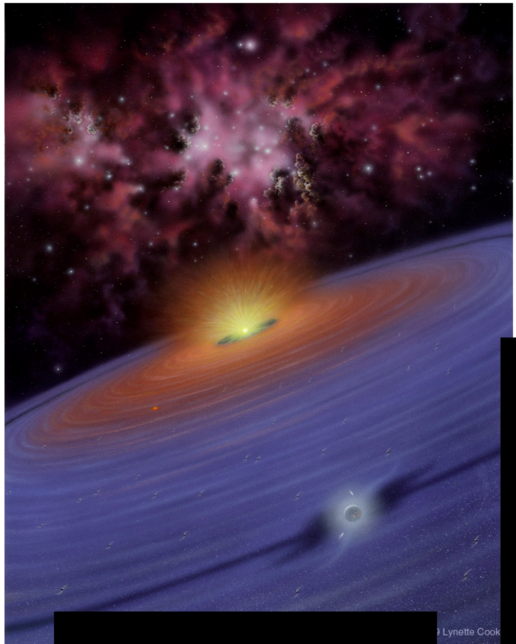
Summer School on Planet Formation

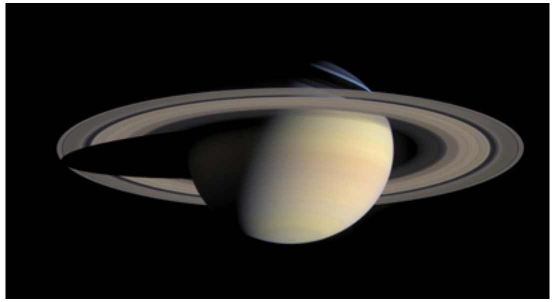
Niels Bohr Institute; Copenhagen, Denmark; 2015 August

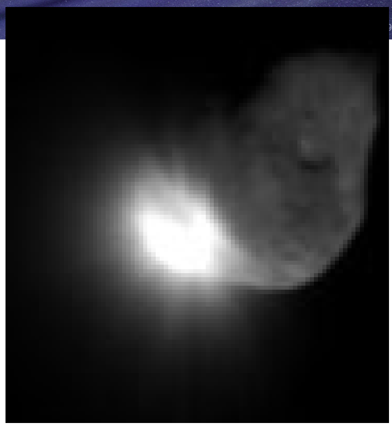
Planets & Planetary Systems

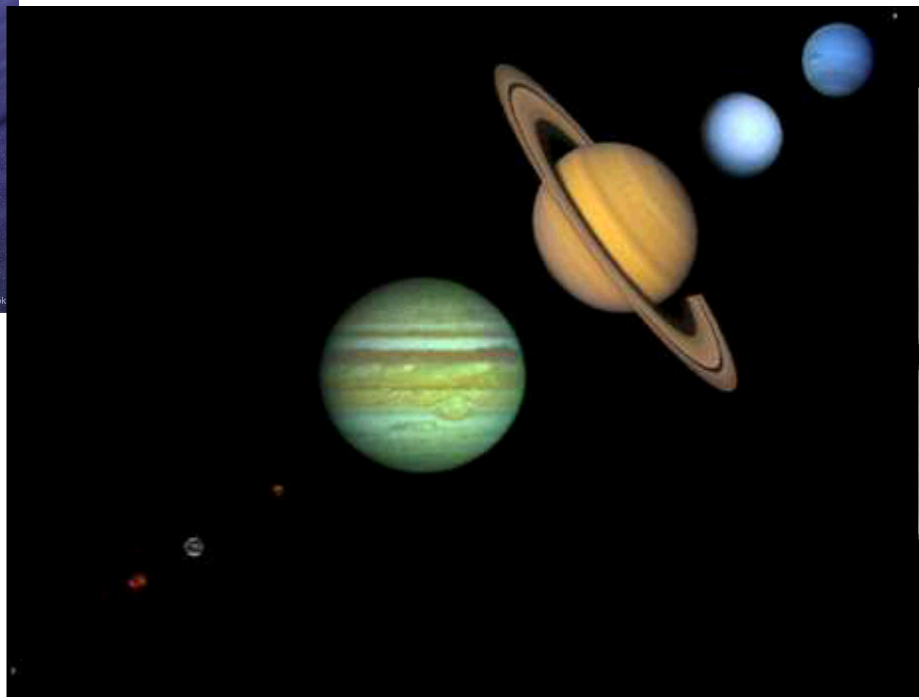


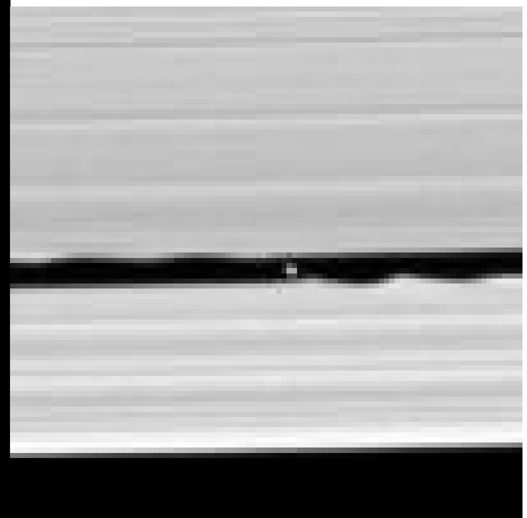
Jack Lissauer

NASA Ames









Planets & Planetary Systems

- **Our Solar System**
- **Extrasolar Planets**

- NASA's *Kepler Mission*
- Giant Planet Formation

Observable Planetary Properties

Orbit

Mass, distribution of mass

Size

Rotation rate & direction

Shape

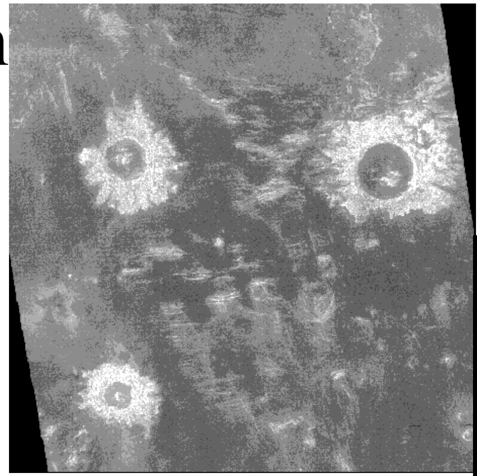
Temperature

Magnetic field

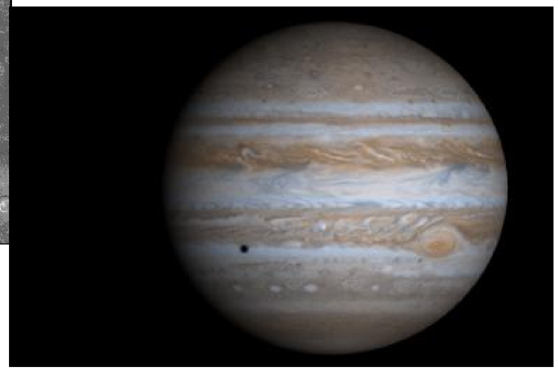
Surface structure & composition

Atmospheric structure & composition

Phobos & Mars *Phobos 2*

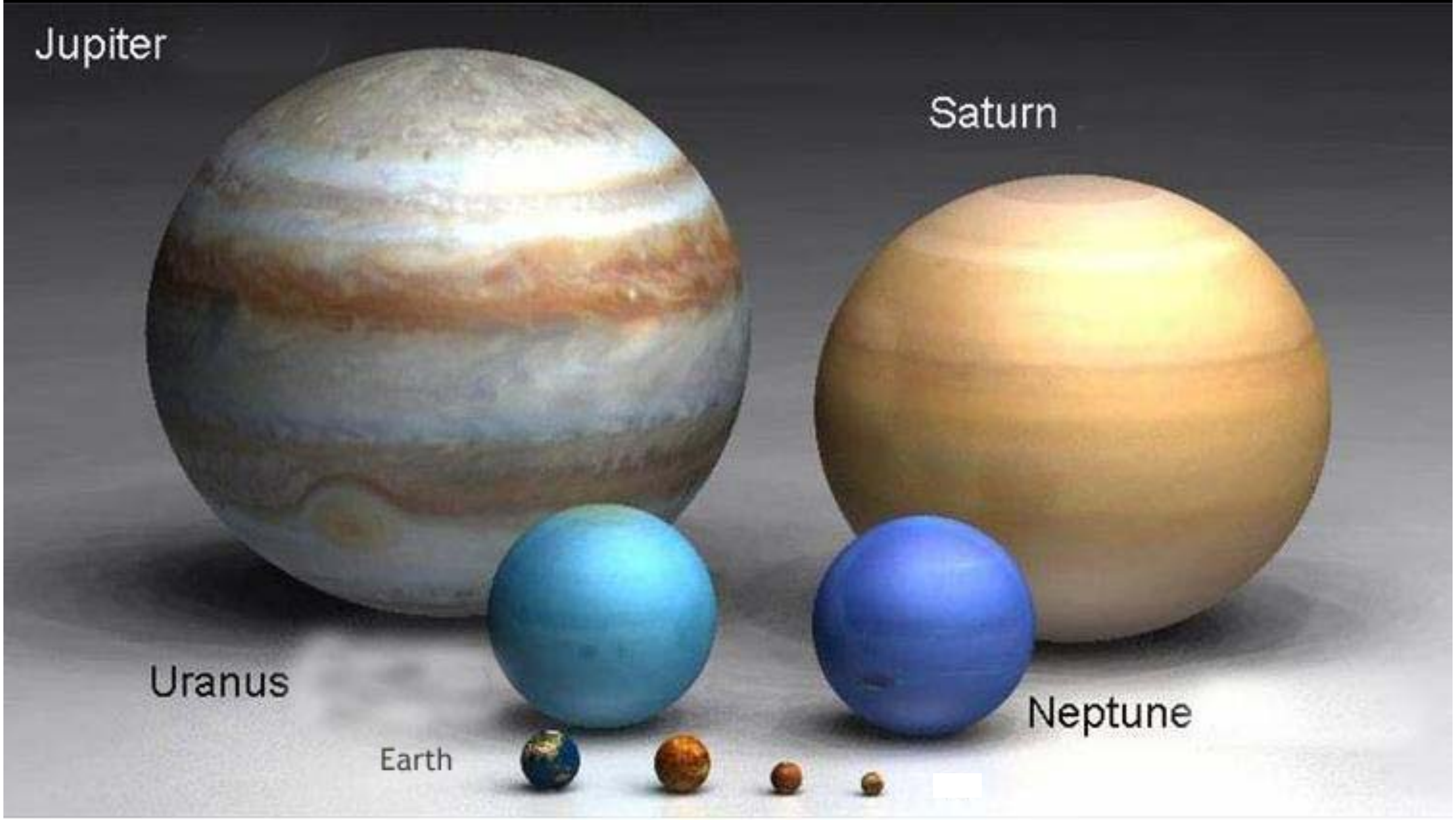


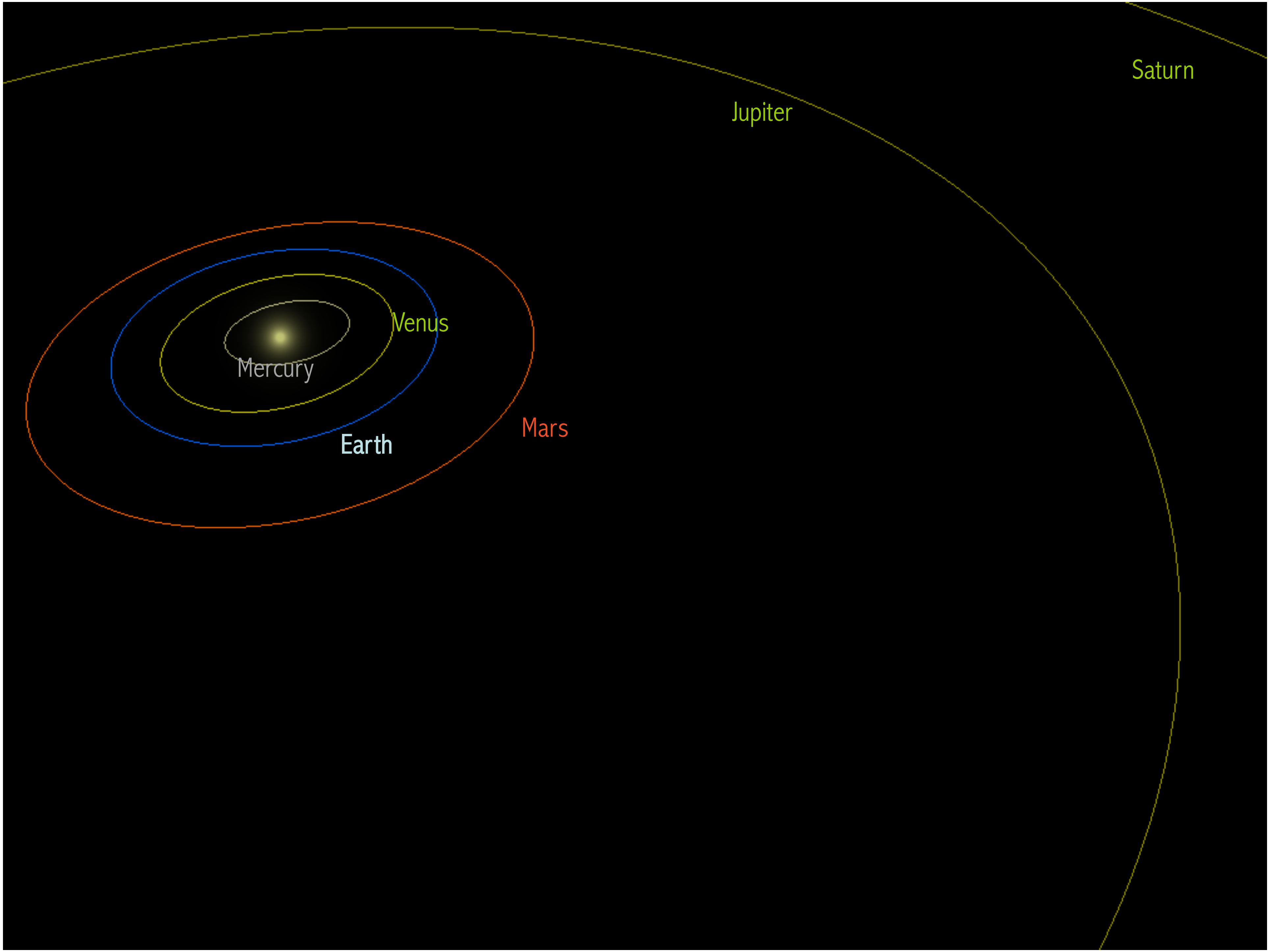
Radar image of craters on Venus *Magellan*

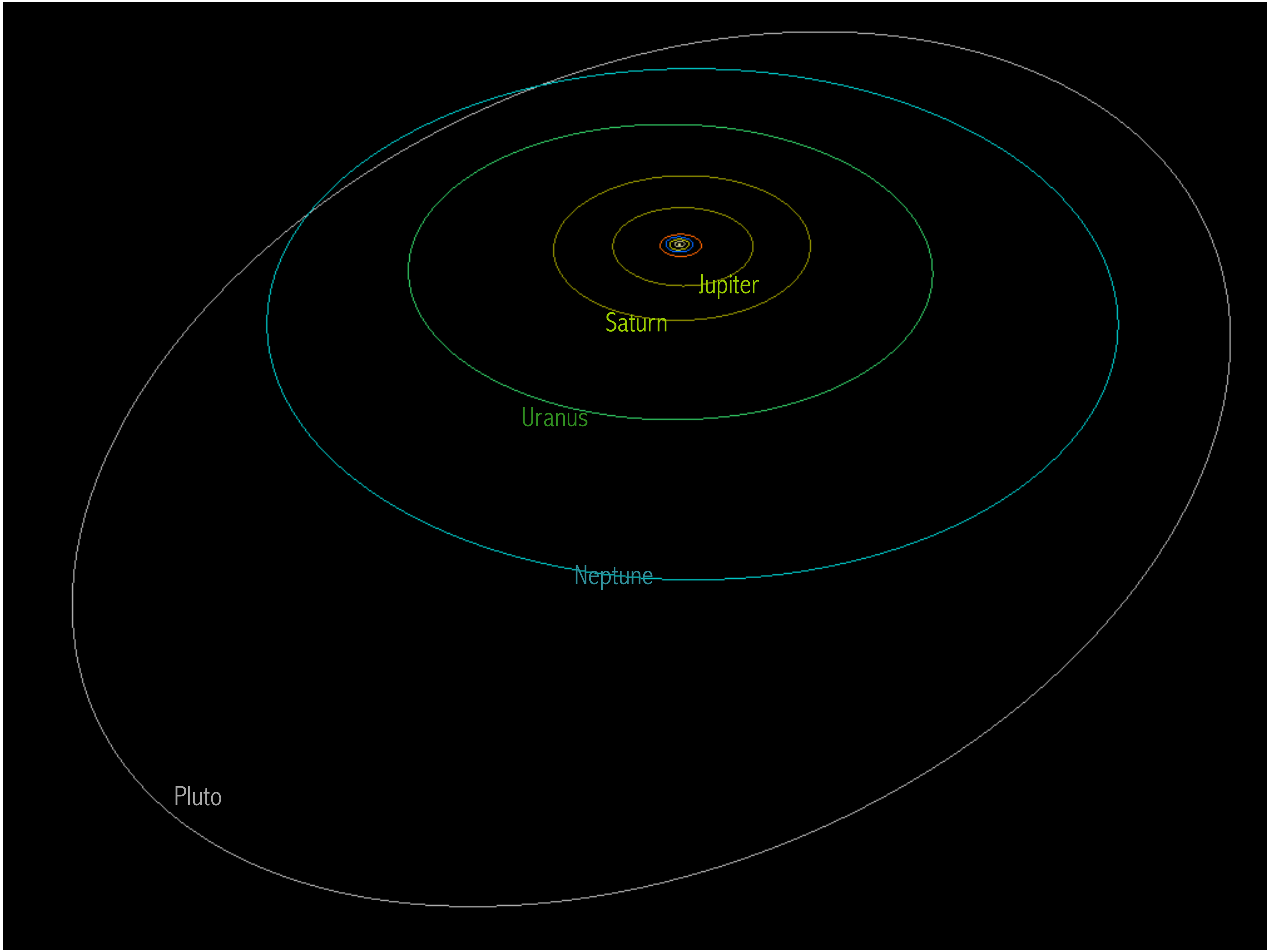


Jupiter w/ Europa’s shadow *Cassini*

Solar System Planets




Saturn
Jupiter
Venus
Mercury
Mars
Earth

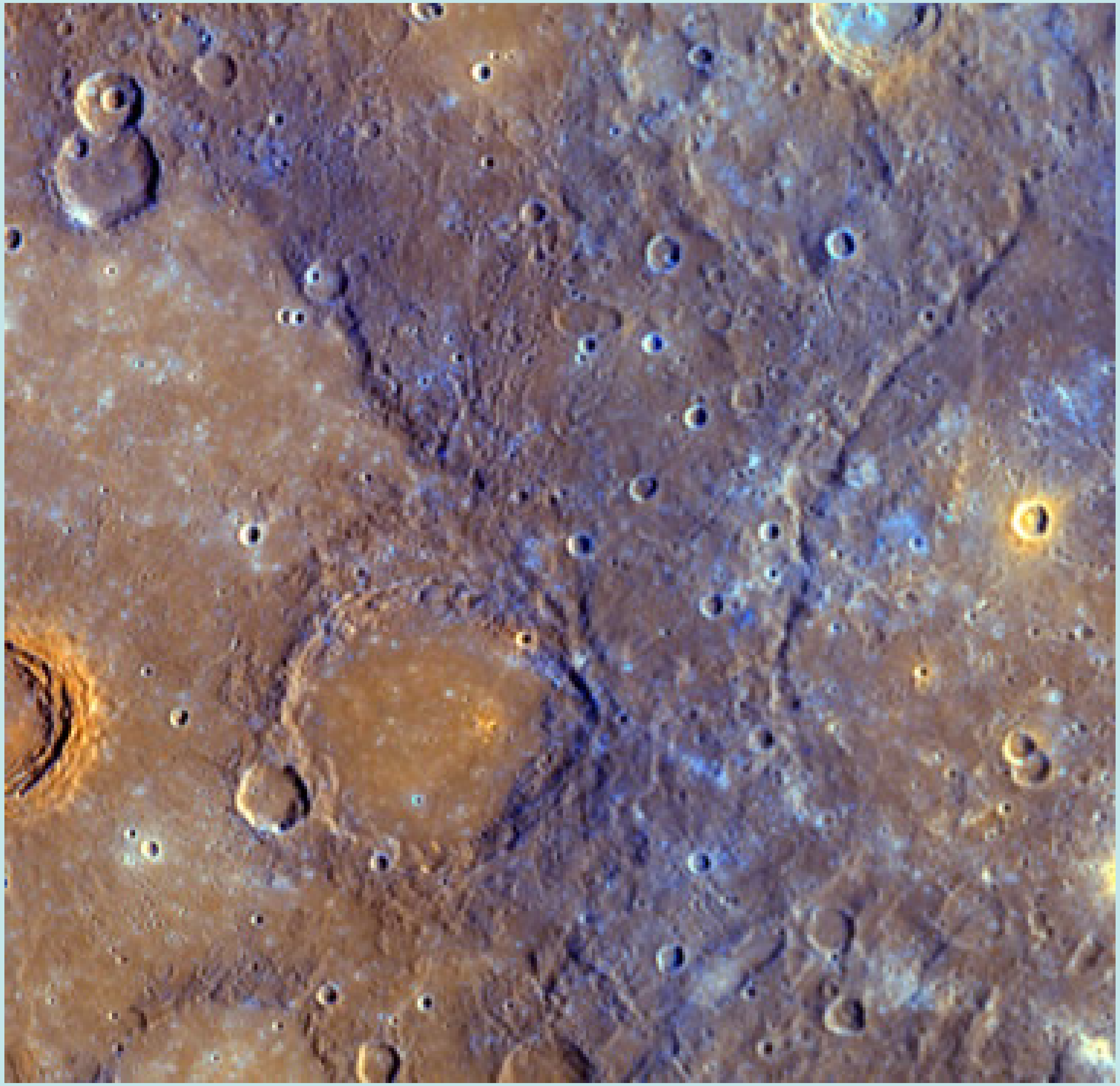

Jupiter
Saturn
Uranus
Neptune
Pluto

Mercury

Mariner 10 mosaic

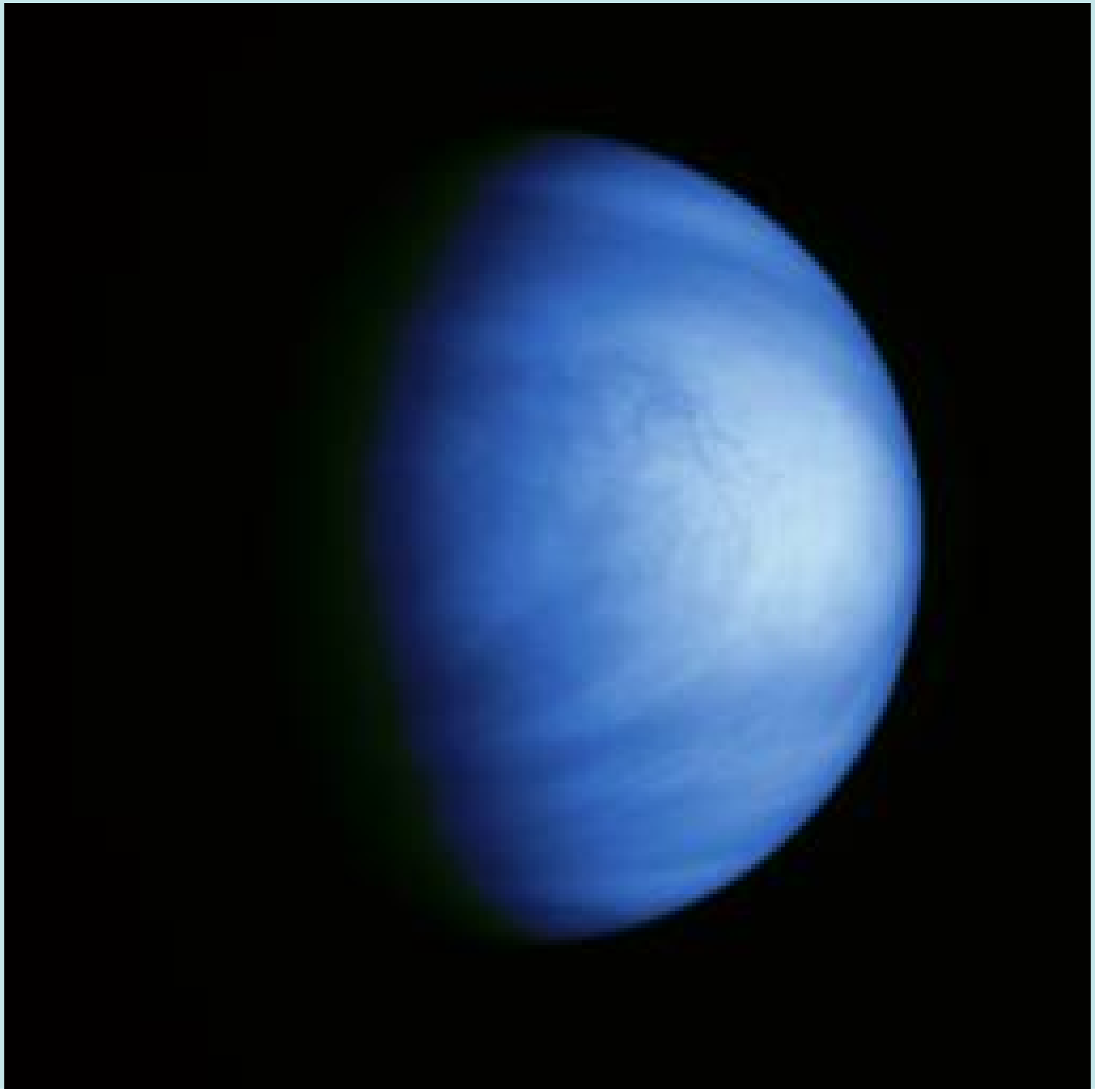
Mercury

MESSENGER close-up (enhanced color)



Venus

Violet light - Galileo spacecraft image



Venus

RADAR - Magellan spacecraft image

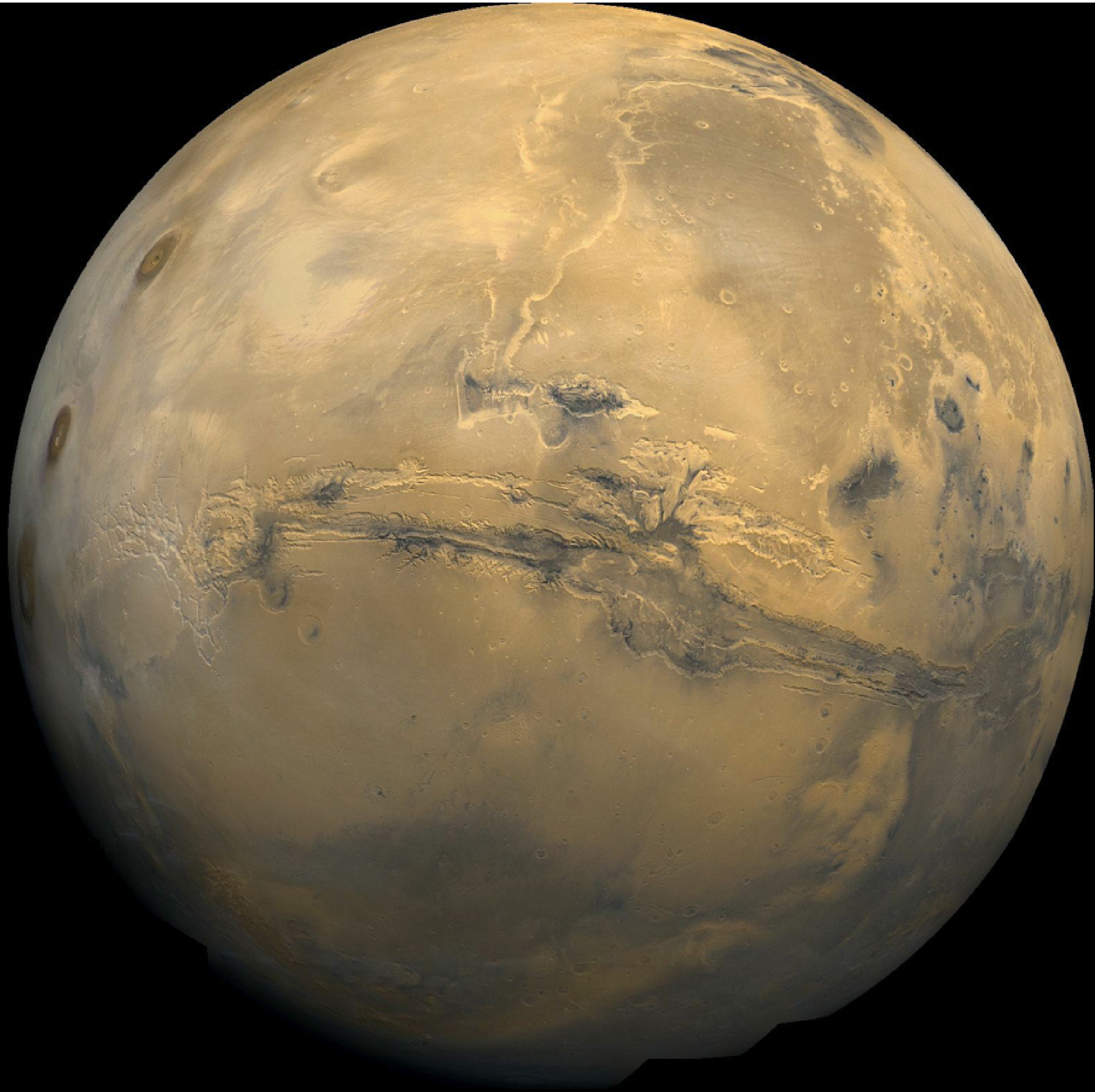
Earth

Moon

Meteor Crater

Arizona, USA Smithsonian 1938

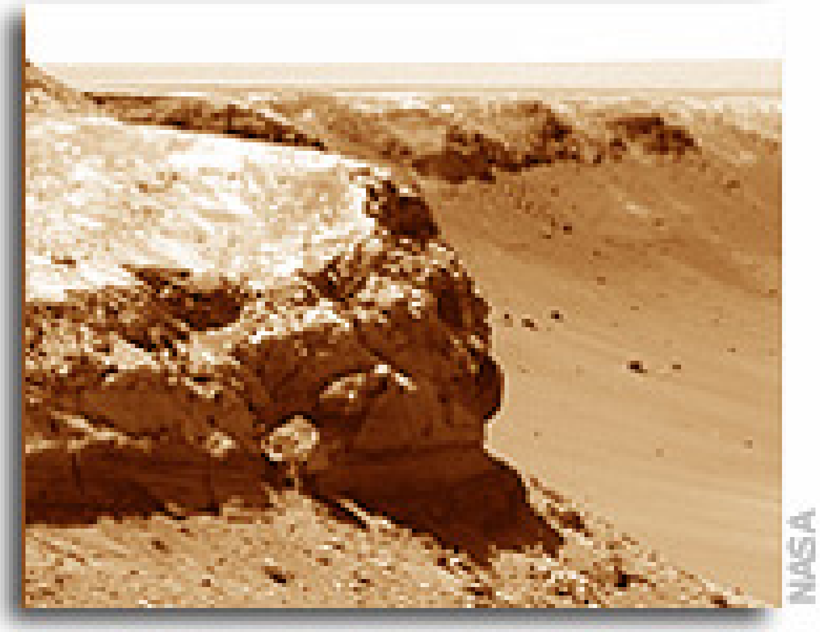
Asteroid Eros

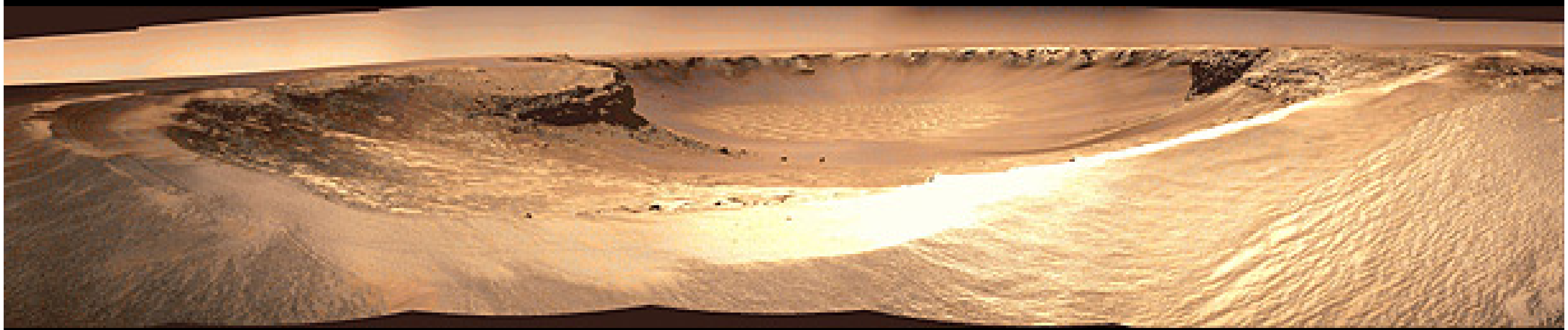


Mars

True-color composite image, taken by Mars Exploration Rover Spirit, shows Martian landscape.

Mars Surface - Opportunity Rover at Victoria Crater





Asteroid Ida and its moon, Dactyl

Sikhote-Alin (eastern USSR) **Iron IIB** Fall 1947 Feb 12

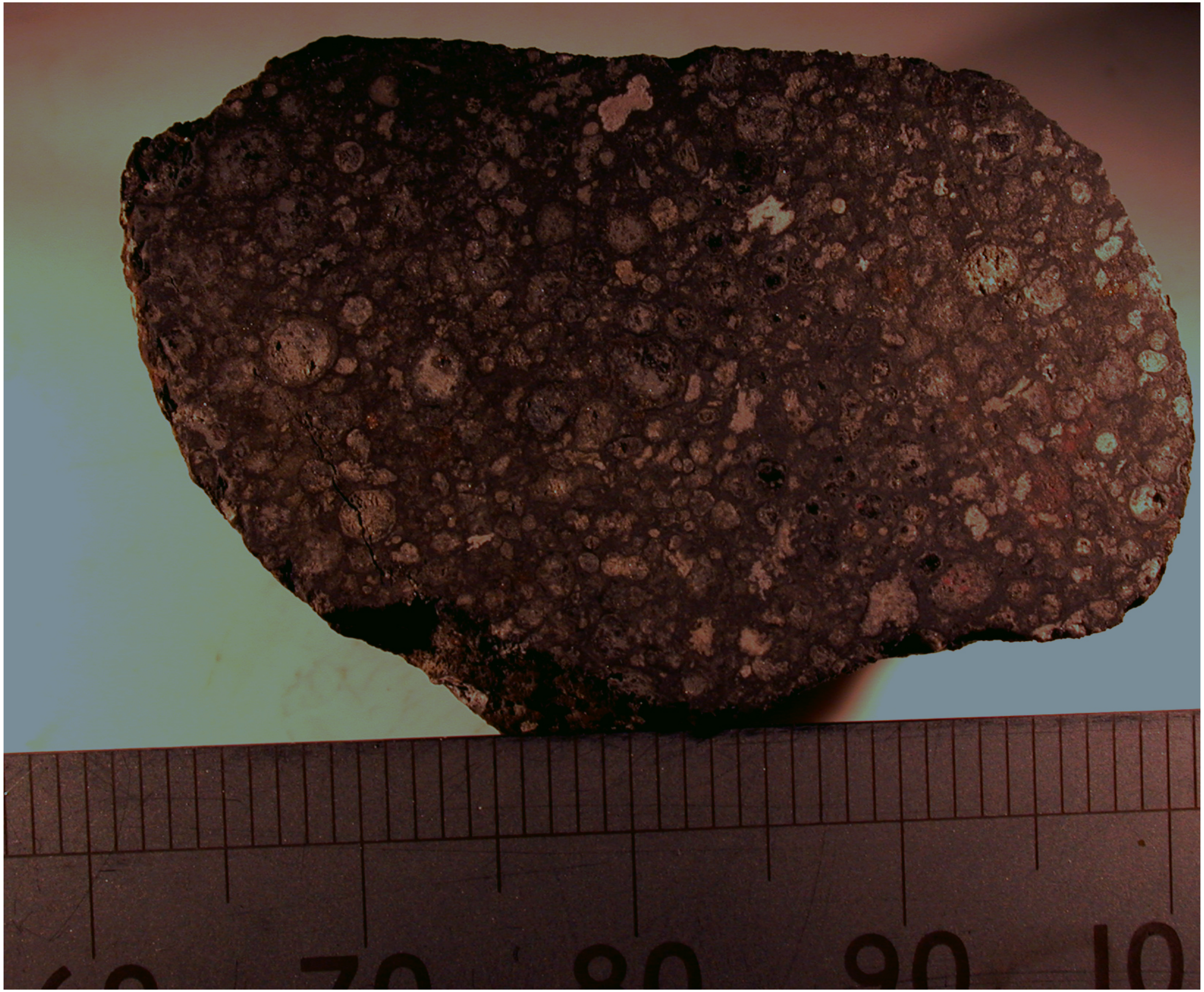
Photo: Jackie Beckett

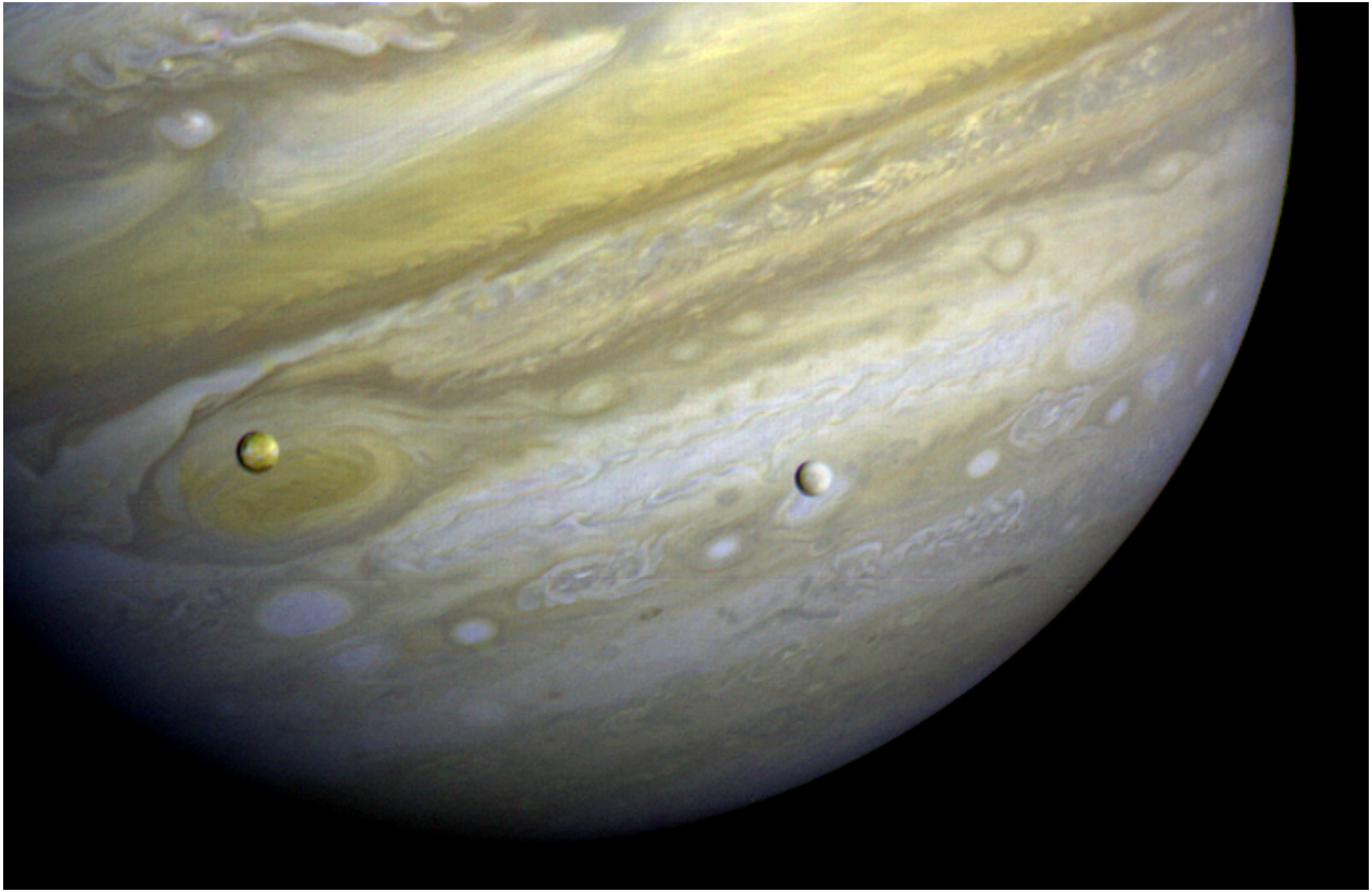
Cape York (Greenland) *"Ahnighito"* **Iron** 31 metric tons

Allende CV3 Carbonaceous Chondrite Meteorite

Close-up view.
This piece is 39 mm long.

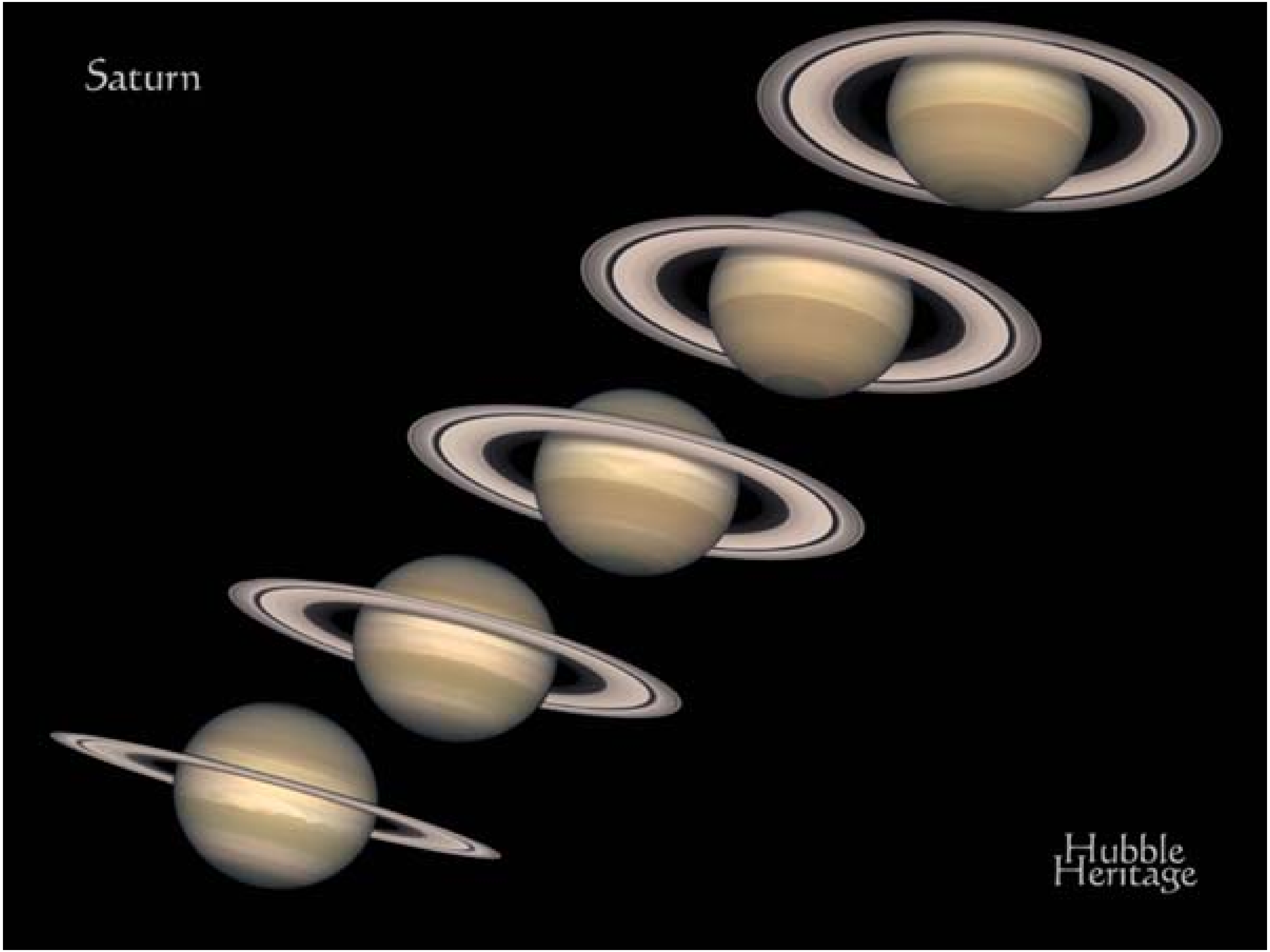
Note CAIs & chondrules.



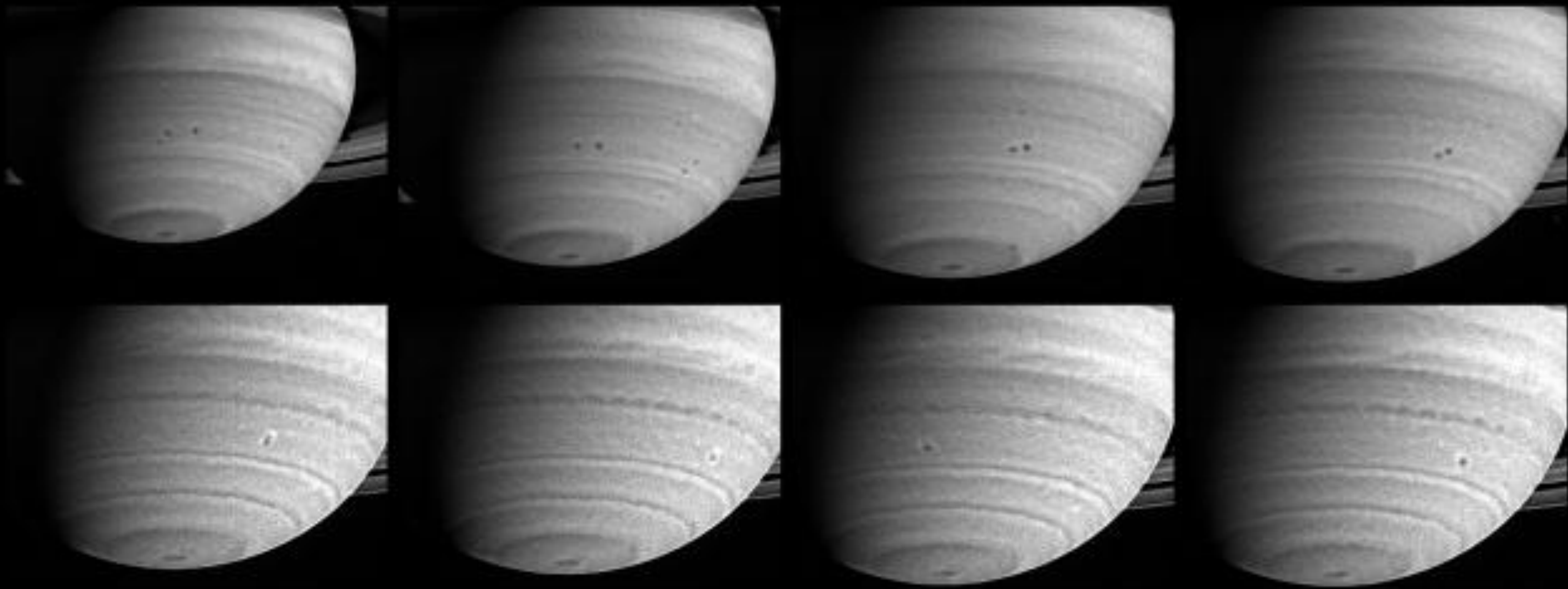


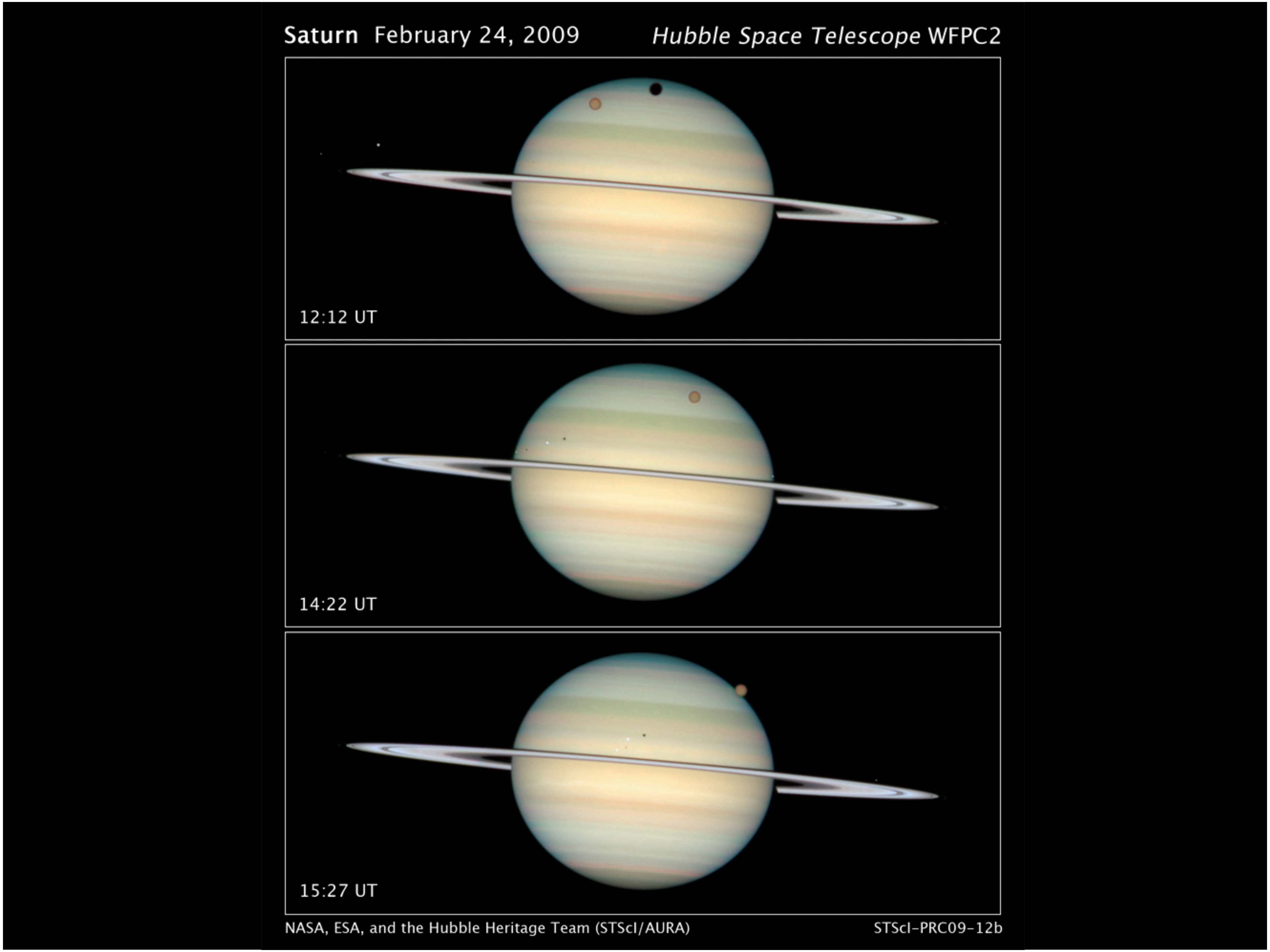
Jupiter, Io & Europa

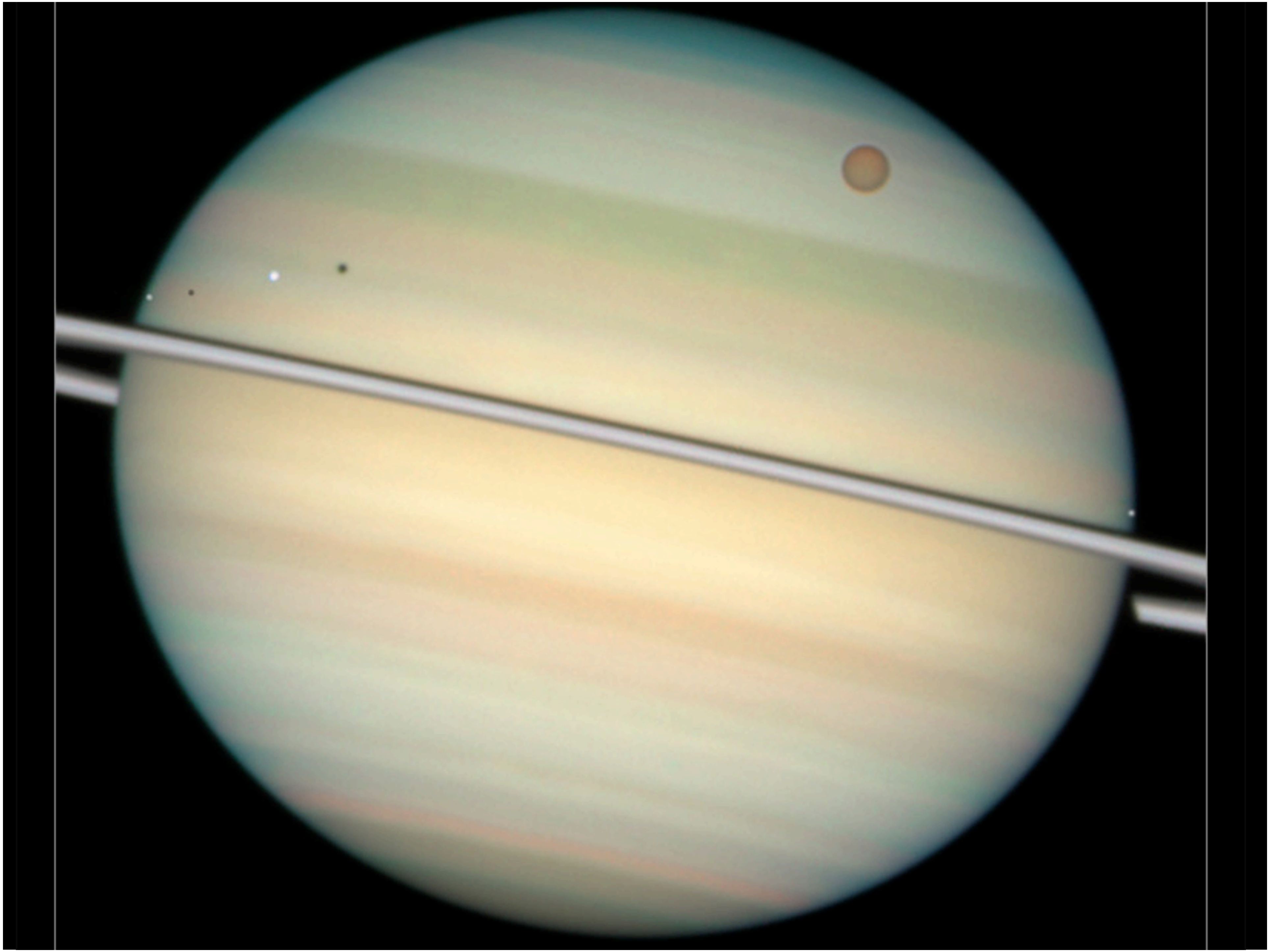
Jupiter's four largest satellites


Saturn
Hubble Heritage

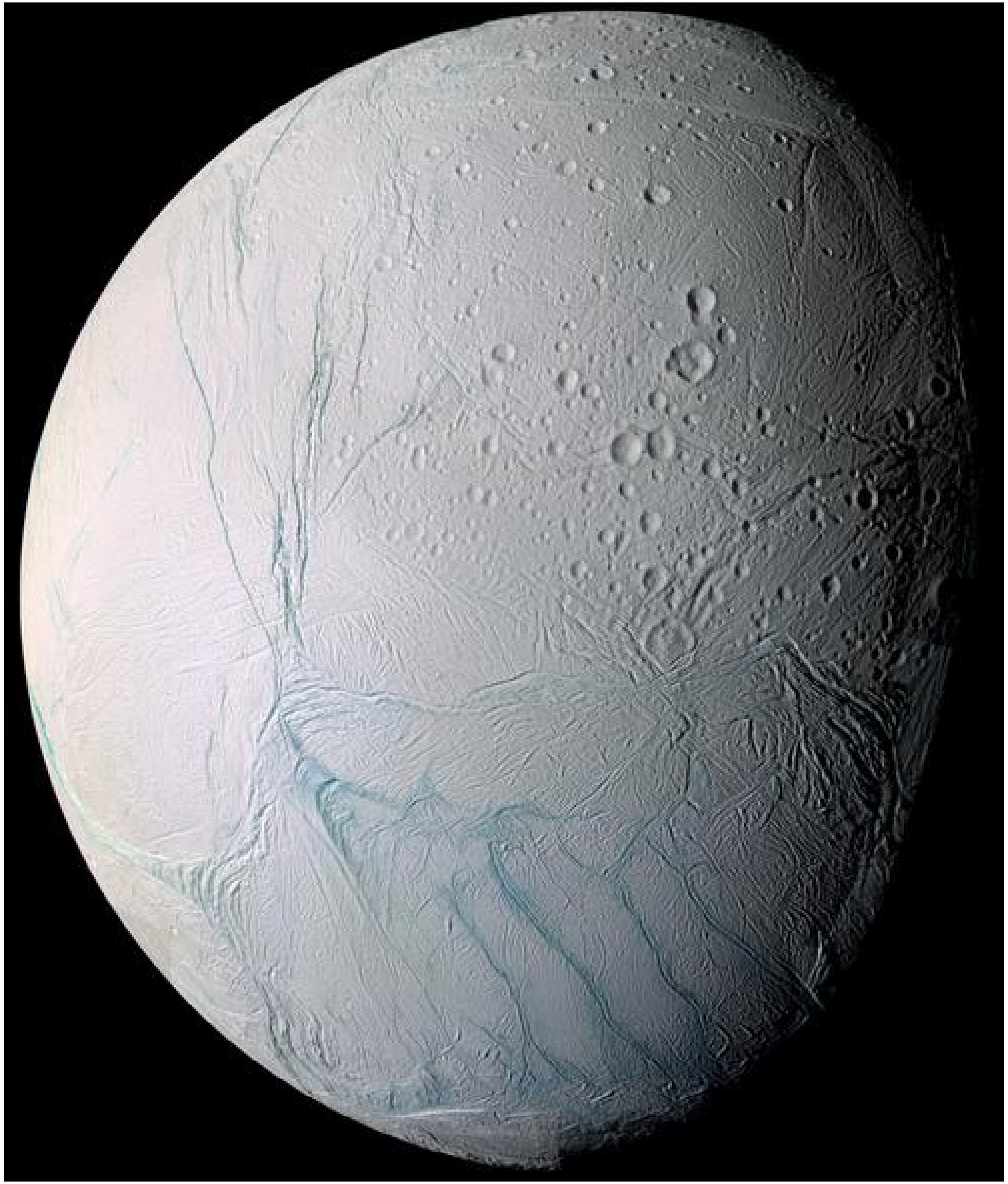
Merging Storms on Saturn
(2004 - Cassini Images)




Saturn February 24, 2009
Hubble Space Telescope WFPC2
12:12 UT
14:22 UT
15:27 UT
NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
STScI-PRC09-12b

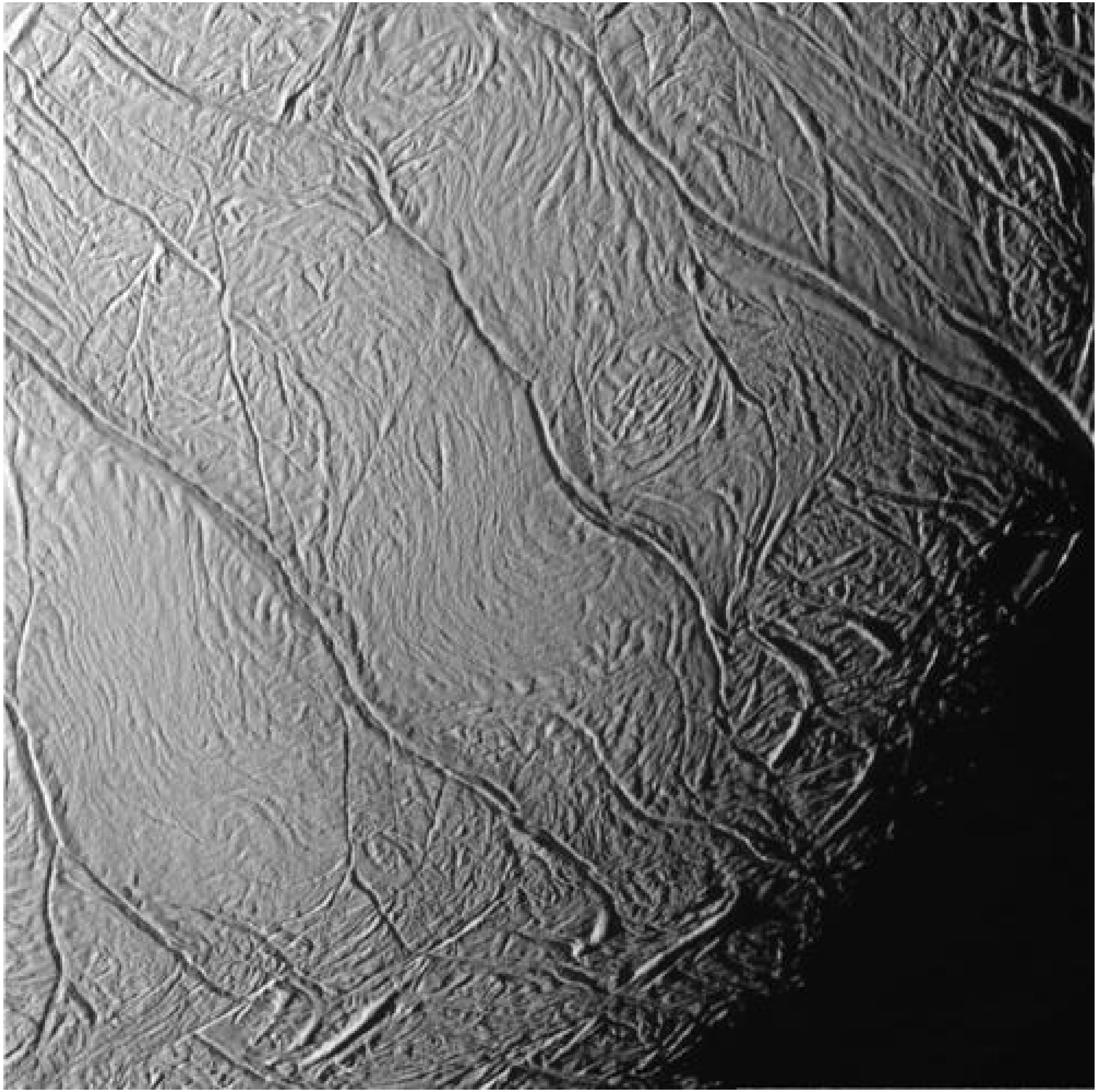


Enceladus

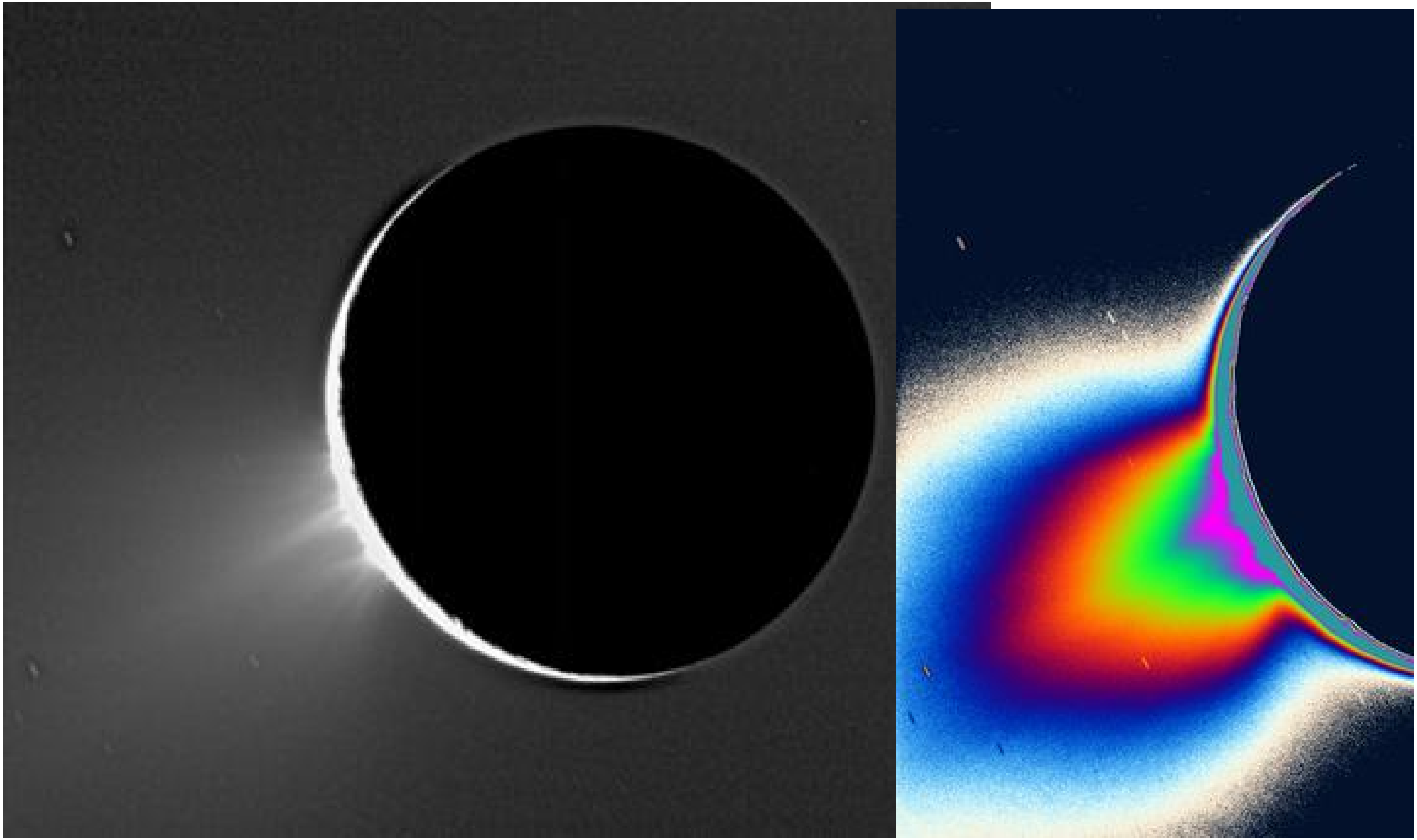


Enceladus:

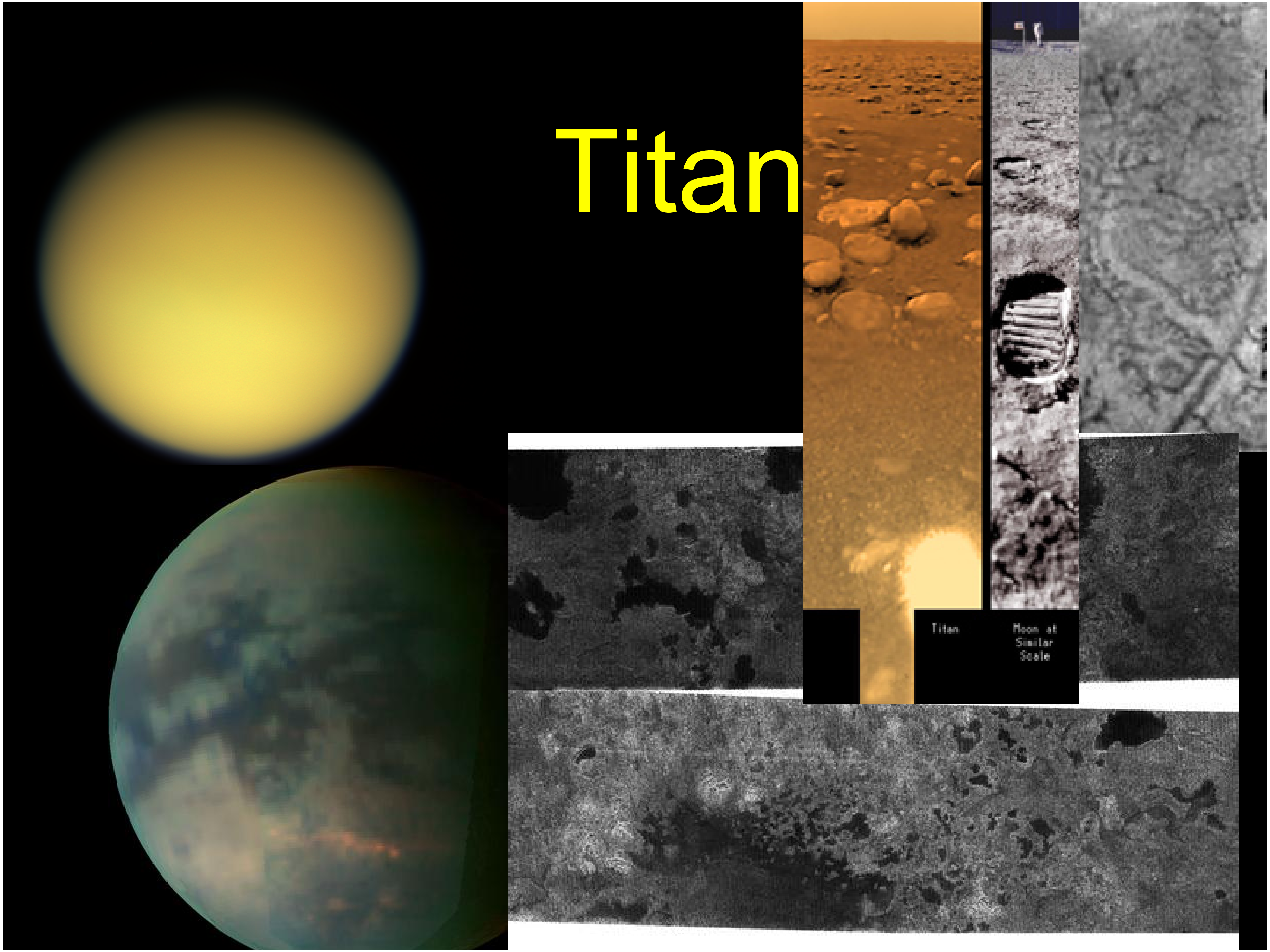
‘Tiger Stripes’



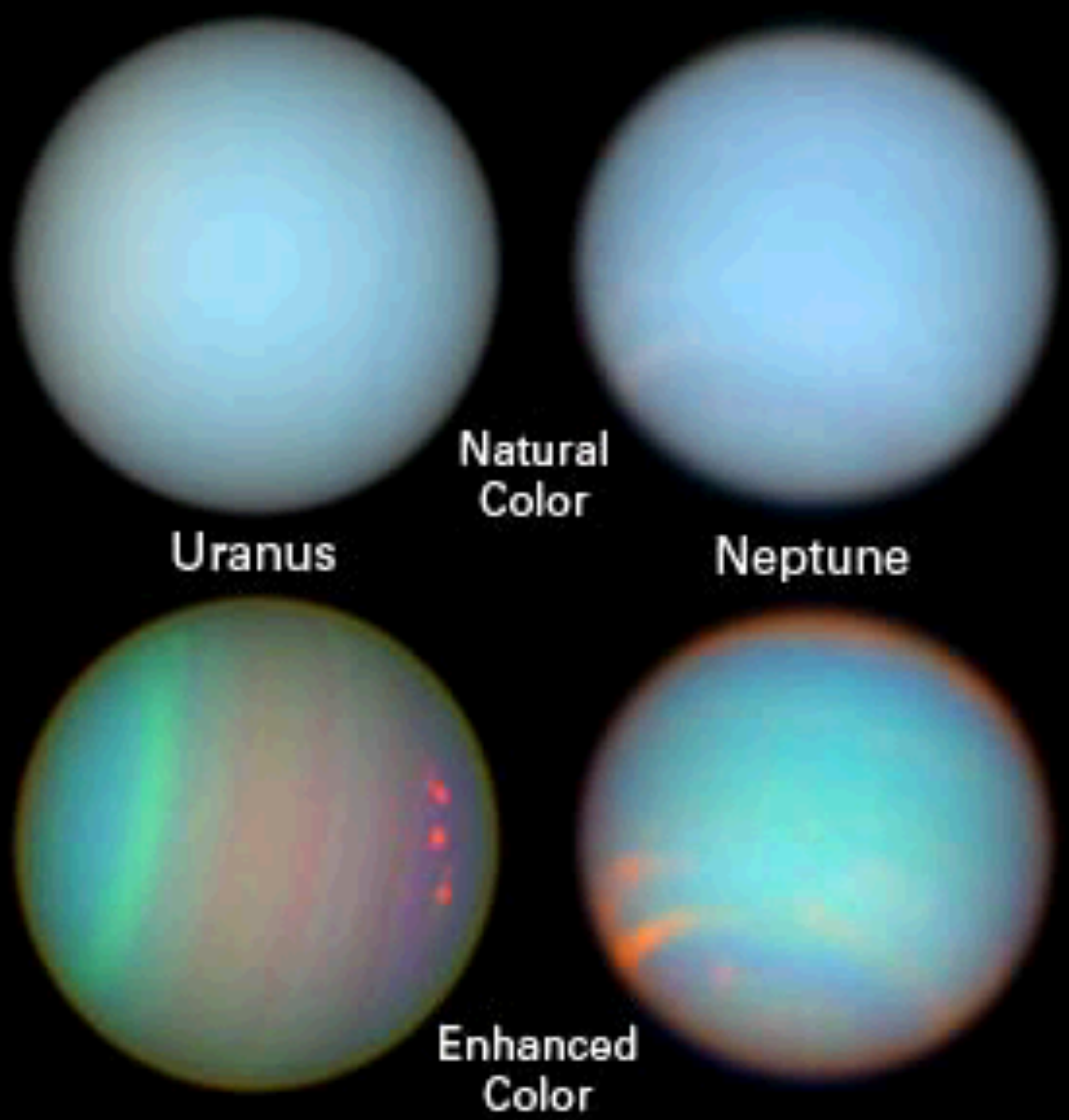
Plumes from Enceladus



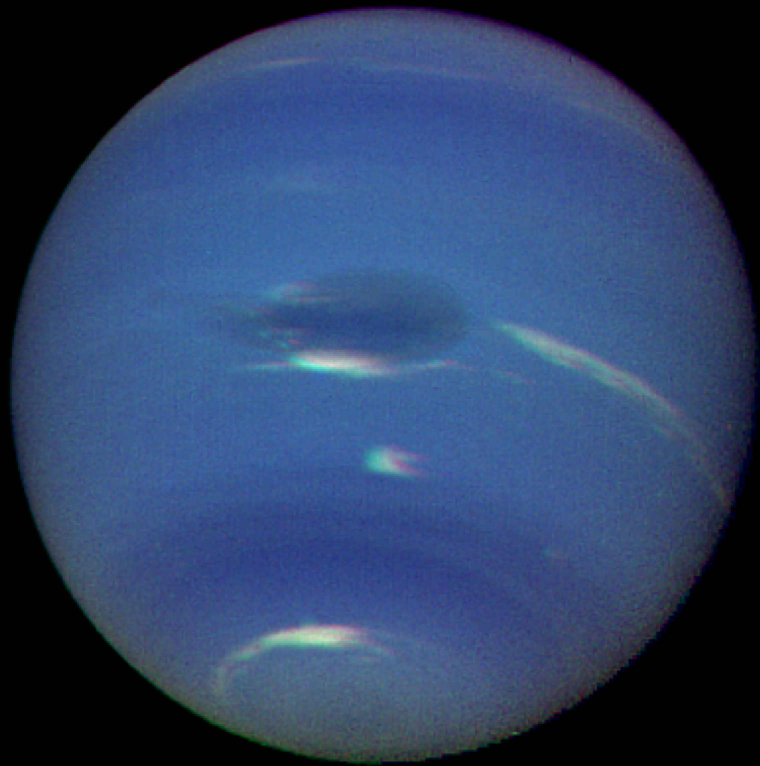
Titan



HST/ACS images 2003

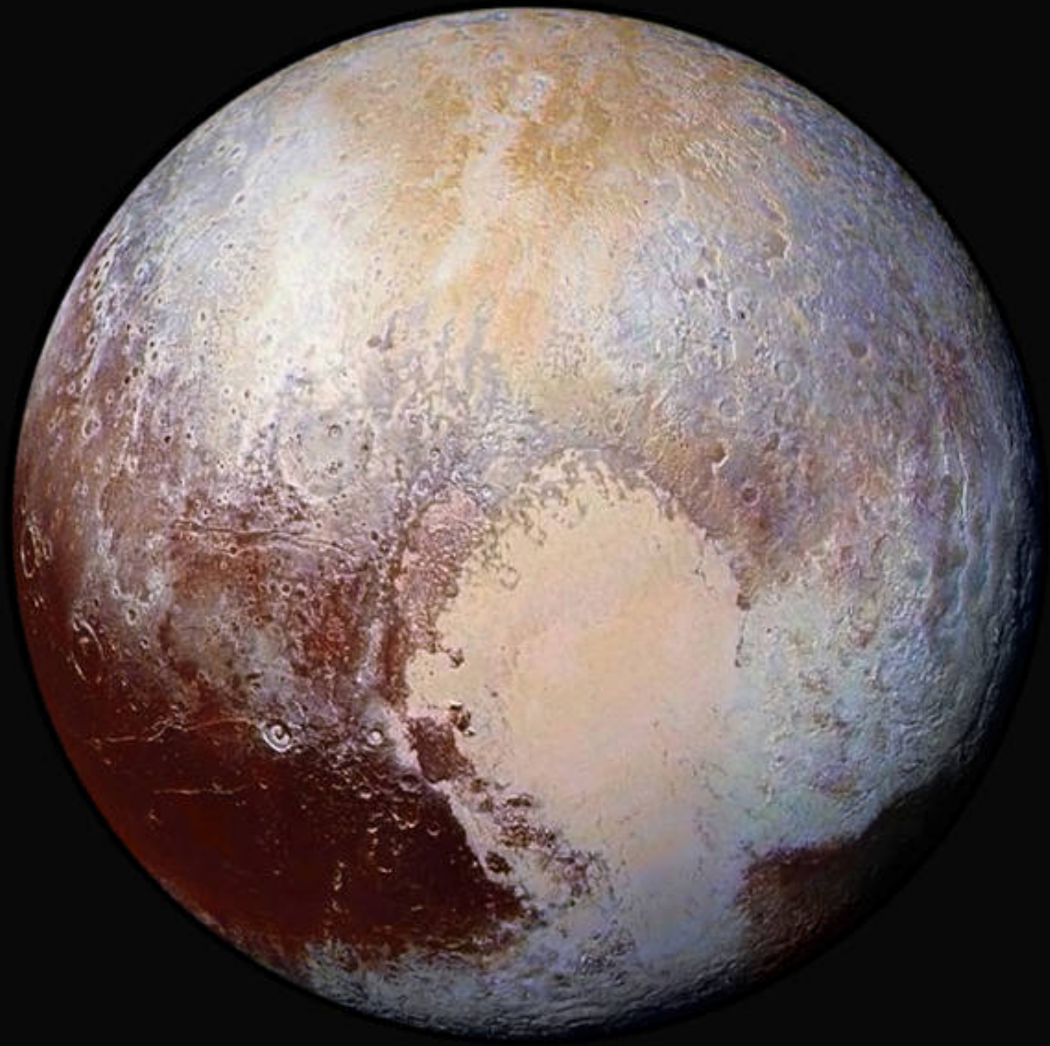


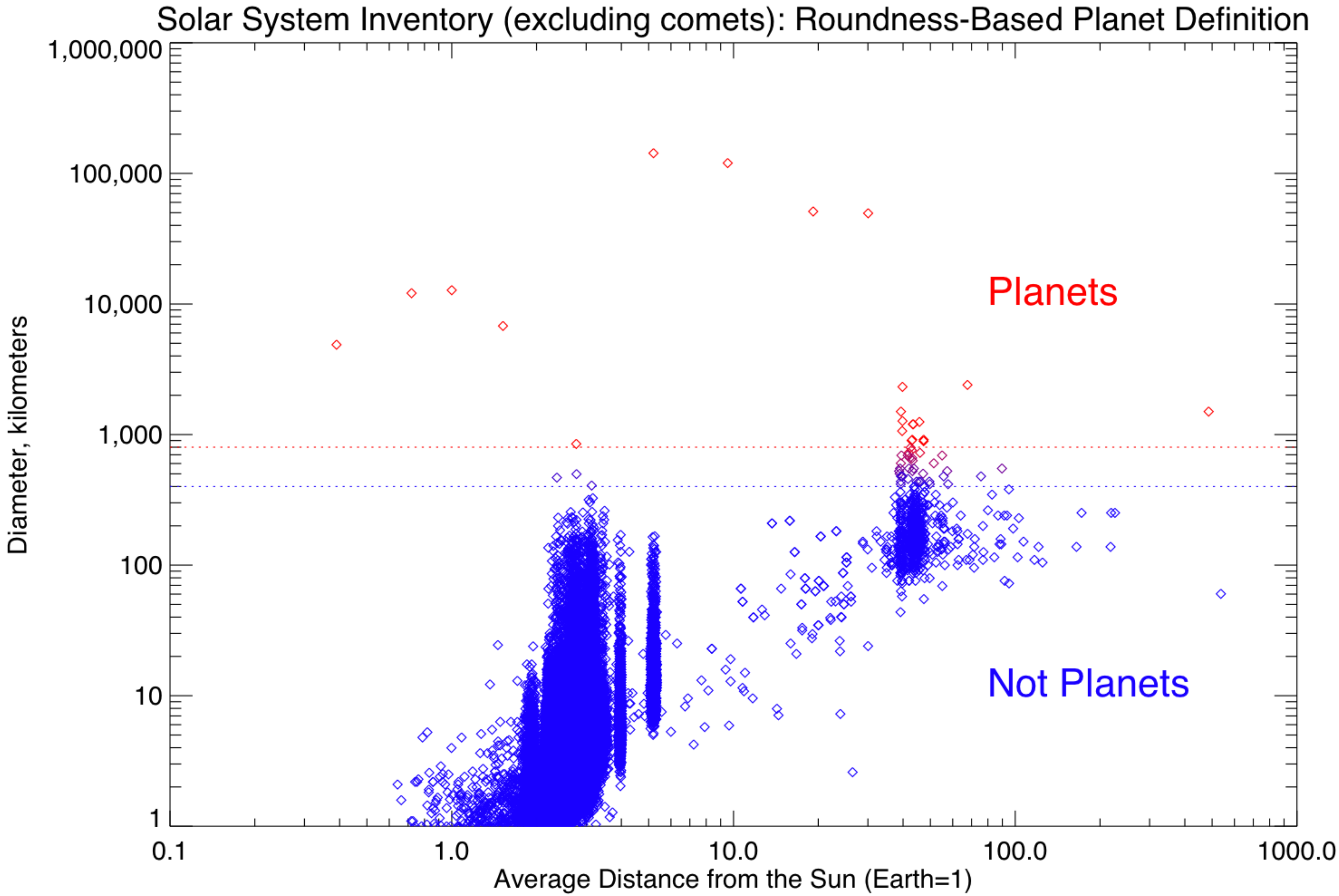
Neptune - Voyager



Triton – Neptune's large moon

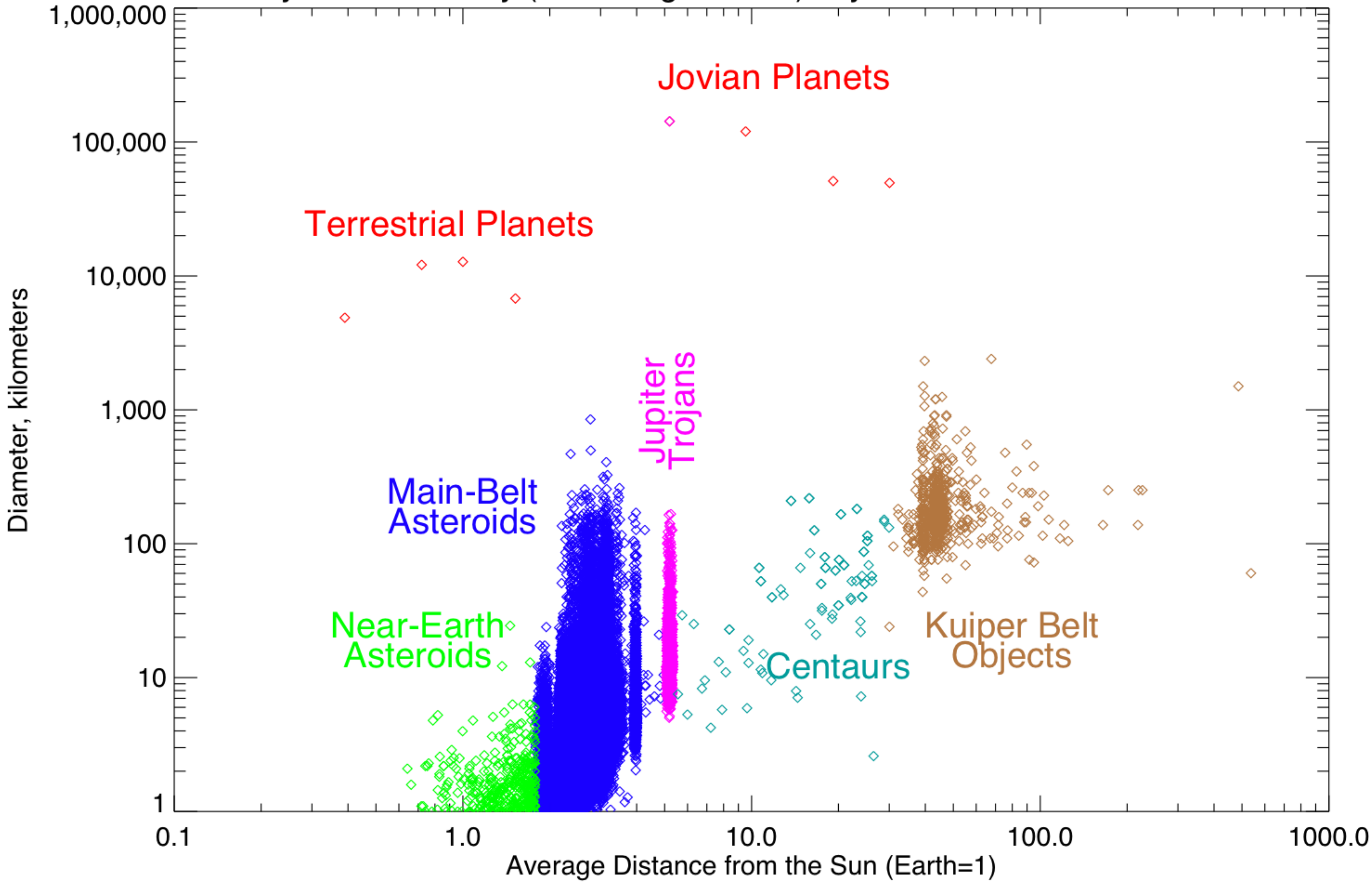
Pluto – New Horizons (false color)





John Spencer, SwRI

Solar System Inventory (excluding comets): Dynamics-Based Planet Definition



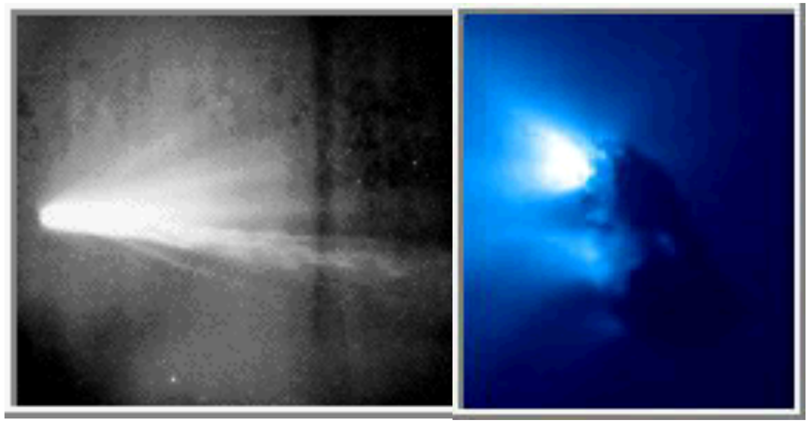
John Spencer,

Small Bodies: Asteroids, Comets, KBOs

- Asteroid = Minor planet with $a < 6$ AU

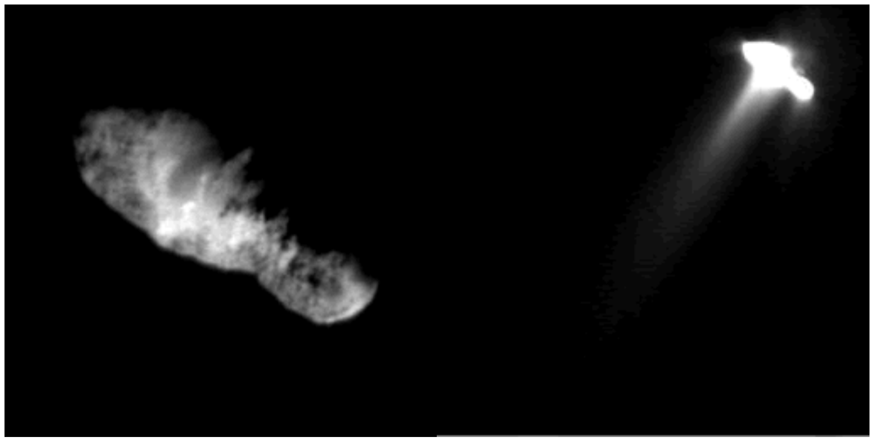
Asteroid 433 Eros

- Comet = Diffuse coma, tails



Comet 1P/Halley

Comet 19P/Borrelly



- Kuiper belt/KBOs

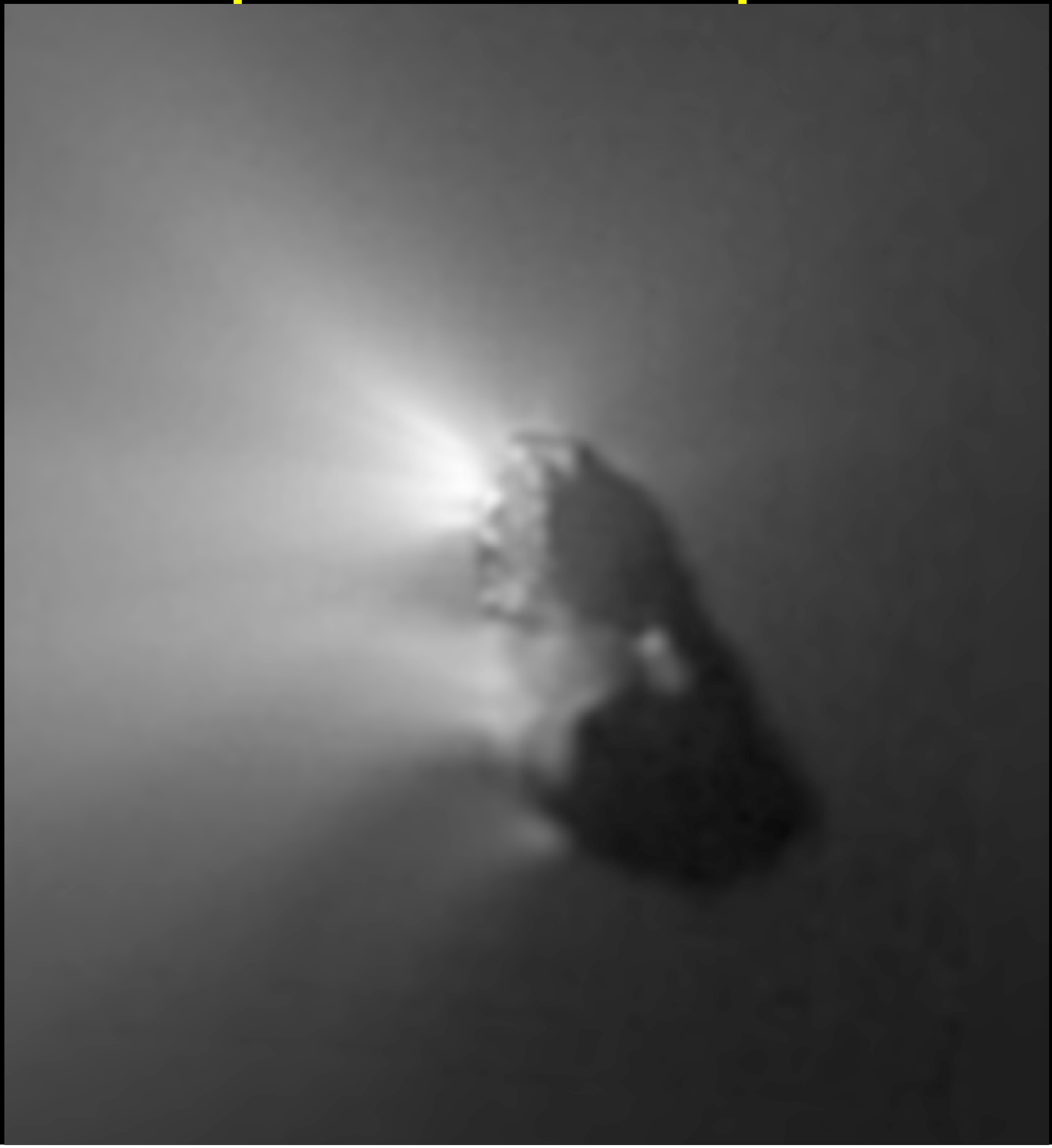
Comets Hyakutake & Hale-Bopp

1996

Comet Halley

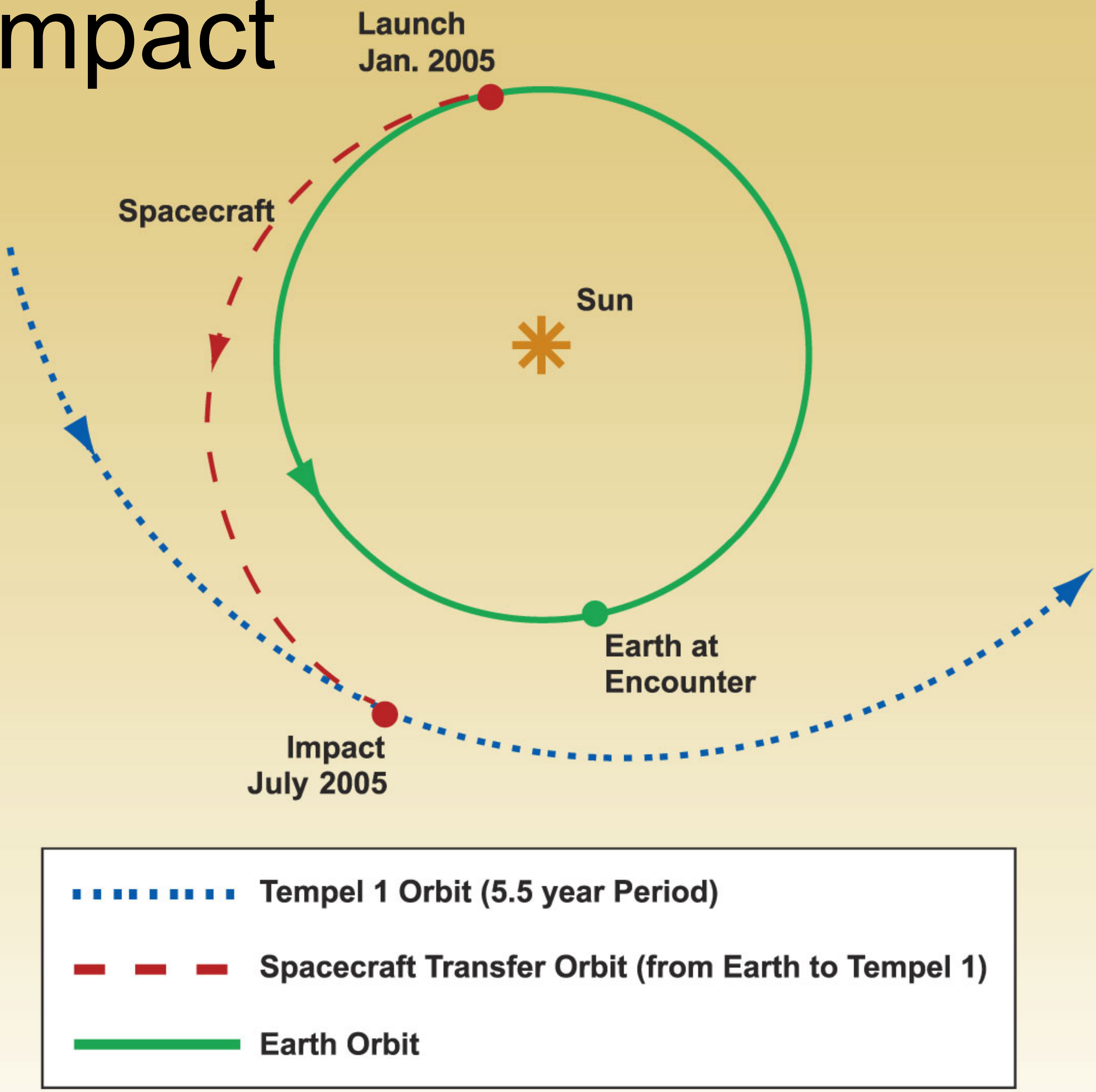
Comet Halley

Close-up -- *Giotto* Spacecraft

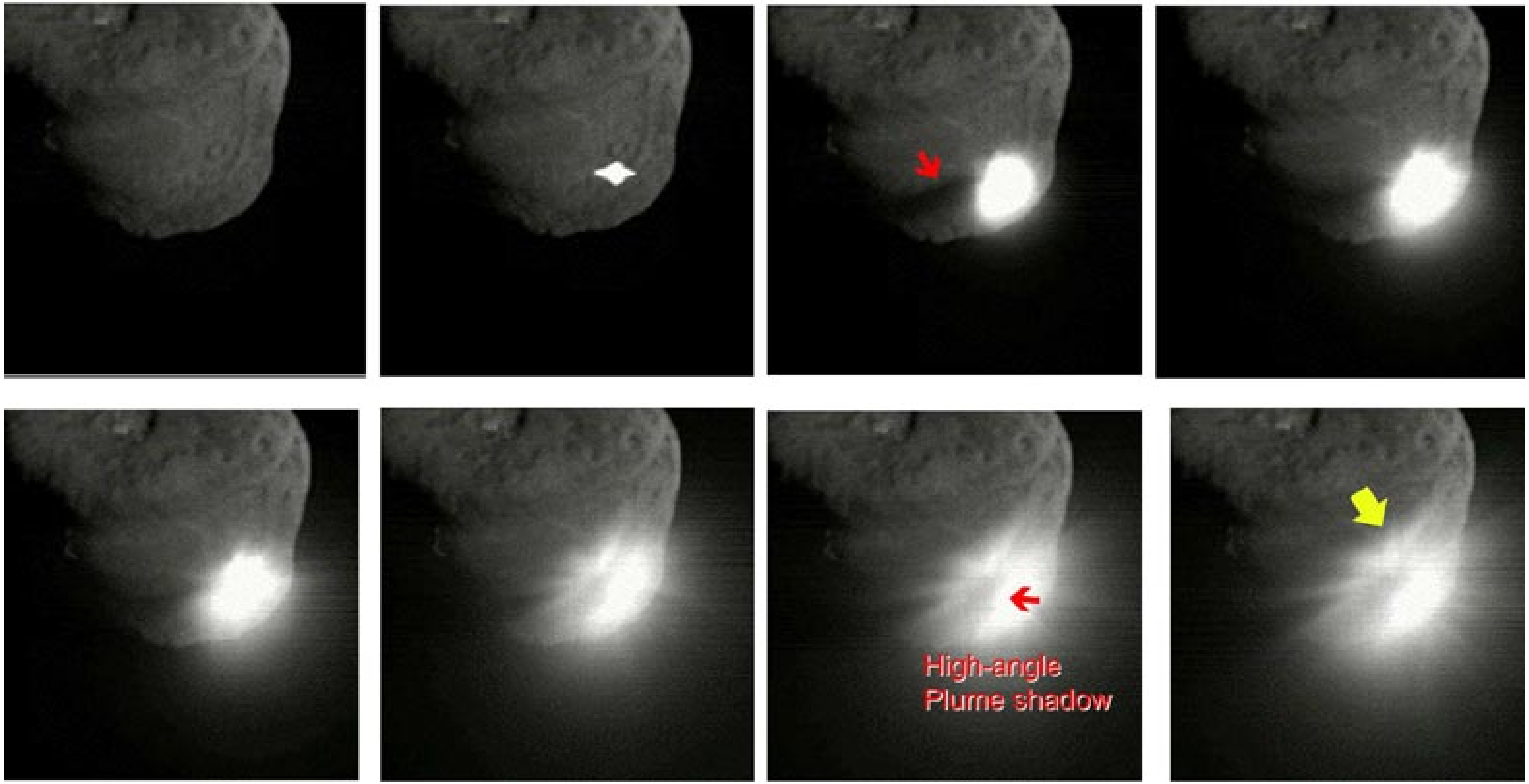


P/Wild 2 Stardust 20 m res.

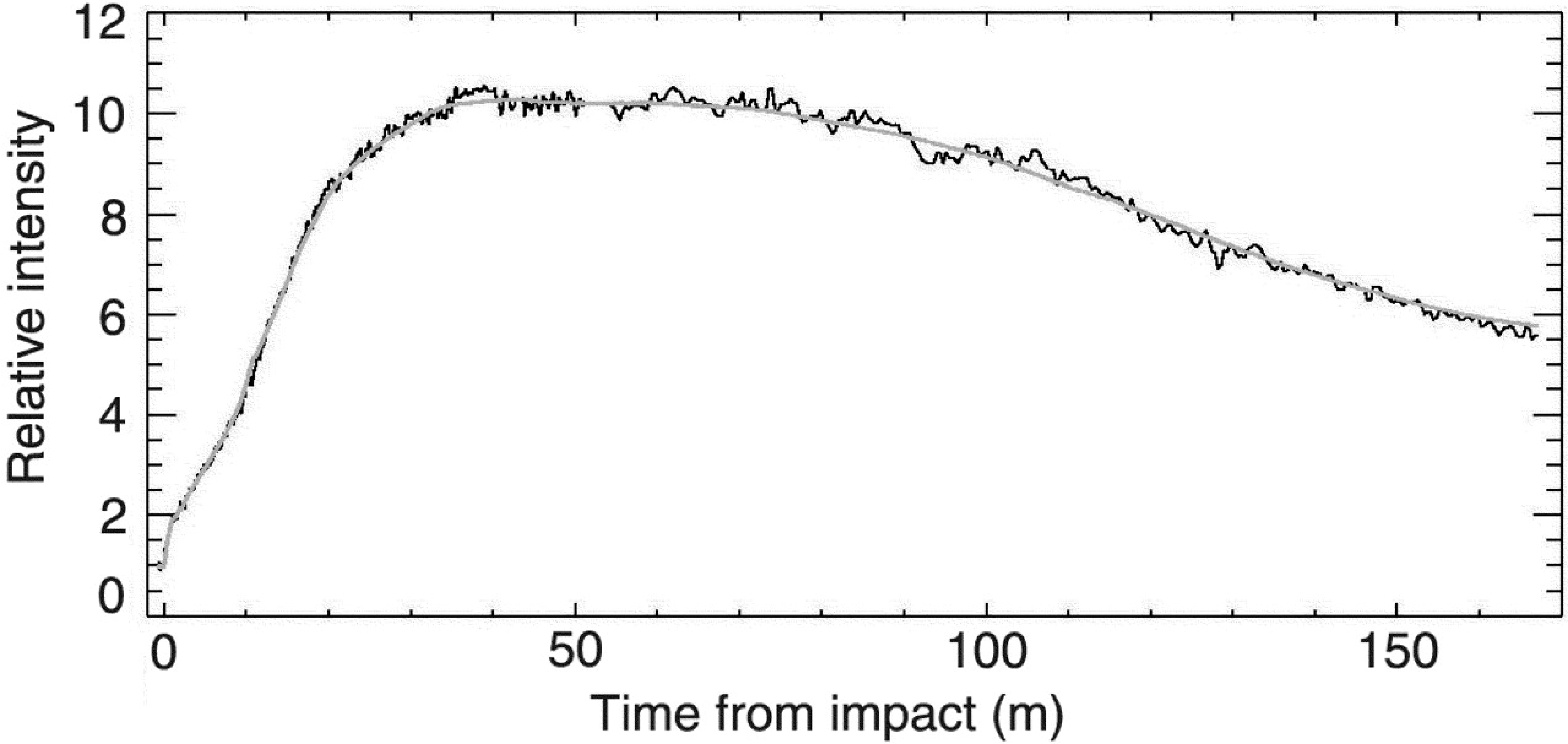
Deep Impact


Launch
Jan. 2005
Spacecraft
Sun
Earth at
Encounter
Impact
July 2005
Tempel 1 Orbit (5.5 year Period)
Spacecraft Transfer Orbit (from Earth to Tempel 1)
Earth Orbit

The Impact (images span 6 seconds)

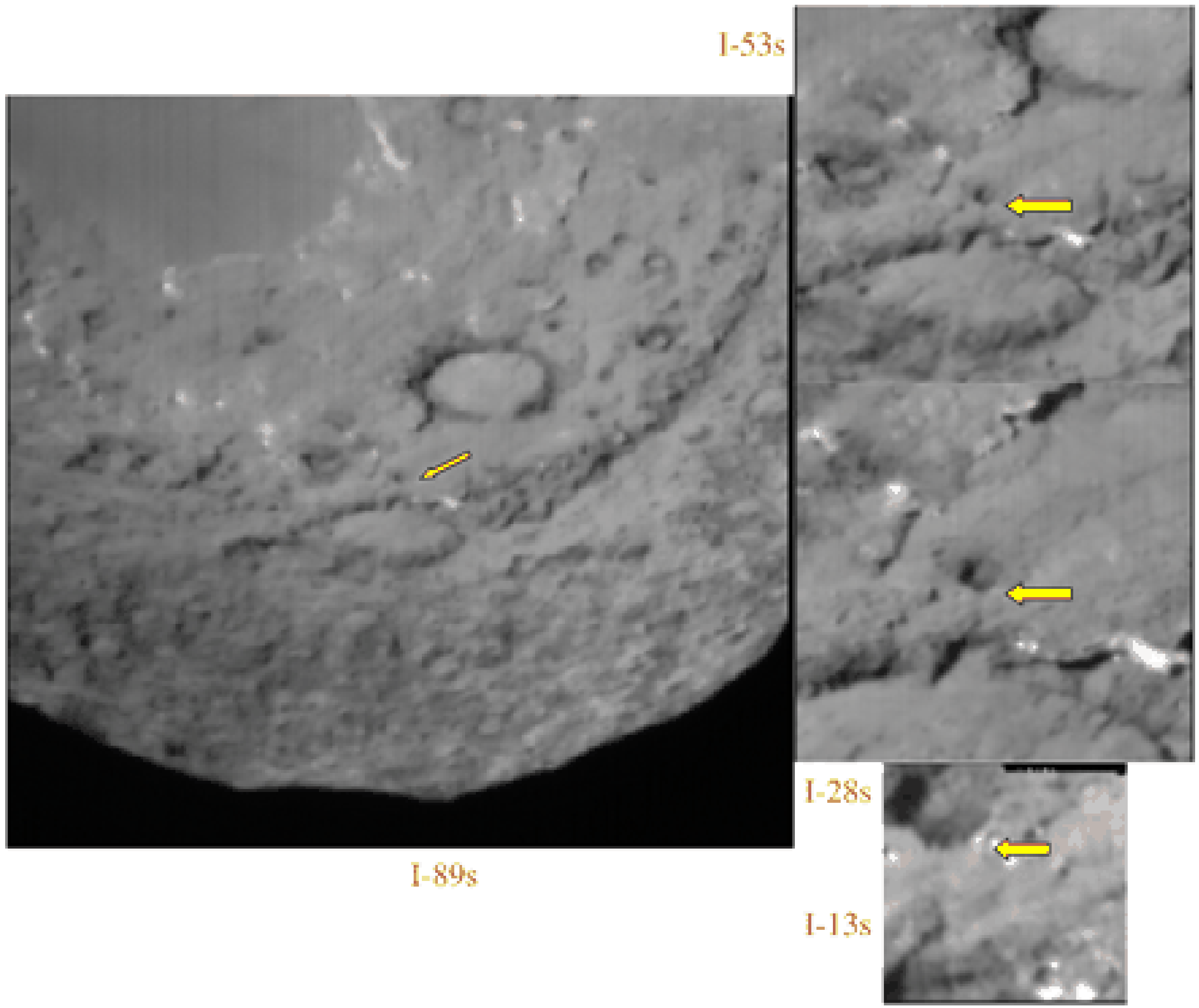


Lightcurve

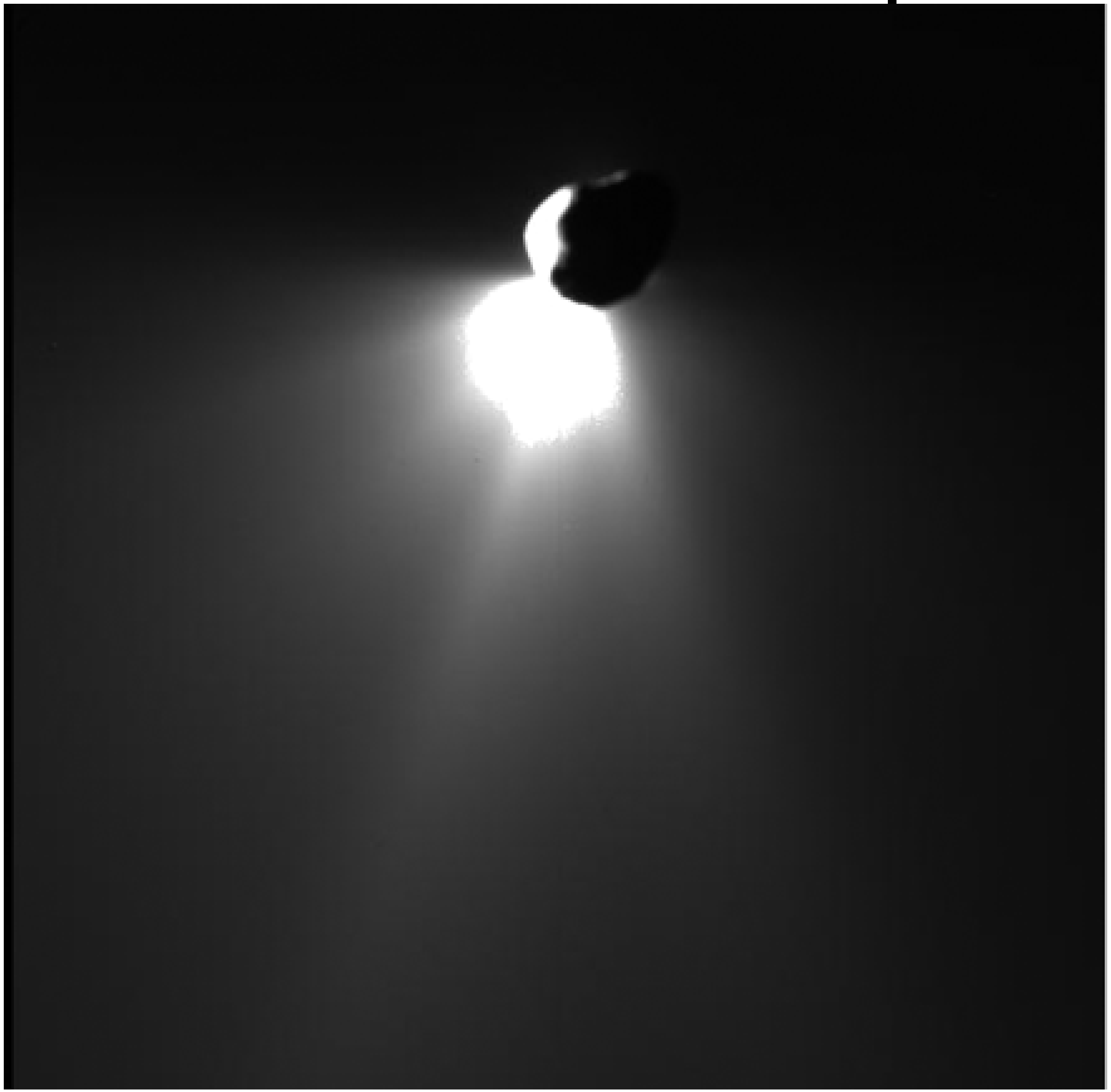


Relative intensity
Time from impact (m)
0
2
4
6
8
10
12
0
50
100
150

Impact Site prior to the impact

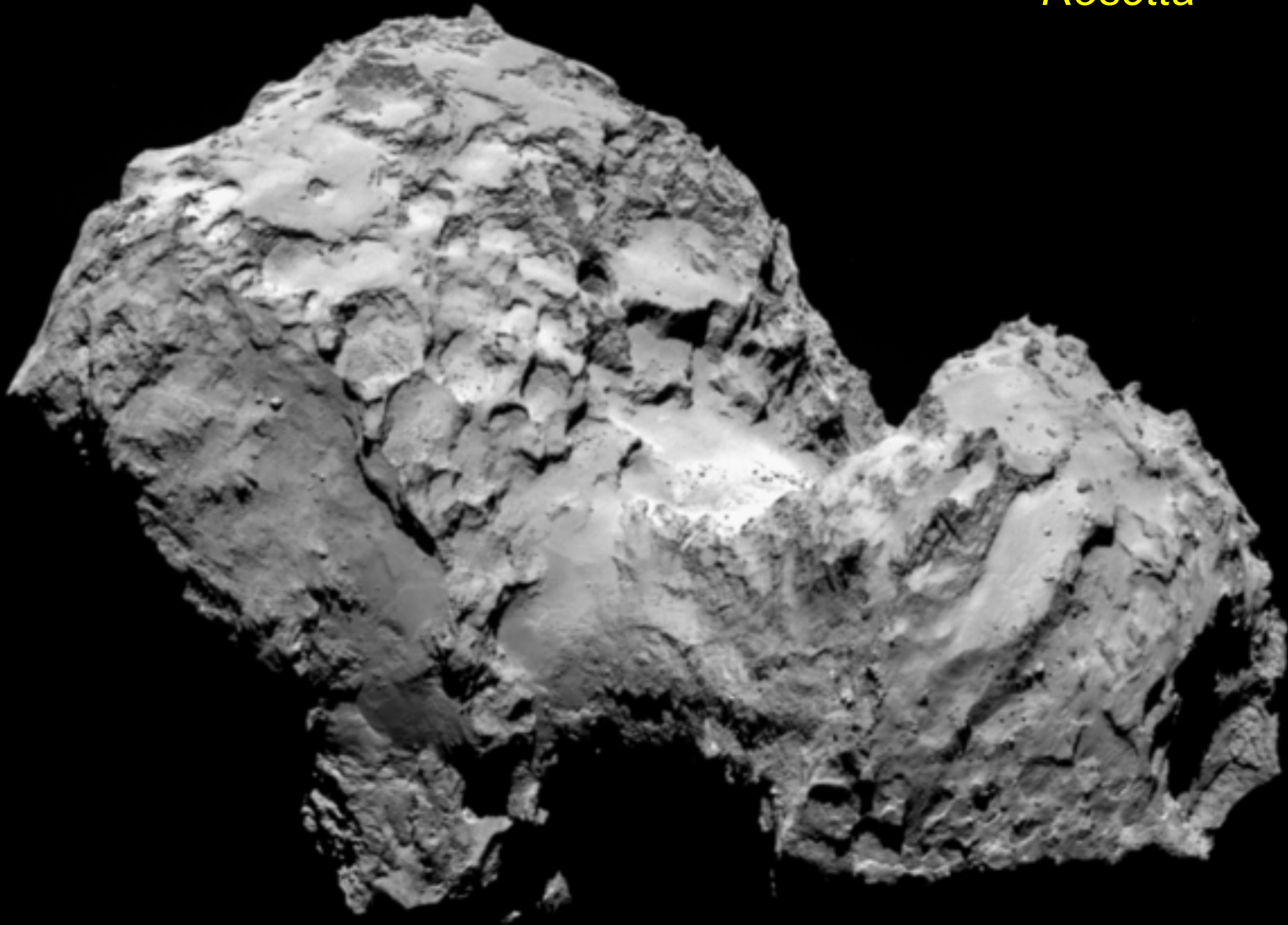


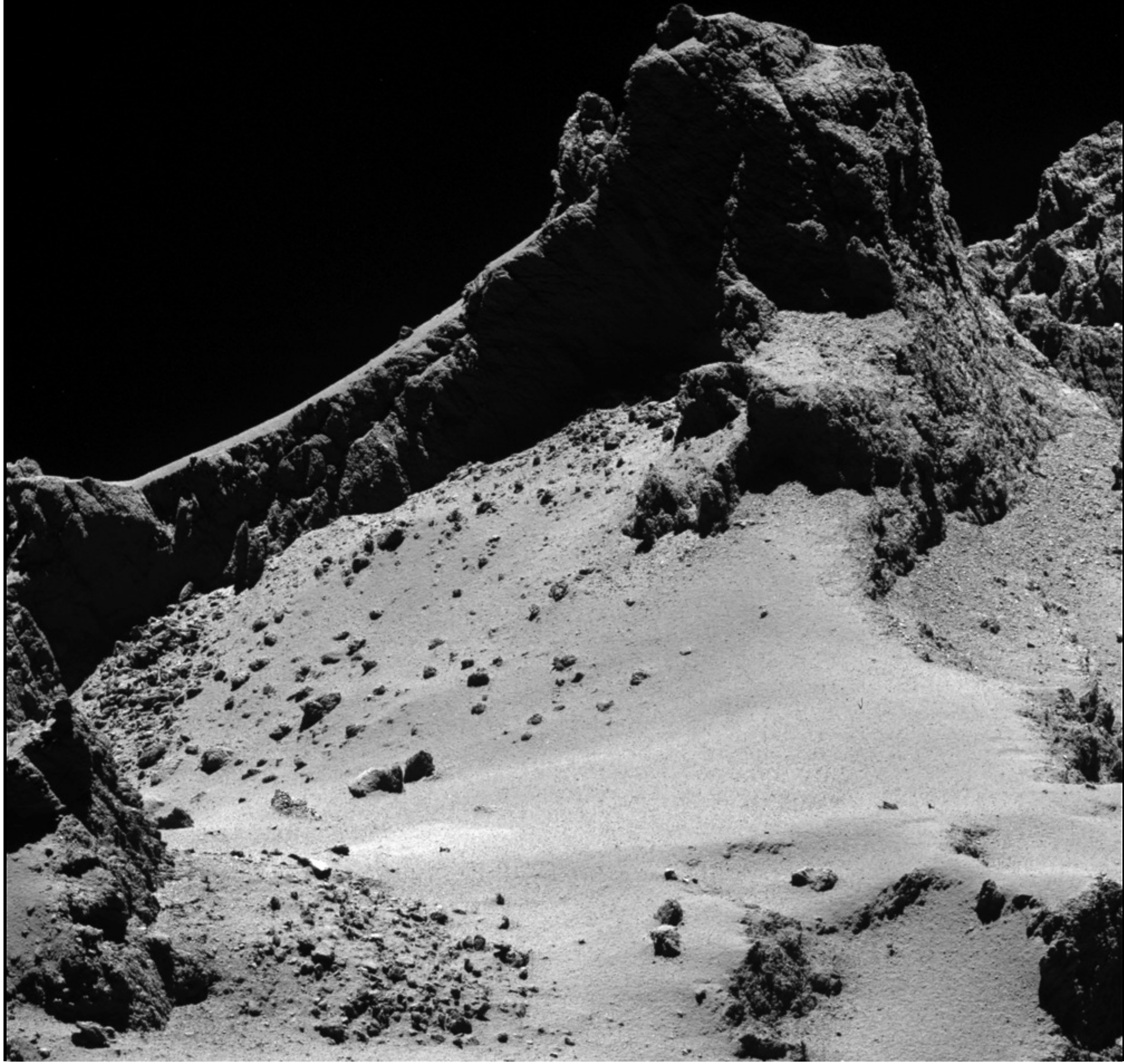
45 minutes after Impact



Comet 67P/Churyumov–Gerasimenko

Rosetta



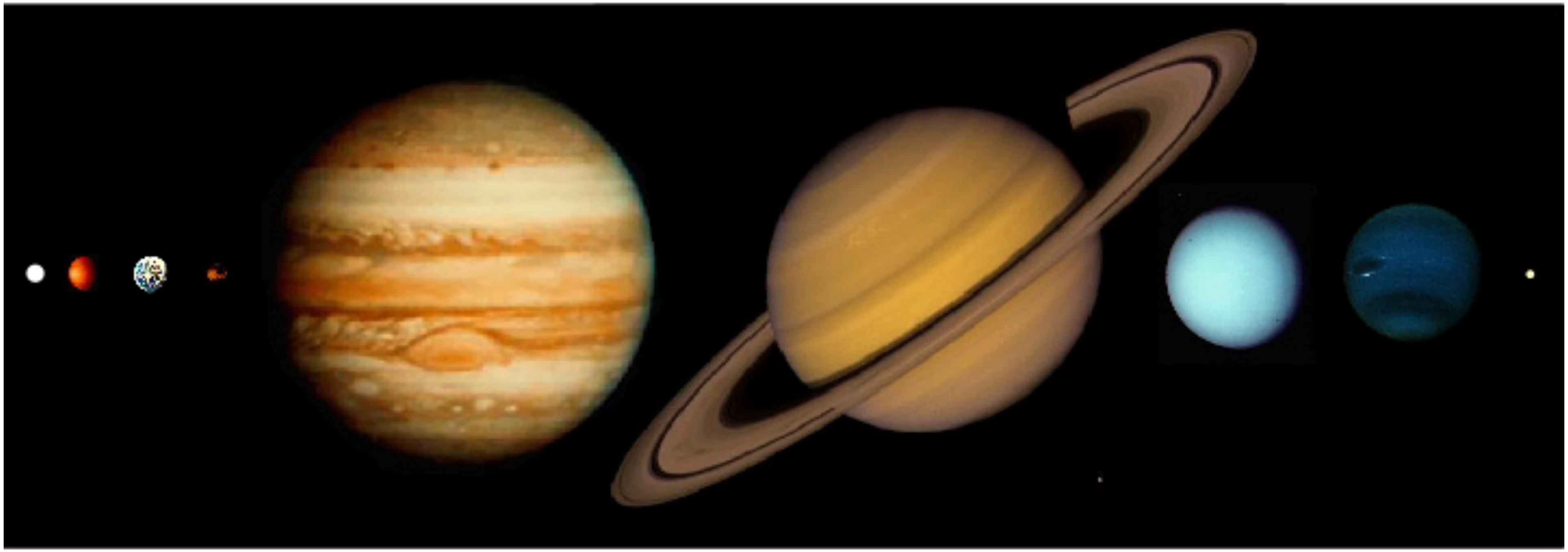


Comet 67/P

Close-up

Rosetta from 8 km

Planets in Our Solar System

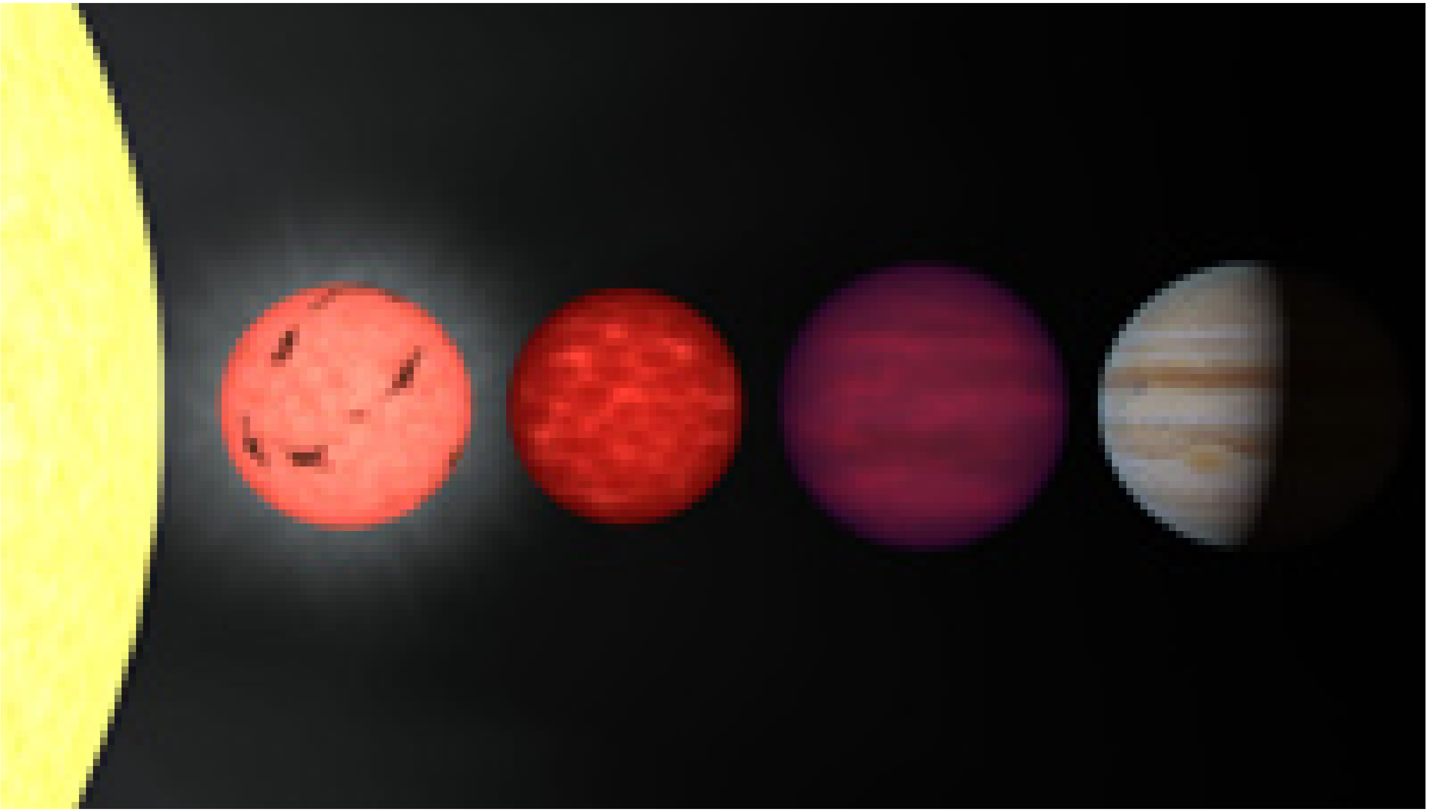


	Terrestrials				Gas giants				
	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
mass	0.055	0.82	1.00	0.11	318	95	14	17	.0002
radius	0.38	0.95	1.00	0.53	11.2	9.4	4.0	3.9	0.18
area	0.15	0.90	1.00	0.28	126	89	16	15	0.03
volume	0.06	0.85	1.00	0.15	1408	844	64	59	0.006
density	0.98	0.95	1.00	0.71	0.24	0.12	0.24	0.32	0.20

(all values are relative to Earth)


Sun
Earth

Stars, Brown Dwarfs & Planets



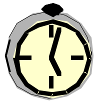
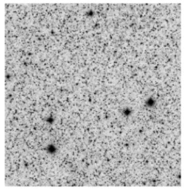
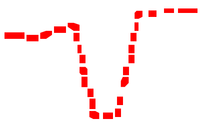
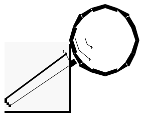
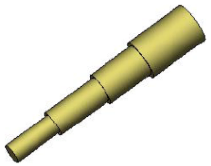
Sun, 75, 60, 30 & 1 Jupiter mass objects

Extrasolar Planets

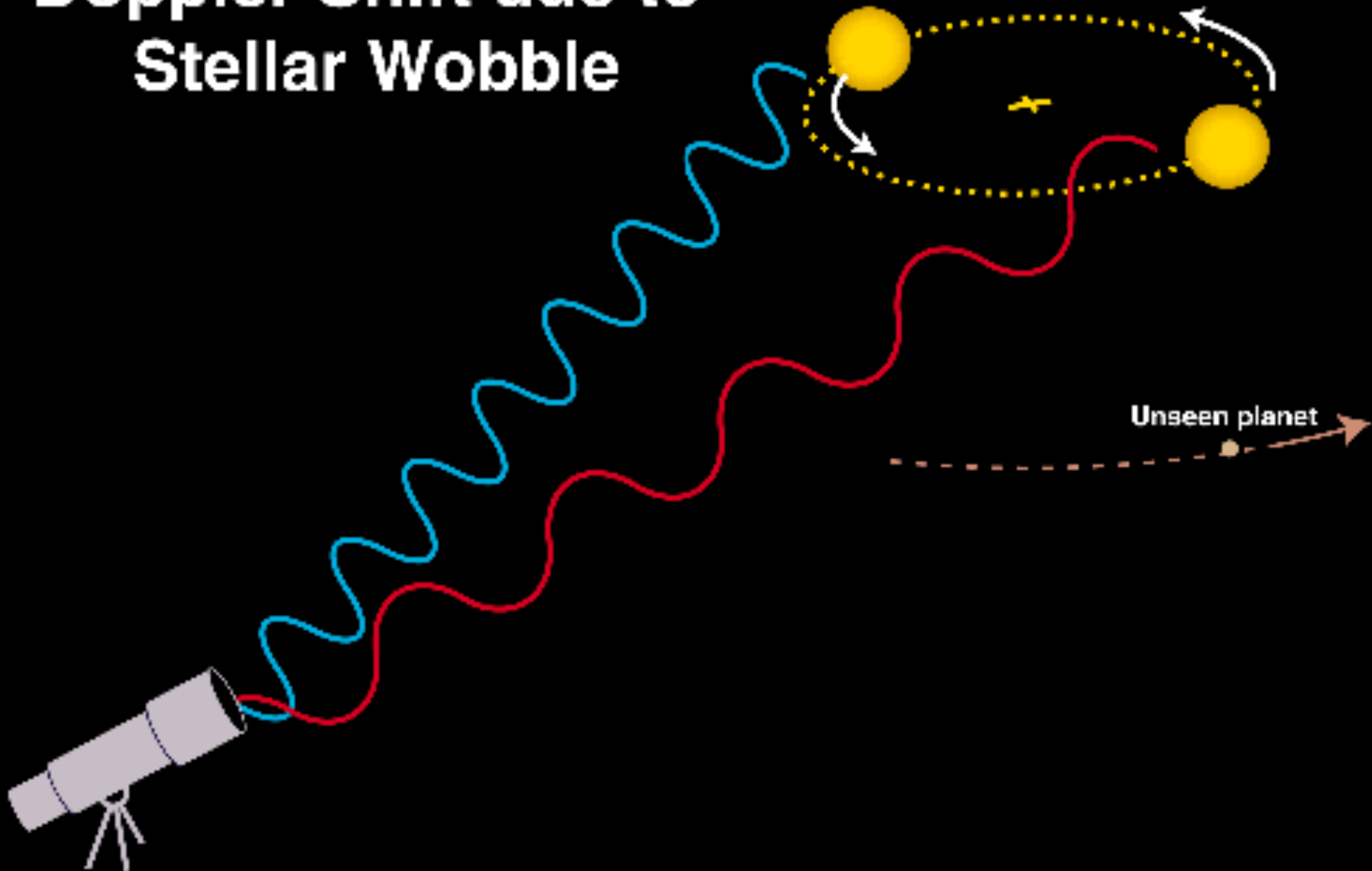
- Detection Techniques
  - Pulsar timing
  - **Radial velocities (Doppler technique)**
  - Astrometry (motion on the sky plane)
  - **Transit photometry (eclipses)**
  - Microlensing (bending of light)
  - Direct imaging
- ***Kepler* results** (next lecture)


FEBRUARY 5, 1996 $2.95
TIME
Dole Drops, Clinton Rises
IS ANYBODY OUT THERE?
How the discovery of two planets brings us closer to solving the most profound mystery in the cosmos

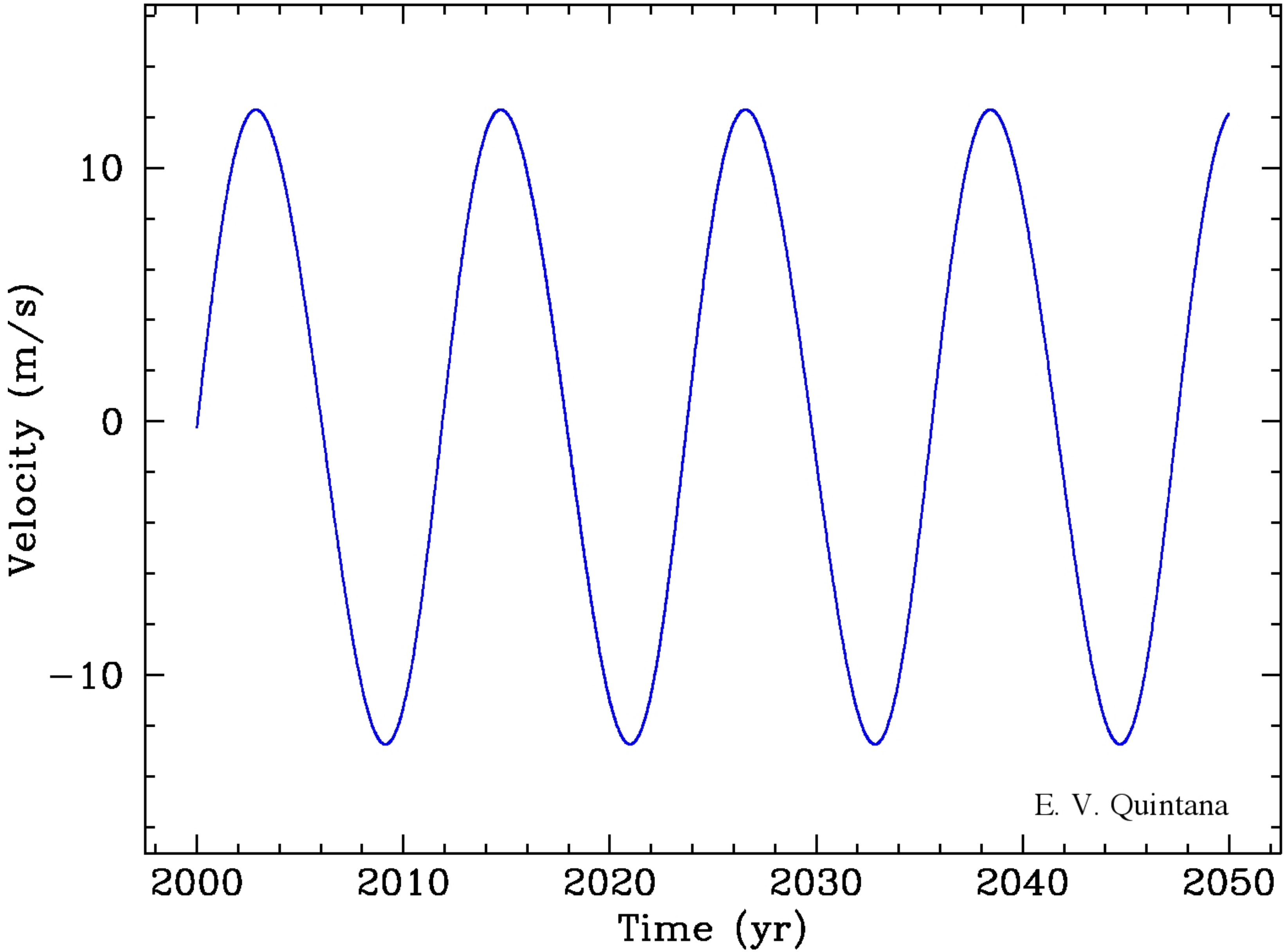
Techniques for Finding Extrasolar Planets

	Method	Yield	Mass Limit	Status
	Pulsar Timing	m/M ; τ	Lunar	Successful (3+~2)
	Radial Velocity	$m \sin i$; τ	super-Earth	Successful (~600)
	Astrometry	m ; τ ; D_s ; a		
	Ground:		Jupiter	Ongoing
	Space:		sub-Jupiter	Ongoing
	Transit Photometry	A ; τ ; $\sin i=1$		
	Ground		sub-Jupiter	Successful (~200)
	Space, 27 cm		sub-Neptune	*CoRoT* (~30)
	Space, 1 m		**Mercury**	***Kepler* (>1000 + >3000)**
	Microlensing:	f(m,M,r,D_s,D_L)		
	Ground		super-Earth	Successful (~40)
	Direct Imaging	*albedo**A ; τ ; D_s ; a ; M		
	Ground		Saturn	Successful (>20)
	Space		Earth	Being studied

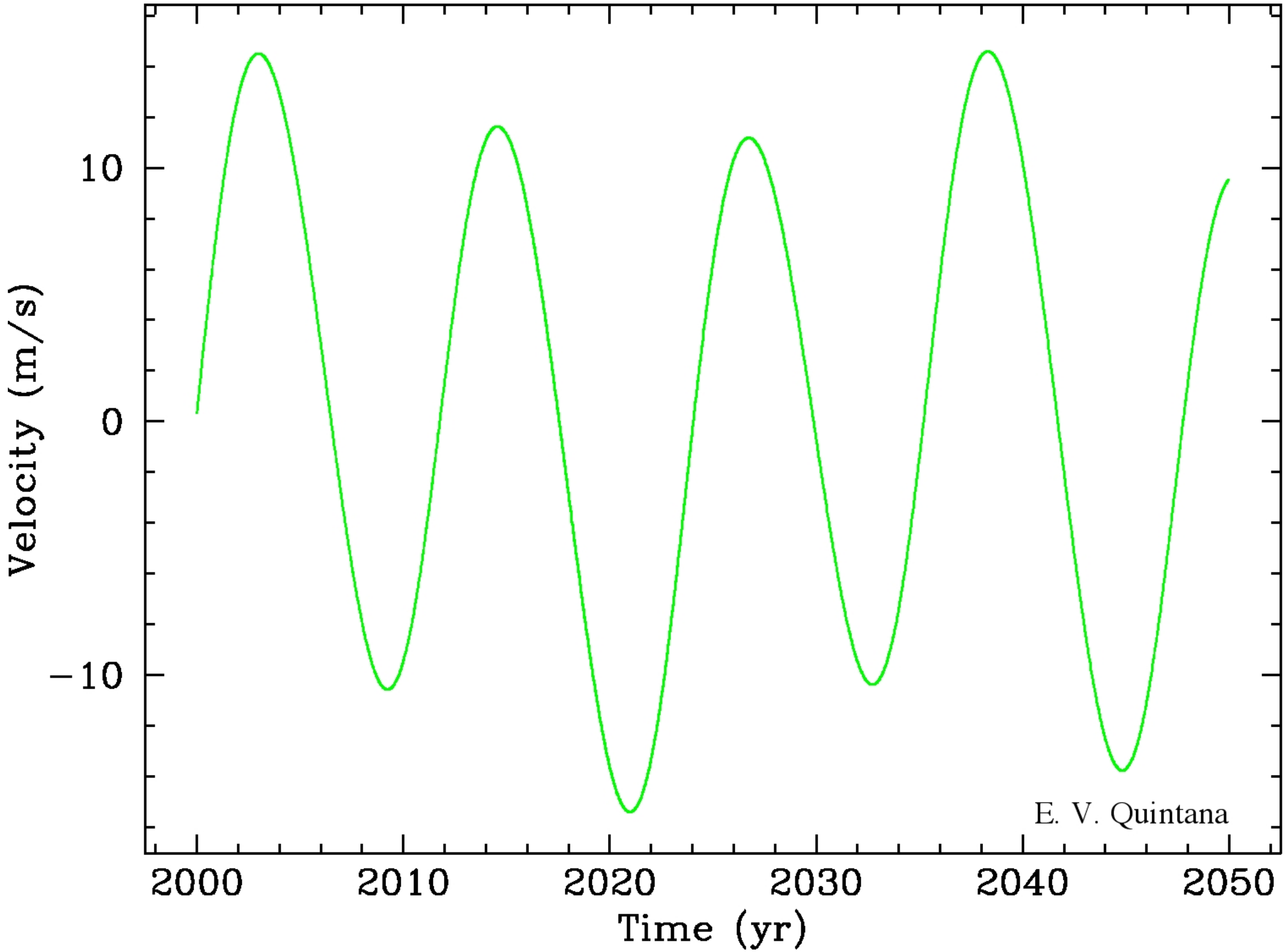
Doppler Shift due to Stellar Wobble



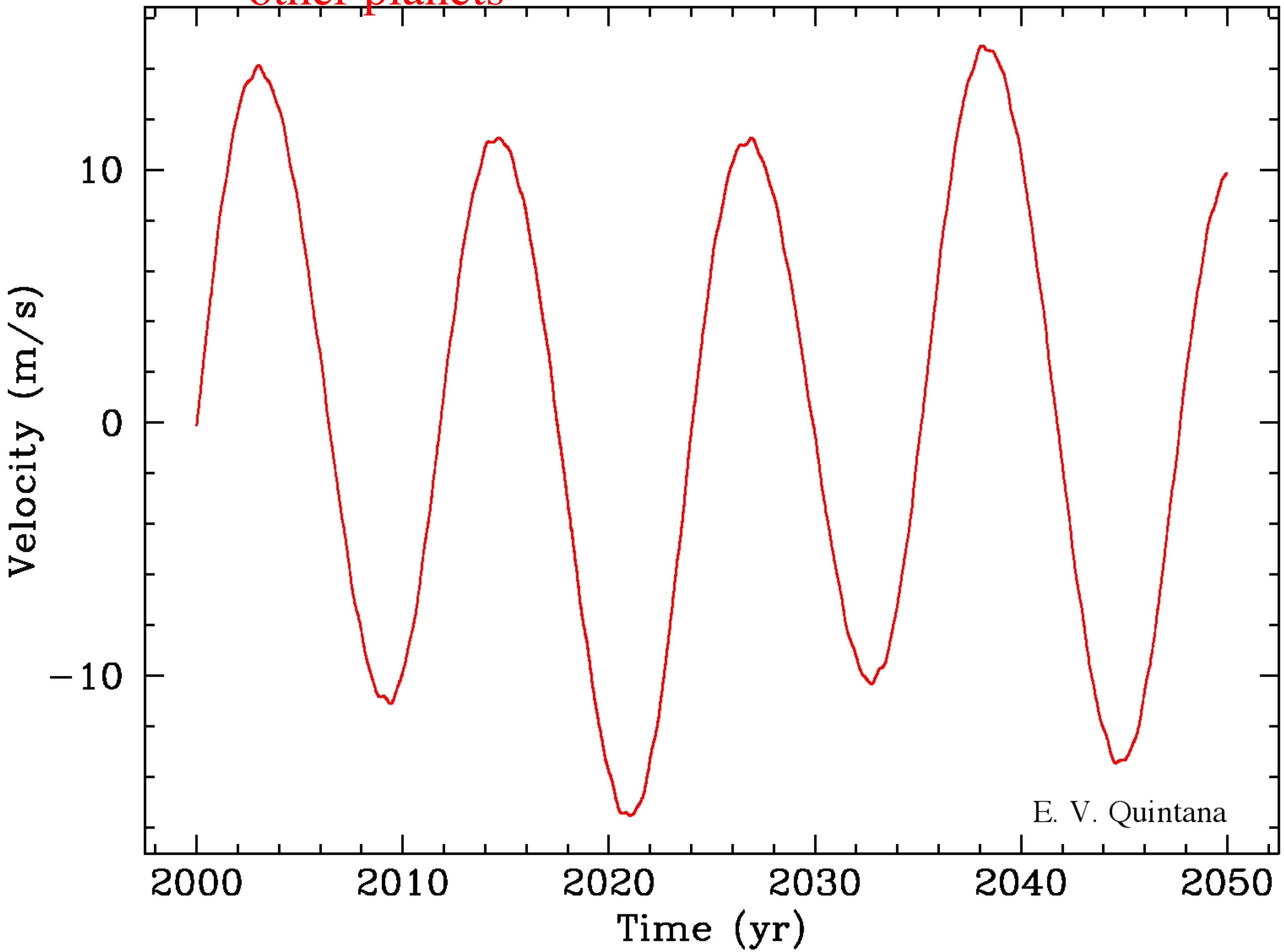
Radial velocity of Sun in response to Jupiter



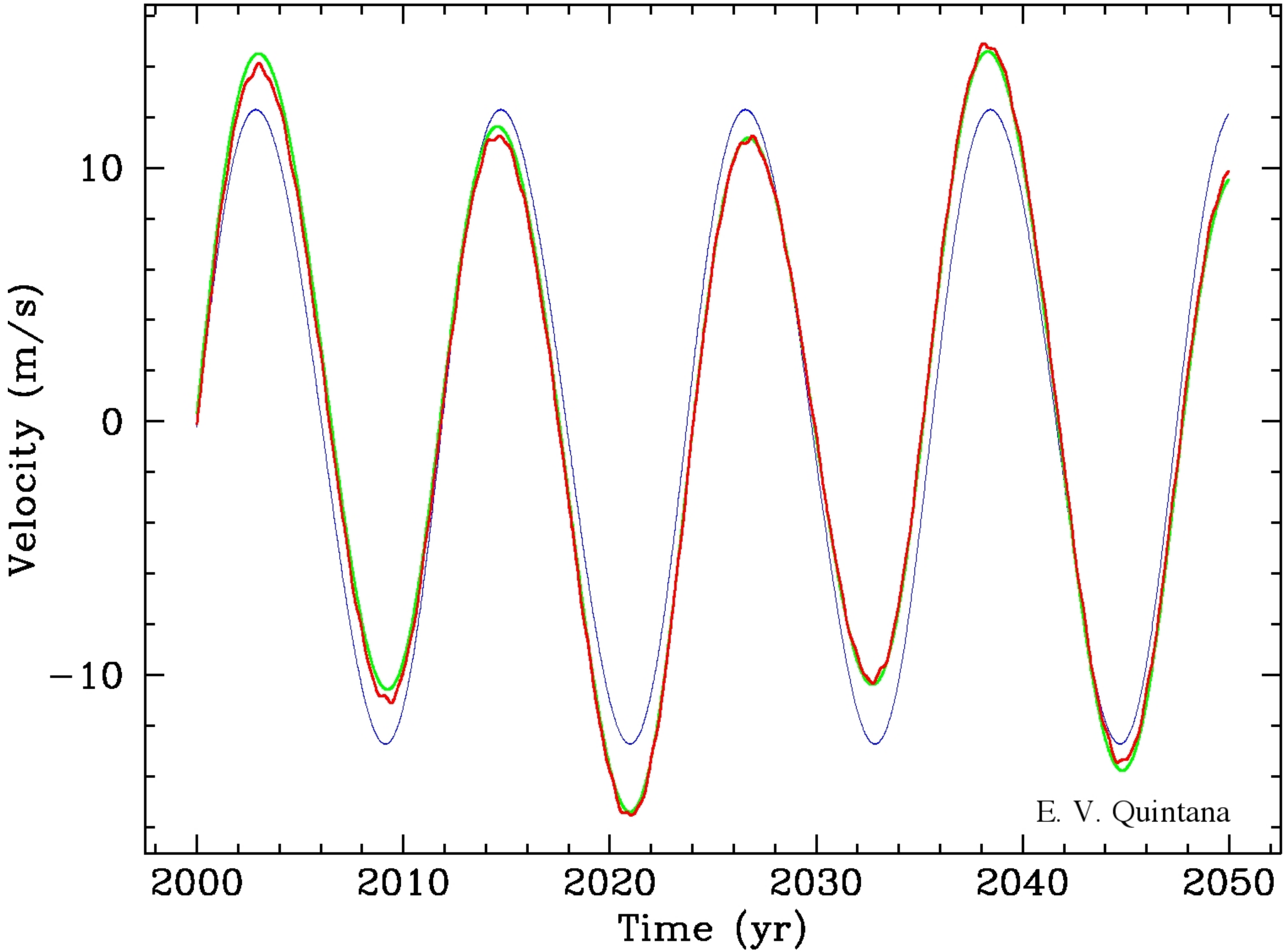
Radial velocity of Sun in response to Jupiter + Saturn

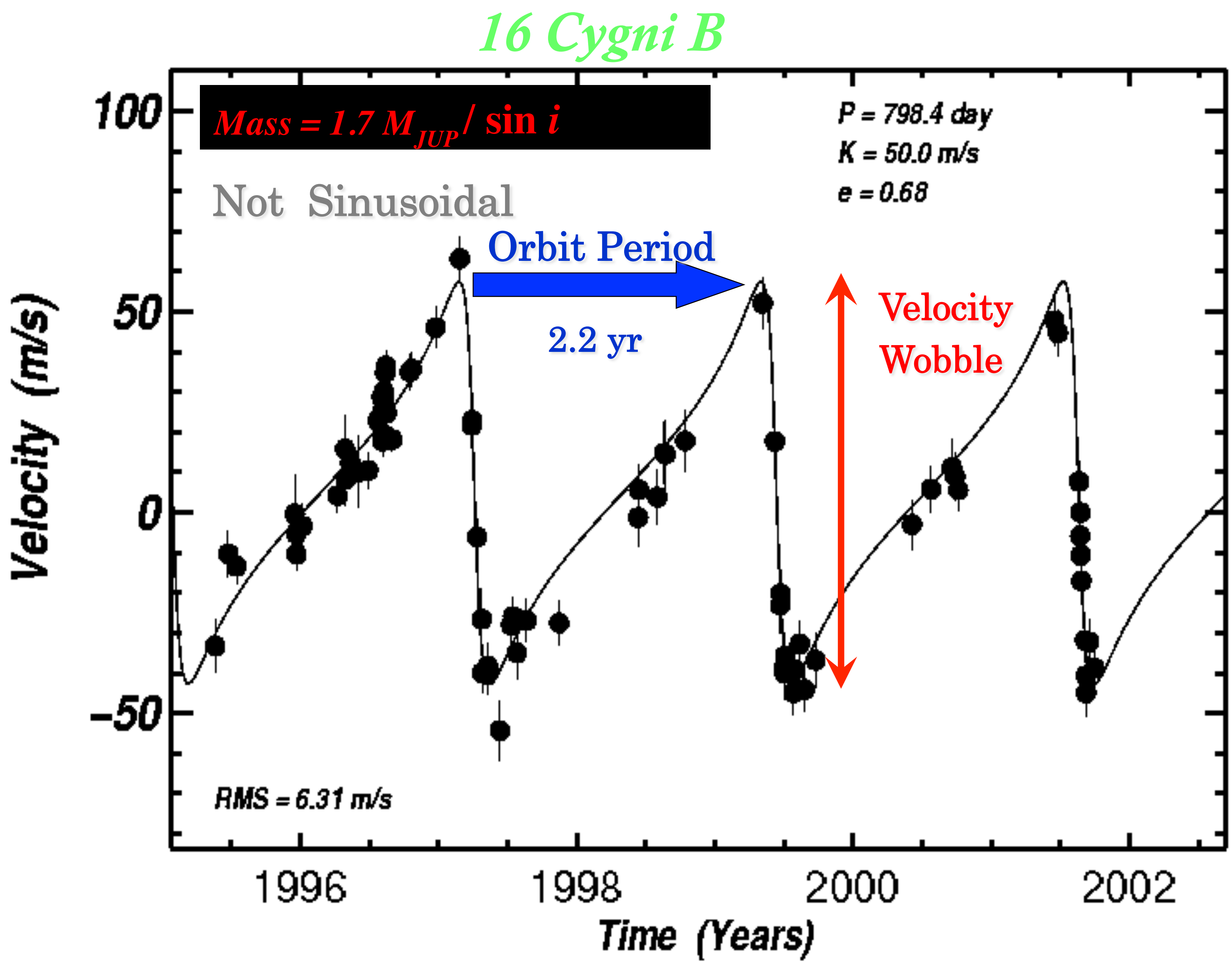


Radial velocity of Sun in response to Jupiter + Saturn + other planets



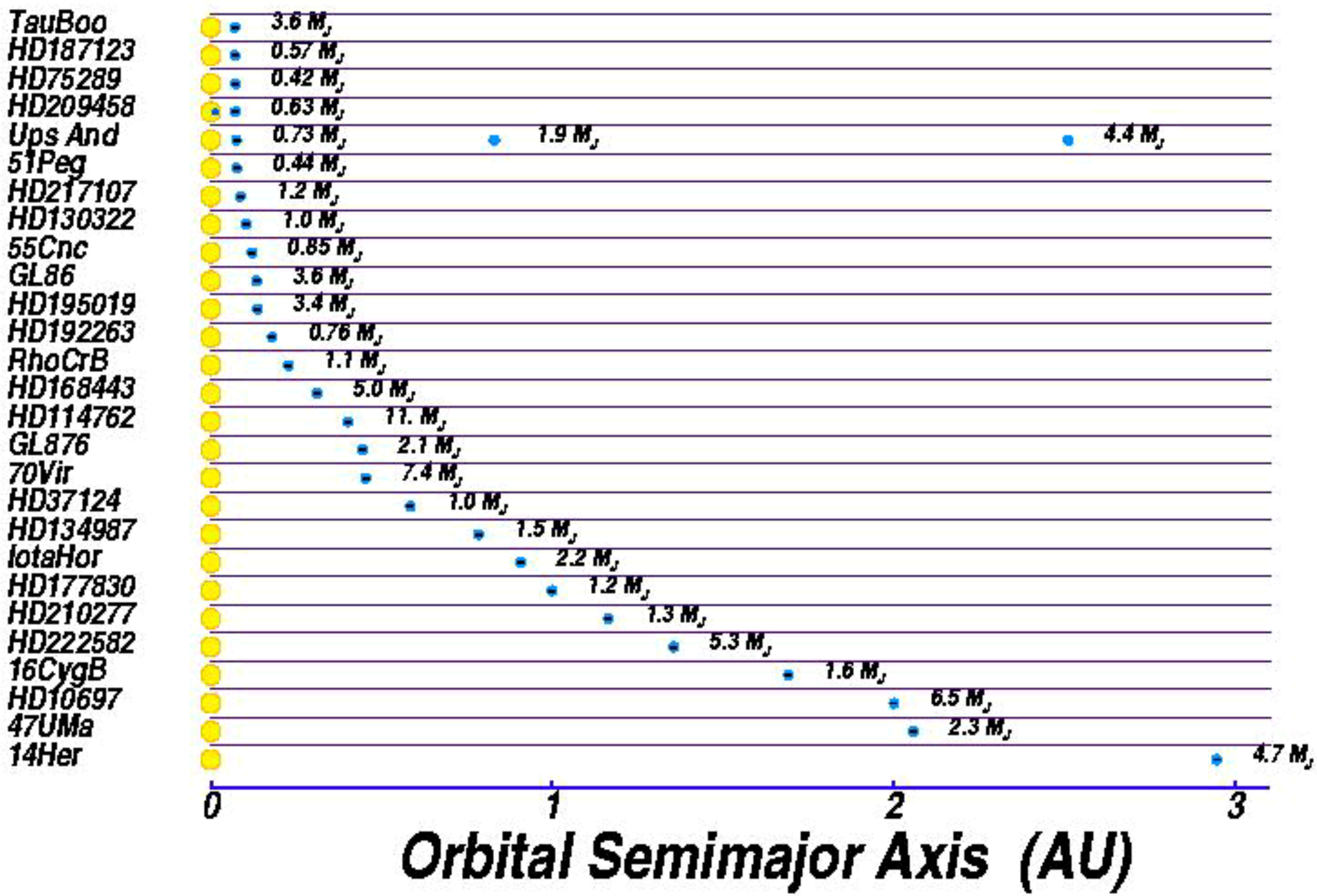
Radial velocity of Sun in response to Jupiter + Saturn + other planets





16 Cygni B
Mass = 1.7 M_JUP / sin i
Not Sinusoidal
Orbit Period
2.2 yr
P = 798.4 day
K = 50.0 m/s
e = 0.68
Velocity
Wobble
RMS = 6.31 m/s
100
50
0
-50
Velocity (m/s)
1996
1998
2000
2002
Time (Years)

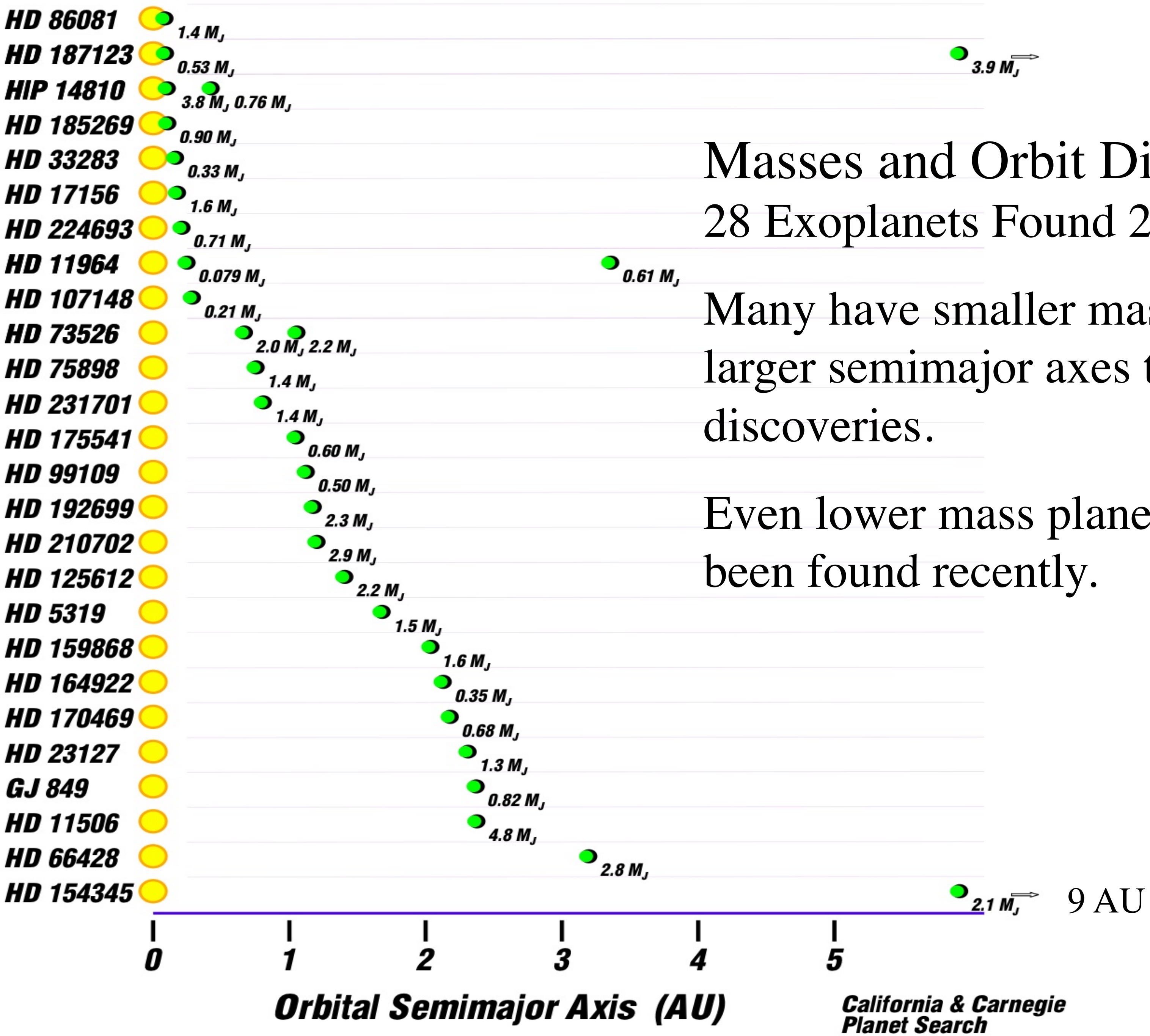
First 29 Exoplanets Discovered by Radial Velocity Surveys



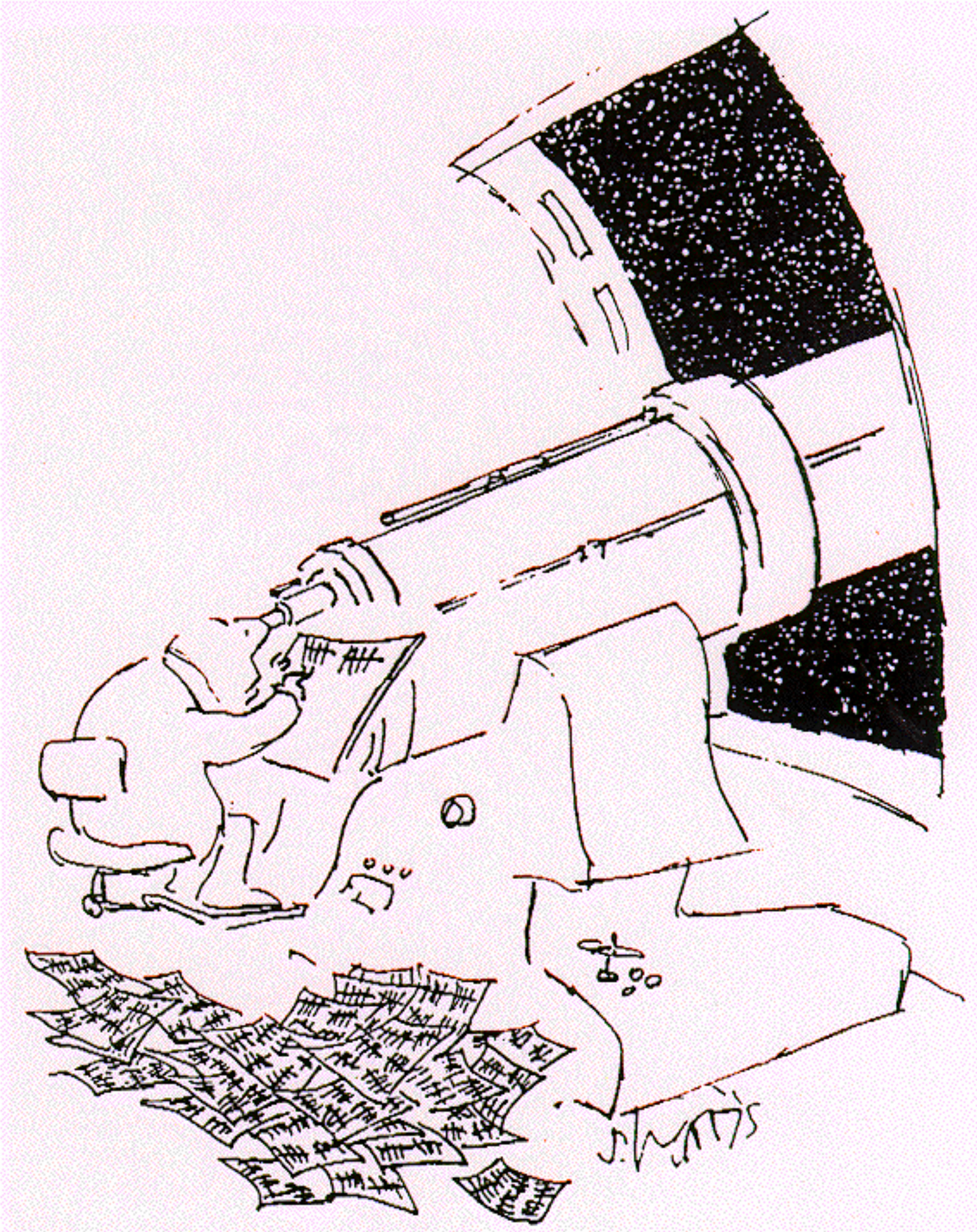
Masses and Orbit Distances of 28 Exoplanets Found 2006-2007

Many have smaller masses and/or larger semimajor axes than early discoveries.

Even lower mass planets have been found recently.



How Many Known Extrasolar Planets?



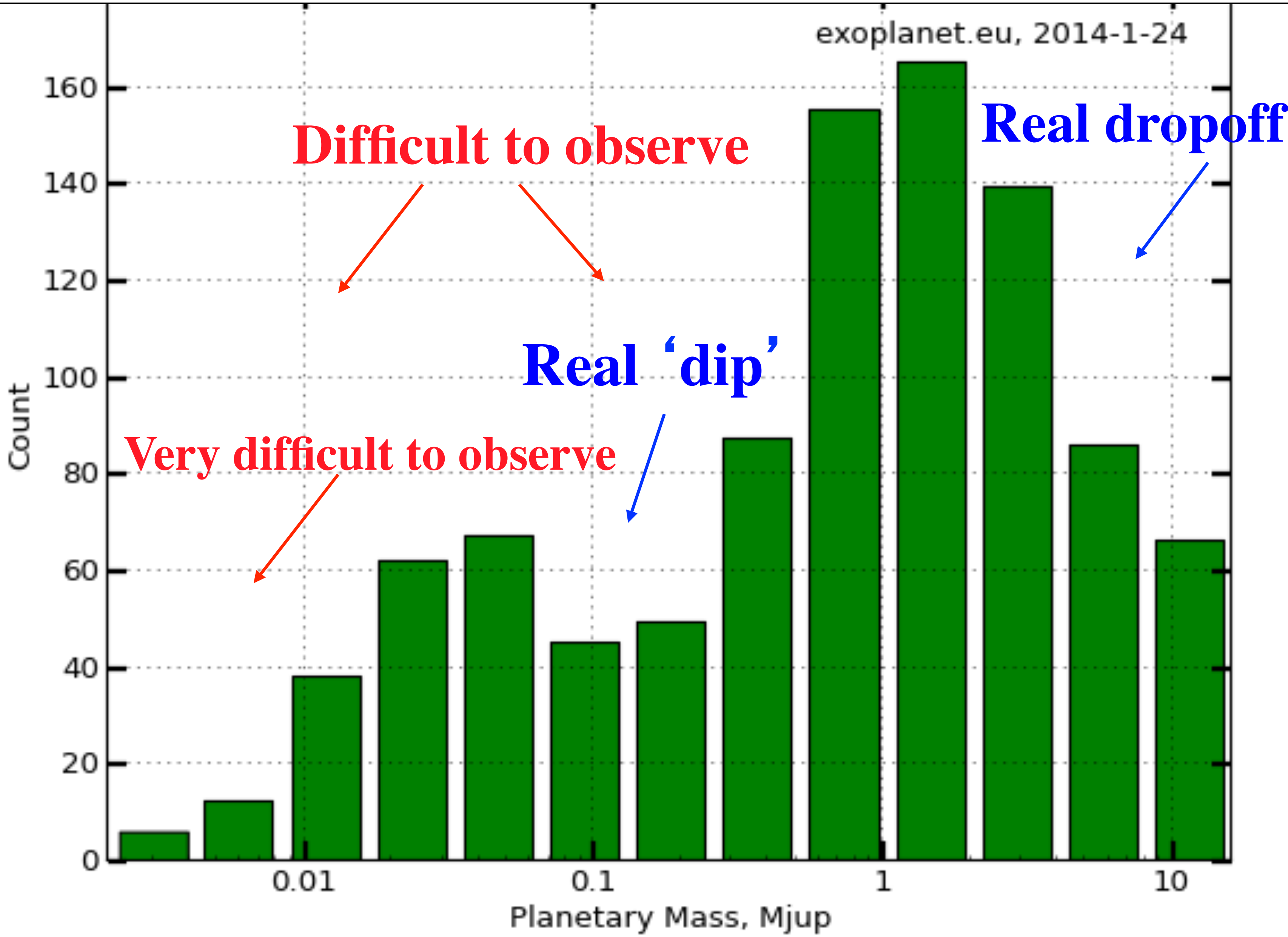
"What's one and one and one and one and one and one and one and one and one and one and one?"

"I don't know," said Alice. "I lost count."

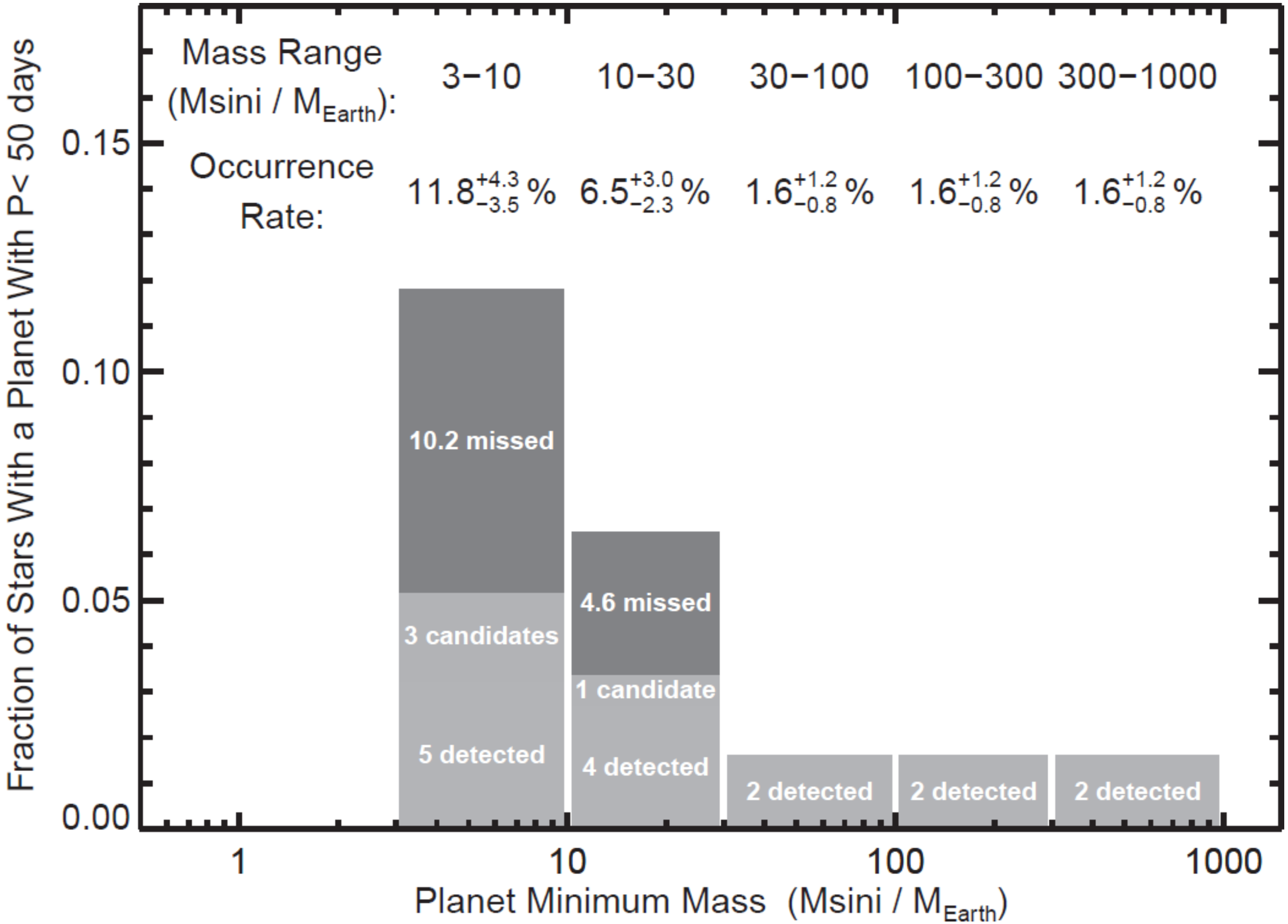
"She can't do addition," said the Red Queen.

Lewis Carrol,
Alice in Wonderland

Mass Distribution of RV Planets

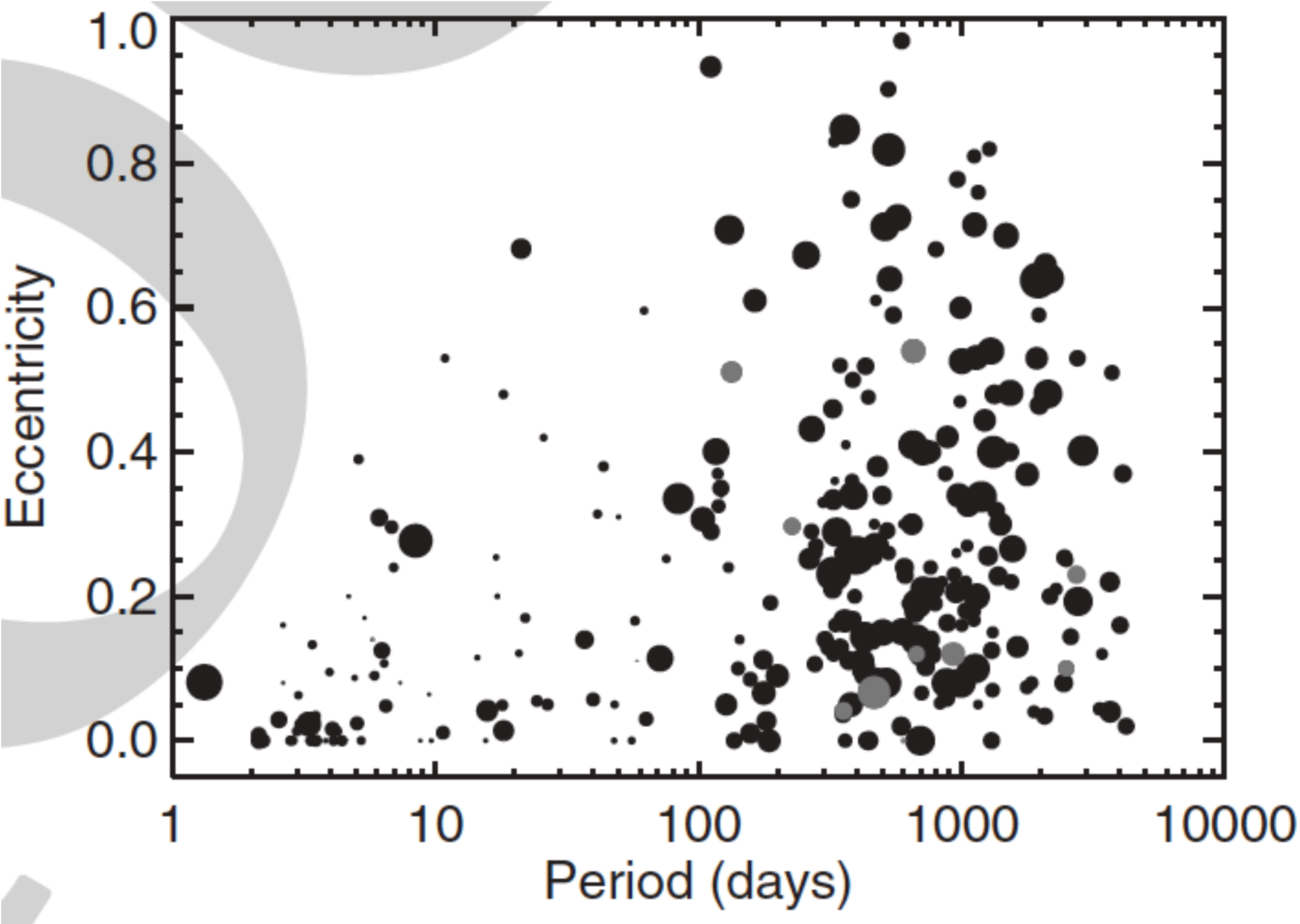


Small Planets are Numerous



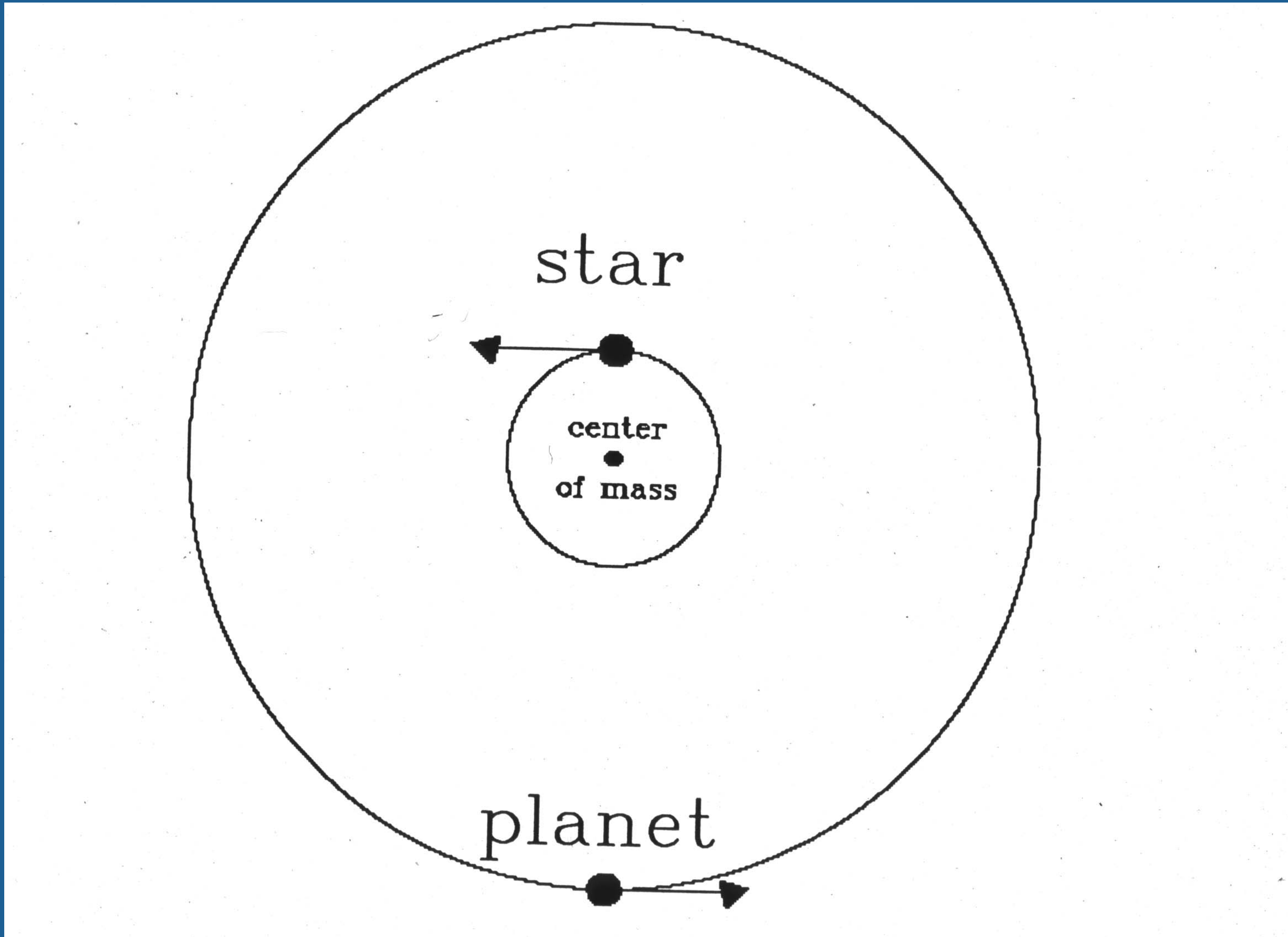
Doppler/Keck (Howard et al. 2010)

Eccentricities of RV Planets

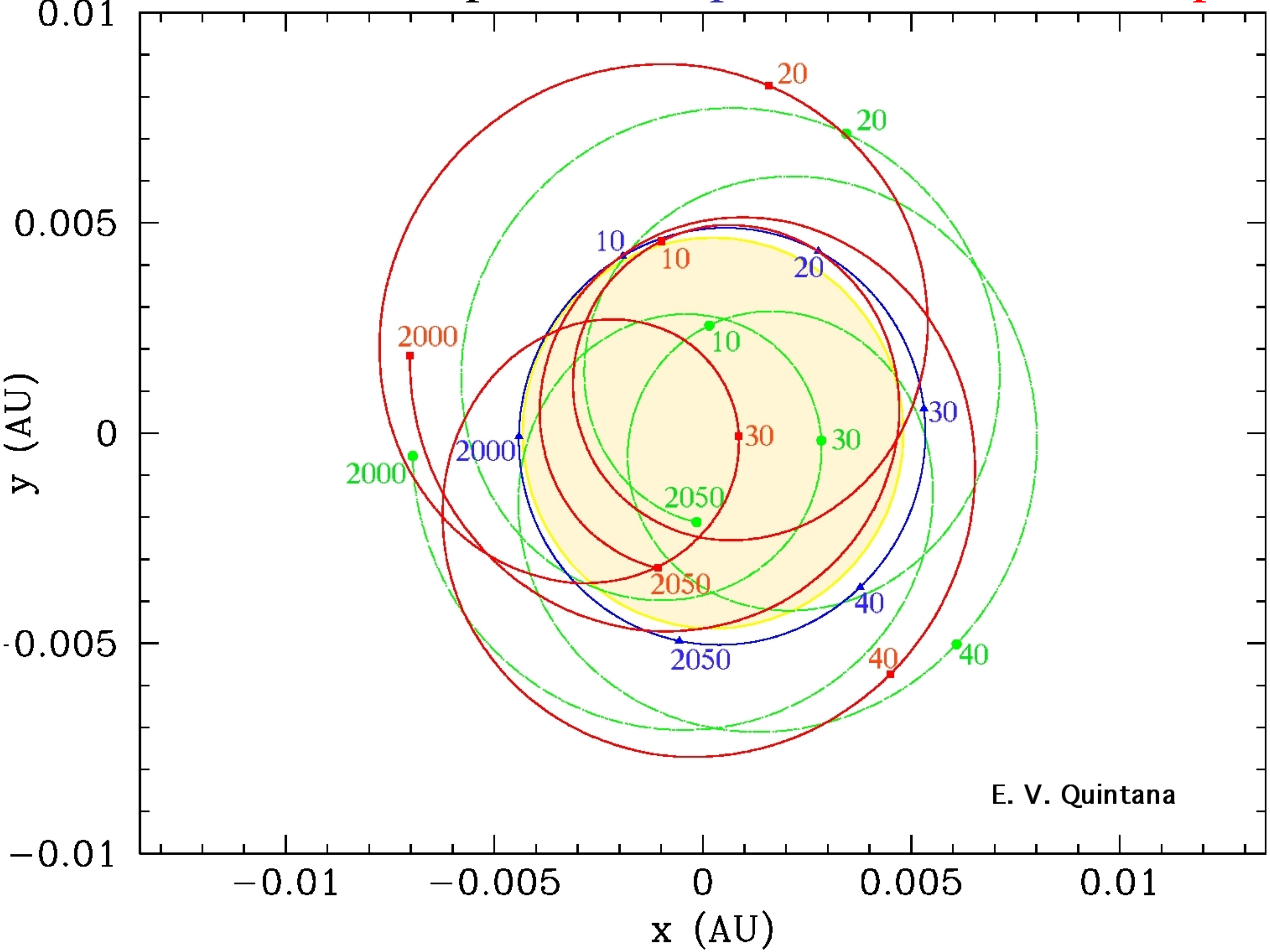


Black = single planets **Gray = planets in multis**

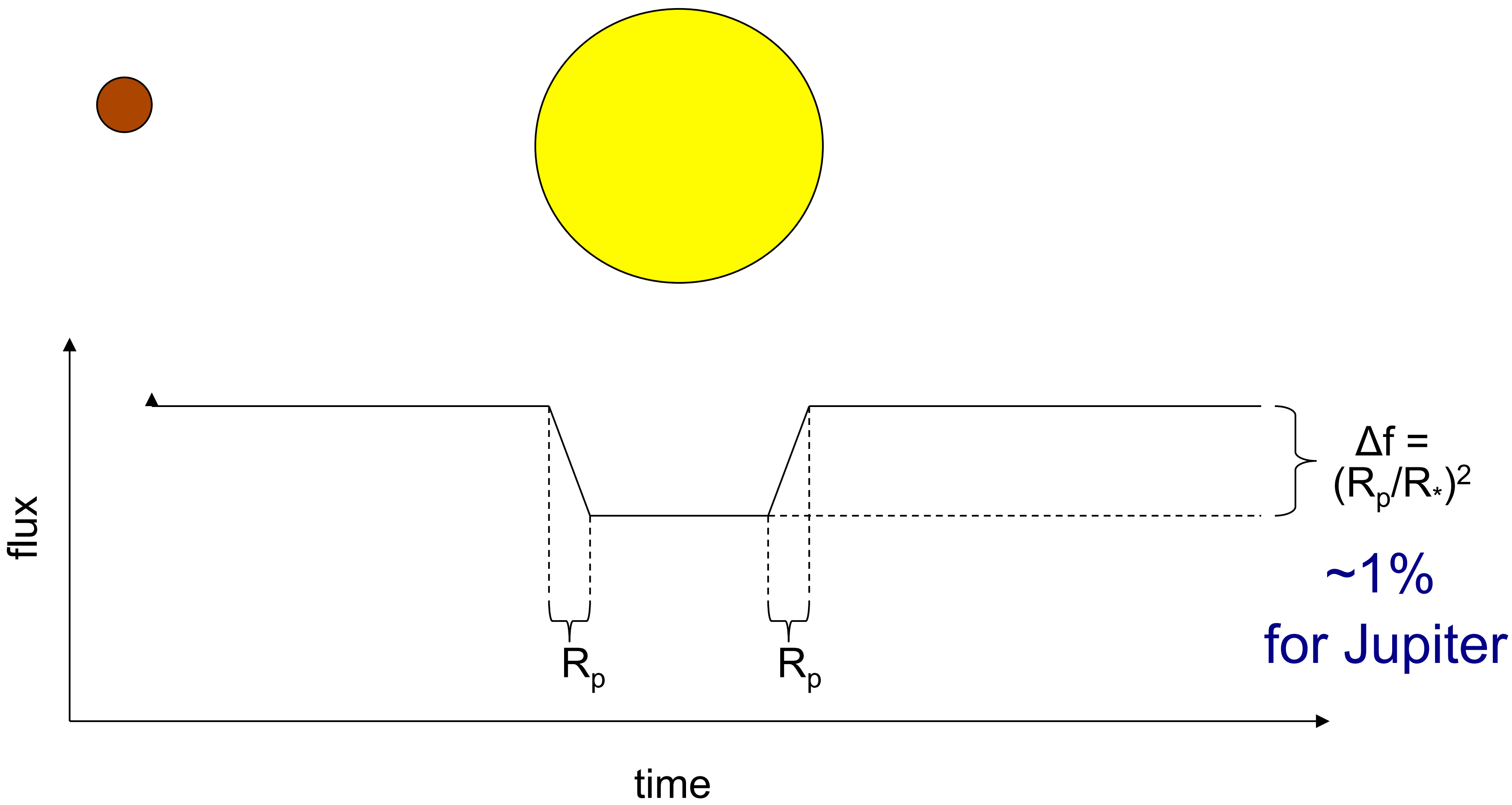
Astrometry



Motion of Sun in response to Jupiter + Saturn + other planets

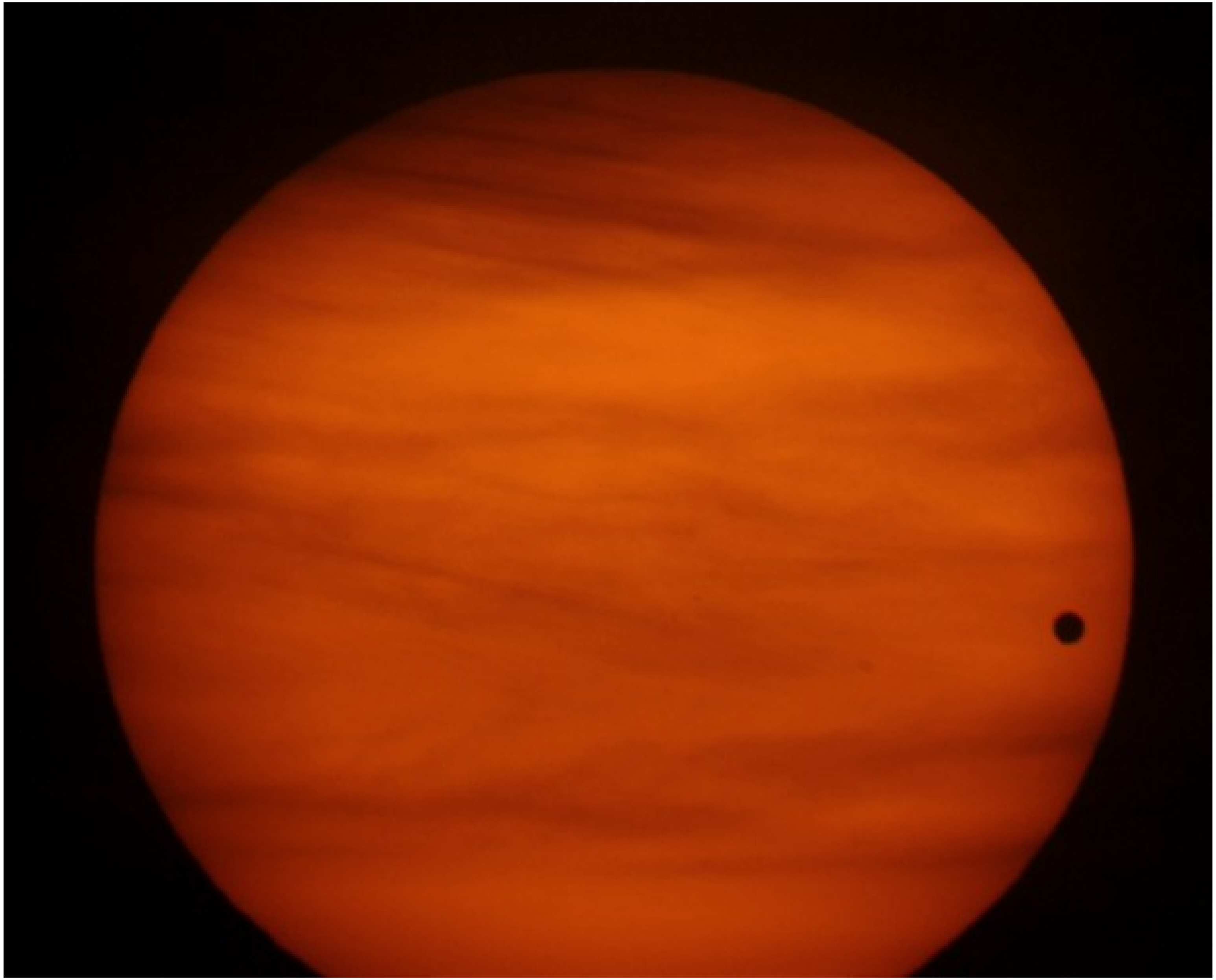


Transit Lightcurve



Josh Pepper

2004 Venus Transit at Sunrise



2004 Venus Transit at Sunrise

Mercury Transit of 2016 May 09

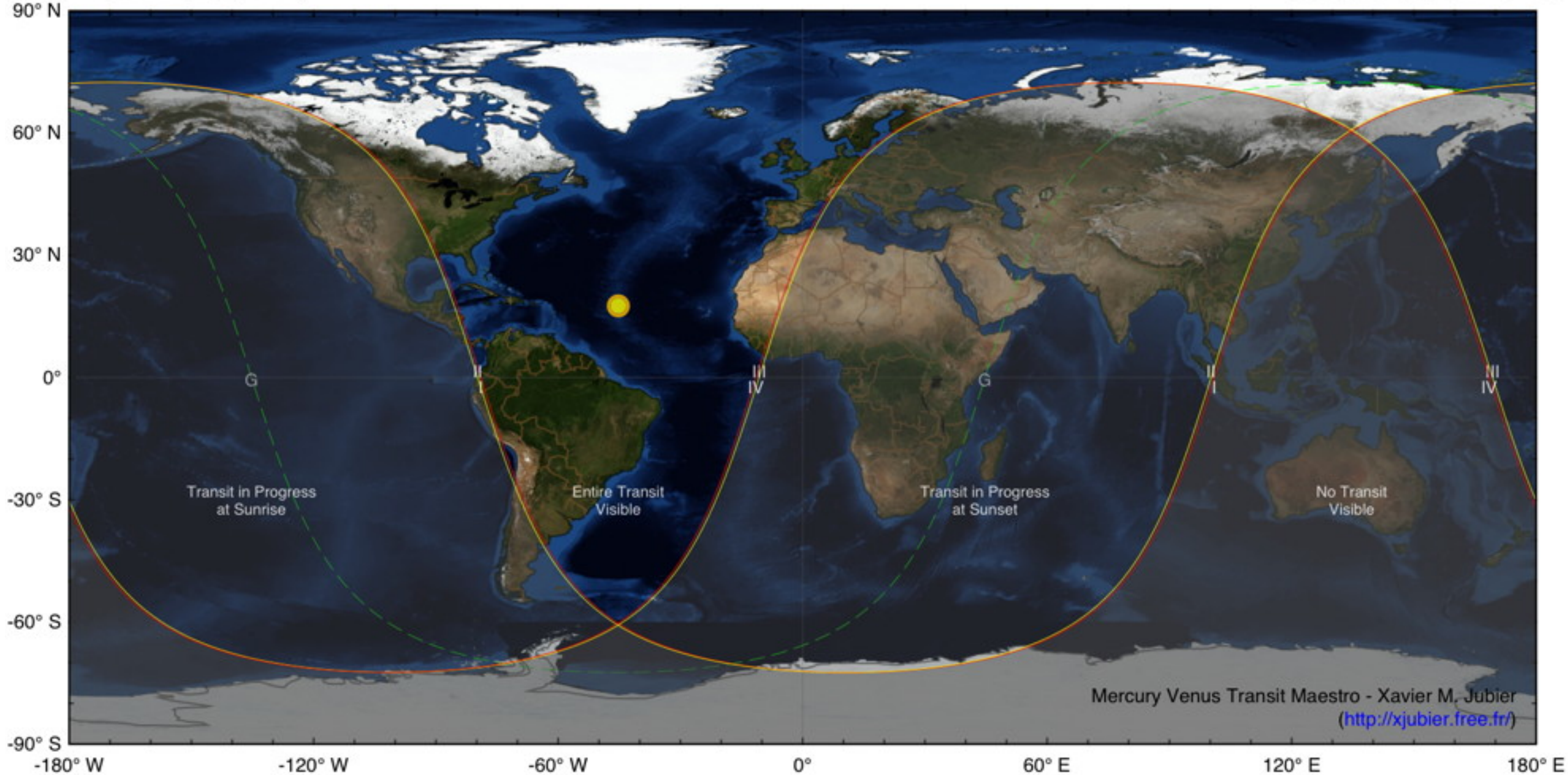
Greatest Transit: 14:57:24.8 UT J.D.: 2457518.123203
ΔT: 68.30s

Transit Geocentric Contacts

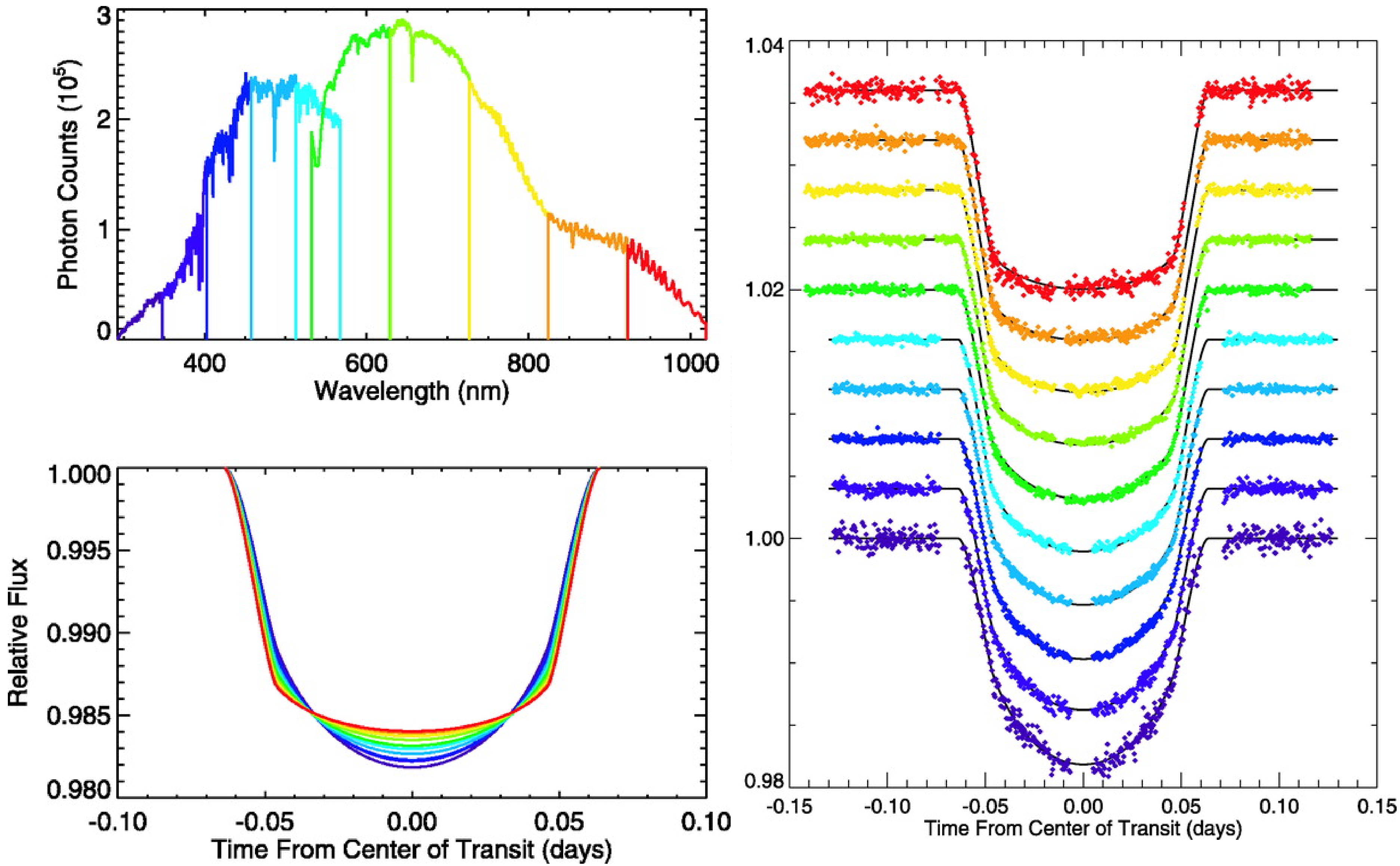
I: 11:12:18 UTC (83.2°)
II: 11:15:30 UTC (83.5°)
G: 14:57:25 UTC (153.8°)
III: 18:39:12 UTC (224.1°)
IV: 18:42:24 UTC (224.4°)

Geocentric Data

Minimum separation: 318.5”
General Duration: 07h30m05s
Central Duration: 07h23m43s



HD 209458 b Transits at Differing Wavelengths - HST (Knutson et al. 2007)



Direct imaging of exo-planets is Difficult:

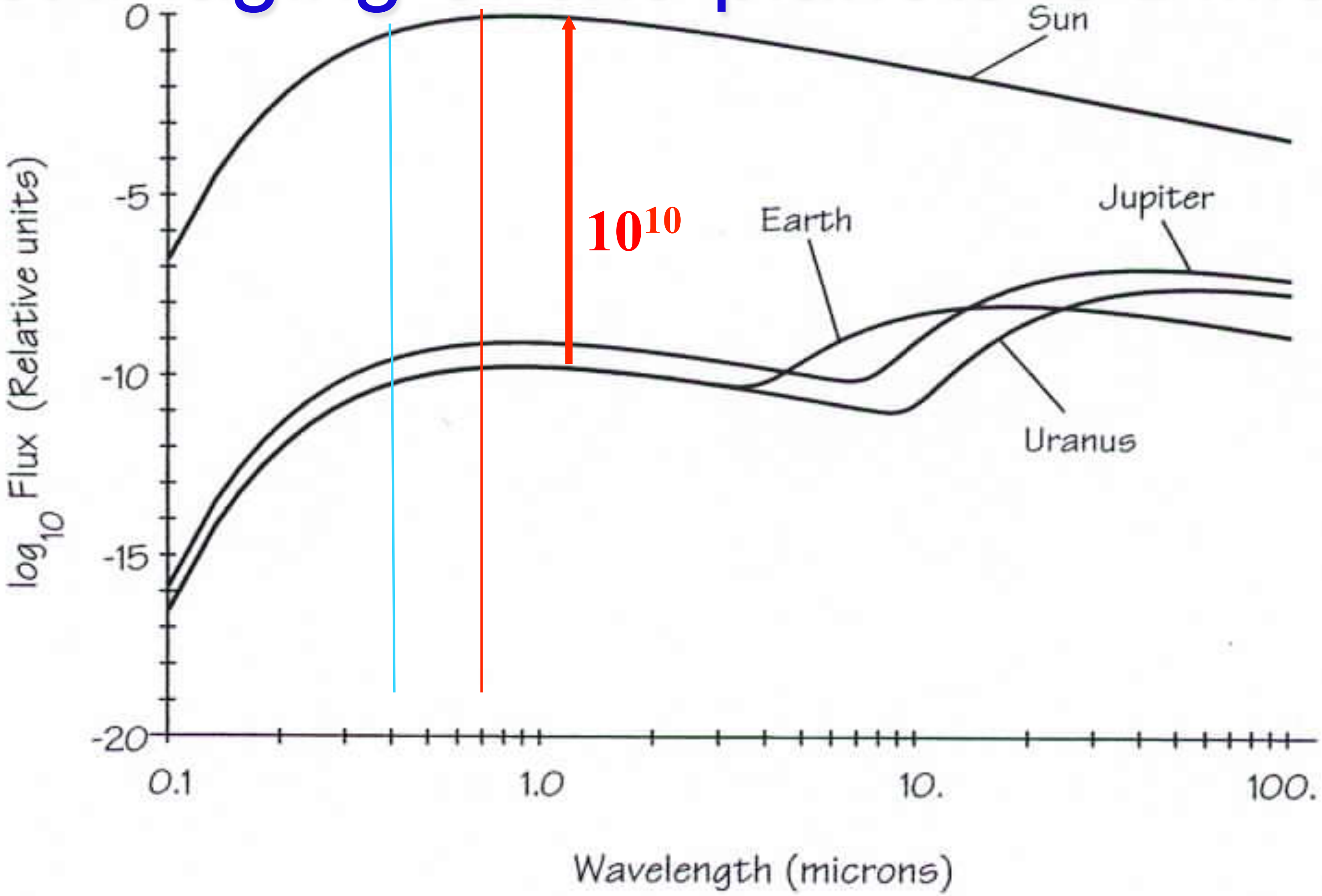
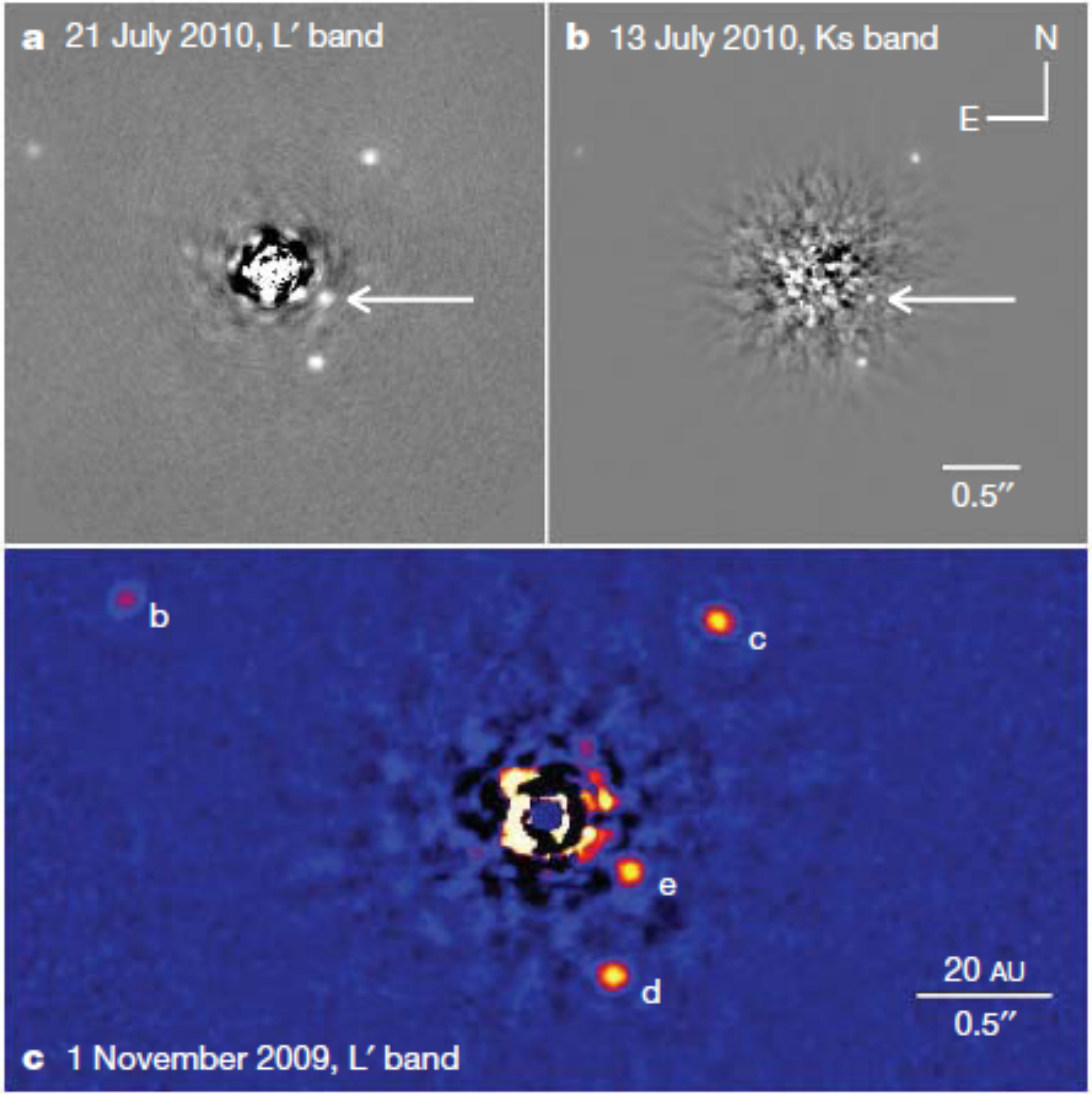
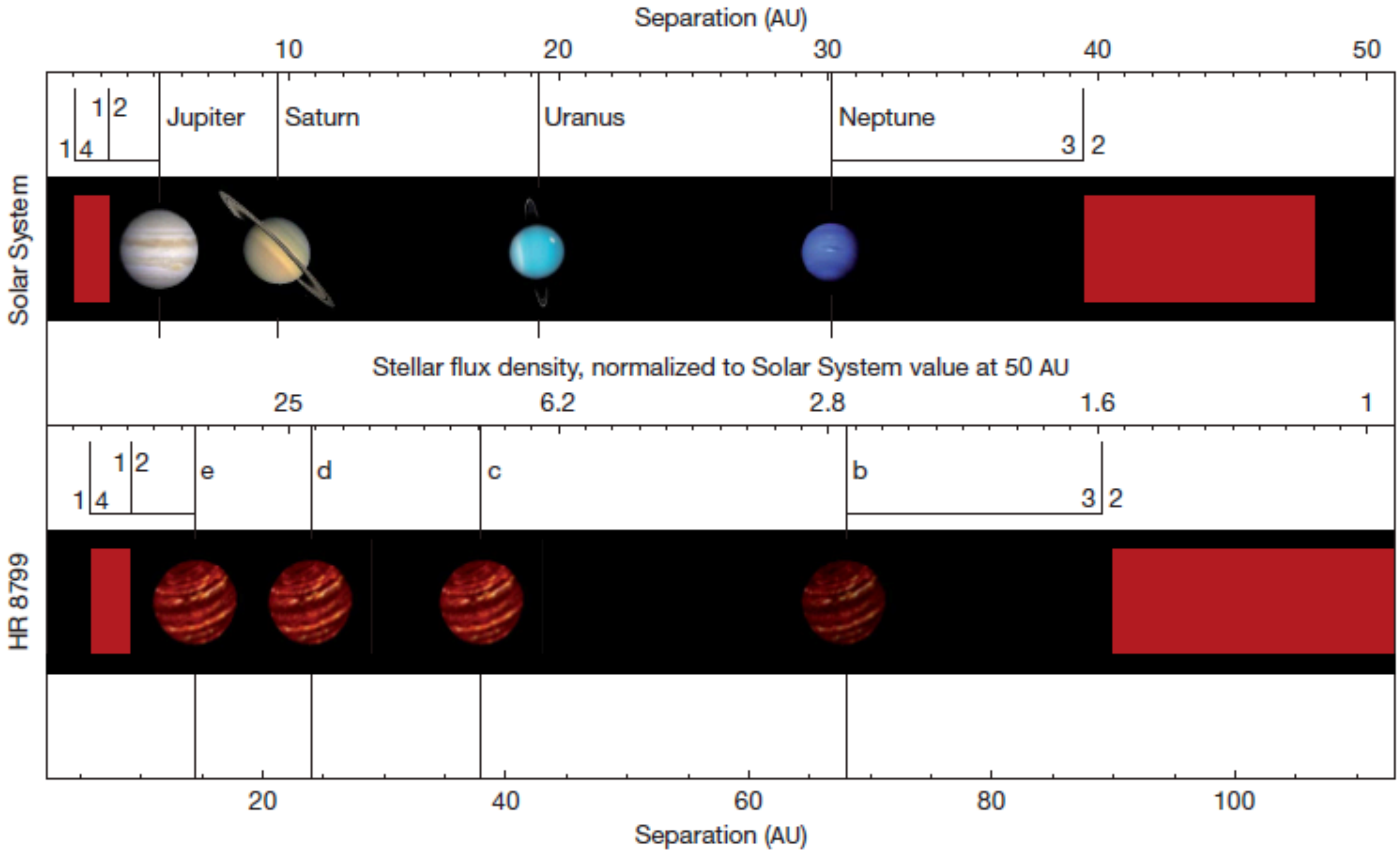


Figure 4-1. The spectral energy distributions of the Sun, Jupiter, Earth, and Uranus as they would appear at 5 pc, averaged over a 10% spectral bandpass. Note the decreased ratio of solar to planetary flux in the thermal infrared, compared to visible wavelengths.

HR 8499: 4 distant giant planets

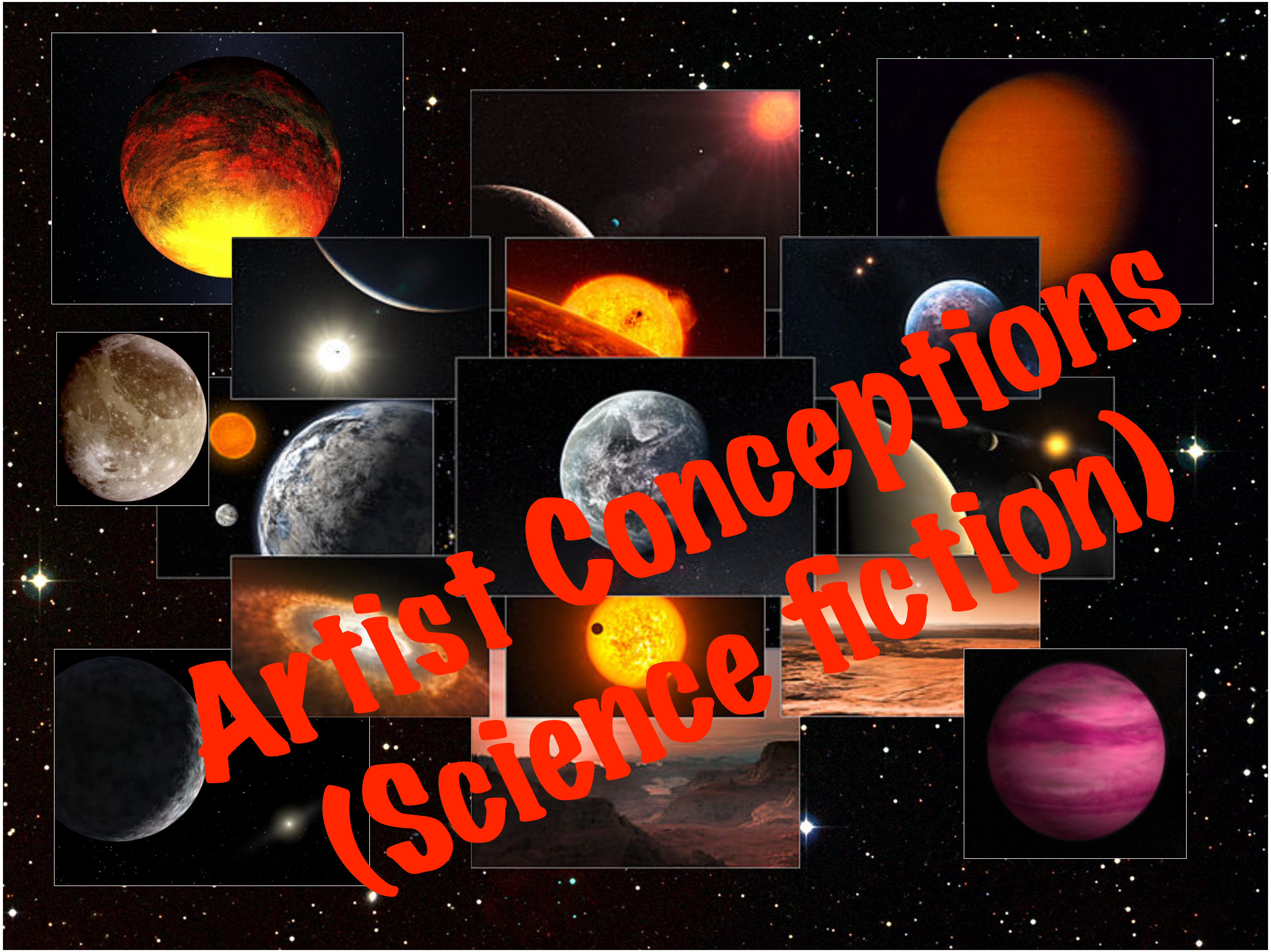


HR 8499 vs Solar System



RV Extrasolar Planets

- ~ 0.7% of Sun-like (late F, G & early K dwarf) stars have planets more massive than Saturn within 0.1 AU
  - Transiting planets known to be gas giants; HD 149026b is metal-rich
  - Models suggest these planets migrated inwards
- ~ 7% of Sun-like stars have planets more massive than Jupiter within 2 AU
  - Many of these planets have very eccentric orbits
- < 2% of M dwarf stars have planets more massive than Jupiter within 1 AU
- Stars with higher metallicity are more likely to host giant planets
- Stars with one detectable planet are more likely to host more detectable planets
- > a few % of stars have Jupiter-like companions (0.5 - 2 M_{Jup}, 4 AU < a < 10 AU), but > 25% do not
- Brown dwarf desert; low-mass planets most common


Artist Conceptions
(Science fiction)