EPOXI and Stardust NExT – The Management Challenges of Two Comet Flybys in Three Months

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The EPOXI and Stardust NExT missions were missions of opportunity utilizing the Deep Impact and Stardust spacecraft, respectively. These new missions took advantage of the cost savings of utilizing spacecraft that were already flying for new science investigations. Both were retargeted to fly by an additional comet. EPOXI visited Hartley 2, significantly smaller than the other Jupiter family comets visited previously. Stardust NExT flew by Tempel 1, providing a second look at the comet previously studied by Deep Impact in 2005. Both projects were part of NASA's Discovery Program. In order to further save costs, the projects were combined into a single project office at JPL. This provided some efficiencies due to the similarity of the missions, but having the flybys space only three months apart posed challenges for the project management team to ensure each project was ready for its critical event and ensuring each received the proper support from the management team. The project office relied on an integrated calendar for tracking and scheduling meetings, reviews, and other key events. The project management team also coordinated their availability for both projects to maintain involvement with each team to ensure effective risk identification and management.

I. Introduction

THe Stardust and Deep Impact spacecraft were launched in 1999 and 2005, respectively. The Stardust spacecraft successfully completed its mission by flying by comet Wild 2 in 2004 and returning samples from deep within its coma to earth in 2006. Likewise, the Deep Impact spacecraft was successful in its comet exploration by delivering an impactor to the surface of comet Tempel 1 in 2005 and observing the aftermath of the collision. Both spacecraft were healthy and available for new assignments and extended missions for both were approved. The Deep Impact spacecraft was re-targeted for another close flyby of a comet, Hartley 2, in November 2010. The Stardust spacecraft was re-directed to fly by comet Tempel 1 in February of 2011, providing a second look at this comet. Preparing for two critical events separated by three months, implemented by a combined project office and significantly overlapping science teams required careful planning and coordination to ensure that both teams were ready and that all the necessary tasks were completed.

II. Missions of Opportunity

An Announcement of Opportunity for Missions of Opportunity was sent out by the Discovery Program to gauge interest in the continued use of the Stardust and Deep Impact spacecraft. The configuration of these spacecraft at launch are shown in Figures 1 and 2. The proposal for Stardust NExT (New Exploration of Tempel 1) was selected for re-use of the Stardust spacecraft. This new mission would take advantage of an Earth gravity assist to adjust the trajectory of the spacecraft to intersect the trajectory of comet 9P/Tempel 1. This would provide scientists the first opportunity to observe the changes that occur on the comet between two consecutive perihelion passes. The changes observed on the surface of the nucleus would provide important insight into the nature of the comet activity during perihelion, whether it is broadly based or localized, what kinds of features are the most affected, and would help discriminate between features that are due to the comet's evolution and which ones might be primordial remnants from the comet formation. This second visit to the comet might also provide an opportunity to view the crater left behind by the 2005 impact with the Deep Impact Impactor spacecraft. Measurement of the crater size would provide important information on the consistency and strength characteristics of the nucleus surface material.

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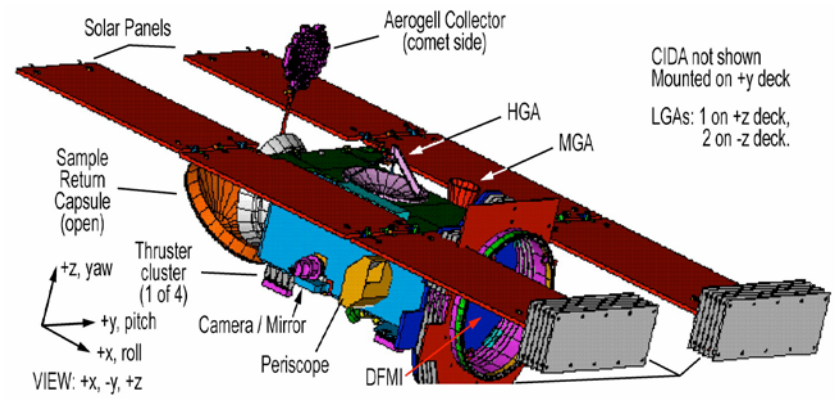

Figure 2 - Stardust spacecraft launch configuration.

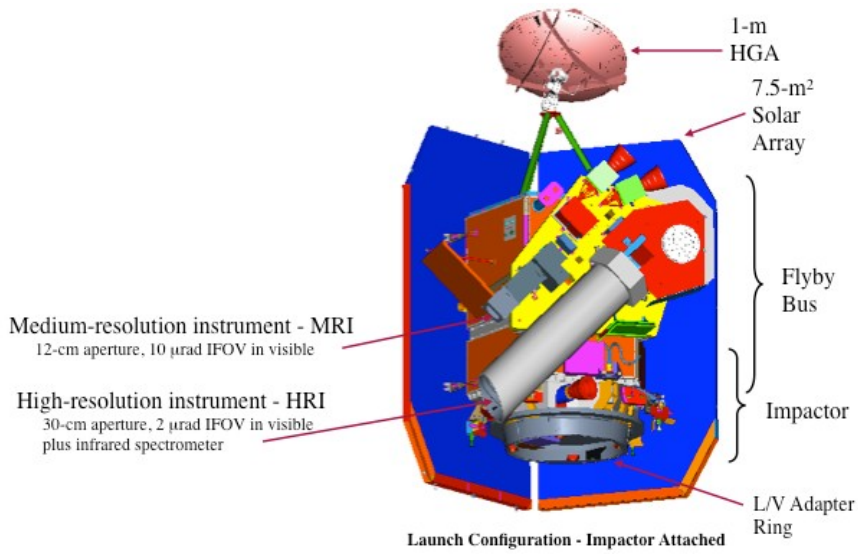

Figure 1 - Deep Impact spacecraft launch configuration.

Along with the Stardust NExT selection, two complementary proposals were selected for the new Deep Impact mission: EPOCh (Exoplanet Observation and Characterization) and DIXI (Deep Impact Extended Investigation). These two were combined into one extended mission – EPOXI. The EPOCh activity would utilize cruise time to observe stars with known transiting planets to perform sensitive photometry, measuring the variation in the star's light as the planet transited in front of the star and as it passed behind the star. These measurements would provide data bounding the size of the transiting planet. The DIXI mission proposed using Earth Gravity Assists and trajectory correction maneuvers (TCMs) to re-target the spacecraft trajectory to meet a small Jupiter family comet, significantly smaller than the comets previously visited by spacecraft (Halley, Borrelly, Wild 2, and Tempel 1).

In order to reduce the overall cost of the extended missions for both spacecraft, the project office was combined into a single office managing both missions. This resulted in overall savings, but meant that one project and mission management team would need to track two different spacecraft operations teams (with involvement of two different partner companies) and interface with two different Principal Investigators and two science teams.

The first challenge that came up was the intended target of the EPOXI mission. Comet Boethin had been the intended target, but when the time came when the ground observers were expected to recover the comet in order to provide last minute observations to feed into the ephemeris and TCM planning, the comet could not be found. As the time came for a decision for the initial TCM, a back-up target was selected – 103P/Hartley 2, and the TCM was executed for this new destination. The first lesson learned was to always be ready for surprises when comets are involved.

III. Combined Project Office

Combining these two projects into a single office meant that key administrative personnel could be shared, but it also placed the burden on the Project Manager and Mission Manager to ensure they effectively spread their time across both projects to understand the challenges, progress, and key issues for each team and suppor the appropriate decisions at the right times. A similar issue faced the science teams since both were comet missions and there was significant overlap in the investigators involved in both projects. An advantage, however, of combining the project offices was that consistent risk management and review processes could be implemented.

One early tool that was put in place was combining both project schedules into a master calendar. This was repeatedly used to track major milestones and review dates. Each project had a set of reviews planned to assess the readiness for the upcoming activities. These included a Peer Review, Risk Review, and a Critical Events Readiness Review (CERR). Each review addressed the issues identified at the previous review in addition to progress made since then. A JPL center level briefing and a NASA Headquarters briefing followed the CERR. This review process began approximately 6 months before each encounter, ensuring that there would be significant project review activity overlap between the two projects at a very busy time. The combined calendar was used to plan the project review schedule in a way that avoided conflicts and took into account the peak activities and critical events on one project while maintaining progress on the other. As schedules changed and dates moved around, the integrated schedule was relied on to avoid conflicts.

The essential element of success for both missions was the spacecraft team. Lockheed Martin Space Systems Company in Denver, Colorado had built the Stardust spacecraft and had operated it since launch. An experienced Team Chief led this team and most of the members of the team had experience operating this spacecraft since launch. This was the same team that had executed the successful flyby of Wild 2 and the subsequent sample capsule Earth return. The Navigation team at JPL, several of whom also had experience dating back to its first comet flyby, completed the operations side of the spacecraft team. Similarly, Ball Aerospace and Technology Company in Boulder, Colorado had built the Deep Impact spacecraft. A spacecraft team located at JPL, with subsystem support from Ball and navigation support from JPL, operated it. This team also had experience dating back to the original Deep Impact mission across all key disciplines. Since costs needed to be kept low by using small operations teams, highly experienced teams ensured that both of these spacecraft could be operated safely and that knowledge and lessons learned from the earlier missions would be preserved and implemented on the new missions. The high level of experience of both teams ensured that appropriate progress was made and decisions were handled at the appropriate level.

The success of the two missions also rested on the ability to properly understand and distill the science requirements and implement them on the operations side. This process started 12 to 18 months before encounter by bringing together the science and operations teams for dedicated planning meetings. The topics covered spacecraft status, capabilities and constraints, navigation challenges and requirements, and observational goals and requirements for the flybys. These meetings provided a forum for each team to understand the desires and constraints of the other. As discussions went deeper into various aspects of the approach and flyby, new approaches would be identified to meet the desired goals and compromises were forged in areas where goals and constraints were at odds. Ideally, this process would have begun 2 years before the encounter, however funding constraints for the science teams meant that full participation was not achieved until 1 year before the encounters. This was mitigated by having personnel with sufficient knowledge of both the spacecraft operations and the science to serve as key interfaces between the teams.

The key function that ensured effective communication between the science and operations team was the project science liaison. This was a member of the science team (a Co-Investigator on EPOXI and the Deputy Principal Investigator on Stardust NExT) and was located at JPL, funded early, and active when most of the science team had not yet been funded. This person designed the observation portion of the sequences, reviewed their implementation in the spacecraft operations sequences and reviewed test results prior to approval for uplink to the spacecraft. Having this interface position ensured that the science needs were understood early and were met by the observations that were planned and implemented on board the spacecraft. This position became a key daily interface between the operations and science functions as the details of the flyby were planned and implemented.

Communication within and between the various teams was implemented by weekly meetings – project meetings, spacecraft team meetings, navigation team meetings, and science team meetings. Since the teams were not co-located, all the meetings were supported by teleconferencing. Each meeting agenda was specific to the needs of each team, and the project meetings provided the forum where information was shared across teams and follow-up

actions were identified. The team meetings increased to 2-3 meetings per week as preparations for the flybys intensified and specific issues needed focused attention. Finally, daily status meetings were held with full participation from the science, navigation, and operations teams during the 60 days of approach for each comet flyby.

IV. Risk Management

Risk management for two concurrent projects required the involvement of all elements of the team along with extra effort from the project and mission managers to understand the key issues, the flyby implementation strategies and sequence development status, and the associated risk posture for the two missions. Every member of the team was encouraged to discuss any risk related issues with their team leaders. When possible, risks were addressed within each team, and when necessary were worked across the appropriate teams. Having small project teams eased the communication process. The project reviews leading up to the Critical Event Readiness Review all focused on identifying the mission risk associated with the implementation of the flybys.

Since each of the flybys were missions of opportunity after having completed the primary missions, the teams had to deal with non-optimal conditions. For example, the Deep Impact spacecraft was configured for its original encounter with comet Tempel 1, locating the high gain antenna so that real time communication with earth could be maintained throughout the final approach and flyby. However, for the Hartley 2 flyby, the geometry was such that this antenna could not be pointed at earth while the spacecraft imagers were pointed at the comet for the last few weeks of approach. The spacecraft had to turn back and forth between comet imaging and earth pointed attitudes. For most of the approach period, the spacecraft would spend a few hours at a time pointed at the comet, then would turn back to earth to downlink data. The last week of approach imaging was conducted by implementing an hourly cadence of turning to comet imaging attitude, turning back to earth for image downlink, and turning back to the comet. This was done in order to maintain a regular observation cadence of the comet, looking for light curve variations and come activity such as jets or outbursts. In order to do this, the spacecraft had to implement these turns to and from comet pointing at a rate much faster than ever before in the mission. After analyzing the requirement and the capability of the reaction wheels, the team was convinced this could be done safely, but an in-flight demonstration of this cadence was implemented to ensure that no unanticipated interactions between the attitude control subsystem and the spacecraft fault protection were being overlooked. After demonstrating this new operating mode successfully, the risk of unexpected problems during the last week of approach activities was significantly reduced.

Since communication with earth via the high gain antenna was not possible while comet pointed, the final 18 hours before the flyby had to be designed for low gain antenna communications and the associated low data rate. This not only required the team to design a telemetry mode that provided essential health and status of the spacecraft at 512 bits per second, but also meant that the high value data – the close up images and IR scans of the comet nucleus – could not be downlinked until after the spacecraft had passed by the comet. All decisions related to the final flyby design were then made with the overriding consideration that the close-up data had to be protected. Not only did sequences and fault protection need to be designed to respond in ways that safeguarded the stored data, but the fundamental risk to the spacecraft of flying deep through the coma of the comet had to be considered to ensure spacecraft survival until data playback. Although the spacecraft had been designed to protect key elements from particle impact damage, this new flyby was faster than the previous one, and the science team's goal was to track and image the comet nucleus all the way through closest approach and initial departure in order to maximize the amount of surface covered by the images. This strategy would expose spacecraft surfaces to the dust flux that had never been designed for this exposure. In order to assess the risk, the original dust impact damage model was updated to account for the predicted dust flux at Hartley 2, with the higher flyby velocity, and the new flyby profile. The analysis, combined with a peer review of the data used to derive the dust environment, was used to assess the risk of the new flyby conditions and strategy. Once the project was convinced that the risk was acceptable, the flyby with comet tracking and imaging all the way through closest approach and look-back became the baseline.

Another project level risk decision was the pointing stability assumption used in designing the flyby imaging sequences. Again, the desire to maximize the observational sampling of the comet drove the desire to use the smallest possible image frame sizes in order to store more images in the spacecraft memory. The science team analyzed the extensive data set from the EPOCh imaging campaign in order to bound the expected level of pointing error. The spacecraft team, however, could not guarantee this level of pointing performance based on the fundamental design of the spacecraft and the performance of the attitude control system. This issue became a risk decision that had to be made between the Project Manager and the Principal Investigator in order to not only move

forward with the sequence design, but also to communicate the mission risk with JPL and NASA senior management. The risk trade balanced the desire to not give up a large portion of the images a priori by using the more conservative design parameters with risking loss of some comet images if the spacecraft could not maintain the more optimistic pointing performance. Ultimately the PM and PI chose the latter approach and mitigated the risk by building a set of tools that could be used to quickly update on board target tables to account for any pointing offsets. This strategy proved successful and the pointing updates were never needed.

The Stardust spacecraft had similar challenges that required in depth understanding not only from the spacecraft team, but also from the project management in order to properly assess the associated risks and support the appropriate decisions. Like Deep Impact, the Stardust spacecraft was not configured to be able to point its high gain antenna at earth while imaging the comet during this new mission. Additionally, this flyby was far enough away from earth that the low gain antenna signal was too faint to be detected by the Deep Space Network antennas and the medium gain antenna signal would likely be too low to support any telemetry. This resulted in a two hour long period around the flyby where spacecraft performance data would not be available. The ground antennas would detect a signal from the spacecraft, but no data content would be resolved. Again, this drove the design of the final sequence and the fault management strategies to consider protection of the stored data as the highest priority. This included disabling any fault responses that might lead to a cold reboot of the processor and the associated loss of data stored in RAM.

Fuel management for the Stardust NExT mission was probably the overriding risk issue that had to be factored into every decision. Since the spacecraft was now down to its last few kilograms of fuel, and the thruster based attitude control used fuel for every control action, the team had to plan the comet encounter down to every tip and turn of the spacecraft in order to properly predict the total fuel consumption for the mission. The fuel budget was tracked down to the daily grams of fuel used for pointing control. Every planned turn was accounted for along with the expected fuel use. The mission activities were adjusted to always maintain a positive fuel margin. Since the stardust spacecraft was built with unbalanced thrusters, every thruster pulse used to turn the spacecraft also resulted in a finite delta V that resulted in a trajectory change over time. Every change to the planned mission activities non only considered the immediate fuel cost, but also had to take into account the downstream trajectory correction that would be required. As the tank approached empty, every available technique was used to predict the amount of remaining fuel. Understanding the impact of every activity on the fuel budget required frequent, active communication among all the teams and constant vigilance on the part of the project leadership. [1] In the end, the spacecraft was successful in its flyby of Tempel 1 and met all of its science requirements and goals. About a month after the February 2011 flyby the spacecraft was decommissioned and the decommissioning burn showed that the tank was empty.

Tracking these issues, understanding the implications, assessing the impact on mission risk of the various approaches to dealing with these challenges, and clearly communicating the final decisions and resulting risk to the various stake holders required the project management team to be tightly involved with the spacecraft, navigation, and science teams as these decisions were being made. In the case of the EPOXI mission, the bulk of the spacecraft operating team and the project office were co-located, facilitating these communications. For the Stardust NExT mission, however, the spacecraft operations team was located in at the Lockheed Martin facility in Denver, requiring frequent communication by telephone as well as frequent travel by the project manager to ensure the proper level of involvement and understanding of the issues as they developed. This was one area where the having the two flybys spaced by only three months made this level of involvement challenging. Managing both projects during the last six months required the management team to carefully plan activities, meetings, and reviews to maintain sufficient insight into the issues affecting mission risk. Multiple daily meetings, teleconferences, and communication within and outside the projects were the norm for the team.

Experienced teams and a very close working relationship between the project management and the team chiefs for both projects were essential to the success of these projects under these circumstances. The project manager and the team leaders needed to operate in a way where communication was frank and open, issues were discussed and dealt with promptly and where they knew each others' capabilities and experience enough to establish a fundamental level of trust to make sound decisions. Working relationships at this level cannot be established by an occasional telephone tag-up or monthly management reviews. They require effort to communicate frequently, travel as much as necessary to maximize the amount of face-to-face communication, getting to know the entire team, and establishing the trust that leads to open communication. In these situations the manager must constantly strive to balance insight and independence to avoid managing at too low a level but still understanding enough of the details to be able to assess and communicate risk. Additionally, the manager must avoid being the focal point for all decisions. This will only serve to slow down progress in the teams and will ultimately stifle the desire of the teams

to fully understand the issues and formulate resolutions on their own. The only way that this was successful on these projects with small teams was the skill and experience of the teams and their leaders.

Another key aspect of managing risk on these projects was clearly establishing the key decision points during critical portions of the mission, when these decisions must be made, who is responsible for making them, and the criteria to be used. For each mission, such a list was established by the time of the Critical Events Readiness Review. Each decision point was firmly identified on the timeline, the data used to make the decision and the criteria to be used were documented, and the decision maker was identified. This was reviewed in detail to assure that everyone understood these. Each project implemented activities where these scenarios were exercised in advance of the actual event. These consisted of operational readiness tests that were carried out using the testbeds to simulate the spacecraft and working through real time mission scenarios. This enabled planners to introduce various simulated anomalies and exercise the team in a manner that closely simulated the data environment that would be seen in flight. Another effective technique used walkthroughs of various scenarios. These were tabletop exercises where the team talked through a portion of the mission, discussing various anomaly situations and talking through the responses to each of these. This became a powerful tool for not only preparing the team to react appropriately, but also provided an in depth review of the implementation strategies, sometimes resulting in changes in strategies due to the outcome of the discussions.

V. Results

Both of these missions of opportunity were successful, exceeding all their mission requirements. The EPOXI flyby revealed Hartley 2's small, very active nucleus, shown in Figure 3. The IR spectra showed that the jet activity at the rough ends of the comet was driven by CO_2, while the smooth area in the middle emitted primarily water vapor. As the spacecraft passed the comet, images from the High Resolution Imager showed large number of ice chunks being ejected from the end of the comet. These ice aggregates then evaporated in the coma, leaving behind vapor and dust. The science findings and conclusions from the EPOXI flyby are reported in [2].

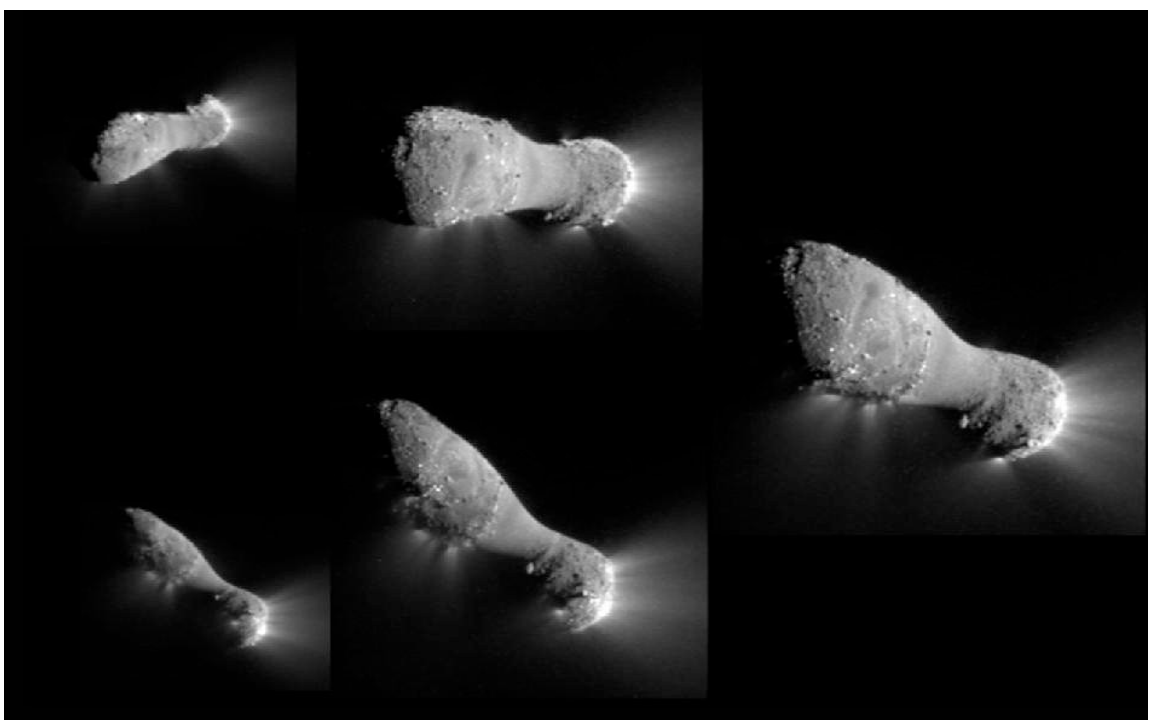

Figure 3 - Nucleus of comet Hartley 2 during EPOXI flyby.

The Stardust NExT mission flew by comet Tempel 1 revealing close up views of areas imaged by Deep Impact at the previous perihelion pass, new terrain, and the location of the impact site from the Deep Impact mission. Figure 2 shows the closest views of Tempel 1 during the flyby. This second look at the comet, showed where significant changes had occurred in the area of a large smooth flow on the surface. It also revealed areas exhibiting significant layering, some indicative of original accretion of material during cometary formation and others where thinner layers provided clues of cryo-volcanism. Most surprising to most operation team members was the remarkably subtle change on the surface due to the collision with the impactor. Analysis of the resulting depression concluded that the comet surface material has the strength and consistence of loosely packed dry snow [3].

Figure 4 -Nucleus of comet Tempel 1 during Stardust NExT flyby.

VI. Conclusion

Missions of Opportunity utilizing spacecraft that have completed their primary missions provide valuable science enhancement at very low additional cost. The cost of each of these missions was less than 10% of the cost of a new Discovery class mission not including launch costs, while the science collected was considered on par with that of a primary mission. Achieving that for these two missions resulted in a challenge for the project management team that tracked both projects. This pace of activities was intense as both spacecraft approached their targets, and one executed its flyby while the other was in the final stages of preparation for its event. Successfully managing both these activities required intense concentration and attention for many months, demanded extra effort as project activities overlapped, and required significant travel to ensure the level of involvement and understanding necessary to effectively manage risk. However, the spectacular science returns achieved by these two mission was a welcome reward. Stardust spacecraft was retired in March 2011 after 12 years of space flight, an asteroid flyby, 2 comet flybys, and a sample return. The Deep Impact spacecraft is still in its heliocentric orbit, ready to take on a new assignment.

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