Gaia

Stereoscopic Census of our Galaxy

http://www.cosmos.esa.int/web/gaia  http://gaia.ac.uk

one billion pixels for one billion stars
one percent of the visible Milky Way

Gerry Gilmore FRS, UK Gaia PI, on behalf of DPAC

Gaia-BP spectra

V1293 Aql (MSIII)

VY UMa (C star)

HR3580 (K5)

HD213048 (K0)

HD64000 (GBIII)

HD151196 (F2IV)

HD207165 (A3)

Gaia-RVS spectrum of HIP 86564

Fe  Fe Ti  Fe  Fe
astrophysics cannot experiment – merely observe and deduce: so how do we analyse the Milky Way?

- 2Dimensions: measure brightness “star counts”
- 3Dimensions: measure distances “parallax”
- 5Dimensions: watch the stars move “proper motion”
- 6Dimensions: measure doppler shift “radial velocity”
- Spectrum also measures chemical elements

- The future: Gaia: taking the census of the Milky Way
How does one study the Milky Way?

Scientific discovery involves knowing an object exists, how it moves, its composition.

Stellar orbits, star formation history, origin of the elements, Galaxy assembly, dark matter, cosmological initial conditions, fundamental physics, solar system(s), ...
There is an elephant in the astrophysics room:
all distances depend on very few, inaccurate, stellar parallaxes
Good distances are known for only ~700 stars

The cosmological distance scale is the weak link in modern astrophysics

I gave my friend an elephant
He said: “thanks”
I said: “don’t mention it”

Thanks to Ian for the elephant
Gaia: the goddess who created the universe and knowledge

**Gaia is transformational** – the first 3-D galaxy
precision distances and motions for 1 billion stars
• Astrometry, photometry, spectroscopy, spectrophotometry,
Teff, log g, Av, [Fe/H], binarity, planets, periods for variables,...

Launch: 12/2013
Work started: ~1993
Project approved: 2000
Operations start: 7/2014
5-7.5 years data
Project end: 2023+
Total cost: 960M€

The heart of Gaia is a large camera array, 1 giga-pixel, sending us a video of the sky for 5-8 years.

The imaging data is being processed in Cambridge.
6 billion transits processed so far

2 telescopes, 1.45 x 0.5 m primary, monolithic SiC optical bench, 0.06arcsec pixels

Data flow: 50Gb/day for 5-8 years; total processed data and archives ➔ 1PByte
Computational challenge: 1.5 x 10²¹ FLOP – and highly sophisticated algorithms
What will Gaia see as stars move?

Trend: stellar orbit ➔ Galactic dynamics, dark matter, assembly history, ...

Cycloid: parallax = 1/distance ➔ Galactic structure, star formation history

Loops: high frequency motion ➔ massive planetary systems

These are real Hipparcos observations

Gaia accuracy 10 to 100 times better

47 UMa

Δδ

Δα cos δ [mas]
Real stellar distances tell us how bright stars really are. This provides the key to how stars evolve.

The Hertzsprung-Russell diagram
The present communication contains the results of the first series of observations for stellar parallax made at the Cambridge Observatory. The plans for the work were prepared by Mr. A. R. Hinks, Chief Assistant at the Observatory, and a Research Assistant of the Carnegie Institution for the purpose of this investigation. Mr. Hinks and the writer are also jointly responsible for the photographic observations in nearly equal shares. The former contributes 49%. For the measurement and reduction of the plates, which was begun at Cambridge and completed at Princeton, and for the results and conclusions here detailed, the writer is alone responsible.

The determinations of photometric magnitude and spectrum were made at the Harvard College Observatory, the latter by Mrs. Fleming, and the former by Prof. E. C. Pickering, to whom the writer's most hearty thanks are due for this extremely important addition to the value of the work.

I. METHODS OF OBSERVATION AND REDUCTION.

A detailed account of the methods employed in the present work, with the reasons for their adoption, is given in the paper by Mr. Hinks and the writer, already referred to.

The photographs were taken with the Sheepshanks Equatorial of the Cambridge Observatory—a coude telescope of the polar siderostat type, of 12 inches effective aperture and 19.3 feet focal length. The stability of this instrument, and the performance of its driving clock and other ancillary mechanisms, were made to guide by hand.

The plates, coated on plate-glass, cover a field a little less than 11° square. Four exposures were usually made on each, separated by ½ mm., in declination. With the standard exposure of five minutes the differential image diminished the photographic plate until the gelatine plate had gone through it by a glass plate, placed on the gelatine plate. This worked very well until the gelatine plate was heated to the glass plate. The fourth magnitude was about 0.05, and the number of the exposures at two epochs for two positions. Data could be given later.

It should be an advantage to have a photograph from this double exposure. The photographs were taken with the Sheepshanks Equatorial of the Cambridge Observatory—a coude telescope of the polar siderostat type, of 12 inches effective aperture and 19.3 feet focal length. The stability of this instrument, and the performance of its driving clock and other ancillary mechanisms, were made to guide by hand.

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Hi Gerry, Simon

Just thought you might find it amusing that Gaia was listed a Near-Earth asteroid for 14 hours today until we realised what it was :-) 

It was found 4 days ago by Pan-STARRS and it had a short life as confirmed asteroid 2015 HP116. (For some reason the automatic satellite identification routines at the Minor Planet Centre screwed up).

All the best
Alan
How does Gaia work?: Sky Scanning Principle

Observe sky with two telescopes

Precision: 50 pico-rad, human hair at 1000km, 2 cm on the moon...
Gaia is a simple 2-telescope optical bench

Gaia Payload Module fully assembled (except for external insulation MLI) ready to start the final environmental tests campaign.
Absolute astrometry

One field gives only relative measures → model dependancy
Two fields break the degeneracy → allows absolute measurements.
Combining data at the limits of accuracy is not trivial!

Single field astrometry

Measurable quantity: $f(t) \cdot (\pi_2 - \pi_1)$ → $\pi_2 - \pi_1$

Two field astrometry

Measurable quantity: $f_2(t) \cdot \pi_2 - f_1(t) \cdot \pi_1$ → $\pi_2$ and $\pi_1$
Observation principles

Why measurements are mainly 1 dimensional (along-scan):

- Basic angle = 106.5 deg

Two stars observed simultaneously in different FOV:

- Along-scan projected angle between stars is independent of instrument orientation to first order (solid versus dashed lines).

→ two-telescope scanning mission is optimal. Since across-scan data is much less important, can save mass and use rectangular mirrors
SINGLE GAIA OBSERVATION = TRANSIT

Camera:
0.75 deg²
pixel: 10x30 μm
(59x177 mas)

0.42 m

0.93 m

windows observed:

→ ~4.4 sec

→ ~45 sec

star < 20 mag
detected!
Place window.

Animation by
Bryce Hall,
Geneva

e2v
What does micro-arcsecond mean?

- Precision: 50pico-rad, human hair at 1000km, coin on the moon
- Astrometry needs more than signal to noise and image processing
- One must have a physical model and understanding of every contribution to the error budget at an appropriate level
- Einstein light bending at the Sun’s edge is 1,750,000 microarcsec
- One mu-as is the limit to which we have tested GR...
- For Gaia the spin rate is controlled to 15 ppm
- The spacecraft distance is known to a few metre (at 1.5 Million km)
- The spacecraft speed is known to a few mm/s
- On-board interferometer measures mirror locations to picometre level every few seconds – a helium atom is 30picometre
- clocks, pixel substructure -- and very much more

- 400 people are busy with the data processing and analysis
Gaia science data flow: 5,000 stars/second on average
Cambridge Data Processing Centre

• The Cambridge team is responsible for the processing of the photometric data, about 50 GB per day for 5+ years.

• Both software and hardware! 2 proud parents
The astrometric data reduction

- $10^{13}$ individual position measurements
- $10^{10}$ unknowns – based on physical models
- all connected – must be determined simultaneously
- a vast modelling and parameter adjustment problem
- Iterative, self-calibrating, needs GR metric
- 5000 million star unknowns (for simple stars)
- 150 million attitude unknowns
- 50+ million calibration unknowns
- a few dozen “global” unknowns
- DPAC involves 400 people and 6 processing centres

Eg, photometric ubercalibration:

- In total we use 200 million measurements with 6 million parameters and solve the system of linear equations to produce a calibration.
- The fit is done in 4 iterations where we reject measurements outlying by more than 1, 0.5, 0.2 magnitudes from the model fitted in the previous iteration.
- We achieve a precision of 0.02-0.025 magnitudes per ccd (i.e. <10 mmag for a transit)

Another order of magnitude to improve, but we are on the way
CCDs, electronics, clocks, communications, spacecraft control, ... functioning nominally

- Micro propulsion system working well
- Attitude and Orbit Control System working well
- Phased Array Antenna operating with healthy link budget
- Clock working at required accuracy
- 106 CCDs, electronics, data acquisition and storage all functioning nominally

Complete sky survey from \(0 < G < 20\)

Mission extension from 5 years to 7.5 years under analysis
Unwanted surprises

- Stray light both from astronomical sources and the Sun
  - Sun stray light paths not yet identified
  - Impacts faint sources especially in spectroscopy
- Transmission loss due to continuing contamination of mirrors by frost
  - Water source not yet exhausted and loss of the best transmission
- Degradation of focus
- Basic Angle variation larger than expected
  - However, Basic Angle Monitor providing very precise measurements of the changes
Scattered Light (RVS): mean level 30x expected adds noise to faint sources – astrometry recovered by mission extension

6 hour period = Gaia’s spin period

RVS is delivering 60million spectra, R=11,000, complete to V<15.3
Gaia is providing a survey of NEO-threat asteroids with orbits interior to Earth and improved orbits for many MB asteroids, with many masses, radii,...
Planetary systems – Gaia will find some transiting systems, but the real value is definition of volume-complete stellar parent samples, plus direct astrometric discovery, and mass determinations, of nearby non-eclipsing jupiters. These will be ideal for follow-up direct coronographic imaging.

RV Jupiters are easy astrometric detections

Fig. 1.— Astrometric signature versus period for objects listed in exoplanet.eu at 2014 September 1 for all 1821 confirmed planets (left), and for a subset of 1129 transiting planets with appropriately known data (right). Note the different scales in abscissa and ordinate. Circle sizes are proportional to planet mass; the prominent object (left) at $P = 0.7 \text{ yr}$, $\alpha = 6300 \mu\text{as}$, is the 28.5 $M_J$ astrometric detection DE0823–49 b. Unknown distances are set to $d = 1000 \text{ pc}$. Transiting planets with $\alpha > 1 \mu\text{as}$ are labelled by (abbreviated) star name, indicating the discovery instrument, both ground ($H = \text{HAT}$, $W = \text{WASP}$) and space ($C = \text{CoRoT}$, $K = \text{Kepler}$). For the transiting planets above this threshold, the unknown distance affects only Kepler–27 b and c, and Kepler–31 b and c. Assuming $d = 500 \text{ pc}$, $\alpha$ would increase by a factor 2, but their astrometric motion would remain undetectable by Gaia.

Perryman et al 2014 arXiv:1411.1173
Precision Cosmology with Gaia
Precision calibration from parallaxes of 9000 Cepheids (only one currently)

Gaia real-time science Alerts
Find 10000 nearby supernovae within Cepheid overlap regime
**Galactic Cepheids**

Cepheids in the inner Galaxy, with $-5^\circ < l < 5^\circ$
- Observable by Gaia
- Too faint for Gaia

- Gaia will observe ~9,000 Galactic Cepheids ([2011arXiv1104.2348W](https://arxiv.org/abs/1104.2348))
- Hundreds are visible near and behind the Galactic centre
- Beyond 5 kpc, all Cepheids are observed outside the plane

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**Parallax horizon for classical Cepheids ($P = 10$ d)**

- **Galactic**
  - Known: 273 (Hipparcos 1997)
  - 509 (Fernie et al. 1995)
  - 455 (Berdnikov et al. 2000)
  - 872 (ASAS catalogue, as in 2011)
  - Estimated for Gaia: 2,000-8,000 (Pojmanski)
  - 9,000 (Windmark 2011)

**Optimist: Gaia will multiply by 10 the Galactic Cepheid number**

- **LMC**
  - Known: 3,361 (OGLE-III, Soszynski et al 2008-2010)

- **SMC**
  - Known: 4,630 (2008-2010)
CU7
Variability Analysis

functional analysis

Sample of Surveyed Stars

- Constant Stars
  - Variable Stars (10 to 30%)
    - 1. Variability detection
    - 2. Periodicity detection
  - Periodic Stars
  - Non-Periodic Stars
    - I, Be, L, SR, RS
  - 3. Periodic Star Classification
  - 4. Non-Periodic Star Classification (irregular, transients,...)

Supervised and unsupervised classification

Variability Detection

- CU5 and CU6 Variable Sources
- TBD Selection of Sources
- Special Variability Detection
- Additional Variables
- Variability Probabilities and Parameters

Catalogue Parameter Production

- Variability Characterisation
  - Classification
    - Class membership Probabilities
    - Specific Object Studies
      - Source Type 1 Processing
        - Parameters for Source Type 1
      - Source Type 2 Processing
        - Parameters for Source Type 2
      - Source Type N Processing
        - Parameters for Source Type N

Validation and Quality Assessment

- Global Variability Studies
- Unexpected Feature Analysis
- Supplementary Observations
  - Results for Community Announcements
  - Quality and Validation Data
ANOMALY DETECTION SYSTEM

Detection

object type

new

various detection criteria

upward

old

downward

astrometric

after

~1.5yrs

brighter than 19 mag*

transients

supernovae

novae

DNe

TDE

AGN flares

GRB OT

M-dwarf flares

microslensing

dwarf novae

supernovae on top of galaxies

novae

Be stars

AGN flares

FUOrs, EXOrs

RCrB

DY Per

single eclipses

dark clouds

* tunable parameter, will evolve during the mission
Gaia science has started!
This will support a big outreach & education programme w. Las Cumbres few 1000 local SNe

AM CVn: Gaia14aee

Table 1. Log of photometric observations of Gaia14aee used in this work.

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Obs. date (UT)</th>
<th>Filter</th>
<th>Exposures (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaia</td>
<td>2014 08 11</td>
<td>G</td>
<td>45</td>
</tr>
<tr>
<td>ASAS-SN</td>
<td>2012 - 2015</td>
<td>V</td>
<td>129×180</td>
</tr>
<tr>
<td>Loiano 1.5m Cassini</td>
<td>2014 10 24</td>
<td>g</td>
<td>3×300, 91×30</td>
</tr>
<tr>
<td>Telescope + BFOSC</td>
<td>2014 10 25</td>
<td>g</td>
<td>135×30</td>
</tr>
<tr>
<td>Bialkow 0.6m, Poland</td>
<td>2014 10 18</td>
<td>BV</td>
<td>30×120</td>
</tr>
<tr>
<td></td>
<td>2014 10 19</td>
<td>BV</td>
<td>37×120</td>
</tr>
<tr>
<td>CIECEM 0.35m, Spain</td>
<td>2014 10 21 to</td>
<td>clear</td>
<td>40×180, 8×150</td>
</tr>
<tr>
<td></td>
<td>2014 11 18</td>
<td></td>
<td>111×120, 399×90</td>
</tr>
<tr>
<td>ptS, La Palma</td>
<td>2014 10 25</td>
<td>V</td>
<td>61×60</td>
</tr>
<tr>
<td></td>
<td>2014 10 22</td>
<td>V</td>
<td>36×60, 21×120</td>
</tr>
<tr>
<td>0.6m ASV, Serbia</td>
<td>2014 10 21</td>
<td>BVRI</td>
<td>6×300</td>
</tr>
<tr>
<td>Belogradchik AO 0.6m, Bulgaria</td>
<td>2014 10 21</td>
<td>BV R</td>
<td>2×300</td>
</tr>
<tr>
<td>Asiago 1.82m Copernico</td>
<td>2014 12 11</td>
<td>r</td>
<td>169×20</td>
</tr>
<tr>
<td></td>
<td>2014 12 12</td>
<td>g</td>
<td>169×20</td>
</tr>
<tr>
<td>4.2m WHT+ACAM</td>
<td>2014 12 18</td>
<td>V</td>
<td>491×5</td>
</tr>
<tr>
<td>Mercator</td>
<td>2015 01 15</td>
<td>g r+i</td>
<td>232×30</td>
</tr>
<tr>
<td>Catalina (historic)</td>
<td>2005 - 2014</td>
<td>clear</td>
<td>107×30</td>
</tr>
<tr>
<td>Pan-STARRS1 (historic)</td>
<td>2010 - 2014</td>
<td>gr icy</td>
<td>66×30</td>
</tr>
</tbody>
</table>

Highlights:

- Lightcurve showed significant brightening
- BP/RP spectrum best fit by model SN Ia

Loiano Telescope follow-up confirms
Period is ~50 mins
**ALERTS VERIFICATION PHASE**

Gaia Follow-Up Network for Transient Objects = Gaia-FUN-TO

- verification if the object exists
- verification of errors of the pipeline and data
- detailed classification and verification of Gaia classification
- network composed of robotic and manually operated telescopes
- reaction within 24h
- automatised reductions
- central data repositories (photometry and spectroscopy)

**Photometry:**
- Loiano (Italy)
- Rozen (Bulgaria)
- Warsaw, Wrocław (Poland)
- OHP (France)
- ASV (Serbia)
- RTT150, RTT100 (Turkey)

**Spectroscopy:**
- NTT (La Silla)
- WHT (La Palma)
- INT (La Palma)
- SAAO 1.9m
- Loiano (Italy)
- Asiago (Italy)

new members welcome!
The Gaia Data Release (GDR) Scenario

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

- GDR1 ~7/16: positions, G-magnitudes (~all sky, single stars) proper motions for Hipparcos stars (~50 µarcsec/yr) – the Hundred Thousand Proper Motions (HTPM) catalogue
- GDR2 ~2/17: + radial velocities for bright stars, two band photometry and full astrometry (α, δ, ϖ, μ_α, μ_δ) where available for intermediate brightness stars
- GDR3 ~1/18: + first all sky 5 parameter astrometric results (α, δ, ϖ, μ_α, μ_δ) BP/RP data, RVS radial velocities and spectra, astrophysical parameters, orbital solutions short period binaries
- GDR4 ~1/19: + variability, solar system objects, updates on previous releases, source classifications, astrophysical parameters, variable star solutions, epoch photometry
- GDR-Final: final data release (thus in 2022/23 or 2025)

Full dataset for more sophisticated modelling released at end of mission
a few Gaia numbers

- One billion stars = 1% of the Milky Way’s stars
- One billion pixel camera
- Total project cost 960 Meuro
- Project lifetime: 1993 – 2023+
- Accuracy – 10 microarcsec = $10^{-10}$ rad = thickness of a human hair at 1000km
- Einstein light bending at the Sun’s edge is 1750000 microarcsec
- Must know Gaia’s location within 150m: it is about 1,500,000m away
- Gaia will travel about 16Mkm over 5 years
- Satellite global timing network extended to picosecs for Gaia
- In one picosec light travels 0.3mm
- Satellite communications link is 300W, total power use 1276W
- 100Tb raw compressed data – our database is 15Tb as of today
- 2 telescopes, 35m focal length, rectangular mirrors
- 3.5M hours of work to study, design & build = 300 people x 7 years
- 400 scientists working on data processing
- Over 30,000 mission documents in archive
- Launch burned 225 tonnes of kerosene+oxygen in 5 minutes
- In orbit micro-propulsion system ejects 1 microgram of nitrogen per thrust
- Gaia measures 40 million stars per day on average
- 60 million stars will have 6-D space motions
- Total number of measurements: 1,000,000,000,000

Find out more at http://gaia.ac.uk

PLUS: 1 million galaxies; 500,000 QSOs; 10,000 Supernovae – in real-time; 250,000 asteroids; 15,000 extra-solar planets; 200,000 white dwarfs; 50,000 brown dwarfs, the new, ....
The videos shown before and during the talk are available at
http://gaia.ac.uk