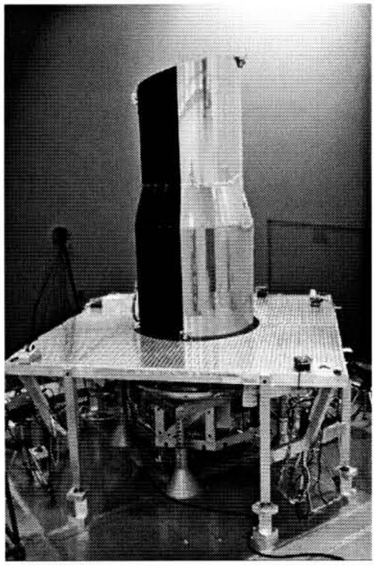

Figure 6. Cryogenic Telescope Assembly

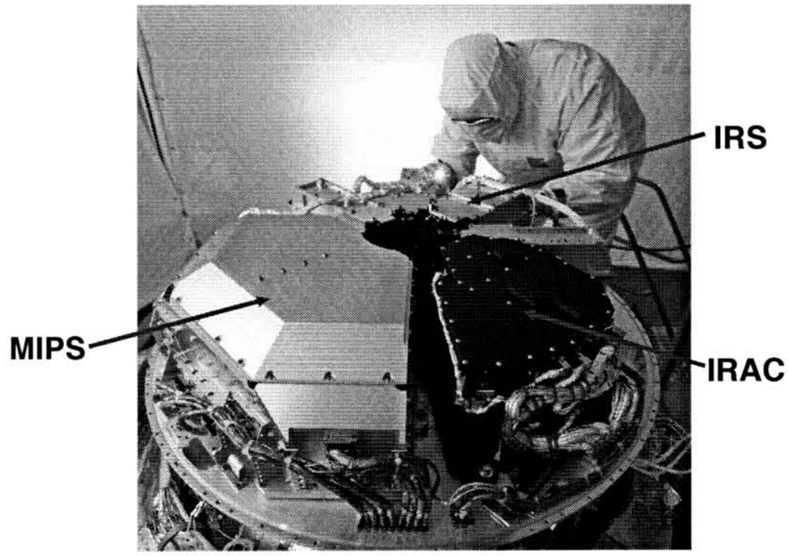

Figure 7. Science Instruments

Science Instruments
The three Spitzer Science Instruments are described below and shown in figure 7 just prior to closure of the MIC.

Infrared Array Camera (IRAC)
IRAC is a four-channel imager packaged in a single module, providing images at 3.6 μm, 4.5 μm, 5.8 μm, and 8.0 μm, with four 256 x 256 arrays. It views simultaneously two nearly adjacent 5.12 x 5.12 arcmin fields of view near the center of the telescope focal plane. Each of these fields are split into two channels by a dichroic beamsplitter, with the 3.6 μm and 5.8 μm channels in one field of view and the 4.5 μm and 8.0 μm channels in the other. Details on the IRAC can be found in Fazio et al. [6]

Infrared Spectrograph (IRS)
The IRS consists of four spectrograph modules that provide low and moderate resolution spectra over the wavelength range from 5 μm to 40 μm. It has no moving parts. One of the modules contains a camera aperture for locating an IR source and placing it accurately on the split of any of the four modules; image centroids from this camera are used by the spacecraft to guide pointing corrections autonomously during IRS observations. Details on the IRS design can be found in Houck et al. [12]

Multiband Imaging Photometer for Spitzer (MIPS)
The MIPS provides imaging, photometry, and total power measurement capability at 24 μm, 70 μm, and 160 μm, as well as low resolution spectroscopy from 55 μm to 96 μm. The 70 μm band was chosen because it is the longest wavelength where the sensitivity is not severely compromised by confusion with faint galaxies. The 24 μm and 160 μm bands were chosen to logarithmically bridge the spectral gaps between the IRAC 8 μm band and ground based observations at 350 μm. Details on the MIPS design can be found in Rieke et al. [7]

Spitzer Firsts

Two key advances have now been proven by the Spitzer Space Telescope. They are the warm launch architecture and the earth-trailing orbit. Both are described briefly below and in detail in accompanying papers.

Warm Launch Architecture

All previous infrared space telescope missions have housed both the telescope and the scientific instrument payload within the cryostat or dewar. On Spitzer, passive cooling is used to cool the outer shell of the CTA to approximately 34K. Cryogen boil-off then cools the telescope to about 5.5K. This approach results in huge savings in cryogen requirements as well as structural and cryogen mass. Spitzer is carrying about 15% of the cryogen carried on the Infrared Space Observatory (ISO) and has a longer predicted lifetime.

Earth Trailing Orbit

The Earth trailing orbit selected for the Spitzer mission provides several key benefits. Observing efficiency is enhanced by removing earth/moon pointing constraints which are present in typical earth orbiting telescopes. In addition, observation planning is simplified by the combination of some objects being available in the continuous viewing zone as well as all objects being visible for two 40-day periods each year. Finally, removing the earth as a heat source allows the passive cooling which is fundamental to the mission.

4. OPERATIONS

Efficient and effective operations for the Spitzer Space Telescope are crucial to harvesting the full scientific benefit of this final Great Observatory. There are two equally important pieces of Spitzer Operations; they are Mission Operations and Science Operations. Failure to do both well could result in wasting cryogen (mission life) or disappointing the scientific community and public with poor data products. The Mission Operations work is largely performed at JPL and Lockheed Martin Denver while the Science Operations are largely performed at the Spitzer Science Center at Caltech.

Mission Operations

The Mission Operations System (MOS) is the hardware, software, people, processes, and procedures that enable and execute Spitzer flight operations. MOS is responsible for operating the Observatory and maintaining its health and safety. MOS builds the sequences containing the integrated science and engineering requests and radiates them to the observatory where they are stored awaiting execution. After execution, MOS receives and processes telemetry from the Observatory (via the DSN) and is involved in fault recovery and in first order pointing reconstruction based on Observatory engineering data. MOS is responsible for scheduling engineering activities, interfacing with the DSN and delivering science and engineering data to the Spitzer Science Center (SSC).

The MOS team is geographically distributed with each piece playing a specific role. The Observatory Engineering Team is located at Lockheed Martin in Denver while the other teams and management reside at JPL. There is also telescope factory support at Ball Aerospace in Boulder, CO. There are two key Mission Support Areas (MSA) for Spitzer operations. They are located in Denver and at JPL. The JPL MSA is the lead MSA and houses the Mission Manager and flight control teams and is the location from which commands are sent. Two testbeds built around flight-like avionics hardware are maintained in Denver for the duration of the mission to support any necessary troubleshooting, testing, and software development. The end-to-end operations dataflow is shown in figure 8.

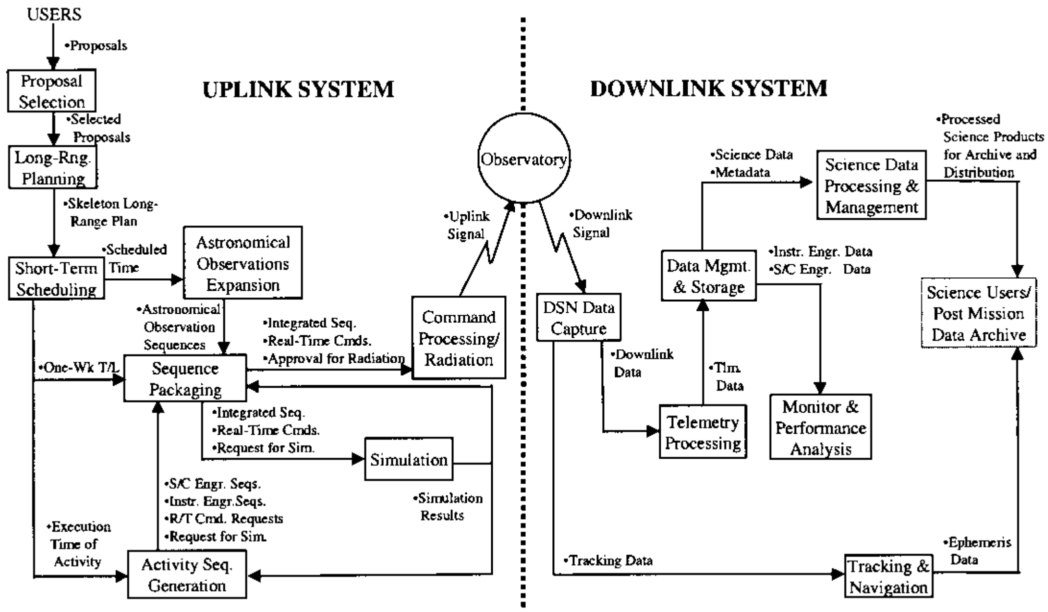

Figure 8. End-to-End Operations Data Flow

Science Operations

The Spitzer science program is being conducted by the SSC which is located on the Caltech campus. The operations processes within the SSC are shown in figure 9. The SSC is responsible for the selection of the Spitzer science program and for the preparation of observation requests, which execute that program. These Astronomical Observation Requests (AORs) are generated via the use of Astronomical Observation Templates (AOTs). An AOT is a web-based electronic form which prompts the observer for the astronomical information (e.g., source position and brightness, size of region to be mapped, etc.) and observing strategy (integration time, dither pattern, etc.) that specifies an observation. To simplify operations, there is only one AOT per observing mode and only 7 distinct observing modes. A database of completed and prioritized AORs for both observation and calibration purposes is created and maintained by the SSC. These AORs are then combined with Spacecraft Engineering Requests (SERs – used for scheduling routine spacecraft engineering activities such as momentum management, PCS calibrations, and data downlink) and Instrument Engineering Requests (IERs – instrument activities not directly related to science data acquisition) by the MOS team and used to create the actual sequence of events scheduled for execution by the spacecraft. Only one instrument is to be powered on and taking science data at a time. Block scheduling is used so that a given instrument is operating for about one week at a time. After this period, the instrument is powered down and science data collection cycles to one of the other two instruments.

The SSC is also responsible for establishing the archive of all Spitzer science and supporting engineering data. At the SSC the data are run through a science processing pipeline which converts the instrument frames into calibrated, cosmetically cleaned images and spectra in the Flexible Image Transport System (FITS) format. There is a well-defined, basic pipeline product for each type of data product. The processed data, raw data, suitable intermediate data products and calibration frames are placed in the Spitzer Science Archive.

There will be multiple opportunities for the community-at-large to propose observational programs on Spitzer. The first of these opportunities, cycle 1, has just completed. In support of the solicitation process, the SSC has designed, built, and maintained Web-based electronic software tools. These tools enable investigators to prepare scientifically valuable programs that maximize the efficiency and utility of the Observatory. These tools include: (i) comprehensive descriptions of the instrument observing modes; (ii) estimates of exposure and wall clock times and expected sensitivity levels; (iii) geometrical and graphical depiction of sky visibility and orientation constraints; (iv) geometrical depiction of mapping patterns used in the relevant observing modes; and (v) estimates of the celestial foregrounds and backgrounds at appropriate wavelengths. The Calls for Proposals, Observatory and Instrument Manuals, and supporting software tools have been made available via the Web. Proposals are also submitted electronically. These electronic exchanges have reduced costs to the SSC and to the user community, while providing the most reliable updated technical information in a timely manner.

Science Operations Timeline

Following in-orbit-checkout and science verification (IOC/SV, Guaranteed Time Observations by the Spitzer Science working group and the Legacy Program began. Although GTO and Legacy Science dominate the first ~ six months of the Spitzer science mission, by the end of the first year and throughout the remainder of the mission the majority of the time will be given over to the General Observer (GO) programs. GO's will be selected on approximately annual cycles via a peer-reviewed proposal process as shown below in figure 10.

Spitzer will be able to respond quickly to Targets of Opportunity (ToO) such as supernovae and newly discovered comets. A target of opportunity can be scheduled and observed within 48 hours of receipt of a valid AOR for the observation. Known classes of targets of opportunity will be observed by pre-selected teams, as has been the policy with NASA's other observatories. Completely unanticipated objects could be observed using Director's Discretionary Time.

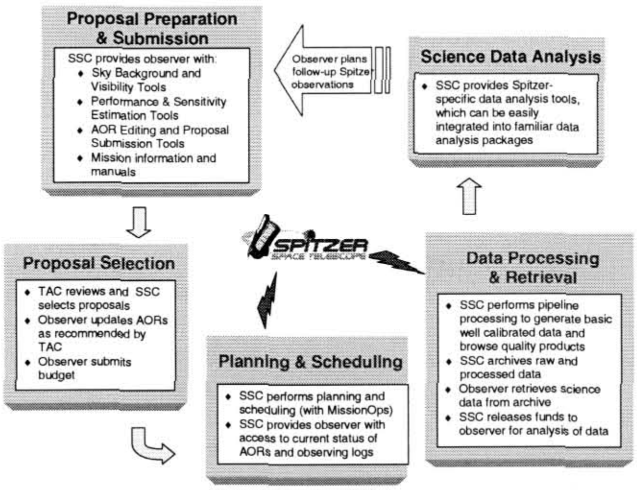

Figure 9. Operations Processes within the Spitzer Science Center

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
									Cycle-1			
2004	AAS (Atlanta)	**Cycle-1 Proposals Due (2/14)**			Cycle-1 Proposal Review (May 3-7), Science Archive Opens	AAS Topical Session @ Denver (June 1)			Initial LegSci Products Delivered		**Cycle-2 CP Issued**	
			Cycle-1						Cycle-2			
2005	AAS (San Diego)	**Cycle-2 Proposals Due**		Cycle-2 Proposal Review	AAS (Minneapolis)						**Cycle-3 CP Issued**	
			Cycle-2						Cycle-3			
2006	AAS (Wash DC)	**Cycle-3 Proposals Due**		Cycle-3 Proposal Review		AAS (Calgary)					**Cycle-4 CP Issued**	
			Cycle-3						Cycle-4			
2007	AAS (Seattle)	**Cycle-4 Proposals Due**		Cycle-4 Proposal Review							**Cycle-5 CP Issued**	
			Cycle-4						Cycle-5			
2008		**Cycle-5 Proposals Due**		Cycle-5 Proposal Review				5-Year Anniversary of Launch				

Figure 10. Spitzer Science Timeline

5. PROJECT MANAGEMENT

The Spitzer Project has been and continues to be managed in a team approach which combines the best of government, academia, and industry. While the Project is funded by NASA and managed by the Jet Propulsion Laboratory, all team members have participated in key decisions and cooperation between partners, even those that usually compete, has been remarkable. The early formation of the team, during phase A, has proven invaluable in establishing a team that is well suited to a collaborative problem solving approach. Design requirements and detailed mission architecture were developed in a joint effort under JPL's leadership prior to NASA's approval to proceed with implementation. The team members are shown in figure 11.

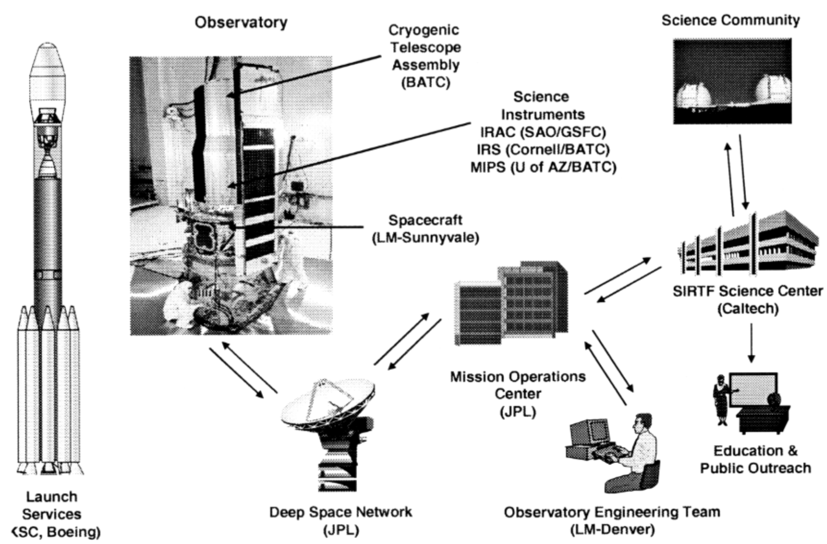

Figure 11. Spitzer Team

6. ON-ORBIT PERFORMANCE

Spitzer requires the unique low-thermal environment of space in order to function properly; the environment both permits the necessary radiative cooling and provides the low backgrounds to allow the science instruments to achieve their high sensitivities. This environment was difficult or impossible to simulate on the ground so that there was some uncertainty in how well the observatory would perform in orbit. We are pleased to report that in almost every respect the on-orbit performance of the observatory meets or exceeds expectations.

Infrared Array Camera

All four IRAC channels are operational and returning useful science data. Bands 1 and 2 are somewhat more sensitive than predicted, while Band 3 is slightly less sensitive than predicted. On-orbit measurements have shown that latent images in the focal plane arrays caused by bright objects are more significant than was predicted, but it has also been demonstrated that these latent images can be completely removed by proper thermal annealing of the detectors. Further details of the on-orbit performance of the IRAC can be found in Hora, et al. [10]

Infrared Spectrograph

All four IRS modules are operational and returning useful science data. All of the IRS module sensitivities are better than predicted, especially the two long-wavelength modules. Further details of the on-orbit performance of the IRS can be found in Houck, et al. [13]

Multiband Imaging Photometer for Spitzer

All three of the MIPS detector arrays are operational and returning useful science data. The 24 μm channel has somewhat better sensitivity than was predicted. The 70 μm array consists of two 5.2 arc-min x 2.6 arc-min halves. Due to a problem in the cold cabling one of the halves has significantly less sensitivity than the other. The 160 μm channel has a short-wavelength filter leak that admits some 1.6 μm light that must be accounted for when observing blue objects. Further details of the on-orbit performance of the MIPS can be found in Rieke, et al.[8]

Spacecraft

In general, the pointing performance of the Spitzer spacecraft is better than the nominal predictions. The star tracker has proven to be very accurate, with a noise-equivalent-angle of approximately 0.11 arcseconds using an average of 35 tracked stars. The cryo-mechanical variation in alignment over time between the star tracker mounted on the warm spacecraft and the cold telescope bore-sight has proven to be very small and easily calibrated, so that the star tracker can be used to directly point the telescope boresight to better than 1 arc-second 1-σ, RMS radial uncertainty. For offset movements less than 30 arcminutes, the PCS meets the 0.4 arcsecond offset accuracy requirement. It takes less than 150 seconds for the telescope to slew 15 degrees and to settle to its commanded position to within the above tolerances. Once the telescope pointing has settled, it is stable to within 0.03 arc-second, 1-σ RMS radial uncertainty, for times up to 600 seconds. Observations of a number of solar system targets demonstrated that the PCS exceeds its requirements to track moving objects at rates up to 0." 1 per second.

Net angular momentum will build up on from a combination of solar pressure and uncompensated helium venting. During the design of the observatory care was taken to align the vector of solar pressure with the center of mass as closely as possible, and the two CTA helium vent nozzles were also balanced very well. This has resulted in very low momentum build-up and a low frequency-once or twice per week – of actuations of the reaction control system to remove angular momentum.

Power, thermal, and CPU performance of the spacecraft are all meeting pre-launch predictions. In addition, the dust cover ejection and telescope focus activity, two mission critical events, both executed flawlessly.

Cryogenic Telescope Assembly

Spitzer requires the unique low-thermal environment of space in order to function properly; the environment both permits the necessary radiative cooling and provides the low backgrounds to allow the science instruments to achieve their high sensitivities. This environment was difficult or impossible to simulate on the ground so that there was some uncertainty in how well the observatory would perform in orbit. We are pleased to report that in almost every respect the on-orbit performance of the observatory meets or exceeds expectations.

Thermal

The outermost CTA shield – the outer shell – attained its final temperature of 34-34.5 K solely by radiative cooling, and the telescope cooled to its operating temperature of 5.6 K in 41 days. The mass of the helium remaining after the initial cooldown was measured to be 43.4 kg by applying a heat pulse to the helium bath 57 days after launch and measuring the accompanying temperature rise. To maintain the telescope at 5.6 K requires a total heat of 5.6 mW to the helium bath, leading to a boil-off of 2.2 g of helium per day. For a fixed telescope temperature, these nominal numbers translate into a 5.3 year post-launch lifetime. In a worst-case scenario where all of the engineering uncertainties stack against us, the lifetime would drop to 4.0 years, which still compares quite favorably with the mission minimum lifetime requirement of 2.7 years. By regulating the power dissipation to accommodate the telescope temperature requirements of the instrument that is in use, we are expecting at least an additional four months of cryogenic lifetime beyond the nominal 5.3 years. The only other expendable, the N_2 gas in the RCS system, should last for more than 10 years. Following the depletion of the cryogens, the telescope will warm up, but it will still be colder than the outer shell. Current estimates suggest that the telescope temperature will always be < 30 K. At this temperature, both the instrumental background and the detector dark current should be low enough for Spitzer to continue natural background-limited operations in the shortest wavelength IRAC bands at 3.6 and 4.5 μm. Additional information on the measured on-orbit thermal performance of the Spitzer CTA can be found in Finley, et al.[18]

Optical Performance

A focus campaign of two secondary mirror movements was initiated once the telescope assembly had cooled to operating temperature to achieve the final focus. On-orbit measurements of the telescope then showed that it provides diffraction-limited performance at wavelengths greater than 5.5 μm, which compares favorably with the requirement of

6.5 μm. After the completion of this campaign all of the science instruments were measured to be confocal to within the depths of their focus.

7. EARLY SCIENCE RESULTS

Over 80 papers reporting early scientific results from Spitzer are published in the 1 September 2004 issue of the Astrophysical Journal Supplements. Rather than attempt to recapitulate or summarize this rich and varied yield, we have chosen here to describe some of the "hallmarks" which will characterize the scientific return from Spitzer as the mission advances, and to illustrate them with examples drawn from these early results. These hallmarks include:

1. Very high sensitivity, both to point sources and to extended emission. This is "Spitzer made simple", as the basic rationale for a cryogenic infrared space telescope is to achieve much higher sensitivity than is otherwise possible. The implications of this for point source studies are clearest in the case of the mapping and surveying discussed further below. Point source sensitivity can be reclaimed in part by a sufficiently large ground-based telescope, but a cryogenic telescope has an unimpeachable gain for studies of extended emission. In the case of Spitzer, this has led to truly spectacular early images early in the mission, including, as examples, IRAC images from the GLIMPSE legacy program [Churchwell et al, 2004] and MIPS and IRAC images of the star-forming complex Henize 206 in the Large Magellanic Cloud [Gorjian et al, 2004].

2. Stable point spread functions. Spitzer optical system and metering paths remain cold and undisturbed throughout the mission. Particularly for the MIPS, the point spread function is very well sampled and well fit by models such as Tiny Tim. This facilitates subtraction of a central point spread function in a search for diffuse emission from circumstellar dust without the need to rely totally on complex deconvolution techniques. Thus Stapelfeldt et al (2004) were able quite easily to determine the extent of the faint, resolved 24um emission from the cometary and asteroidal debris disk around the nearby star Fomalhaut.

3. Robust and efficient spectroscopy. The large-format arrays in the IRS provide spectra at many points along the slits of the lo-resolution modules and a full spectrum of an entire octave in echelle mode for the high-resolution modules. The inherent sensitivity of the arrays is thus accompanied by a huge multiplex advantage which will allow the IRS to take infrared spectroscopy to an entirely new level. For example, the results presented by Werner et al (2004) on the reflection nebula NGC7023 show that Spitzer will be able to delineate – essentially for the first time - variations across the source in the nature of the aromatic hydrocarbon materials which dominate the 5-15um spectra of this and many other astronomical targets. Spectra of an otherwise undistinguished ultraluminous galaxy at Z~0.3 presented by Spoon et al (2004) show a rich variety of absorption features due to interstellar organic materials, seen at an epoch roughly coincident with the formation of our own solar system. Other IRS spectra show environments ranging from warm neutral gas, to gas excited by young stars, to gas illuminated by x-rays from an accreting black hole, all in a single extragalactic target.

4. Efficient mapping and surveying. This is another chapter of "Spitzer made simple", enabled by the large, sensitive arrays and by the incorporation into the operations scenarios of efficient procedures for carrying out extensive surveys. Many examples of this are to be found in the ApJ Supplement issue. Of particular note are surveys which add results from Spitzer to those already obtained by Hubble and Chandra on fields of particular interest such as the Chandra Deep Field South (Dickinson et al, 2004; Alonso-Herrero et al, 2004).

5. Ability to study large samples of objects. This is an important by product of Spitzer high sensitivity, which allows observations to be done very quickly. Rather than the relative handful of objects which may have characterized previous studies, for example of dust around young stellar objects, Spitzer can study hundreds or perhaps thousands of targets. This will make the results much less reliant on the properties of a few peculiar or unusual objects which might dominate a smaller sample. In other cases, the large sample may be truly revolutionary from a scientific perspective. Thus the MIPS and IRAC teams are combining on surveys for circumstellar dust around stars in dozens of clusters ranging in age from one million to one

billion years. The result should be a much better understanding of the time scales for formation of planetary systems and dissipation of the remnant disk material. Most strikingly, the IRAC team [Pahre et al, 2004] has obtained images of several dozen [of a planned several hundred] nearby galaxies and shown that the infrared images produce dramatic new insights into the fundamental structure of galaxies; insights which could not have been drawn based on observations of one or two isolated objects.

6. Ability to look to very high redshifts to probe the distant, early Universe. As was stated earlier, in the scientific planning for Spitzer it was deemed desirable to reach back to a redshift Z~3, so that Spitzer could study the epoch when the universe was but one-quarter of its present size. In fact, Spitzer observations, both imaging and spectroscopic, have already gone far beyond that benchmark. Most dramatically, the gravitationally lensed arcs in the galaxy cluster Abell 2218 identified by [Kneib et al, 2004] as images of a galaxy at redshift Z~7 [the current record holder] were detected fairly easily by [Egami et al, 2004] in an IRAC image of the cluster. The Spitzer data are consistent with the HST data reported by Kneib et al, and the combined [observed] infrared plust optical spectral energy distribution is consistent with what would be expected from a young starburst – consistent with the fact that in conventional models the Universe is only about 700 million years old at the epoch probed by these observations.

8. CONCLUSION

The Spitzer mission is the successful culmination of a long conceptualization and technology development period which began in the late 1970's. The result described here is the direct result of perseverance and ingenuity on the part of the science community, NASA, and the implementing organizations. During the evolution of the Spitzer concept, the many innovations (described above) led to reduced cost and improved scientific productivity. We believe that the elegant simplicity of the Spitzer Observatory and its operations approach, is a worthy model for future space observatory development. Up to date results and status of the Spitzer mission can be found at the Spitzer website (http://spitzer.caltech.edu).

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REFERENCES

1. A. Alonso-Herrero, et al. *The Astrophysical Journal Supplement Series*, **154**, 2004.
2. A. Mainzer, et al. "Post-Launch Performance of the Pointing Calibration and Reference Sensor for Spitzer Space Telescope", *Astronomical Telescope and Instrumentation* – Proc. SPIE, **5487-07** (this issue), 2004.
3. D. B. Gallagher, W. R. Irace, M. W. Werner, *Development of the Space Infrared Telescope Facility (SIRTF)*, – Proc. SPIE, **4850-04**, 2002.
4. E. Churchwell, et al. *The Astrophysical Journal Supplement Series*, **154,** 2004.
5. E. Egami, et al. *The Astrophysical Journal Supplement Series*, **154**, 2004.
6. G. G. Fazio, et al. "The Infrared Array Camera (IRAC) for the Spitzer Space Telescope", *The Astrophysical Journal Supplement Series,* **154**, 2004.
7. G. H. Rieke, et al. "The Multiband Imaging Photometer for Spitzer", *The Astrophysical Journal Supplement Series,* **154**, 2004.
8. G. H. Rieke, et al. "On-orbit Performance of the MIPS Instrument", *Astronomical Telescope and Instrumentation* – Proc. SPIE, **5487-04** (this issue), 2004.
9. H. Spoon, et al. *The Astrophysical Journal Supplement Series*, **154**, 2004.
10. J. L. Hora, et al. "In-flight performance and calibration of the Infrared Array Camera (IRAC) for the Spitzer Space Telescope", *Astronomical Telescope and Instrumentation* – Proc. SPIE , **5487-06** (this issue), 2004.

11. J. P. Kneib, R. S. Ellis, M. B. Santos, J. Richard, "A Probable Z = 7 Galaxy Strongly Lensed by the Rich Cluster A2218: Exploring the Dark Ages", *The Astrophysical Journal* 607, 697, 2004.
12. J. R. Houck, et al. "The Infrared Spectrograph on the Spitzer Space Telescope", *The Astrophysical Journal Supplement Series,* **154**, 2004.
13. J. R. Houck, et al. "The in-flight Performance of the Infrared Spectrograph", *Astronomical Telescope and Instrumentation* – SPIE, **5487-04** (this issue), 2004.
14. K. Stapelfeldt, et al. *The Astrophysical Journal Supplement Series*, **154**, 2004.
15. M. Dickinson, et al. *The Astrophysical Journal Supplement Series*, **154**, 2004.
16. M. Pahre, et al. *The Astrophysical Journal Supplement Series*, **154**, 2004.
17. M. Werner, et al. *The Astrophysical Journal Supplement Series*, **154**, 2004.
18. P. T. Finley, et al. "Flight Cooling Performance of the Spitzer Space Telescope Cryogenic Telescope Assembly", *Astronomical Telescope and Instrumentation* – Proc. SPIE, **5487-02** (this issue), 2004.
19. T. L. Roellig, et al. "On-orbit Performance of the Spitzer Space Telescope", *Astronomical Telescope and Instrumentation* – Proc. SPIE, **5487-03** (this issue), 2004.
20. V. Gorjian, et al. *The Astrophysical Journal Supplement Series*, **154**, 2004.