Gaia: Satellite and data processing status

William O'Mullane

Gaia Science Operations Centre
European Space Astronomy Centre
Madrid, Spain

April 17th 2015 CERN

special thanks to Anthony Brown for many of these slides

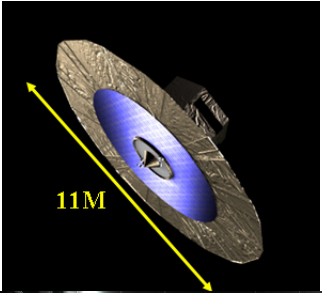
A little background and context ..

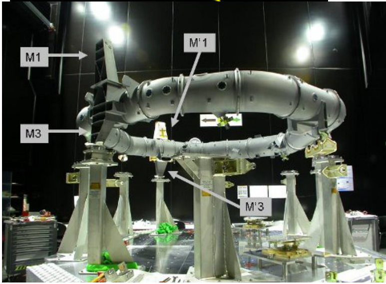
- Space astrometry with Hipparcos 1989 to 1993 (Perryman, 2009, 2010)
- Thoughts on Hipparcos II 1991
- Gaia proposed to ESA October 1993 (Lindegren & et al, 1993)
- Concept and technology study approved 1996
- Science Programme Committee (SPC) Oct 2000 selected Gaia as Corner Stone 6 (BepiC as 5)
- April 2005 Data Analysis Consortium Committee (DACC) for set up
- August 2005 Science Operations Centre (SOC)
- Phase B2 (development) Feb 2006
- May 2007 SPC accept Data Processing & Analysis Consortium
- Launch 19 December 2013 - nominal ops 25 July 2014.

Personal: MSc Computing 1993, Spacecraft control 1993-1997, Hipparcos 1997(Catalogue), Gaia 1998 (White Book), Gaia data processing 1999-2007, Sloan Digitized Sky Survey 2003-2005, Gaia Science Operations 2005-2015, PhD Physics/Astronomy 2012

Satellite overview

- Mission:
  - ESA Corner Stone 6
    - ESA provided the hardware and launch
      Mass: 2120 kg (payload 743 kg)
      Power: 1631 W (payload 815 W)
  - Launched December 19 2013.
  - Stereoscopic Census of Galaxy over 5 years
    - Possible extension of 1 year - have fuel for at least that
  - μarcsec Astrometry $G < 20$ (10^9 sources)
  - Radial Velocities $G < 16$
  - Photometry millimag $G < 20$
- Final catalogue ≈ 2022





Some novel points on Hardware

- Torus and mirrors (most of the body) made with Silicon Carbide.
- Clock Distribution Unit - ultra stable Rubidium Atomic Clock
- passive cooling radiators (operating temperature 110K)
- 7 $\times$ Video processing units - SCS750 PowerPC board, Maxwell Technologies (Loosing one looses one row of CCDs)
    - On board software
- Phased Array Antenna (X band) - no moving parts.
- Cold gas micro propulsion system (original baseline FEEPs failed) - redundant A and B systems
- Attitude and Control System has input from Star Mappers for spin rate

Survey not observatory

- Two fields of view for wide angle astrometry
- Cruised to L2, keeping 45deg sun aspect angle in Lissajous orbit
- Following scan law for 5 years
- Nominally not much interaction with satellite

Average 70 visits for each source.

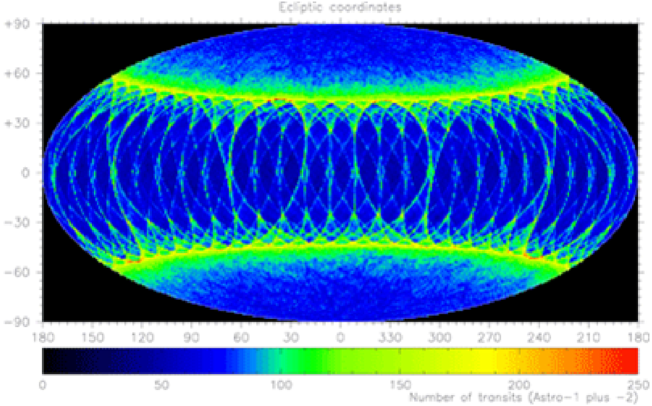
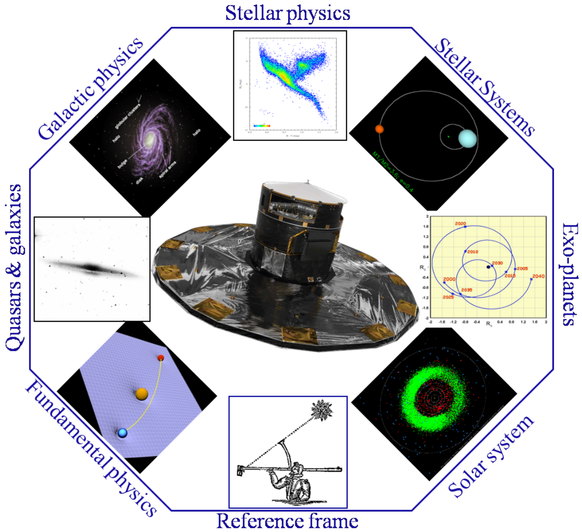
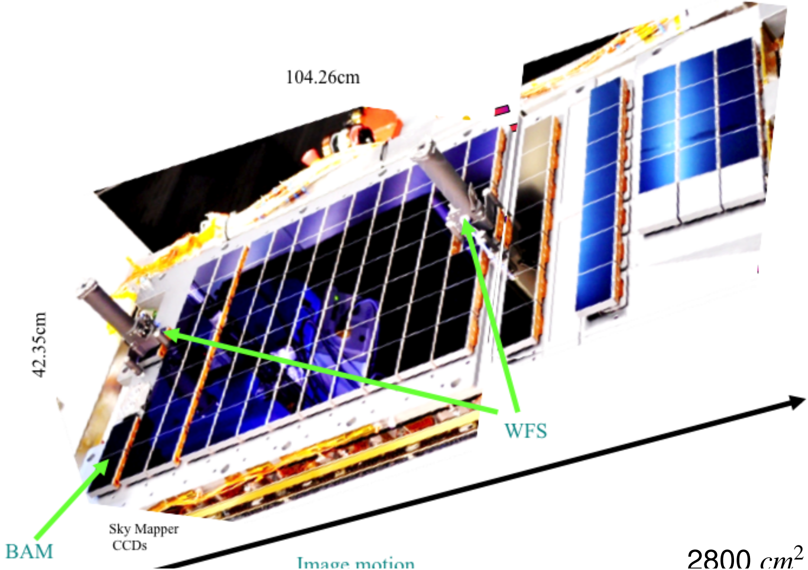


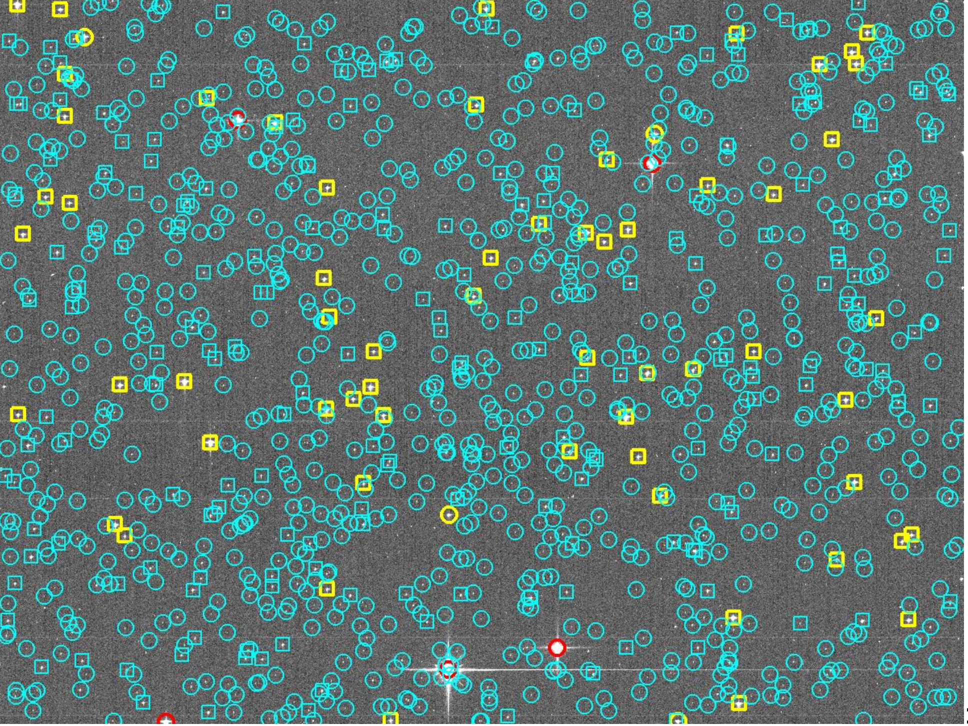
Image: de Bruijne

Science topics



106 CCDs, 938 million pixels





Data processing - challenging

- Astrometric centroid of the CCD image to be determined to an accuracy of 1% of the pixel size!
  - There will be 10^{12} images ≈ 100TB downlink need to handle ≈ 1PB
  - At 1 millisecond each that is ≈ 30years
  - Processing estimate remains $\approx 10^{20}$ FLOP
- Reconstructed attitude is required to order 10 μarcsec
  - Path of light through instrument needed to nanometre level
  - System must be extremely stable
  - Must consider relativistic light bending from solar system objects.
- Attitude and Geometric calibration can only by done using Gaia's own observational data. (AGIS)
- Testing and verification is very difficult - still running Operational Rehearsals

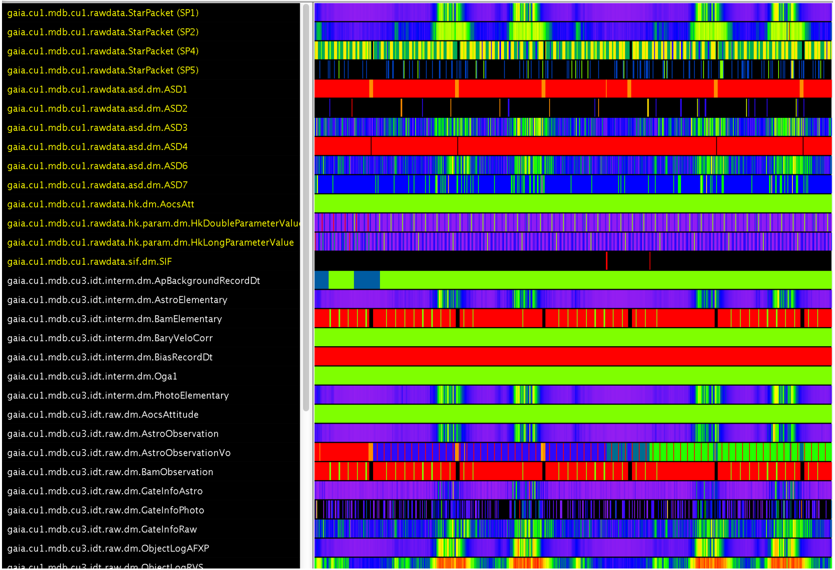
Downlink

- Using Cebreros (35M)
  - $3 - 8Mb/s$ downlink
    - depends on encoding
    - which depends on weather !
- $\approx 30GB/day- > \approx 100TB$ total
- occasionally New Norcia / Malargue
  - during Galactic plane scans
  - data accumulated onboard
  - downlinked later
- Exact hours booked by Mission Operation Centre (MOC) using predicted onboard memory occupancy from SOC

- Mission Operation Centre also provide station delays (for time correlation)

Data collection stats

Example TM time line with Galactic plane crossings (OBMT rev 516–517, courtesy J. Hernández)

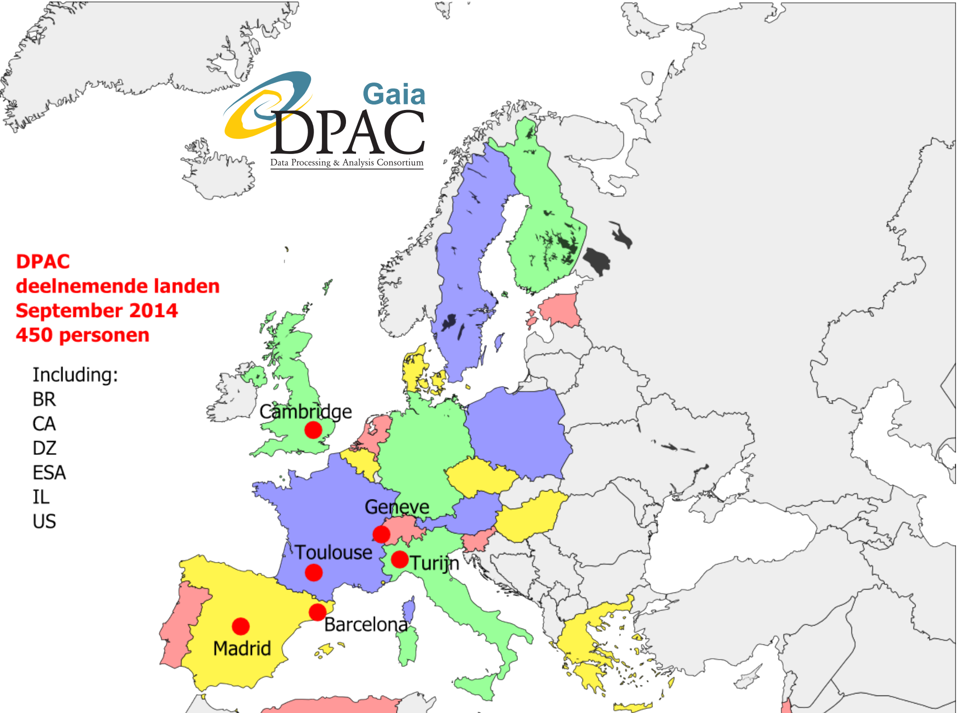


Data Processing and Analysis Consortium

- Formed to answer the Announcement of Opportunity (AO) for Gaia data processing (2006)
- Involves large number of European institutes and observatories (> 400 people, > 20 institutes)
- The science community must fund the majority of the Gaia processing
- Lead by Executive (leaders of Coordination Units) and Project office for management and planning.
- A steering committee formed of funding agency representatives (and ESA) sits on top - this governs the multi lateral agreement on funding.

DPAC
deelnemende landen
September 2014
450 personen

Including:
BR
CA
DZ
ESA
IL
US



Coordination Units & DPCs

|

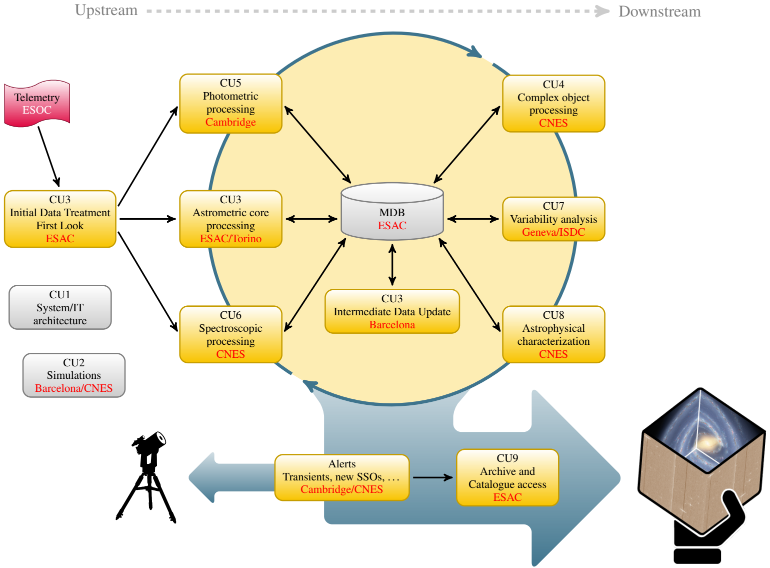
- CU1: System Architecture
- CU2: Data Simulations
- CU3: Core Processing
- CU4: Object Processing
- CU5: Photometric Processing
- CU6: Spectroscopic Processing
- CU7: Variability Processing
- CU8: Astrophysical Parameters
- CU9: Catalogue Access

ESA Contribution

Data Processing Centres underpin and support CUs. They integrate and operate the processing system(s).

- ESAC (CU1,3) Madrid
- BPC (CU2,3) Barcelona
- CNES (CU4,6,8) Toulouse
- ISDC (CU7) Geneva
- IoA (CU5) Cambridge
- OATO (CU3) Torino

Simplified processing overview



Astrometric Solution

Just one part of the processing !
From the Hipparcos catalogue (ESA, 1997, Volume 3 Chapter 23).

Minimisation problem for astrometry

$$\min_{\mathbf{a},\mathbf{n}} \|\mathbf{g}^{\mathbf{obs}} - \mathbf{g}^{\mathbf{calc}}(\mathbf{a},\mathbf{n})\|_M \quad (1)$$

- $\mathbf{a}$ is the vector of unknowns describing a star's barycentric motion represented by the measurement vector $\mathbf{g_k} = (G_k, H_k)'$ and associated statistics.
- $\mathbf{g}^{\mathbf{obs}}$ represents the vector of all measurements
- $\mathbf{g}^{\mathbf{calc}}$ represents the vector of detector coordinates calculated from the astrometric parameters.
- $\mathbf{n}$ is a vector of nuisance parameters - required for realistic modelling (e.g. attitude, instrument calibration)
- M metric defined by the statistics of the data, (error weighting)

The complete new formulation for Gaia is in (Lindegren et al., 2012).

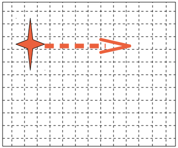
Put more simply the data reduction must:
find the astrometric parameters (catalogue) best predicting the focal plane observations of the sources. (O'Mullane et al., 2011)

Gaia Focal Plane

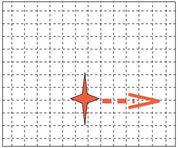
Catalogue Data

ID	α	δ	ϖ	μ_α	μ_δ	μ_r
...						
0000101	1.4	3.1	0.1	0.02	0.02	-
....						
1001000	2.7	1.2	0.2	0.05	0.01	0.01

$\Longrightarrow$



t_{obs} 1



t_{obs} n

Astrometric Global Iterative Solution

AGIS solves Equation (1) block iteratively using least squares fitting for each part.
The problem is broken into four blocks:

- S : The source update - which assumes some values for A,G,C
- A : The attitude update - which assumes some values for S,G,C
- G : The global update - which assumes some values for S,A,C
- C : The calibration update - which assumes some values S,A,G

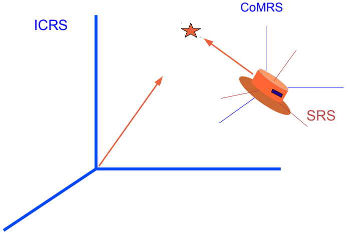
Each block must be solved (Cholesky decomposition)
The completion of all blocks is termed an outer iteration.

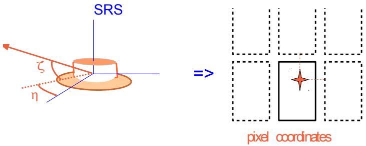
- Theoretically the order of the blocks is unimportant.
- In fact we do A,G,C in parallel.
- Conjugate Gradient Solver used to drive the outer iterations.
- Hipparcos solution was great circle based - not global.

Look at one block: Source modelling

The mapping or modelling of the observables **g** is done by three successive transformations:

1. from astrometric parameters to the celestial directions of a star at the instant of observation, using an astrometric model
2. from celestial to instrument frame directions using an attitude model
3. and finally from instrument directions to detector coordinates using an instrument model





Apparent sky position

($\alpha\ \delta\ \varpi\ \mu_\alpha\ \mu_\delta\ \mu_r$) - catalogue data - describe the positions and velocity of a source in ICRS (GAIA-LL-055)

- we do not make observations in ICRS rather from Gaia in CoMRS
- we need Gaia ephemeris and attitude
- there are perspective and parallactic effects to account for from L2
- light bending (relativistic) and stellar aberration also

Apparent observed direction

$$\mathbf{u_{ik}} = u(\mathbf{a_i}|t_k, e) \tag{2}$$

Source Update

We fit the model to the observations:

Least squares for source update

$$\mathbf{A}\mathbf{x} \sim \mathbf{b} \pm \sigma \tag{3}$$

$$\text{where } \mathbf{b}_i = \mathbf{y}_i - f_i(\mathbf{a}, \mathbf{q}) \tag{4}$$

Here $\mathbf{y}_i$ are the observed field angles f_i is a function to calculates field angles from the the current model.
In java (SourceUpdateCalculatorWrapper):

```
// get calculated angles + derivatives ...
ExtendedFieldAngles ecfa = angleCalc.getCalculatedEtaZeta(ae, origSrc, UpdateBlock.Source.getId());

// ... from those, get just calculated angles
double[][] calcEtaZeta = ecfa.getEtaZeta();

// ... and the observed ones from the angle calculator
double[][] obsEtaZeta = angleCalc.getObservedEtaZeta(ae);

// compute residuals [rad] and attach those to the Elementary
double[][] etaZetaRes = AgisUtils.subtractArrays(obsEtaZeta, calcEtaZeta);
```

Yes it is ALL in Java.

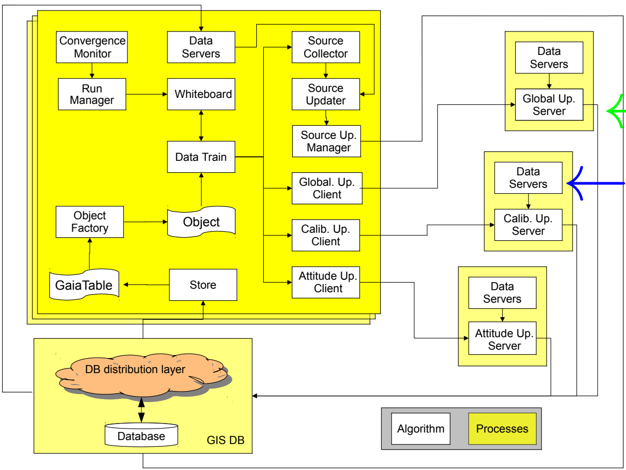
AGIS implementation in Java

(O'Mullane et al., 2011)

- Yes all in Java (was Sun now owned by Oracle)
- On April 14 - 218276 lines $\rightarrow$ 140305 code + 77971 comments
- Some code moved to GaiaTools over the years.
- Started 2005 with O'Mullane and Lammers
- Algorithms provided by Lindegren
  - usually as tech notes e.g. Lindegren (LL-072), Lindegren (LL-065), Bombrun et al. (LL-096)..
  - and sometimes Java code
- Guiding principle has been to take a minimalist approach (Datatrain (O'Mullane et al., 2006))
  - access data as little as possible
  - distribute: take advantage of multi core distributed systems
  - try to cut down on single point bottlenecks
  - try to keep the algorithm isolated from the framework

AGIS Logical Model

Many DataTrains may run



Some parts must run as a single process. These are update servers.

Data servers load frequently accessed data once per machine e.g. current attitude, ephemeris etc.

Running in ESAC 6-20 nodes (64GB 20 cores) - previously scaled with up to 50 nodes on Amazon

Flawless lift off 19/12/2013 06:12am

Photo: R. Gill

- On Day 2 the crucial manoeuvre to L2 was also flawless.
- Next heating and outgassing.
- Finally on Jan 3 the VPUs were switched on.
- Then the long commissioning started (until mid July 2014).

First problem was seen on day one:
Sun shield is *very* flat - Gaia magnitude is $\approx$20.5 (expected 19) at L2.
Need larger telescopes for optical tracking.
Delta DOR (Differential One way Request) will be used when needed.

First image NO SPIN, NOT FOCUSED

First Spinning images Jan 8th

Still not focused and spinrate not corrected - but no more streaks.
Clearly see the lack of focus in the zoom (right).
Really great for us to see the CCDs working !

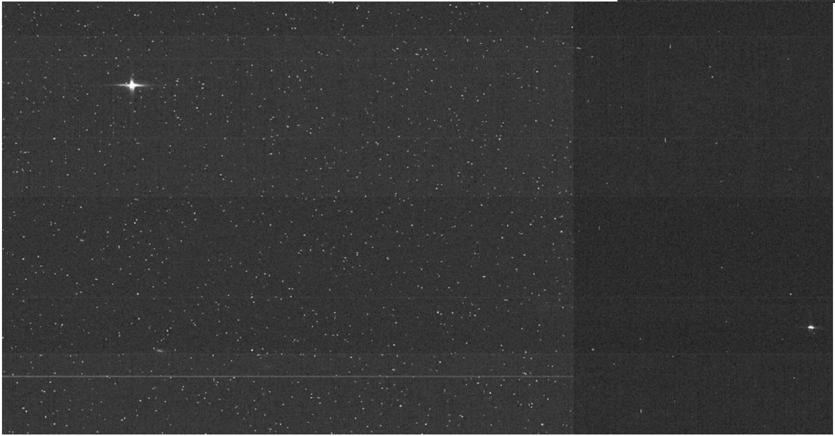
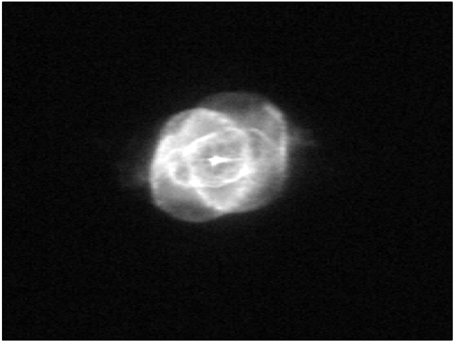


Image Gaia SOC

Searching for Focus

Focus and spinrate are intertwined. So it was an iterative process for some weeks.

left spinrate close to TDI read out rate - right image blurry while spinrate incorrect.



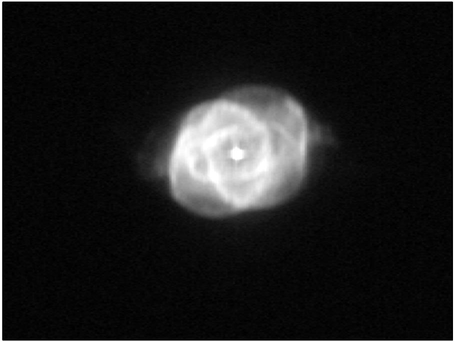
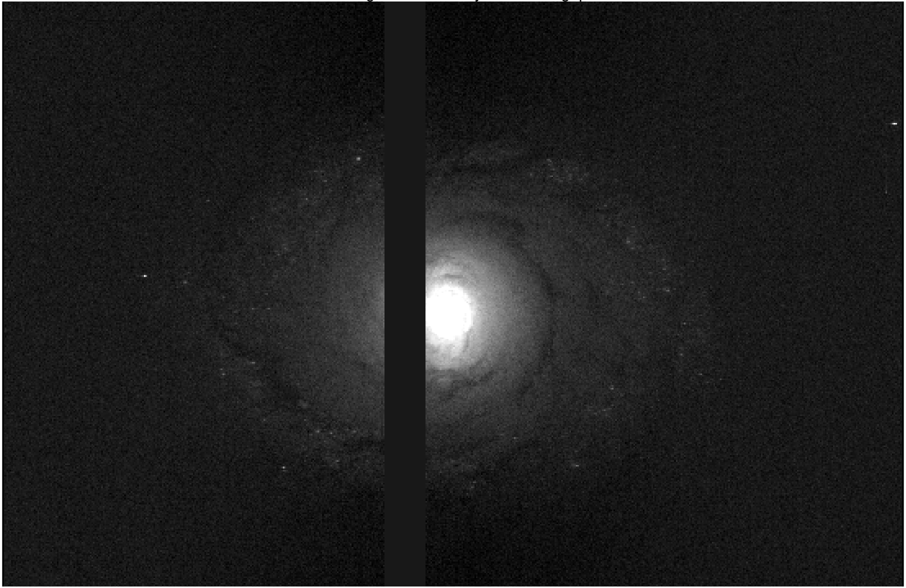


Image Gaia SOC

Don’t mind the gap !

Reminder not what Gaia is designed for - here you see the gap between CCDs on M94.



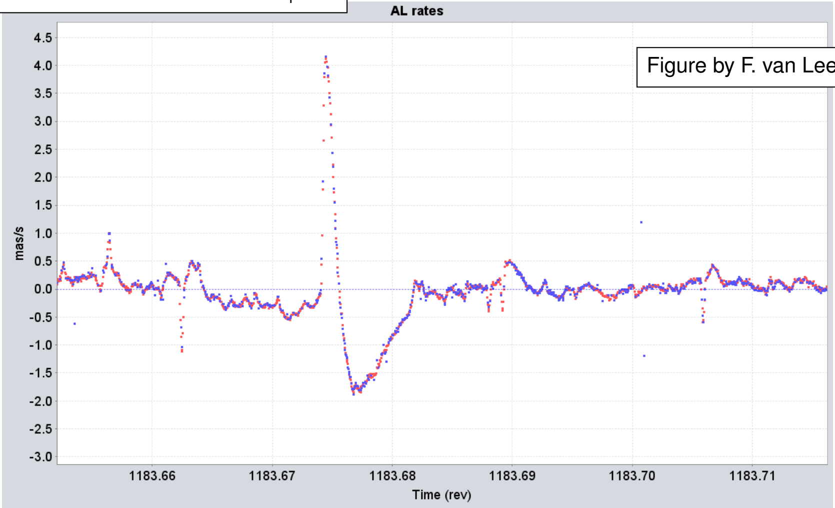
Micro and Chemical Propulsion System

- Malfunctioning mass-flow sensor in one of the thrusters (#3A) of the micro propulsion system
  - Erroneous feedback from this thruster to the Attitude and Orbit Control System, leading to increased gas consumption, and possibly degraded attitude control
- MPS anomaly root cause still under investigation
- AOCS now working on B-branch
  - AOCS works very well
  - Slight cold gas over-consumption due to thruster bias drifts
  - Bias being monitored and calibrated
  - Studies ongoing to optimise MPS usage

- Chemical thruster #3B is electrically dead
- Using the redundant unit now
  - lost redundancy for this CPS thruster
  - New CPS mode implemented which makes Gaia robust against thruster #3A failure (called survival mode)

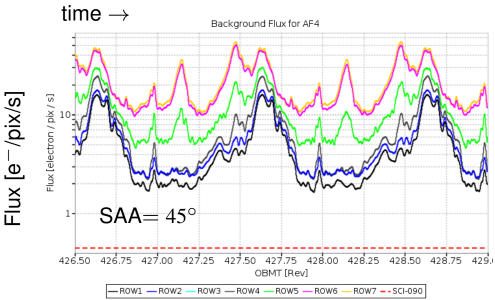
Impacts on Gaia at L2?

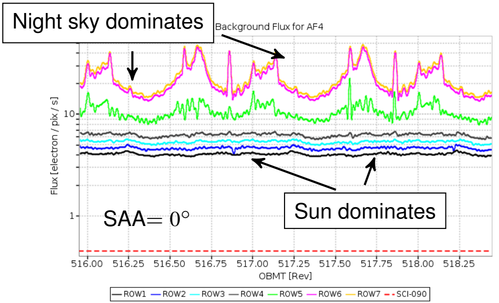
Factor ≈ 10 more of these events than expected



Along Scan deviations from mean spin rate (AOCS works really well). Probably mechanical

Stray light

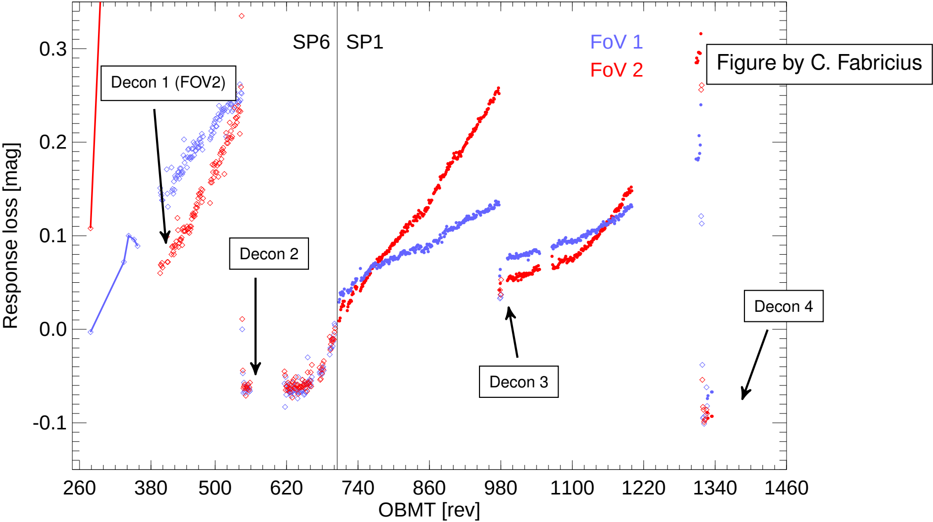




- Strong stray light levels all over focal plane
- In the peaks orders of magnitude above requirements
- Sun light diffracted and/or scattered at sun-shield edges
  - Varies over 6 hour spin period
- Light from night sky sources along unforeseen paths
  - Varies according to sky scanned

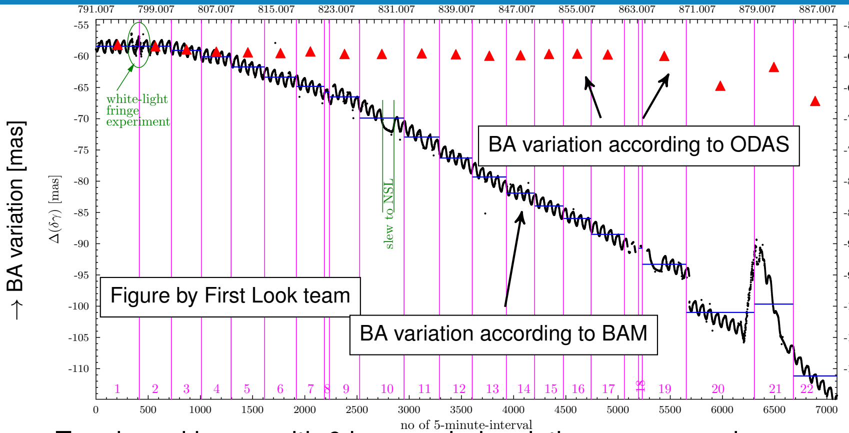
Figures by M. Davidson

Throughput loss



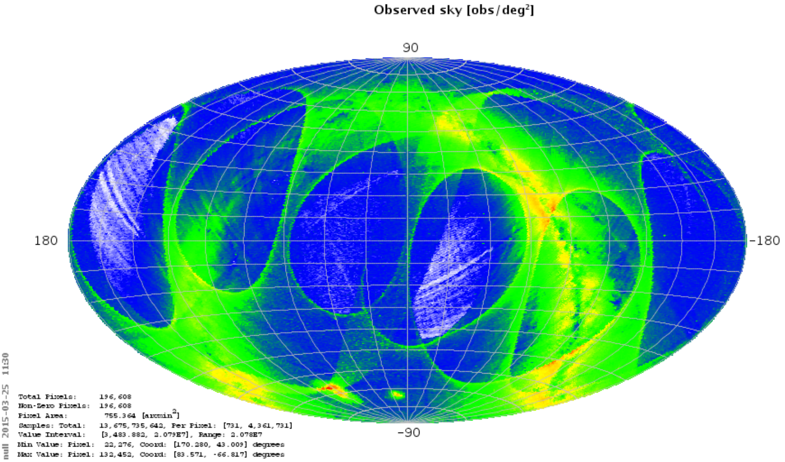
Monitoring of response by comparison to Tycho-2 photometry

Basic angle variations



- Trends and jumps with 6 hour period variation superposed
  - 6 hour variations can cause systematic errors in astrometry
  - Basic Angle Monitor (BAM) in place to measure the variations so they can be accounted for in processing
  - Astrometric solutions indicate that BAM measures real variations
  - Analysis shows BAM measurements precise to $\sim 10\ \mu$as level

Nominal mission sky coverage



Need at least two full scans to get Gaia astrometry.

Early astrometric performance assessment

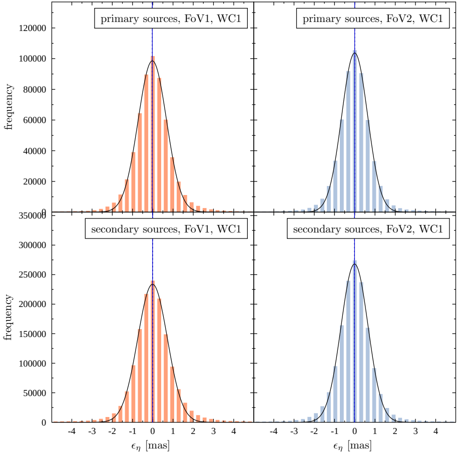
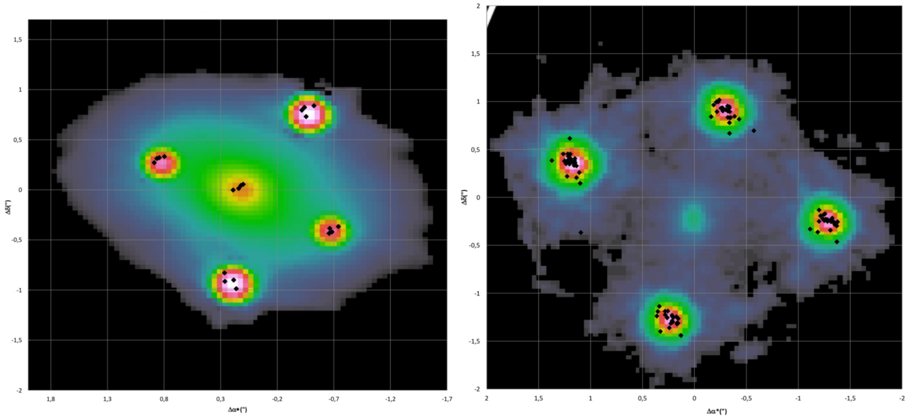


Figure courtesy First Look team

- Residuals from one-day astrometric solution at $G = 15$ already better than 1 mas
- Caveats at this stage
  - unstable instrument
  - poor PSF calibrations
  - imperfect stray light corrections
  - throughput loss
- For clean telescopes throughput is as expected
- Read noise within requirements
- Corrections for bias non-uniformity under control
- High accuracy timing works (detailed verification pending)

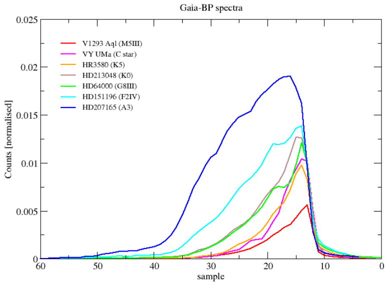
International year of light

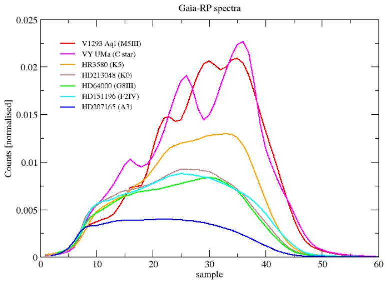


http://www.cosmos.esa.int/web/gaia/iow_20150409

Einstein Cross (left) and HE0435-1223 (right)
Gaia astrometric positions placed over HST images.
Gaia onboard detection works well
4 lenses detected in both cases within the $\approx 2''^2$ area.

Early photometric performance assessment





- Spectra appear as expected: classification and parametrization possible
- For clean telescopes throughput is as expected
- Read noise within requirements
- Corrections for bias non-uniformity under control

Figure courtesy C. Jordi & J.-M. Carrasco

Early spectroscopic performance assessment

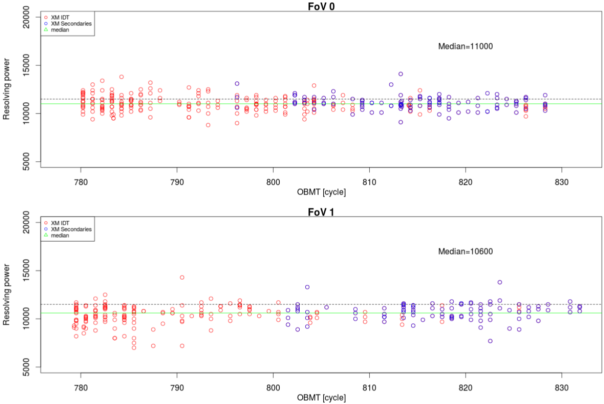
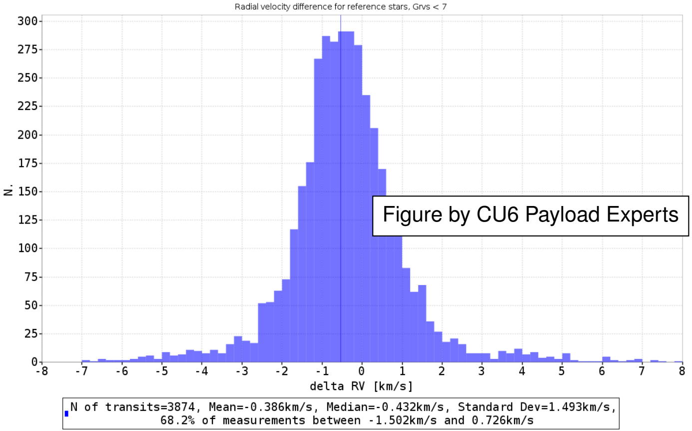


Figure courtesy D. Katz & O. Marchal

- Resolving power nominal
- Read noise within requirements
- Corrections for bias non-uniformity under control
- Wavelength zero point stability pending

Preliminary RVS performance at bright end



- Differences between measured and expected v_{rad} for bright ($G_{\mathrm{RVS}} < 7$) ground based radial velocity standards
- 68% of measurements are within 1.1 km s^{-1} from the median!

Gaia performance predictions at IOCR

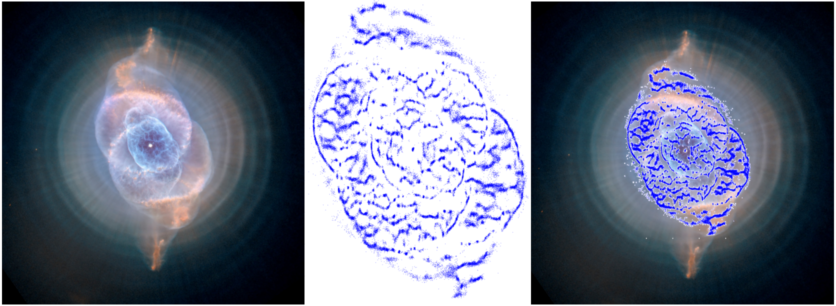
Performance predictions for G2V star			
V magnitude	Astrometry (parallax)	Photometry (BP/RP integrated)	Spectroscopy (radial velocity)
3 to 12	5–14 μas	4 mmag	
3 to 12.3			1 km s^{-1}
15	24 μas	4 mmag	
15.2			15 km s^{-1}
20	540 μas	60 (RP) – 80 (BP) mmag	

Up-to-date information always at: `http://www.cosmos.esa.int/web/gaia/science-performance`

Conclusion and Issues

- Gaia hardware is commissioned and the mission is on !
- There is more straylight than expected
  - impacts astrometry on the faint end - more time will help a littl
  - we loose spectra also on the faint end - we will only do high re spectra
- The basic angle varies more than expected - the BAM is mea this.
  - could impact parallaxes - complicates modelling
- We see some water ice contamination
  - Heating removes this for a while - this story continues ..
- Gaia flying well and commanding from MOC is very good.
- DPAC has processed all the data so far coping with the actua satellite and its issues very well.
- Like all science missions Gaia is a mixture of innovative hard scientific algorithms, software and people.
- We are working hard to get the first catalogue out in 2016.

The END



Gaia observations of Catseye Nebula over HST image.

Questions ??

- The Gaia ESA home page `http://www.cosmos.esa.int/web/gaia`
- You may send any question to `mailto:gaia-helpdesk@cosmos.esa.int`

Acronyms I

The following table has been generated from the on-line Gaia acronym list:

Acronym	Description
AF	Astrometric Field (in Astro)
AGIS	Astrometric Global Iterative Solution
AO	Announcement of Opportunity
AOCS	Attitude and Orbit Control Sub-system
BA	Basic Angle
BAM	Basic-Angle Monitoring (Device)
BP	Blue Photometer
BPC	Barcelona Processing Centre
CCD	Charge-Coupled Device
CERN	Centre Europénne pour la Recherche Nucléaire
CNES	Centre National d'Etudes Spatiales (France)
CPS	Chemical Propulsion Sub-system (thrusters used in SAM, IGM, OCM)
CoMRS	Centre of Mass Reference System
DACC	Data Analysis Coordination Committee (obsolete)
DOR	Differential One-way Range
DPAC	Data Processing and Analysis Consortium
DPC	Data Processing Centre
ESA	European Space Agency
ESAC	European Space Astronomy Centre (VilSpa)
ESO	European Southern Observatory
FEEP	Field-Emission (or Field-Effect) Electric Propulsion

Acronyms II

FL	First Look
FLOP	FLoating-point OPeration
FLS	First-Look Scientist
GB	GigaByte
GBOT	Ground-Based Optical Tracking
HST	Hipparcos Science Team
ICRS	International Celestial Reference System
IOCR	In-Orbit Commissioning Review
ISDC	INTEGRAL Science Data Centre
IoA	Institute of Astronomy (Cambridge; also denoted IOA)
MOC	Mission Operations Centre
MPS	Micro-Propulsion Sub-system
MSc	Multiple-Star Classifier
OATO	Osservatorio Astronomico di Torino
OBMT	On-Board Mission Timeline
ODAS	One-Day Astrometric Solution
PSF	Point Spread Function
PhD	Doctorate in Philosophy
RP	Red Photometer
RVS	Radial Velocity Spectrometer
SAG	Science Advisory Group (obsolete; superseded by GST)
SGC	South Galactic Cap
SOC	System On a Chip
SPC	Science Programme Committee (ESA)
TB	TeraByte

Acronyms III

TDI	Time-Delayed Integration (CCD)
TM	Telemetry (Packet)
TOC	Table of Contents
VLBI	Very Long Baseline Interferometry
VPU	Video Processing Unit
XP	Shortcut for BP and/or RP (generic name for Blue or Red Photometer)

References I

[LL-096], Bombrun, A., Lindegren, L., Hobbs, D., et al., 2011, *A conjugate gradient algorithm for the astrometric core solution of Gaia*,
GAIA-C3-CP-LU-LL-096,
URL http://www.rssd.esa.int/cs/livelink/open/3093833

ESA, 1997, *The Hipparcos and Tycho Catalogues*, ESA,
ESA SP-1200

[GAIA-LL-055], Lindegren, L., 2004, *A proposed new algorithm for source updating*,
GAIA-LL-055,
URL http://www.rssd.esa.int/cs/livelink/open/390988

[LL-065], Lindegren, L., 2006, *Functional description of the Astrometric Global Iterative Solution (AGIS)*,
GAIA-C3-SP-LU-LL-065,
URL http://www.rssd.esa.int/cs/livelink/open/892105

[LL-072], Lindegren, L., 2007, *Mathematical framework for the AGIS system orientation*,
GAIA-C3-TN-LU-LL-072,
URL http://www.rssd.esa.int/cs/livelink/open/2766637

Lindegren, L., et al, M.P., 1993, *GAIA : Global Astrometric Interferometer for Astrophysics*, Tech. rep., Lund,
URL http://www.astro.lu.se/%7Elennart/Astrometry/gaia_proposal.PDF

Lindegren, L., Lammers, U., Hobbs, D., et al., 2012, A&A, 538, A78, ADS Link

O'Mullane, W., Lammers, U., Bailer-Jones, C., et al., 2006, ArXiv Astrophysics e-prints, ADS Link

O'Mullane, W., Hernández, J., Hoar, J., Lammers, U., 2009, In: D. A. Bohlender, D. Durand, & P. Dowler (ed.) Astronomical Data Analysis Software and Systems XVIII, vol. 411 of Astronomical Society of the Pacific Conference Series, 470, ADS Link

O'Mullane, W., Lammers, U., Lindegren, L., Hernandez, J., Hobbs, D., 2011, Experimental Astronomy, 31, 215, ADS Link

Perryman, A., 2010, *The Making of History's Greatest Star Map*, Astronomers' universe, Springer,
URL http://books.google.es/books?id=P-5pZ8GNuPIC

Perryman, M., 2009, *Astronomical Applications of Astrometry: Ten Years of Exploitation of the Hipparcos Satellite Data*, Cambridge University Press