

# Phoebe's orbit from ground-based and space-based observations

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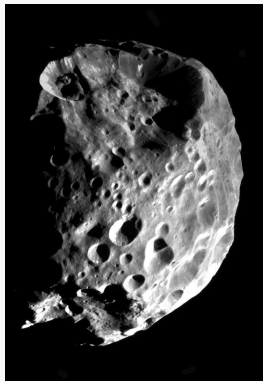
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## Introduction

### Phoebe

- Phoebe : Saturn IX discovered by W.H. Pickering in 1899
- First object discovered by photography
- Diameter :  $\sim 220$  km
- Period :  $\sim 18$  months
- Retrograde orbit ( $i = 176$  deg)
- Visited by Cassini on June 2004



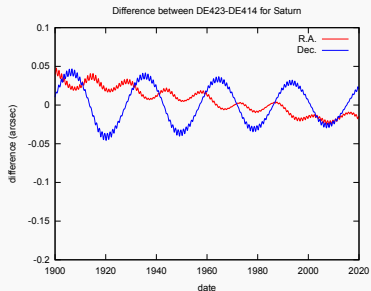
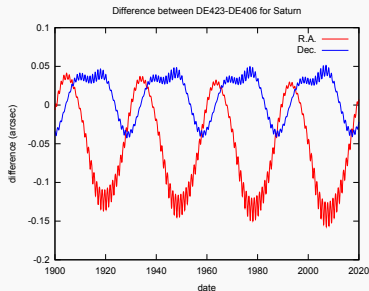
## Introduction

### Ephemeris of Phoebe

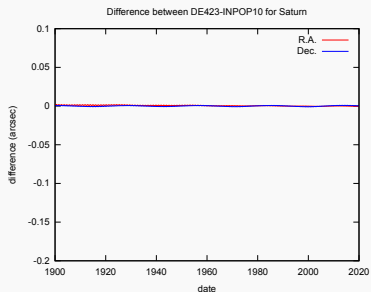
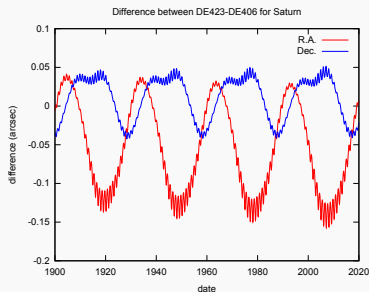
The ephemeris of Phoebe is not very accurate :

- Dynamical model (perturbations of planets)
- Astrometry (non homogeneous observations)
- Dependance of Saturn's motion theory (planetary ephemerides)

## Difference between several ephemeris of Saturn



## Difference between several ephemeris of Saturn



# Dynamical Model

## Dynamical Model

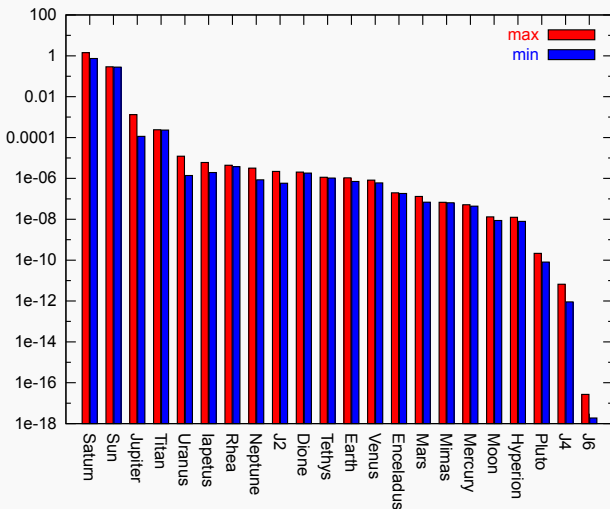


Figure 1: Comparison of the magnitude of perturbations

## Flexible Dynamical Model

### Dynamical Model

The dynamical model can take into account :

- Perturbations of the planets (with most recent theory : DE423 or INPOP10)
- Flatness of Saturn ( $J_2, J_4$ )
- Perturbations of the main Saturnian satellites (Theory of Lainey 2012)

The equations of motions are numerically integrated using the RADAU integrator and 6 initial parameters (initial position and velocity) are deduced from least-square method.



# Astrometry

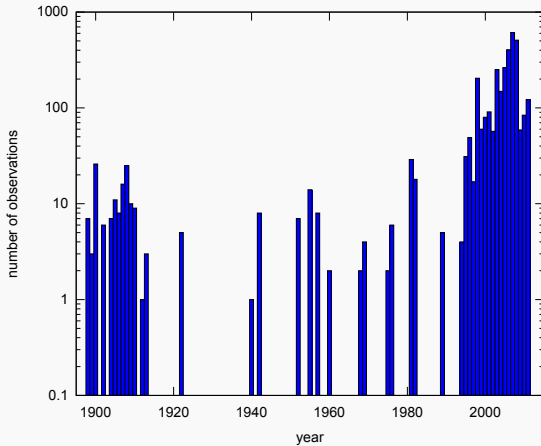
## Astrometry of Phoebe

### Statistics of Phoebe's Observations

- Total number of observations : **3523 from 1898 to 2011**
- Total number of ground-based observations : 3292
- Total number of space-based observations : 231 (Voyager 1981 : 8, Cassini 2004 : 223)
- Also 5 observations from WISE considered as ground-based observations

Most of the observations are in absolute coordinates

⇒ the reduction will depend on catalogue & the computed positions depend on planet's theory



**Figure 2:** Distribution of Phoebe's observations per year

## Improvement of astrometry

### New reduction of old observations from Pickering

Pickering C.D., Lick Observatory Bulletin, 1904

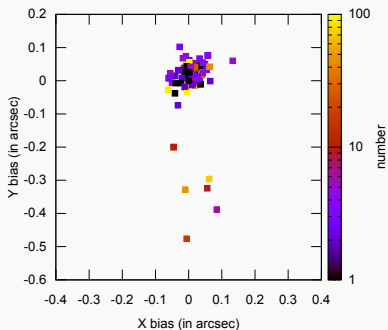
- These observations are published compared to star positions (poor accurate stellar catalogue)
- With current stellar catalogue, it is possible to measure the absolute position of Phoebe
- Unfortunately, the proper motions of stars are quite inaccurate and the accuracy of observations remains bad.

⇒ Solution : Gaia stellar catalogue (accurate position and proper motions of stars)

## Bias in stellar catalogue

Chesley et al., 2010, (*Icarus* 210) propose a treatment of star catalog biases in asteroid astrometrical observations

- 1869 observations from 1998 to 2011 can be corrected from star catalog bias (about 55%)
- the correction can reach almost 0.5 arcsec



**Figure 3:** Bias correction for Phoebe observations

# Results

## Ephemeris of Phoebe

### Four models

- **Model 1** : Planets (all planets + Moon + Pluto) + 8 Satellites +  $J_2$
- **Model 2** : Planets (Sun, Jupiter, Uranus & Neptune) + Satellites (Titan, Iapetus, Rhea) +  $J_2$
- **Model 3** : Planets (Sun, Jupiter) + Titan
- **Model 4** : Planets (Sun, Jupiter)

⇒ Comparison of the four models fitted on Phoebe observations

## Post-fit Residuals

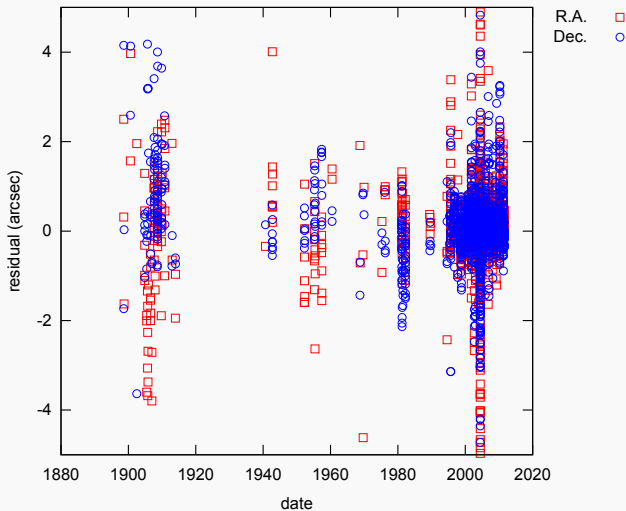
**Table 1:** Mean and rms of O-C

		ground-based obs.			Cassini obs.		
		$\mu$	rms	$N$	$\mu$	rms	$N$
Model 1	$\alpha$	0.0097	0.4606	3243/ 3292	0.1411	2.2020	223/223
	$\delta$	0.0837	0.4885	3243/ 3292	-0.2988	1.5523	223/223
Model 2	$\alpha$	0.0096	0.4607	3243/ 3292	0.1415	2.2020	223/223
	$\delta$	0.0837	0.4886	3243/ 3292	-0.2980	1.5523	223/223
Model 3	$\alpha$	0.0090	0.4635	3243/ 3292	0.1350	2.2016	223/223
	$\delta$	0.0803	0.4891	3243/ 3292	-0.2992	1.5519	223/223
Model 4	$\alpha$	0.0086	0.4714	3243/ 3292	0.1212	2.2009	223/223
	$\delta$	0.0724	0.4969	3243/ 3292	-0.3022	1.5512	223/223

Note : O-C > 5 arcsec were rejected

In distance, the residuals represent 4300km for ground-based observations and 4.3km for Cassini data





**Figure 4:** Post-fit residuals

## Correction of bias in stellar catalogs

**Table 2:** Post-fit residuals after correction or not

		uncorrected		corrected		Number
		$\mu$	rms	$\mu$	rms	
Model 1	$\alpha$	0.0253	0.4769	0.0097	0.4606	3243/3292
	$\delta$	0.0875	0.4890	0.0837	0.4885	3243/3292

Note : O-C > 5 arcsec were rejected

## Conclusion

- Development of new dynamical model
- Improvement of astrometry (much more observations, correction of bias, Cassini data)
- Accurate ephemeris of Phoebe

## Prospects

Gaia stellar catalog will allow an improvement of Phoebe astrometry :

- accurate positions of stars for reduction
- accurate proper motions of stars for reduction of old data (Pickering)

Thank you for your attention !