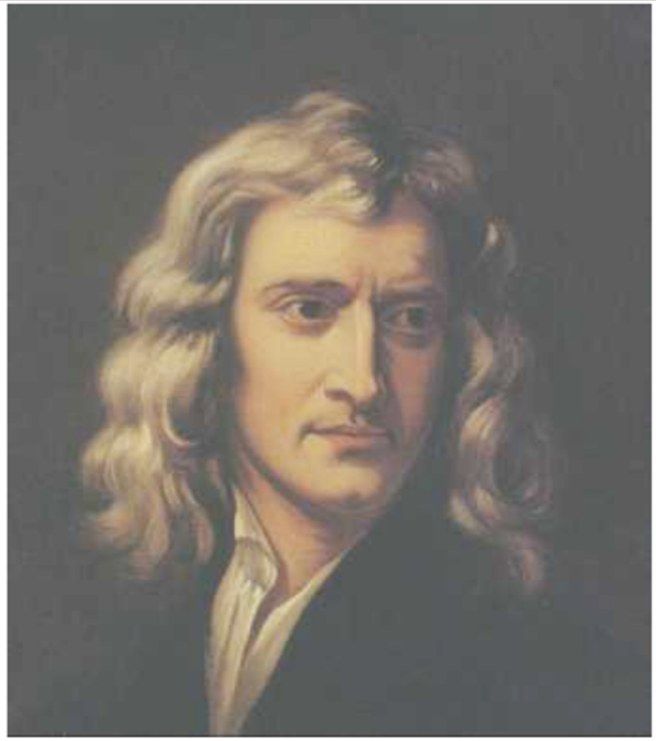
Shannon Lecture XXVI

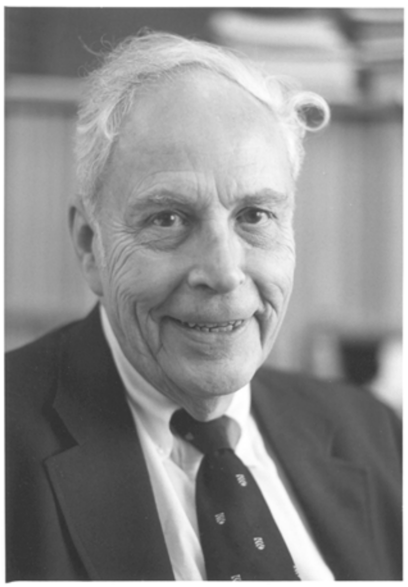
June 30, 2004
Chicago, Illinois



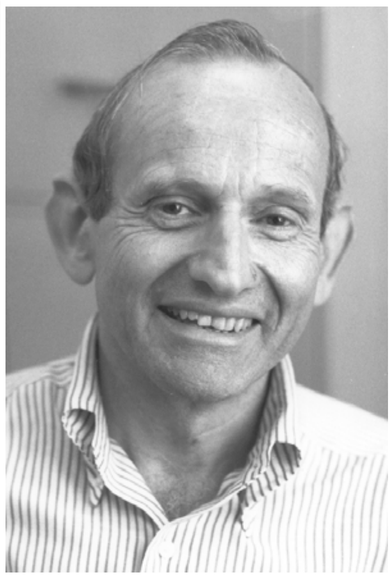
“If I have seen further it is by standing on the shoulders of giants.”

“If I have seen further it is by standing on the shoulders of giants.”

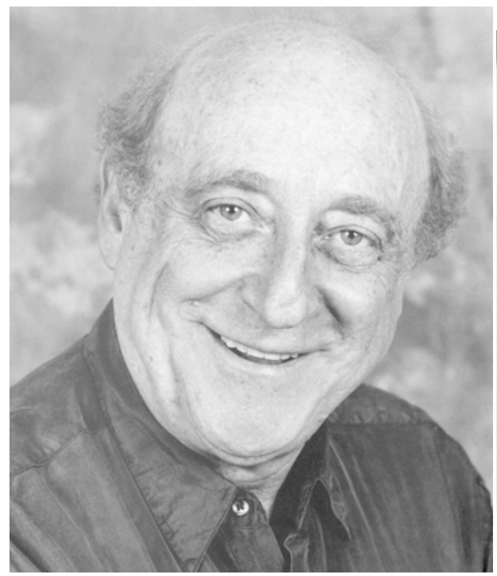
Four Giants



Hall



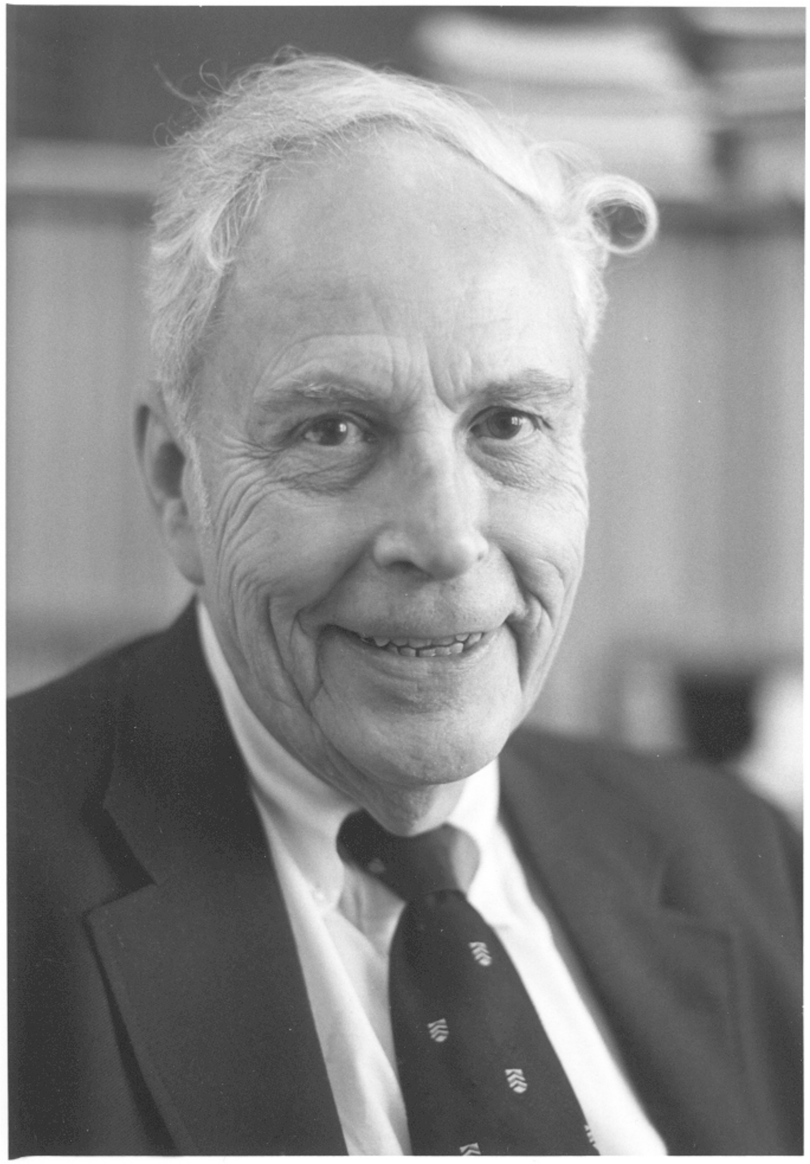
Posner



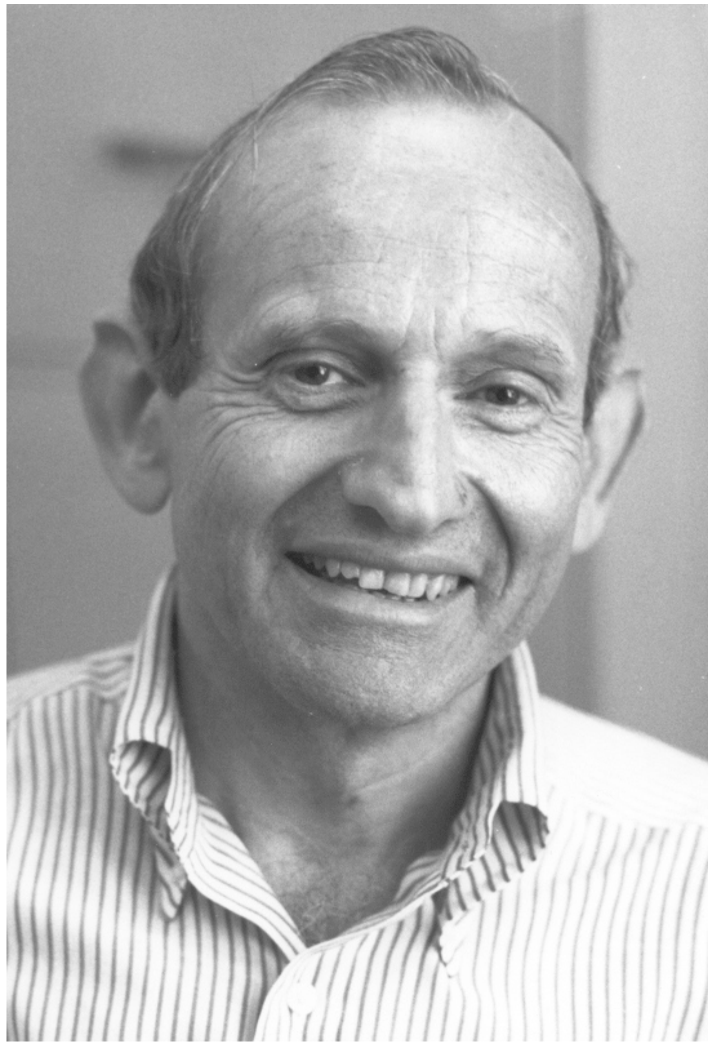
Solomon

Rumsey

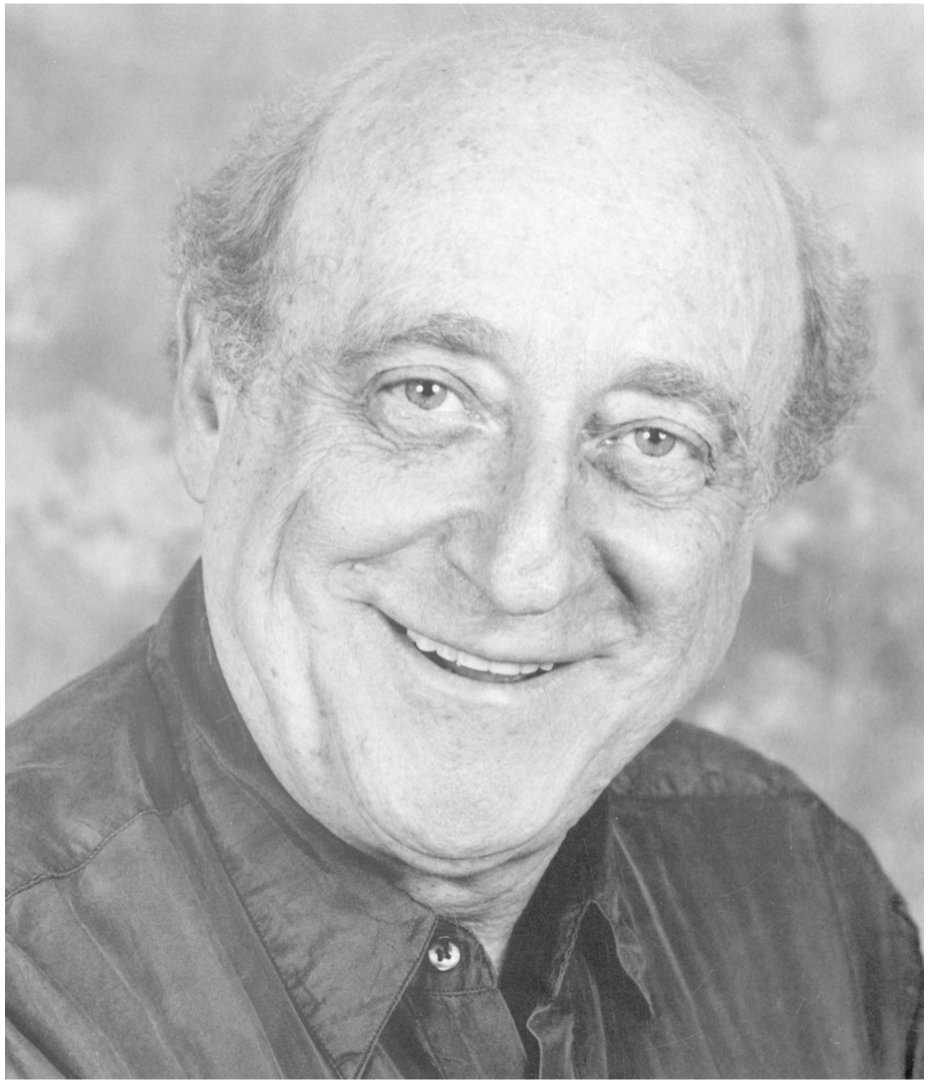
Marshall Hall, Jr.



Ed Posner



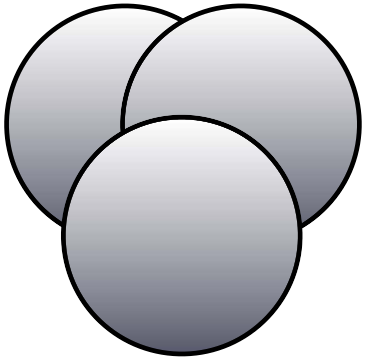
Gus Solomon



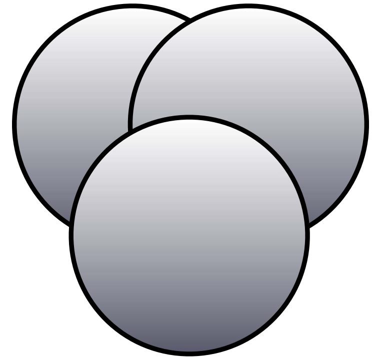
Howard Rumsey, Jr.

And Now For Something Completely Different.

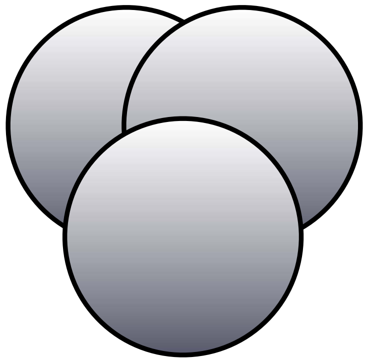
Summary



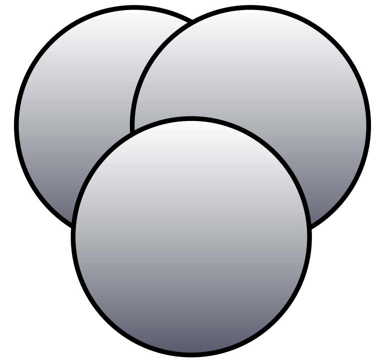
Summary



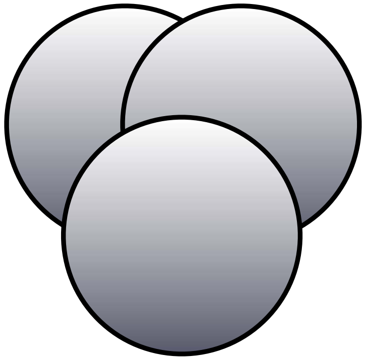
- Of the 35 patterns of three erasures:



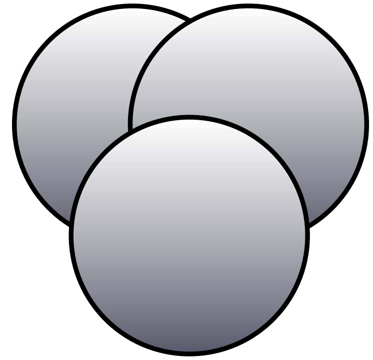
Summary



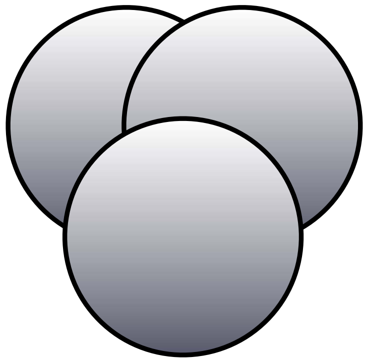
- Of the 35 patterns of three erasures:
  - 25 are correctable



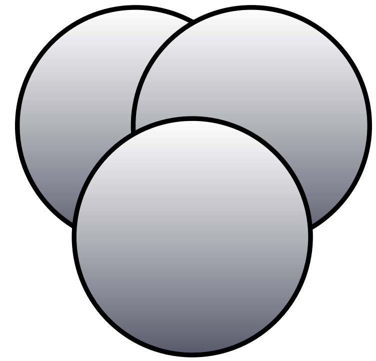
Summary



- Of the 35 patterns of three erasures:
  - 25 are correctable
  - 7 are uncorrectable (codewords)



Summary



- Of the 35 patterns of three erasures:
  - 25 are correctable
  - 7 are uncorrectable (codewords)
  - 3 are ambiguous (stopping sets, but not codewords)

In General:

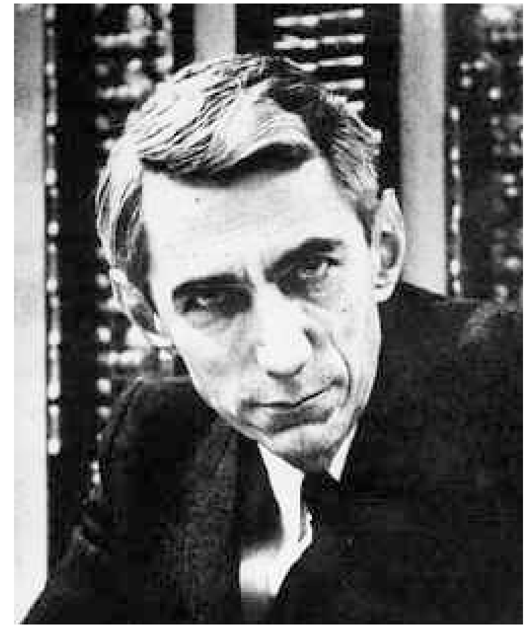
Theorem. *The number of weight* 3 **codewords** *in a Hamming code of length* $n = 2^m - 1$ *is*

$$\frac{1}{6}\left(4^m - 3 \cdot 2^m + 2\right) \sim \frac{1}{6} n^2 .$$

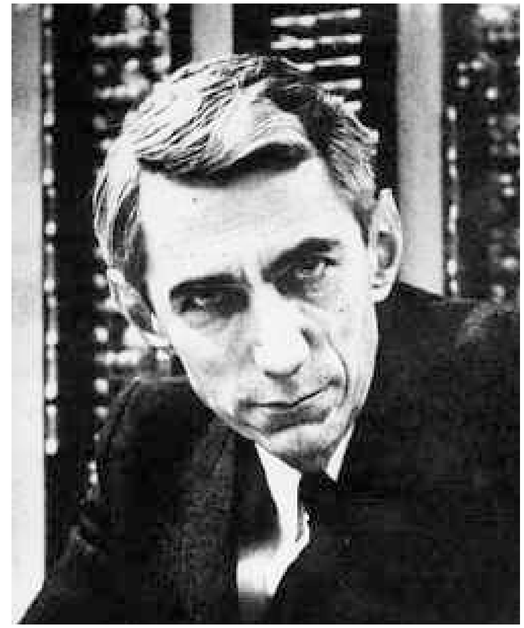
Theorem. *The number of weight* 3 **stopping sets** *in a Hamming code of length* $n = 2^m - 1$ *is*

$$\frac{1}{6}\left(5^m - 3^{m+1} + 2^{m+1}\right) \sim \frac{1}{6} n^{2.322} .$$

Feature Presentation



Feature Presentation



"The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point."

Feature Presentation

"The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point."

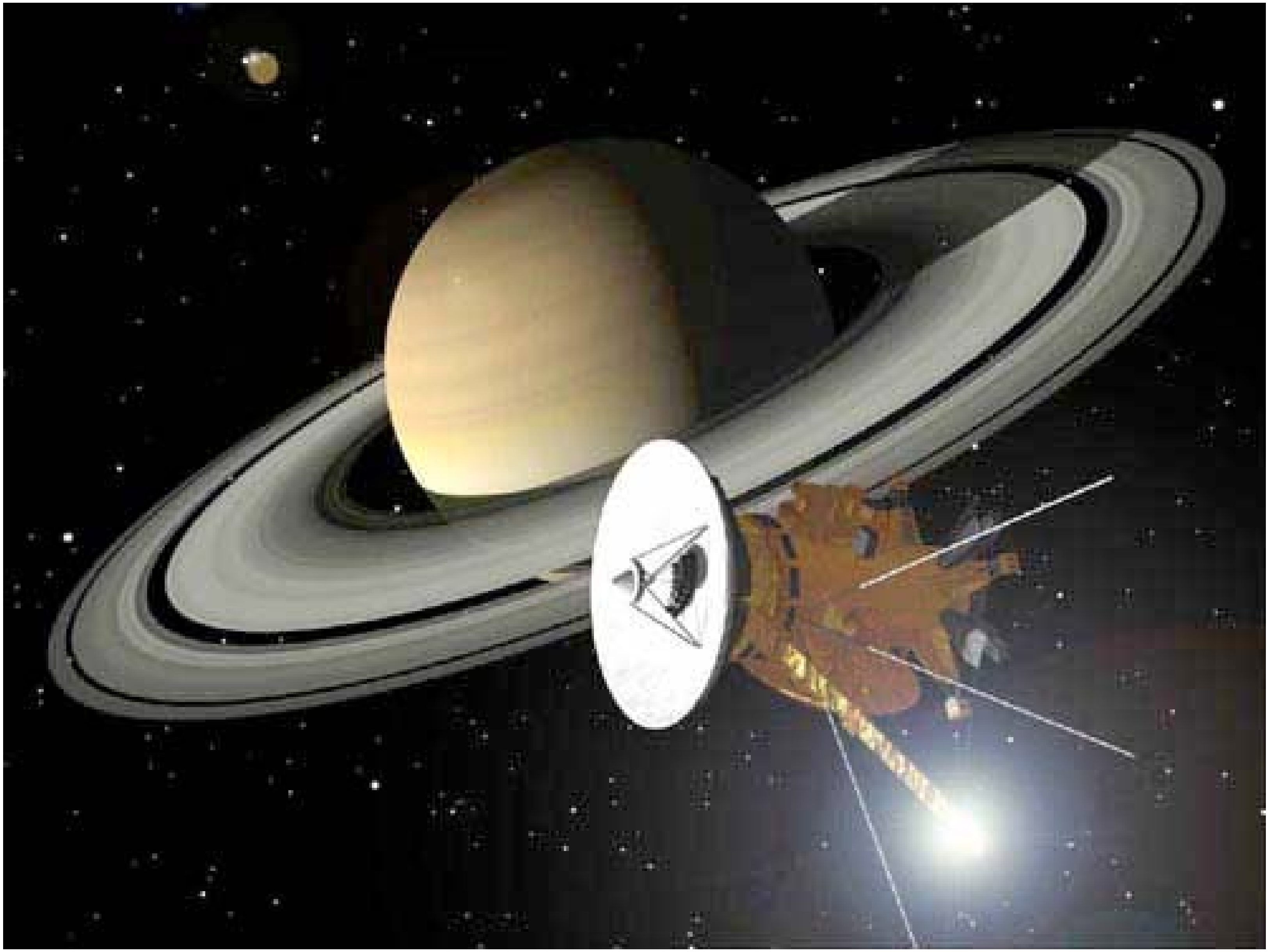
"Frequently the messages have *meaning*"

Feature Presentation

"The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point."

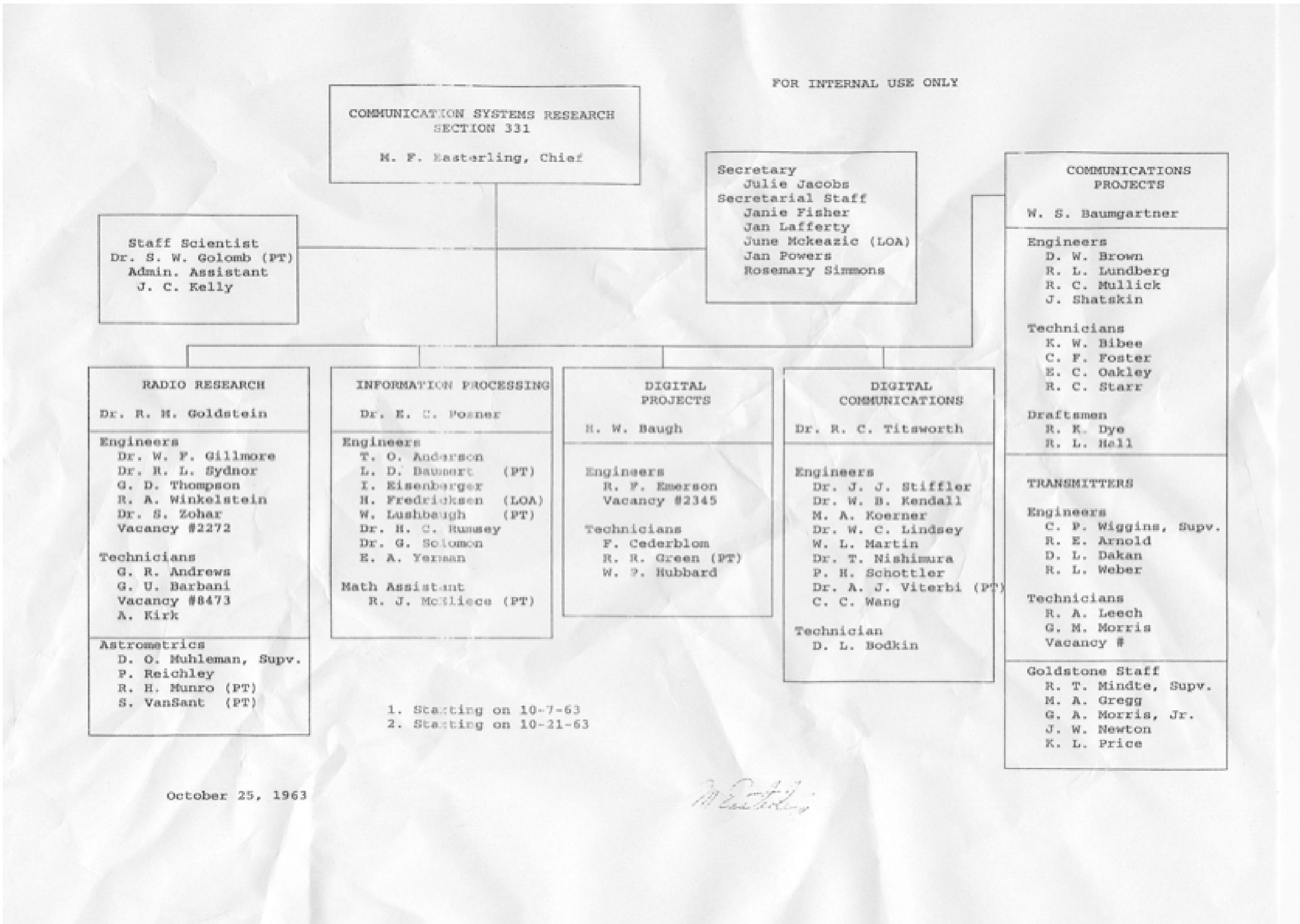
"Frequently the messages have *meaning*"

"... [which is] irrelevant to the engineering problem."



Jet Propulsion Laboratory
California Institute of Technology

Communications Systems Research Section 331, October 25, 1963



Jet Propulsion Laboratory
California Institute of Technology

Communications Systems Research Section 331, October 25, 1963

FOR INTERNAL USE ONLY

Staff Scientist
Dr. S. W. Golomb (PT)
Admin. Assistant
J. C. Kelly

Secretary
Julie Jacobs

Secretarial Staff
Janie Fisher
Jan Lafferty
June Mckeazic (LOA)
Jan Powers
Rosemary Simmons

RADIO RESEARCH
Dr. R. M. Goldstein

Engineers
- Dr. W. F. Gillmore
- Dr. R. L. Sydnor
- G. D. Thompson
- R. A. Winkelstein
- Dr. S. Zohar
- Vacancy #2272

Technicians
- G. R. Andrews
- G. U. Barbani
- Vacancy #8473
- A. Kirk

Astrometrics
- D. O. Muhleman, Supv.
- P. Reichley
- R. H. Munro (PT)
- S. VanSant (PT)

INFORMATION PROCESSING
Dr. E. C. Posner

Engineers
- T. O. Anderson
- L. D. Baumert (PT)
- I. Eisenberger
- H. Fredricksen (LOA)
- W. Lushbaugh (PT)
- Dr. H. C. Rumsey
- Dr. G. Solomon
- E. A. Yerman

Math Assistant
- R. J. McEliece (PT)

DIGITAL PROJECTS
N. W. Baugh

Engineers
- R. F. Emerson
- Vacancy #2345

Technicians
- F. Cederblom
- R. R. Green (PT)
- W. P. Hubbard

DIGITAL COMMUNICATIONS
Dr. R. C. Titsworth

Engineers
- Dr. J. J. Stiffler
- Dr. W. B. Kendall
- M. A. Koerner
- Dr. W. C. Lindsey
- W. L. Martin
- Dr. T. Nishimura
- P. H. Schottler
- Dr. A. J. Viterbi (PT)
- C. C. Wang

Technician
- D. L. Bodkin

COMMUNICATIONS PROJECTS
W. S. Baumgartner

Engineers
- D. W. Brown
- R. L. Lundberg
- R. C. Mullick
- J. Shatskin

Technicians
- K. W. Bibee
- C. F. Foster
- E. C. Oakley
- R. C. Starr

Draftsmen
- R. K. Dye
- R. L. Hall

TRANSMITTERS

Engineers
- C. P. Wiggins, Supv.
- R. E. Arnold
- D. L. Dakan
- R. L. Weber

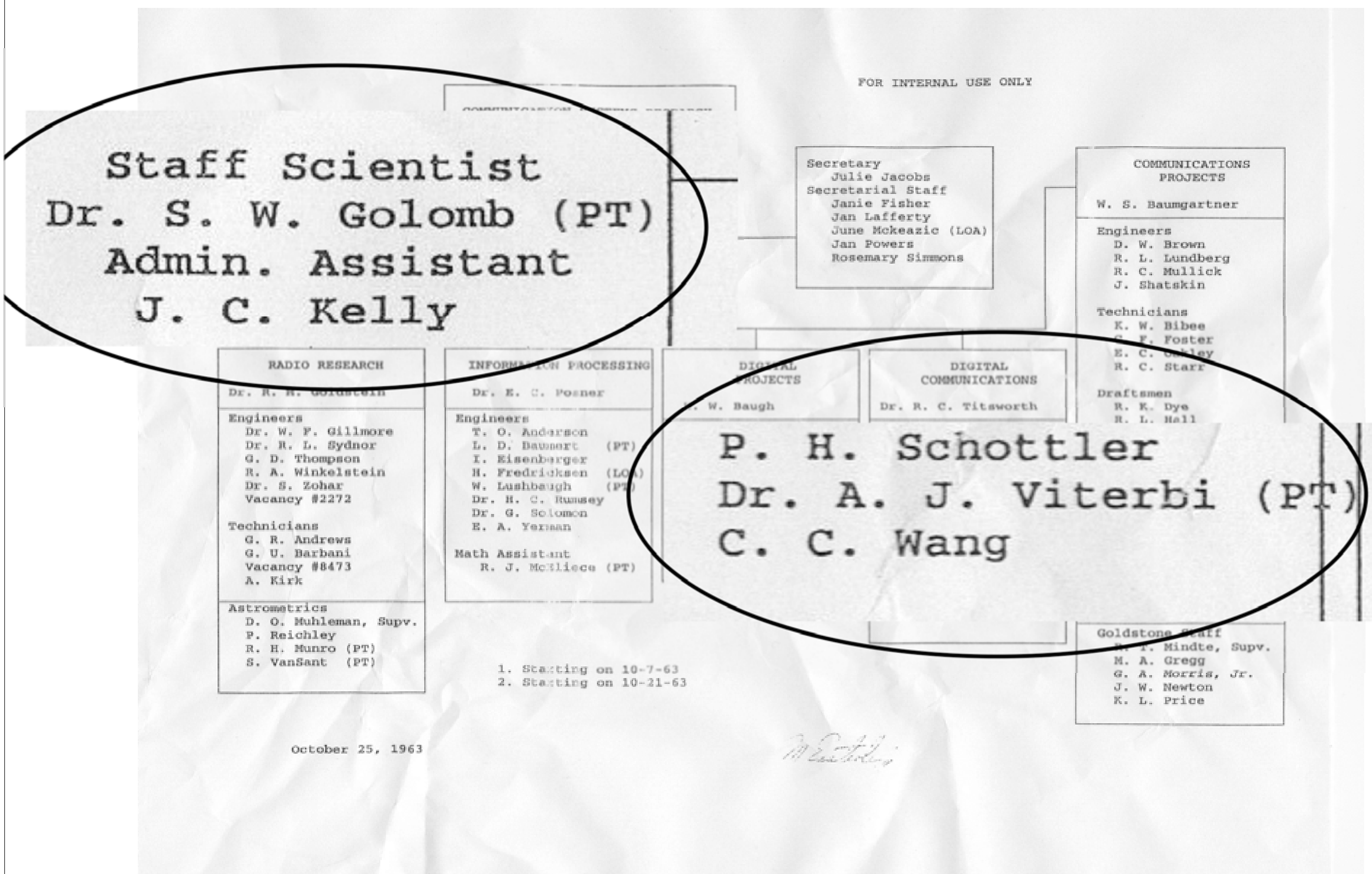
Technicians
- R. A. Leech
- G. M. Morris
- Vacancy #

Goldstone Staff
- R. T. Mindte, Supv.
- M. A. Gregg
- G. A. Morris, Jr.
- J. W. Newton
- K. L. Price

1. Starting on 10-7-63
2. Starting on 10-21-63

October 25, 1963

Communications Systems Research Section 331, October 25, 1963



Jet Propulsion Laboratory
California Institute of Technology

Communications Systems Research Section 331, October 25, 1963

NAL USE ONLY

Sta
Dr. S
Adm
J.

INFORMATION PROCESSING

Dr. E. C. Posner

Engineers
- T. O. Anderson
- L. D. Baumert (PT)
- I. Eisenberger
- H. Fredricksen (LOA)
- W. Lushbaugh (PT)
- Dr. H. C. Rumsey
- Dr. G. Solomon
- E. A. Yerman

Math Assistant
- R. J. McEliece (PT)

ff
c (LOA)
mons

COMMUNICATIONS PROJECTS

W. S. Baumgartner

Engineers
- D. W. Brown
- R. L. Lundberg
- R. C. Mullick
- J. Shatskin

Technicians
- K. W. Bibee
- F. Foster
- E. C.
- R. C. Starr

Draftsmen
- R. K. Dye
- R. L. Hall

DIGITAL COMMUNICATIONS

C. Titsworth

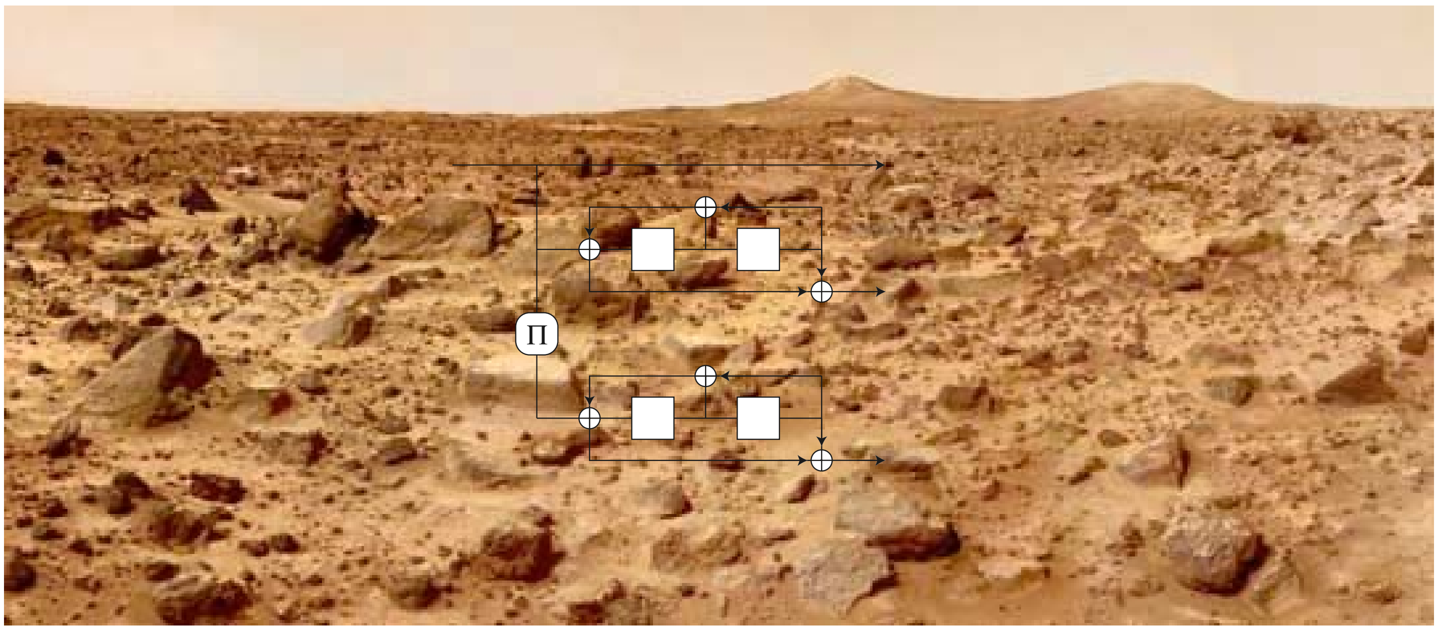
chottler
J. Viterbi (PT)
ang

Goldstone
- Mindte, Supv.
- M. A. Gregg
- G. A. Morris, Jr.
- J. W. Newton
- K. L. Price

Are There Turbo-Codes on Mars?

Robert J. McEliece
California Institute of Technology

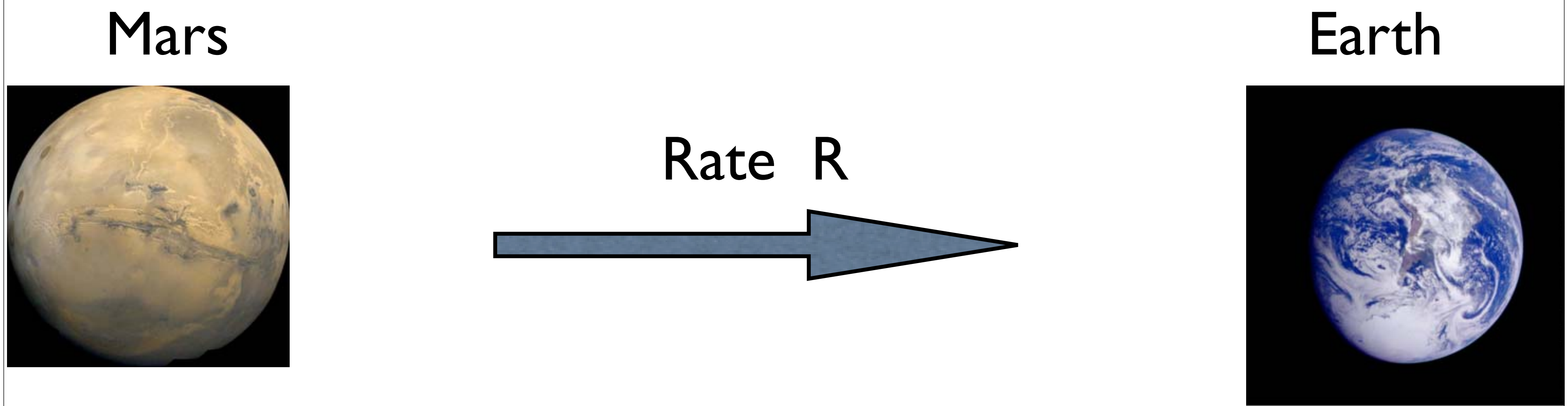
Are There Turbo-Codes on Mars?

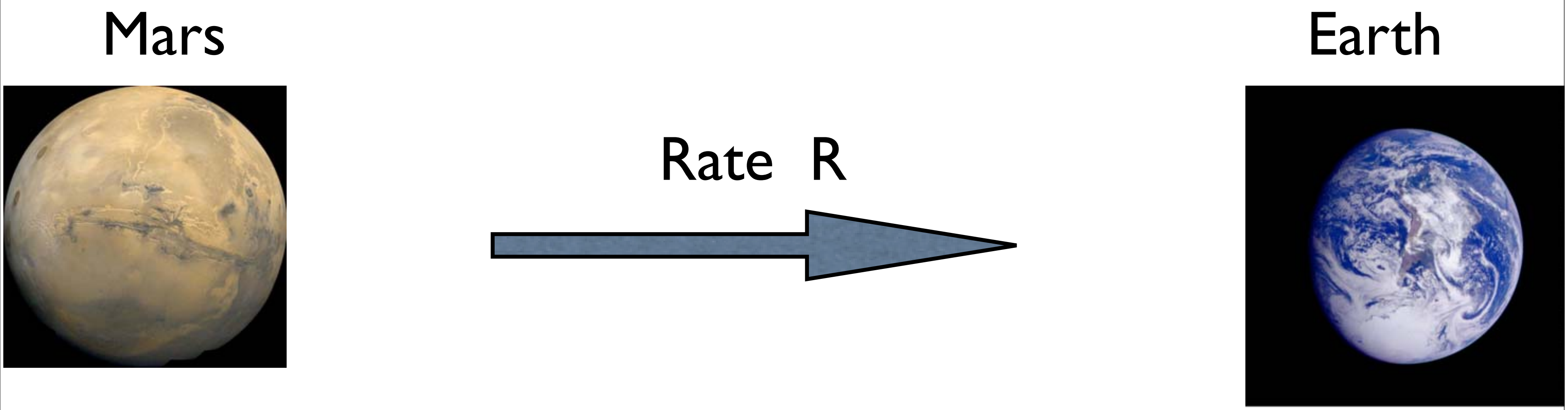


Robert J. McEliece
California Institute of Technology

Are There Turbo-Codes on Mars?

Robert J. McEliece
California Institute of Technology


Mars
Rate R
Earth



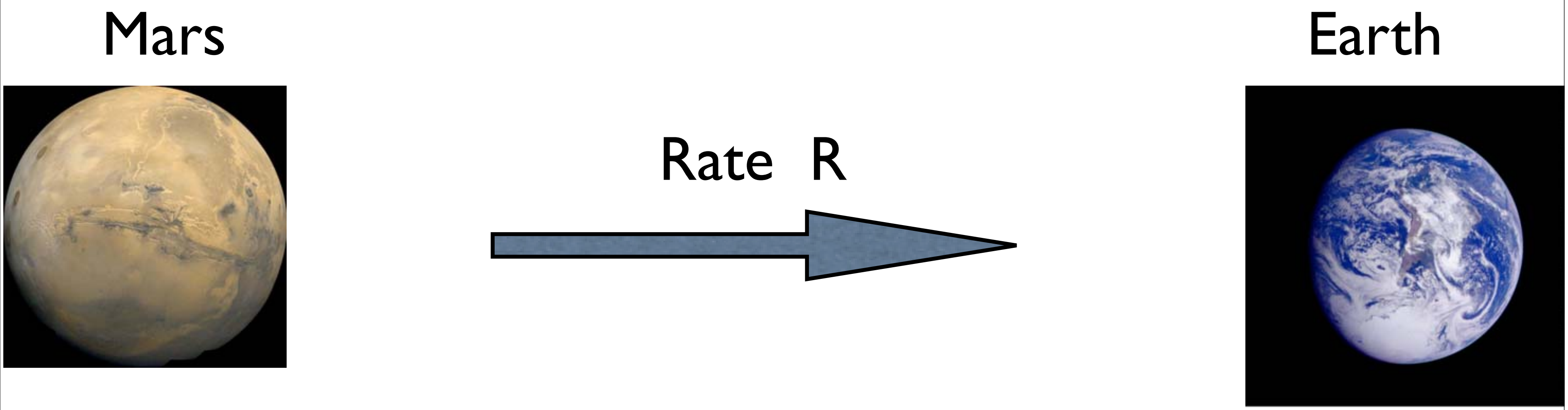
- The source, "Mars," produces a sequence of image bits. This is the message.

Mars

Rate R

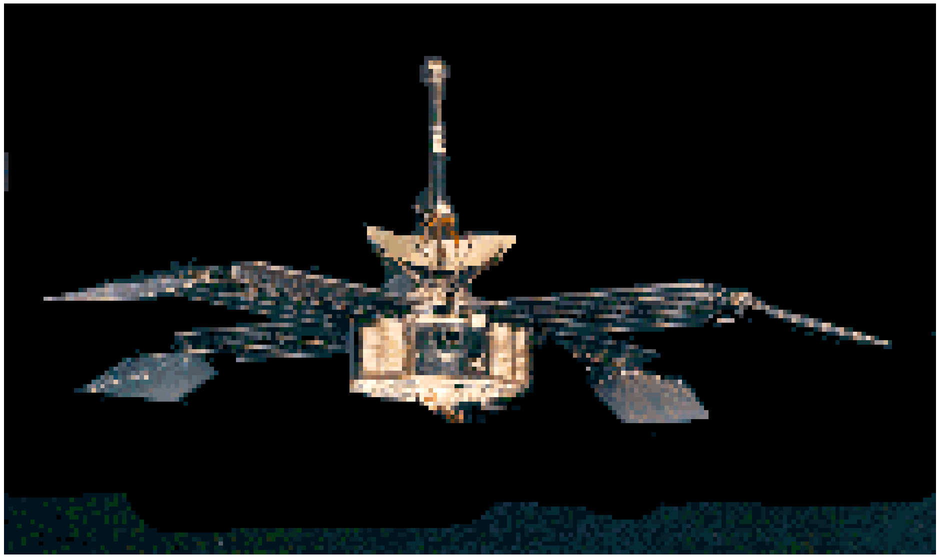
Earth

- The source, "Mars," produces a sequence of image bits. This is the message.
- The object is to communicate these i-bits reliably from Mars to Earth, as rapidly as possible.



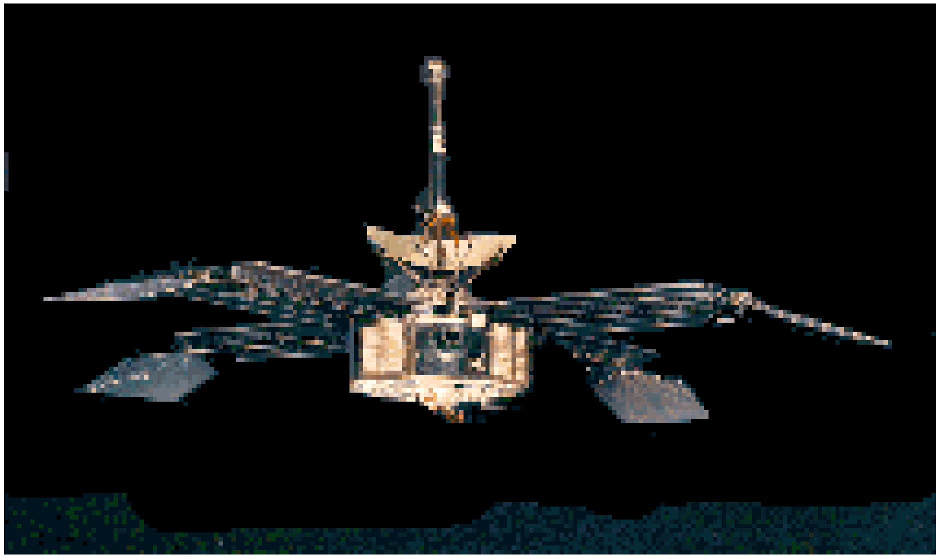
- The source, "Mars," produces a sequence of image bits. This is the message.
- The object is to communicate these i-bits reliably from Mars to Earth, as rapidly as possible.
- All compression algorithms being considered are (subjectively) noiseless.

Example: Mariner 4 (1965)



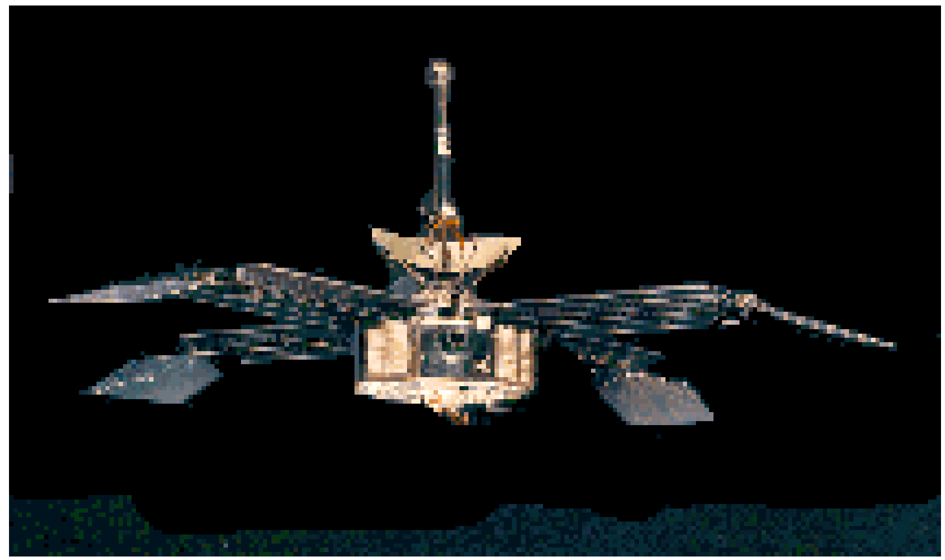
Example: Mariner 4 (1965)

- F = 2.3 GHz (S-band)



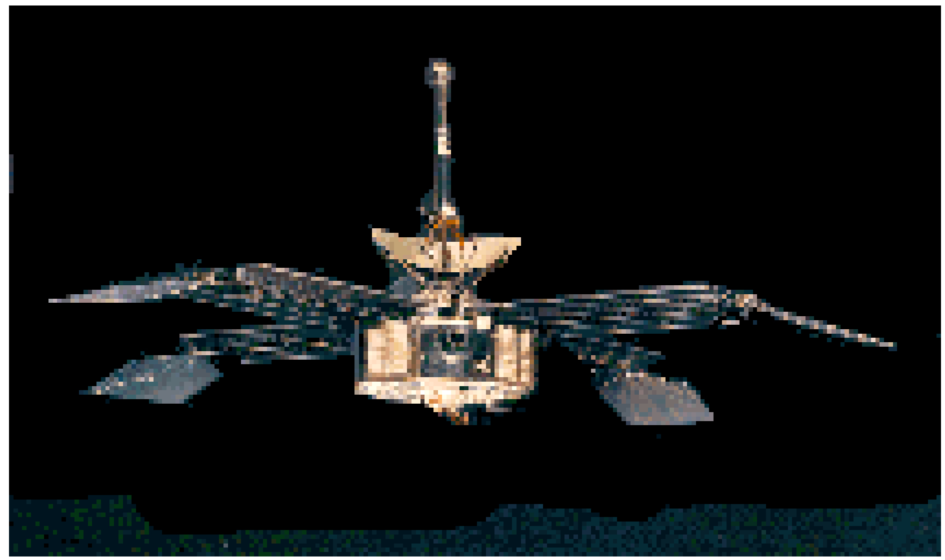
Example: Mariner 4 (1965)

- F = 2.3 GHz (S-band)
- R = 8.33 ibps



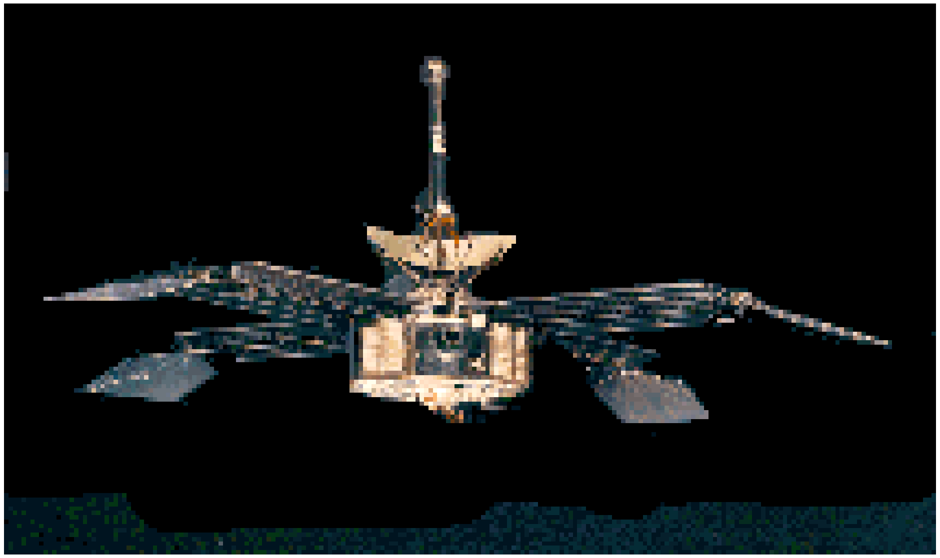
Example: Mariner 4 (1965)

- F = 2.3 GHz (S-band)
- R = 8.33 ibps
- No Coding (rep twice)



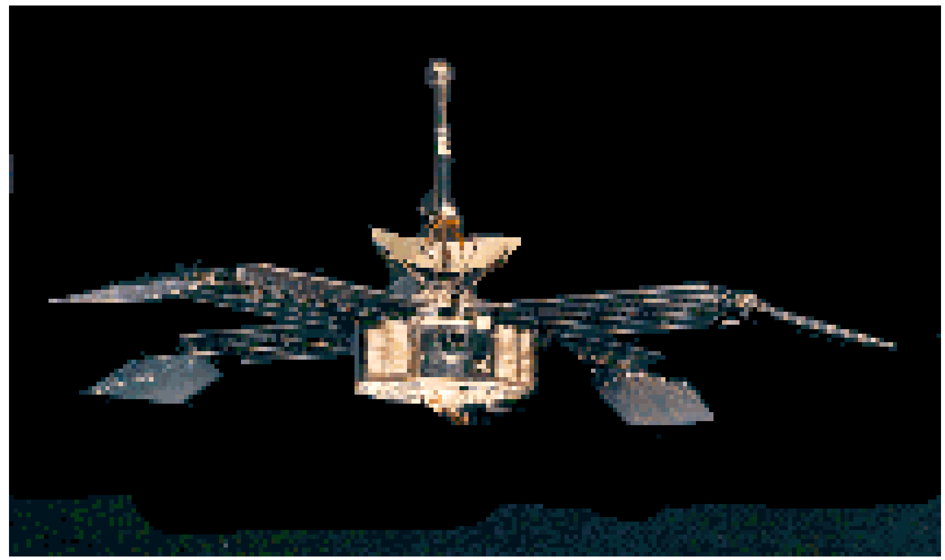
Example: Mariner 4 (1965)

- F = 2.3 GHz (S-band)
- R = 8.33 ibps
- No Coding (rep twice)
- No Compression



Example: Mariner 4 (1965)

- F = 2.3 GHz (S-band)
- R = 8.33 ibps
- No Coding (rep twice)
- No Compression



This is our baseline system.

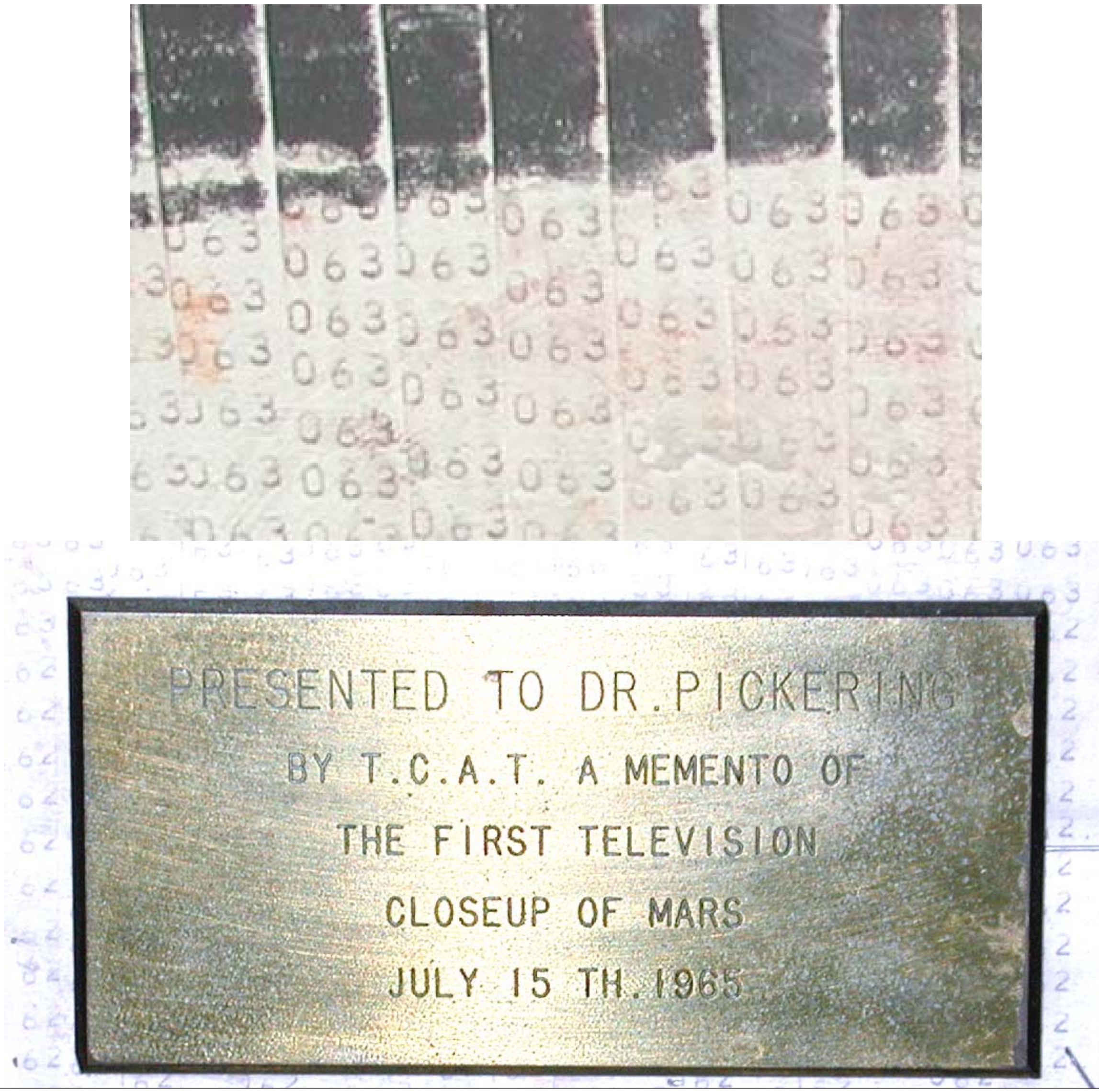
Mariner 4

The First Close-Up of Mars

First close-up image of Mars, before and after image processing

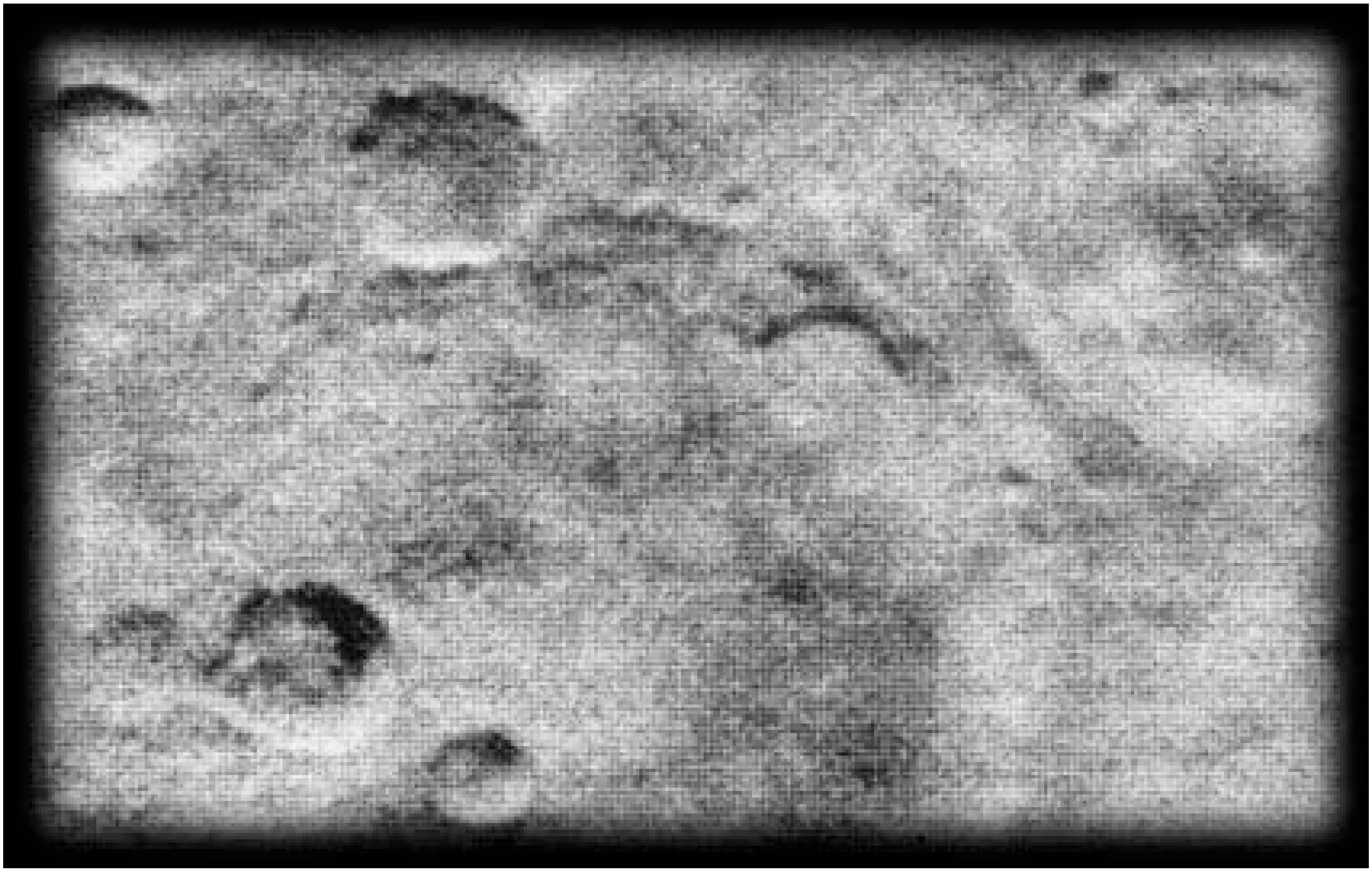
Mariner 4

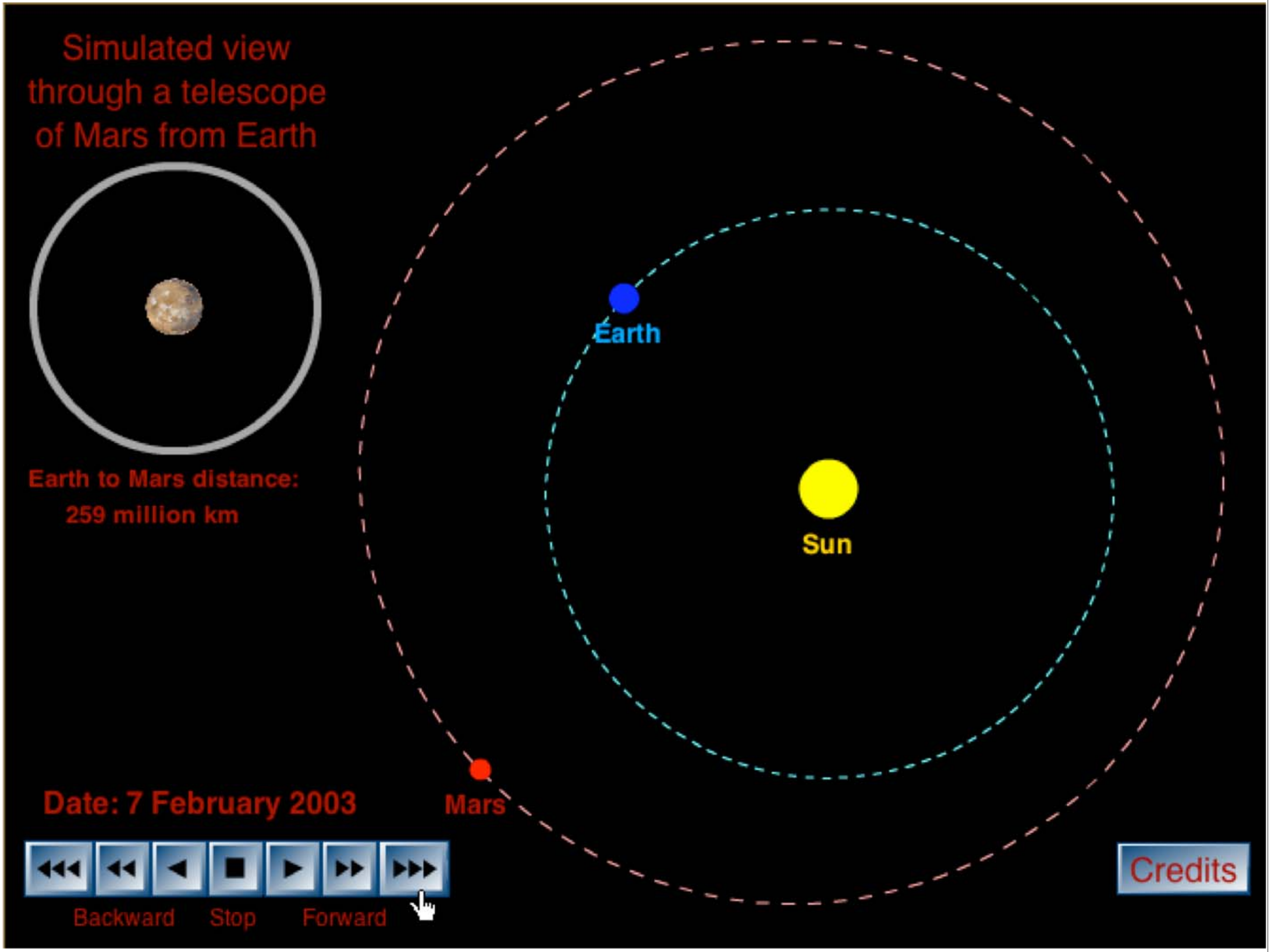
A Memento



Mariner 4

Another Mariner 4 Picture




Simulated view
through a telescope
of Mars from Earth
Earth to Mars distance:
259 million km
Earth
Sun
Mars
Date: 7 February 2003
Backward
Stop
Forward
Credits

Mars

Normalized Rate R*

Earth

Mars

Normalized Rate R*

Earth

- We normalize the data rate R to R*, the rate in i-bits/sec @ D = 215 Gm (the Mariner 4 distance).

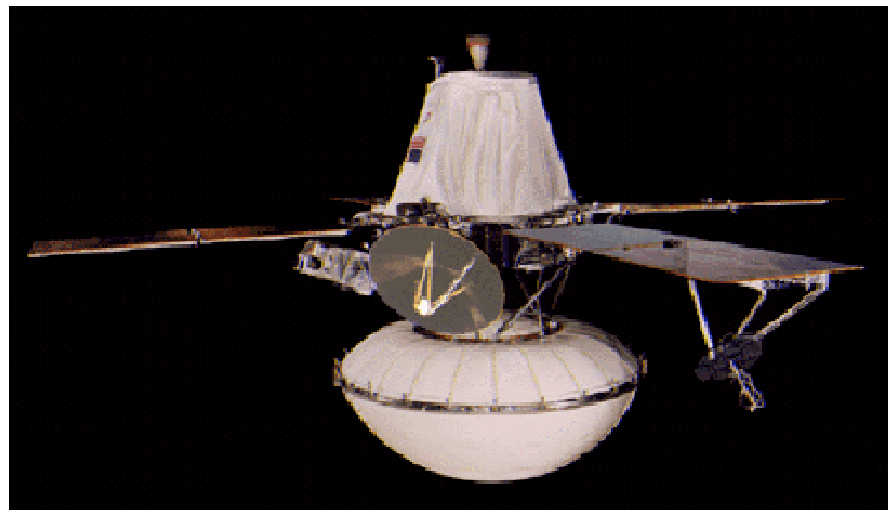
Mars

Normalized Rate R*

Earth

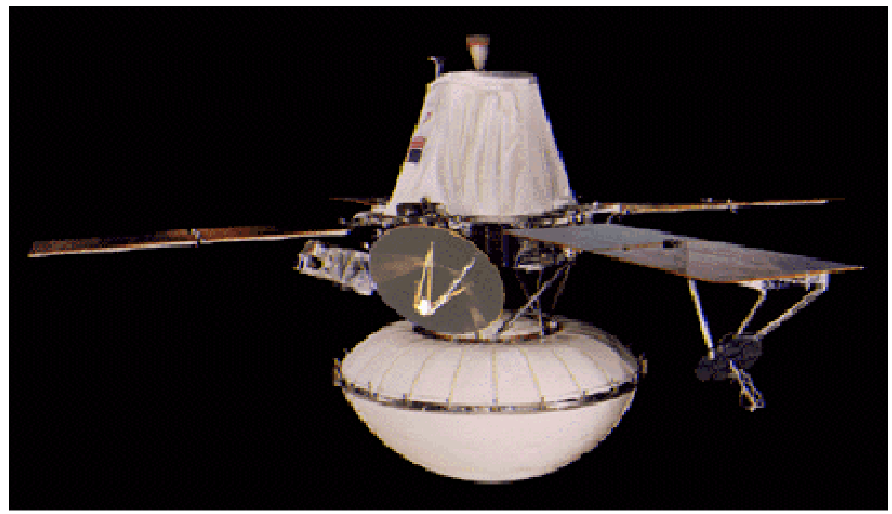
- We normalize the data rate R to R*, the rate in i-bits/sec @ D = 215 Gm (the Mariner 4 distance).
- Example: R = 256 bps @ D = 100 Gm with 2:1 compression is equivalent to
  $R^* = 256 \times (100/215)^2 \times 2 = 111$ ibps

Viking Mars Orbiters/ Landers (1976)



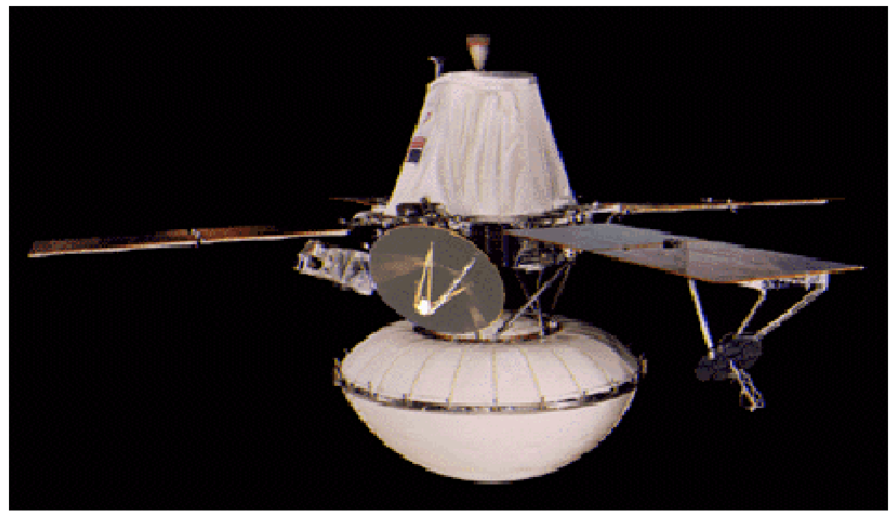
Viking Mars Orbiters/ Landers (1976)

- F = 2.3 GHz (S-band)



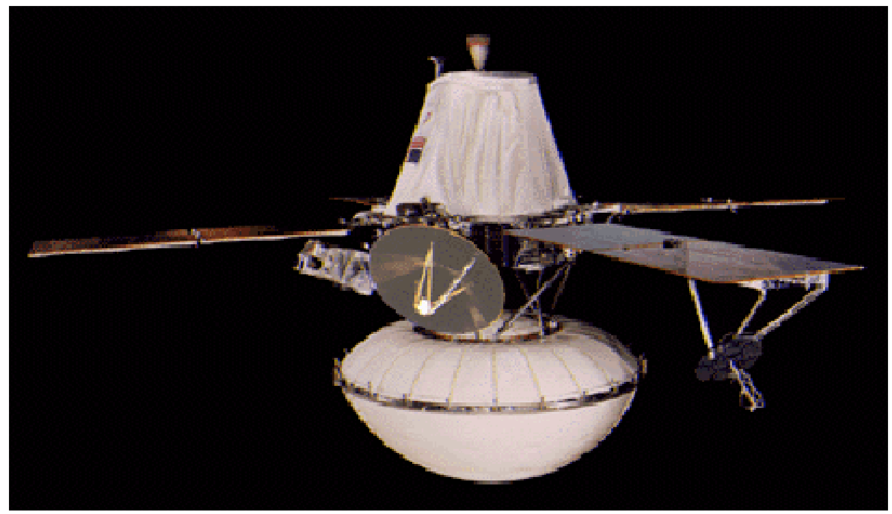
Viking Mars Orbiters/ Landers (1976)

- F = 2.3 GHz (S-band)
- R* = 3K ibps



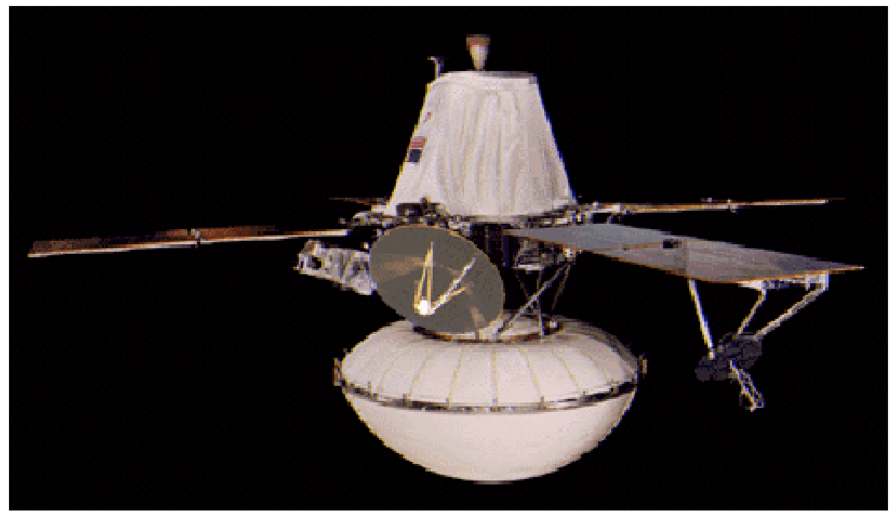
Viking Mars Orbiters/ Landers (1976)

- F = 2.3 GHz (S-band)
- R* = 3K ibps
- (32,6) Biorthogonal Code

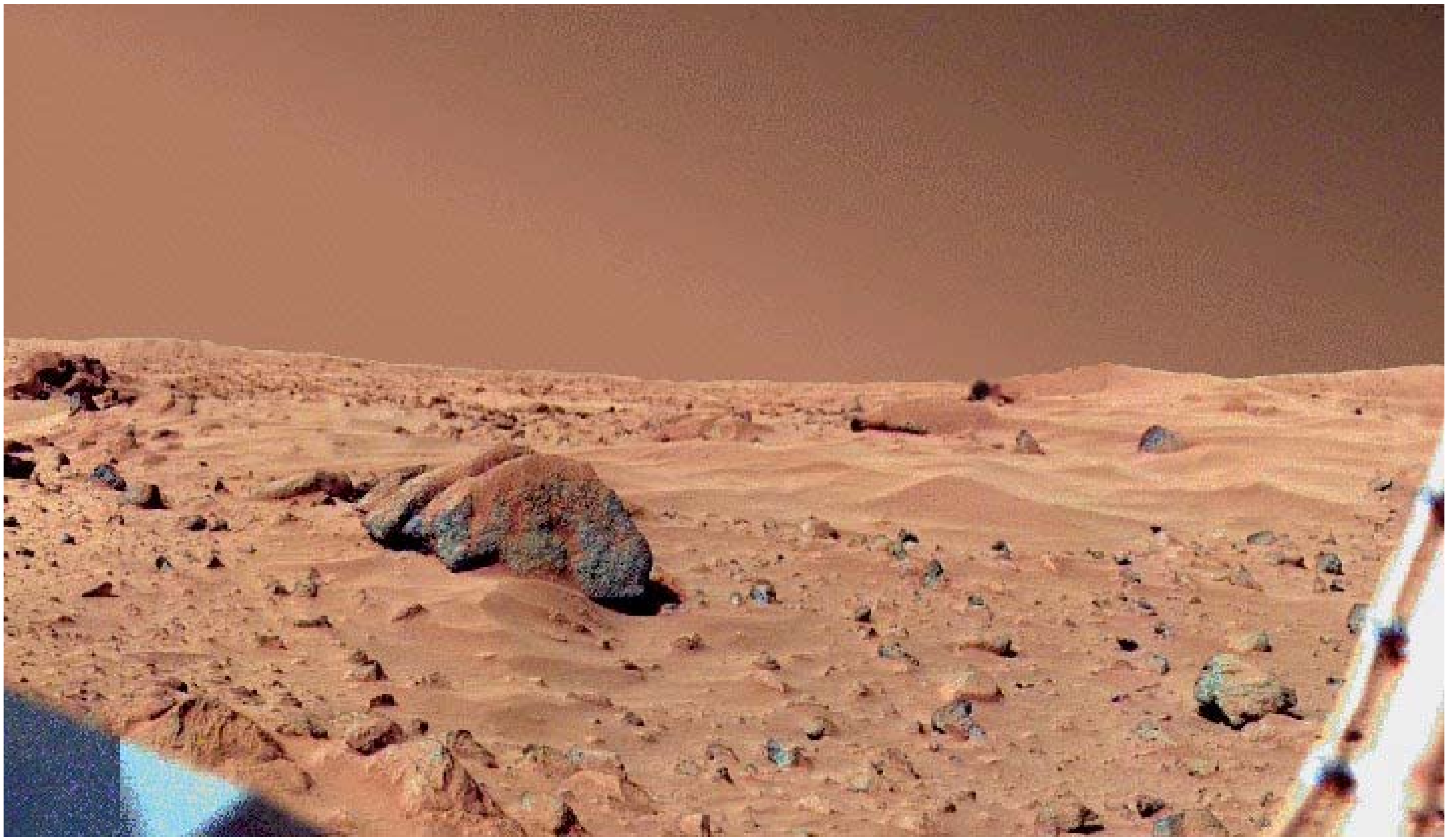


Viking Mars Orbiters/ Landers (1976)

- F = 2.3 GHz (S-band)
- R* = 3K ibps
- (32,6) Biorthogonal Code
- No compression



Viking I Landscape

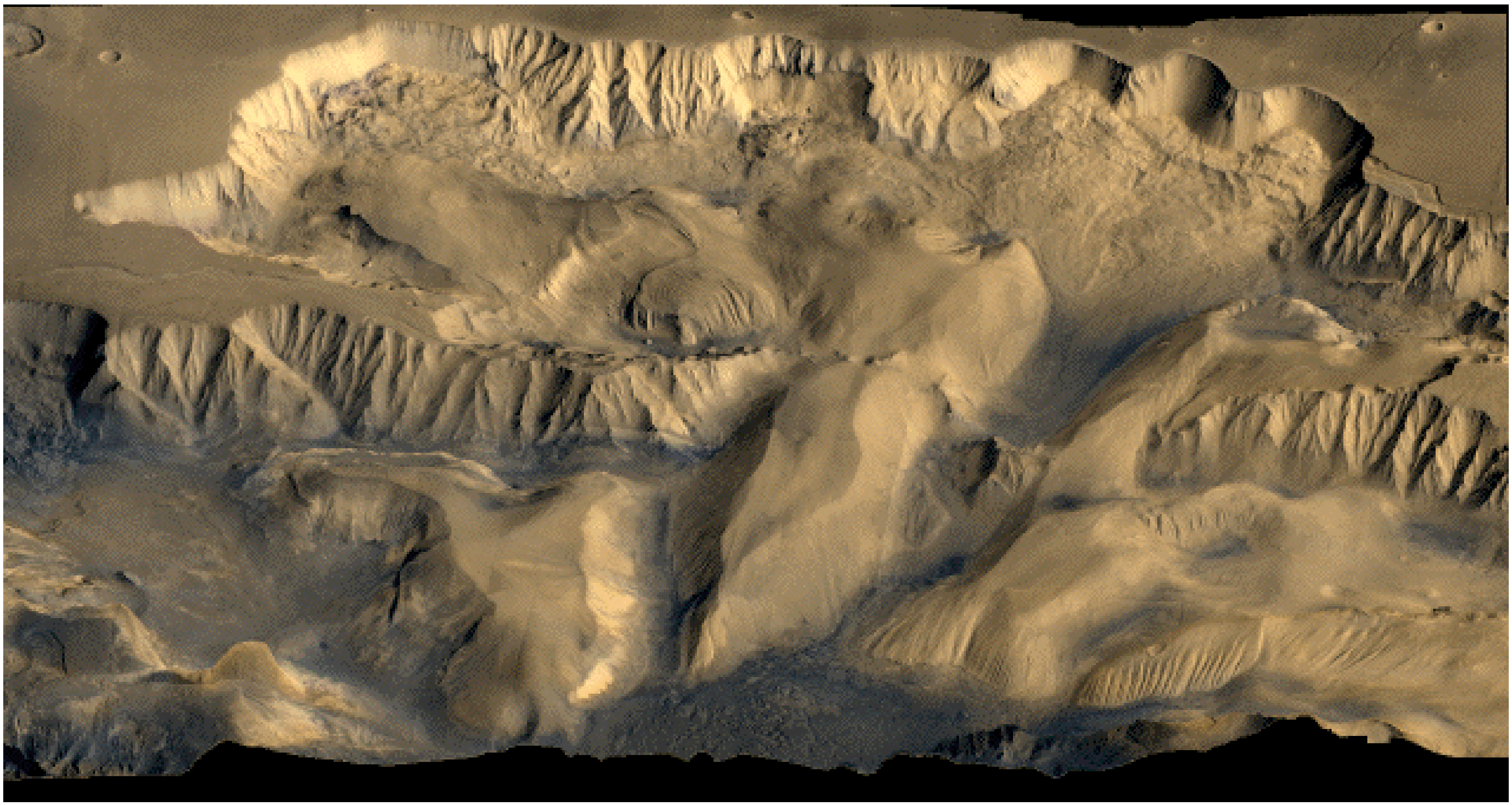


Viking Lander

Sunset on Mars

Viking Orbiter

The Great Equatorial Canyon



A 20-Year Gap and Then:

Mars Global Surveyor (1997)

Mars Global Surveyor (1997)

- F = 8.4 GHz (X - band)

Mars Global Surveyor (1997)

- F = 8.4 GHz (X - band)
- R* = 128K ibps

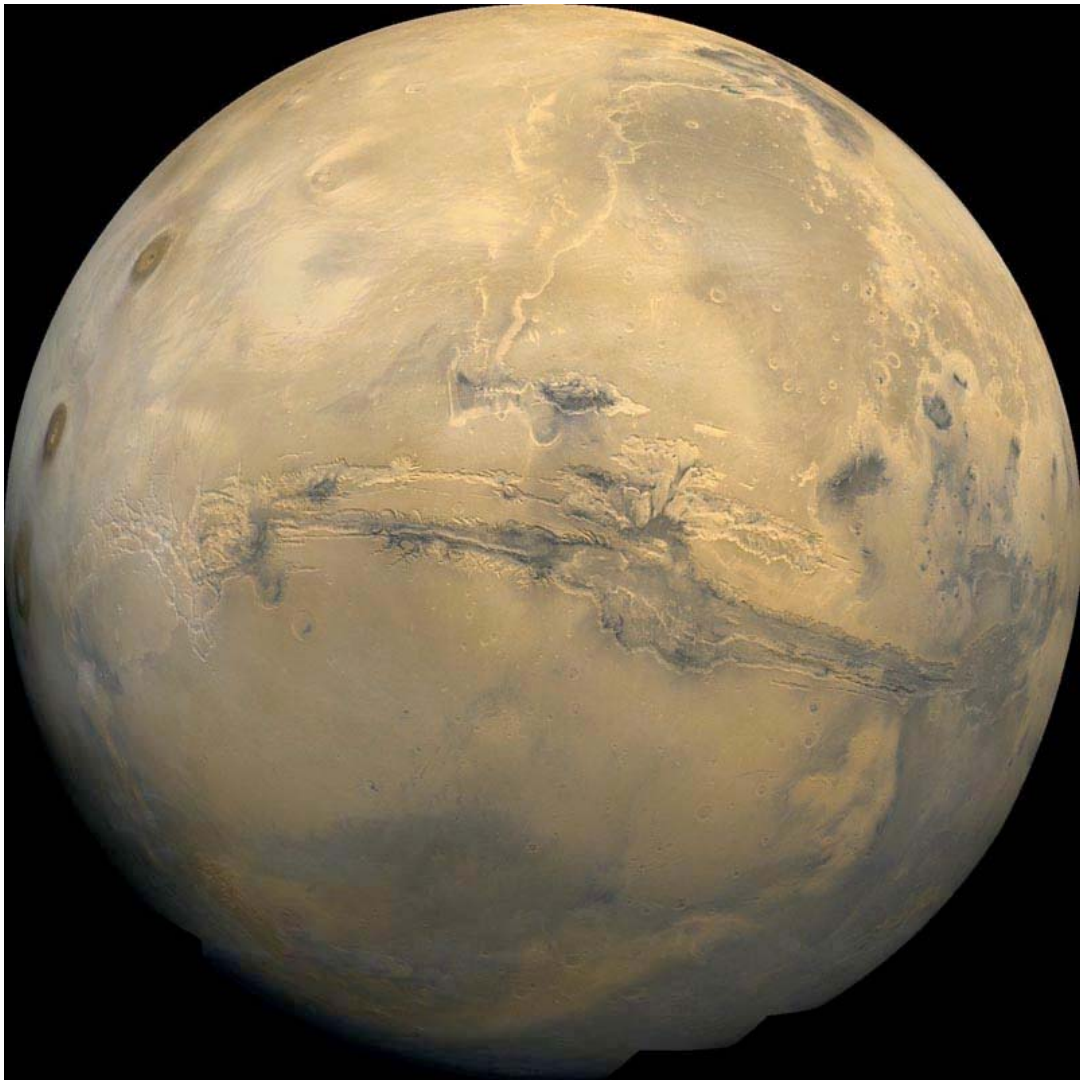
Mars Global Surveyor (1997)

- F = 8.4 GHz (X - band)
- R* = 128K ibps
- (7, 1/2)CC + (255,223)RS

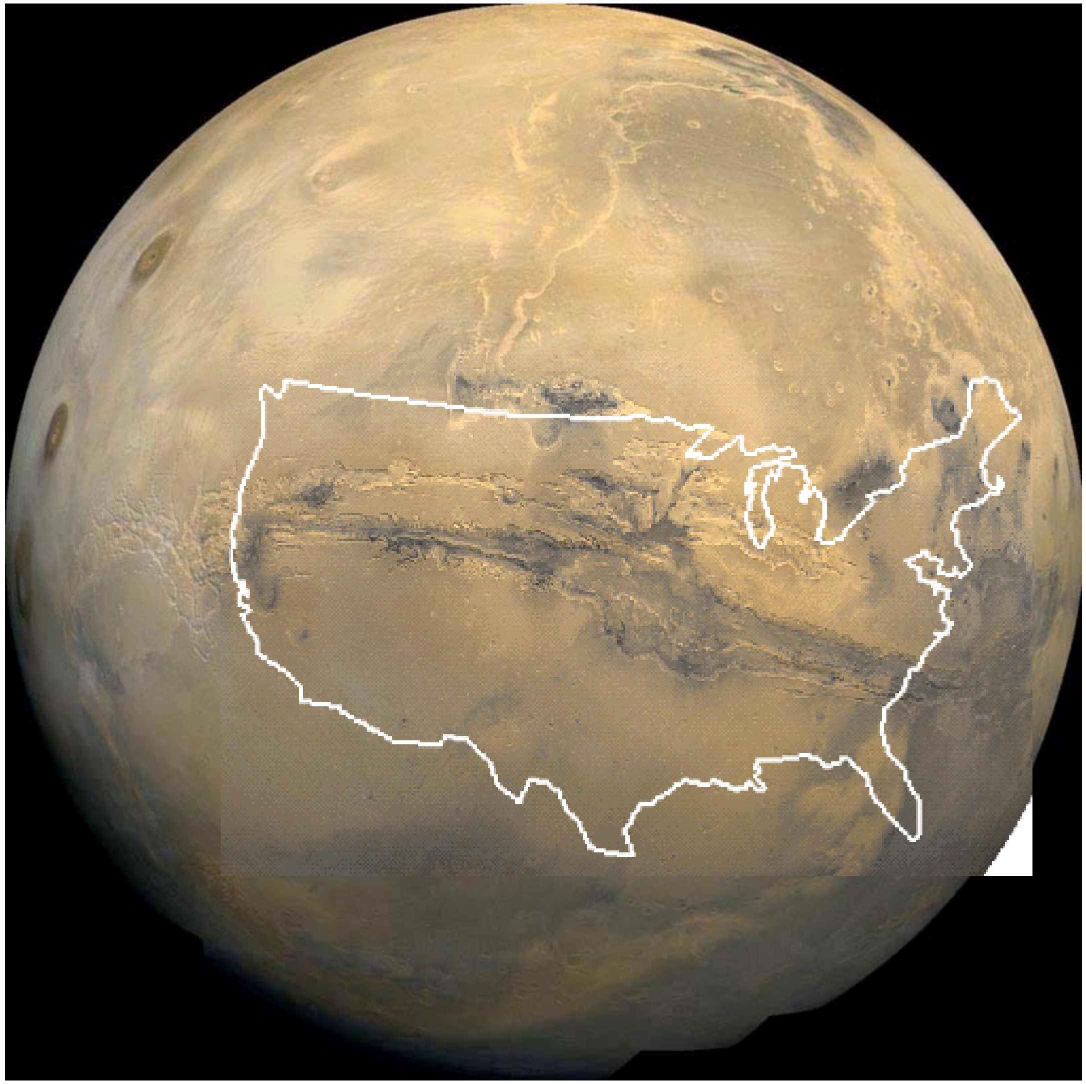
Mars Global Surveyor (1997)

- F = 8.4 GHz (X - band)
- R* = 128K ibps
- (7, 1/2)CC + (255,223)RS
- ~2:1 lossless Rice compression

MGS

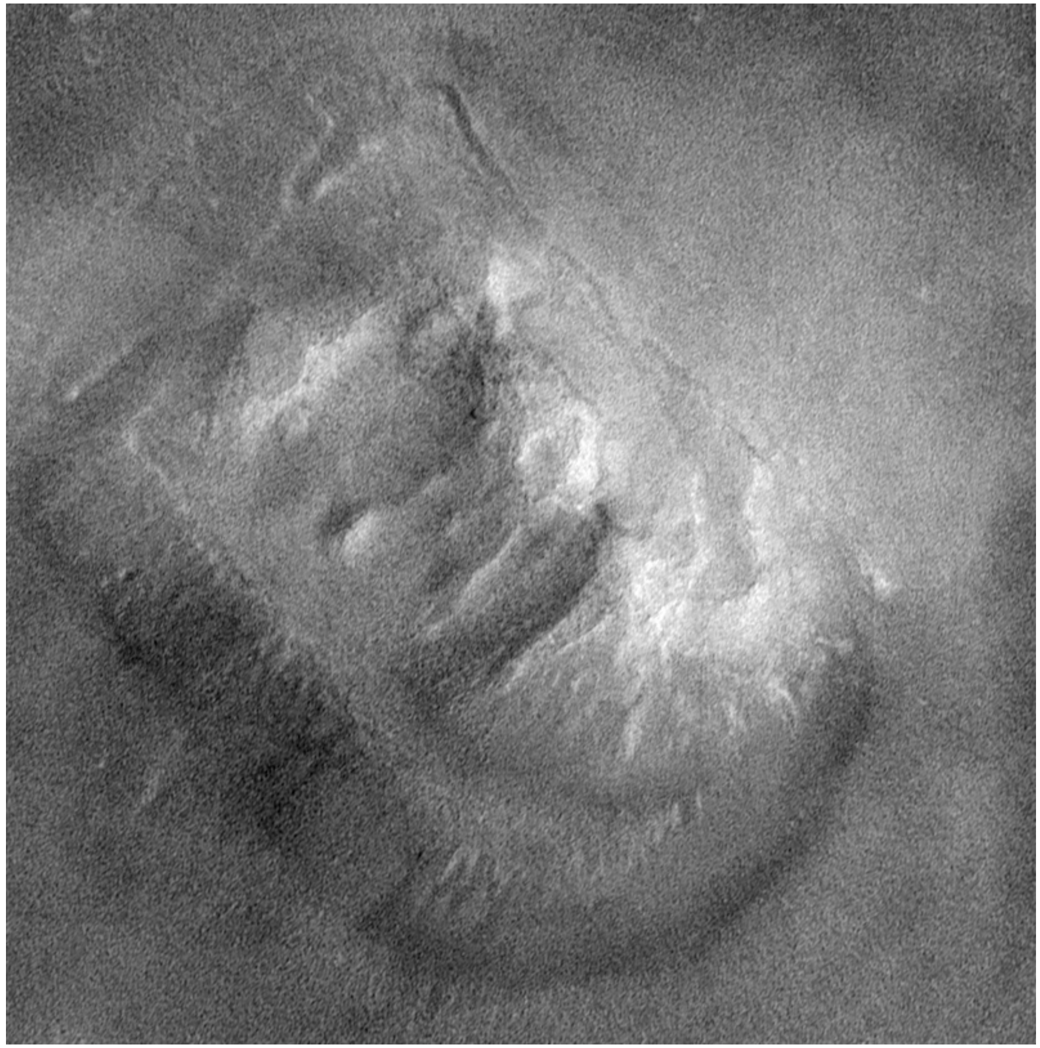


MGS



MGS

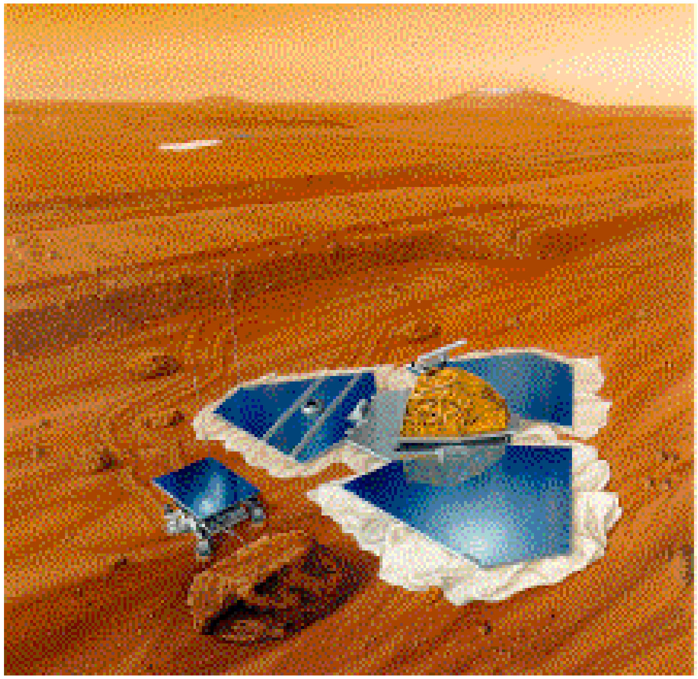
The "Face" on Mars (Cydonia)



MGS

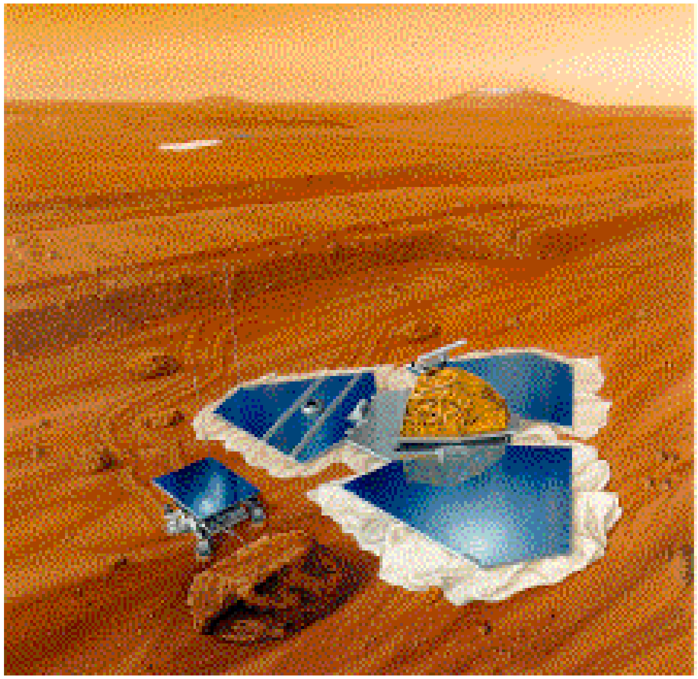
Earth and Moon from MGS

Mars Pathfinder (1997)



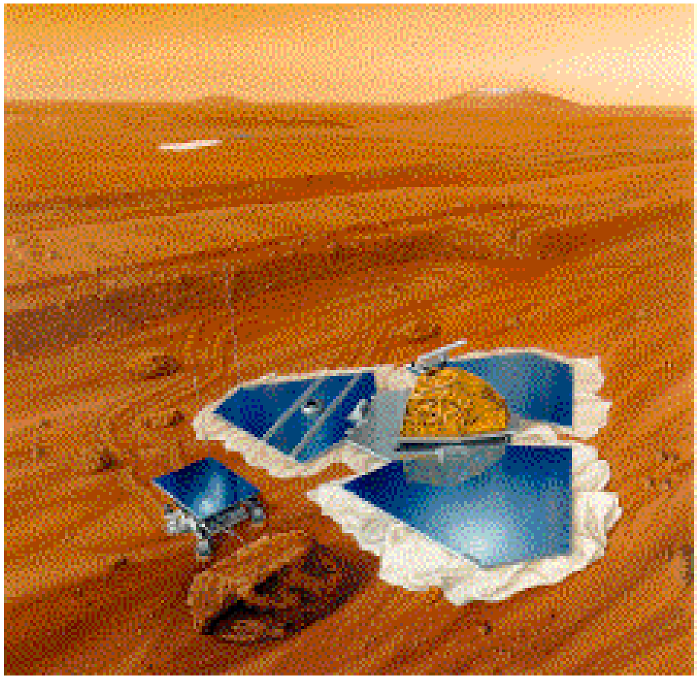
Mars Pathfinder (1997)

- F = 8.4 GHz (X-Band)



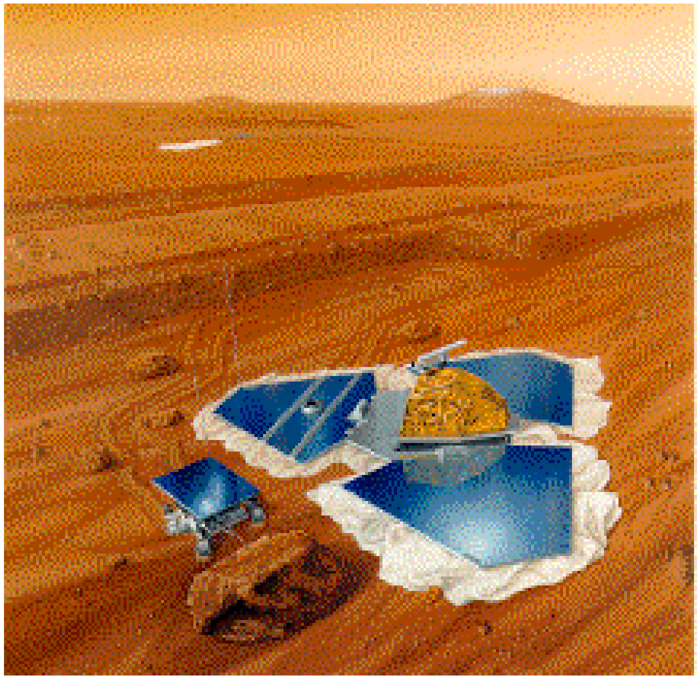
Mars Pathfinder (1997)

- F = 8.4 GHz (X-Band)
- R* = 8K ibps



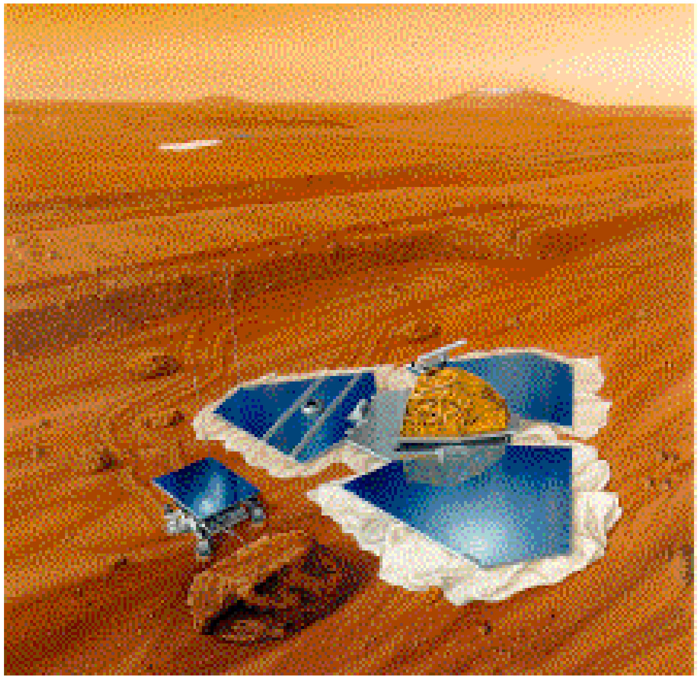
Mars Pathfinder (1997)

- F = 8.4 GHz (X-Band)
- R* = 8K ibps
- (15, 1/6)CC + (255,223)RS



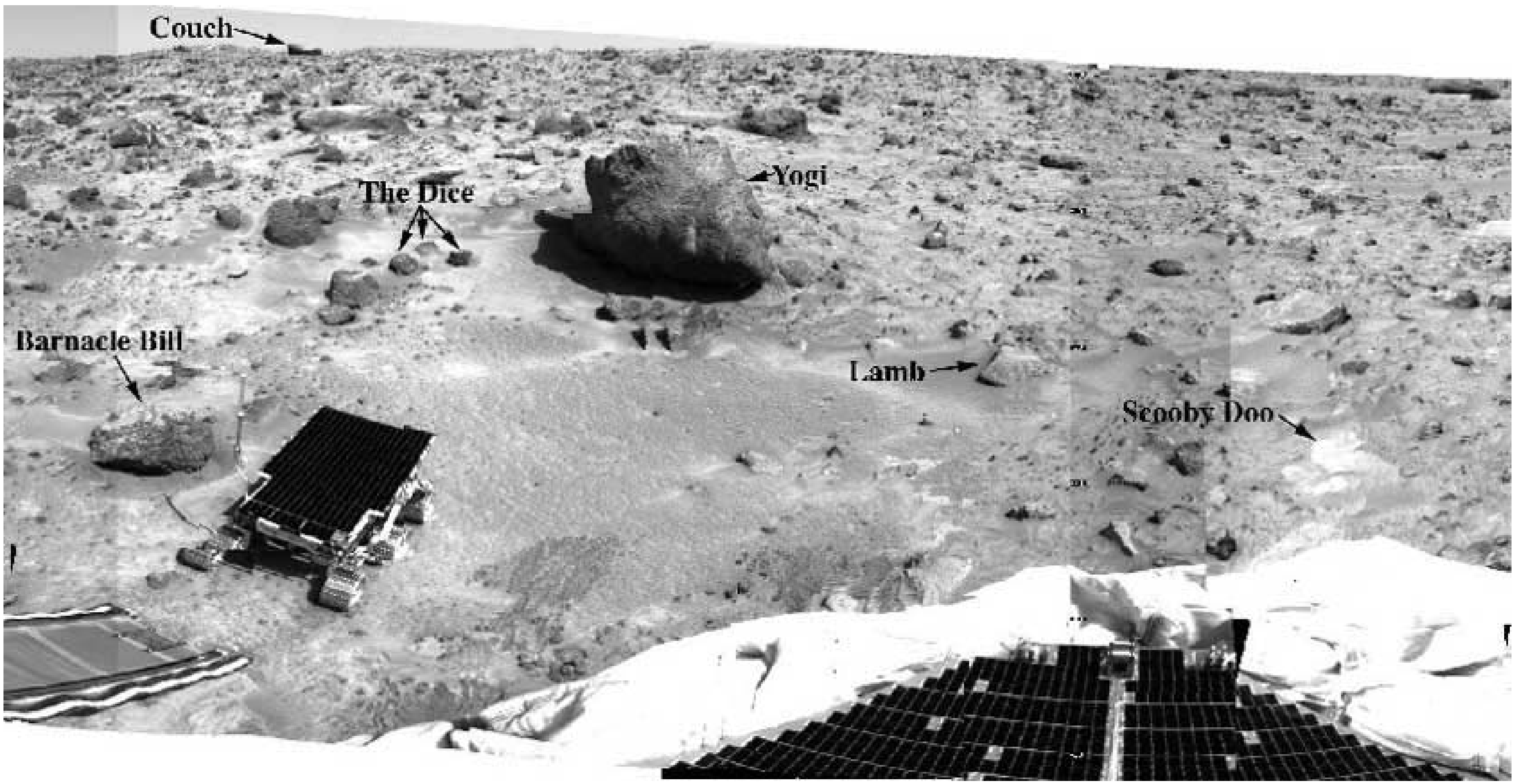
Mars Pathfinder (1997)

- F = 8.4 GHz (X-Band)
- R* = 8K ibps
- (15, 1/6)CC + (255,223)RS
- 6:1 lossy JPEG compression



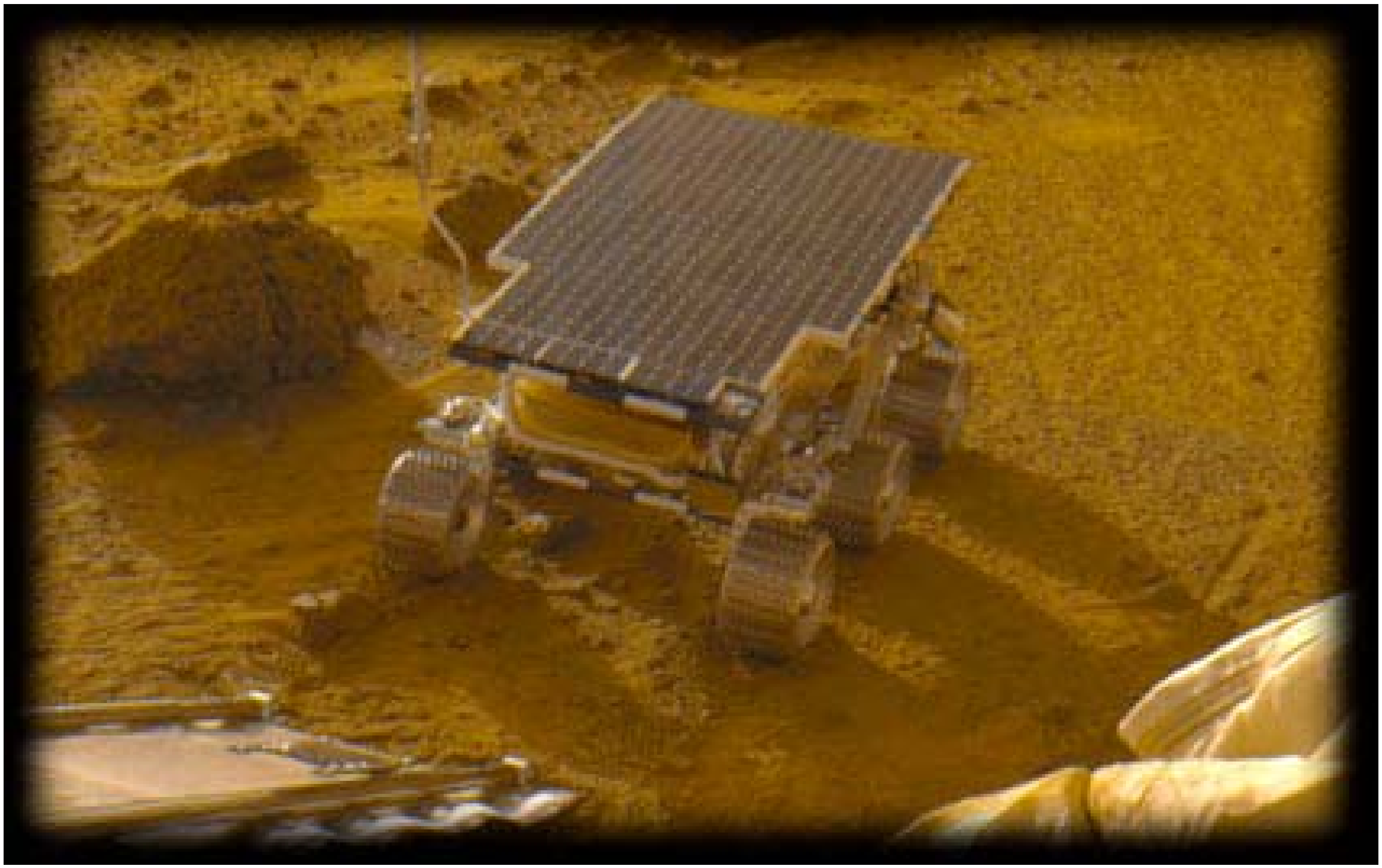
Pathfinder

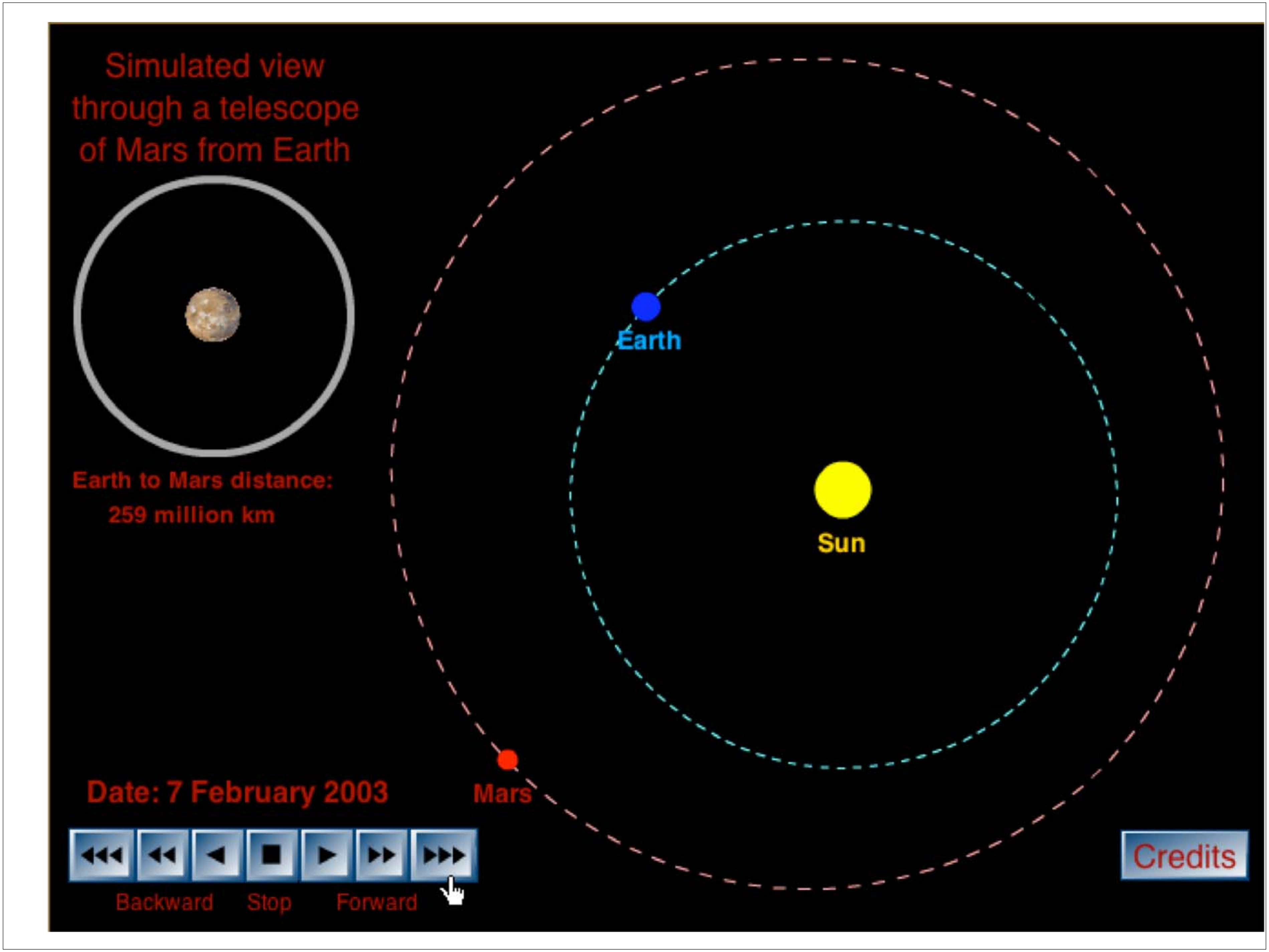
Pathfinder on Mars



Pathfinder

"Sojourner"




Simulated view
through a telescope
of Mars from Earth
Earth to Mars distance:
259 million km
Earth
Sun
Mars
Date: 7 February 2003
Backward
Stop
Forward
Credits

Mars Exploration Rovers (2004)

Mars Exploration Rovers (2004)

- F = 8.4 GHz (X -Band)

Mars Exploration Rovers (2004)

- F = 8.4 GHz (X -Band)
- R* = 168K ibps

Mars Exploration Rovers (2004)

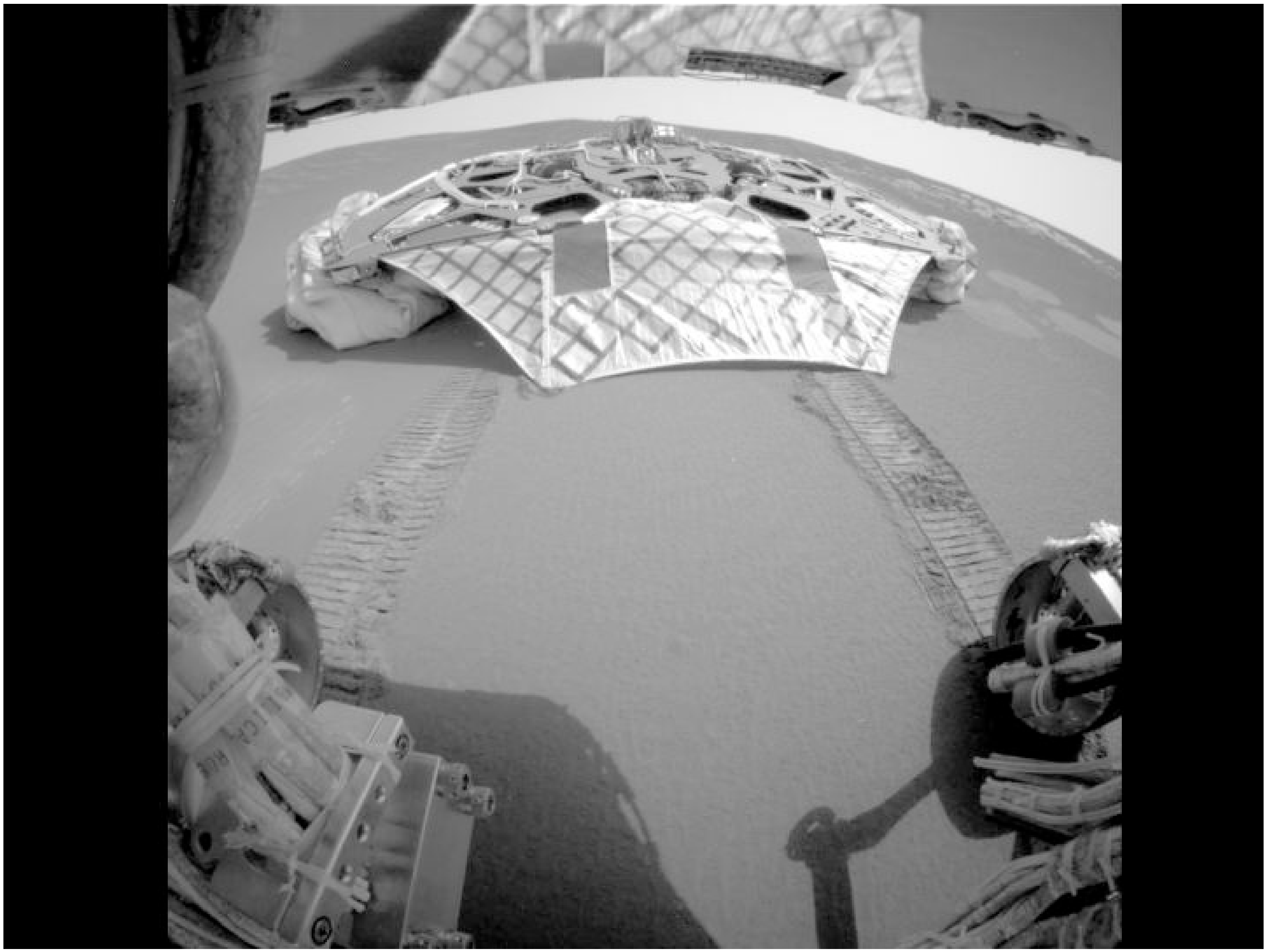
- F = 8.4 GHz (X -Band)
- R* = 168K ibps
- (15, 1/6)CC + (255,223)RS

Mars Exploration Rovers (2004)

- F = 8.4 GHz (X -Band)
- R* = 168K ibps
- (15, 1/6)CC + (255,223)RS
- 12:1 lossy ICER compression

MER

Leaving the Lander

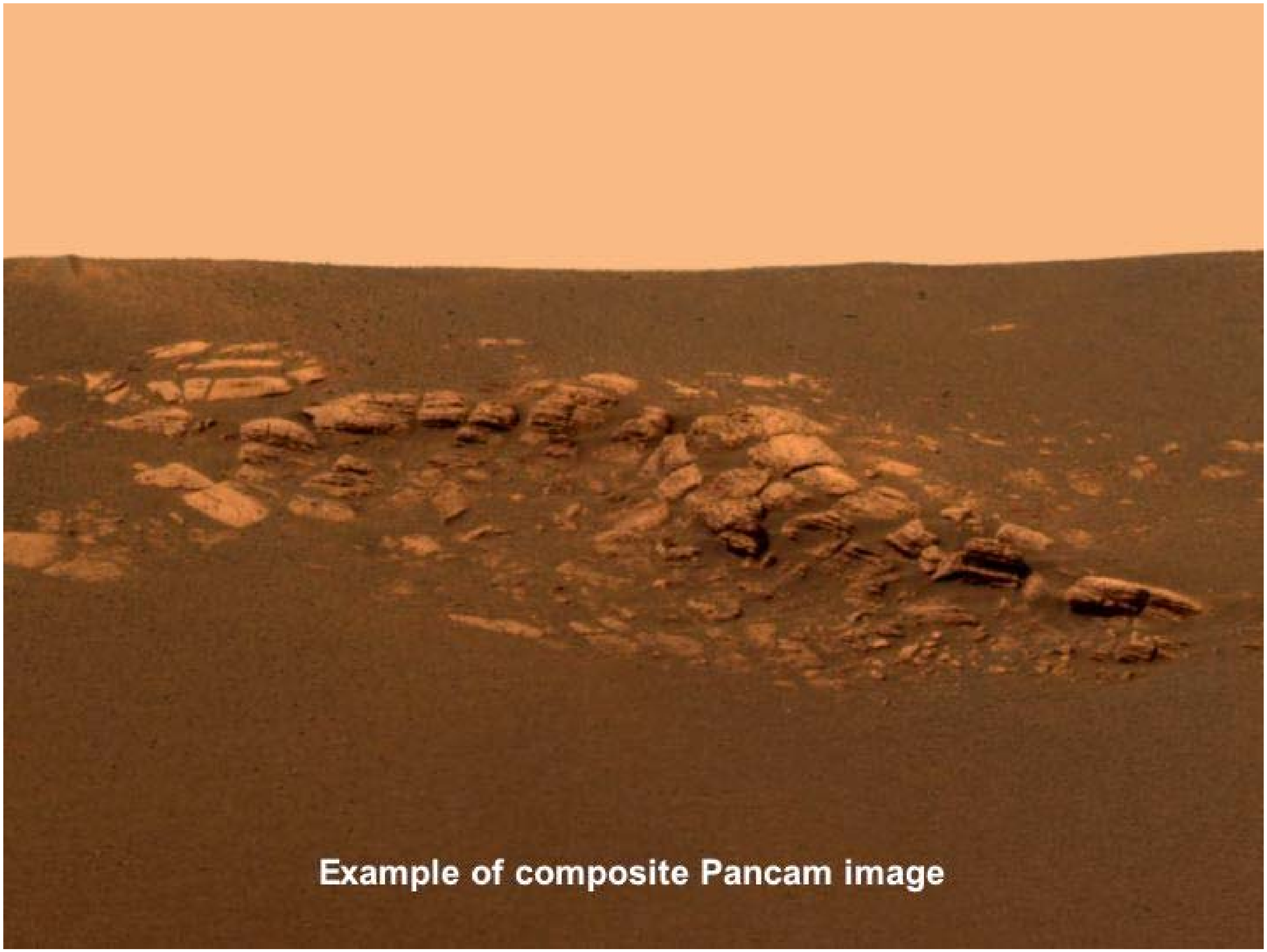


MER

The "Columbia Hills" (Spirit)

MER

Eagle Crater (Opportunity)



Progress 1965-2004

Progress 1965-2004

- 1965 (Mariner 4): 8.33 ibps

Progress 1965-2004

- 1965 (Mariner 4): 8.33 ibps
- 2004 (MER-direct to earth) : 168K ibps

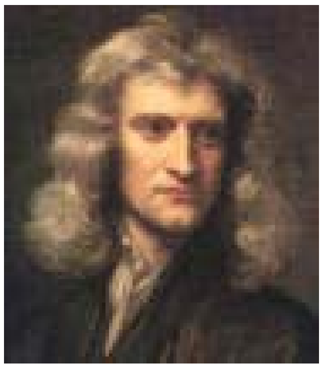
Progress 1965-2004

- 1965 (Mariner 4): 8.33 ibps
- 2004 (MER-direct to earth) : 168K ibps
- This is a 20000-fold increase, or 4.3 orders of magnitude (43 dB).

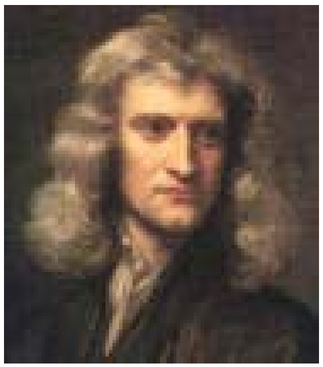
Progress 1965-2004

- 1965 (Mariner 4): 8.33 ibps
- 2004 (MER-direct to earth) : 168K ibps
- This is a 20000-fold increase, or 4.3 orders of magnitude (43 dB).
- How much of the increase is due to Shannon?

Newton vs. Shannon

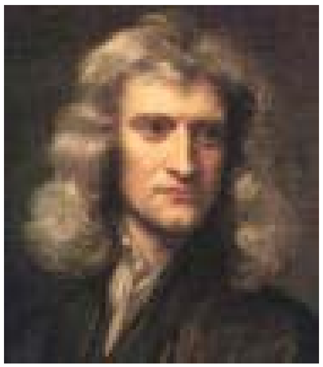


Newton vs. Shannon



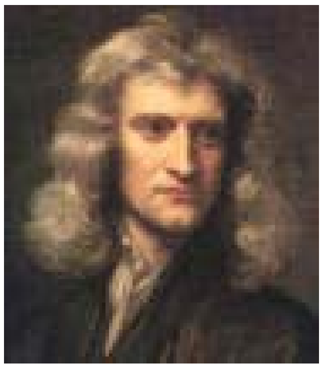
- Newton (Physics)

Newton vs. Shannon



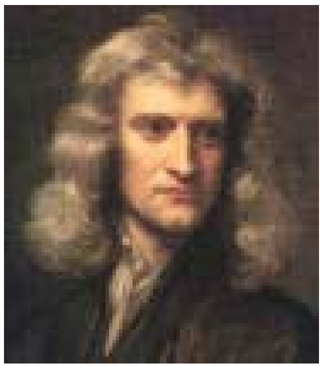
- Newton (Physics)
  - Aperture

Newton vs. Shannon



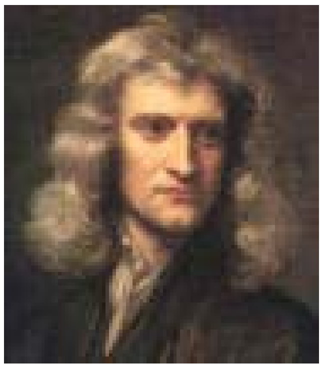
- Newton (Physics)
  - Aperture
  - Frequency

Newton vs. Shannon



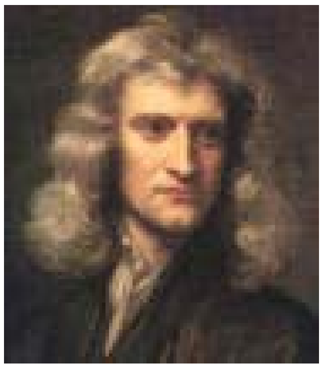
- Newton (Physics)
  - Aperture
  - Frequency
  - Power

Newton vs. Shannon



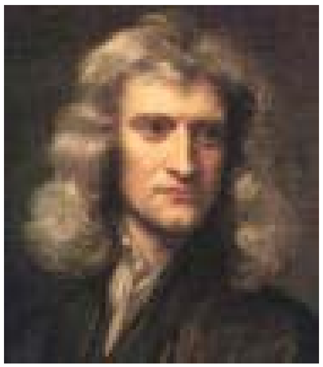
- Newton (Physics)
  - Aperture
  - Frequency
  - Power
  -

Newton vs. Shannon



- Newton (Physics)
  - Aperture
  - Frequency
  - Power
  -
- Shannon (Mathematics)

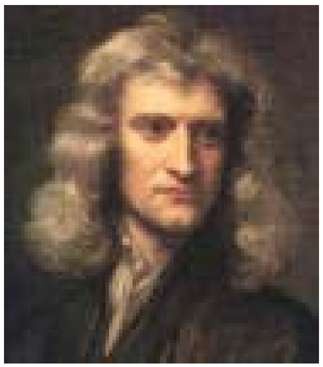
Newton vs. Shannon



- Newton (Physics)
  - Aperture
  - Frequency
  - Power
  -

- Shannon (Mathematics)
  - Source Coding

Newton vs. Shannon



- Newton (Physics)
  - Aperture
  - Frequency
  - Power
  -

- Shannon (Mathematics)
  - Source Coding
  - Channel Coding

4.3 Orders of Magnitude Improvement in Image Bit Rate, 1965-2004

4.3 Orders of Magnitude Improvement in Image Bit Rate, 1965-2004

Shannon
37%

Newton
63%

4.3 Orders of Magnitude Improvement in Image Bit Rate, 1965-2004

4.3 Orders of Magnitude Improvement in Image Bit Rate, 1965-2004

Next Round

Mars Reconnaissance Orbiter (2006)

Mars Reconnaissance Orbiter (2006)

- F = 8.4 GHz (X - Band)

Mars Reconnaissance Orbiter (2006)

- F = 8.4 GHz (X - Band)
- R* = 12M ibps

MRO

Mars Reconnaissance Orbiter (2006)

- F = 8.4 GHz (X - Band)
- R* = 12M ibps
- (8920, 1/6)CCSDS turbo code

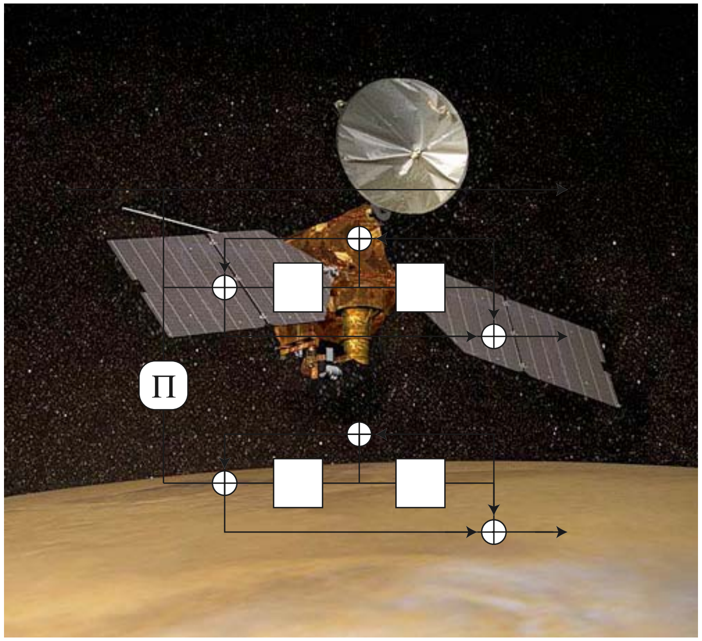
Mars Reconnaissance Orbiter (2006)

- F = 8.4 GHz (X - Band)
- R* = 12M ibps
- (8920, 1/6)CCSDS turbo code
- ~2:1 lossless FELICS compression

MRO

Mars Reconnaissance Orbiter (2006)

- F = 8.4 GHz (X - Band)
- R* = 12M ibps
- (8920, 1/6)CCSDS turbo code
- ~2:1 lossless FELICS compression



Mariner 4 vs. MRO 1965-2006

Mariner 4 vs. MRO 1965-2006

- Mariner 4: 8.33 ibps

Mariner 4 vs. MRO 1965-2006

- Mariner 4: 8.33 ibps
- MRO : 12M ibps

Mariner 4 vs. MRO 1965-2006

- Mariner 4:   8.33 ibps
- MRO : 12M ibps
- This is a 6.2 order of magnitude increase (62 dB).

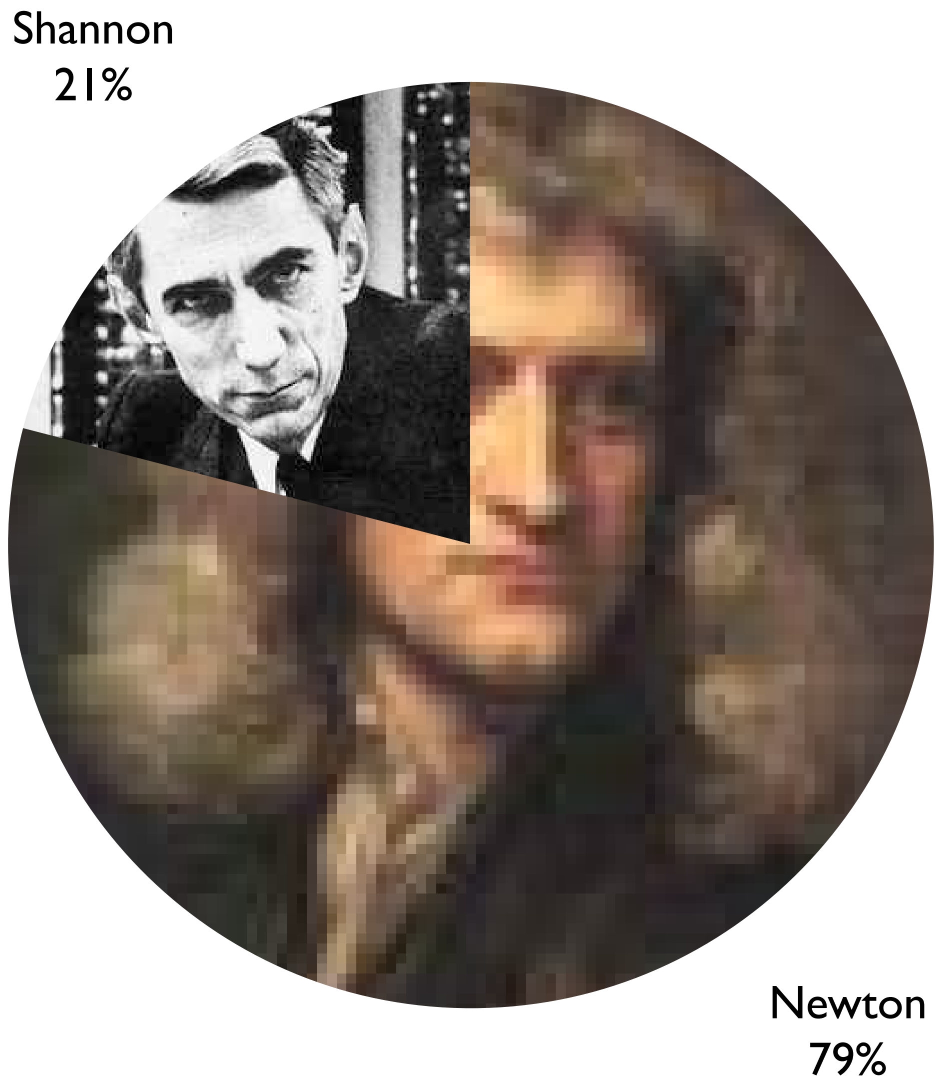
Mariner 4 vs. MRO 1965-2006

- Mariner 4:   8.33 ibps
- MRO : 12M ibps
- This is a 6.2 order of magnitude increase (62 dB).
- How much of the increase is due to Shannon?

6.5 Orders of Magnitude Improvement in Image Bit Rate, Mariner 4 - MRO

6.5 Orders of Magnitude Improvement in Image Bit Rate, Mariner 4 - MRO

6.5 Orders of Magnitude Improvement in Image Bit Rate, Mariner 4 - MRO



LDPC Codes: The Final Frontier?

LDPC Codes: The Final Frontier?

- RA Codes

LDPC Codes: The Final Frontier?

- RA Codes
- IRA Codes

LDPC Codes: The Final Frontier?

- RA Codes
- IRA Codes
- IRPA Codes

LDPC Codes: The Final Frontier?

- RA Codes
- IRA Codes
- IRPA Codes
- ARA Codes

LDPC Codes: The Final Frontier?

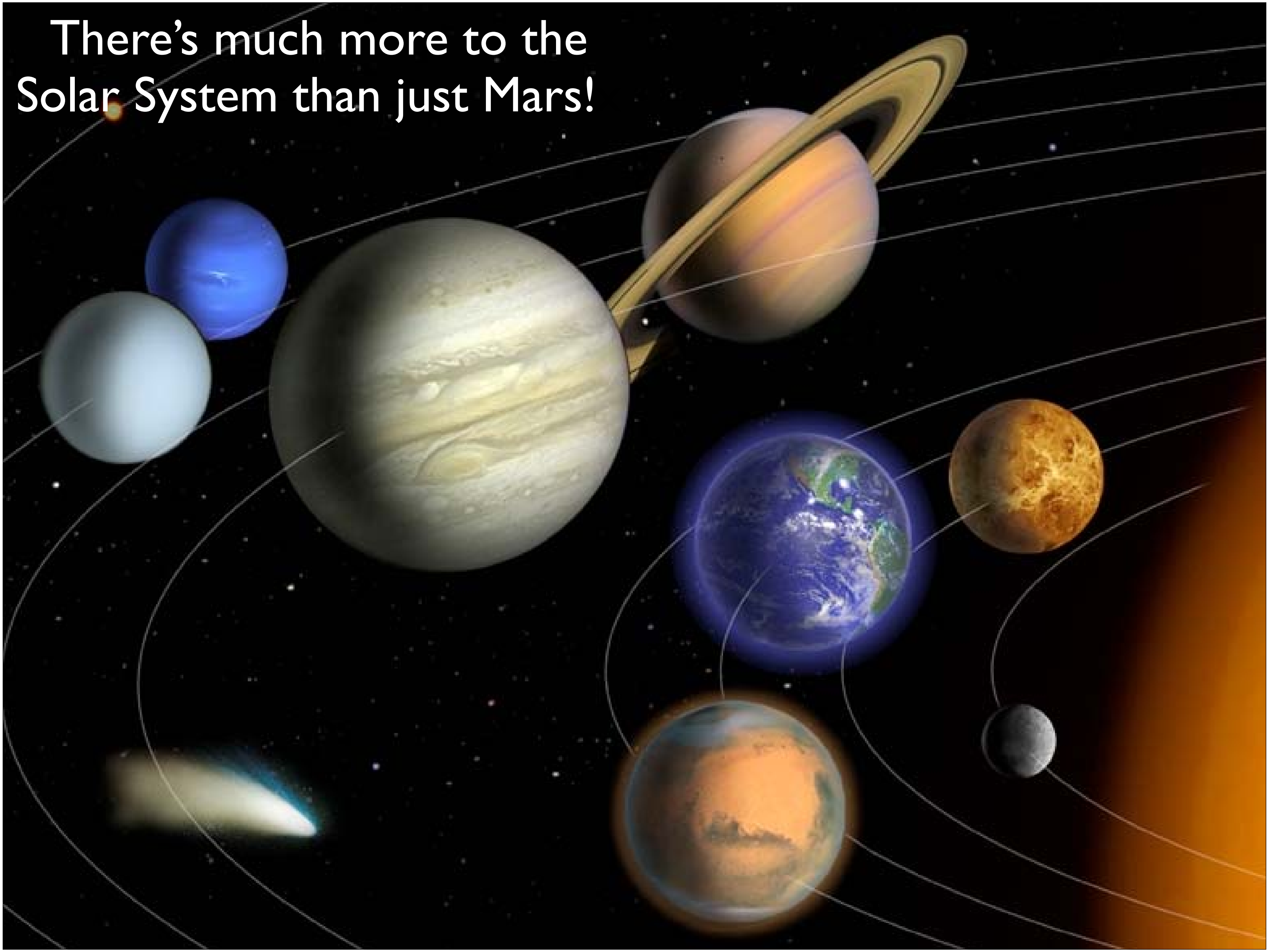
- RA Codes
- IRA Codes
- IRPA Codes
- ARA Codes
- ARAA Codes

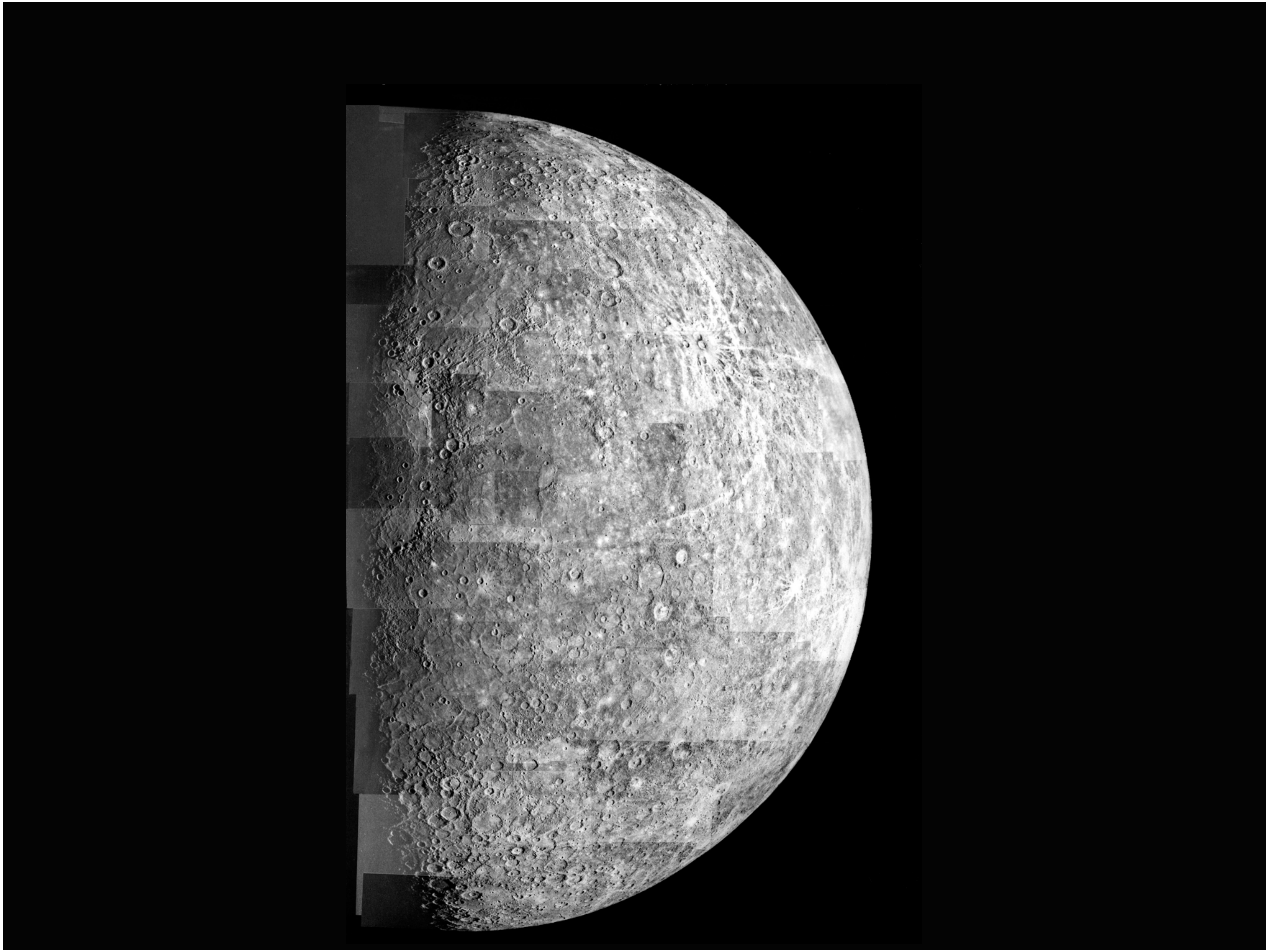
LDPC Codes: The Final Frontier?

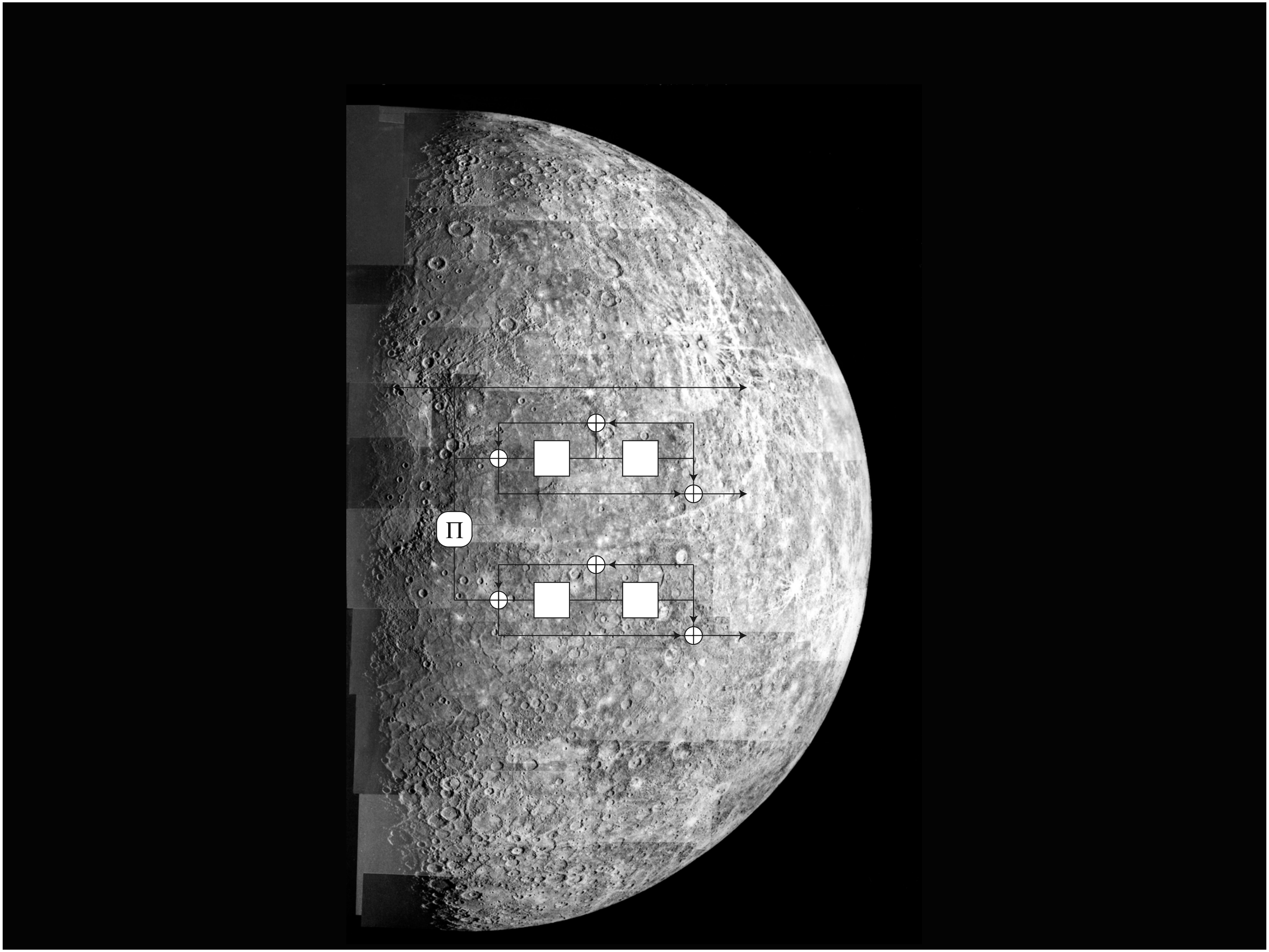
- RA Codes
- IRA Codes
- IRPA Codes
- ARA Codes
- ARAA Codes
- AARP Codes

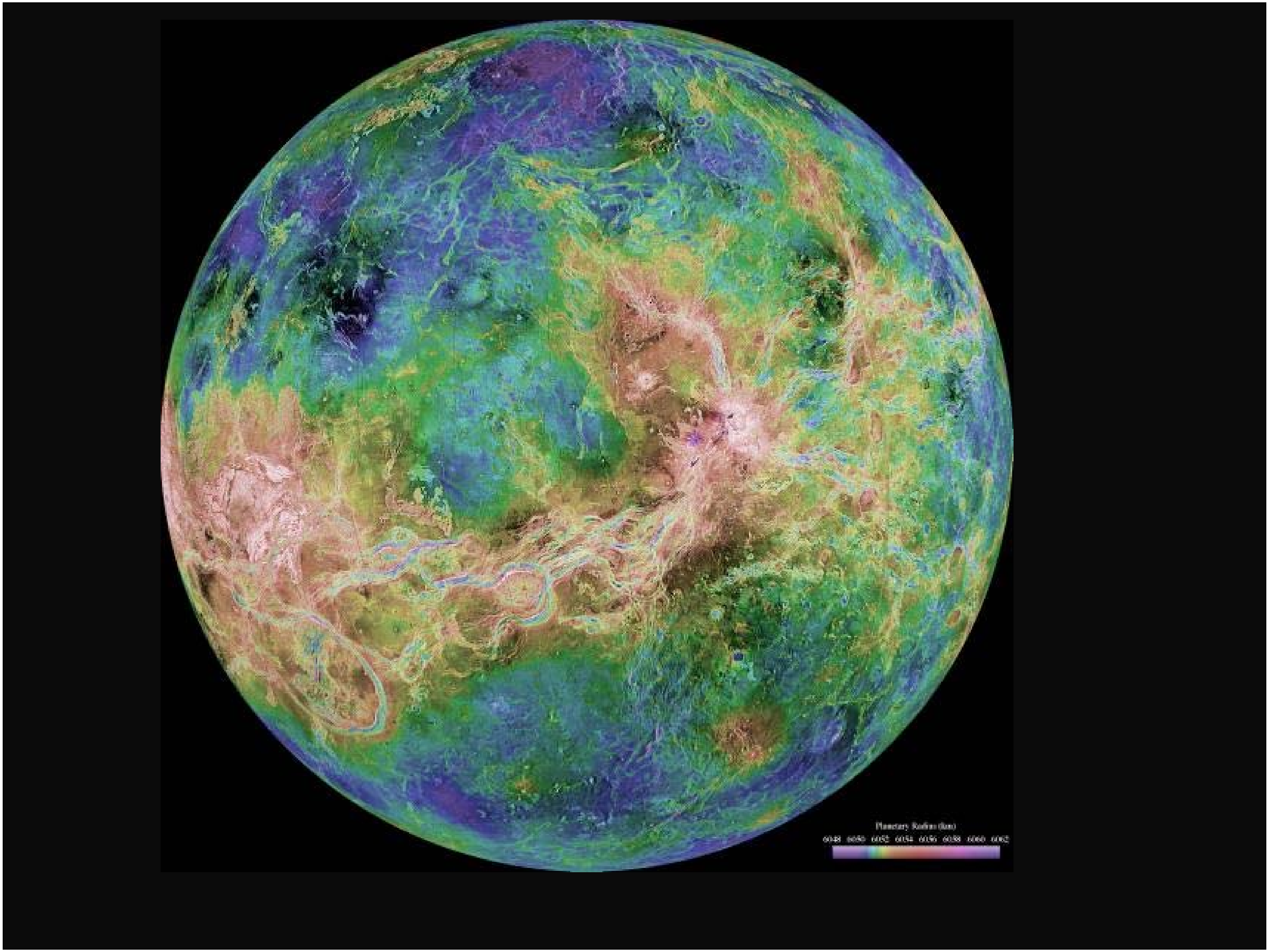
LDPC Codes: The Final Frontier?

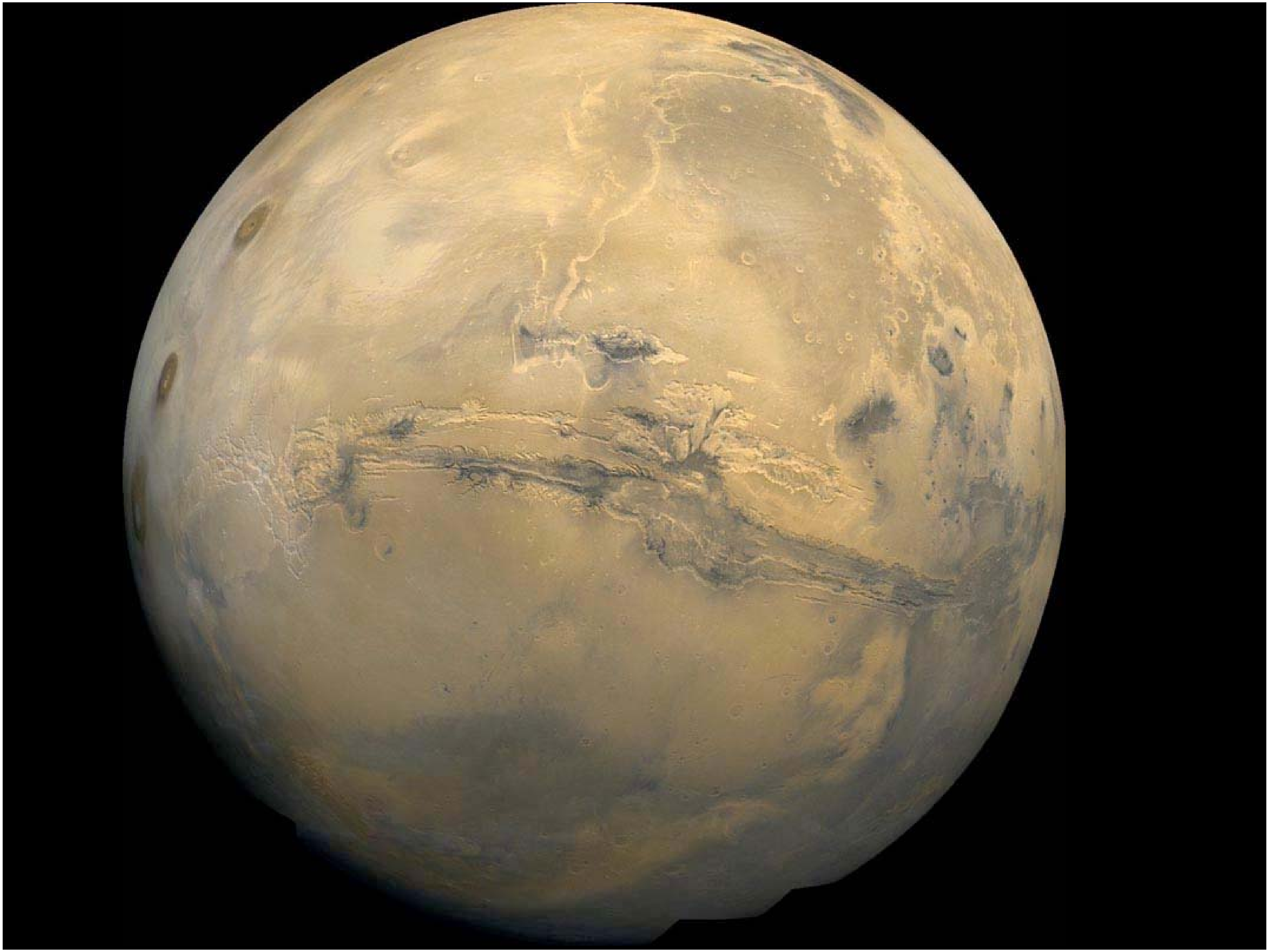
- RA Codes
- IRA Codes
- IRPA Codes
- ARA Codes
- ARAA Codes
- AARP Codes

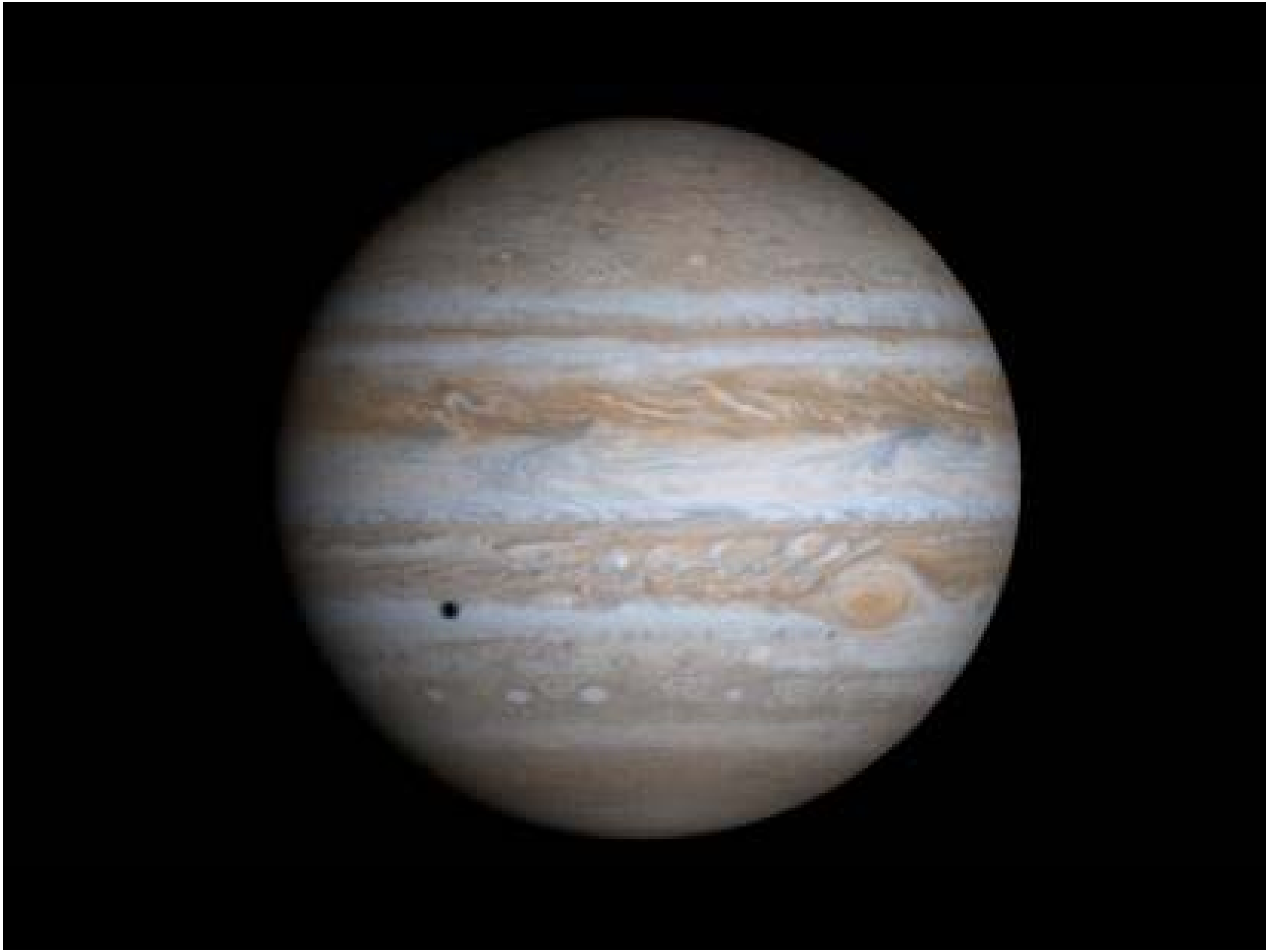

There's much more to the
Solar System than just Mars!

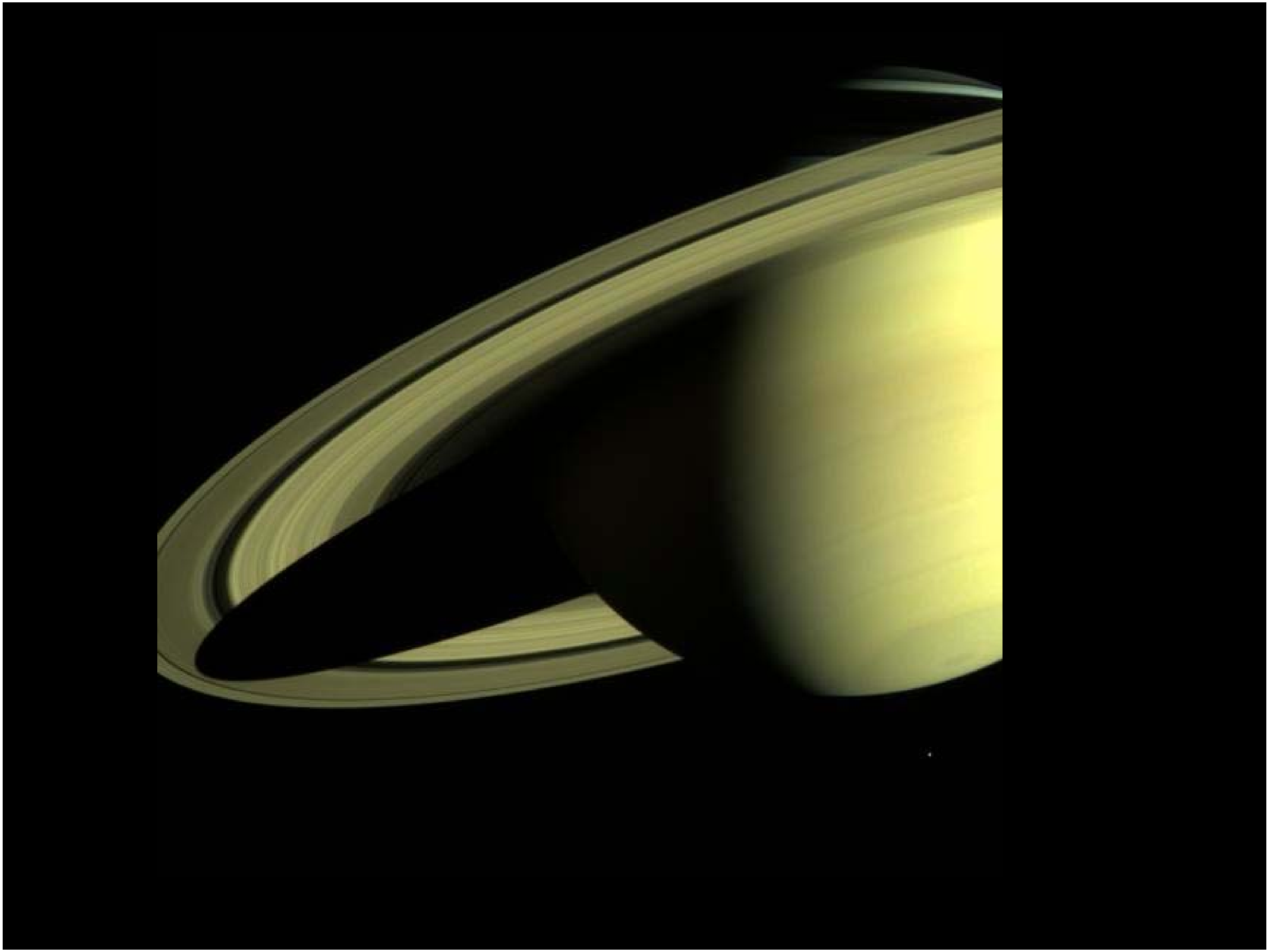


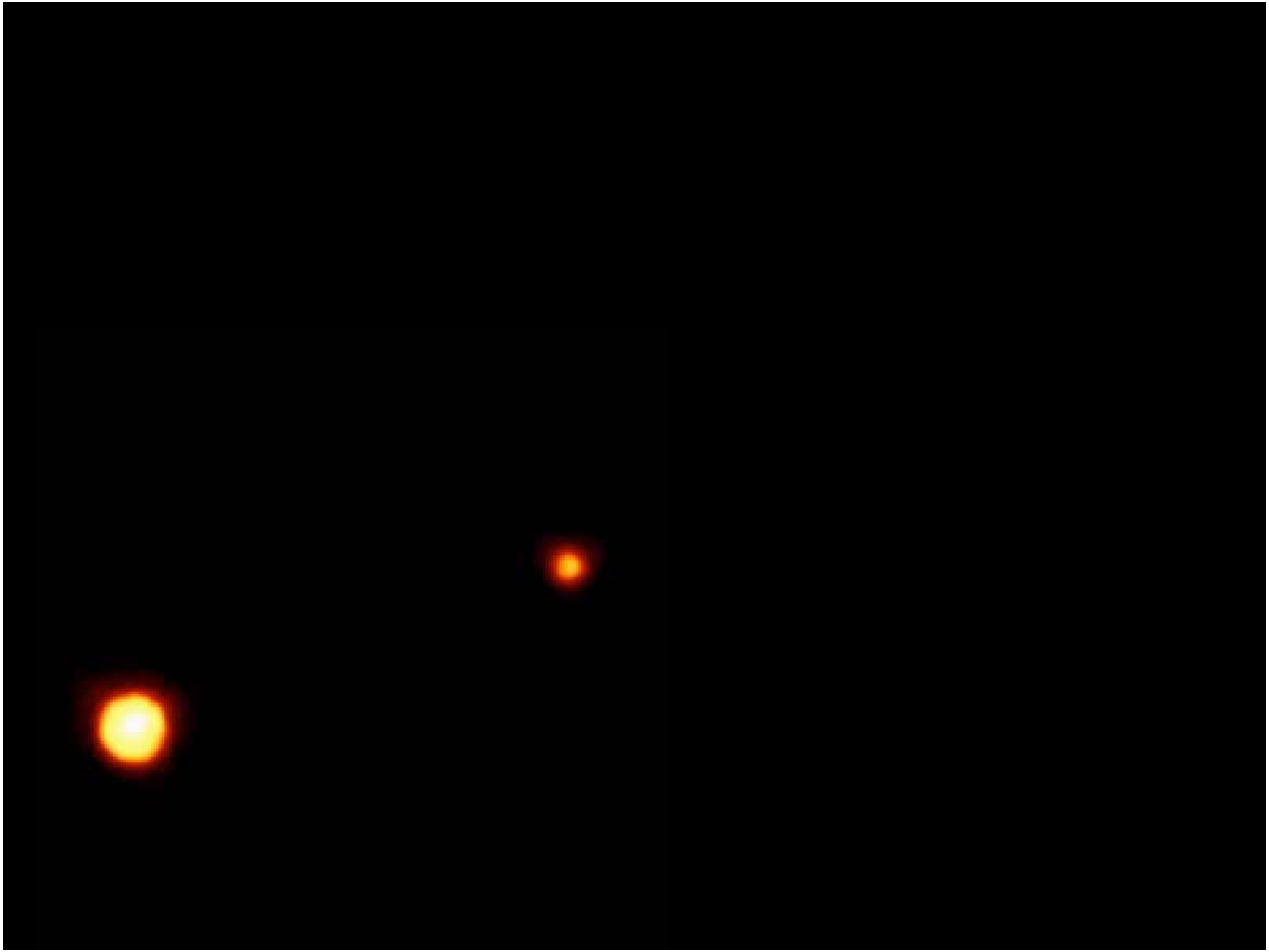

Π


Planetary Radius (km)
6048 6050 6052 6054 6056 6058 6060 6062









T. S. Eliot

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

Shannon Lecture XXVI

June 30, 2004
Chicago, Illinois

Some Information -Theoretic Anagrams

Some Information -Theoretic Anagrams

- A Sound Channel

Some Information -Theoretic Anagrams

- A Sound Channel
- Brainy Coed

Some Information -Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles

Some Information -Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles
- Cubed Roots

Some Information -Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles
- Cubed Roots
- UCLA Shenanigans

Some Information -Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles
- Cubed Roots
- UCLA Shenanigans
- Coordinate Spasm

Some Information -Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles
- Cubed Roots
- UCLA Shenanigans
- Coordinate Spasm
- Momentary Mixup