Gaia broad band photometry as preparatory tool for the PLATO mission

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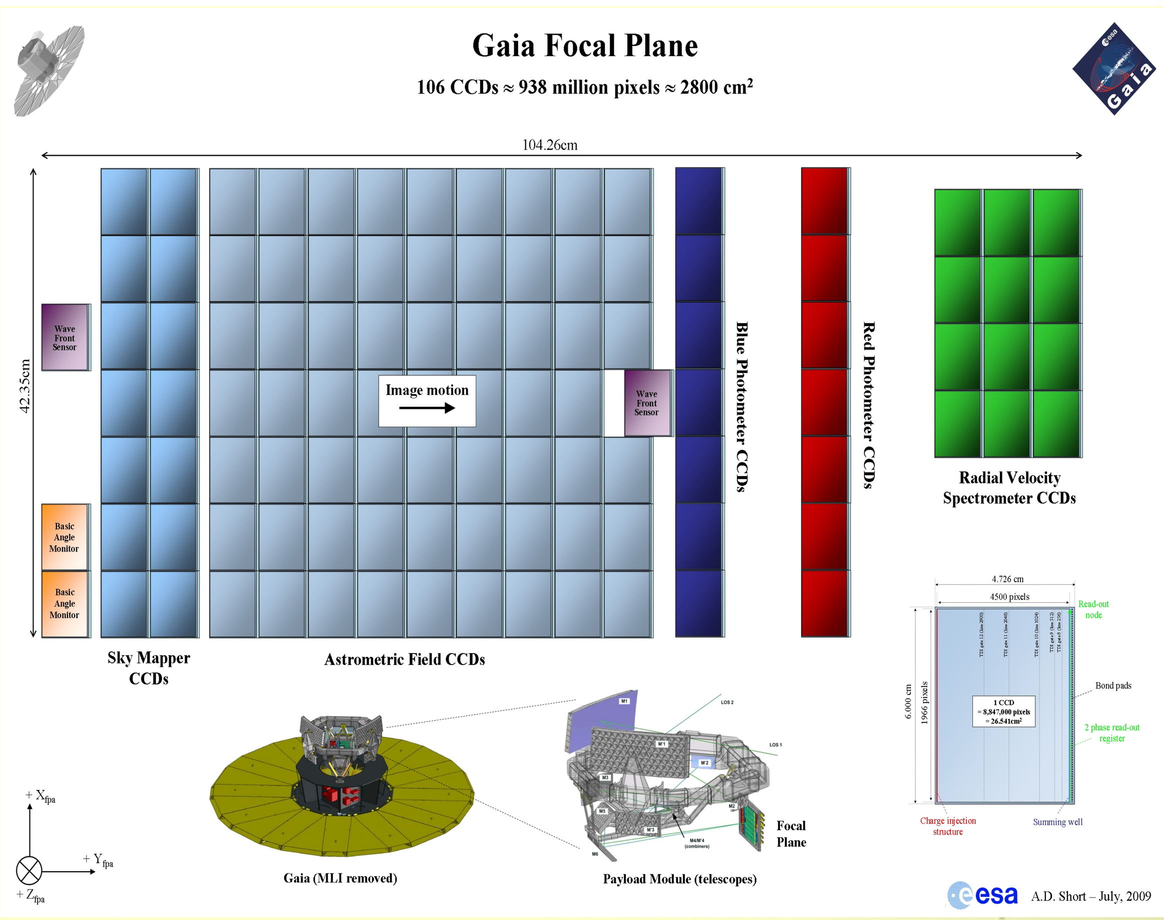
Abstract

The astrometric, photometric and spectroscopic observations of the *Gaia* mission will cover all the targets observed by PLATO. Scientific results obtained by *Gaia* are shown which will be helpful for the preparation of the PLATO mission. This includes relationships between *Gaia* magnitudes and other photometric systems, expected photometric errors and high resolution 2D images. Example lightcurves of variable stars, eclipsing binaries and planetary transit systems are presented.

Gaia mission overview

Mission specifications:

- Launch NET March 2013
- Orbit: Sun-Earth L2
- Continuous scanning 5 years
- Two telescopes separated by 106.5 deg
- Entrance pupil: 1.45 x 0.5 m²
- Optical transmission > 0.86
- Spin period 6h
- Sun/spin axis angle 45 deg
- Non-deployable, 6-mirror SiC optics
- 106 TDI CCDs (4500 x 1966 pixels illuminated)
- Pixel scale 59 x 177 mas²
- **Astrometry** and **photometry** by 62 AF CCDs (white light, G magnitude), Magnitude range G: 5.7-20.0 (V ~ 20-25 mag), 1+ billion sources, Average total observations/object 2 x 40 TDI integration time per CCD 4.42 sec
- **Spectrophotometry** (BR/RP magnitudes) with 2 x 7 CCDs
- **High resolution spectroscopy** in Ca IR triplet (RVS, 3 x 4 CCDs, G < 17)



Mission objective:

The main goal of the *Gaia* mission is to provide data to study the formation, dynamical, chemical and star formation evolution of the Milky Way. Therefore, *Gaia* will chart a 3D map of the Milky Way (see Perryman et al, 2001.). *Gaia* will measure positions, parallaxes, and proper motions for about 1 billion sources in our Galaxy and throughout the Local Group. It will also observe the SED of the objects (BP/RP instrument) to derive their astrophysical properties (**T_{eff}, log g** and **[M/H]**). The third of the 3D components (radial velocity) of the sources is measured by the RVS instrument.

The light rays coming from the two *Gaia* telescopes are dispersed in wavelengths, in BP/RP and RVS case. The viewing directions of both telescopes are super-imposed on the common focal plane. From unfiltered (white) light, *Gaia* will yield **G**-magnitudes. The integrated flux of the two low-resolution spectra (BP and RP) will yield **G_{BP}**- and **G_{RP}**-magnitudes.

Expected photometric precision

Gaia photometry is conducted for the whitelight broadband (G magnitude), a blue broadband (G_{BP} magnitude), and a red broadband (G_{RP}). For the wavelength ranges of these bands please see the figure to the right.

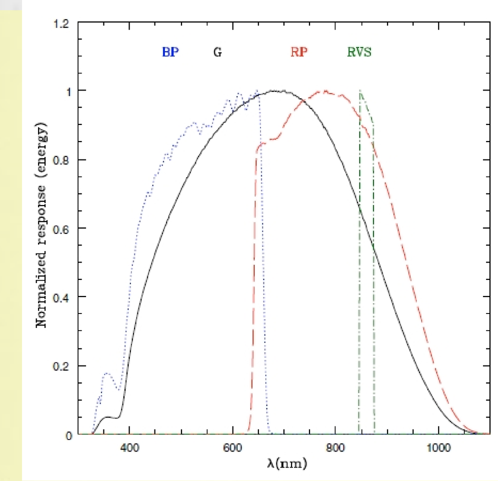
Following an aperture photometry approach the observation noise is computed based on the latest information about the total detection noise per pixel/sample including the noise due to the read-out and the sky background. Reduced exposure times are used for the bright sources to avoid saturation. The number of CCD transits is assumed to be 9 for AF and 1 for BP/RP.

An error of 20% of the observation noise is added to account for calibration errors. Recent studies using simulated data were showing that calibration errors lower than 20% of the observation error can be obtained for the photometric range and colour ranges. Because the simulated data did not contain all known effects (e.g.. CTI, non-linearities), it is still uncertain if this level of photometric precision can be really obtained for real Gaia data.

From this computation, the estimated photometric precision for single FoV transits is shown in the figures to the right. G and integrated G_{BP} and G_{RP} yield uncertainties around the mmag level for the majority of the magnitude intervals.

The magnitude error at the end of mission can be derived by accounting for the number of FoV transits per source. The mean number of FoV transits was determined to be 81 but it can vary depending on the Galactic coordinates of the sources (please see the table to the right). Furthermore some dead time not used for regular observations has to be assumed. Therefore a realistic assumption for the mean number of **FoV transits** is seen to be **70**.

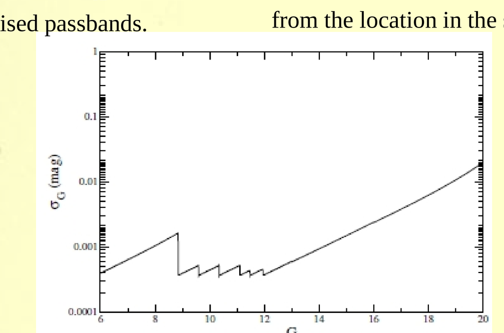
For more details please see **Jordi et al (2010**, *A&A*, 528A, 48).

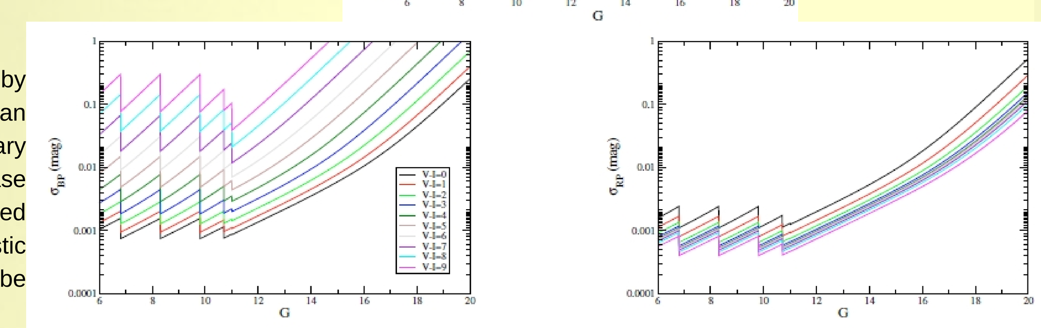


Gaia G (solid line), G_{BP} (dotted), G_{RP} (dashed) and G_{RVS} (dot-dashed) normalised passbands.

$\lvert\sin(\beta)\rvert$	β_{min} (deg)	β_{max} (deg)	N_{obs}
0.025	0.0	2.9	61
0.075	2.9	5.7	61
0.125	5.7	8.6	62
0.175	8.6	11.5	62
0.225	11.5	14.5	63
0.275	14.5	17.5	65
0.325	17.5	20.5	66
0.375	20.5	23.6	68
0.425	23.6	26.7	71
0.475	26.7	30.0	75
0.525	30.0	33.4	80
0.575	33.4	36.9	87
0.625	36.9	40.5	98
0.675	40.5	44.4	122
0.725	44.4	48.6	144
0.775	48.6	53.1	106
0.825	53.1	58.2	93
0.875	58.2	64.2	85
0.925	64.2	71.8	80
0.975	71.8	90.0	75
Mean	0.0	90.0	81

Mean number of *Gaia* transits in dependence from the location in the sky (ecliptic latitude β).





Photometric performance of *Gaia* for a single FoV transit in the whitelight G band, the blue G_{BP} band and the red G_{RP} band.

Gaia lightcurves of variables

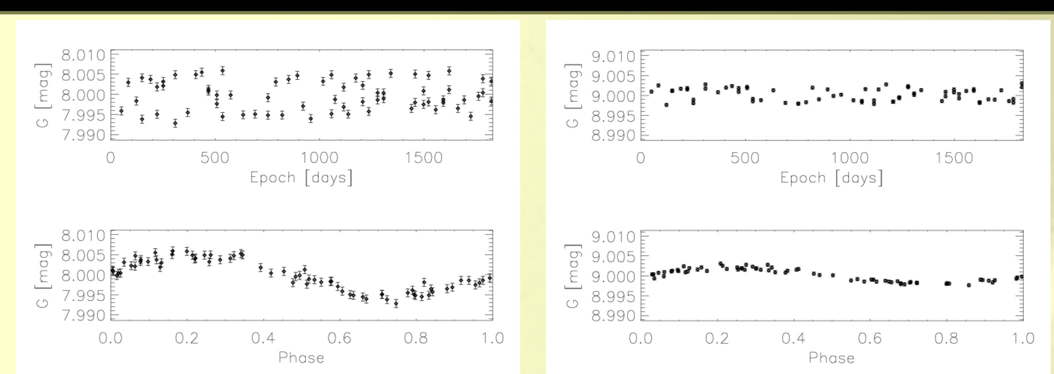
Due to the high precision in space photometry it will be possible to detect relatively small flux variations.

In the section about the expected photometric precision it can be seen, that measurement errors of sub-millimagnitudes are expected nearly for the entire magnitude range of the PLATO targets (assuming that the PLATO broadband magnitude is very similar to the G magnitude of Gaia). There is only a magnitude interval around G = 8.5 where this measurement error exceeds the mmag level due to the reduced exposure times for bright sources (to avoid saturation).

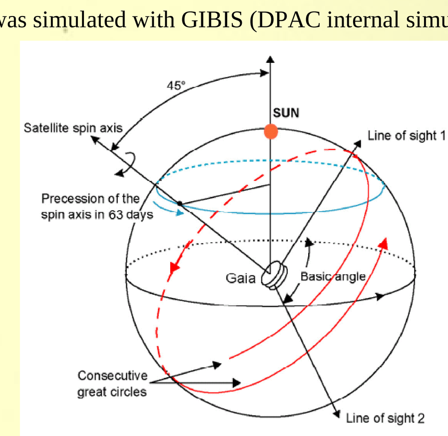
Some examples of lightcurves for δ scuti type variables can be seen in the upper figures to the right. Variations of a few mmag can easily be discovered in the lightcurves.

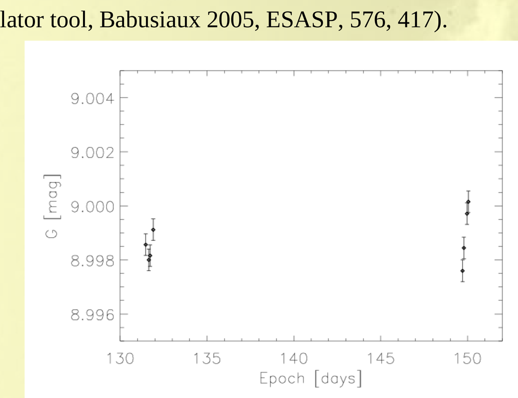
Note, that the instrument of Gaia is not optimized for photometry. The main objective of the Gaia space mission is to determine the dynamics in the Milky Way. Therefore, the observations are optimized for astrometric measurements. One aspect of this optimization is that the positions in the sky are recorded on a regular basis but with gaps of several weeks duration as seen in central figure showing that between two sets of measurements is a gap of about 18 days. In extreme cases these gaps show a duration of about 63 days. Thus, short events with a duration of few hours like eclipses can be missed depending on the phase of the events in relation to the scanning law.

Simulated data of an eclipsing binary (P = 1.5081 days) can be seen in the low figures to the right in epoch and phase space. The right plot shows the photometry derived for this binary with 70 FoV transits. Only two measurements were obtained during the main eclipse, non during the secondary eclipse. Additional gaps in the coverage are visible in the phase plot. If the same binary is observed more often, then the chances to miss to eclipses decrease significantly as can be seen in the left plot of the figure showing 121 FoV transits, 12 of them were measured during eclipses.

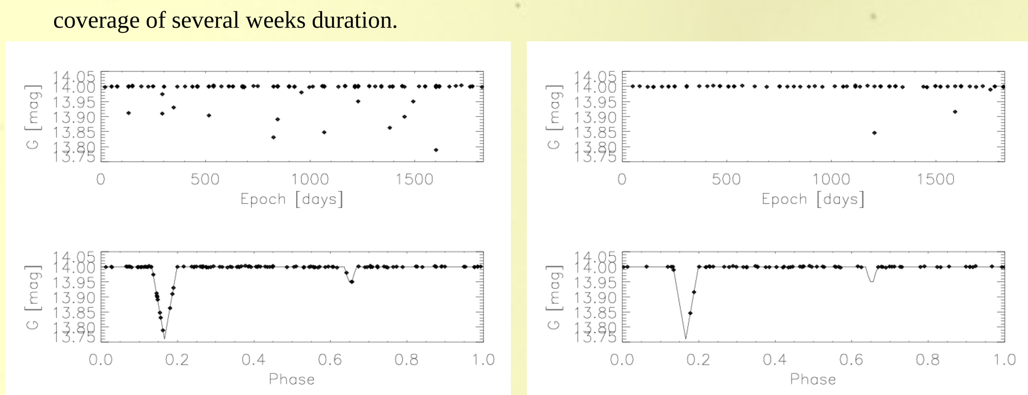


Typical lightcurves of δ Sct type stars as they will be measured by the *Gaia* satellite. The scanning law was simulated with GIBIS (DPAC internal simulator tool, Babusiaux 2005, ESASP, 576, 417).





The *Gaia* scanning law is optimized for astrometric purposes and therefore there will be gaps in the coverage of several weeks duration.



Simulated *Gaia* lightcurves of an eclipsing binary with an period of about 1.51 days. Depending on the number of FoV transits short-duration events can be missed like the secondary eclipse for a 70 FoV transits (right) in comparison to 121 FoV transits (left.)

Planetary transits as seen by Gaia

Gaia photometry will allow to detect exoplanetary candidates by the transit method. The relatively low phase coverage due to the low number of FoV transit measured (70 transits x 4 min average) during the five year mission will not allow to detect all transiting planets. A study was performed to evaluate the number of expected transit candidates discovered by Gaia. As a first step the stellar sample from was derived with the GASS simulator tool (DPAC internal simulator) describing 1/10 of the stellar content of the Milky Way. This sample contains about 10 million stellar sources up to G magnitude 17. The G magnitude was computed from the V magnitude and the V-I colour by using the corresponding photometric relationship from Jordi et al (2010), which is also described in the left section below.

Based on the statistics from the Extrasolar Planets Encyclopedia from J. Schneider (www.exoplanet. eu) it was assumed, that the distribution of planets with a radius from 0.5-1.2 R_{Jup} and orbital periods **P < 10 days** is flat. Large giant planets with 1.2-1.5 R_{Jup} are assumed to be 5 times less frequent. Further assumptions made are:

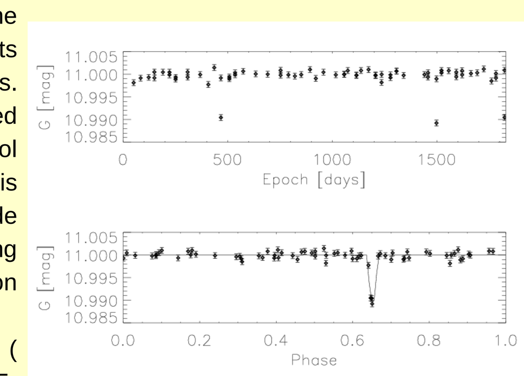
- 1-2% of the stars have a planet with the characteristics described above.
- The detection probability due the alignment of the planetery orbit in relation to the line of sight was set to 10%. This is justified by the fact that very short-period planets are preferred to be detected by Gaia observations than planets with orbital periods of several days.
- There are about 100 million single target stars with G < 17 to be observed by Gaia with a mean number of 70 FoV transits.

The planets were distributed to the host stars in a Monte Carlo approach. The phases of the planetary orbits were simulated randomly. A transiting exopanet was detected with 3 independent signals measured above a detection threshold. This detection threshold was set to 5σ of the noise of the individual lightcurve. This is an optimistic assumption valid for the simulated lightcurves with white noise. More realistic lightcurves will contain other noise sources. Therefore also a higher detection threshold of 7σ was for the single signals considered additionally.

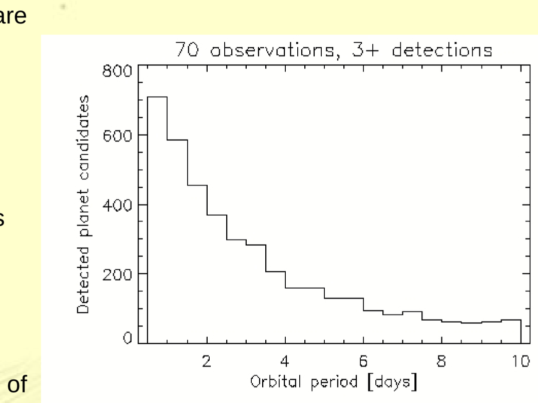
With the probability of 2% that a star has a planet with an orbital period less than 10 days and the 5σ detection threshold **4062 transiting planets** were detected in this analysis. For a detection threshold of 7σ the number of detected transiting planets is reduced to 1674.

Note that this 2% probability of having a planet with P < 10 days is a conservative assumption compared to the recent results from the Kepler mission. A probability of 5% seems to be more realistic if most of the planet candidates discovered by Kepler indeed can be confirmed to be planets.

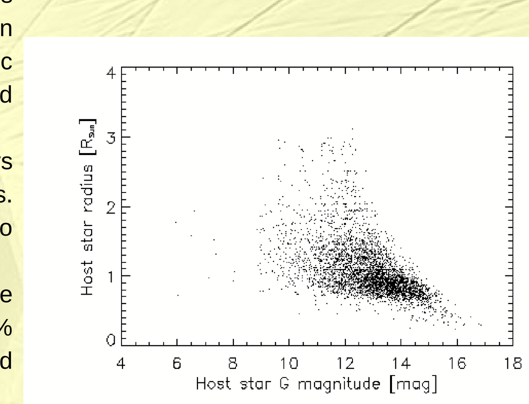
Therefore it seems realistic that *Gaia* will detect a **few thousand transiting planet candidates, many of them in the PLATO target fields.**



Lightcurve of a star with a transiting planet showing four in-transit measure-ments. Note that one in-transit signal occurs during the ingress phase and is below the detection threshold.



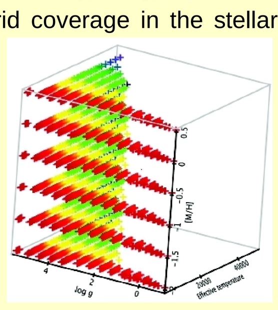
Periodogram of the detected transiting planet candidates with a 5σ detection threshold. Short-periodic planets show a preference in detection.



Distribution of magnitudes and radii for the host stars of the detected transit candidates. The majority of the planets is found orbiting host stars of G magnitudes from 11 to 14 and about 1 solar size.

Photometric relationships

Relationships between Gaia magnitudes and other photometric systems are provided in (Jordi et al, 2010). The BaSeL-3.1 (Westera et al, 2002 A&A, 381, 524) synthetic SED library was used to derive this photometric relationships. The grid coverage in the stellar parameter space is the following:



- 2000 < T_{eff} < 50000 K
- -1.0 < log g < 5.5 dex
- -2.0 < [M/H] < +0.5 dex
- ξ_t = 2 km s⁻¹
- 9.1 < λ < 160 000 nm

The SEDs have been reddened by several amounts (A_v = 0,1,3,5 mag) following the reddening law of Cardelli et al. (1989) and assuming R_v = 3.1. In this way colours have been derived from synthetic photometry on these SEDs.

Please see the derived colour-colour diagrams which are relating the *Gaia* magnitudes to the **Johnson-Cousins** colours, in the figure to the right. Shown are the relations with V-I_C which is the one with the lowest residuals. The residuals are increasing in all cases for T_{eff} < 4500 K due to effects by surface gravity and metallicity.

This increased dispersion for cool stars is also seen in the relationships computed for other photometric systems:

- the **Sloan Digital Sky Survey** photometric system (Fukugita et al. 1996, AJ, 111, 1748) used in several large surveys like UVEX, VPHAS, SSS, LSST,
- and the **Hipparcos** photometric passbands (ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200).

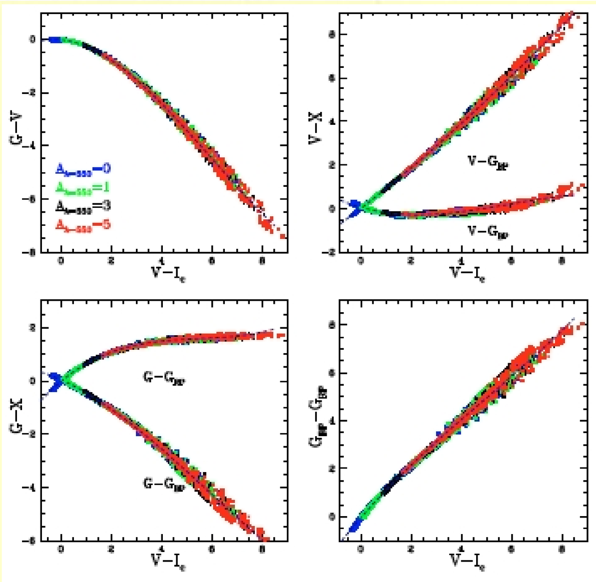
The latter will allow to establish the correspondence between the two very broad bands of the two mission Hipparcos and *Gaia*. This is of special interest as there is an idea under discussion to have a release of a catalogue early in the *Gaia* mission combining Hipparcos and *Gaia* data.

The photometric relationships can generally be described with the polynomial expression

$$C_1 = a + bC_2 + cC_2^2 + dC_2^3$$

where the colour C_1 is related to the colour C_2. The derived coefficients ***a, b, c, d*** can be seen for the Gaia/Johnson-Cousins relationships in the table to the right. Additionally, the residuals of the fitting processes are given. Please see the results for the relationships with other photometric systems in Jordi et al (2010).

Similar relationships could be computed for the PLATO broadband magnitude to allow the direct comparison of PLATO data with *Gaia* data.



Colour-colour diagram involving all *Gaia* passbands and the V-I_C Johnson-Cousins passband.

		$(V-I_C)$	$(V-I_C)^2$	$(V-I_C)^3$	σ
$G-V$	−0.0257	−0.0924	−0.1623	0.0090	0.05
$G-G_{RVS}$	−0.0138	1.1168	−0.1811	0.0085	0.07
$G-G_{BP}$	0.0387	−0.4191	−0.0736	0.0040	0.05
$G-G_{RP}$	−0.0274	0.7870	−0.1350	0.0082	0.03
$V-G_{RVS}$	0.0119	1.2092	−0.0188	−0.0005	0.07
$V-G_{BP}$	0.0643	−0.3266	0.0887	−0.0050	0.05
$V-G_{RP}$	−0.0017	0.8794	0.0273	−0.0008	0.06
$G_{BP}-G_{RP}$	−0.0660	1.2061	−0.0614	0.0041	0.08
		$(V-R_C)$	$(V-R_C)^2$	$(V-R_C)^3$	σ
$G-V$	−0.0120	−0.3502	−0.6105	0.0852	0.10
$G-G_{RVS}$	0.0267	2.3157	−0.7953	0.0809	0.10
$G-G_{BP}$	0.0344	−0.9703	−0.2723	0.0466	0.10
$G-G_{RP}$	0.0059	1.5748	−0.5192	0.0558	0.05
$V-G_{RVS}$	0.0388	2.6659	−0.1847	−0.0043	0.15
$V-G_{BP}$	0.0464	−0.6200	0.3382	−0.0386	0.05
$V-G_{RP}$	0.0180	1.9250	0.0913	−0.0294	0.13
$G_{BP}-G_{RP}$	−0.0284	2.5450	−0.2469	0.0092	0.14
		(R_C-I_C)	$(R_C-I_C)^2$	$(R_C-I_C)^3$	σ
$G-V$	−0.0056	−0.4124	−0.2039	−0.0777	0.13
$G-G_{RVS}$	−0.0279	2.0224	−0.5153	0.0176	0.06
$G-G_{BP}$	0.0682	−1.0505	0.1169	−0.1052	0.10
$G-G_{RP}$	−0.0479	1.5523	−0.5574	0.0776	0.03
$V-G_{RVS}$	−0.0223	2.4347	−0.3113	0.0953	0.14
$V-G_{BP}$	0.0738	−0.6381	0.3208	−0.0276	0.06
$V-G_{RP}$	−0.0423	1.9646	−0.3535	0.1553	0.14
$G_{BP}-G_{RP}$	−0.1161	2.6028	−0.6743	0.1829	0.12
		$(B-V)$	$(B-V)^2$	$(B-V)^3$	σ
$G-V$	−0.0424	−0.0851	−0.3348	0.0205	0.38
$G-G_{RVS}$	0.1494	1.2742	−0.2341	0.0080	0.15
$G-G_{BP}$	−0.0160	−0.4995	−0.1749	0.0101	0.35
$G-G_{RP}$	0.0821	0.9295	−0.2018	0.0161	0.09
$V-G_{RVS}$	0.1918	1.3593	0.1006	−0.0125	0.45
$V-G_{BP}$	0.0264	−0.4144	0.1599	−0.0105	0.05
$V-G_{RP}$	0.1245	1.0147	0.1329	−0.0044	0.46
$G_{BP}-G_{RP}$	0.0981	1.4290	−0.0269	0.0061	0.43

Coefficients of the relationships between the *Gaia* passbands and the Johnson-Cousins passbands.

Additional useful information

Based on the *Gaia* data several stellar parameters of the PLATO targets can be derived with high precision. Using the low-resolution spectroscopy allows to derive the following parameters for stars with G < 16 (and therefore for all PLATO targets):

- **T_{eff} ± 5%**
- **A_v ± 0.05 – 0.2 mag**
- **log g ± 0.2-0.3 dex**
- **[M/H] ± 0.2-0.4 dex**
- **[α /Fe] ± 0.2 dex**

Additionally, the **astrometric accuracy** of less than **10 µas** for the parallax and the position of a stars with G < 11 can be obtained. Proper motions can be derived with an error of 5 µas/yr. The astrometric accuracy of single FoV transits for stars with G < 12 will be about 35 µas.

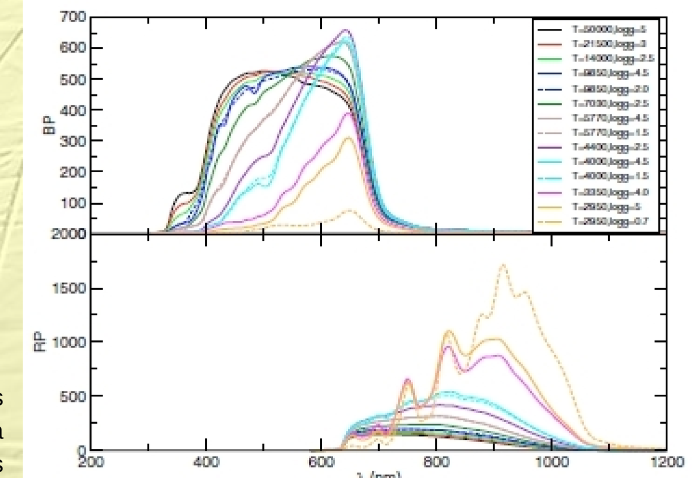
From RVS spectroscopy radial velocities will be determined for all stars with G < 17. For stars brighter than G = 13 rotational velocities, some atmospheric parameters, interstellar reddening will be obtained.

Information about the **variability** and the **binarity/ multiplicity** will be available for all sources.

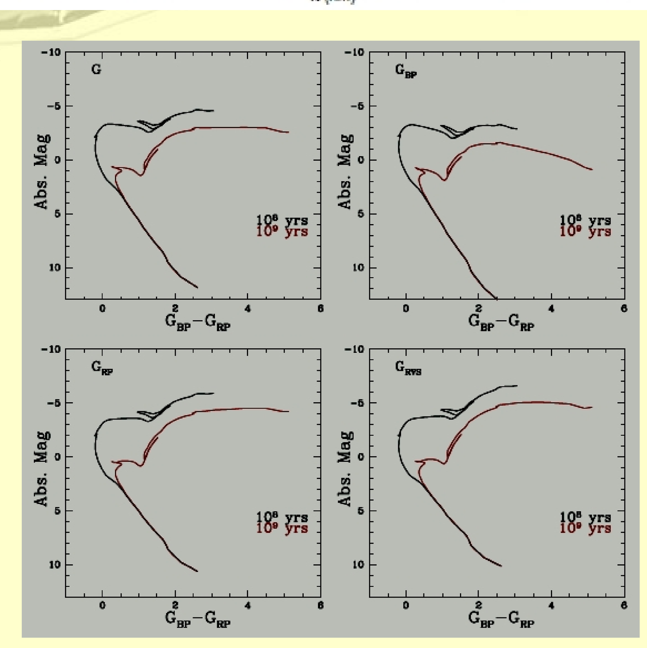
Accurate **distances** will be determined for all sources across the HR diagram.

Thousands of **exoplanetary systems** can be discovered **astrometrically**. The astrometric precision will allow to detect Jupiter mass planets with P < 10 yrs around 105 FGK stars within 200 pc distance. For nearby stars with a Distance less than 10 pc planets with masses of about 10 M_{Earth} masses can be detected astrometrically.

References: http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance



Gaia BP/RP low-resolution spectra for a sample of 14 stars with G = 15 mag and solar metallicity. The flux is given in photons s⁻¹ sample⁻¹. These kind of low-resolution spectra are used to derive several stellar parameters.



Padova isochrones (Marigo et al. 2008) computed in the Gaia passbands for solar metallicity and for different ages. Stellar tracks and isochrone files in the *Gaia* passbands are available at (http://stev.oapd.inaf.it). The age of stars can be determined with these isochrones.

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