Scientific potential of the future space astrometric missions

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Scientific objectives of space astrometry

- Space astrometry exploits the directional information of light from (unresolved) celestial bodies in order to:
  - **establish a celestial reference frame (positions)**
    identification of objects, consistent reporting of observations
  - **determine geometric distances (parallax)**
    stellar physics, distance scale, space distribution
  - **determine transverse motions (proper motions)**
    stellar kinematics, galactic dynamics, dark matter, populations and galactic evolution
  - **determine accelerations (orbits)**
    masses in the solar system, stellar masses in binaries, detection of invisible companions including exoplanets
  - **perform fundamental physics experiments**
    compare observations with predictions from different models

Fundamental limitations

- Directional measurements are ultimately limited by diffraction and photon noise (+ wave noise at long λ)

$$\sigma_\theta \geq \frac{\lambda}{\pi D \sqrt{N}} \quad [\mathrm{rad}]$$

for wavelength λ, aperture size D, and N detected photons

- In practice, the ”photon gain factor” $N^{-1/2}$ cannot be made much less than ~0.0001 (requiring $N \geq 10^8$) due to calibration limitations
- Thus for λ ~ 0.8 μm: $\sigma_\theta \geq \frac{5\,\mu\mathrm{as}}{D\,[\mathrm{m}]}$
- Conclusions: μas astrometry in principle ”easy”, nano-arcsecond astrometry will be a challenge. D > (few m) $\Rightarrow$ interferometry

The Parallax Horizon

Trigonometric parallaxes are individually useful only if $\sigma_\pi/\pi < 0.1$

$\Rightarrow$ "parallax horizon" at $r = (100\ \mathrm{pc})/(\sigma_\pi\ [\mathrm{mas}])$

σ_π	mission	parallax horizon	possible target
1 mas	Hipparcos	100 pc	solar neighbourhood
10–25 μas	Gaia (V = 15)	4–10 kpc	Galaxy
1–4 μas	SIM PlanetQuest	25–100 kpc	Nearest Local Group
25 nas	(D ~ 200 m)*	4 Mpc	M81 Group
5 nas	(D ~ 1 km)*	20 Mpc	Virgo Cluster

* **Note:** Use of trigonometric parallax requires sources of size < 1 AU. To reach sufficient photon flux at Earth, this implies $T_{\mathrm{eff}} \propto r^2$ for a black-body radiator. This could make nano-arcsec parallax work unfeasible, as there are perhaps no targets small and hot enough.

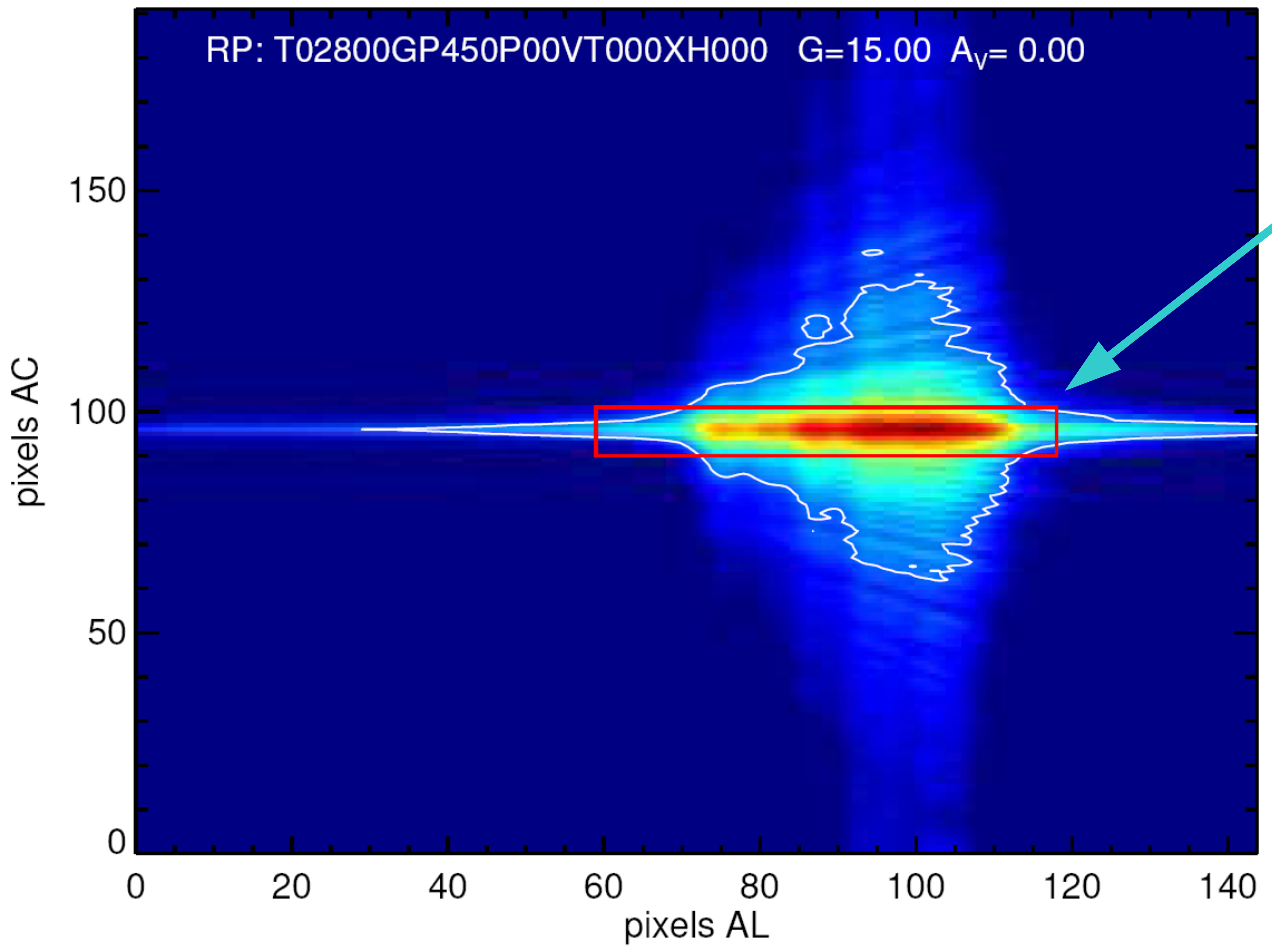
Performance of Hipparcos and Gaia

		Hipparcos (1997)	Gaia (2020)
magnitude limit		12	20–21
completeness		7.3–9	20
number of stars		120 000	35×10^6 (V < 15) 350×10^6 (V < 18) 1300×10^6 (V < 20)
astrometric accuracy		1–2 mas	7 μas (V < 12) 12–25 μas (V = 15) 150–300 μas (V = 20)
distances	$\sigma_\pi/\pi < 0.1\%$	0 stars	100 000 stars
	$\sigma_\pi/\pi < 1\%$	150 stars	11×10^6 stars
	$\sigma_\pi/\pi < 5\%$	6 200 stars	77×10^6 stars
	$\sigma_\pi/\pi < 10\%$	21 000 stars	150×10^6 stars
spectro-photometry		(Hp, B_T, V_T)	330–1050 nm (R ~ 13–30)
radial velocity		–	2–10 km/s (V < 17)

Gaia Photometry and Radial Velocities

- Photometric measurements:
  - in the wide (330–1050 nm) astrometric G band at full spatial res.
  - in the Blue Photometer (BP, 330–650 nm) using a prism
  - in the Red Photometer (RP, 640–1050 nm) using a prism
  - dispersed BP and RP images are a few arcsec in size
  - indicative precision (per observation) at 15 mag:
    - 0.002 mag in G
    - 0.02 mag per resolution element in BP and RP
- Radial-velocity measurements:
  - in the dedicated RV spectrometer part of the field
  - wavelength range 847–874 nm (incl. Ca II triplet), R = 11 500
  - accuracy 1–10 km/s (V < 16–17 mag)

Dispersed image in Red Photometer (RP)

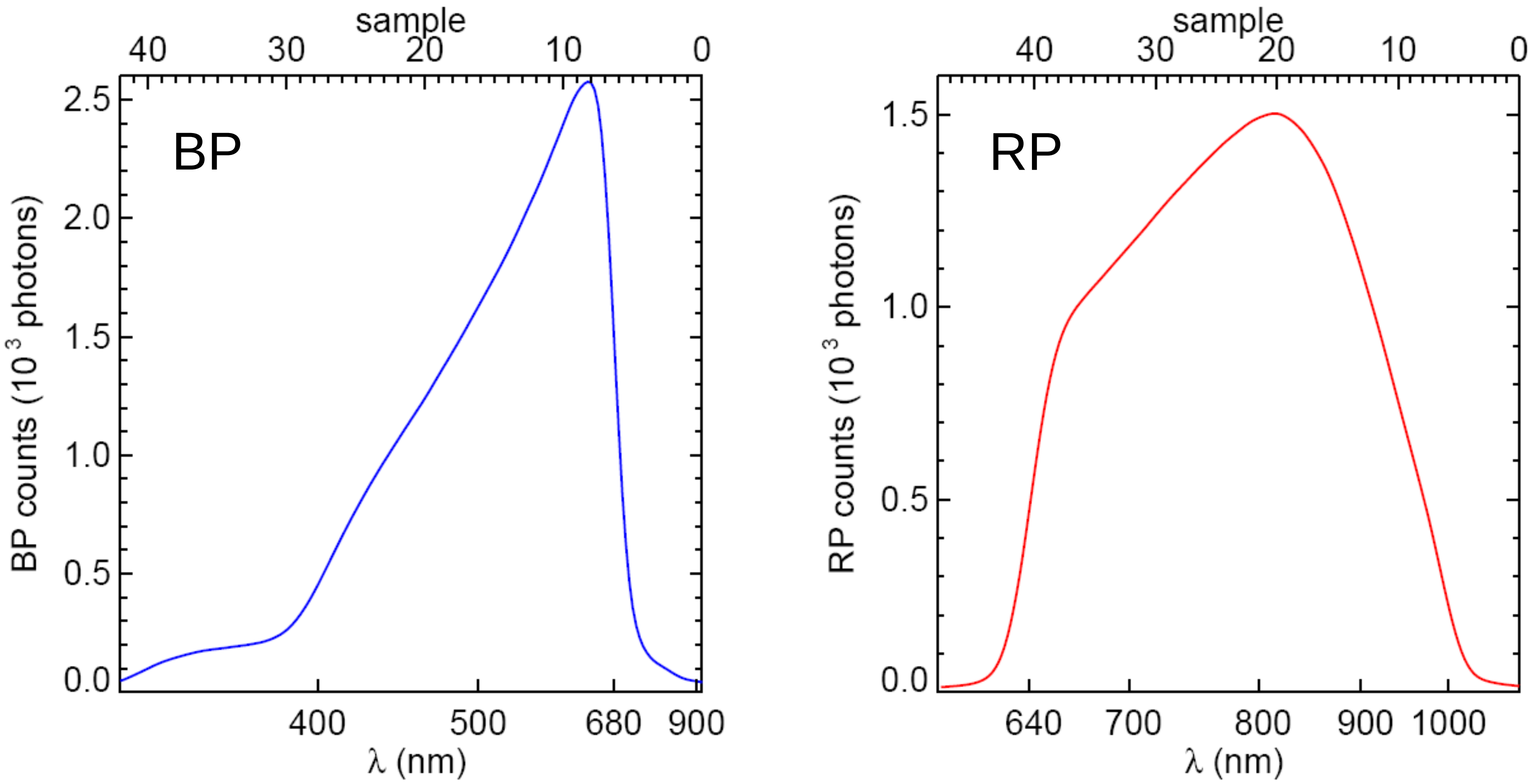


Extracted window
60 x 12 pixels
(3.5 x 2.1 arcsec^2)
$\Rightarrow$ 48 samples
along spectrum

Simulated dispersed image of M6V star (no noise)

(A. Brown, 2006)

Gaia Blue and Red Photometers (BP, RP)



Simulated spectra for a flat SED (constant ph/nm) at G = 15 mag

(A. Brown, 2006)

Gaia Science: Stellar Physics

- Accurate distances to large numbers of stars (e.g. 11×10^6 better than 1%) + multicolour photometry provide:
  - stringent tests of stellar structure and evolution models
  - access to rare objects and rapid evolutionary phases
  - physical parameters (incl. ages and masses) for large samples
  - accurate calibration of primary distance indicators
- Multi-epoch photometry (typically ~80 epochs <0.01 mag):
  - survey of stellar variability across the HR diagram
  - identification of ~500 000 eclipsing binaries, etc
- Spectroscopic, astrometric and resolved binaries:
  - total and individual masses for ~10^4 systems $\Rightarrow$ M/L relations
  - complete census of binaries within 250 pc from the Sun
  - binary statistics vs. age, kinematics, metallicity

Gaia Science: Galactic Structure

- Large stellar samples with a well-defined (flux limited) selection function allows to
  - map density and velocity distributions of tracer stars
    $\Rightarrow$ total mass density as function of position (incl. dark matter)
  - identify dynamical processes (bars, warps, merger events) that have modified the phase space distributions
  - map time and position dependent star formation rates
  - study age-metallicity relation versus position and kinematics
    $\Rightarrow$ constrain scenarios for the formation of the Galaxy
- Survey and characterization of all stars to 20 mag:
  - stellar luminosity function (LF) incl. white dwarfs (~200 000) and brown dwarfs (20 000?)
  - initial mass function (IMF) through inversion of LF: is it constant?
  - 3D mapping of extinction over a large volume

Gaia Science: Exoplanets

- Astrometric detection of exoplanets is sensitive to large planets (> 30 M_{Earth} = 0.1 M_{Jup}) and moderately long periods (0.1–10 years)
  - v_R detection biased towards short periods
- Applicable to all host star spectral types
  - v_R detection difficult for O-B-A and M
- Unambiguous determination of planet's mass (m)
  - v_R orbit gives $m \times \sin i$
- ~5×10^6 stars can be searched for >1 M_{Jup} companions
  - census of large planet & brown dwarf companions (to 100 pc)
  - unbiased mass statistics in the relevant range
  - frequency of planetary systems vs. stellar mass, age, metallicity
  - constraints on formation and evolution of planetary systems

Gaia Science: Solar System

- Survey of the whole sky at 45 – 135° from the Sun
- ~15 observations/year @ <1 mas
- Simultaneous spectrophotometry
- Expected results:
  - about 500 000 asteroids detected, mostly main belt (many new), some Near Earth Objects and trans-Neptunian objects
  - orbits: ~30 times more accurate than at present
    $\Rightarrow$ proper elements, dynamical families
  - masses: ~100 from close encounters
  - rotation, pole, shape from light-curve analysis
  - taxonomy and diameters
  - perihelion precession for 300 planets
    $\Rightarrow$ GR testing and solar J_2

Gaia Science: Reference Frame and GR

- All astrometric results expressed in BCRS coordinates (including TCB for the time)
- Gaia reference frame will be linked to ICRS by means of
  - 500 000 quasars providing a kinematically non-rotating frame
  - optical counterparts of VLBI sources for frame orientation
  - expected accuracy: 0.5 μas yr^{-1} rotation, 30 μas orientation
- Cosmological (galactocentric?) acceleration of BCRS determined to 10% from apparent quasar streaming
- General Relativity (GR) adopted as model for data reduction, but this can be tested e.g. in terms of
  - PPN parameters γ (to 5×10^{-7}) and β (to 5×10^{-4})
  - GR prediction for light deflection by major planets
  - GR prediction for effect of quadrupole moment of Jupiter

Gaia: Schedule

- Project (except data analysis) fully financed by ESA
- Detailed design phase (B2/C/D) started in March 2006
- EADS Astrium awarded contract to build Gaia (incl. science instrument)
- Gaia Data Processing and Analysis Consortium (DPAC) formed in June 2006 (Chair: F. Mignard, Nice)
- Scheduled launch late 2011
- 5 + 1 year nominal operations from June 2012
- Early data releases expected
- Final results available 2020