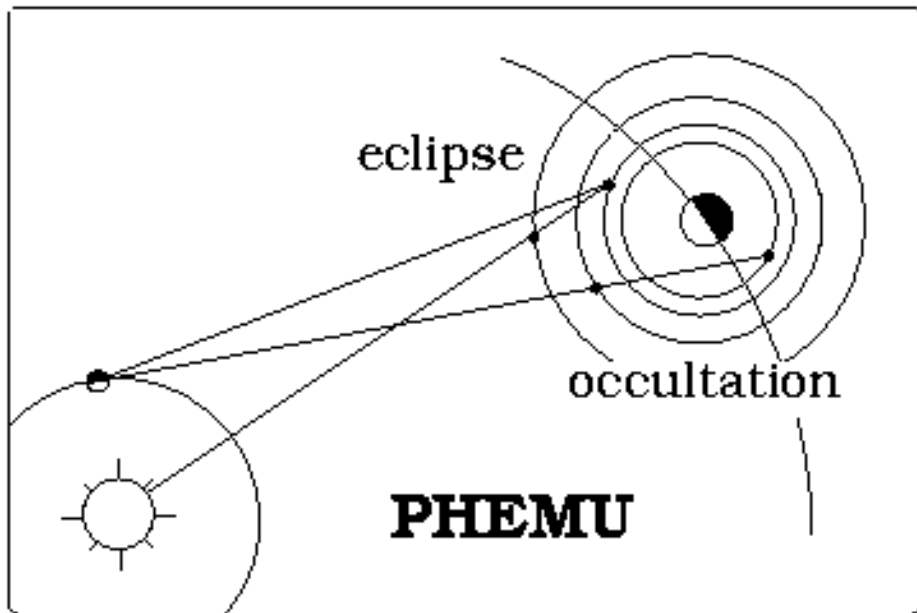
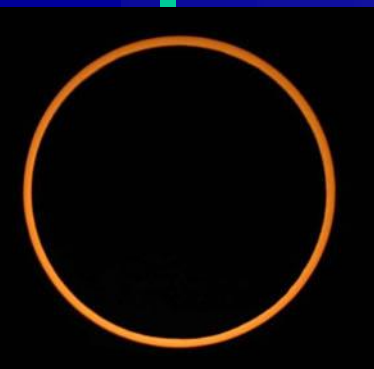
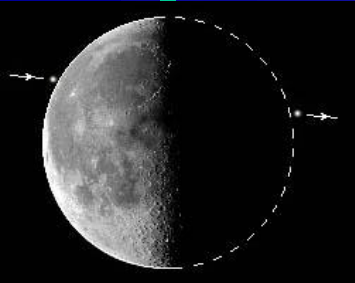


The observation of the mutual phenomena and the natural planetary satellites (1973-2015)

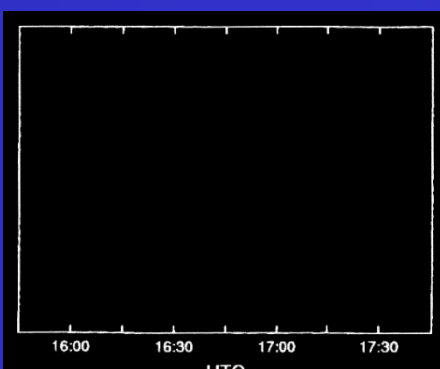
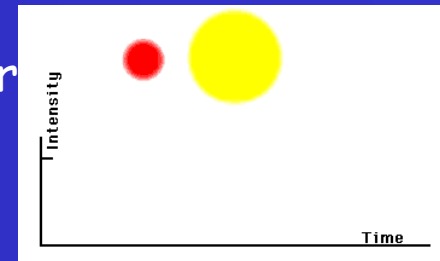
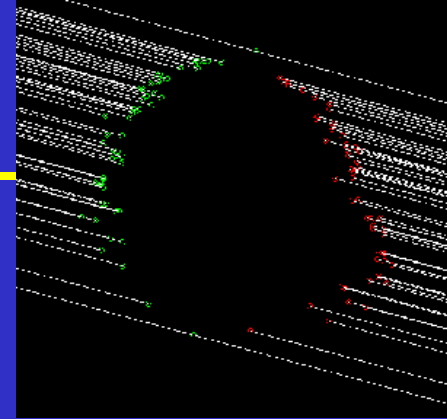
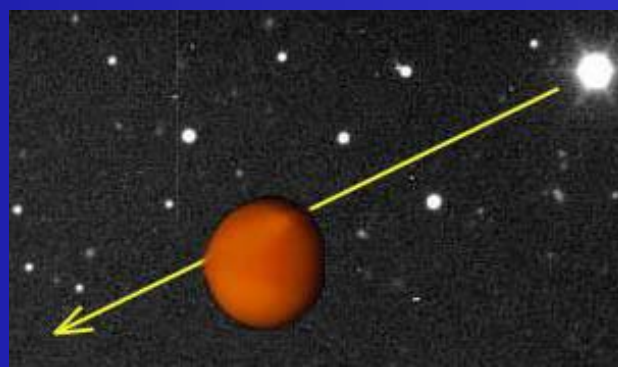


J.E. Arlot
IMCCE/obs. de Paris

Phenomena in the Solar system



- Eclipses of the Sun and of the Moon
- Phenomena of the Galilean satellites of Jupiter
- Transits of Venus in front of the Sun
- Occultations of stars by the Moon
- Occultations of stars by asteroids
- Mutual occultations and eclipses



A need of accurate observations of the natural planetary satellites

Natural planetary satellites are similar to small solar or extra-solar systems. Their observation may help understanding such systems and allow to explore these worlds from the ground.

The detection of small effects such as an acceleration in the motion of the satellites will provide constraints on the dynamics, on some physical parameters and on the internal structure of the satellites.

For this purpose we made very complete dynamical models and we need samples of observations of good accuracy spread on a sufficient interval of time.

This is the goal of the observation of the mutual phenomena

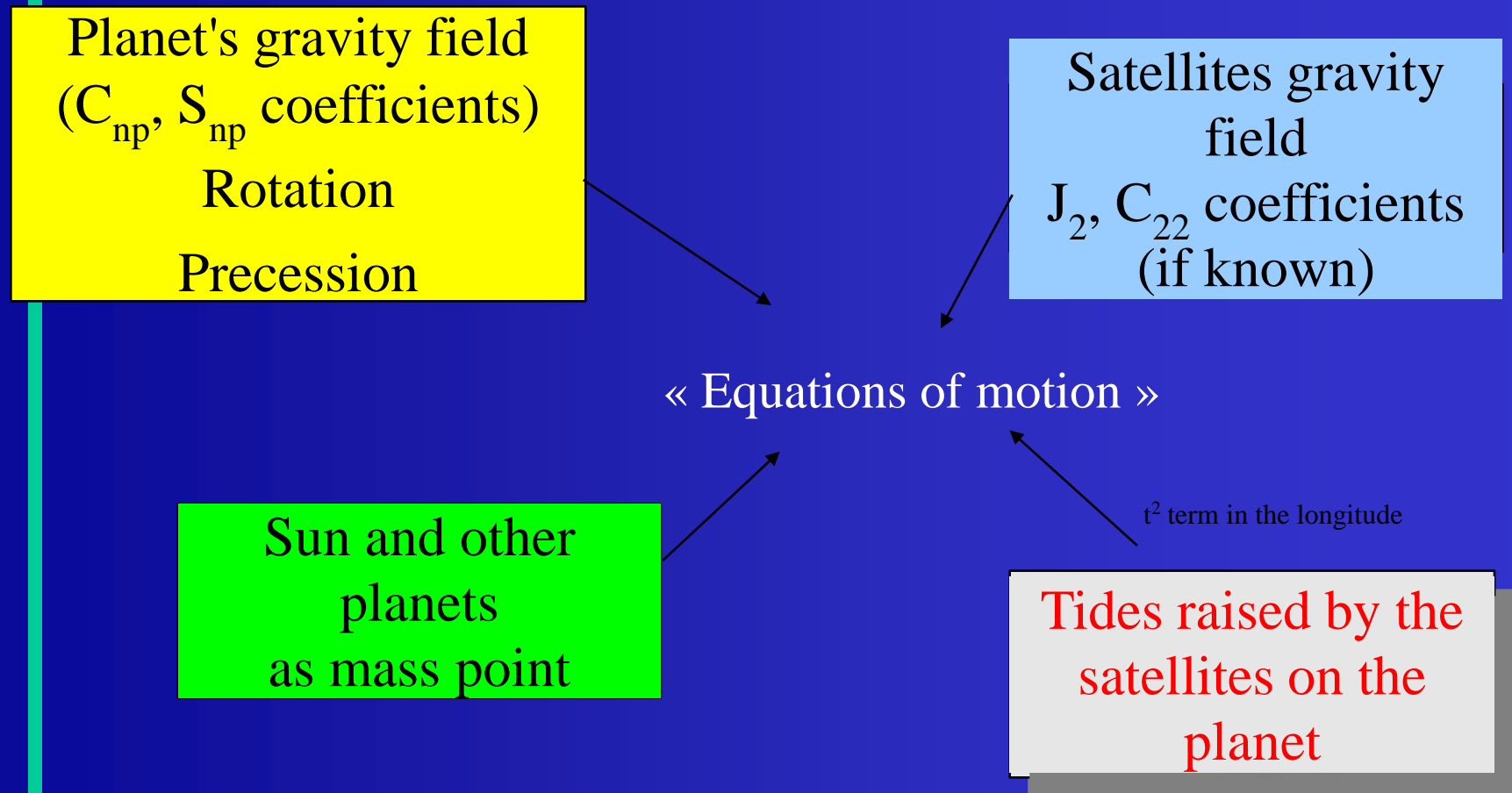
The prediction of the phenomena

- The prediction of the mutual events needs accurate ephemerides.

We must avoid predicting events which will not occur!

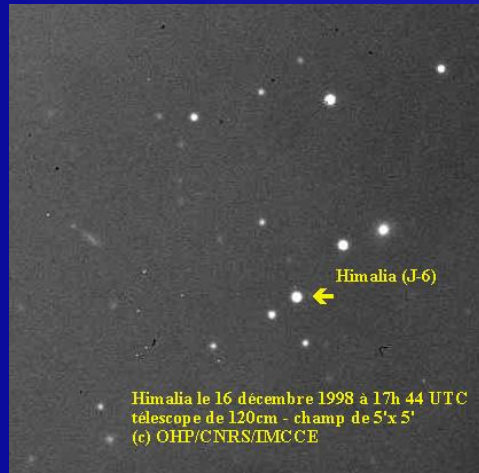
Ephemerides elaboration

Step 1: Dynamical model



Ephemerides elaboration

Step 2: Observations

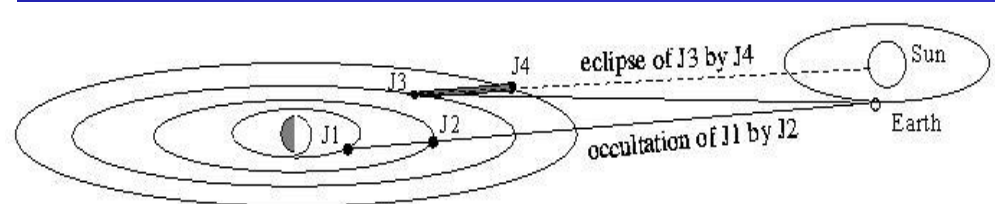
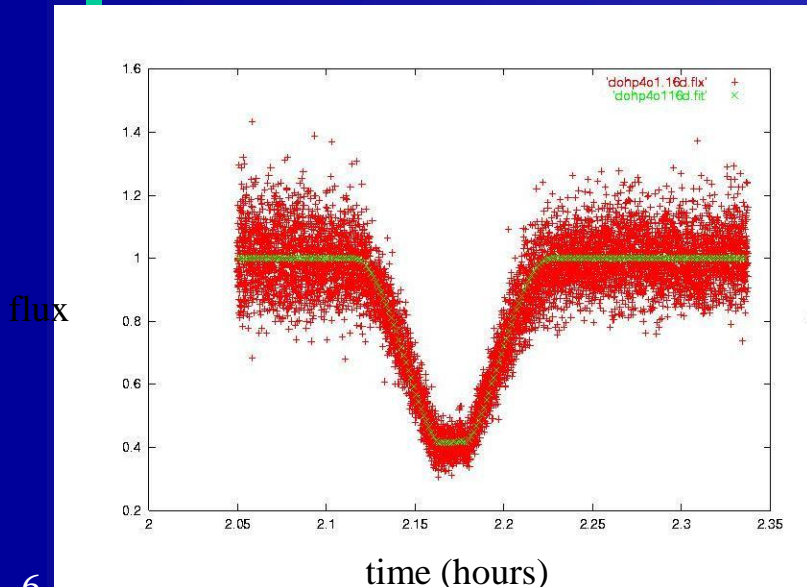


Astrometric observations

Corrections of:

- time scale
- frame
- aberration
- light time

Few different kind,
but **many different format!**



The mutual events (occurring each 6 years)

Photometric observations

Ephemerides elaboration

Step 3: Fit

Observations

Theory

Integration of partial
derivatives

Linear system
approximation
=> **Least squares
method**

$$\left(\mathbf{r}_s^{(k)} - \mathbf{r}_s^{(k)}\right) = \sum_{l=1}^{6N+M} \frac{\partial \mathbf{r}_s^{(k)}}{\partial c_l}(\mathbf{c}) \Delta c_l + O((\Delta c_l)^2)$$



If the observational errors are gaussian and assuming a perfect modelling...

If not, use a random hold out or bootstrap method for the fit

Ephemerides elaboration

Interpolation

Step 4: Making a representation

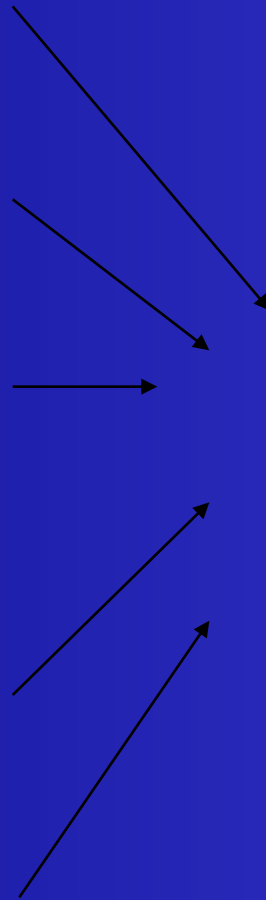
Polynomials of time

Chebyshev
polynomials

Fourier analysis

Mixed functions

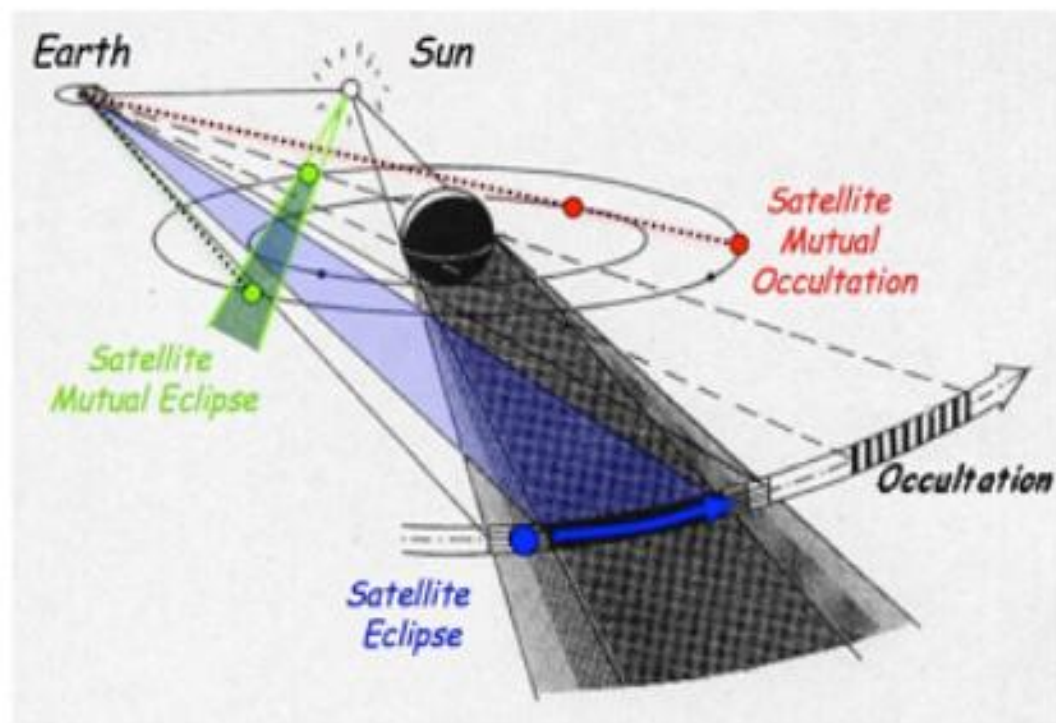
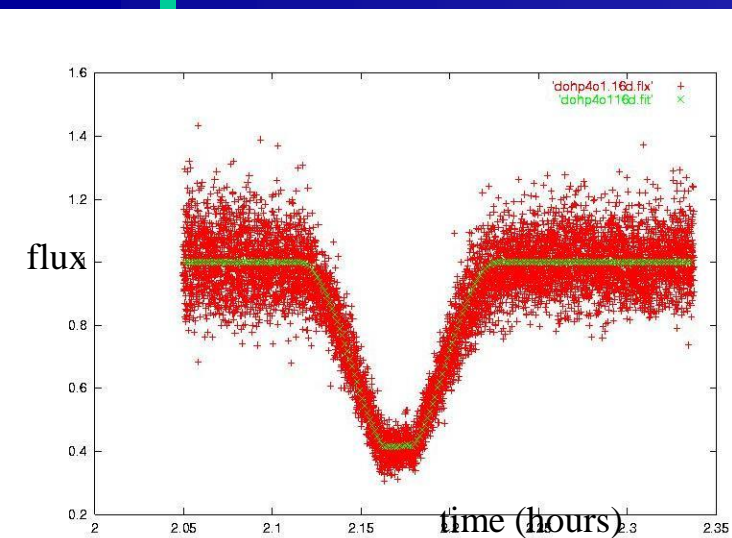
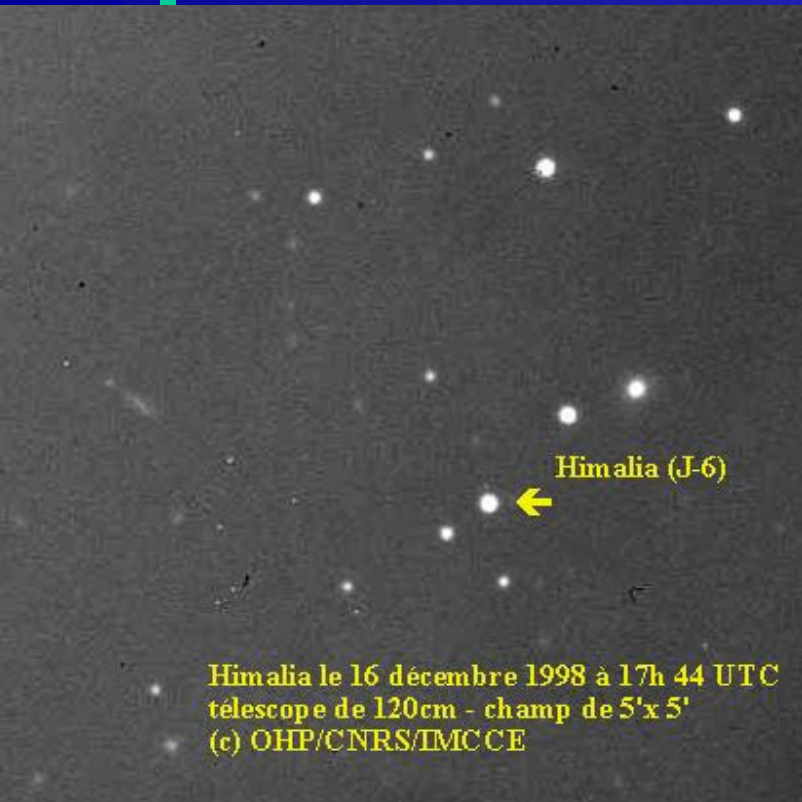
« EPHEMERIDES »



Two types of observations

Direct observations through
astrometric images

Photometric observation of
phenomena



Choosing the observational techniques (1 mas = 3km)

Technique	Accuracy	Objects	Remarks
Transit circle	50 → 100 mas	mag 6-15	Obs. of a passage
Scanning telescope	50 → 100 mas	→ mag 20	RA & DEC measure
Tangential focal plane images	20 → 2000 mas	all	CCD imaging
AO, IR	a few mas (relative)	inner objects	objects close to their primary
<u>Photometric events</u>	<u>1 → 10 km (relative)</u> <u>i.e. 0.3 → 3 mas</u>	<u>main planetary satellites, asteroids</u>	<u>Occultations and eclipses</u>
Gaia	0.1 → 1 mas	mag 7 → 20	50 obs./5 years
VLBI, Doppler space probes	2 → 10 mas	objects visited by space probes	Precise but few observations
Radar	10 → 100 m	Near Earth Objects	Galilean sat.?
LLR	1 → 3 cm	The Moon	

What is a mutual phenomenon?

- Satellites are orbiting around planets in the planetary equatorial plane.
- When the Earth and the Sun pass through the planetary equatorial plane (it is the time of **equinoxe**), occultations and eclipses occur between the satellites: these are mutual phenomena.

Observing the mutual events

- Phenomena of eclipses by the shadow of Jupiter are well known since the XVIIth century. Mutual events were observed by chance without any prediction.
- The prediction of these events is made only since the 1970's thanks to the arrival of computers.
- A mutual event occurs or not by a few kilometers: before the 1970's the ephemerides were accurate to 3000 km!
- The first organized and planned observations were made in 1973.
- Results were encouraging allowing also to determinate the diameters of the satellites.
- At the present time, the observation of these events may provide positions accurate to a few kilometers (1 mas or better)

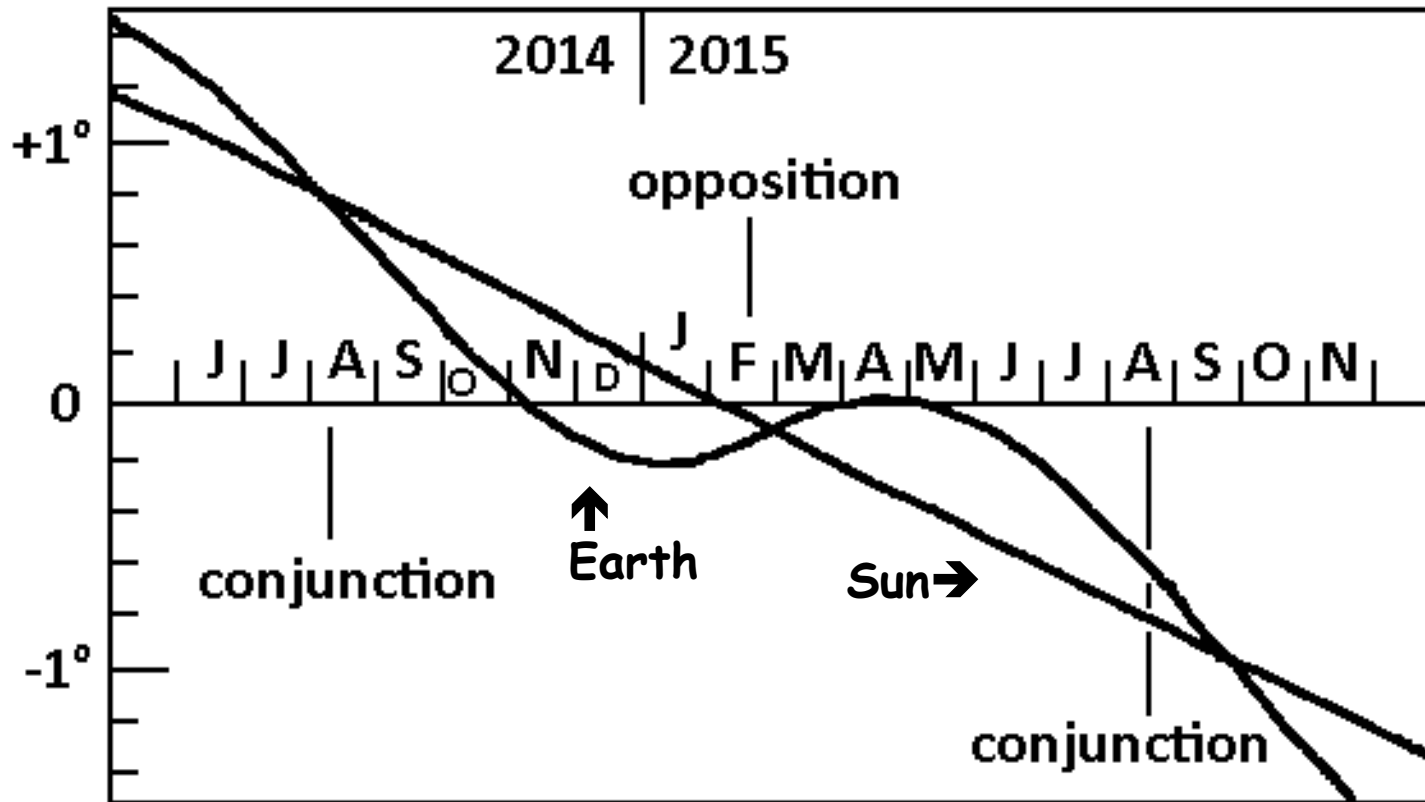
Equinoxes on the giant planets

Jupiter: 1973, ..., 2003, 2009, 2015 (every 6 years)

Saturne: 1980, 1995, 2009, 2024 (every 15 years)

Uranus: 2007, ... (every 42 years)

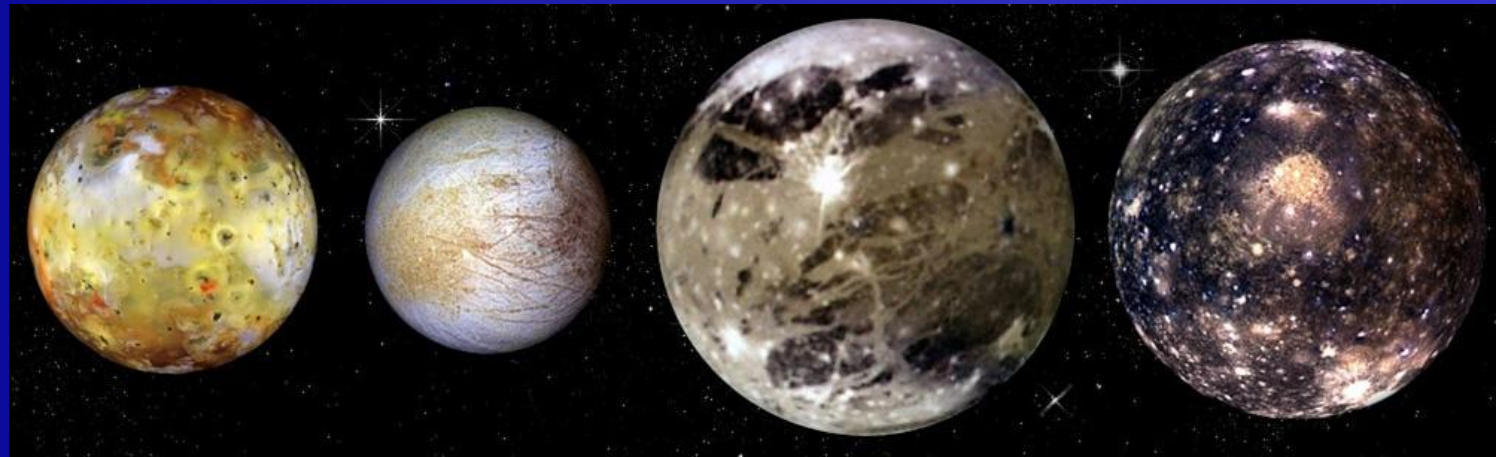
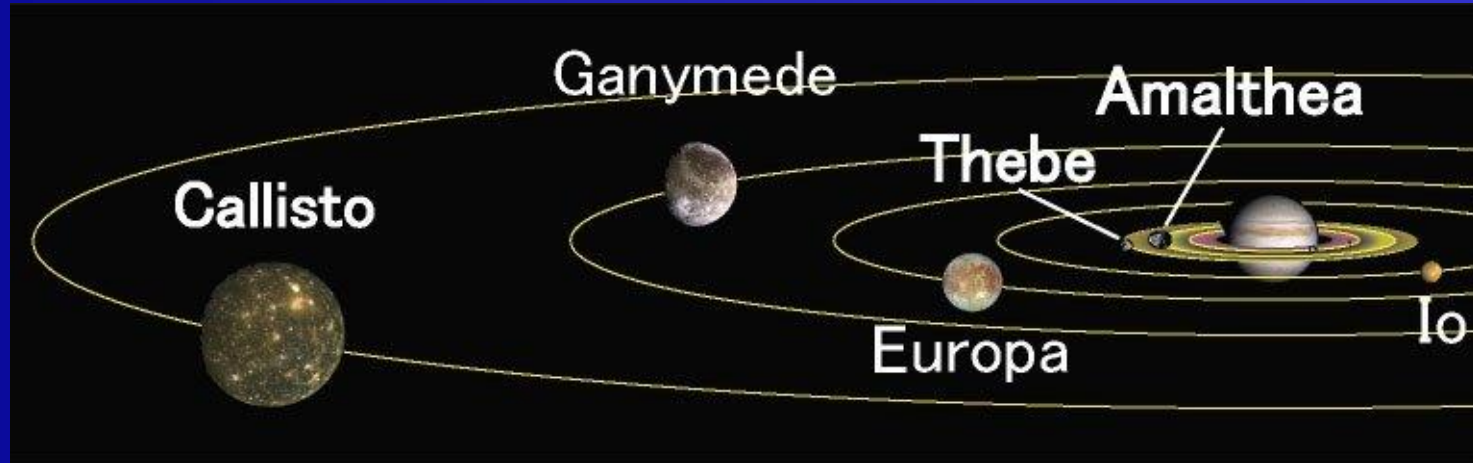
The joventric declination of the Sun and the Earth



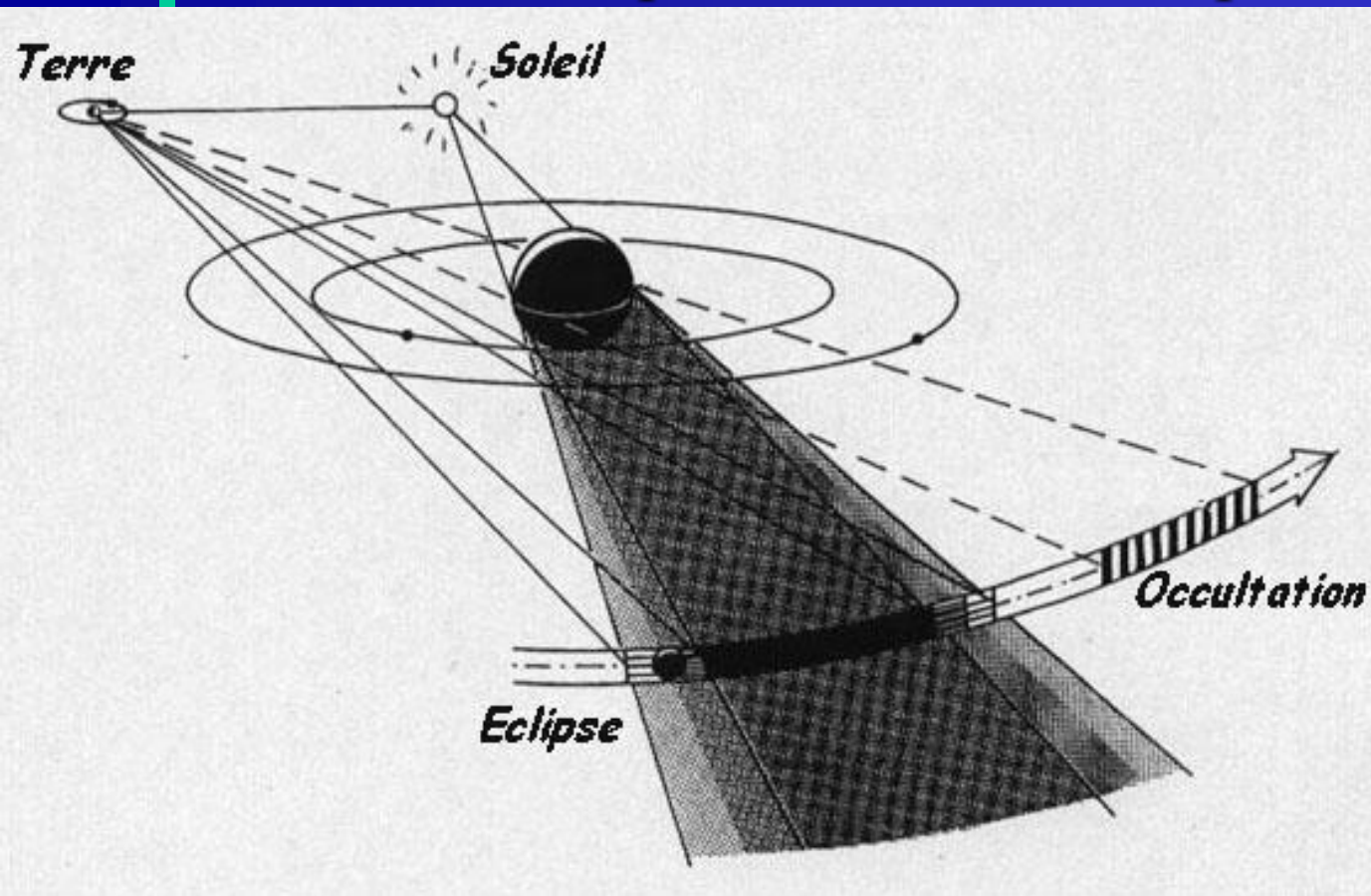
Events occur when the planetocentric declination of the Sun and the Earth is less than one degree.



The Galilean satellites : small planets



Classical phenomena with Jupiter are numerous



Earth



Moon



Jupiter



Io

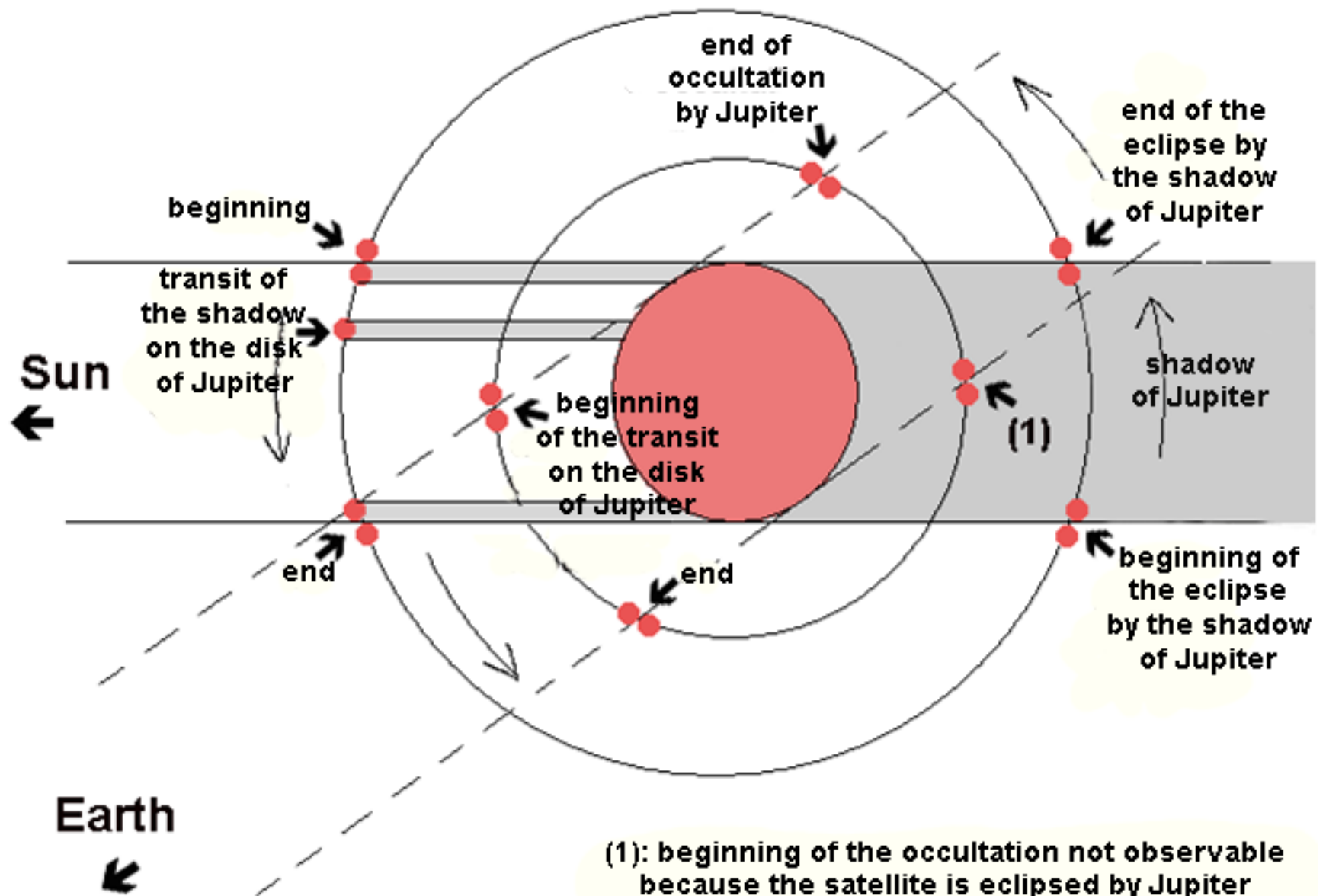
The well-known events so called « classical »

- These events satellites/Jupiter are known since Galileo
- The eclipses by the shadow of Jupiter have been used to build the first ephemerides of Jupiter
- The observation of an eclipse = the measure of the instant of the disappearance or of reapparance of the satellite in the shadow of Jupiter
- At that time, we observe a geometric configuration of the Jovian system corresponding to a specific positions of the bodies.

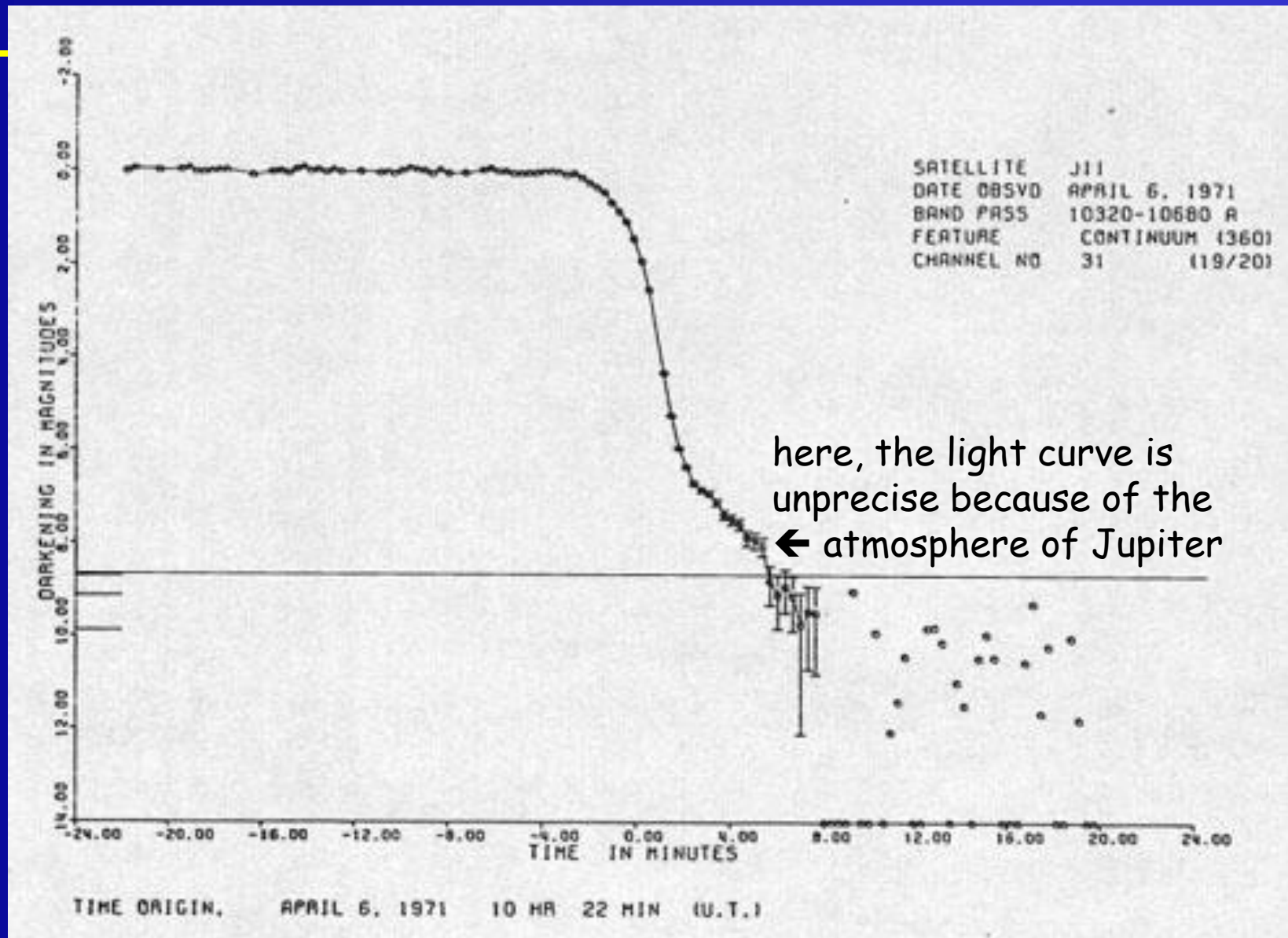








The observation of an eclipse = a photometric observation



Refraction in the atmosphere of Jupiter

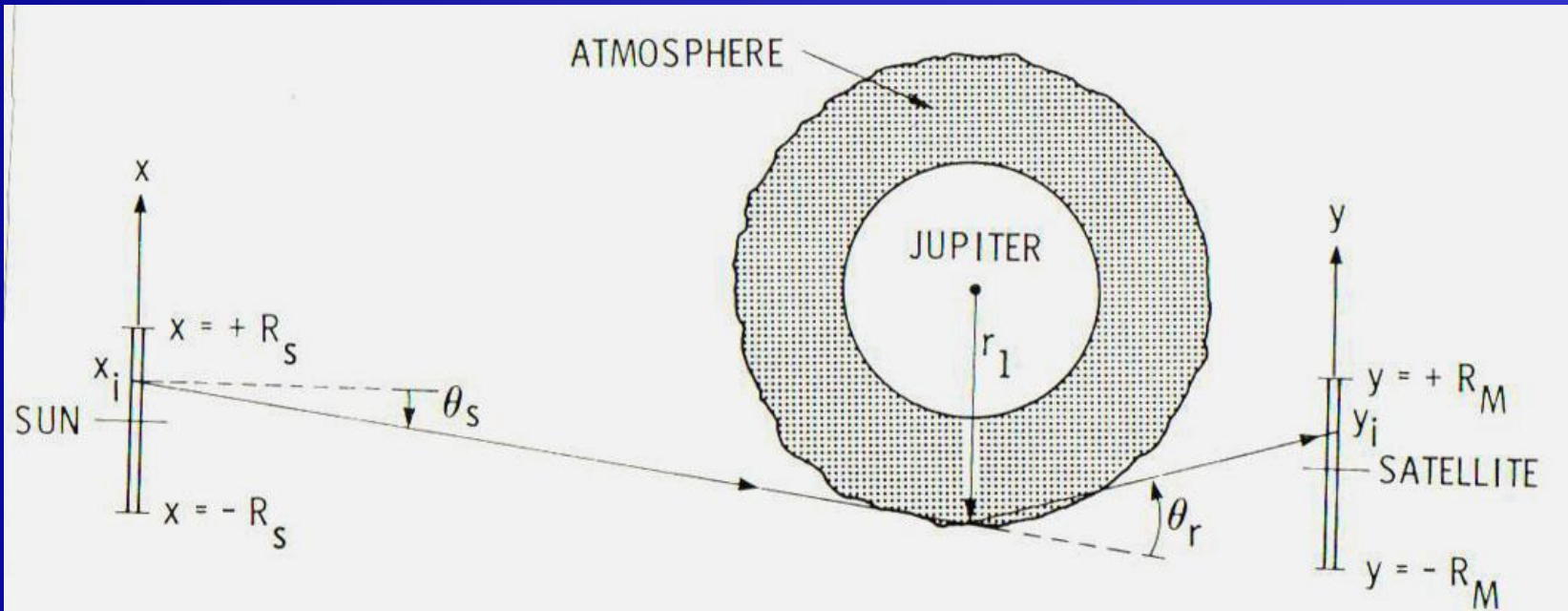
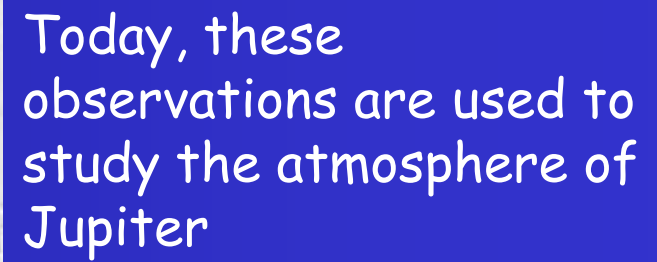


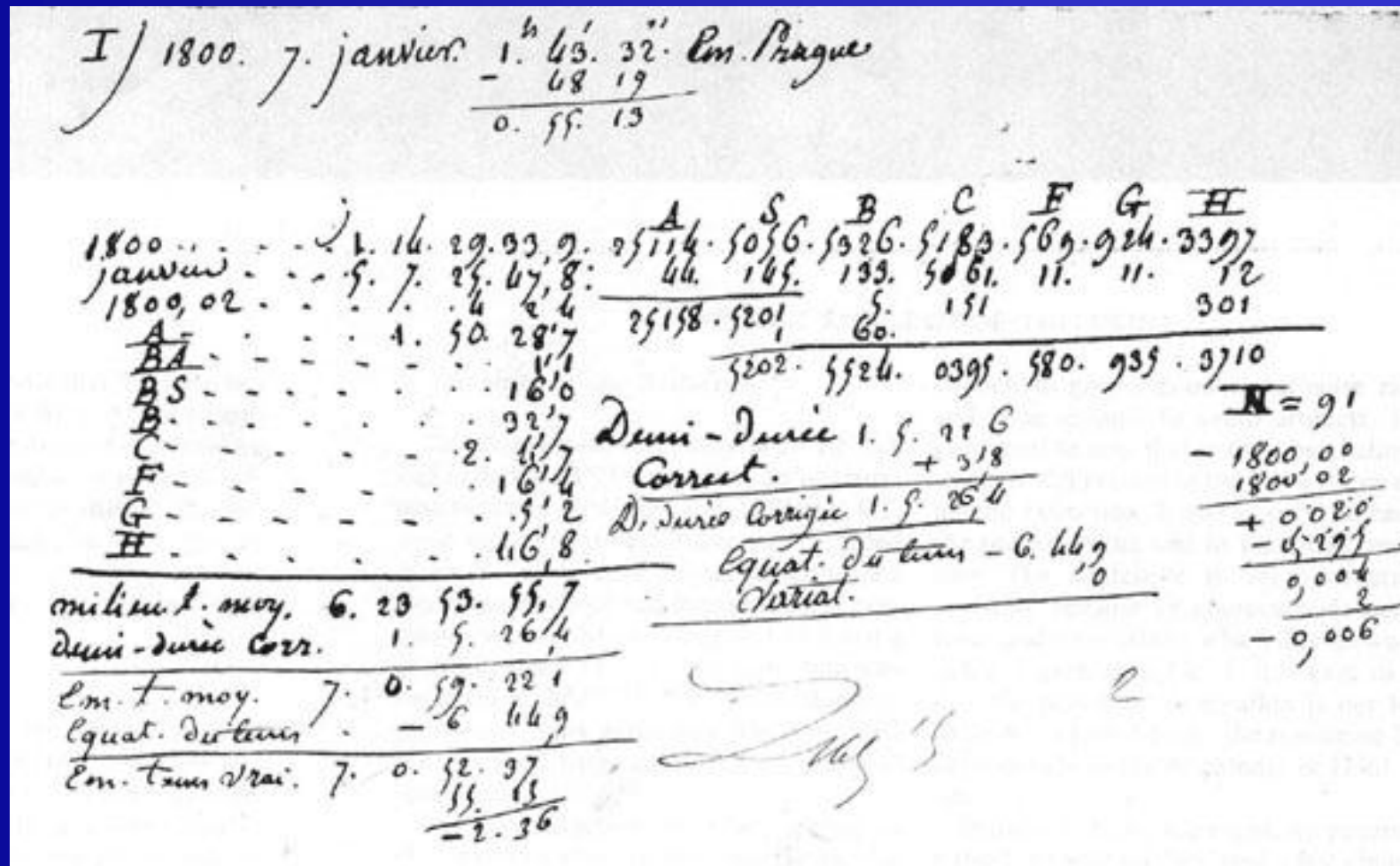
Figure VII-1 Typical Ray Path

A ray leaves the sun at x_i and θ_s . At the nearest approach distance, r_1 , it is refracted through θ_r and falls on the satellite at y_i .



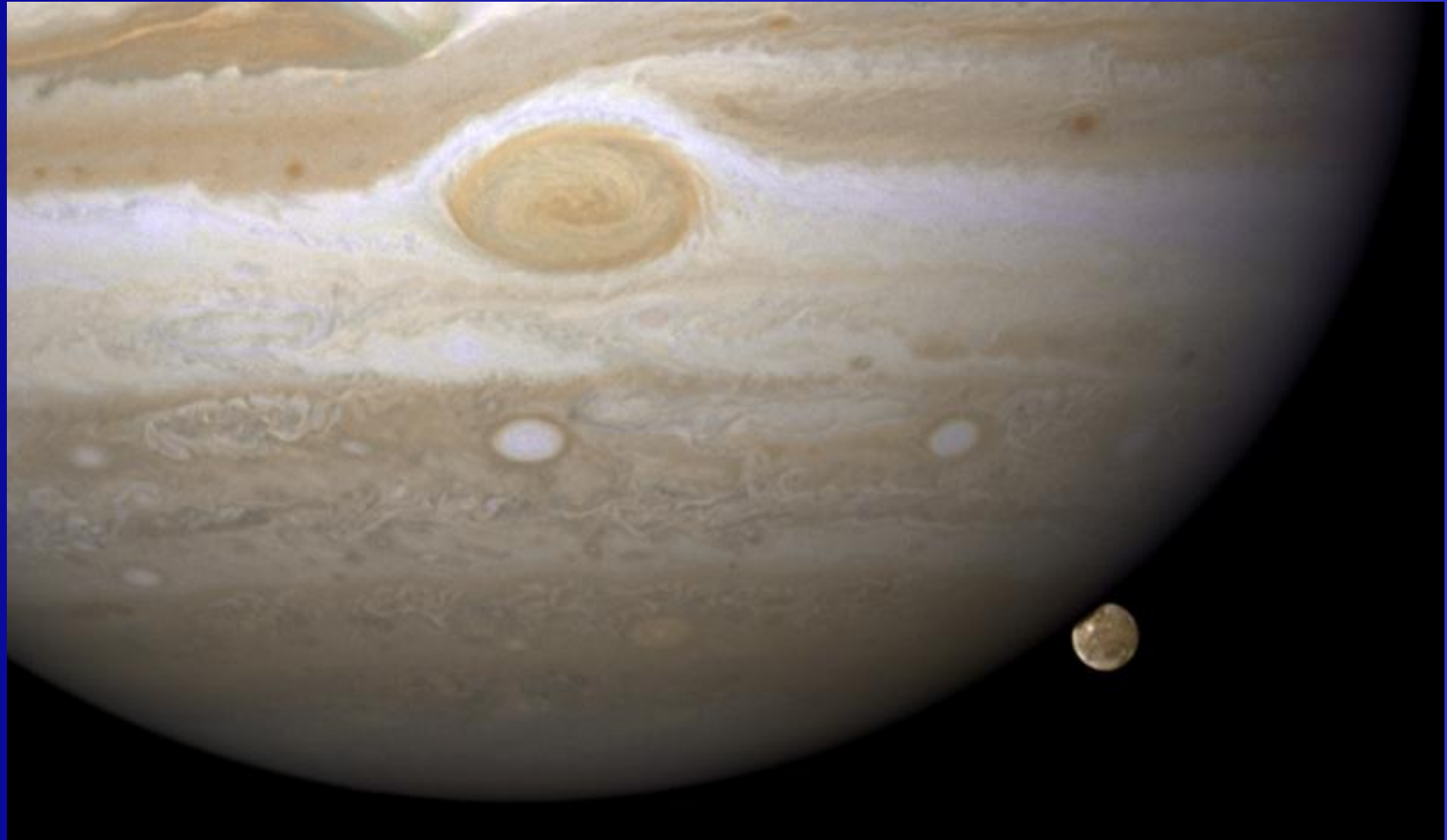
Today, these observations are used to study the atmosphere of Jupiter

An observation made by Delambre in 1800



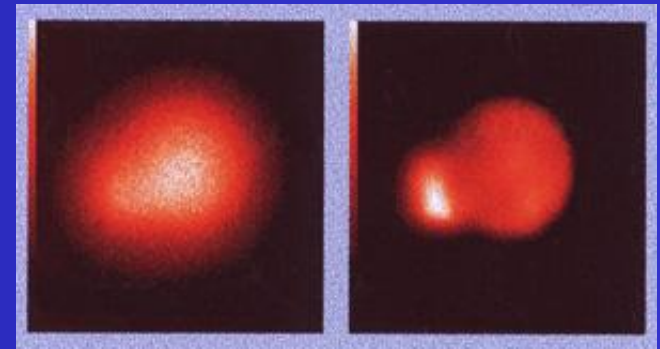
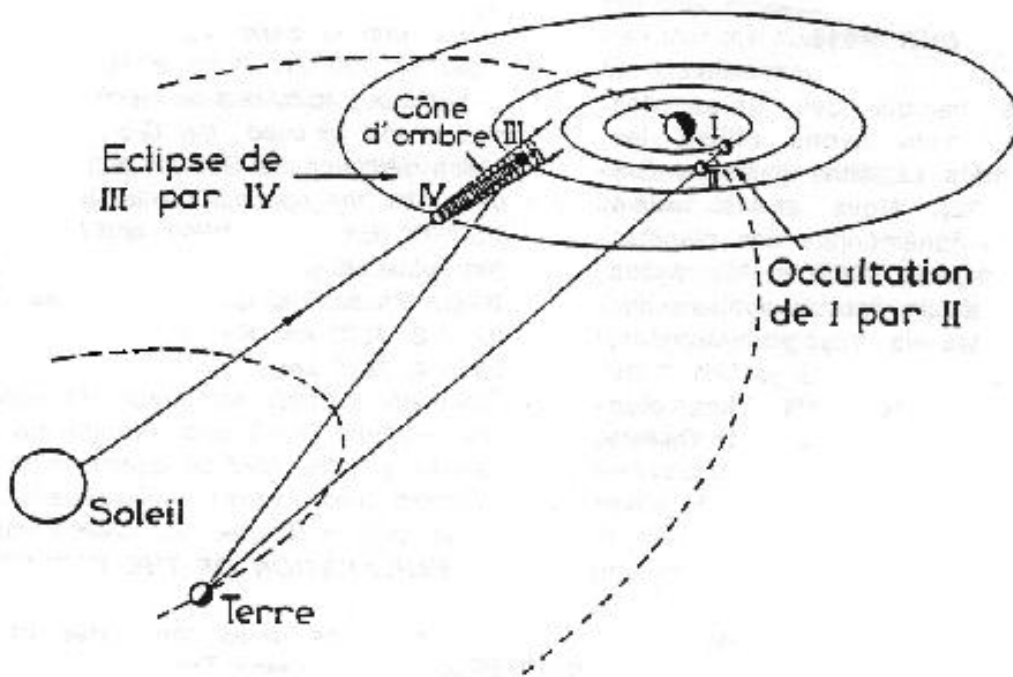
A very rigorous observation but the timing is not sure
 Good precision but bad accuracy due to the conversion:
 True solar time → mean time → universal time → terrestrial time

Jupiter and Ganymedes as seen by the HST

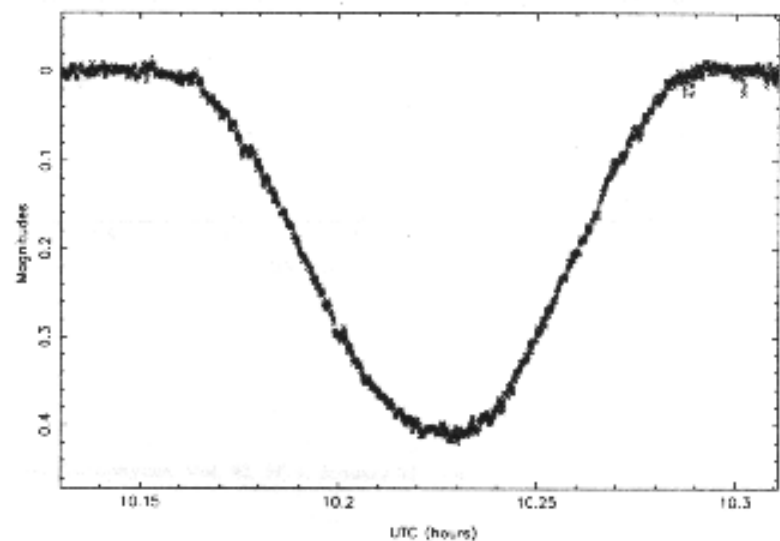


The atmosphere of Jupiter is a limit to the determination of its position

The mutual phenomena



An occultation as seen in adaptive optics



← A very clear light curve of a mutual phenomenon: the inversion of the light curve will be easy to determine the astrometric and physical parameters

The accuracy of the observation of the mutual events

- Drop in magnitude: accuracy from 0.01 to 0.001 mag
 - accuracy in position : 20 to 2 km
(in inclination of the orbits)
- Timing: accuracy of 1 to 0.1 second of time
 - accuracy in position from 10 to 1 km
(in the orbit)

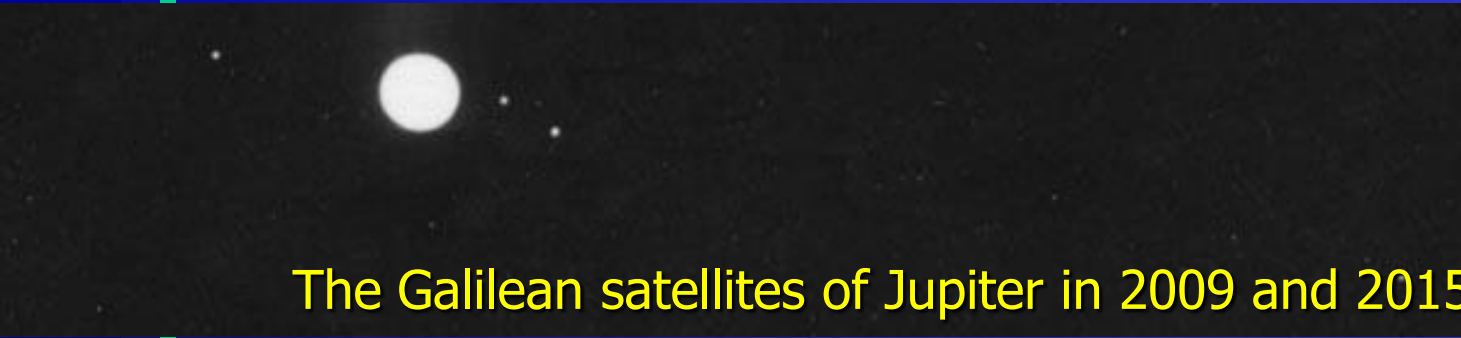
All these accuracies do not depend on the distance
to the Earth!

Why observing the natural satellites?



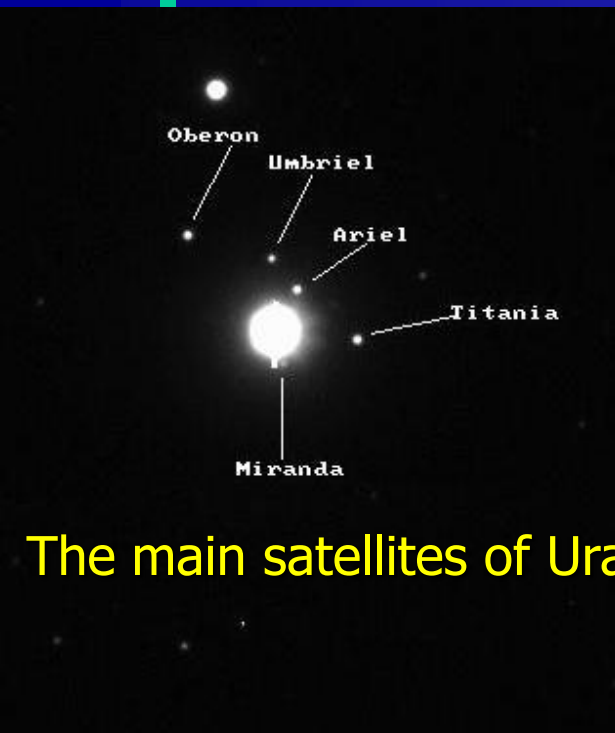
Compared sizes of the satellites and of the terrestrial planets

Which systems of satellites are concerned?



The Galilean satellites of Jupiter in 2009 and 2015

The « icy or terrestrial » satellites



The main satellites of Uranus in 2007

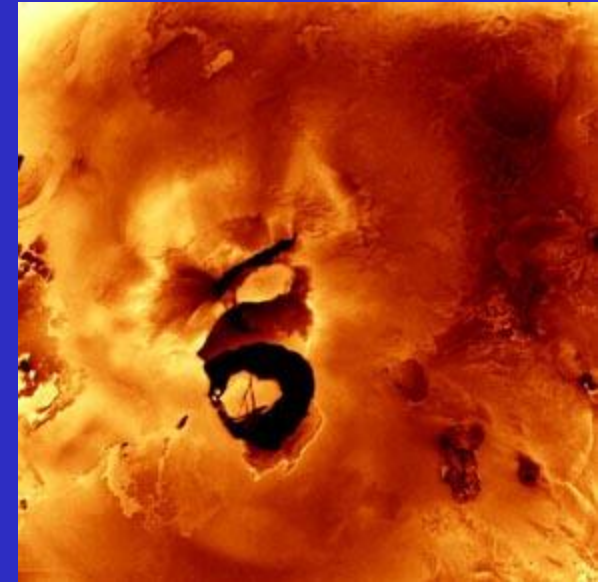


The main satellites of Saturn in 2009

First goal: observing and understanding the volcanoes of Io

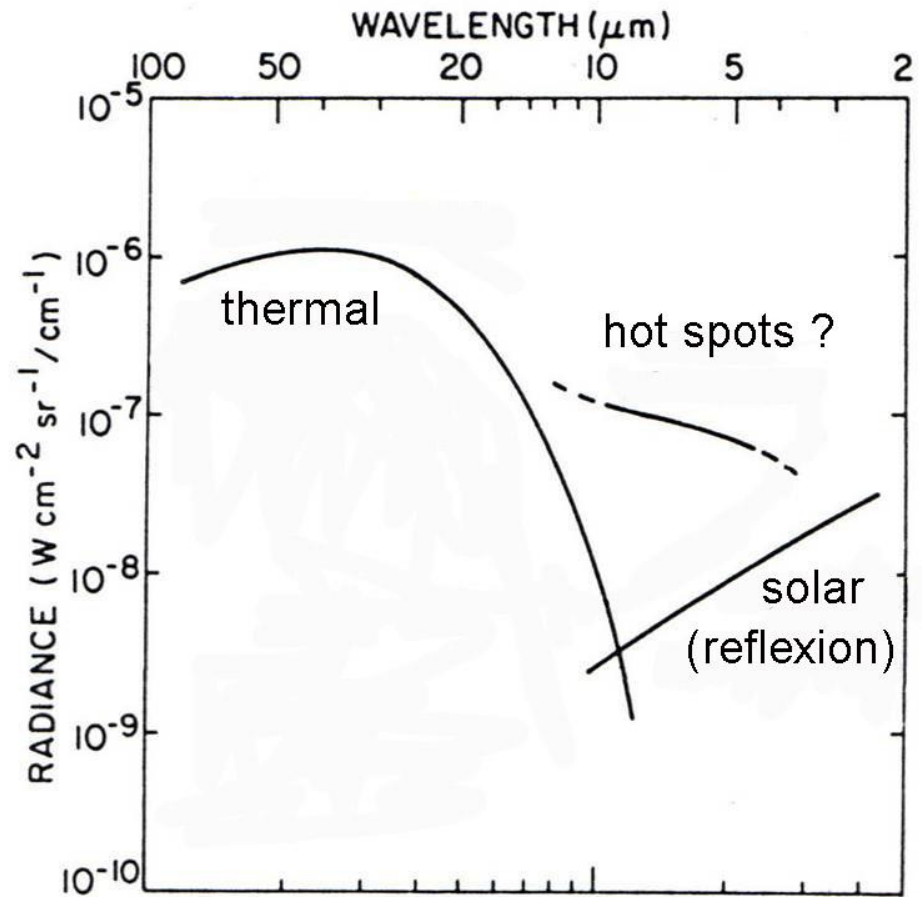


Io the first satellite of Jupiter has active volcanoes visible from the ground through IR



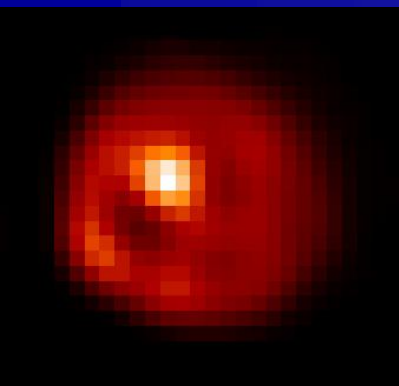
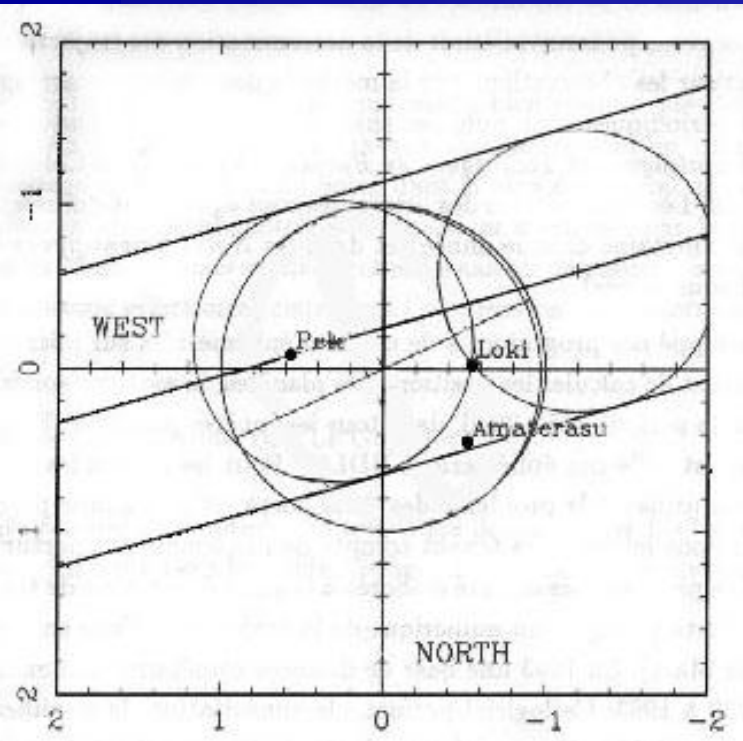
Infra red observations

- The emission of the surface of a satellite of Jupiter
- The case of Io



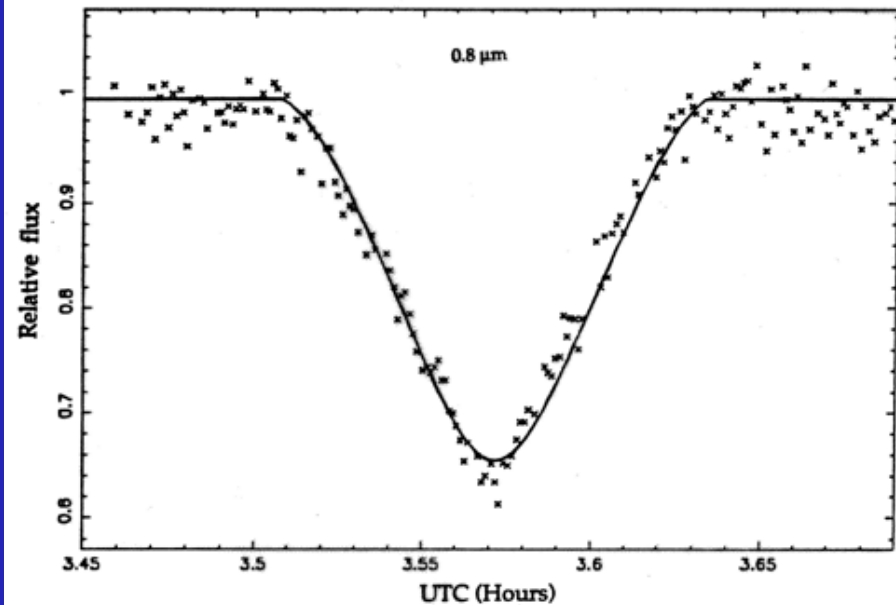
Infra red observations

Occultation of Io by Europa

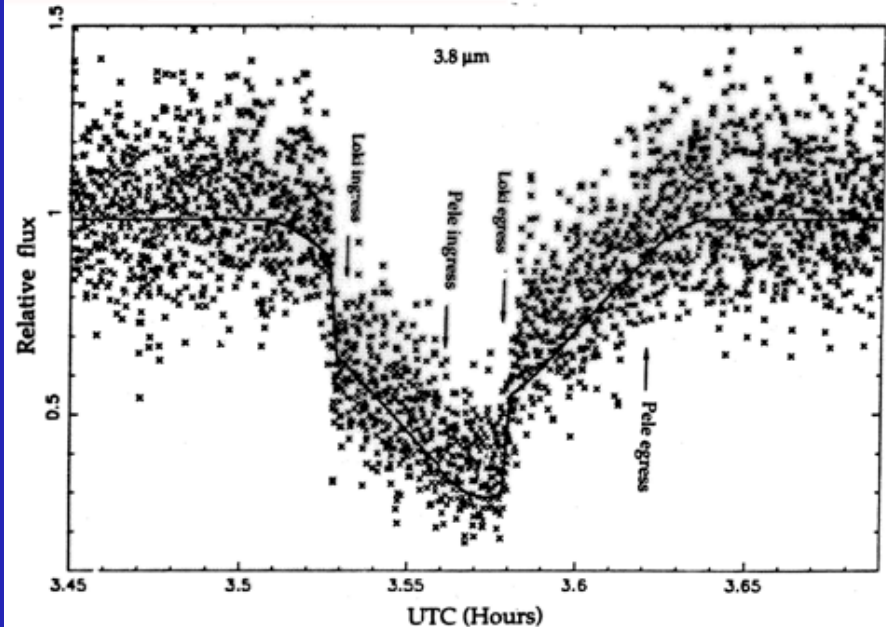


The first detection of the volcanoes of Io from the ground through an occultation of this satellite →

← a recent observation in L-band

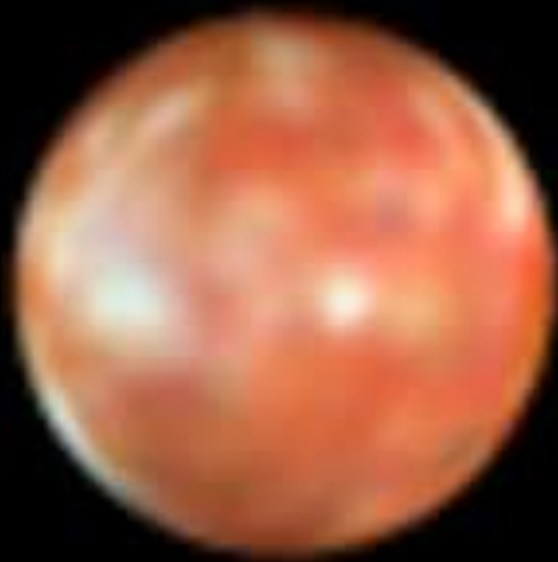


Lightcurve observed at 0.8 μm and the model (line) during the occultation of Io by Europa on February 20, 1991, at the 1-m telescope of the Pic du Midi Observatory (Colas *et al.*, in preparation).

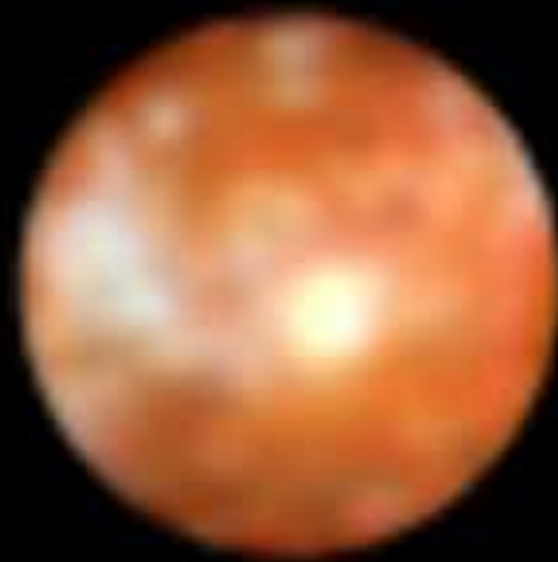


Lightcurve observed at 3.8 μm and the model (line) during the occultation of Io by Europa on February 20, 1991, at the 1-m telescope of the ESO.

HST infra red observation



March 1994



July 1995

Changes on the Surface of Io

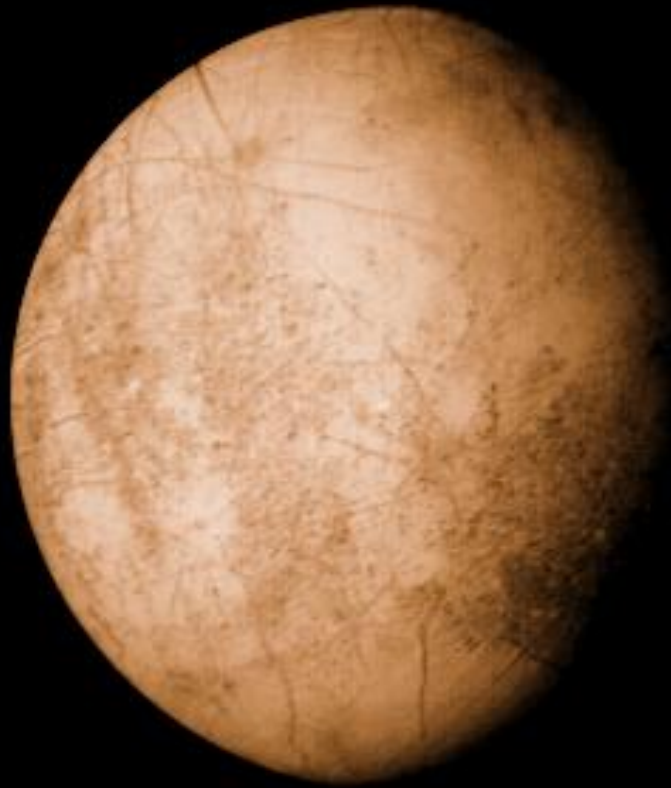
HST • WFPC2

PRC95-37 • ST ScI OPO • October 9, 1995 • J. Spencer (Lowell Obs.), NASA

Scientific goals: the internal structure of the satellites

- The systems of satellites are similar to solar or extra-solar planetary systems
- All gravitational and non-gravitational effects are present
- High accurate astrometry of the orbits provides constraints on the internal structure of the satellites
- Measuring accelerations in the motion of the satellites allows to measure the dissipation of energy inside the satellites

Case of Europa



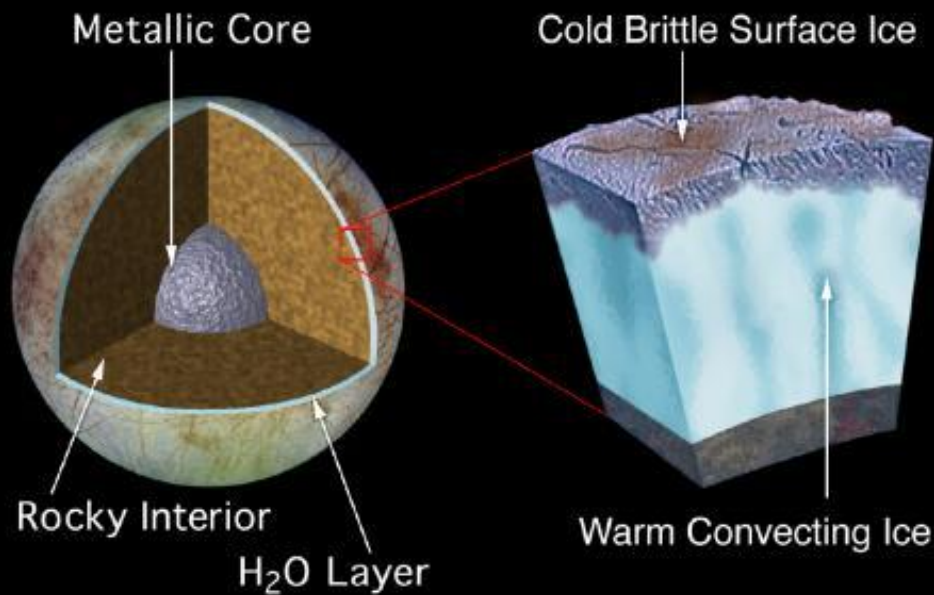
Europa, the second Galilean satellite is covered by a ice pack with an eventual ocean beneath.



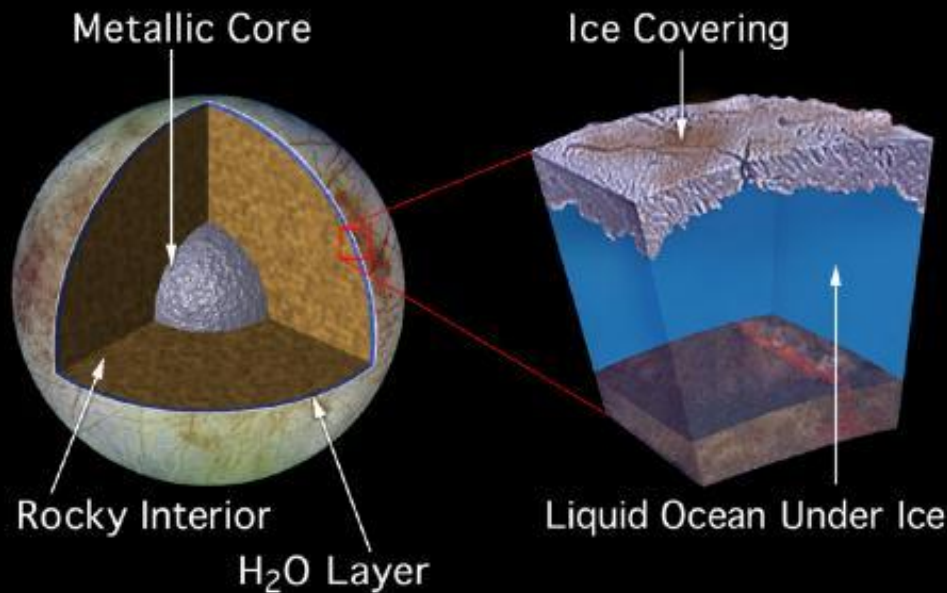
Life in an ocean on Europa?



EUROPA'S CORE



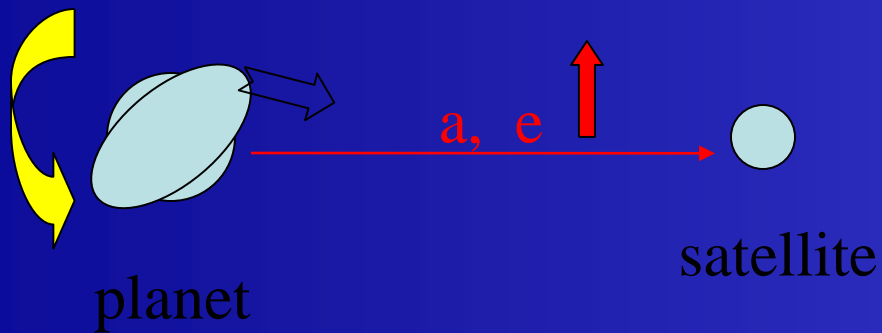
The internal structure of Europa is not yet known



← several models of internal structure for Europa

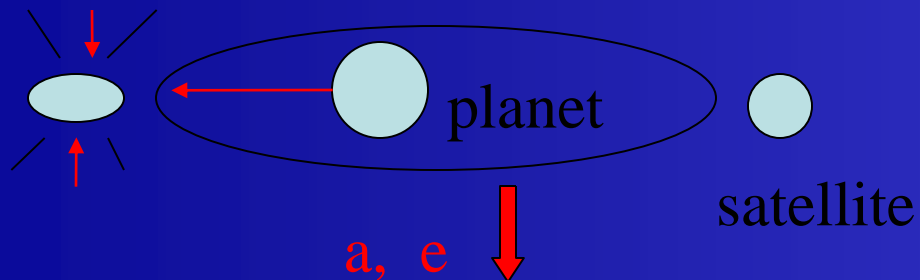
A question to be solved with accurate astrometry

Tidal effects in the jovian system



Tides from satellite to planet

↳ Satellite escapes



Tides from planet to satellite

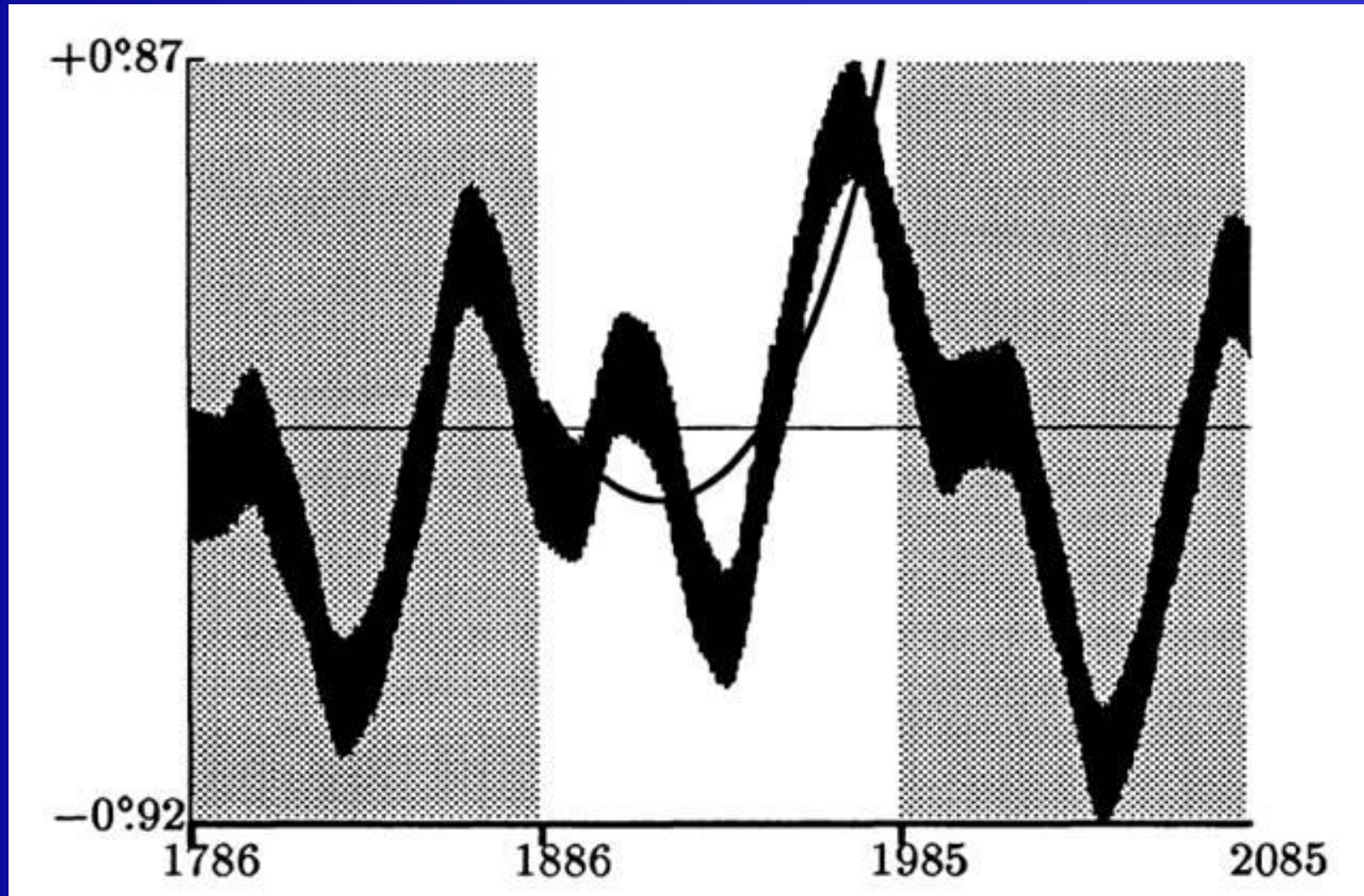
↳ Satellite falls

Measures of the acceleration of J1, J2 and J3

Quantification of the tidal effects and of the internal dissipation of energy(in 10^{-11} per year): **the need of a good dynamical model including all periodic terms especially the long periods similar to secular effects but not the consequence of tidal effects**

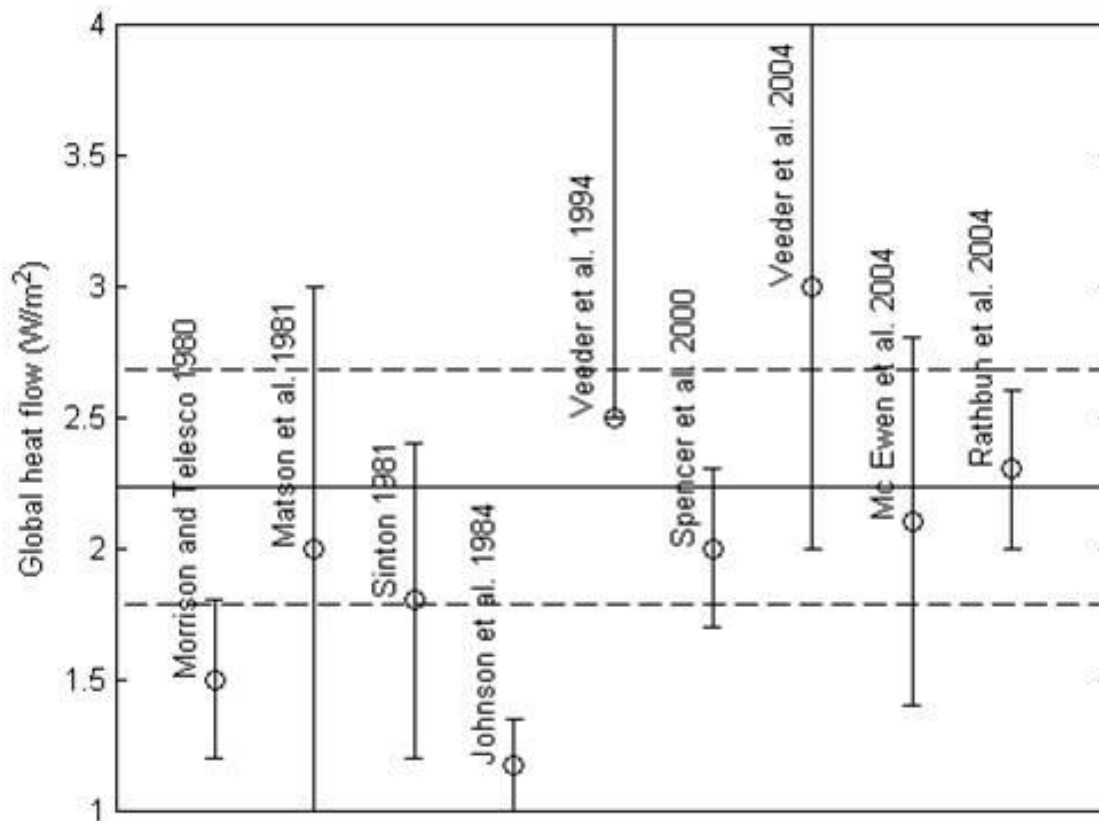
	n'_1/n_1	n'_2/n_2	n'_3/n_3
De Sitter, 1928	+33 (+/- 5)	+27 (+/- 7)	-15 (+/- 6)
Greenberg, 1986	+32 (+/- 8)	-16 (+/- 4.5)	-16 (+/- 4.5)
Goldstein, 1996	+70 (+/- 75)	+56 (+/- 57)	+28 (+/- 20)
Vasundhara, Arlot, 1996	+22.7 (+/- 7.9)	-6.1 (+/- 9.3)	+10.6 (+/- 10.6)
Aksnes, Franklin, 2001	+54.7 (+/- 16.9)	+27.4 (+/- 8.4)	-27.4 (+/- 8.4)
Arlot, Lainey, 2006	+4.0 (+/-11.0)	-5.0 (+/- 7.0)	-7.0 (+/- 7.0)

Secular term or long period term ?



Knowing only the central part will let think that we have a secular term

The heat flux emitted by Io



← Here the flux calculated from the observation of the acceleration of the satellite

- We see that the calculated heat flux from the astrometric observation of the acceleration is equal to the measured heat flux at the surface by space probes or infra red observations.
→ Io is in thermal equilibrium

The accuracy depends on the type of observation

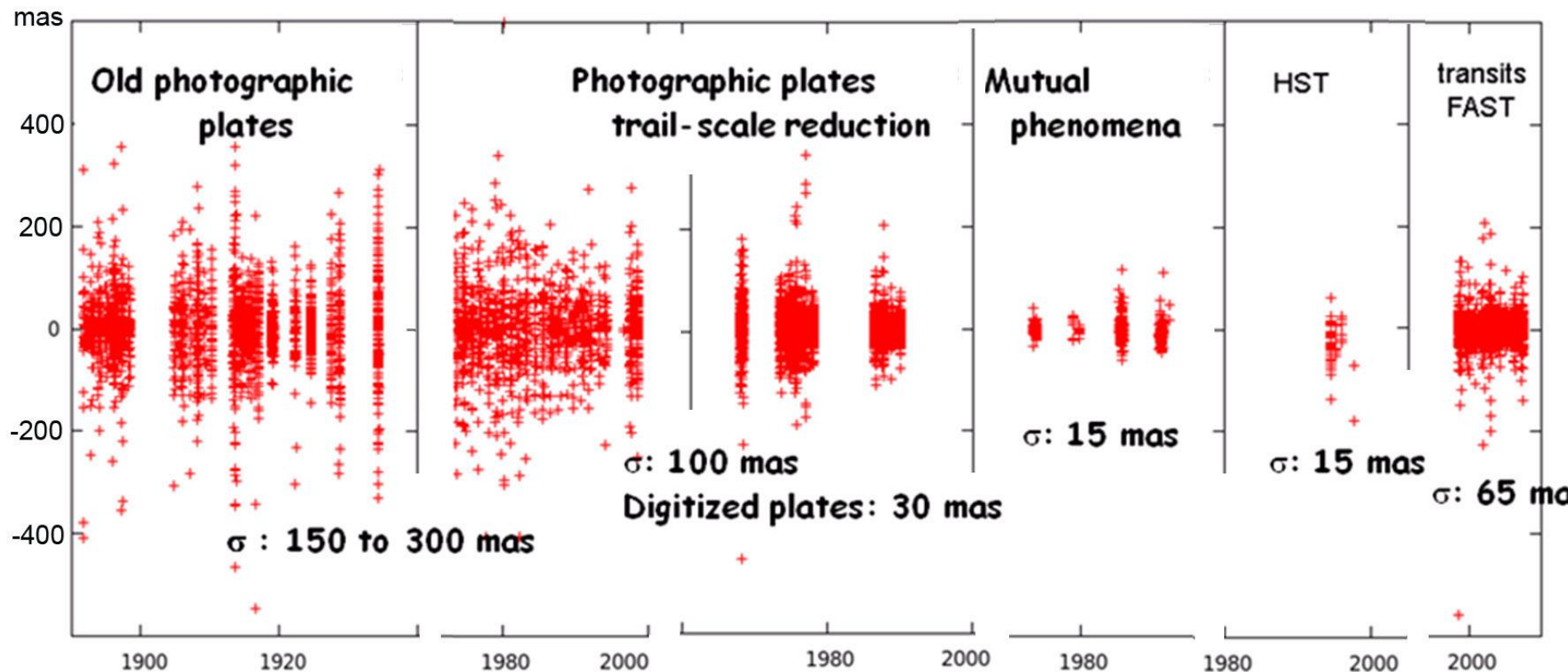
Case of the Galilean satellites of Jupiter

Type of observation	Accuracy in mas	Accuracy in km
Eclipses by Jupiter	150	450
Photographic plates	100	300
Transit circle	60	180
Digitized plates	40	120
CCD observations	40	120
Mutual phenomena	5	15

For the phenomena, the accuracy is given in kilometers, not depending on the distance to the Earth

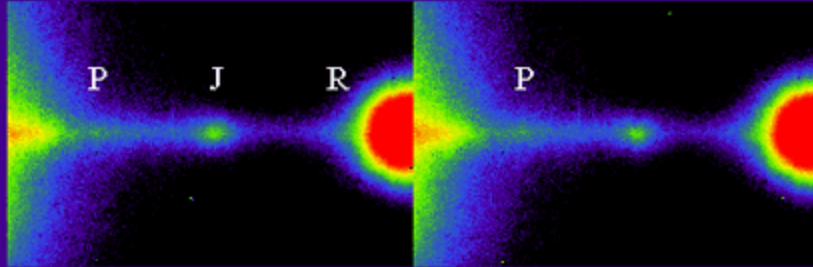
Analysis of astrometric observations

O-C residuals

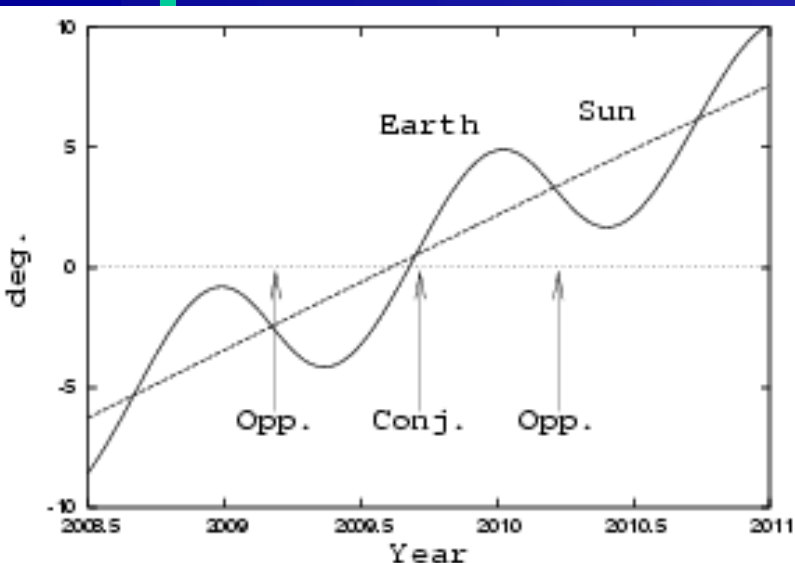


For Saturn: disappearance of the ring

DETECTION OF PANDORA AND 1995-S6
AT EARTH RING PLANE CROSSING



Disparition
During equinox in 2009

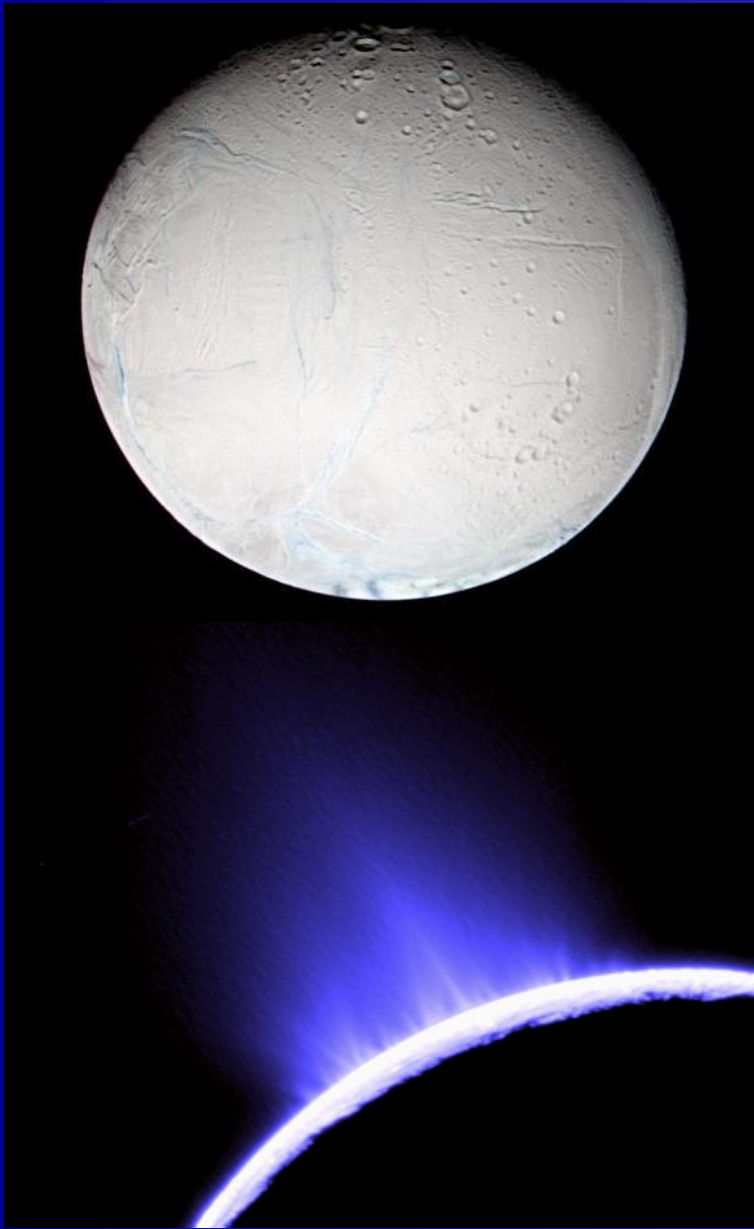


SATURN at EARTH-CROSSING TIME : 1995-05-22 3 h 59 U

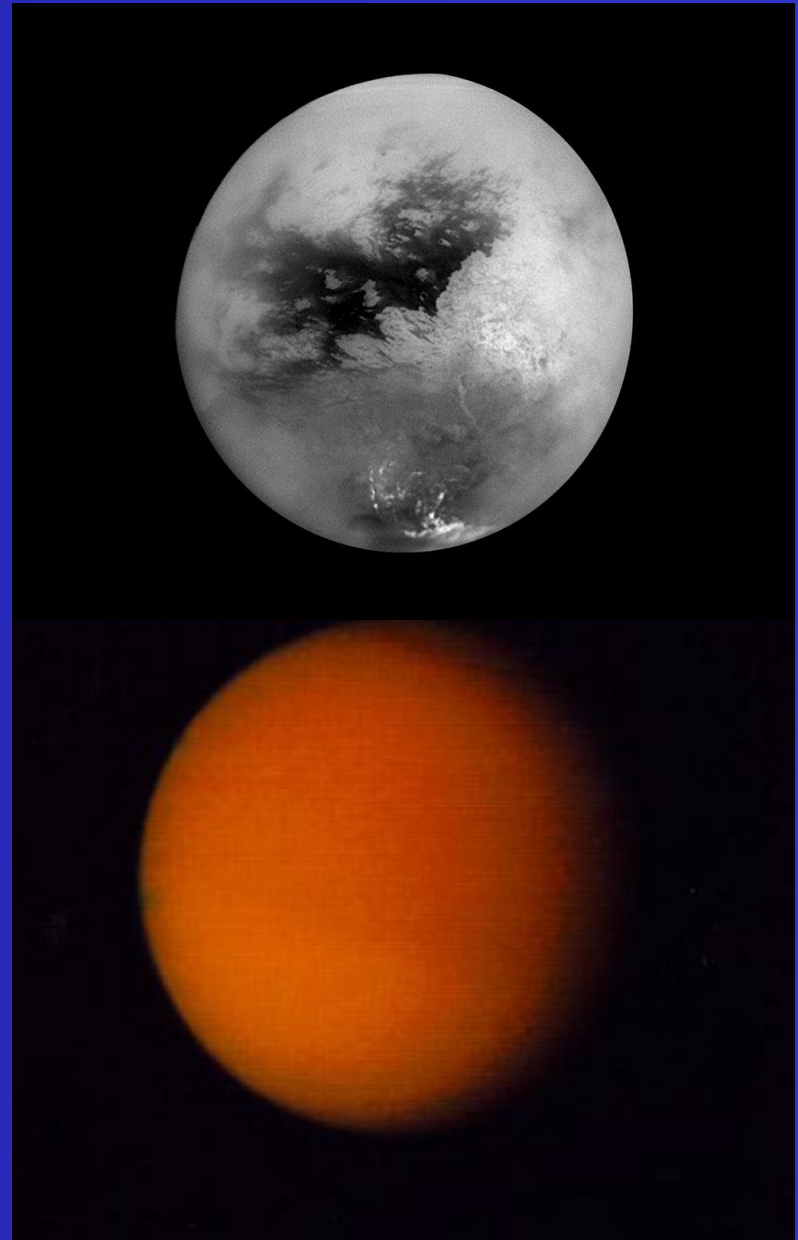


PIC du MIDI

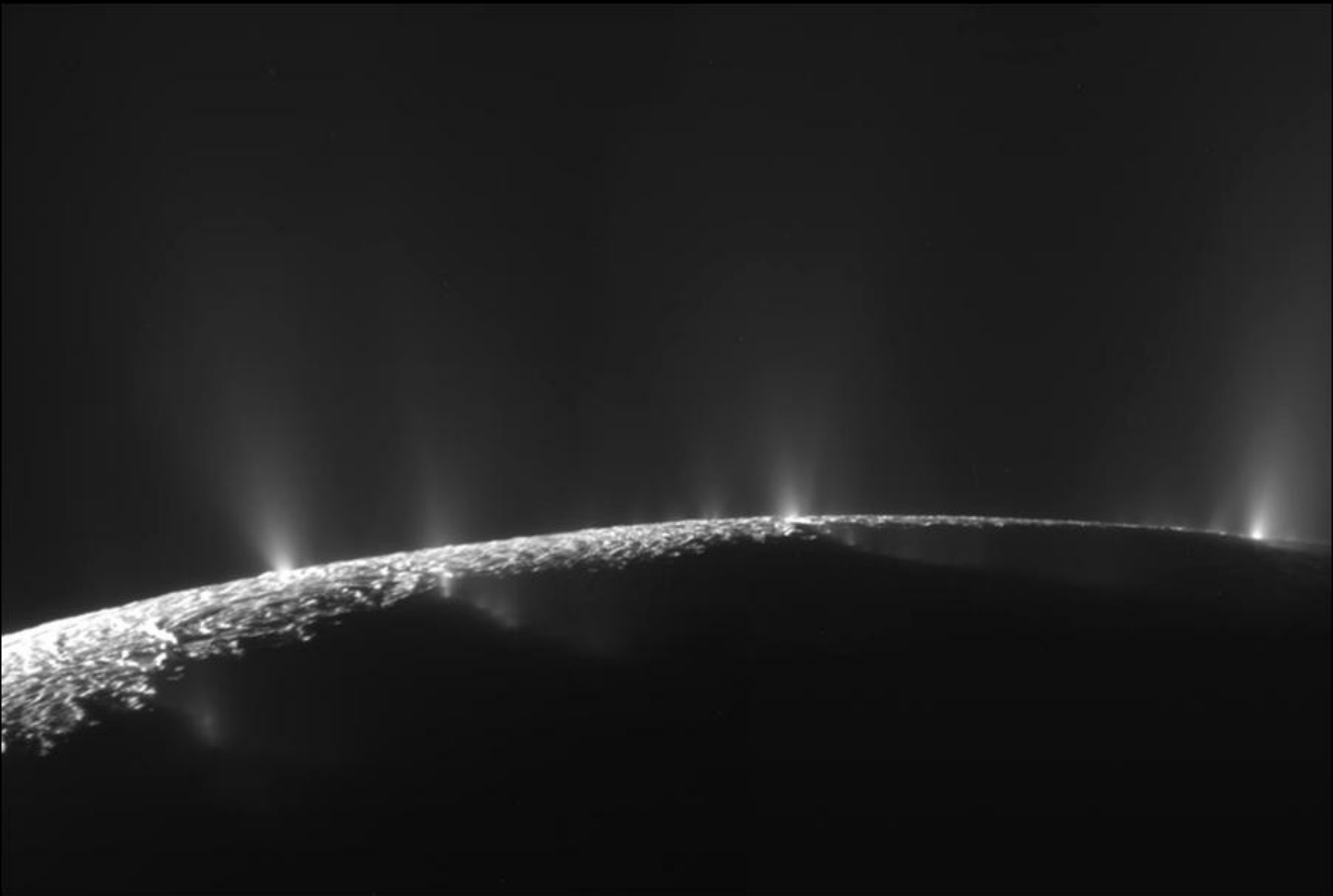
The eight main satellites of Saturn



Enceladus perturbed by tides



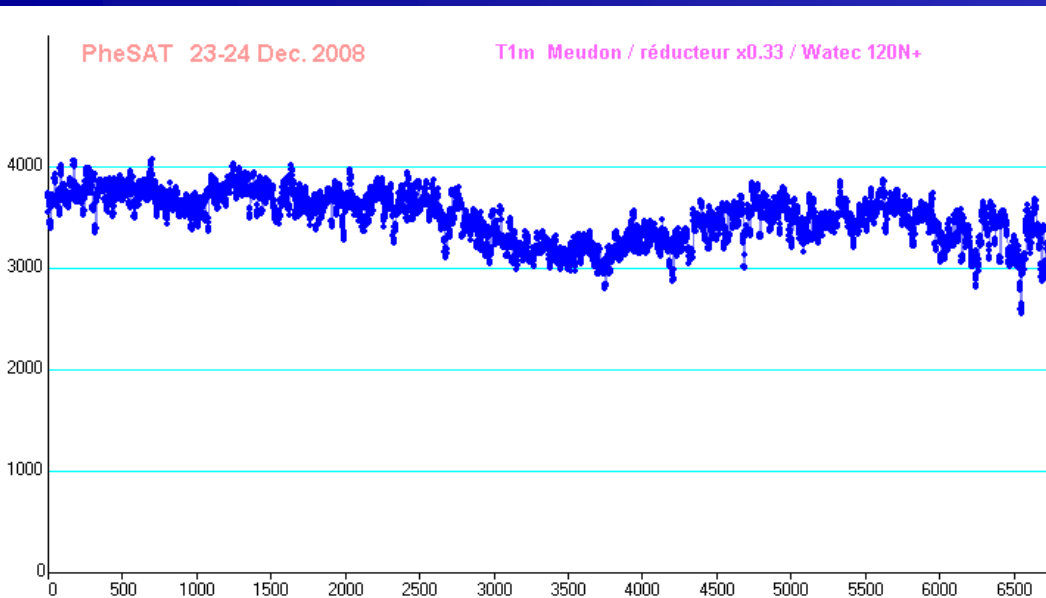
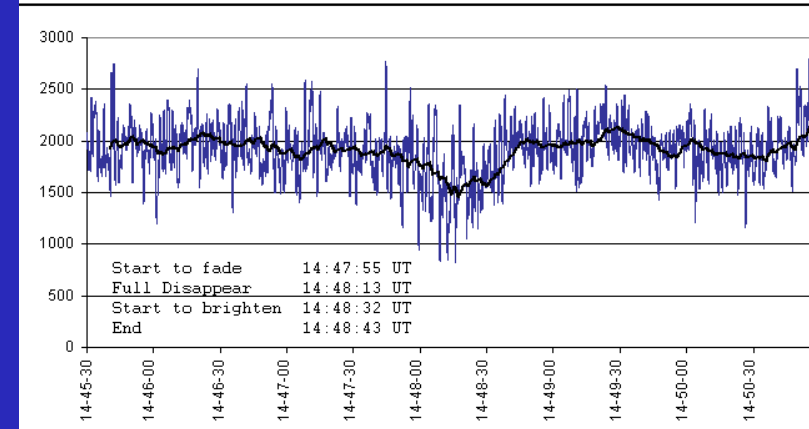
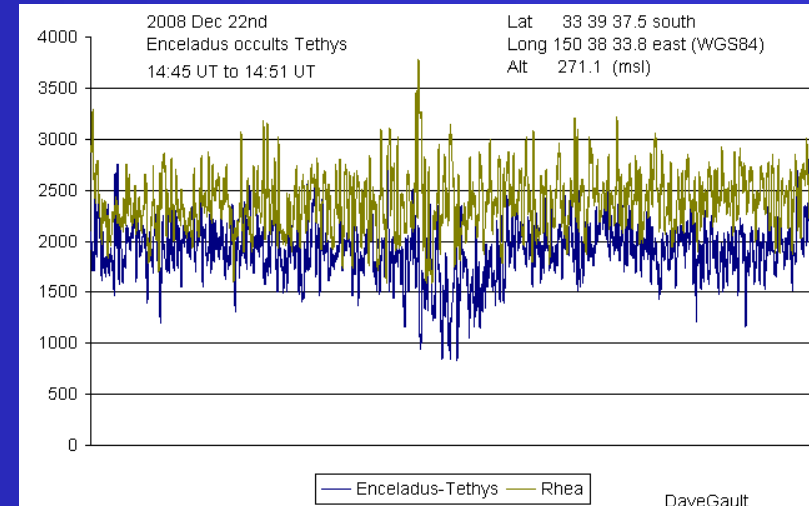
Titan has a large eccentricity



The events observed in 2009 (Meudon and Australia)

- Used to be compared to Cassini observations
- Residuals O-C reach 300km
→

2%→



Accuracy depending on the type of observations

Case of the satellites of Saturn

Type of observation	Precision in mas	Precision in km
Automatic transit circle	30	200
Observations CCD	30	200
Mutual phenomena	5	30

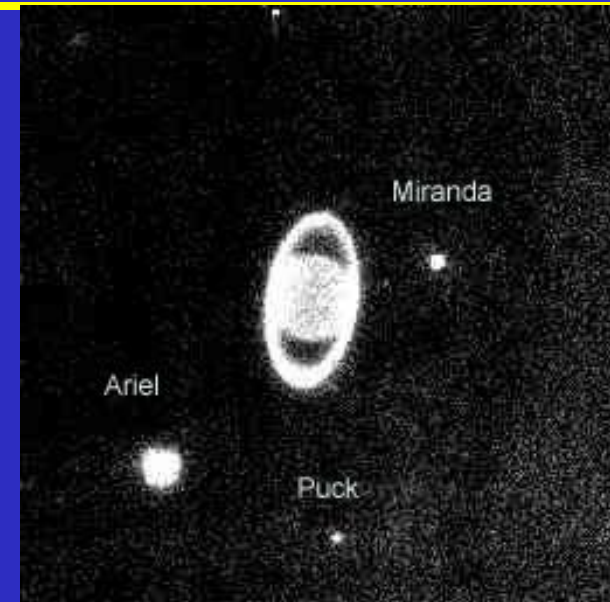
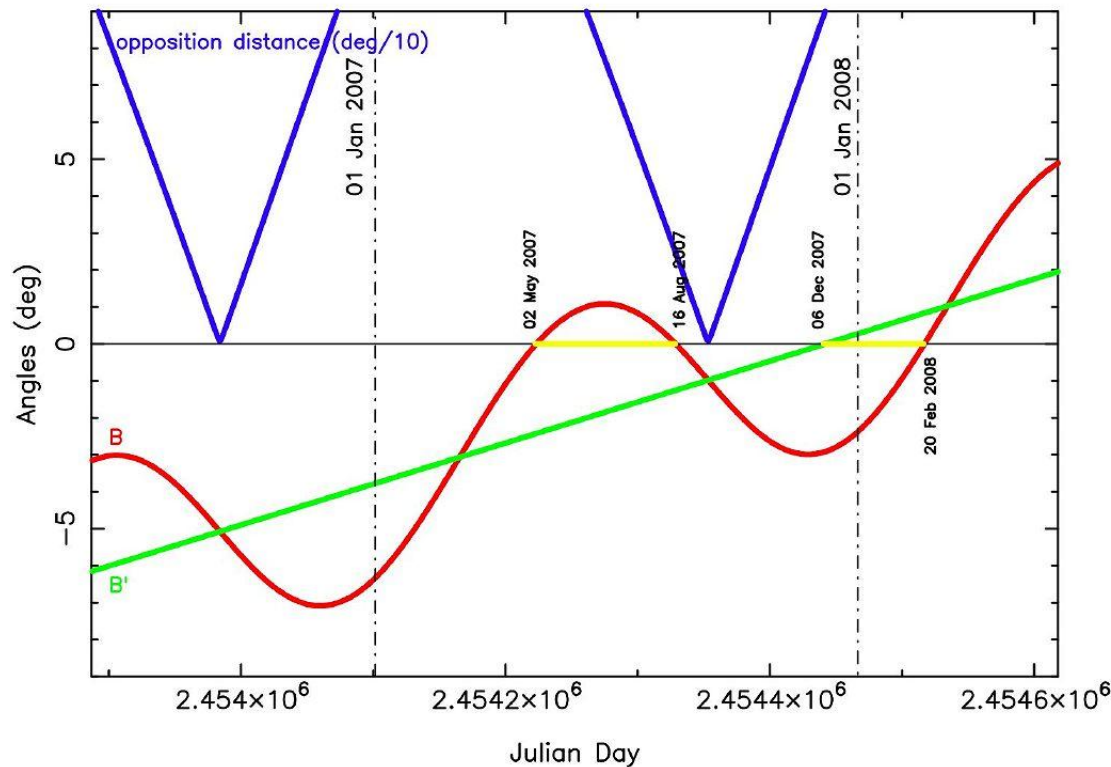
Case of the satellites of Uranus

Type of observation	Precision in mas	Precision in km
Observations CCD	40	400
Mutual phenomena	5	50

The uranocentric declination of the Earth and the Sun

Equinox in 2007 (every 42 years)

Uranus ring plane crossing 2007

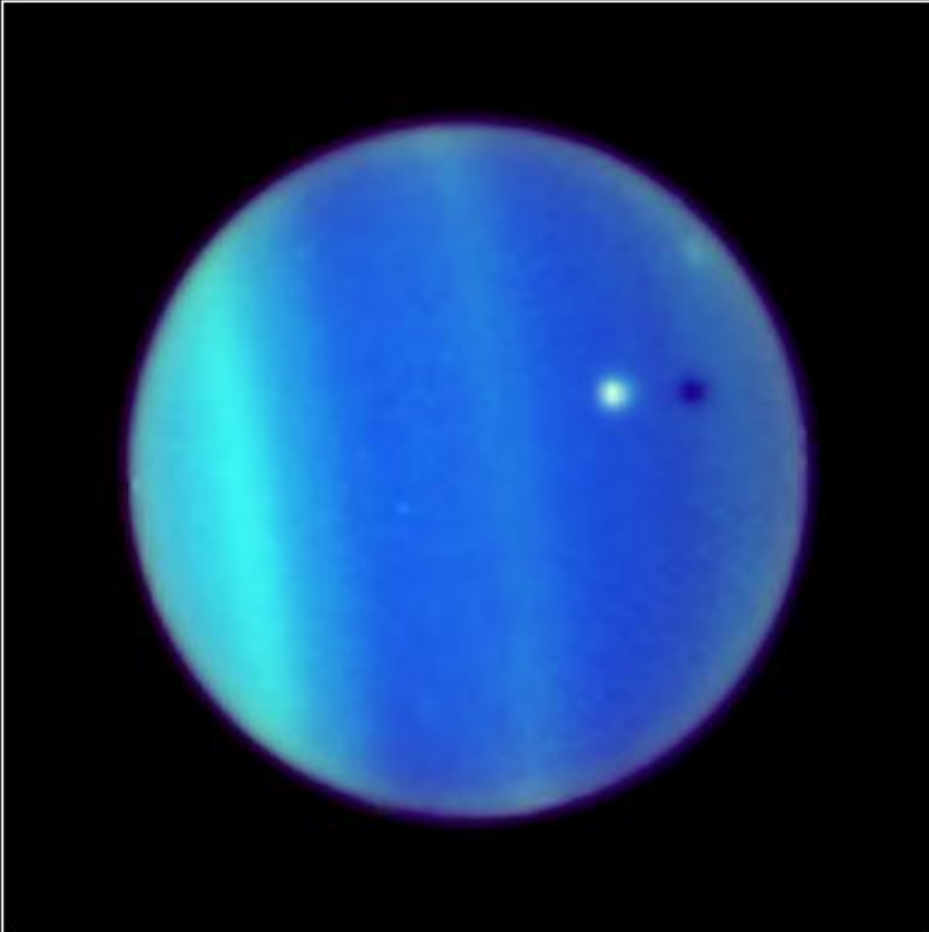


Observation difficult,
(band of methane or
band K):

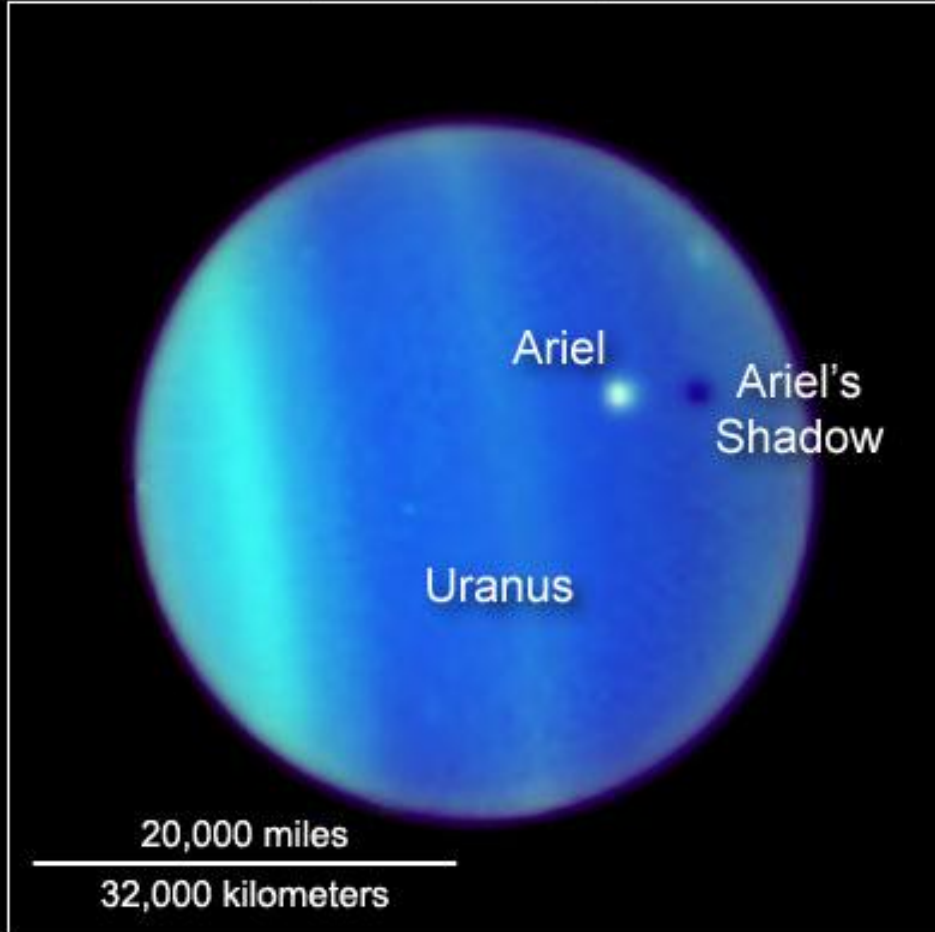
Ariel: magnitude 14.4
Umbriel: magnitude 14.8
Titania: magnitude 13.8
Oberon: magnitude 14.2
Miranda: magnitude 16.5
Puck: magnitude 20

The satellites of Uranus

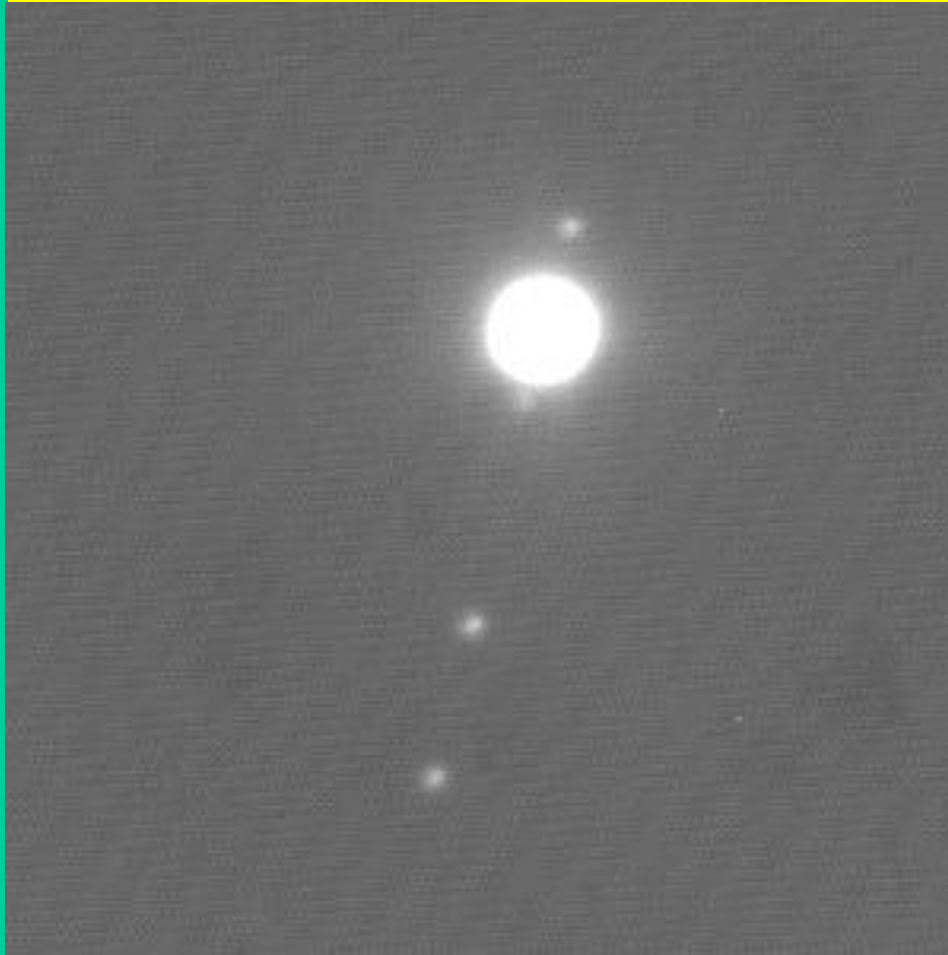
Uranus and Ariel



Hubble Space Telescope ■ ACS/WFC



Hanle (Himalaya) T 2m – bande V

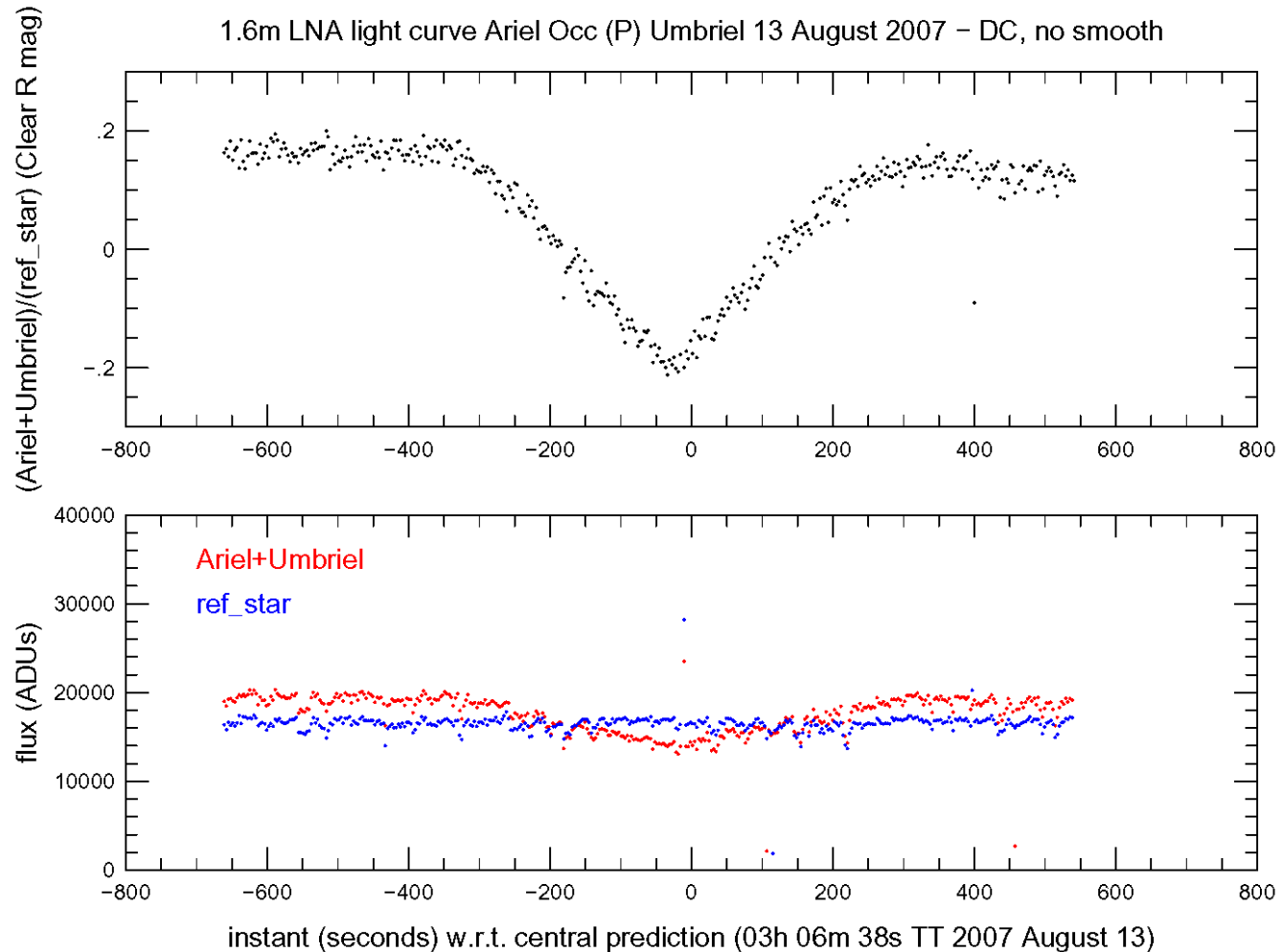


In the V band, the planet Uranus is very bright.

The only observable phenomena are those occurring far from the planet.

© R. Vasundhara et al.

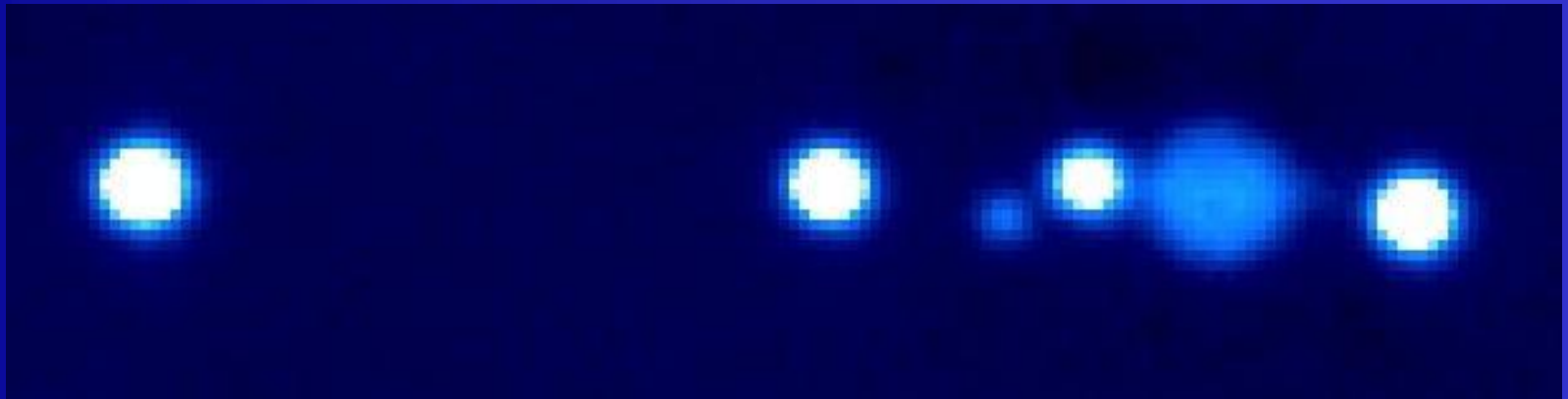
LNA (Itajuba, Brazil) T 1.6m – bande R



Phenomena of the satellites of Uranus: La Silla – NTT 3.5m – K band

In the K band (infra red 2.2 micrometers), the planet Uranus is darkened.

Then the phenomena are observable even near the limb of the planet.



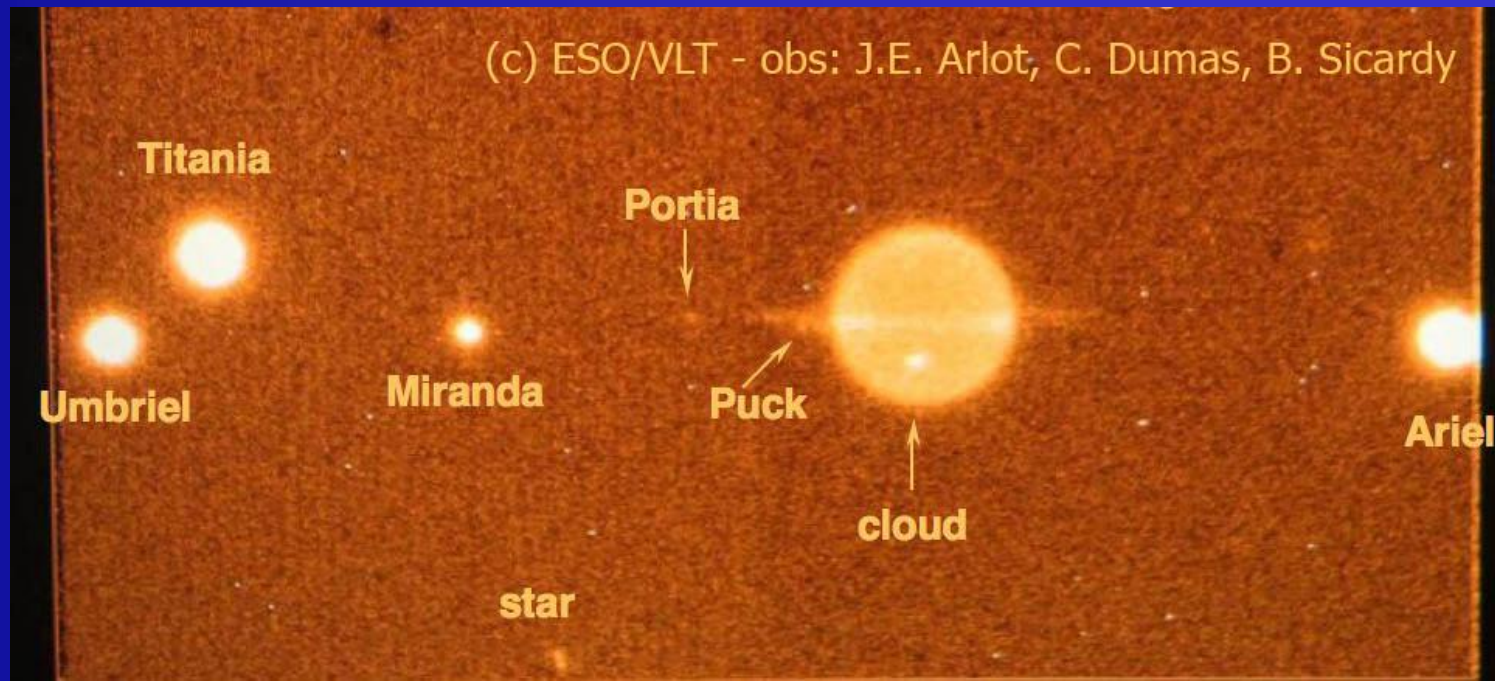
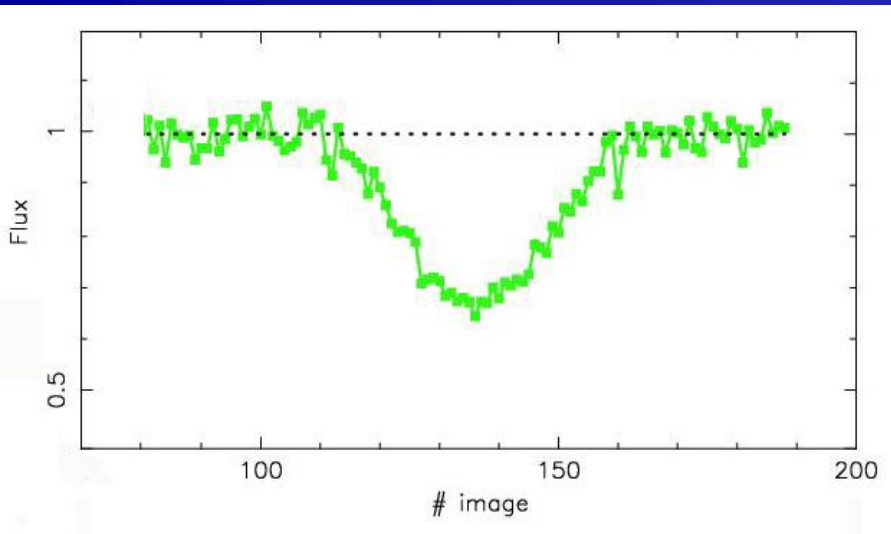
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Paranal - VLT 8m – band K' – NACO (adaptative optics)

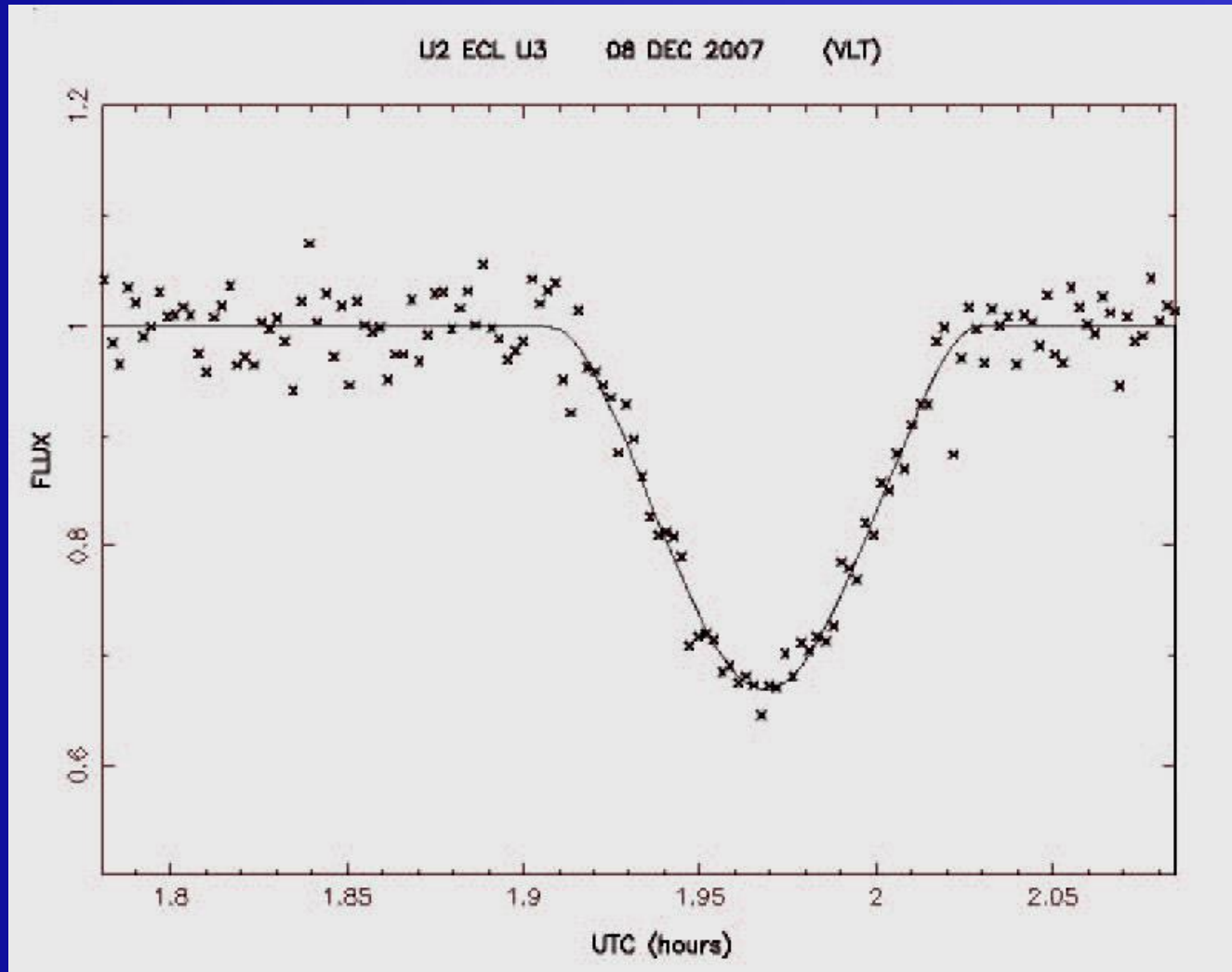
Umbriel U-2 eclipses Titania U-3 on 8 December 2007.

Uranus is very dark but the narrow filter needs a large telescope.

The adaptative optics reveals details on Uranus



Fitting the light curve



Résultats de l'observation du phénomène U-2 éclipse U-3 le 8 décembre 2007 (VLT)

	Time of minimum UTC	Flux drop (from 0 to 1)	Impact parameter (km)
Laskar- Jacobson 1986	1h 55m 37s	0.417	425
Lainey-Arlot 2006	1h 57m 43s	0.218	790
Reduction 1 (Arlot)	1h 58m 3s +/- 6s	0.304	635 +/- 30 km
Reduction 2 (Emelianov)	1h 58m 6.6s	0.308	627 +/- 12 km

- astrometric precision : 10-30km i.e. 1 to 3 mas

10 km = 1 mas

Conclusion

- Mutual phenomena are observed since 30 years (since 1973)
- The reduction of the observations allows to get a precision in position better than 15 km
- The tidal effects are now detectable and every new observations allow to increase the signal/noise ratio → let's go on observing!
- Site Web: <http://www.imcce.fr/phemu>
- e-mail: arlot@imcce.fr