Global astrometry with GAIA

Rudolf Le Poole

Abstract

- Why
  - Scientific case:
    - Milky Way : Structure, Dynamics, Star Formation
    - Stellar Physics : Luminosities, Ages, Masses
    - Solar System
    - Extragalactic: Galaxies, Quasars, Reference Frame
    - Fundamental Physics
- How
  - Mission Concept, and Design Considerations
    - Global vs Narrow Field Astrometry
    - Basic Angle
    - Scanning Strategy
    - Limiting Magnitudes
    - Limiting Accuracies
    - Completeness
    - Radial Velocities
    - Photometry
  - Payload
    - Configuration
    - Optical Layout
    - Focal Planes
    - On Board Object Detection
  - Data Analysis
    - Requirements and concept
- Mission and Spacecraft requirements
    - Mission Duration
    - Orbit
    - Thermal
    - Mass
    - Power
    - Telemetry

GAIA

Composition, Formation and Evolution of our Galaxy

Cornerstone Presentations, Paris, 13 September 2000

Scientific Case:	P. T. de Zeeuw
Payload, Accuracy and Data Analysis:	L. Lindegren
Spacecraft and Mission Implementation:	O. Pace
Why, How and When:	G. Gilmore

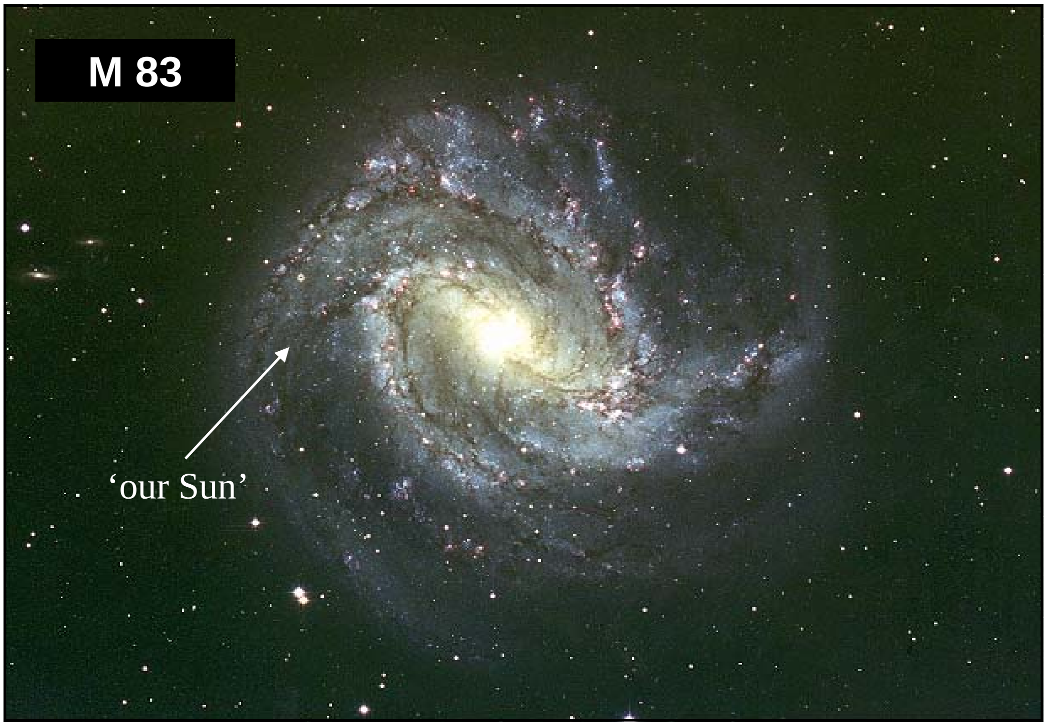
...on behalf of the GAIA Science Advisory Group, GAIA working groups, ESA Future Projects & Astrophysics Division, and industrial teams

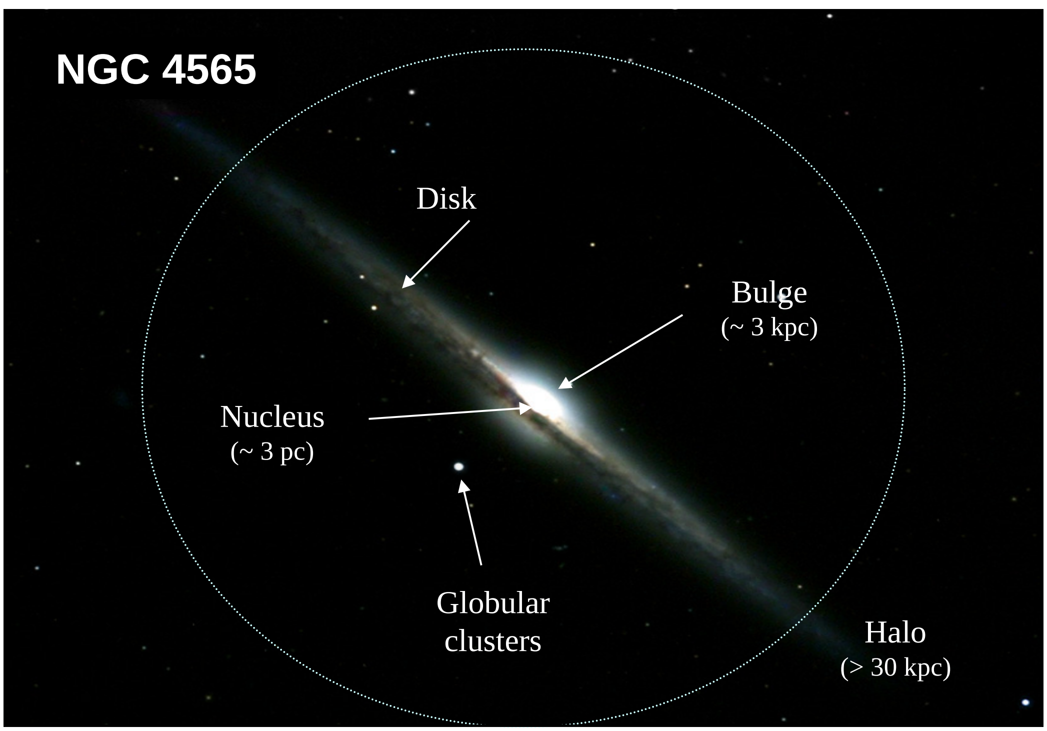
GAIA Science Advisory Structure

- Sscience Advisory Group members (1997-2000):

K.S. de Boer (Bonn)	L. Lindegren (Lund)
G. Gilmore (Cambridge)	X. Luri (Barcelona)
E. Hoeg (Copenhagen)	F. Mignard (Grasse)
M.G. Lattanzi (Torino)	P.T. de Zeeuw (Leiden)

- Associated Working Groups:
  - Science Working Group (17 members)
  - Instrument Working Group (16 members)
  - Photometry Working Group (17 members)
  - Members at Large (47 members)
- ESA:
  - O. Pace (Future Projects, Study Manager)
  - M.A.C. Perryman (Astrophysics Division, Study Scientist)


M 83
'our Sun'


NGC 4565
Disk
Bulge
(~ 3 kpc)
Nucleus
(~ 3 pc)
Globular
clusters
Halo
(> 30 kpc)

GAIA: Key Science Objectives

- Structure and kinematics of our Galaxy:
  - shape and rotation of bulge, disk and halo
  - internal motions of star forming regions, clusters, etc
  - nature of spiral arms and the stellar warp
  - space motions of all Galactic satellite systems
- Stellar populations:
  - physical characteristics of all Galactic components
  - initial mass function, binaries, chemical evolution
  - star formation histories
- Tests of galaxy formation:
  - dynamical determination of dark matter distribution
  - reconstruction of merger and accretion history

$\Rightarrow$ Origin, Formation and Evolution of the Galaxy

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GAIA: Complete, Faint, Accurate

	Hipparcos	**GAIA**
Magnitude limit	12	20-21 mag
Completeness	7.3 – 9.0	~20 mag
Bright limit	~0	~3-7 mag
Number of objects	120 000	26 million to V = 15 250 million to V = 18 1000 million to V = 20
Effective distance limit	1 kpc	1 Mpc
Quasars	None	$\sim 5 \times 10^5$
Galaxies	None	10^6 - 10^7
Accuracy	~1 milliarcsec	4 μarcsec at V = 10 10 μarcsec at V = 15 200 μarcsec at V = 20
Broad band	2-colour (B and V)	4-colour to V = 20
Medium band	None	11-colour to V = 20
Radial velocity	None	1-10 km/s to V = 16-17
Observing programme	Pre-selected	On-board and unbiased

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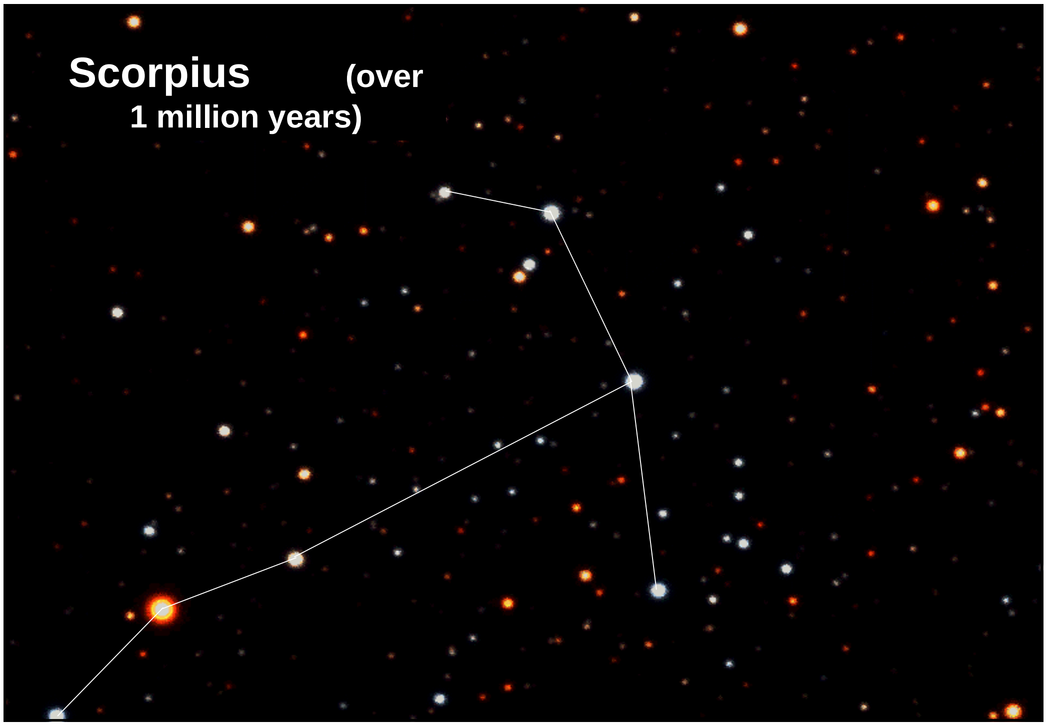
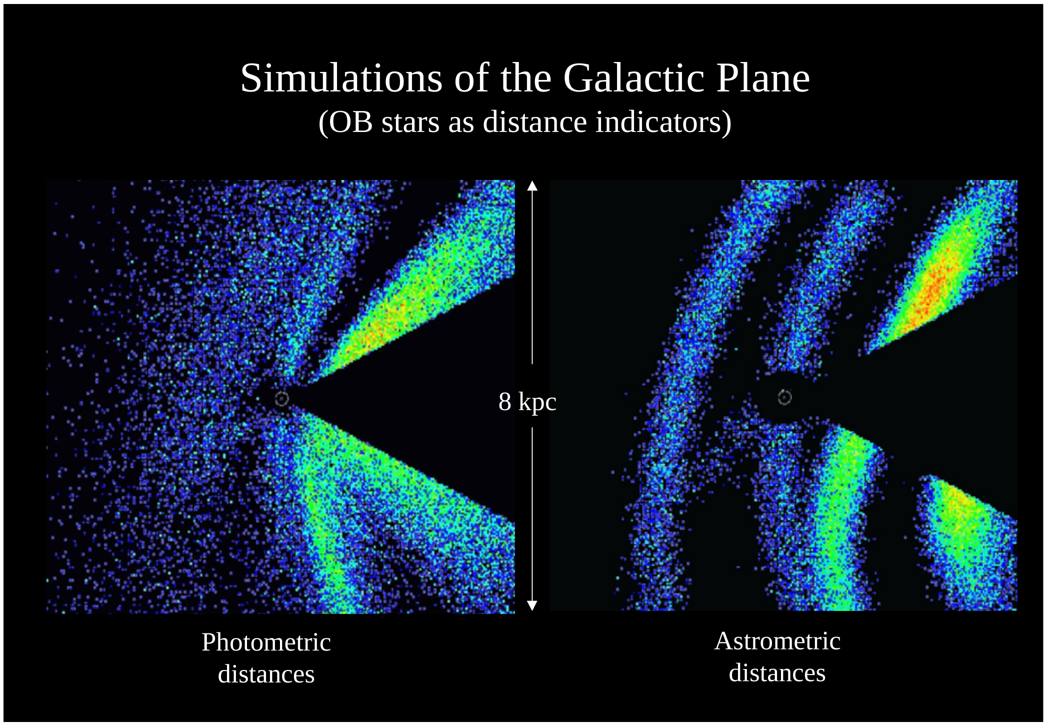
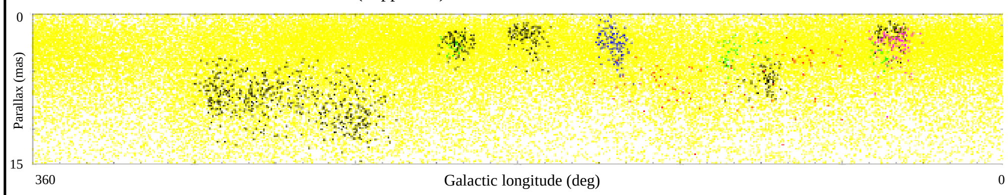

Scorpius (over
1 million years)

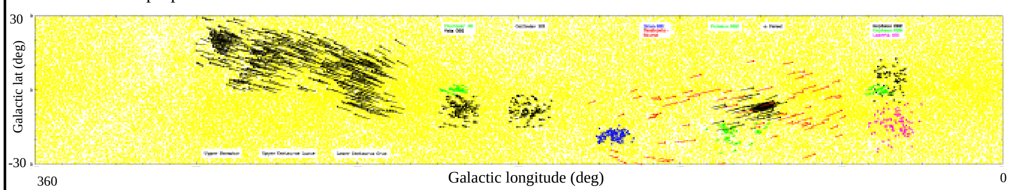

Simulations of the Galactic Plane
(OB stars as distance indicators)
8 kpc
Photometric
distances
Astrometric
distances

Structure of Star Forming Regions

Parallaxes of OB association members (Hipparcos)



Positions and proper motions of selected members



GAIA will allow:

- detection of stellar groups across the Galaxy
- tracing back of orbits to time and location of formation

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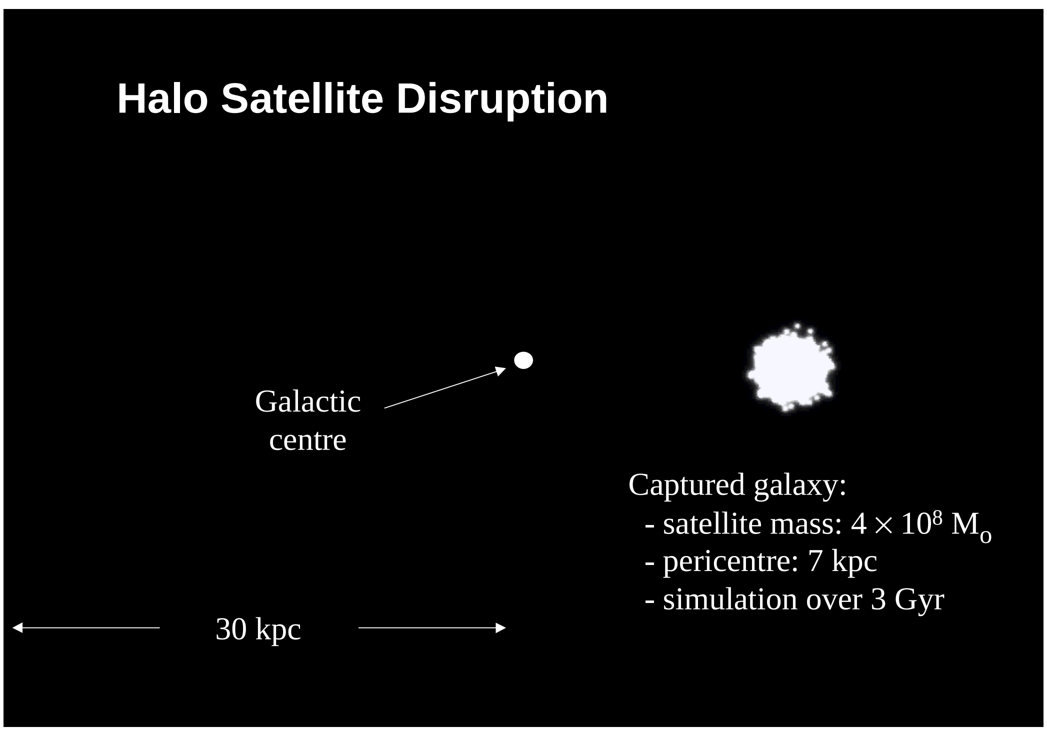
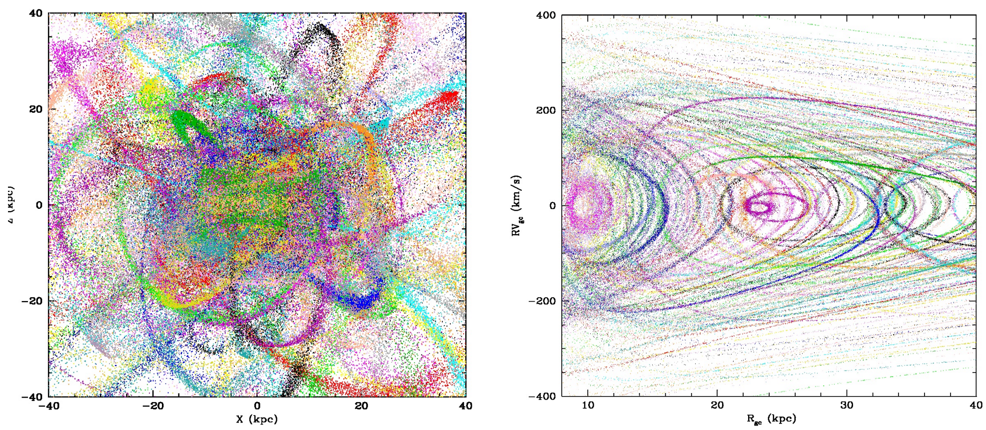
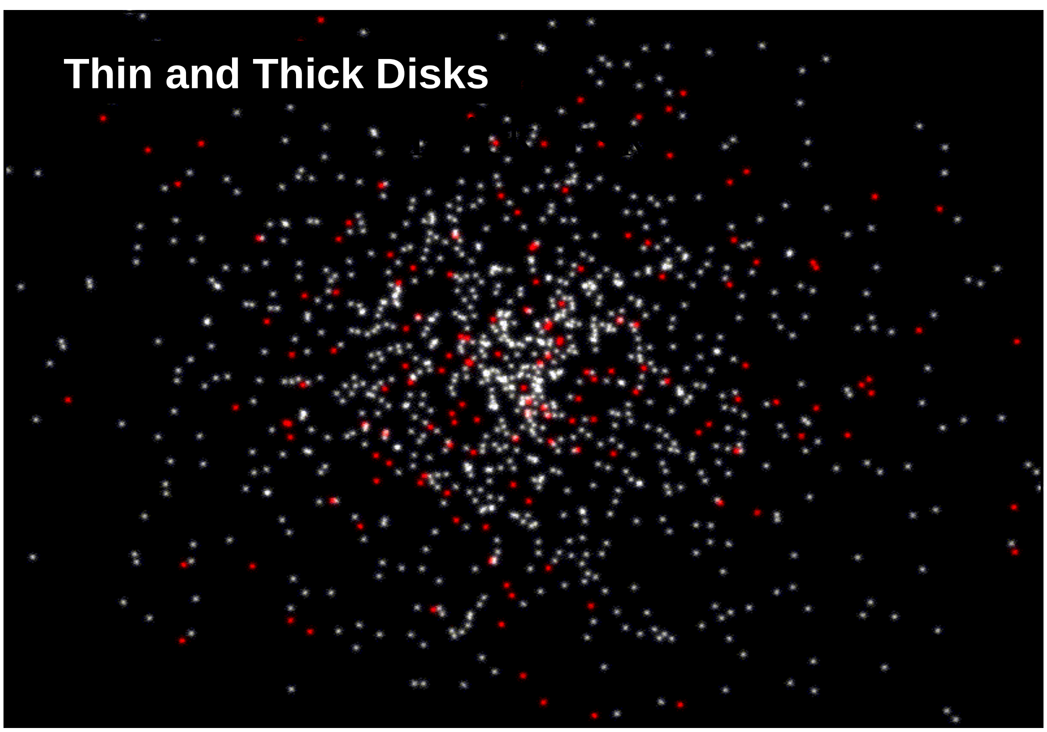


Tidal Streams in the Galactic Halo

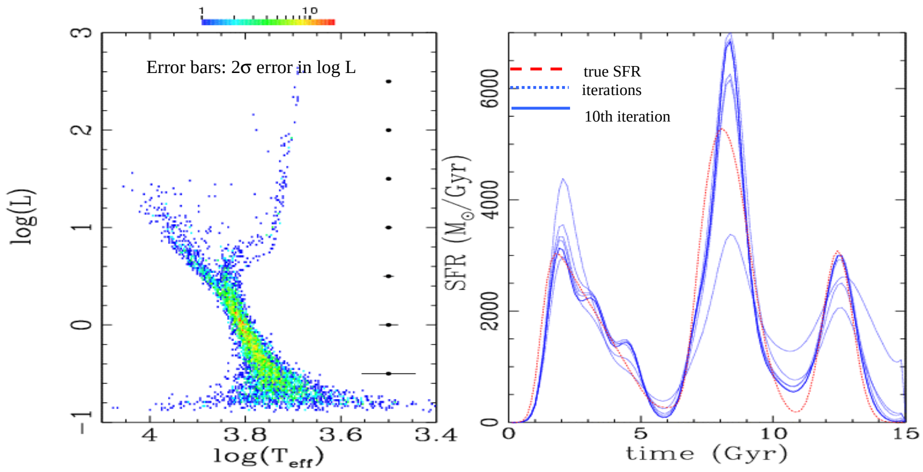
(simulation of accretion of 100 satellite galaxies)



⇒ GAIA will identify details of phase-space substructure



Star Formation History



⇒ GAIA will yield L, T_{eff}, [Fe/H], and ages throughout the Galaxy

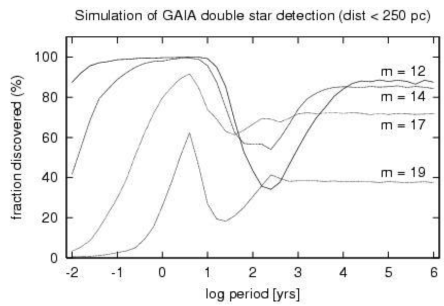
Stellar Astrophysics

- Comprehensive luminosity calibration, for example:
  - distances to 1% for 18 million stars to 2.5 kpc
  - distances to 10% for 150 million stars to 25 kpc
  - rare stellar types and rapid evolutionary phases in large numbers
  - parallax calibration of all distance indicators
    e.g. Cepheids and RR Lyrae to LMC/SMC
- Physical properties, for example:
  - clean Hertzsprung-Russell sequences throughout the Galaxy
  - solar neighbourhood mass function and luminosity function
    e.g. white dwarfs (~200,000) and brown dwarfs (~50,000)
  - initial mass and luminosity functions in star forming regions
  - luminosity function for pre main-sequence stars
  - detection and dating of the oldest (disk and halo) white dwarfs

Binary and Multiple Stars

- Constraints on star formation theories
- Orbits for > 100,000 resolved binaries (separation > 20 mas)
- Masses to 1% for > 10,000 objects throughout HR diagram
- Full range of separations and mass ratios
- Interacting systems, brown dwarf and planetary companions

Photocentric motions:
  ~10^8 binaries
Photometry:
  >10^6 eclipsing binaries
Radial velocities:
  >10^6 spectroscopic binaries



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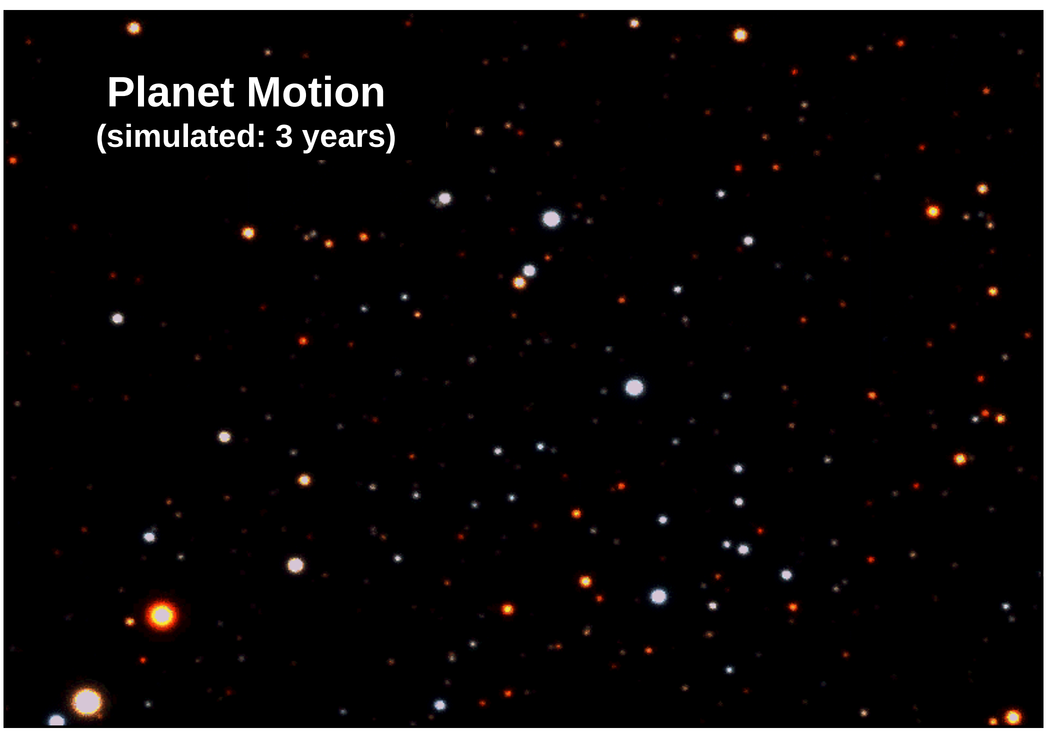

GAIA: Discoveries of Extra-Solar Planets

- Large-scale detection and physical characterisation
- 20,000- 30,000 giants to 150-200 pc

  e.g. 47 UMa: astrometric displacement 360 µas
- complete census of all stellar types (P = 2-9 years)
- masses, rather than lower limits (m sin i)
- orbits for many (≈5000) systems
- relative orbital inclinations for multiple systems
- mass down to 10 M_{Earth} to 10 pc

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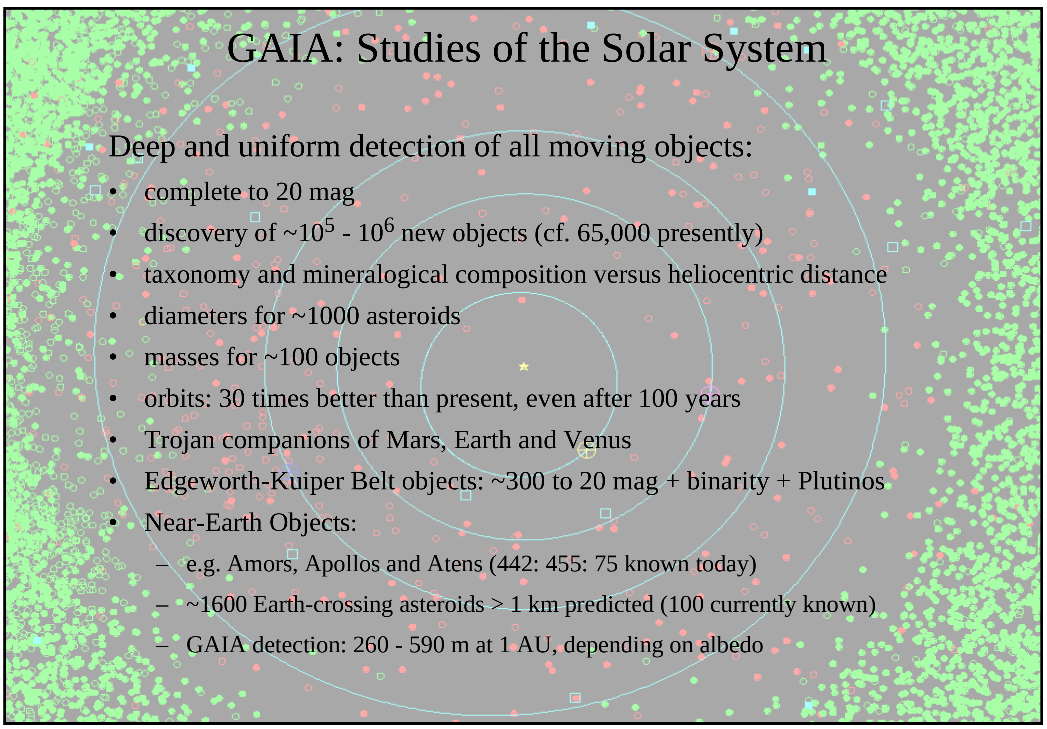

GAIA: Studies of the Solar System

Deep and uniform detection of all moving objects:

- complete to 20 mag
- discovery of ~10^5 - 10^6 new objects (cf. 65,000 presently)
- taxonomy and mineralogical composition versus heliocentric distance
- diameters for ~1000 asteroids
- masses for ~100 objects
- orbits: 30 times better than present, even after 100 years
- Trojan companions of Mars, Earth and Venus
- Edgeworth-Kuiper Belt objects: ~300 to 20 mag + binarity + Plutinos
- Near-Earth Objects:
  - e.g. Amors, Apollos and Atens (442: 455: 75 known today)
  - ~1600 Earth-crossing asteroids > 1 km predicted (100 currently known)
  - GAIA detection: 260 - 590 m at 1 AU, depending on albedo

Galaxies, Quasars, and the Reference Frame

- Parallax distances, orbits, and internal dynamics of nearby galaxies
- Galaxy survey, including large-scale structure
- ~500,000 quasars: kinematic and photometric detection
- ~100,000 supernovae
- Ω_M, Ω_Λ from multiple quasar images (3500 to 21 mag)
- Galactocentric acceleration: 0.2 nm/s^2 $\Rightarrow$ Δ(aberration) = 4 µas/yr
- Globally accurate reference frame to ~0.4 µas/yr

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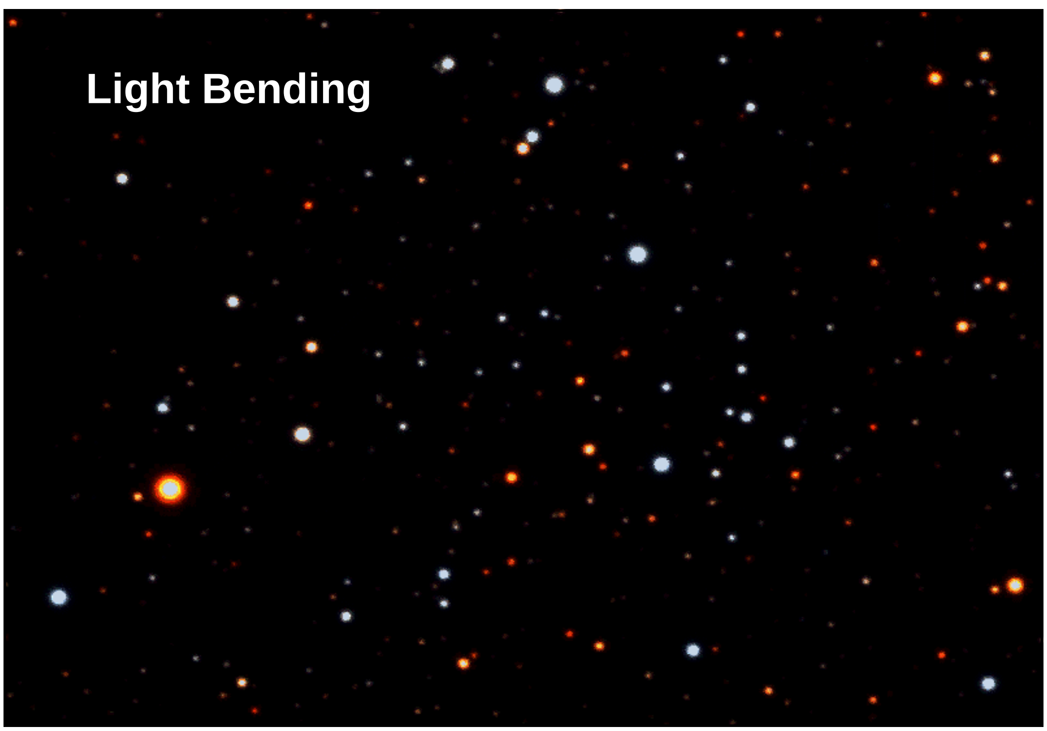


General Relativity/Metric

- From positional displacements:
  - γ to 5×10^{-7} (cf. 10^{-5} presently) $\Rightarrow$ scalar-tensor theories
  - effect of Sun: 4 mas at 90°; Jovian limb: 17 mas; Earth: ~40 μas
- From perihelion precession of minor planets:
  - β to 3×10^{-4} - 3×10^{-5} (×10-100 better than lunar laser ranging)
  - Solar J_2 to 10^{-7} - 10^{-8} (cf. lunar libration and planetary motion)
- From white dwarf cooling curves:
  - dG/dT to 10^{-12} - 10^{-13} per year (cf. PSR 1913+16 and solar structure)
- Gravitational wave energy: $10^{-12} < f < 10^{-9}$ Hz
- Microlensing: photometric (~1000) and astrometric (few) events
- Cosmological shear and rotation (cf. VLBI)

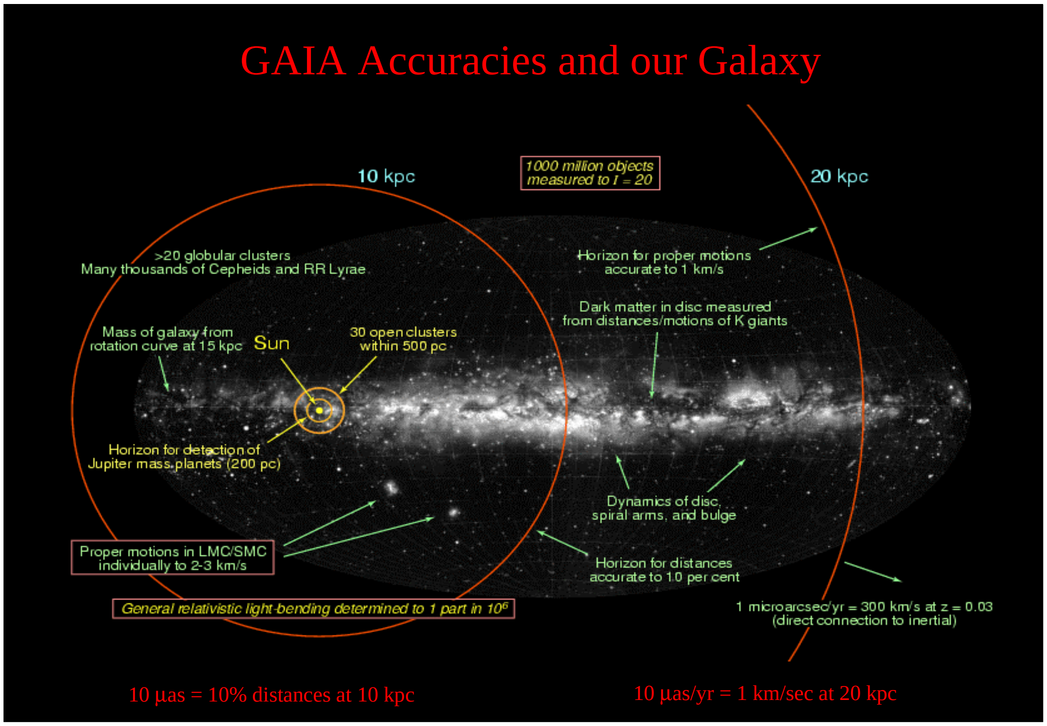
Summary

GAIA will determine:

- when the stars in the Milky Way formed
- when and how the Milky Way was assembled
- how dark matter in the Milky Way is distributed

GAIA will also make substantial contributions to:

- stellar astrophysics
- Solar System studies
- extra-solar planetary science
- cosmology
- fundamental physics



Design Considerations

- Astrometry (V < 20):
  - completeness ⇒ on-board detection
  - accuracies: 10 µas at 15 mag (Survey Committee + science)
  - scanning satellite, two viewing directions
    - ⇒ global accuracy, optimal with respect to observing time
  - windowing reduces data rate from 1 Gbps to 1 Mbps
- Radial velocity (V < 17-18):
  - third component of space motion
  - measurement of perspective acceleration
  - astrophysical diagnostics, dynamics, population studies
- Photometry (V < 20):
  - astrophysical diagnostics (4-band + 11-band) + chromatic correction
    - ⇒ extinction; ΔT_{eff} ~ 200 K, [Fe/H] to 0.2 dex

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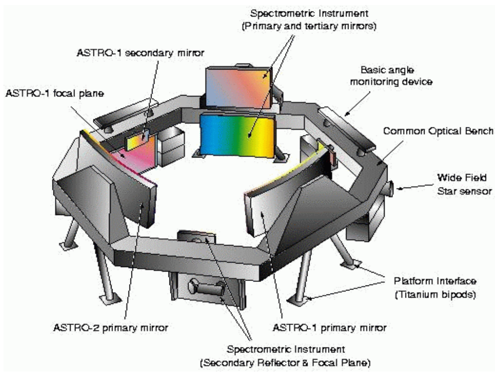
Astrophysically Driven Payload



- Two astrometric instruments:
  - field of view = $0.6^{\circ} \times 0.6^{\circ}$
  - separation = 106°
- Monolithic mirrors: 1.7 m × 0.7 m
- Non-deployable, 3-mirror, SiC optics
- Astrometric focal planes: TDI CCDs
- Radial velocity/photometry telescope
- Survey principles:
  - revolving scanning
  - on-board detection
  - complete and unbiased sample

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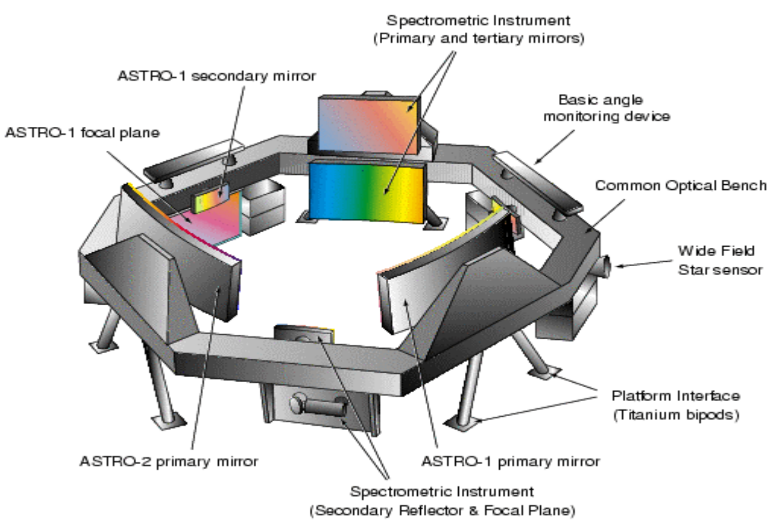
Payload Configuration



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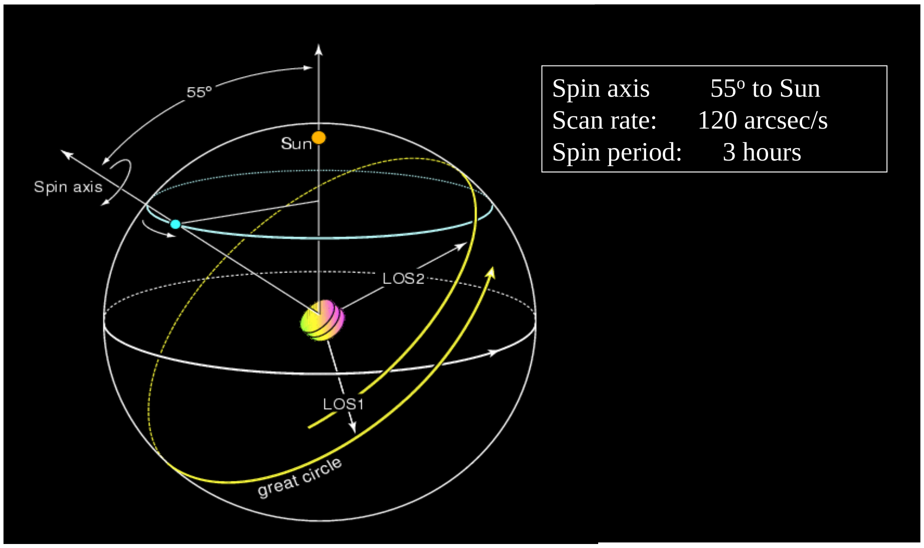
Sky Scanning Principle



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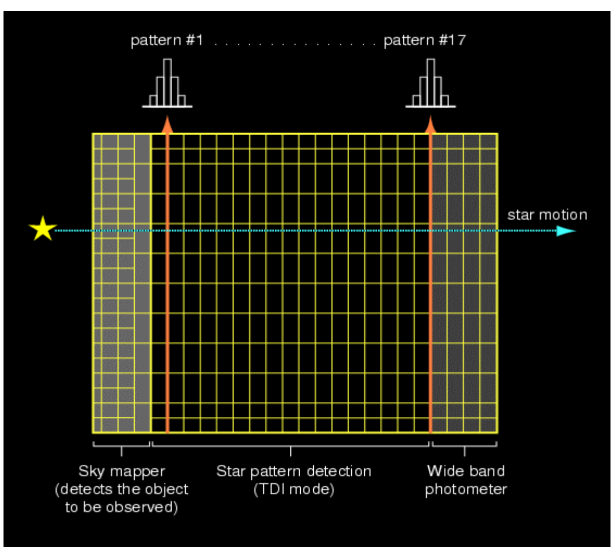
Astrometric Focal Plane



Sky mapper:
- detects all objects to 20 mag
- rejects cosmic-ray hits
- mag and x,y to main field

Main field:
- area: 0.3 deg^2
- size: 60×70 cm^2
- Number of CCD chips: 136
- CCDs: 2780 x 2150 pixels

Pixels:
- size: 9 x 27 μm^2
- window area: 6 x 8 pixels
- flush frequency: 15 MHz
- readout frequency: 30 kHz
- total read noise: $6e^-$ rms

Broad-band photometry:
- 4 colour

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On-Board Object Detection

Requirements:

- unbiased sky sampling (mag, colour, resolution, etc)
- no all-sky catalogue at GAIA resolution (0.1 arcsec) to V~20

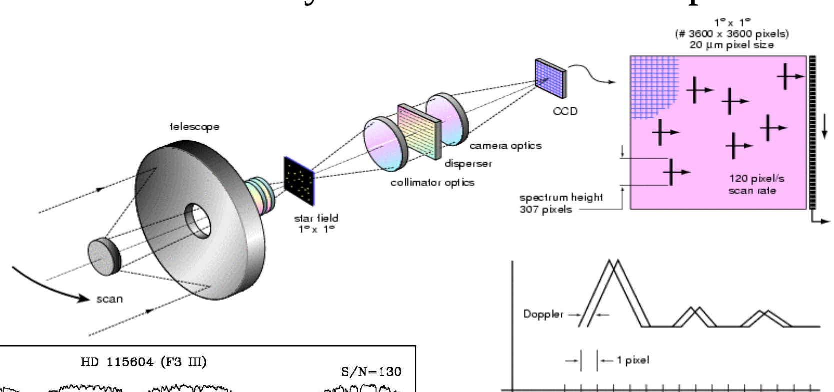
Solution: on-board detection:

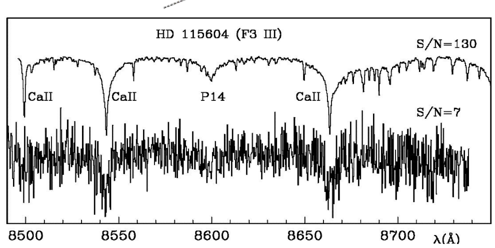
- no input catalogue or observing programme
- good detection efficiency to V~21 mag
- low false detection rate, even at very high star densities
- maximum star density: ~ 3 million stars/deg^2 (Baade's Window)

Will therefore detect:

- variable stars (eclipsing binaries, Cepheids, etc)
- supernovae: 10^5 expected
- microlensing events: ~1000 photometric; ~100 astrometric
- Solar System objects, including near-Earth asteroids and KBOs

Radial Velocity Measurement Concept

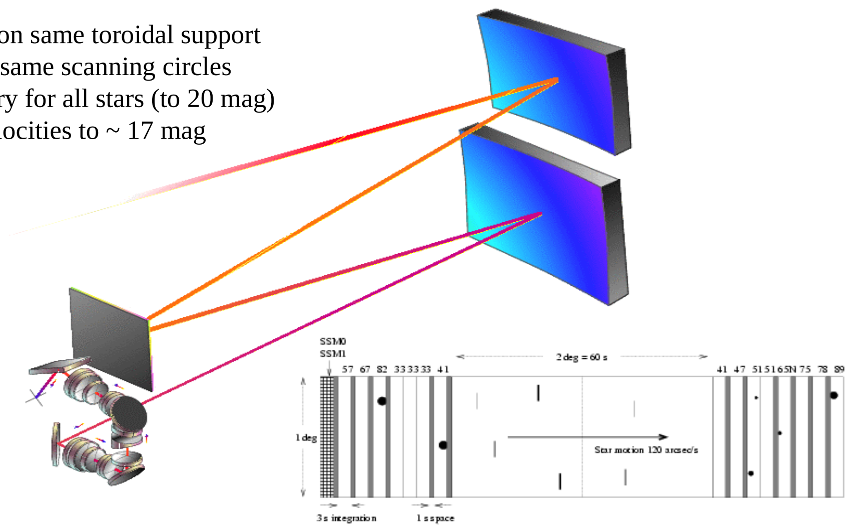




F3 giant
S/N = 7 (single measurement)
S/N = 130 (summed over mission)

Radial Velocity and Photometric Instrument

- Mounted on same toroidal support
- Observes same scanning circles
- Photometry for all stars (to 20 mag)
- Radial velocities to ~ 17 mag



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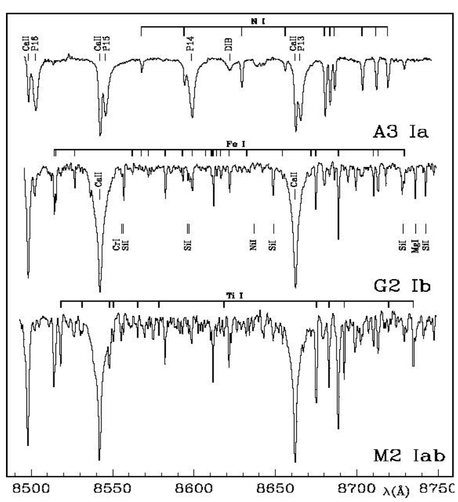
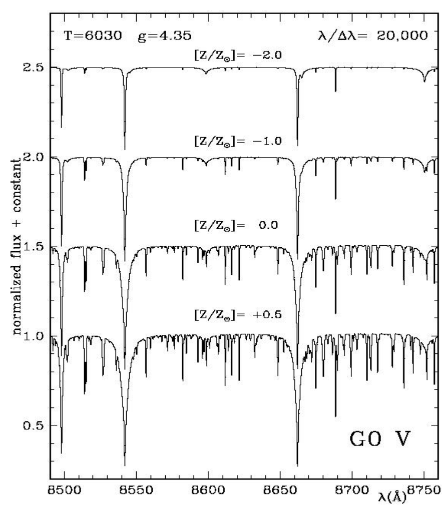
Spectral Sequences around Ca II



Effect of temperature: A to M stars



Effect of metal abundance in G stars

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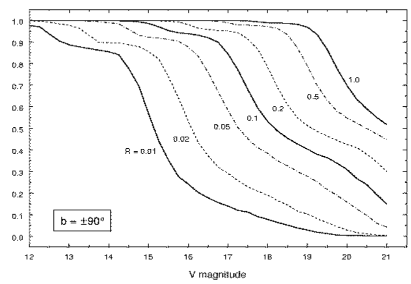
Astrometric Accuracy

G (~V mag)	10	11	12	13	14	15	16	17	18	19	20	21
Parallax	4	4	4	5	7	11	17	27	45	80	160	500
Position	3	3	3	4	6	9	15	23	39	70	140	440
Annual proper motion	3	3	3	4	5	8	13	20	34	60	120	380

5-year accuracies in µas

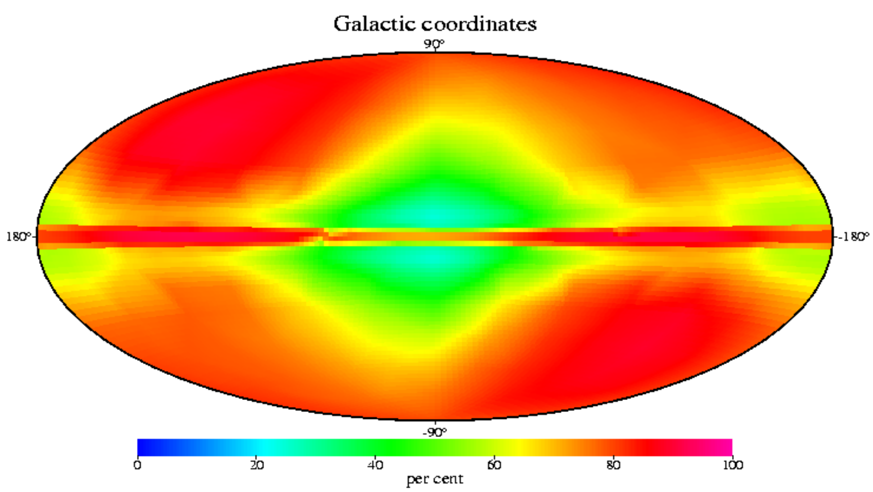
Derived from comprehensive analysis:

- image formation (polychromatic PSF)
- evaluation versus spectral type/reddening
- comprehensive detector signal model
- sky background and image saturation
- attitude rate errors and sky scanning
- on-board detection probability
- on-ground location estimation
- error margin of 20 per cent included
- results folded with Galaxy model

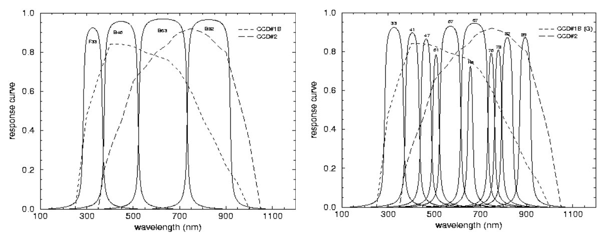


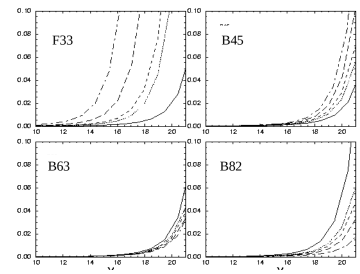
Fraction with given relative parallax error towards Galactic poles

Accuracy Example: Stars at 15 mag with $\sigma_\pi/\pi \leq 0.02$

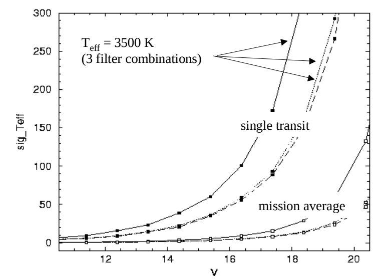


Photometric Accuracies and Diagnostics

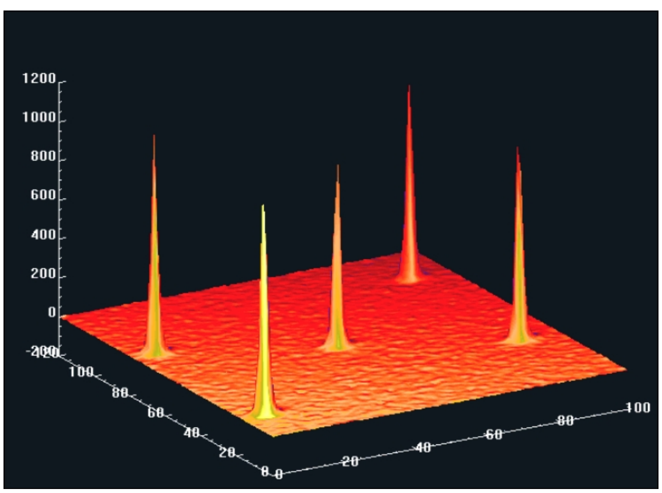




- **Photometric system (above):**
  - optimised for astrophysical diagnostics
- **Photometric accuracy assessment (top right):**
  - photon noise, sampling, CCD response, etc.
  - single transit + mission average (100 transits)
- **Astrophysical diagnostics (right):**
  - ⇒ reddening, T_{eff}, [Ti/H], [M/H], etc.



CCD Centroiding Test Results

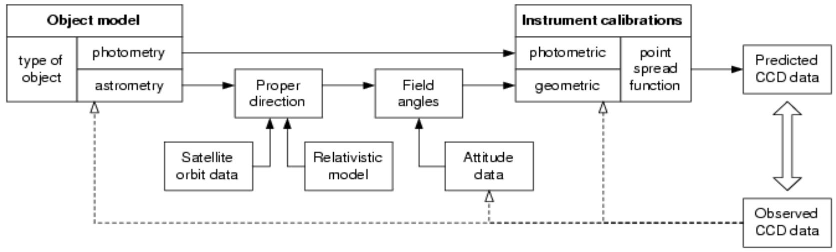


Astrium contract (Sep 2000)
'GAIA-mode' operation
EEV CCD 42-10
3-phase, 13µm pixels
Illumination: 240,000 e^-

Frequencies:
TDI: 2.43 kHz
Dump: 4 MHz
Binning: 1 MHz
Readout: 90 kHz

Differential centroid errors:
rms = 0.0038 pixels
(≈1.2× theoretical optimum)

Data Analysis: Concept and Requirements



Capacity: ~100 Terabytes

Overall system: centralised global iterative approach

Accessibility: quasi-random, in temporal and object domains

Processing requirements: entire task is ~10^{19} flop

Numerical: 0.1 microarcsec = 10^{-13} of a circle (64-bit marginal)

Data base structure: e.g. Objectivity (cf. Sloan)

Results: time-critical results available early (NEO, supernovae etc)

⇒ **Prototype:** Hipparcos global astrometry re-reduced during concept study

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Main Performances and Capabilities

Accuracies:

– 4 µas at V = 10 10 µas at V = 15 0.2 mas at V = 20
– radial velocities to few km/s complete to V = 17.5
– sky survey at ~0.1 arcsec spatial resolution to V = 20
– multi-colour multi-epoch photometry to V = 20
– dense quasar link to inertial reference frame

Capabilities:

– 10 µas ≡ 10% at 10 kpc ≡ 1 AU at 100 kpc
– 10 µas/yr at 20 kpc ≡ 1 km/s

⇒ every star in the Galaxy and Local Group will be seen to move

⇒ GAIA will quantify 6-D phase space for over 300 million stars, and 5-D phase-space for over 10^9 stars

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Main Payload Requirements (1/2)

Orbit:	Earth/Sun straylight	minimised
	Earth/Moon occultation	minimised
	Thermal/radiation impact	minimised
	Eclipse during observation	avoided
Thermal:	Optical bench stability	few tens of μK
	CCD temperature	≈200 K
Mechanical:	Mechanical and dynamic interference minimised	
Outage:	Mission outages minimised	
Lifetime:	5 years nominal; 6 years extended	

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Main Payload Requirements (2/2)

- Payload composed of:
  - two identical astrometric telescopes:
    - separated by 106°
    - knowledge to 1 μas over one revolution (3 h)
  - spectrometric telescope:
    - medium-band photometer
    - radial-velocity spectrometer
- Astrometric accuracy:
  - < 10 μas rms for V = 15 mag
  - complete between V = 3–20 mag
- Stars measured in Time-Delayed-Integration (TDI) over 17 CCDs
- Star profiles, along scan, generated at 1 Mbps

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Launch and Operational Orbit Strategy

Operational orbit - around Lagrangian L2 of Sun-Earth system

Transfer orbit duration -220 to 260 days, according to launch date

Launcher - Ariane 5 in dual/multiple configuration

GAIA location - within SPELTRA, as lower passenger

Launch strategy - Ariane 5 injection into a standard GTO orbit
- transfer orbit and final injection around L2 by autonomous satellite propulsion system (option: to use Ariane 5 third stage)

Launch window - daily window compatible with Ariane 5 midnight window for dual launches

Launch date - 2009

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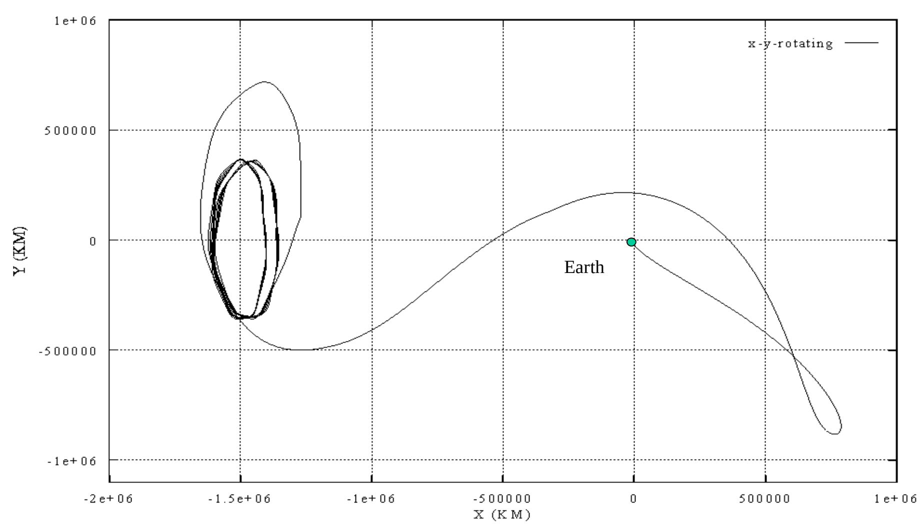
Transfer Orbit



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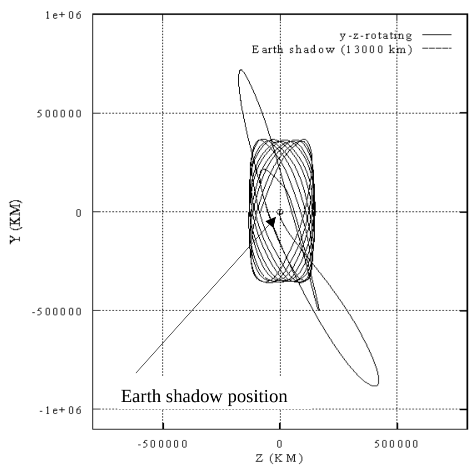
Operational Orbit



- L2, Lissajous
- Semi-axes:
  400.10^6 km $\times$ 100.10^6 km
- Orbit period: 6 months
- Sun-Satellite-Earth angle:
  $\leq 15°$ (40° to 70°)
- With one avoidance manoeuvre, eclipse-free condition kept for much longer than 5 years (~12y)
- Ground station visibility:
  8 hrs/day (Perth)

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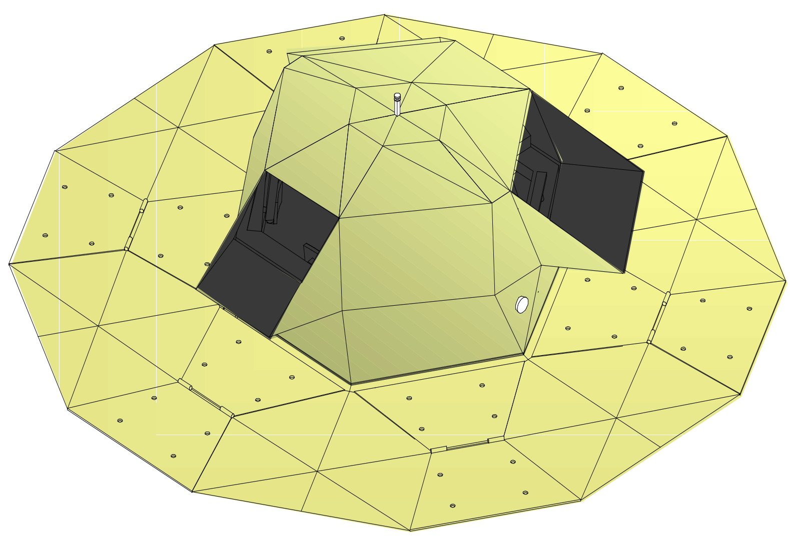
Spacecraft: Top View



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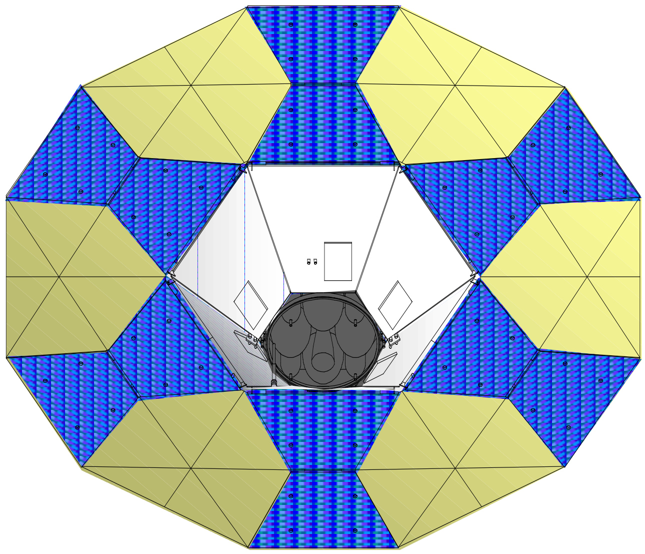
Spacecraft: Bottom View



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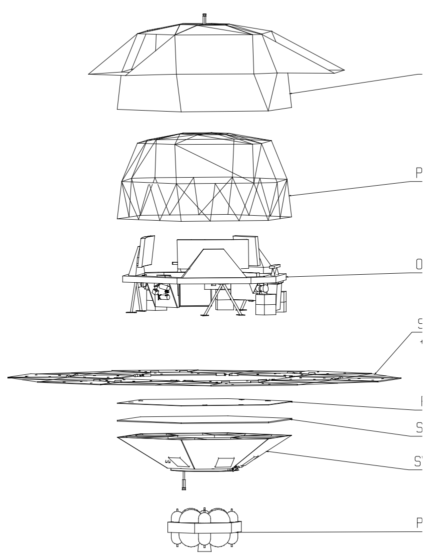
Satellite Exploded View



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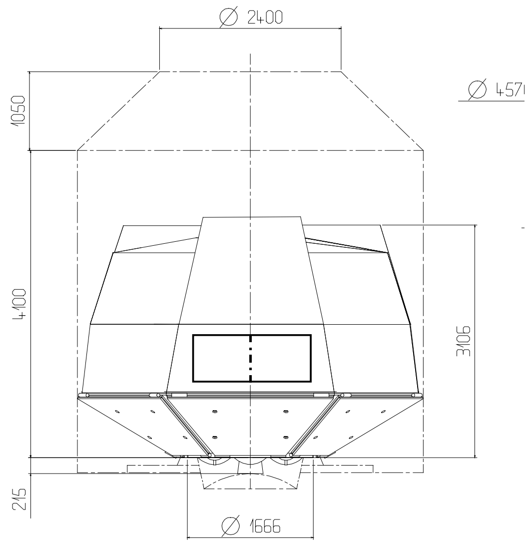
Spacecraft: Undeployed Configuration



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Spacecraft Design Approach (1/5)

- Mission Lifetime — 5 years nominal, >4 years observation
- Solar Aspect Angle — >120° (payload protection from Sun)
- Spacecraft — stabilised 3-axis, with 120 arcsec/sec scanning law (1 revolution every 3 hr)
- Lift-off Mass (with 20% system margin) — 3137 kg, with autonomous propulsion; 2337 kg, without propulsion
- Power (with 10% system margin) — 2468 W at 5-year end-of-life; 2616 W at 6-year end-of-life
- Pointing Accuracy (3σ):
  - absolute pointing error — < 5 arcmin
  - relative pointing error — < 0.002 arcsec/sec (1σ)

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Spacecraft Design Approach (2/5)

- Configuration — Modular: service module (SVM) and payload module (PLM) thermo-mechanically decoupled
- SVM structure — Truncated hexagonal pyramid shape, to avoid turning shadow on sunshield, with six lateral walls to support SVM (and PLM) electronics
- PLM structure — Monolithic, toroidal optical bench of SiC, with 3+3 SiC mirrors and three focal plane assemblies. 3 isostatic connections with SVM
- Stabilisation — 3-axis attitude control with star sensor, coarse sun sensor, 1-axis gyro and 6 redundant, 10N bi-propellant thrusters
- Attitude control — Continuous scanning by 1 mN FEEP thrusters

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Spacecraft Design Approach (3/5)

- Propulsion — Bi-propellant system, with single 400 N engine, integrated by the 6x10 N thrusters for orbit correction, final orbit injection and maintenance

  Four standard propellant tanks; two pressurant
- Thermal Control — Passive, with heaters, ensuring efficient payload stability and PLM/SVM thermal decoupling
- Power Supply — Solar array: deployable, six wings of 2 GaAs panels each (24 m^2), within annular sunshield of 4.5 m inner and 8.5 m outer diameters

  Regulated power bus: 28 V, with two Li-ion 14Ah batteries for eclipses during launch and transfer phases (no eclipses in operational orbit)

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Spacecraft Design Approach (4/5)

- Data Handling – On-Board Data Handling, with packet Telemetry and Telecommand
  – Centralised control unit: spacecraft operation, attitude and orbit control, and thermal control
  – 100 Gb mass memory, allowing for science date rate dumping at 3 Mbps (1 Mbps continuous payload data rate)
- Communications Standard ESA X-band up- and down-links; 2 kbps for housekeeping and omni-directional coverage (2 low-gain antennas and 17W-RF)
- Science telemetry: X-band down-link at 3 Mbps (typical); six electronically-scanning phased-array antennae (EIRP > 32 dbW)

Spacecraft Design Approach (5/5)

Budgets	**Mass (kg)**	**Power (W)**
Payload module	893	1527
Service module	895	717
Margin	339	224
Propulsion	1010	
Total	**3137**	**2468**

Identified Key Technology Activities

- Validation of CCD performance and CCD development
- Focal plane assembly, detection and data handling electronics
- Large size silicon-carbide mirrors (1.7×0.7 m^2)
- Ultra-stable large size SiC structures for payload optical bench
- Large deployable solar array/sunshield assembly
- High-stability optical benches (basic angle verification)
- Phased-array antenna for high data rates and far orbits
- Optimised on-board compression algorithm
- Ground calibration/verification approach and facilities
- Database architecture

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Cost at Completion

(current Cornerstone 5 Budget Envelope = 541.7 MEuro)

Project Cost Estimate	**MEuro (EC 2000)**
Procurement Cost (ESA + Industry + Overheads + Contingency)	413.8
Spacecraft Operations	35.3
Science Operations	12.9
Launch	111.9
Total Project Cost Estimate	**573.9**

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