It Was Twenty Years Ago Today:
The Clementine Mission and Gene Shoemaker

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Shoemaker Lecture
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Lunar Exploration

Post-Apollo, pre-Clementine

No American lunar missions after Apollo 17, December 1972

Lunar Polar Orbiter - JSC proposal and subsequent efforts

Lunar Geoscience Observer Workshops 1985-1988

SEI and Lunar Observer (cost > $1B)

NASA Code X and Lunar Scout program
The Clementine Concept

SDI and Brilliant Pebbles
  Multiple, small satellite interceptors; 3-axis stabilized, self-propelled spacecraft
  Adapt mass produced COTS tactical sensors for space use

White House Space Council and Synthesis Group
  Concern that Bush-41 SEI was floundering; needed small quick lunar mission to get data for jump start

Truly letter (1989) - committed NASA to cooperate with DoD on a deep space sensor test

NRL and Livermore
An international effort (CNES)
The Mission

NASA selects Science Team; they devise operational plan and select filters for imaging
Launch January 25, 1994 from Vandenberg AFB on surplus Titan II ICBM
Mission Control: The “Batcave”, an old National Guard armory
Phasing loops, near-loss of mission after translunar injection
Lunar orbit (Feb. 19, 1994) for 71 days
Lunar orbital phasing in late March and bistatic experiment
Moon departure (May 3, 1994) and spacecraft loss
Clementine data

Images
  Almost 2 million mapping images ~100-200 m/pixel in eleven wavelengths in UV, visible and near-IR
  Selected high-resolution (~20 m/pixel) broadband and thermal IR (8.75 m) images

Altimetry
  Laser ranging from +/- 75 degrees latitude
  Stereo images of polar regions

Gravity
  Combine Clementine tracking data with previous global gravity maps. Degree 70th SH field

Star Tracker images and horizon glow
Bistatic experiment
  Improvised RF experiment to search for polar ice
Science from Clementine

Global multispectral map
  Mineralogy
  Fe and Ti mapping
Polar environment and lighting
  Observed 71 days from northern summer solstice to near-equinox
Global topographic and gravity maps
  Multi-ring basins, SPA
  Basin mascons; crustal thickness
Bistatic RF experiment and lunar ice controversy
Clementine Science

Mineralogy and Petrology

False color composite shows major color boundaries, pyroxene composition, mare Ti content

Five-point spectra of UVVIS permit identification of rock types

Central peak compositions show global heterogeneity of crust

First global inventory of mare basalt types (far side)

SPA basin floor is major mafic compositional anomaly on far side
Method of Lucey et al. (1995) was a major breakthrough in elemental mapping.

Full UVVIS resolution images of lunar Fe and Ti concentration.

Both relations break down at extreme compositions (high end for Fe, low end for Ti).

Results show major compositional provinces in both highlands and maria.

SPA basin floor, ancient maria are mafic.
Clementine Science

Global topography and gravity

LIDAR produced useful ranging data between 75 N and S latitudes
Binned into global ~100 km topographic map
Polar DEM from redundant stereo coverage
All altimetry combined into UCLN 2005 global map
Gravity and crustal thickness model (GLGM-1)
Shows extremes of relief on the Moon (-8 to +8 km)
Preservation of South Pole-Aitken basin relief (12 km)
Very thin crust under major basin floors (Orientale, Crisium)
Clementine Science

*Multi-ring basins*

Full topographic extent of South Pole-Aitken basin revealed

Role of SPA in crustal evolution and cratering history

New clarity to geologic relations of some basins (e.g., Schrödinger)

Old, degraded basin inventory

Some verified (e.g., Mendel-Rydberg), others disproved (e.g., Al-Khwarizmi-King)

Crustal thinning beneath some basin floors

Mantle within a few km of surface under Orientale, Crisium floor
Clementine Science

The Poles of the Moon

First systematic look at polar topography and morphology over partial season
Identification of large amounts of permanently shadowed terrain
Identification of extended sunlit areas (up to 75% daylight at south in winter; 100% daylight at north in summer)

Inspired the attempt to conduct a bistatic experiment
Data obtained for four passes
Southern results highest S/N;
One pass directly over pole (Shackleton crater), other over normal, sunlit highlands
Clementine Science

Bistatic experiment and lunar ice controversy

Stu Nozette conceived idea of using spacecraft transmitter as RF source for bistatic radar

Obtained good data, especially for south (northern perilune, so longer dwell time in south = better S/N)

High CPR directly over south pole (Shackleton) but not over adjacent control orbit

CPR peak symmetric about $\beta=0$; suggests CBOE and $\sim 1-2$ wt.% water ice content

Arecibo and Stanford radar groups questioned results; ten years of debate
Clementine: The Mission Legacy

Faster Better Cheaper - Myth and Reality
Mars Observer failure, Discovery program
Clementine cost ~$140 M, 22 months start to launch

Space-qualified 22 new technologies, including solid-state data recorder, Ni-H₂ batteries, low-impact release devices

NRC study concluded that small missions can significantly contribute to our knowledge
Lunar exploration legacy (Lunar Prospector, SMART-1, VSE, lunar ice)
Chang’E 2 and its significance: Clementine Reveidivus
Clementine and Gene Shoemaker

Involved pre-project and an early, enthusiastic supporter
Gene lent his enormous scientific and programmatic prestige to pudknocker project
Attempt to cancel Clementine before launch was averted
Missing Geographos segment was a big disappointment (but accomplished on NEAR)
Actively engaged in both planning and execution of the bistatic experiment and strongly supported the published interpretation of water ice
The Clementine Mission

*A Milestone in Space History*

Showed what could be achieved with FBC and small missions

Showed value of global (vs. regional), multi-variable surveys

Showed value of the Moon
  - Moon is complex and interesting
  - Moon contains the resources (sunlight and water) necessary to enable permanent human presence in space

Clementine may be “lost and gone forever” but it found the gold it was looking for.