# EPOXI (Combined EPOCh and DIXI) Description

*The following material was adapted from the EPOXI mission web site and includes some text provided by the science team.*

# Mission Overview

EPOXI, a Mission of Opportunity for the NASA Discovery program, is the combination of two independently proposed scientific investigations utilizing the Deep Impact (DI) flyby spacecraft as an extended mission: EPOCh (Extrasolar Planet Observation and Characterization) and DIXI (Deep Impact eXtended Investigation).

From 22 January through 31 August 2008, EPOCh took advantage of the permanent on-orbit defocus of the High Resolution telescope (HRI) by using the High Resolution Visible CCD (HRIV) to collect over 172,000 usable, photometric- quality, visible light images of eight known transiting planet systems (hot Jupiters): HAT-P-4, HAT-P-7, GJ 436, TrES-2, TrES-3, XO-2, XO-3, and WASP-3. Time series of continuous 50-second integrations in a subframe mode of 128x128 or 256x256 pixels with the clear #6 optical filter extending from 350 to 1000 nanometers were used to observe each system for about three weeks, typically covering five or more transits as well as secondary eclipses. An exception is XO-3 which was observed only briefly before the spacecraft unexpectedly entered safe mode. The transiting planet systems were observed in the integrated light of the planet and star; no spatially resolved image of the planet was possible. The out-of-focus HRI telescope defocuses the images to about 10 pixels or 4 arcseconds at full-width half-max and introduces visible structure. Each target series was typically bracketed by a set of dark and internal stimulator lamp frames to monitor changes in the HRIV CCD detector for calibration purposes.

On 18-19 March, 28-29 May, and 4-5 June 2008, EPOCh also observed Earth with the HRIV CCD and the High Resolution Infrared Imaging Spectrometer (HRII) to characterize it as an analog for extrasolar planets. The observations comprised imaging in seven optical narrow-band (100 nanometer) filters and 2- to 5-micron infrared spectroscopy over a full Earth rotation. The optical images used a 512x512-pixel subarray of the HRIV CCD detector at a scale of about 0.4 arcsec/pixel, and each frame of the HRII spectrometer was 512 (wavelength) by 128 pixels (spatial, 2 arcsec/pixel). HRIV CCD images were acquired once every hour with three filters centered on 350, 750 and 950 nanometers and once every 15 minutes with the 450-, 550-, 650- and 850-nanometer filters. Infrared spectra were obtained twice per hour by scanning the slit of the HRII spectrometer over the earth, using three scans to ensure coverage of the entire disk; the slit was aligned perpendicular to the terminator during the scans. The spacecraft orbit was approximately in the plane of the ecliptic which provided an equatorial view of Earth with about 62 to 77 percent of the disk illuminated. Each of the three Earth observing periods lasted approximately 24 hours. During the 29 May observation, the Moon transited Earth as seen from the spacecraft (0.3 AU from Earth).

EPOCh continued observations in 2009. These included Earth at both northern and southern latitudes using the same sequence from 2008. Additionally, that same sequence was used to observe Mars with the HRII and HRIV instruments in November 2009. On 5-8 October 2009, EPOCh continuously imaged the exoplanet microlensing event MOA-2009-BLG-266 by reusing the sequence from the HRIV exoplanet transit observations in 2008.

DIXI consisted of a flyby of comet 103P/Hartley 2 in November 2010 to study a second comet with the same set of instrumentation as was used by the Deep Impact mission during the encounter with comet 9P/Tempel 1 in July 2005. Closest approach to 103P/Hartley 2 occurred at 13:59:47.31 UTC on 4 November 2010 at a distance of 694 km and a flyby speed of 12.3 km/s. The spacecraft flew under the comet on a slightly northward trajectory in an ecliptic reference frame, then rotated to keep the body-mounted instruments pointed at the comet for departure imaging. Over 100,000 visible images and IR spectra of 103P/Hartley 2 were taken, beginning on 5 September, 60 days before encounter, and continuing through 26 November 2010, three weeks after the flyby.

103P/Hartley 2 passed perihelion on 28 October, only seven days before DIXI flyby, and was known to be more active than comet 9P/Tempel 1. Since the DIXI encounter occurred at a smaller heliocentric distance than Deep Impact, the project realized a significant improvement to the signal-to-noise ratio of all visible and IR measurements.

Various in-flight calibrations were performed throughout the EPOXI mission, from October 2007 to February 2011. In late 2011, the Deep Impact flyby spacecraft was redirected for a flyby of Apollo asteroid 163249 (2002 GT) in January 2020.

From 20 February to 09 April 2012, EPOXI acquired IR spectra and HRIV and MRI visible images of comet C/Garradd (2009 P1). From 17 January through 06 March 2013, EPOXI acquired IR spectra and MRI visible images of comet C/ISON (2012 S1).

On 14 August 2013, the flyby spacecraft failed to phone home. The operations team eventually traced the issue to a problem with a time computation that put the spacecraft computer into an infinite reboot loop, thereby losing both attitude control and communications. After trying unsuccessfully for more than a month to regain contact, NASA announced the end of operations for the Deep Impact flyby spacecraft on 20 September 2013.

# Mission Phases

The EPOXI mission has five main phases: *Cruise 1*, *EPOCh*, *Cruise 2*, *DIXI/Hartley 2 Encounter*, and *Cruise 3*. Most phases include several events or activities. The timeline for the mission and description of the phases and events are described below.

## Mission Timeline

**Phases and Events Start Date/DOY Stop Date/DOY**

*Cruise 1*  2007-09-26/269 2008-01-21/021

Spacecraft Wakeup 2007-09-26/269 2007-09-26/269

Instrument Checkout 2007-10-04/277 2007-10-04/277

EPOCh Photometry Test 2007-11-04/308 2007-11-09/313

Instrument Checkout Retest 2007-12-04/338 2007-12-04/338

HRIV Scattered Light Calibration 2007-12-17/351 2007-12-17/351

Lunar Calibration 2007-12-29/363 2007-12-29/363

Earth Flyby #1 2007-12-31/365 2007-12-31/365

Standard Cruise Calibration 2008-01-09/009 2008-01-09/009

HRII Dark Retake for Lunar Cal 2008-01-16/016 2008-01-17/017

*EPOCh* 2008-01-22/022 2008-08-31/244

Exoplanet Transit Observations 2008-01-22/022 2008-08-31/244

Earth Observations (#1) 2008-03-18/078 2008-03-19/079

Earth Observations (#4) 2008-05-28/149 2008-05-29/150

Earth Observations (#5) 2008-06-04/156 2008-06-05/157

Standard Cruise Calibration 2008-06-23/175 2008-06-25/177

*Cruise 2* 2008-09-01/245 2010-09-02/245

HRII Reciprocity Test 2008-09-18/262 2008-09-18/262

HRII Dark Flush Test 2008-09-26/270 2008-09-26/270

HRII Encounter Darks Rerun 2008-10-02/276 2008-10-02/276

HRII Dark Gap Test 2008-10-08/282 2008-10-08/282

Interplanetary Internet Test 2008-10-15/289 2010-11-15/319

HRIV PSF Calibration 2008-12-17/352 2008-12-17/352

Earth Flyby #2 2008-12-29/364 2008-12-29/364

HRII Subframe Gain Calibration 2009-01-26/026 2009-01-26/026

EPOCh Earth North Pole 2009-03-27/086 2009-03-28/087

HRII Lunar Radiometry & Flats 2009-06-01/152 2009-06-02/153

HRII Lunar Rad. & Antisat Filter 2009-06-09/160 2009-06-09/160

HRII Linearity Calibration 2009-06-18/169 2009-06-18/169

Distant Earth Flyby #1 2009-06-29/180 2009-06-29/180

EPOCh Earth South Pole #1 (partial) 2009-09-27/270 2009-09-28/271

Checkout after HRI Turnoff 2009-09-30/273 2009-09-30/273

HRIV Mechanical Checkout 2009-10-01/274 2009-10-01/274

EPOCh Earth South Pole #2 (full) 2009-10-04/277 2009-10-05/278

EPOCh Microlensing MOA-2009-BLG-266 2009-10-05/278 2009-10-08/281

HRII Radiometric Cal #1 (Beta Hyi) 2009-10-13/286 2009-10-24/297

HRII Dark Subframe Test 2009-11-20/324 2009-11-20/324

EPOCh Mars 2009-11-20/324 2009-11-21/325

HRII Lunar Flats/Radiometric Cal #1 2009-12-05/339 2009-12-05/339

HRII Lunar Flats/Radiometric Cal #2 2009-12-12/346 2009-12-12/346

HRII Lunar South Pole Radiometry 2009-12-18/352 2009-12-18/352

Distant Earth Flyby #2 2009-12-28/362 2009-12-28/362

Standard Cruise Calibration 2010-02-16/047 2010-02-16/047

HRII NoSave Flush Test 2010-04-20/110 2010-04-20/110

HRII Radiometric Cal #2 (Beta Hyi) 2010-05-03/123 2010-05-17/137

Earth Flyby #3 2010-06-27/178 2010-06-27/178

MRI Dosido Fast Slew Test 2010-07-12/193 2010-07-12/193

*DIXI/Hartley 2* 2010-09-03/246 2010-11-28/332

HRIV PSF Calibration 2010-09-03/246 2010-09-03/246

Approach Imaging 2010-09-05/248 2010-11-03/307

E-60 to E-50 days (VIS only) 2010-09-05/248 2010-09-15/258

E-50 to E-40 days (VIS only) 2010-09-15/258 2010-09-25/268

HRII Spectrometer Cooldown 2010-09-25/268 2010-10-01/274

Pre-Encounter Standard Cruise Cal 2010-09-28/271 2010-09-29/272

E-34 to E-8 days (Start HRII) 2010-10-01/274 2010-10-27/300

E-8 days to E-18 hours 2010-10-27/300 2010-11-03/307

Encounter Imaging 2010-11-03/307 2010-11-06/310

E-18 hours to E+2 days 2010-11-03/307 2010-11-06/310

Flyby and Closest Approach 2010-11-04/308 2010-11-04/308

Departure Imaging 2010-11-06/310 2010-11-26/330

E+2 to E+12 days 2010-11-06/310 2010-11-16/320

E+12 to E+21 days 2010-11-16/320 2010-11-26/330

Post-Encounter Standard Cruise Cal 2010-11-27/331 2010-11-28/332

*Cruise 3* 2010-11-29/333 2013-09-20/263

HRII 50-Frame Extended Linear. Cal 2011-02-05/036 2011-02-06/037

Comet Garradd Observations 2012-02-20/051 2012-04-09/100

HRII Spectra 2012-03-26/086 2012-04-03/094

HRIV/MRI Vis Imaging 2012-02-20/051 2012-04-09/100

Comet ISON Observations 2013-01-17/017 2013-03-06/065

HRII Spectra 2013-02-16/047 2013-02-17/048

MRI Vis Imaging 2013-01-17/017 2013-03-06/065

End of Mission 2013-09-20/263 2013-09-20/263

## Cruise 1

Start Time : 2007-09-26 (DOY 269)

Stop Time : 2008-01-21 (DOY 021)

### Spacecraft Wakeup and Instrument Checkout

After 25 months in hibernation, the Deep Impact spacecraft was woken on 26 September 2007. The spacecraft functioned as expected. On 4 October 2007, the HRII (High Resolution Infrared Imaging Spectrometer), HRIV (High Resolution Visible CCD), and MRI (Medium Resolution Visible CCD) instruments were turned on for the first time in more than two years. A brief checkout test was performed and confirmed the mechanical components were functioning. The three science instruments exhibited nominal behavior of background levels although several HRII detector pixels had a different response when compared to Deep Impact. After checkout, several Trajectory Correction Maneuvers (TCM) were performed in November and December 2007 to alter the trajectory of the spacecraft to put it on course to flyby the Earth for a gravity-assist to reach comet 103P/Hartley 2 in 2010.

### EPOCh Photometry Test

On 4-9 November 2007, EPOCh photometry tests were performed. During these tests, the HRIV instrument observed a bright (V=9) visual binary star (HD 80607) for 12 continuous hours to check pointing and photometric stability. The observations were taken using the 256-by-256 sub-array mode of the HRIV CCD. The spacecraft successfully captured the star images and held them on the sub-array for the full duration of the test. However, the images were unexpectedly offset by about 59 microradian (12.2 arcsec). This was due to stellar aberration which was not included for stellar observations during the Deep Impact mission. After correcting for aberration, the spacecraft pointing was within specifications.

### Instrument Checkout Retest

Instrument Checkout Retest: On 4 December 2007 a retest of the October instrument checkout sequence was performed for the three science instruments. The focus of this retest was to determine if HRII pixels that had an odd response during checkout had changed or improved.

### HRIV Scattered Light Calibration

On 17 December 2007, a calibration for scattered light using Earth's moon was performed for the HRIV instrument. Many of these images were obtained with the moon outside but near the field of view of the HRIV CCD to allow analysis of the amount of light that is scattered into the field of view from bright objects just outside or within the field of view.

### Lunar Calibration and Earth Flyby #1

On 29 December 2007, as the spacecraft approached Earth, the HRIV, HRII, and MRI instruments used the Moon as a target to acquire data for recalibration purposes. Due to a minor error in the lunar calibration sequence, a series of HRII dark frames were not recorded. A retest to acquire the missing HRII darks was scheduled for 16 January 2008. At 19:29:20.66 UTC on 31 December 2007, the flyby spacecraft achieved its closest approach to Earth at an altitude of only 15,567.63 km above eastern Asia.

### Standard Cruise Calibration

On 9 January 2008, the first of the standard cruise calibrations for the HRII, HRIV, and MRI instruments was performed. The calibration sequence included observations of several standard stars, both solar analogs and hot stars with few absorption lines in their spectra for absolute calibration of all instruments, a stellar cluster for checking geometric distortion in the cameras, and a planetary nebula for checking the wavelength calibration of the spectrometer. This sequence was designed such that it could be rerun, with few if any changes, after completion of the EPOCh observations and then again just before and just after the observing program for comet 103P/Hartley 2.

### HRII Dark Retake for Lunar Cal

Due to a minor error in the lunar calibration sequence that was executed in December, a series of HRII dark frames was not recorded. However, that sequence was successfully rerun on 16-17 January 2008.

## EPOCh

Start Time : 2008-01-22 (DOY 022)

Stop Time : 2008-08-31 (DOY 244)

EPOCh observations of eight known extrasolar planetary systems transits began on 22 January 2008 with the HAT-P-4 system and ended nearly six months later with the HAT-P-7 system on 31 August 2008. Taking advantage of the permanent on-orbit defocus of the HRI telescope, EPOCh used the HRIV CCD to collect over 172,000 usable, photometric-quality, visible light images of eight known transiting planet systems. Time series of continuous 50-second integrations in a subframe mode of 128x128 or 256x256 pixels with the clear #6 optical filter extending from 350 to 1000 nanometers were used to observe each system for about three weeks, typically covering five or more transits as well as secondary eclipses. An exception is XO-3 which was observed only briefly before the spacecraft unexpectedly entered safe mode. In most instances, the 128x128-pixel subarray size was used. The 256x256-pixel subarray was utilized during some transit and secondary eclipse periods to ensure that pointing jitter did not cause the star to fall beyond the edges of the subarray. Each series was typically bracketed by a set of dark and internal stimulator lamp frames to monitor changes in the HRIV CCD detector for calibration purposes.

The transiting planet systems were observed in the integrated light of the planet and star; no spatially resolved image of the planet was possible. The out-of-focus HRI telescope defocuses the images to about 10 pixels or 4 arcseconds at full-width half-max and introduces visible structure.

The following extrasolar planetary systems were the targets for EPOCh transit photometry and are described in Ballard, et al. (2009a):

|  |  |  |  |
| --- | --- | --- | --- |
| **Stellar** | **#Transits** | **Target V\_mag** | **Observed Points of Interest** |
| HAT-P-4 | 11.22 | 10 | Low density planet, large radius for its mass |
| XO-3 | 9.91 | 1 | Eccentric orbit, second planet suspected |
| TrES-3 | 12.40 | 7 | Short period (31 hours), reflected light targe |
| XO-2 | 11.18 | 3 | Fainter component in wide visual binary, metal rich |
| GJ 436 | 10.67 | 8 | Eccentric orbit, unseen planet suspected, star is M-dwarf |
| TrES-2 | 11.41 | 7 | Kepler target, additional planets possible |
| WASP-3 | 10.64 | 8 | Strongly heated, reflected light and visible thermal emission possible |
| HAT-P-7 | 10.50 | 8 | Kepler target, even more strongly heated than WASP-3 |

On 18-19 March, 28-29 May, and 4-5 June 2008, EPOCh also observed Earth with the HRIV CCD and the High Resolution Infrared Imaging Spectrometer (HRII) to characterize it as an analog for extrasolar planets. The observations comprised imaging in seven optical narrow-band (100 nanometer) filters and 2- to 5-micron infrared spectroscopy over a full Earth rotation. Because the HRI telescope is defocused, the spatial resolution as observed is about 4 arcsec in each case.

The optical images of Earth used a 512x512-pixel subarray of the HRIV CCD detector at a scale of about 0.4 arcsec/pixel, and each frame of the HRII spectrometer was 512 (wavelength) by 128 pixels (spatial, 2-arcsec/pixel scale). HRIV CCD images were acquired once every hour with three filters centered on 350, 750 and 950 nanometers and once every 15 minutes with the 450-, 550-, 650- and 850-nanometer filters. Infrared spectra were obtained twice per hour by scanning the slit of the HRII spectrometer over the earth, using three scans to ensure coverage of the entire disk; the slit was aligned perpendicular to the terminator during the scans. The spacecraft orbit was approximately in the plane of the ecliptic which provided an equatorial view of Earth with about 62 to 77 percent of the disk illuminated. Each of the three Earth observing periods lasted approximately 24 hours. During the 29 May observation, the Moon transited Earth as seen from the spacecraft (0.3 AU from Earth).

The following table chronologically lists EPOCh observations. For most stellar exoplanet transit targets, preview imaging was performed to determine if the pointing bias needed to be modified for that target series. Scheduled Earth observations #2 and #3 were canceled due to a telecommunications anomaly (see below).

**Target Start Date/DOY Stop Date/DOY Comments**

HAT-P-4 2008-01-22/022 2008-02-12/043

XO-3 2008-02-12/043 2008-02-17/048 S/C entered safe mode

TrES-3 2008-03-06/066 2008-03-08/068

XO-2 2008-03-09/069 2008-03-11/071 Preview for pointing bias

TrES-3 2008-03-11/071 2008-03-18/078

Earth 2008-03-18/078 2008-03-19/079 Obs #1

XO-2 2008-03-20/080 2008-03-28/088

GJ 436 2008-05-04/125 2008-05-27/148

Earth 2008-05-28/149 2008-05-29/150 Obs #4

Earth 2008-06-04/156 2008-06-05/157 Obs #5

TrES-2 2008-06-28/180 2008-06-29/181 Preview for pointing bias

HAT-P-4 2008-06-29/181 2008-07-08/190

TrES-2 2008-07-08/190 2008-07-17/199

WASP-3 2008-07-17/199 2008-07-19/201 Preview for pointing bias

TrES-2 2008-07-20/202 2008-07-30/212

WASP-3 2008-07-30/212 2008-08-08/221

HAT-P-7 2008-08-08/221 2008-08-10/223 Preview for pointing bias

WASP-3 2008-08-10/223 2008-08-16/229

HAT-P-7 2008-08-16/229 2008-08-31/244

After the observations of XO-3 on 17 February 2008 were downlinked, the spacecraft autonomously entered safe mode as it was turning to an optimal attitude to transmit data to Earth. EPOXI mission controllers believed the safe mode was triggered when one of the reaction wheels, which helps maintain spacecraft attitude, experienced slightly higher temperatures than what the on-board fault protection software would allow. After some engineering data was slowly brought down to Earth, controllers determined the spacecraft could be brought out of safe mode without triggering new problems. On 29 February the spacecraft successfully exited safe mode and began downlinking the EPOCh images taken before safe mode was entered.

On 6 March 2008, EPOCh observations were restarted with TrES-3 as the target. EPOCh imaging continued without problems until a telecommunication anomaly occurred after the March 28th downlink of 5000 photometric HRIV frames of transiting planet system XO-2. This was the largest volume of data in a single downlink for EPOXI to date. Following this downlink, EPOCh observations were paused to investigate the cause of an 8-dB (33%) loss of downlink signal and some slightly elevated temperatures on the spacecraft as it passed through perihelion. As the spacecraft cooled over three weeks (a combination of moving further from the sun and all instruments being turned off), telemetry strength returned, and the project restarted EPOCh by first downlinking the images of XO-2 that had been stored on board the spacecraft since the end of March. Telecommunications functioned as expected and observations of stellar exoplanet transit targets resumed with the remaining scheduled target, GJ 436. The fourth and fifth sets of Earth observations were performed in late May and early June as planned, and a standard cruise calibration for the three instruments was successfully performed on 23-25 June 2008.

During the telecom anomaly, observations of these scheduled targets were missed: the end of the XO-2 sequence, TrES-2, the second and third sets of Earth observations, and the beginning of GJ 436. As a result of skipping these targets, the EPOCh investigation could no longer meet some of its objectives. Therefore, NASA approved contingency observations starting on 27 June 2008 and continuing through 31 August 2008 to replace the science lost during the safe mode entry and telecom problems experienced in the spring. The targets for the contingent observations were TrES-2, HAT-P-4 (revisit), WASP-3, and HAT-P-7.

While waiting for the EPOCh contingency observations to begin, a standard cruise calibration was performed on 23-25 June 2008 for the HRII and HRIV instruments. The sequence was very similar to that used for the calibration performed on 9 January 2008, except the MRI instrument was turned off because of thermal and telecommunication concerns. Also a trajectory correction maneuver was performed to put the flyby spacecraft on course for a rendezvous with Hartley 2 on 4 November 2010.

Since the second and third sets of EPOCh Earth imaging were canceled because of the telecommunications anomaly, NASA approved a request from the team to perform two Earth observations in 2009.

## Cruise 2

Start Time : 2008-09-01 (DOY 245)

Stop Time : 2010-09-02 (DOY 245)

Various calibration sequences and tests as well as several Earth flybys were performed for this phase. During Cruise 2, EPOCh continued observing Earth as as a contingency for the two observing periods that were lost in early 2008 because the telecommunications anomaly. EPOCh also observed Mars as an extrasolar planetary analog and an exoplanet microlensing event named MOA-2009-BLG-266.

### HRII Reciprocity Test

On 18 September 2008, an HRII reciprocity test was performed to determine the background signal level of the READ and RESET frames of the IR spectrometer as a function of the past history of integration delay times and the timing gap between sets of frames using the diagnostic imaging mode (number 6). The ultimate objective of this test along with the HRII Dark Flush, HRII Dark Gap, and HRII Subframe Gain tests performed over the next four months is to develop a more accurate model of the variation in the background level of the IR spectrometer.

### HRII Dark Flush Test

On 26 September 2008, an HRII dark frame flush test was performed to determine the type of IR spectrometer instrument operation needed to remove all traces of the residual (previous) image.

### HRII Encounter Darks Rerun

On 02 October 2008, a set of HRII dark frames for several IR exposure IDs from the Deep Impact Tempel 1 encounter sequence was acquired by the HRII spectrometer. The exposures were those acquired from about 19 minutes before the impact with Tempel 1 through the first few hours of lookback imaging.

### HRII Dark Gap Test

On 10 October 2008, an HRII dark gap test was performed to characterize the change in the residual image and the dark level in the IR spectrometer as a function of wait time and number of readouts after acquiring data in the subframe imaging modes (numbers 2 and 3).

### First Interplanetary Internet Test

From mid-October to mid-November 2008, the first deep space communications network, also known as the Interplanetary Internet, was successfully tested using the Deep Impact flyby spacecraft. Using software called Delay-Tolerant Networking (DTN) dozens of images were transmitted to and from the flyby spacecraft located more than 32 million kilometers from Earth.

### HRIV PSF Calibration

On 17 December 2008, additional data were acquired for improving point spread functions (PSF) for the HRIV CCD. Analysis of early EPOXI calibration data and EPOCh stellar observations indicated the PSFs had changed since mid-2005 when the functions were last generated for Deep Impact. The project plans to rerun this sequence in 2010 for the Hartley 2 flyby.

### Earth Flyby #2

At about 21:40 UTC on 29 December 2008, the Deep Impact flyby spacecraft achieved its closest approach to Earth at an altitude of only about 43,450 km, about midway between New Zealand and Tierra Del Fuego and at a latitude of about 49 degrees south.

### HRII Subframe Gain Calibration

On 26 January 2009, an HRII subframe gain calibration was conducted to observe differences in the IR spectrometer signal response rates when observing an external radiance source to differentiate between gain and offset effects when using the various subframe modes. The test was performed by scanning the spectrometer across the moon at multiple speeds with various subframe modes while the HRI telescope barrel was warm.

### EPOCh Earth North Pole

On 27-28 March 2009, EPOCh observed Earth at high northern latitudes for 24 hours with the HRIV CCD and the IR spectrometer to continue characterizing it as an analog for extrasolar planets. The observations comprised narrow band filter images (350-950 nanometers) and 2- to 5-micron infrared spectroscopy, over a full Earth rotation. Observations were acquired once per hour with the filters centered on 350, 750 and 950 nanometers, whereas the 450-, 550-, 650-, and 850-nanometer data were taken every 15 minutes. Infrared spectral scans of the Earth's disk were acquired twice per hour.

### HRII Lunar Radiometry & Flats

On 1-2 June 2009, the HRII spectrometer acquired a series of north/south scans of the moon for lunar radiometry and east/west scans along IR slit for flats. These data were the best obtained to date for the purpose of generating flat fields for the IR spectrometer.

### HRII Lunar Radiometry & Anti-saturation Filter

On 9 June 2009, the HRII spectrometer imaged the moon using north/south scans to better characterize the effects of the anti-saturation filter in the IR spectra.

### HRII Linearity Calibration

On 18 June 2009, HRII darks were acquired to check the linearity of the IR spectrometer. The sequence was identical to the one used during standard cruise calibrations for linearity.

### Distant Earth Flyby #1

A distant flyby of Earth occurred on 29 June 2009 at a geocentric distance of about 1,350,000 km.

### EPOCh Earth South Pole #1 (partial)

On 27-28 September 2009, EPOCh observed Earth at high southern latitudes with the HRIV CCD and the IR spectrometer using the same sequence as the observations at northern latitudes in March 2009 to continue characterizing it as an analog for extrasolar planets. However the sequence ended prematurely because HRI was turned off by fault protection although the spacecraft was fine. MRI remained on.

### Checkout after HRI Turnoff & HRIV Mechanical Checkout

Before repeating the Earth South Pole observation, a standard imaging checkout of the HRII, HRIV, and MRI instruments was performed after HRI was powered up on 30 September 2009. Also a mechanical checkout of HRIV was performed on 01 October: a miniature HRIV Earth observing sequence that cycled through the filters 21 times was run to check for 5-V telemetry channel noise. The results of the tests were satisfactory.

### EPOCh Earth South Pole #2 (Full)

On 04-05 October 2009, EPOCh successfully acquired a full set of observations (24 hours) of Earth with the HRIV CCD and the IR spectrometer using the same sequence as the observations at high northern latitudes in March 2009 to continue characterizing it as an analog for extrasolar planets. The observations comprised narrow band filter images (350-950 nanometers) and 2- to 5-micron infrared spectroscopy, over a full Earth rotation. Observations were acquired once per hour with the filters centered on 350, 750 and 950 nanometers, whereas the 450-, 550-, 650-, and 850-nanometer data were taken every 15 minutes. Infrared spectral scans of the Earth's disk were acquired twice per hour.

### EPOCh Microlensing MOA-2009-BLG-266

On 05-08 October 2009, HRIV imaged for about four days the known exoplanet microlensing event named MOA-2009-BLG-266, where the foreground lensing star and its exoplanet bend light of the source star. EPOCh reused the sequence from the HRIV exoplanet transit observations in 2008 to obtain these data. A second campaign to observe MOA-2009-BLG-266 in early 2010 for parallax measurements was canceled in preparation for the Hartley 2 encounter.

### HRII Radiometric Cal #1 (Beta Hyi)

From 13 October to 24 October 2009, the HRII spectrometer imaged the star Beta Hyi to improve the radiometric calibration for that instrument.

### HRII Dark Subframe Test

On 20 November 2009, the HRII spectrometer acquired dark frames to further characterize the response for the subframe imaging modes (numbers 2 and 3).

### EPOCh Mars Obs

On 20-21 November 2009, EPOCh observed Mars for 24 hours with the HRIV CCD and the IR spectrometer, reusing the Earth sequence, to characterize it as an analog for extrasolar planets and look for methane. The observations comprised narrow band filter images (350-950 nanometers) and 2- to 5-micron infrared spectroscopy, over nearly a full Mars rotation. Observations were acquired once per hour with the filters centered on 350, 750 and 950 nanometers, whereas the 450-, 550-, 650-, and 850-nanometer data were taken every 15 minutes. Infrared spectral scans of Mars' disk were acquired twice per hour.

### HRII Lunar Flats/Radiometric Cal #1 and

### HRII Lunar Flats/Radiometric Cal #2

On 05 and 12 December 2009 as the spacecraft approached Earth, the IR spectrometer made north/south scans of the moon for radiometry and east/west scans along the slit for lunar flats and a radiometric calibration.

### HRII Lunar South Pole Radiometry

On 18 December 2009, about 10 days before the distant flyby of Earth the IR spectrometer made north/south scans of the lunar south pole for radiometric analysis.

### Distant Earth Flyby #2

Another distant flyby of Earth occurred 28 December 2009 at a geocentric distance of about 1,330,000 km.

### Standard Cruise Calibration

A full, standard cruise calibration for HRII, HRIV, and MRI was completed on 16 February 2010.

### HRII NoSave Flush Test

On 20 April 2010, tested an HRII sequence designed to reduce the amount of charge buildup that results in abnormally high signals in the first 1 to 4 images of a multi-frame IR exposure. The sequence consisted of flushing the IR detector before science imaging by alternating between saving frames of one exposure ID for science and not saving those from the next exposure (i.e., flush frames).

### HRII Radiometric Cal #2 (Beta Hyi)

From 03 May to 17 May 2010, the HRII spectrometer imaged the star Beta Hyi to further improve the radiometric calibration for that instrument.

### Earth Flyby #3

The final near flyby of Earth for the EPOXI mission occurred on 27 Jun 2010 at a geocentric distance of about 30,426 km.

### MRI Dosido Fast Slew Test

On 12 July 2010, the MRI Dosido fast slew sequence involved a test of the observing strategy planned from 8 days to one day before the Hartley 2 encounter that included periods during which the spacecraft attitude was maneuvered once per hour between the Earth downlink attitude and the comet viewing attitude. The spacecraft was slewed at a high rate between these two attitudes, and the Deep Space Network was required to lockup on the downlink quickly every hour. MRI images of dark space were taken each hour at the comet viewing attitude as they will be during the actual encounter sequence in early November 2010.

## DIXI/Hartley 2

Start Time : 2010-09-03 (DOY 246)

Stop Time : 2010-11-28 (DOY 332)

### HRIV PSF Calibration

On 03 September 2010, the HRIV CCD imaged Canopus to monitor the point spread functions (PSF) for that instrument. Analysis of HRIV calibration data since 2005 and EPOCh stellar observations in 2008 indicate the PSFs can change over time.

### Approach Imaging: E-60 to E-50 Days (VIS only)

The MRI and HRIV visible instruments began imaging 103P/Hartley 2 every six hours on 05 September 2010, 60 days before the encounter (E-60 days) encounter and continued for 10 days. However, due to thermal issues with a traveling wave tube amplifier the entire HRI system including the HRIV CCD was turned off on 06 September until 20 September. MRI continued its imaging sequence as planned through E-50 days. The comet was observed for 16 hours at a time with 8 hours devoted to downlinking the data.

### Approach Imaging: E-50 to E-40 Days (VIS only)

From 15 to 25 September 2010, the imaging cadence for MRI increased to every two hours. On 20 September the HRIV CCD was turned on, and it begin imaging 103P/Hartley 2 once every two hours for the duration of the period. The comet was observed for 16 hours at a time with 8 hours devoted to downlinking the data.

### HRII Spectrometer Cooldown

From 25 to 01 October 2010, no data were acquired except for the Pre-Encounter Standard Cruise Calibration (below). During this period, the IR spectrometer was allowed to thermally cool before beginning spectral scans of Hartley 2 on 01 October.

### Pre-Encounter Standard Cruise Calibration

A full, standard cruise calibration for HRII, HRIV, and MRI was performed on 28-29 September 2010.

### Approach Imaging: E-34 to E-8 Days (Start HRII)

From 01 to 28 October 2010, MRI and HRIV imaged 103P/Hartley 2 about every 5 minutes while the HRII spectrometer scanned for outbursts once every 30 minutes. The instruments observed the comet for 16 hours per day allowing for 8 hours of downlinking; the same sequence was repeated daily yielding one full cycle per day. Data from the 6th cycle on 06 October 2010 (DOY 279) were never downlinked because of a pointing problem with the Deep Space Network. Those data had to be erased on board the spacecraft to make room for the next daily cycle and could not be recovered.

### Approach Imaging: E-8 Days to E-18 Hours

From 28 October to 03 November 2010, the MRI and HRIV imaged 103P/Hartley 2 continuously and HRII scanned the comet about every hour for 16 hours per day allowing for 8 hours of downlinking punctuated by hourly maneuvers, called dosido, to observe the comet. During this imaging phase there was only a single downlink of all images with zero margin; thus some images were occasionally lost as expected. The first cycle (DOY 300/301) was abbreviated such that the first comet-imaging session was only 6-hours long, followed by the standard 8-hour dosido.

### Encounter Imaging: E-18 Hours to E+2 Days, including

### Flyby and Closest Approach

From 03 to 06 November 2010, the HRII, HRIV, and MRI performed high resolution encounter imaging of 103P/Hartley2. The HRIV and MRI instruments began sampling about once every two hours until one hour before encounter when the cadence changed to once every 15 minutes. At E-30 minutes the VIS instruments began continuously imaging of the comet in clear and color filters. At E+30 minutes simultaneous observing and data playback began with samples being taken every 30 minutes.

During the encounter imaging period, HRII infrared spectral scans occurred every two hours until four hours prior to encounter when the cadence increased to hourly then more frequently one hour before closest approach. Near-continuous scans of the coma and nucleus were acquired during the 20 minutes about closest approach. Nadir imaging was performed at closest approach.

### Departure Imaging: E+2 to E+12 Days

From 06 to 16 November 2010, the HRII spectrometer scanned 103P/Hartley 2 every 15 minutes while the MRI CCD imaged the comet every 2 minutes and HRIV once every hour.

### Departure Imaging: E+12 to E+21 Days

From 16 to 26 November 2010, the HRII spectrometer scanned 103P/Hartley 2 every 30 minutes, and HRIV performed rotation sampling at the same cadence. MRI performed rotation sampling every 30 minutes and imaging using gas filters every two to four hours.

### Post-Encounter Standard Cruise Calibration

A full post-encounter standard cruise calibration for HRII, HRIV, and MRI was performed on 27-28 November 2010. The sequence was nearly identical to the pre-encounter calibration performed in September.

## Cruise 3

Start Time : 2010-11-29 (DOY 333)

Stop Time : 2013-09-20 (DOY 263)

### HRII 50-Frame Extended Linearity Calibration

From 05 to 06 February 2011, the HRII spectrometer took 50 dark frames for a set of integration times and for each imaging mode to gather enough data to perform a thorough analysis of the linearity of each active pixel in the IR focal plane array.

### Comet C/Garradd (2009 P1)

From 20 February through 09 April 2012, the HRIV and MRI instruments acquired VIS images of comet C/Garradd (2009 P1). During this window, the HRII spectrometer acquired scans of the comet during two separate observing campaigns, one on 26 March and the other spanning 02-03 April.

### Comet C/ISON (2012 S1)

From 17 January through 06 March 2013, the MRI instrument acquired VIS images of comet C/ISON (2012 S1). During this window, the HRII spectrometer acquired scans of the comet during one 36-hour observing campaign on 16-17 February 2013.

### End of Mission

On 20 September 2013, NASA announced the end of operations for the Deep Impact flyby spacecraft, after trying unsuccessfully since 14 August 2013 to regain contact with the spacecraft.

# Recommended Reading

## Relevant Publications from Deep Impact

Information about the design of the Deep Impact mission, scientific objectives, and instrumentation that are relevant to EPOXI are found in the work by A'Hearn, et al. (2005b) Blume (2005), Hampton, et al. (2005), Klaasen, et al. (2005), Mastrodemos, et al. (2005), Thomas, et al. (2005), and Yeomans, et al. (2005). The calibration of the Deep Impact instruments and the resulting data processing pipeline are explained by Klaasen, et al. (2008) and Klaasen, et al. (2005). Image restoration to correct for the HRI defocus is described by Lindler, et al. (2007).

Initial results from the encounter at comet 9P/Tempel 1 in July 2005 are described by A'Hearn, et al. (2005a). A summary of the results from Deep Impact are presented by A'Hearn and Combi (2007a), A'Hearn and Combi (2007b), and A'Hearn and Combi (2007d). Three volumes of Icarus are dedicated to results from Deep Impact. Please see Combi and A'Hearn (2007a), Combi and A'Hearn, (2007b), and A'Hearn and Combi (2007c). Belton, et al. (2011) discuss how the central horizontal gap of the VIS CCDs was handled for aperture photometry of 9P/Tempel 1.

## EPOXI

For a brief overview of the EPOXI mission including the EPOCh and DIXI investigation, see A'Hearn (2008), A'Hearn, et al. (2008), Deming, et al. (2007), Deming, et al. (2008a), and Deming, et al. (2008b).

Initial results from the EPOCh investigation are presented by Ballard, et al. (2008), Ballard, et al. (2009a), Christiansen, et al. (2008), and Hewagama, et al. (2008).

Detailed results based on the EPOCh observations of transiting planet systems are presented in conference proceedings by Christiansen, et al. (2009), Ballard, et al. (2009b), and Ballard, et al. (2010) as well as in publications by Ballard, et al. (2010), Christiansen, et al. (2010), Christiansen, et al. (2011), and Ballard, et al. (2011).

Detailed results based on the EPOCh Earth observations are presented in publications by Cowen, et al. (2009), Livengood, et al. (2011) and Crow, et al. (2011), and in conference proceedings by Robinson, et al. (2009).

Rieber and Sharrow, (2009) discuss the design approach for EPOCh exoplanet transit imaging as well as the pointing stability of the flyby spacecraft.

Initial results from the DIXI investigation are presented in A'Hearn, et al. (2011). Sunshine, et al. (2009) discuss the variability of OH/H2O on the lunar surface based on HRII calibration data. Klaasen, et al. (2013) describe the changes implemented to the EPOXI pipeline for processing Hartley 2 data. Restoration of Hartley 2 flyby image to correct for the HRI defocus is described by Lindler, et al. (2013). The spin state and shape model of Hartley 2 are described by Belton, et al. (2013) and Thomas, et al. (2013).

Initial results from the IR and VIS observations of comet C/Garradd (2009 P1) are presented in Farnham, et al. (2013) and Feaga, et al. (2013).

# Mission Data

The following mission-related data are or will be archived at the PDS:

* Raw HRII, HRIV, and MRI science and calibration observations acquired throughout the mission,
* Calibrated EPOCh exoplanet transit observations, including exoplanet microlensing event MOA-2009-BLG-266, in units of radiance (HRIV only),
* Calibrated EPOCH Earth observations in units of radiance (HRII and HRIV) and I/F (HRIV),
* Calibrated EPOCH Mars observations in units of radiance (HRII and HRIV) and I/F (HRIV),
* Raw and calibrated science observations acquired during the approach to and encounter with comet Hartley 2 (HRII, HRIV, and MRI),
* SPICE data, including 5-Hz telemetry from the Attitude Determination and Control System (ADCS) as a CK kernel, and
* Higher-level products, including light curves for EPOCh stellar transit (exoplanet) targets, a shape model of Hartley 2, and surface temperature maps for Hartley 2.

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