The Gaia Challenge

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acknowledgements: ESA, the Gaia scientific community and industrial partners

Gaia in a nutshell

high accuracy astrometry:
parallaxes, proper motions

radial velocities, photometry

Entire sky to V=20, 100 times over 5 years

6D phase space survey + physical parameters

ESA mission for 2011 launch

Science objectives

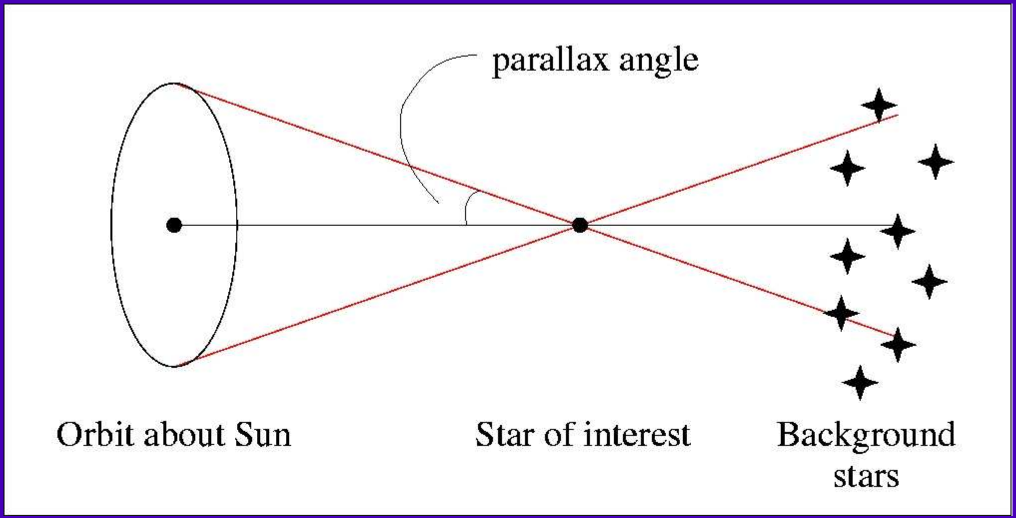
Main science driver: Galactic composition and formation

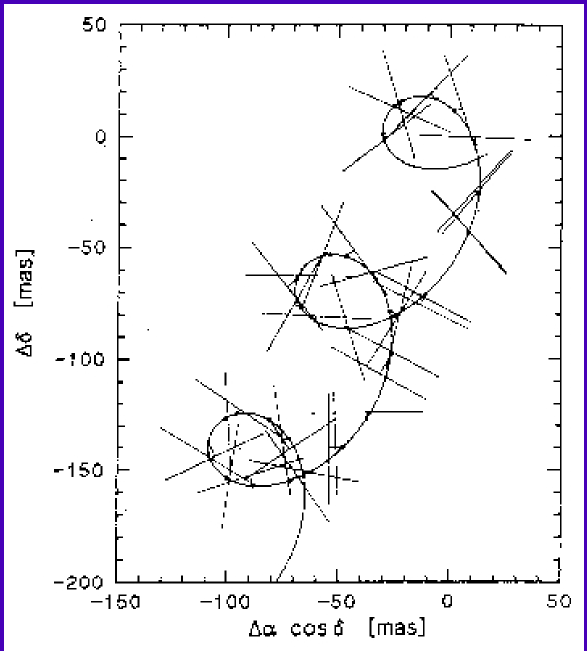
- sets parallax/proper motion precision and magnitude limit
- *dark matter, merger history, chemical evolution ...*

- Stellar astrophysics *(HRD, abundances, binaries)*
- Star formation *(OB assoc., clusters)*
- Exoplanets *(orbits, masses, transits)*
- Solar system *(new discoveries, orbits, taxonomy, NEOs)*
- Extragalactic *(local group galaxies, SNe)*
- Cosmic distance scale *(geometric to 10 kpc, Cepheids, RR Lyr)*
- Reference frame *(quasars)*
- Fundamental physics *(light bending, γ to 5×10^{-7})*

What is astrometry?

- Mean positions
  - Right Ascension, Declination
- Distances
  - parallaxes
- Kinematics
  - 2D (angular) proper motions
  - combined with parallaxes
    => 2D transverse velocities





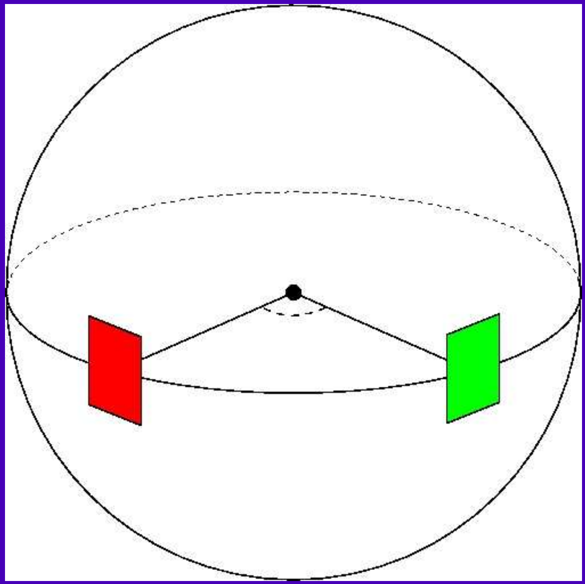
Astrometry gives five components of **r**,**v** phase space

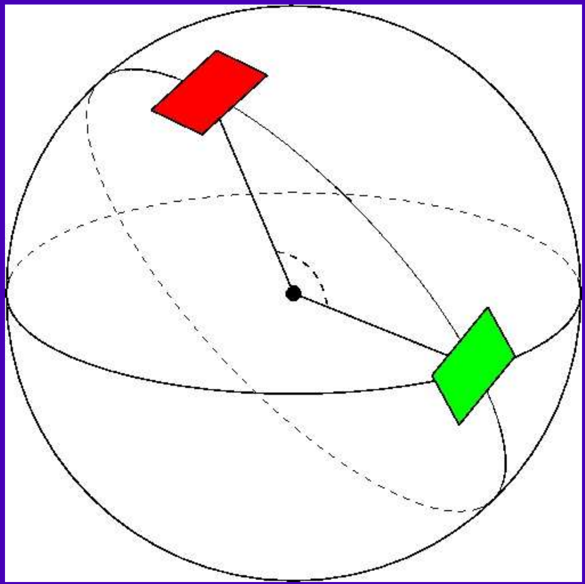
Distances

- important in every area of astronomy
  - angular scales $\rightarrow$ length scales proper motions $\rightarrow$ velocities
  - 3D spatial structure
  - intrinsic stellar luminosities (HRD, ages)
- all other measures calibrated with parallaxes
- strength of Gaia is accuracy *and* statistics
  - 1% distance accuracy at 1kpc for V=15
  - 500,000 stars with distance accuracy better than 0.1%
  - 20 million stars 1%
  - 200 million stars 10%
- only from space, and only Gaia

Global astrometry from space

- Ground-based astrometry
  - narrow (single) field
  - reference stars share common parallax effect
  - therefore only *relative* astrometry
  - limited to a few milliarcseconds precision
- Space-based astrometry
  - observe simultaneously in two widely separated fields separated by a fixed *basic angle*
  - measure relative positions along great circle
  - repeat for many orientations over whole sky





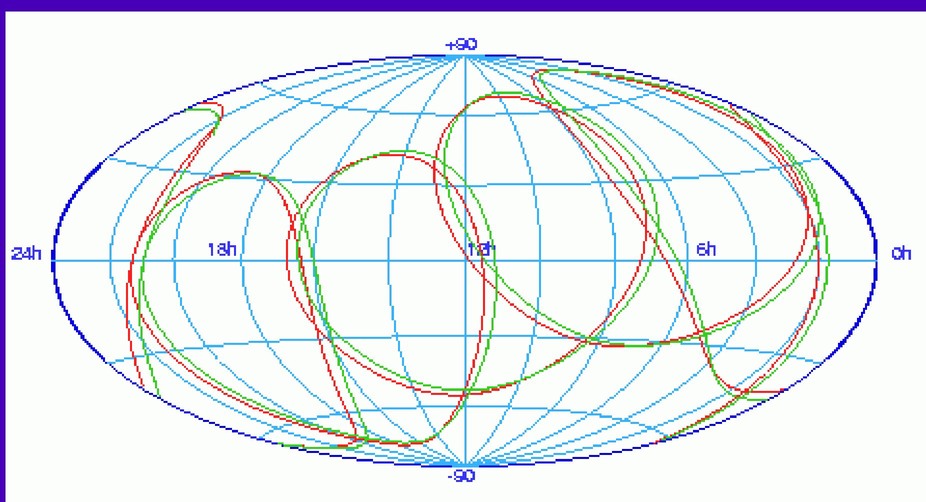
Sky scanning principle

Continuous three-axis motion:

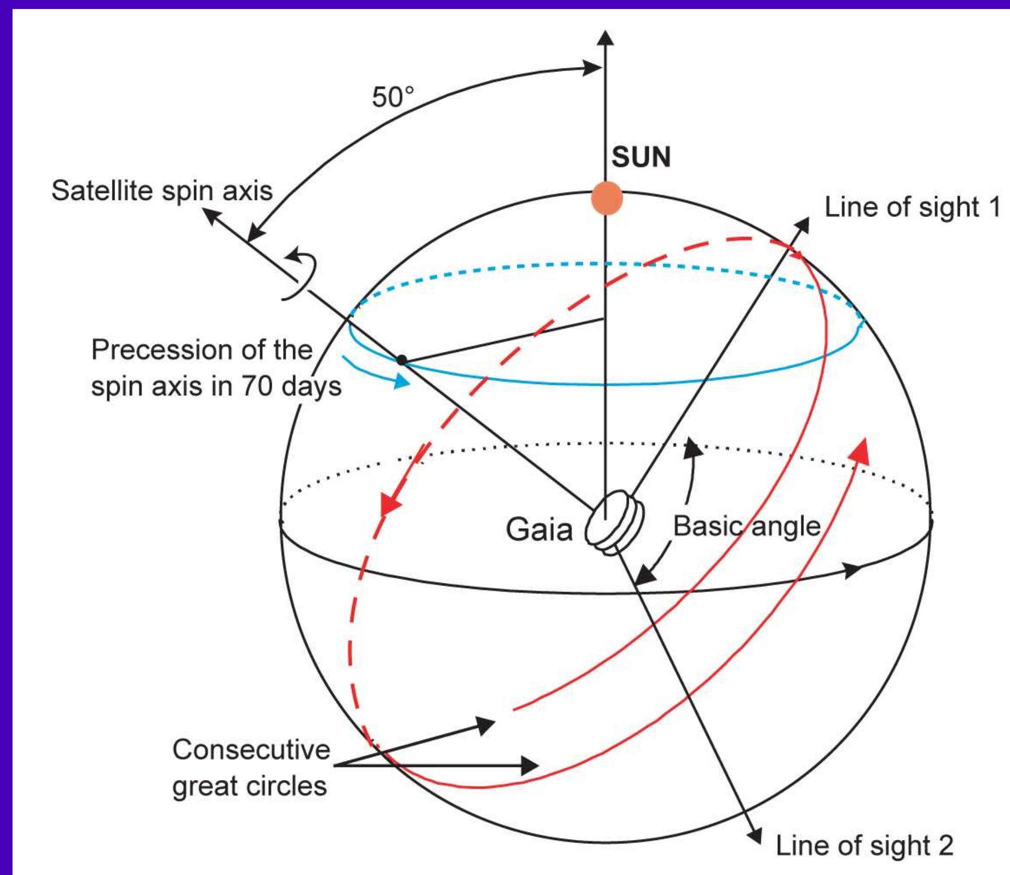
- axis rotation (P = 6 days)
- fixed sun angle precesion (P = 70 days)
- orbit around sun (P = 1 year)

Traces quasi great circles on sky

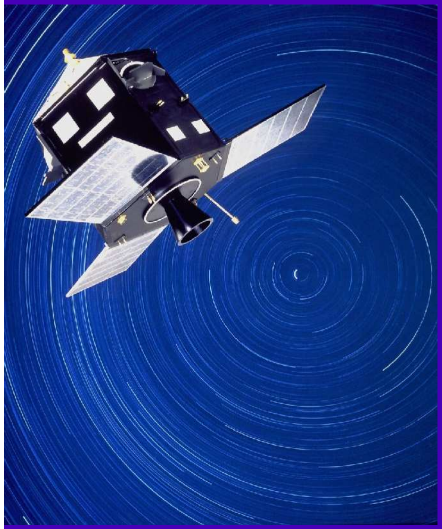
5 year mission



Ecliptic co-ordinates

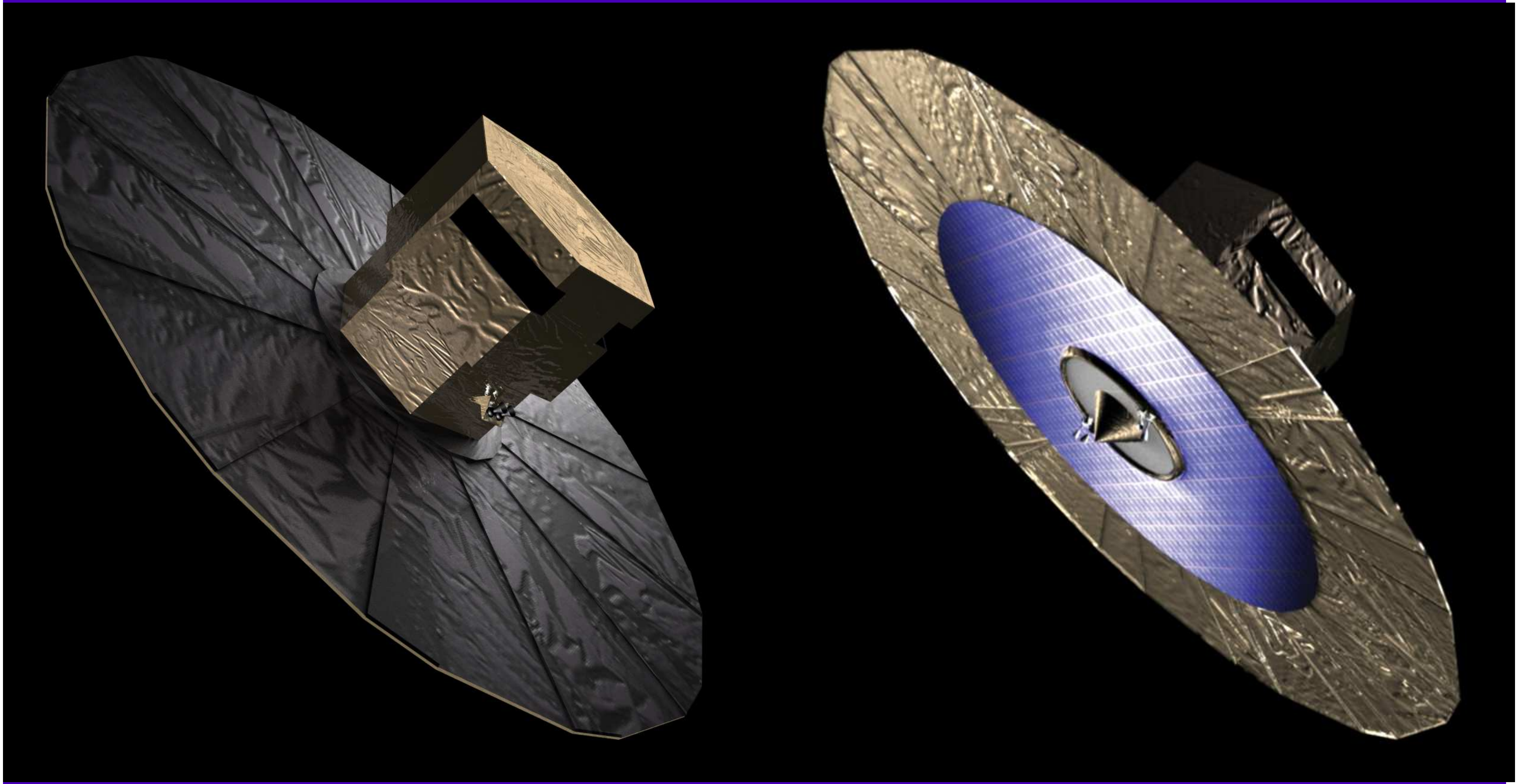


Hipparcos vs. Gaia



	Hipparcos	**Gaia**
Magnitude Limit	12.4	20
No. sources	120 000	1000 000 000
No. quasars	none	0.5-1 million
No. galaxies	none	1-10 million
Astrometric accuracy	~1000 μas	7 μas at V<10
		12-25 μas at V=15
		100-300 μas at V=20
Photmetry	2 bands	19 bands
Radial velocities	none	1-10 km/s to V=17-18

The satellite

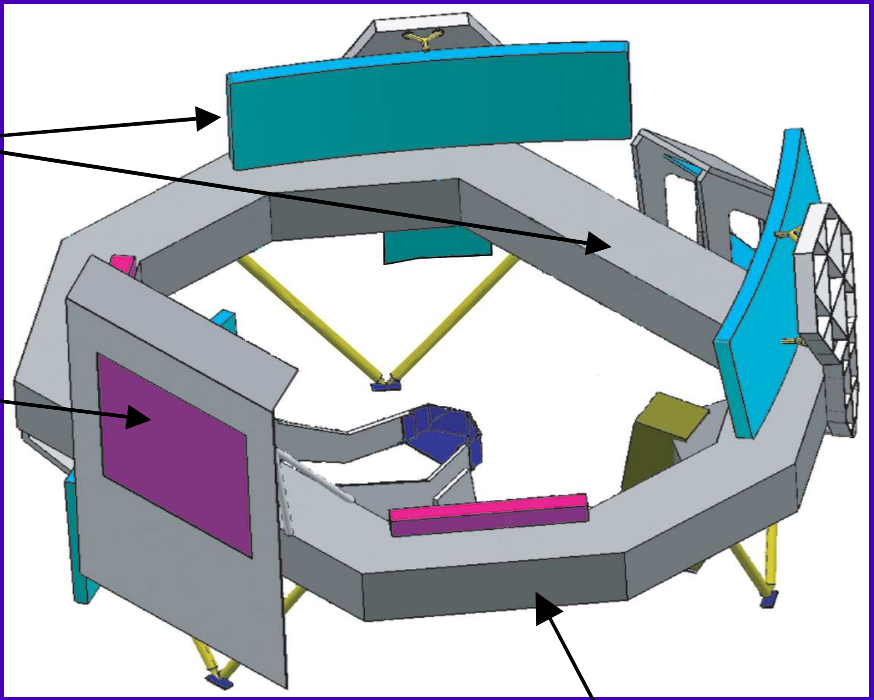


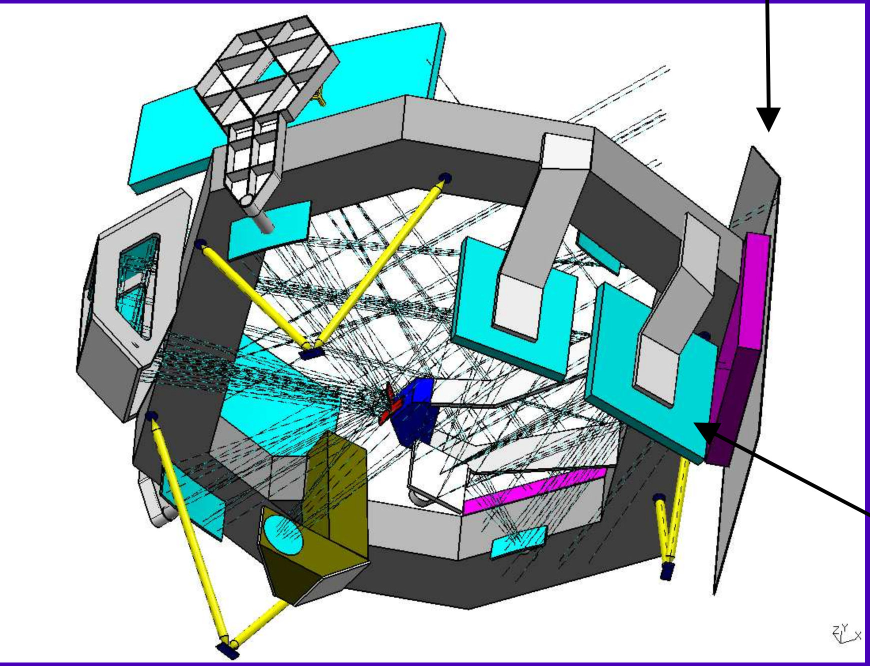
Sunshield diameter = 11m Total mass = 1700kg (800kg telescope/instruments)

Payload overview

Astrometric instrument:
1.4m x 0.5m primary mirrors

Astrometric focal plane

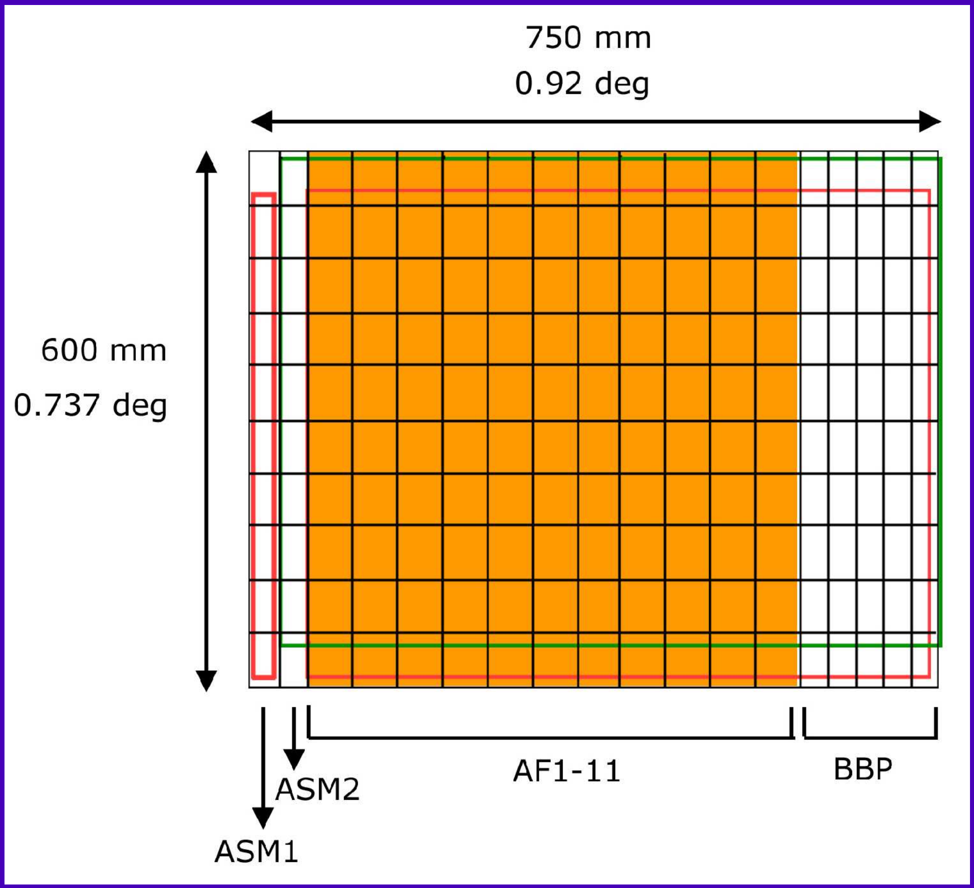




SiC optical bench

Spectroscopic instrument:
0.56m x 0.45m primary mirror

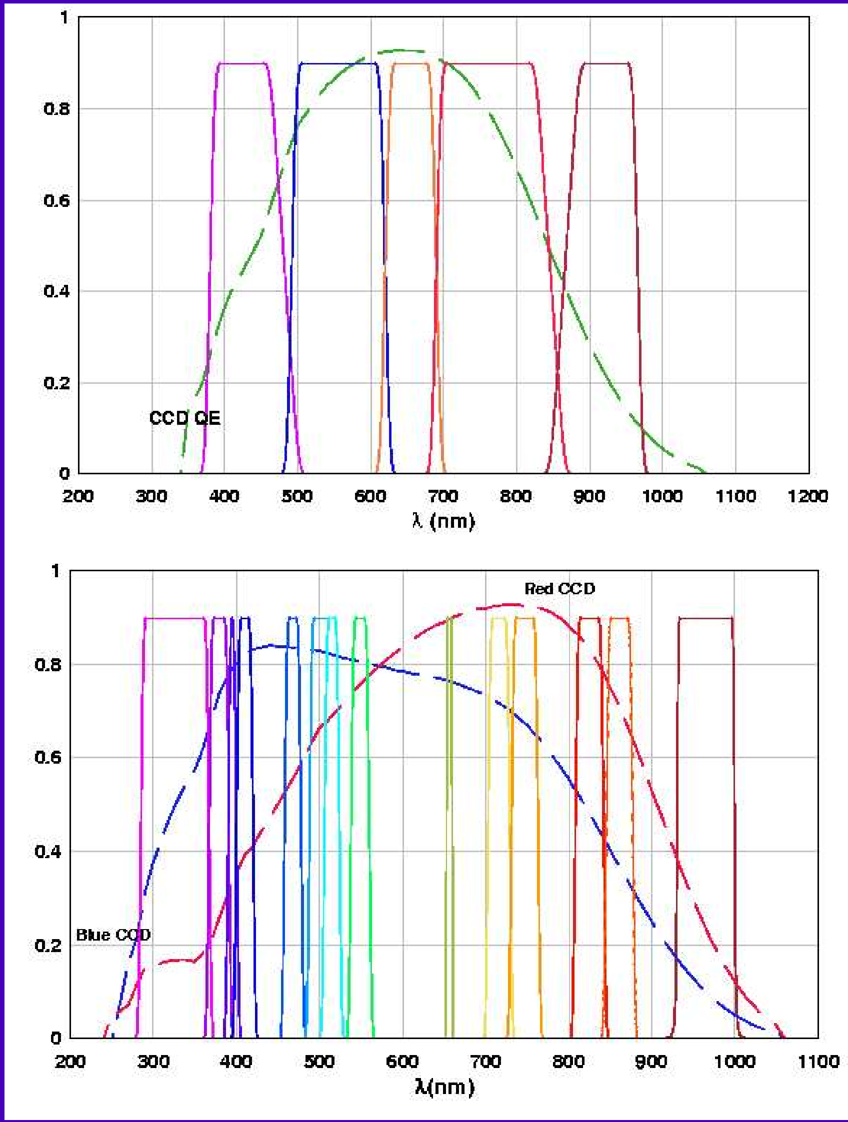
Astrometric focal plane



direction of motion across focal plane

- the two fields-of-view are superimposed on a single CCD focal plane
- 180 CCDs (2000 x 5600 pixels)
- CCDs clocked in “TDI mode”
- real-time detection of objects
- transmission only of “windows” around objects

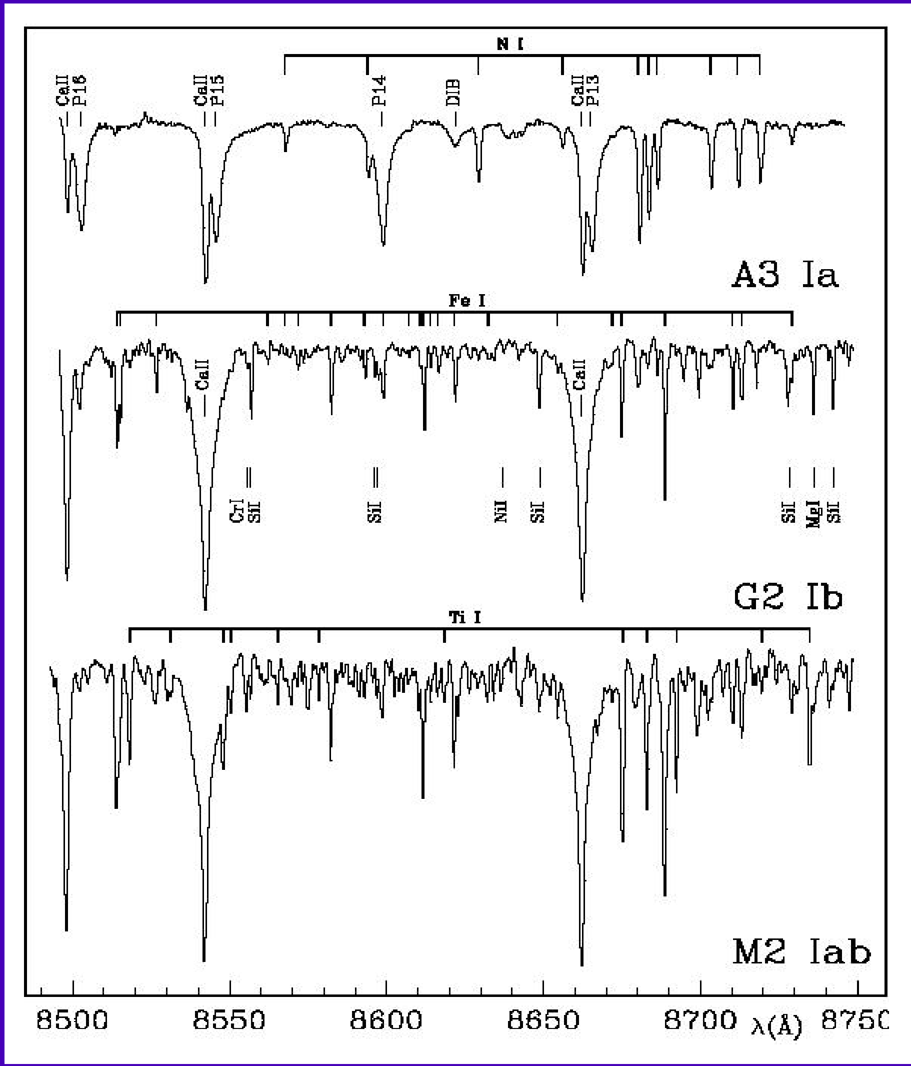
Gaia photometry



- Broad Band Photometric system (BBP)
  - 5 broad bands
  - primarily for chromatic correction
- Medium Band Photometric system (MBP)
  - 14 medium bands
  - object classification
  - determinaton of stellar parameters and interstellar extinction
- systems optimized specifically for Gaia (Jordi et al. 2006)
- vital for exploiting astrometric data!

Gaia spectroscopy

- Slitless spectrograph
- R = 11 500
- around CaII triplet (848–874 nm)
- radial velocities (Doppler effect)
- V_{rad} to 1–10 km/s for V < 17.5
- high SNR spectra for millions of stars with V < 14
    - physical stellar parameters, e.g. [α/Fe]



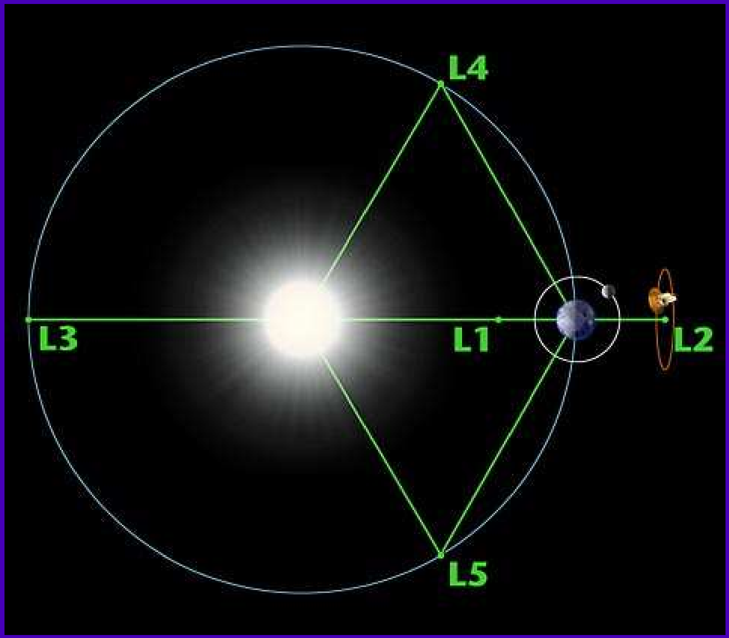
Launch and orbit

basic angle must be stable to ~1 μas over 6 hours

⇒ 25 μK thermal stability
⇒ high mechanical stability (no moving parts!)

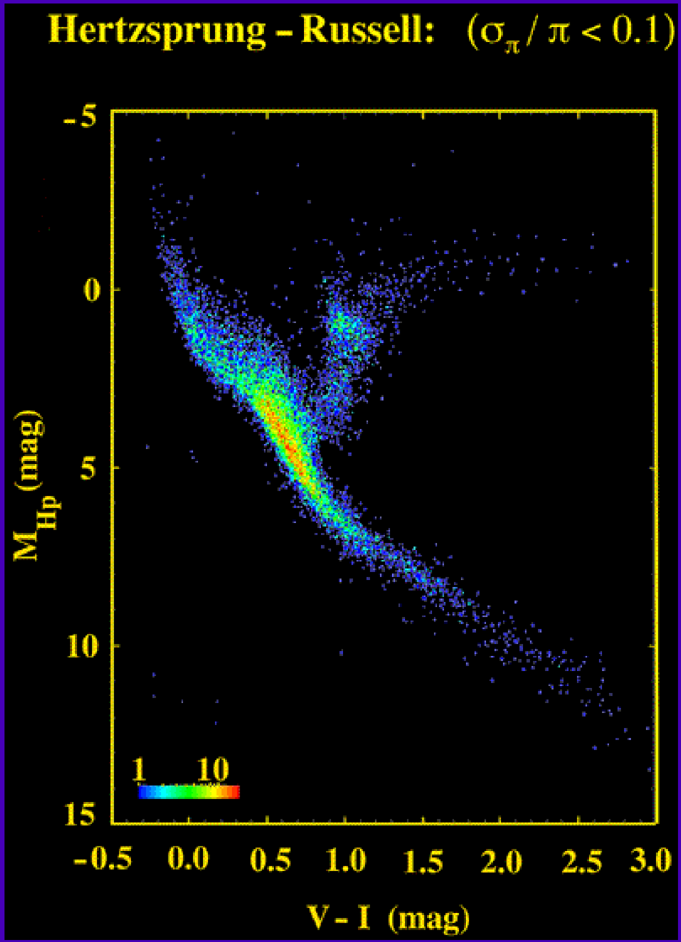
Lissajous' orbit about Earth-Sun L2 point
5 year mission

Phased antenna array:
- 3 Mb/s for 8 hours per day
- single ground station (Madrid)

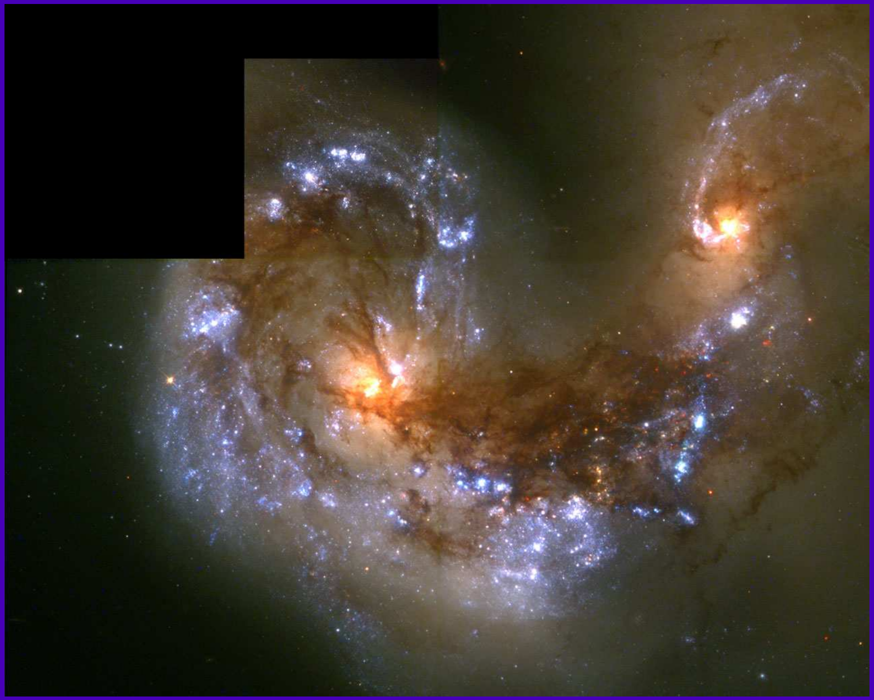


Stellar structure and evolution

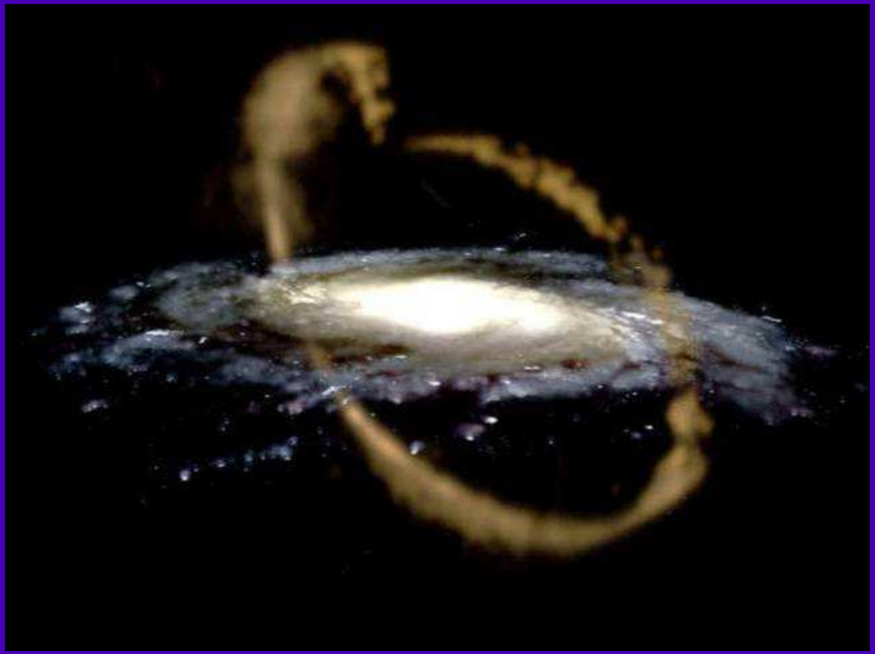
- structure models
  - luminosities (also need A_V and T_{eff})
  - helium abundances (not available in spectrum; need accurate luminosities)
- open clusters and SFRs
  - 70 within 500pc, providing *individual* distances to 0.5-1% (<5pc) at V=15
  - accurate ages from position in HRD of MS turn off
  - Gaia will discover thousands more (from clustering in 6D space, HRD)
- binaries
  - directly calibrate Mass-Luminosity relationship



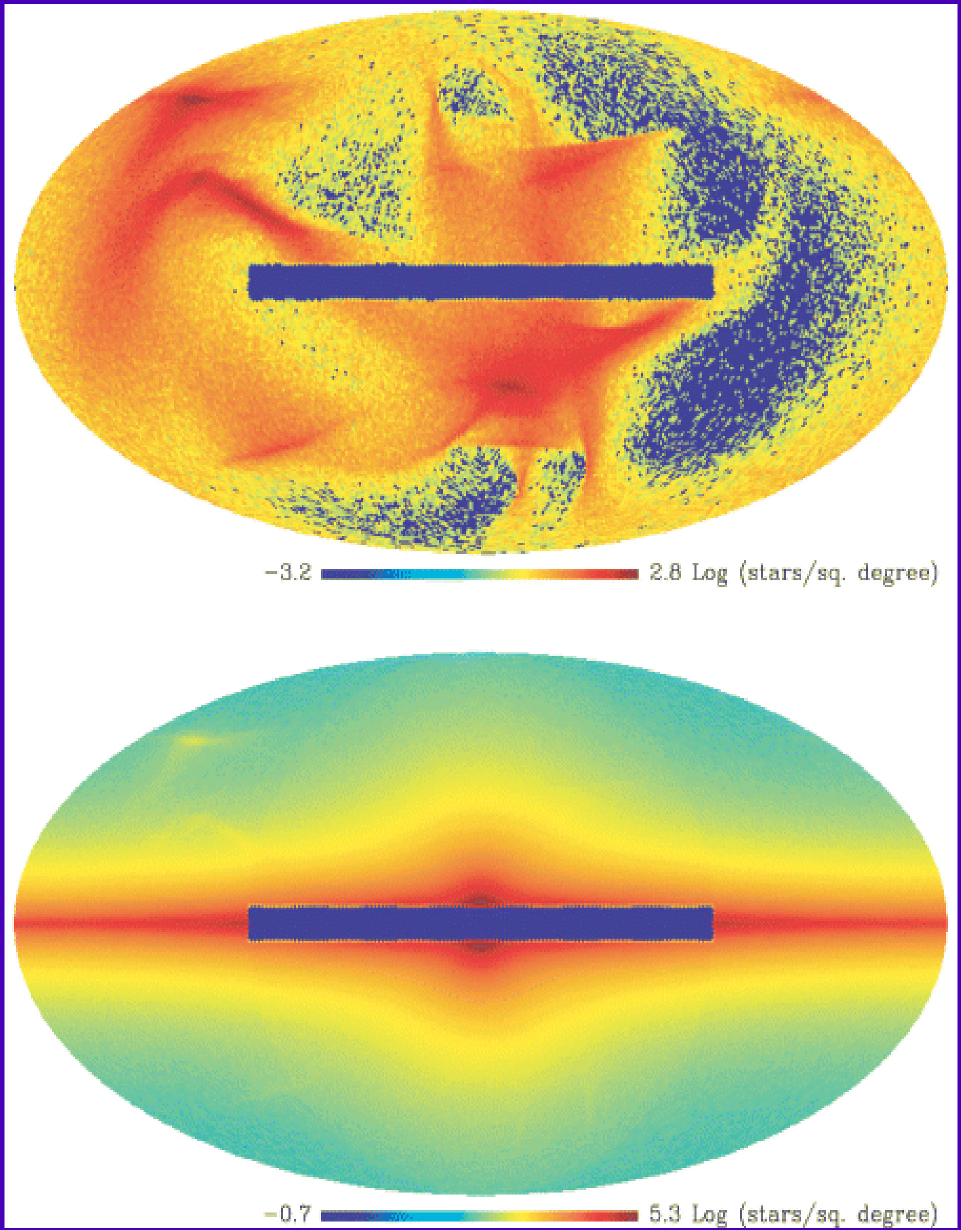
Galaxy formation



- ΛCDM models
  - galaxies built up by many small units
- look for evidence of mergers/accretion
  - in external galaxies
  - but in more detail in our Galaxy



Spatial overdensities in the halo

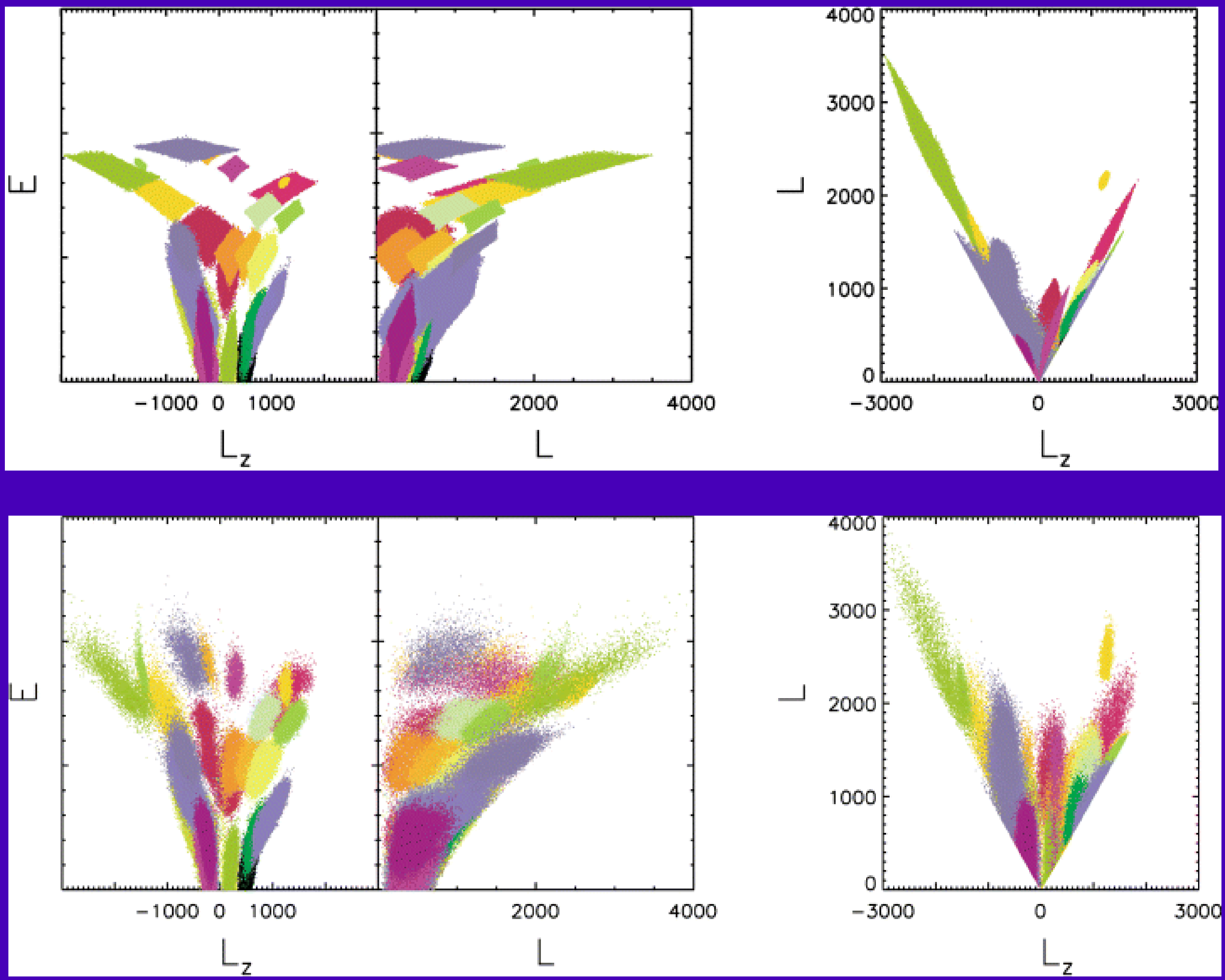


Brown et al. 2005

- spatial overdensities/streams found
  - Sagittarius dSph
  - Canis Major
- but limited discovery space
  - low contrast
  - projection effects
  - streams well-mixed spatially
- can improve with
  - radial velocities
  - better identification of tracers
- ultimately need astrometry

Substructure fossils in phase space

Helmi & de Zeeuw 2000



Initial distribution

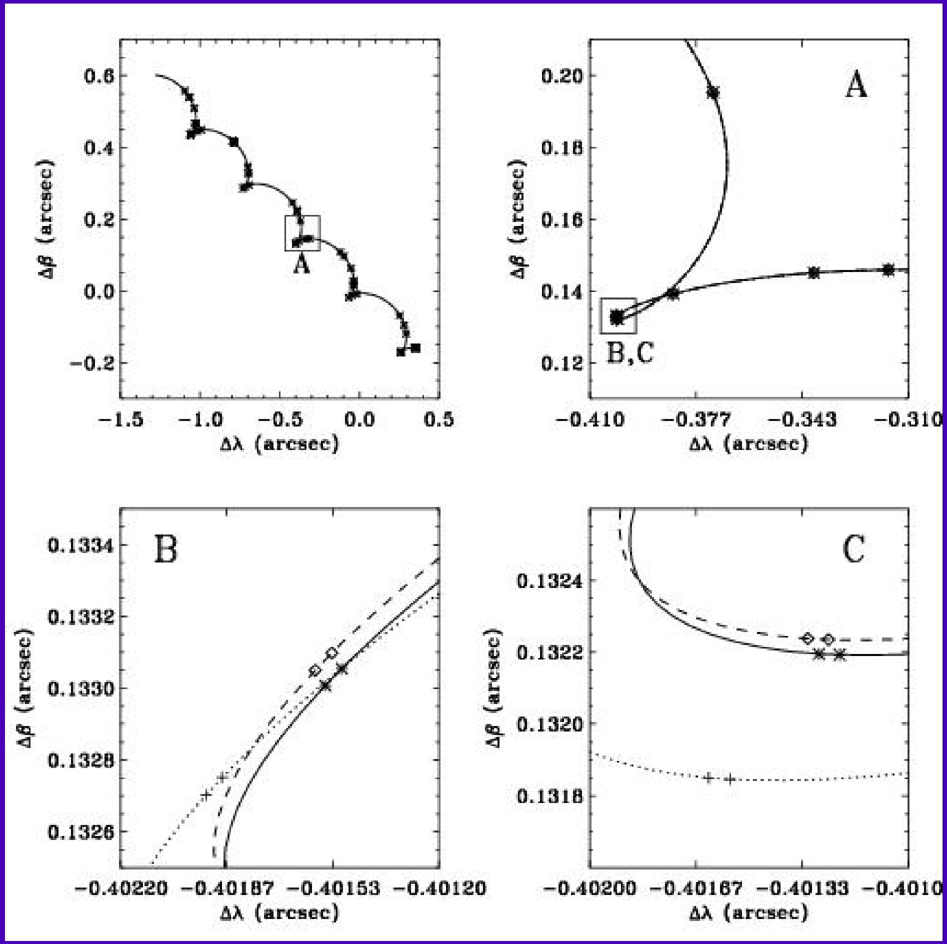
Final distribution after 12 Gyr convolved with Gaia errors

Galactic thin and thick disks

- mass of the disk
  - determine gravitational potential from stellar motions
  - from stellar LF determine dark matter distribution
- formation of disk
  - monolithic collapse or via accretion of satellites?
  - is there a smooth age-metallicity-kinematic relation?
  - phase space measurements to look for substructure
  - age from WD luminosity function (200,000, precise to <0.5 Gyr)

Exosolar planetary systems

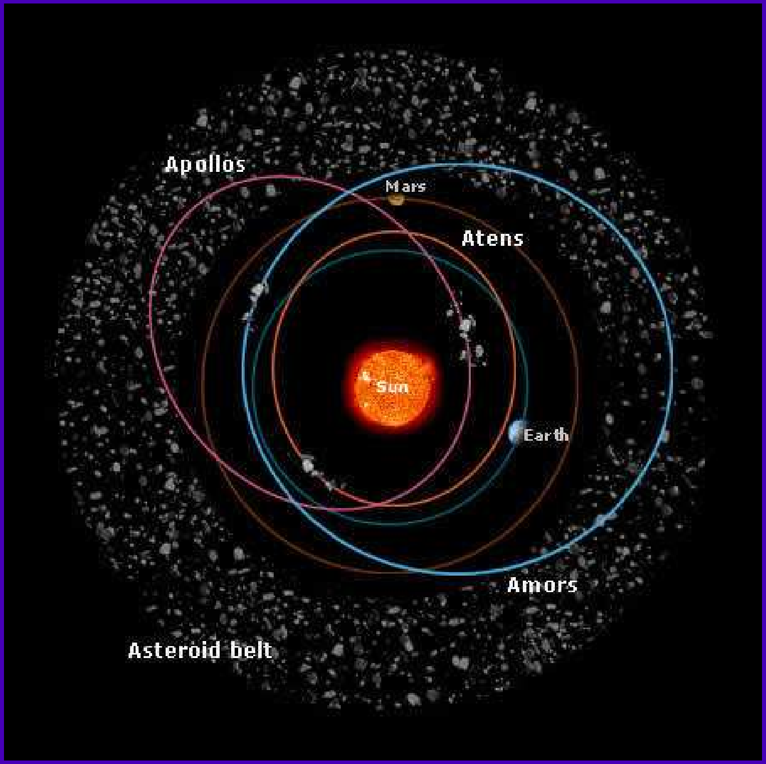
- astrometric binaries (AB1)
  - $\alpha = (M_p/M_s)(a_p/d)$
- extensive, unbiased survey
  - monitor 10^5 stars to 200 pc (V<13)
  - all stellar types to P ~ 10 years
  - ~ 5000 new planets expected
  - orbital solutions for 1000 – 2000 systems
- need additional spectroscopy to determine mass (ratio)
  - masses to few 10 M_{Earth} to 10pc
  - no sin i ambiguity



47 Ursa Majoris astrometric displacement = 360 μas (Sozzetti et al. 2001)

Solar system

- Gaia capabilities
  - all sky complete survey to G=20, to within 40° of Sun (“daytime”)
  - discovery of $10^5 – 10^6$ new objects (cf. 65000 now)
  - very accurate orbital elements (~30 times better)
  - multi-band photometry (taxonomy, chemistry)
- main belt asteroids
  - solar system formation
  - sizes, albedos, masses (~ 100, cf. 10 now)
- Near-Earth Objects
  - expect 1600 Earth-crossing (vs. 100 now)
- General Relativity
  - light bending (Sun: 4 mas at 90°), γ to $5\text{x}10^{-7}$
  - perihelion precession (and solar J_2)



Our challenge: the data processing

- 1 Mb/s for 5 years (~ 100 TB raw)
- complex data treatment
  - objects mixed up in time and space
  - astrometry, photometry and spectroscopy
  - iterative adjustment of parameters for ~100 million stars
- *many* tasks, e.g.
  - object matching, attitude modelling, global astrometric processing, binary star analysis, radial velocity determination, photometry, variablity analysis, CCD calibration, object classification, determination of stellar physical parameters, solar system objects...
- ~10^{21} FLOPS (10^{17} FLOPS from 1 PC in 1 year)
  - 1s per star for *all* operations would require 30 years
- basic data processing prototype (GDAAS)

Timeline and the scientific community

- Fully approved and funded ESA mission
  - prime contractor selected in January 2006
  - optimization and implementation phase starts mid 2006
  - launch December 2011
  - nominal mission in 2012 – 2016
  - data processing complete ca. 2018
- Scientific community is responsible for the data processing
  - funding by national agencies
  - currently setting up the Data Processing and Analysis Consortium
  - major partners already identified (following “Letters of Intent”)
  - significant commitment, investment and expertise required
  - but rewards will be extensive

Organisation

Gaia Science Team

Data Processing and Analysis Consortium

Consortium Executive

- CU1: System Architecture
- CU2: Data Simulations
- CU3: Core Processing
- CU4: Object Processing
- CU5: Photometric Processing
- CU6: Spectroscopic Processing
- CU7: Variability Processing
- CU8: Astrophysical Parameters
- CU9: Catalogue Access

Payload advisory group

Scientific exploitation

Data Analysis Coordination Committee

CU8: Astrophysical Parameters

- stellar parameters
  - T_{eff}, log g, [Fe/H], A_V, [α/Fe]
  - include parallax to derive luminosity; evolutionary model to derive age
- Gaia observes entire sky to V=20
  - no prior information; very wide parameter space
  - need an initial classification (esp. QSO identification)
- many complications
  - optimal combination of photometry, spectroscopy and astrometry
  - differing spatial resolutions and flux limits; source variability
  - parameter degeneracy; problem of “weak” parameters
- solutions
  - supervised machine learning methods (extensive development required!)

Summary

Formation and evolution of the Galaxy
Stellar structure and formation
Exoplanets
Solar system
Fundamental physics

All sky survey to V=20 (10^9 stars)
5D phase space (6D to V~17)

Physical stellar properties
(multiband photometry)

Accuracy = 15 μas @ V=15:
⇒ distances to <1% for 20 million stars
⇒ transverse velocities to 1km/s at 20 kpc

Launch 2011; 5 year mission
http://www.rssd.esa.int/Gaia