Tests of fundamental physics with the Gaia mission

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The Gaia mission

ESA mission

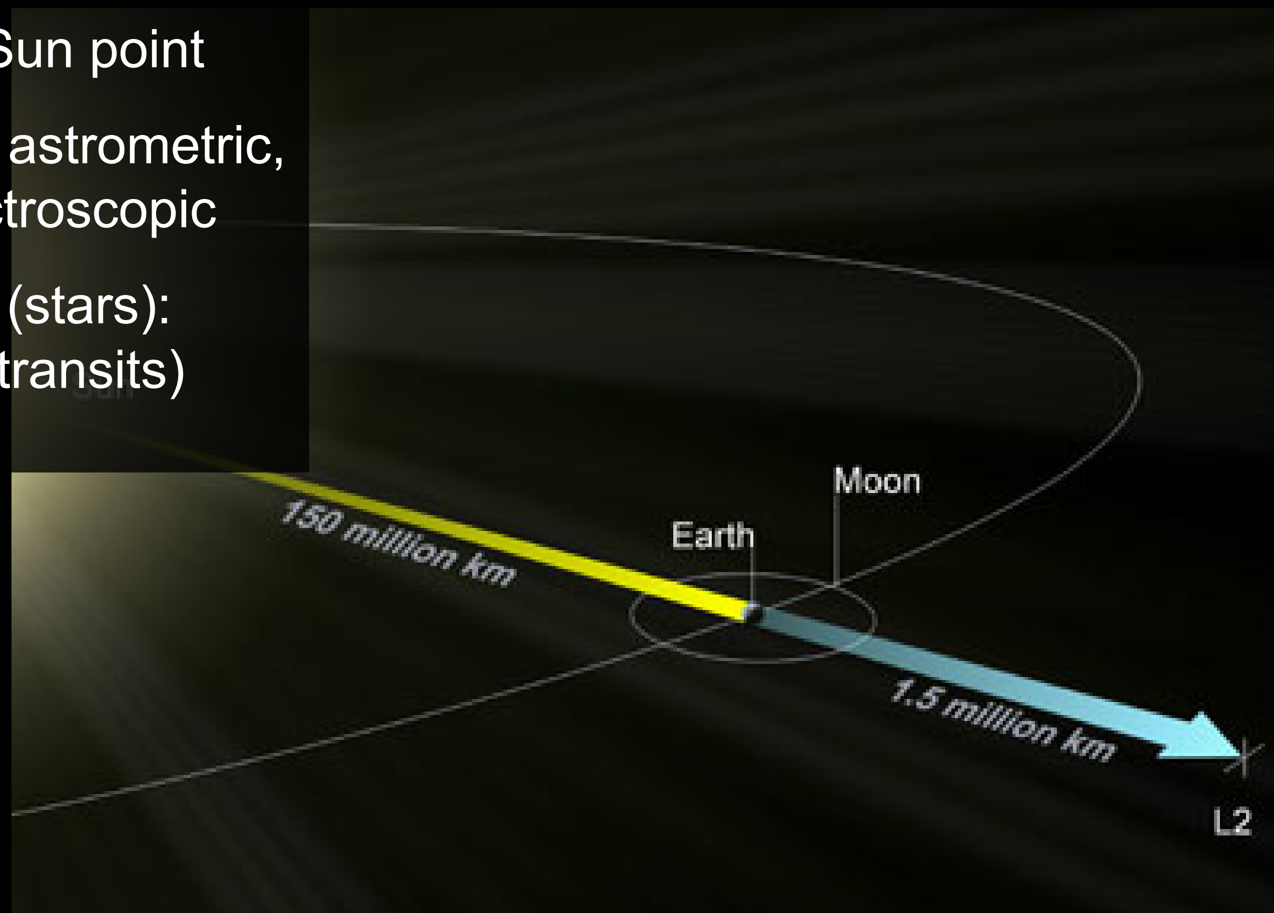
Launch : 2012 (Autumn)

Duration : 5 years

Location: L2 Earth-Sun point

Type of observations: astrometric, photometric and spectroscopic

Astrom. precision (stars):
10 μas at V=15 (80 transits)



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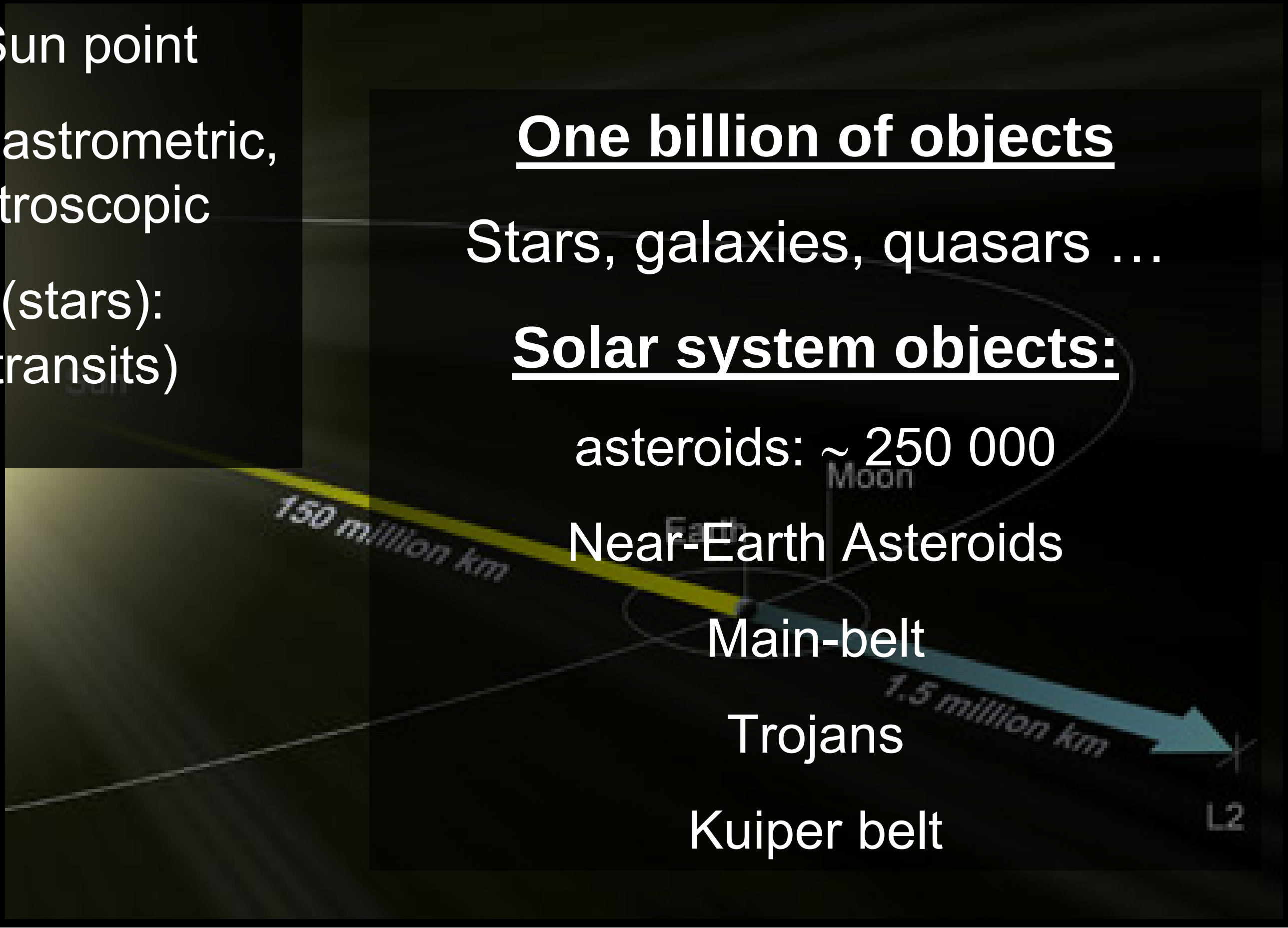


One billion of objects

Stars, galaxies, quasars …

Solar system objects:

asteroids: ~ 250 000

Near-Earth Asteroids

Main-belt

Trojans

Kuiper belt

The observation of minor planets

Determination of Gaia transits: 2012 – 2017

- 509,552 asteroids (Astorb database)
- Software by F. Mignard (complex scanning law, orbit around the L2 point, apparent magnitude limitation…)

229,657 asteroids expected to be observed

		Nb of obs. > 20
Main-belt	207,819	84,589
Near-Earth	1,689	351
Jovian Trojans	1,321	930
TNOs	18	16
Total	229,657	94,500

Astrometric precision

Position for one transit

- Signals collected from rows of CCDs (10 - optimal case)
- Precision estimation: global tests in preparation

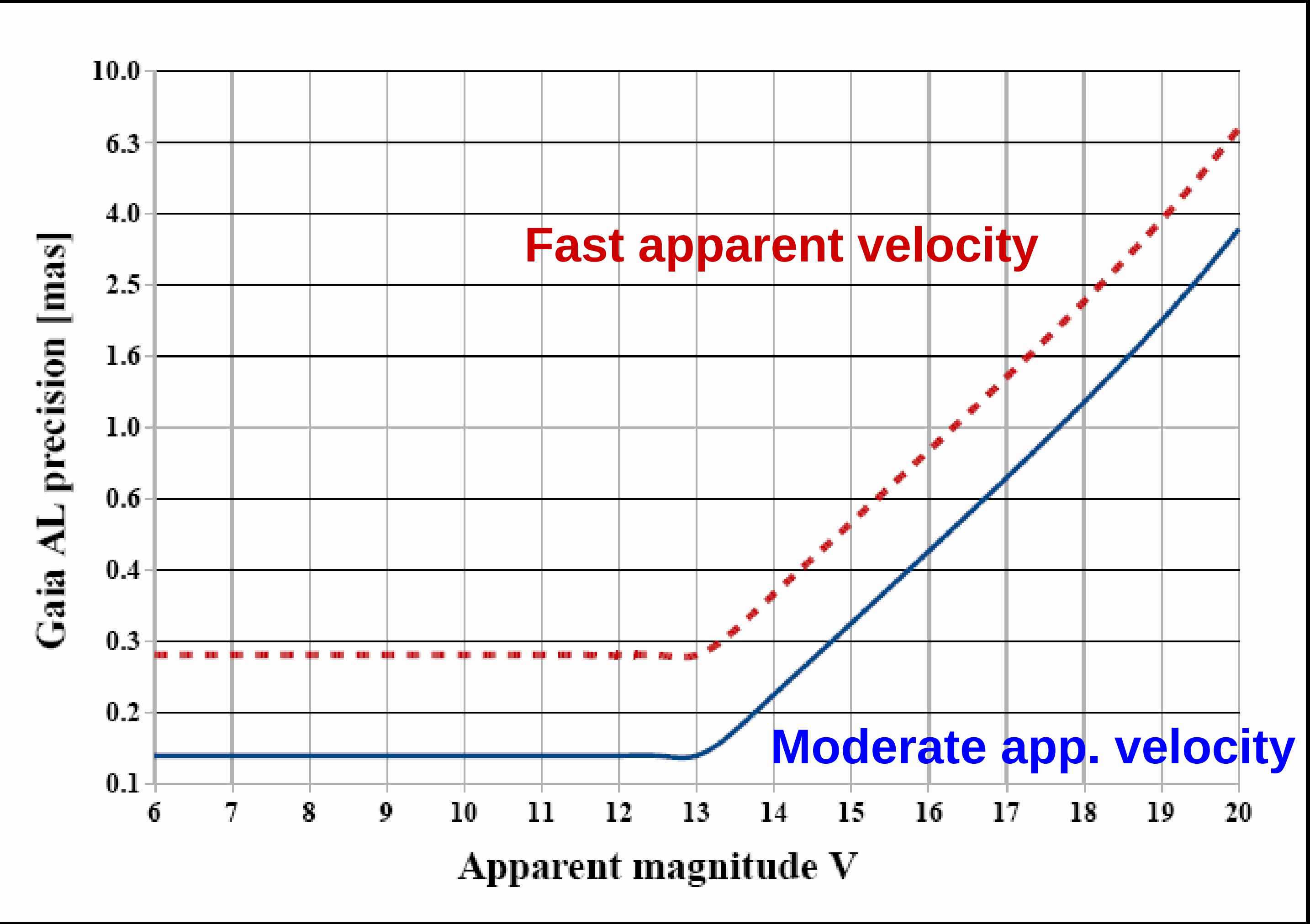
Error estimate from simulations for one CCD

- Nominal error for non-moving objects +

  → Moderate apparent velocity → additional error: +20%

  → Fast apparent velocity (NEAs) → add. error: x 2 or more (extreme cases) → 130%

Astrometric along-scan precision



Variance analysis

Realistic simulated data:
observation dates, astrometric precision,
position of the satellite

$$O - C = A\Delta\mathbf{u}$$

Least-squares techniques

$$\Delta\mathbf{u} = (A^t A)^{-1} A^t (O - C)$$

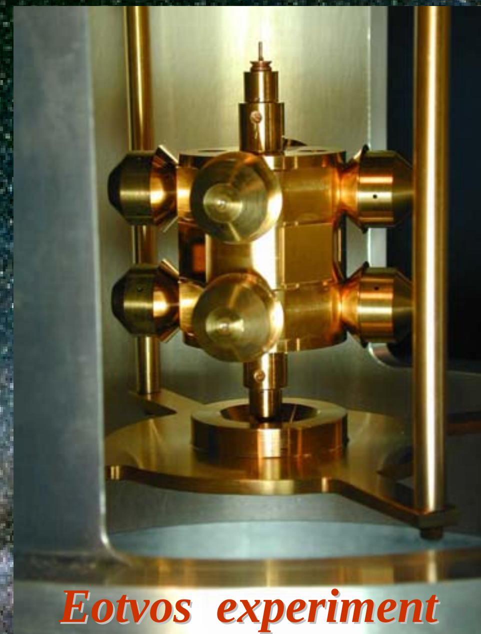
Δu: corrections to the initial conditions at the reference time

(asteroid position-velocity and global parameters

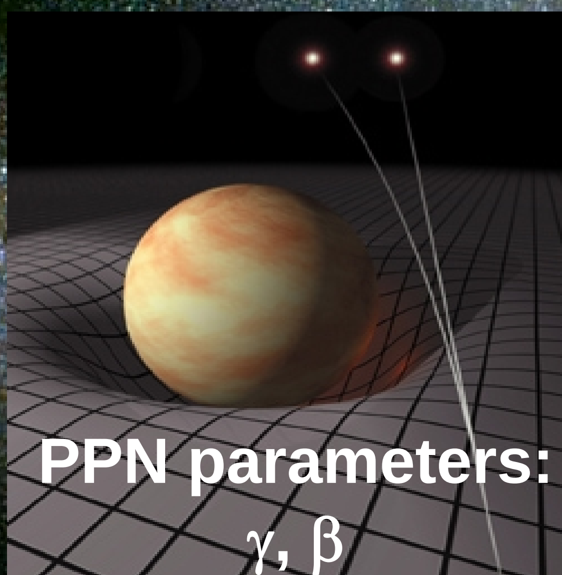
Formal precision

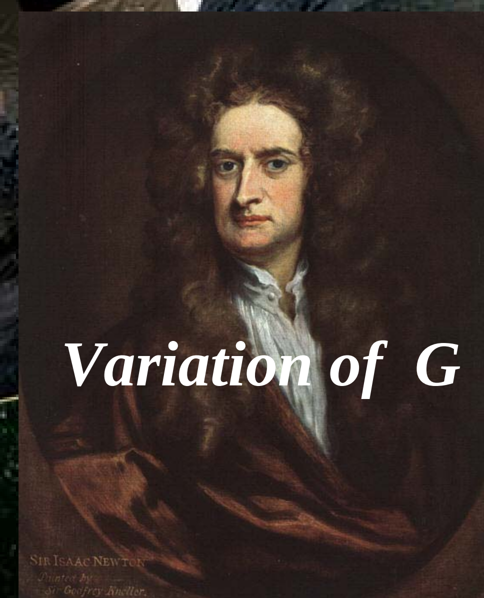
$\sigma(\Delta\mathbf{u})$: **diagonal elements of** $\sqrt{(A^t A)^{-1}}$

Fundamental physics



Violation of the Equivalence Principle
Nordtvedt parameter





Nordtvedt effect

$$m_i \neq m_g \rightarrow \frac{m_g}{m_i} = 1 + \eta \left(\frac{\Omega}{m_r c^2} \right)$$

η is the Nordtvedt parameter

Ω is the self gravitational energy

- **Dynamical model:**

$m_i \neq m_g$ only for the Sun → anomalous planetary "perturbations"

$(\Omega/m_r c^2) \sim -3.52 \times 10^{-6}$ [Anderson et al. ApJ, 1996; Ulrich, ApJ,1982]

$$\ddot{\mathbf{r}}_\mathbf{k} = -\mathbf{G}\left[m_s + (\mathbf{1} + \eta\,\Delta_s) m_k\right] \frac{\mathbf{r_k}}{\left|\mathbf{r_k}\right|^3} + \sum_{j \neq k} G m_j \frac{\mathbf{r_j} - \mathbf{r_k}}{\left|\mathbf{r_j} - \mathbf{r_k}\right|^3} - \underbrace{(\mathbf{1} + \eta\,\Delta_s) G m_j}\, \frac{\mathbf{r_j}}{\left|\mathbf{r_j}\right|^3}$$

The most important term - Jupiter

Results

Table 3. Overview of the expected formal precisions from Gaia on the estimation of the global parameters: the PPN parameters β and γ, the solar quadrupole J_2, the variation in time of the gravitational constant $\dot{G}$, the Nordtvedt parameter η and the GM of Jupiter.

Parameter	Initial value	Best Current		Precision Gaia	Future other missions	
β	$1^{\dagger}$	$\sim 10^{-4}$	Planetry ephem.	$\mathbf{1.48\times10^{-3}}$	2×10^{-6}	BepiColombo[1]
γ	$1^{\dagger}$	2.3×10^{-5}	Cassini[2]	$\mathbf{8.08\times10^{-4}}$	10^{-9}	ASTROD[3]
J_2	2×10^{-7}	$\sim 5\times10^{-8}$	Planetry ephem.	$\mathbf{2.53\times10^{-7}}$	10^{-8}	BepiColombo[4]
$\dot{G}/G$ [$year^{-1}$]	$0^{\dagger}$	9×10^{-13}	LLR[5]	$\mathbf{2.99\times10^{-12}}$	$\sim 7.3\times10^{-14}$	LLR[6]
η	$0^{\dagger}$	4.5×10^{-4}	LLR[5]	$\mathbf{2.86\times10^{-3}}^{\dagger\dagger}$	$\sim 10^{-5}$	LLR[6]
GM_j [AU^3/d^2]	2.82×10^{-7}	3.35×10^{-15}	Jovian satellites[7]	$\mathbf{2.78\times10^{-15}}$		

† Theoretical value

†† The solar gravitational self-energy found in Anderson et al. (1996) was used: $\frac{E_g^{\odot}}{m_r^{\odot}c^2} \sim -3.52\times10^{-6}$

1 Milani et al., 2002

2 Bertotti et al., 2003

3 Ni, 2008

4 Benkhoff et al., 2010

5 Williams et al., 2004a

6 Williams et al., 2004b

7 Jacobson, R.A. 2005. "Jovian Satellite ephemeris - JUP230" private communication.

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Table 4. Correlation matrix for the fit of the global parameters listed in Tab. 3

	β	J_2	η	GM_j	$\dot{G}$
β	1.0				
J_2	0.672	1.0			
η	-0.035	-0.015	1.0		
GM_j	-0.040	-0.037	0.097	1.0	
$\dot{G}/G$	-0.008	-0.008	0.217	0.049	1.0

Results: GMs of planets

Table 6. Formal precisions expected with Gaia on the *GM* estimates of the planets and Pluto.

Body j	GM_j $[AU^3/d^2]$	Gaia precision $[AU^3/d^2]$	Current precision $[AU^3/d^2]$	Estimation method—references
Mercury	4.91×10^{-11}	1.33×10^{-15}	2.029×10^{-15}	Space probes (Anderson et al. 1987)
Venus	7.24×10^{-10}	6.48×10^{-16}	1.338×10^{-17}	Space probe (Konopliv et al. 1999)
Earth	8.89×10^{-10}	2.41×10^{-16}	3.122×10^{-18}	Moon (LLR)[1]
Mars	9.55×10^{-11}	3.17×10^{-16}	6.243×10^{-19}	Space probes (Konopliv et al. 2006)
Jupiter	2.82×10^{-07}	3.76×10^{-15}	3.345×10^{-15}	Natural satellites[2]
Saturn	8.46×10^{-08}	6.84×10^{-14}	2.453×10^{-15}	Natural Satellites and Space probes (Jacobson et al. 2006)
Uranus	1.29×10^{-08}	1.04×10^{-12}	1.338×10^{-14}	Natural satellites Jacobson (2007)
Neptune	1.52×10^{-08}	2.90×10^{-12}	2.230×10^{-14}	Space probe and Natural satellites (Jacobson 2009)
Pluto	1.95×10^{-12}	3.43×10^{-12}	2.163×10^{-14}	Natural satellites[3]

[1] Folkner, W.M. and Williams, J.G. 2008. "GM parameters and uncertainties in planetary ephemeris DE421." Interoffice Memo. 343R-08-004 (internal document), Jet Propulsion Laboratory, Pasadena, CA.

[2] Jacobson, R.A. 2005. "Jovian Satellite ephemeris - JUP230" private communication.

[3] Jacobson, R.A. 2007. "The orbits of the satellites of Pluto - Ephemeris PLU017" private communication.

Conclusion

Competitive determinations

- From new category of objects
- Short period of time for obs. → limitation of systematic errors
- Gaia Star catalogue → improve the obs. reduction → possibility to combine the Gaia data with other obs. from the ground

Results obtained should be better:

- Underestimated astrometric precision
- New objects will be discovered (e.g. NEOs) → β and J_2