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LUMINOSITY CALIBRATION AND DISTANCE SCALE

Catherine Turon

Observatoire de Paris, DASGAL/UMR CNRS 8633, 92195 Meudon Cedex, France

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Abstract. With an astrometric and photometric survey at the microarcsec level over a significant part of our Galaxy (1 %), also reaching the brightest objects in the closest galaxies of the Local Group, *Gaia* will provide distances of extreme accuracy for all types of stars of all stellar populations, even those which are very sparsely represented in the solar neighborhood. With the parallel determination of extinction/reddening and metallicities by the use of multicolor photometry and low resolution spectroscopy, this huge amount of basic data will provide an extended basis for reading in situ stellar and galactic evolution. All parts of the Hertzsprung-Russell diagram will be comprehensively calibrated, especially the stellar candles (pulsating variable stars, cluster sequences, supergiants, central stars of planetary nebulae, etc.), stimulating a revolution in the methods used to determine cosmic distance scales.

Key words: Galaxy: distance scale, globular clusters – stars: parallaxes, absolute magnitudes, HR diagram – orbiting observatories: Hipparcos, Gaia

1. INTRODUCTION

With astrometric accuracy of 4 μas at magnitude $V = 12$, 10 μas at $V = 15$, and 0.2 mas at $V = 20$ for more than one billion stars, the *Gaia* project (Lindegren & Perryman 1996, 1997, Perryman et al. 1997, Gilmore et al. 1998), proposed as a Cornerstone of the ESA Horizon 2000+ program, will revolutionize many fields of astronomy, in particular – galactic and stellar population studies. With the additional contribution of simultaneous photometric and spectroscopic observations, it will make possible to directly read the evolution of our Galaxy, by providing, without any a priori assumption about the physical state of the objects, a direct painting of the spatial, kinematic and chemical distributions of stars of all stellar populations, even those in the most rapid evolutionary phases (subgiants, planetary nebulae, etc.), those which are very sparsely represented in the solar neighborhood (brightest supergiants, halo or bulge components), those in the most crowded regions (galactic bulge, globular clusters), or those which are intrinsically very faint (red, brown and white dwarfs).

The ESA *Hipparcos* mission (Perryman et al. 1992, ESA 1997) already provided a spectacular increase, qualitatively and quantitatively, of the basic distance information available from trigonometric parallaxes, but our major methods for further calibrating specific physical characteristics (sequence fitting and period-luminosity relations, for example) had to remain unchanged outside the close vicinity of the Sun. With *Gaia*, there would be such a jump (about two orders of magnitude) in the astrometric accuracy and in the number of stars (Lindegren 1998) that our very approach to stellar and galactic history would have to be drastically changed.

Extremely accurate trigonometric parallaxes and proper motions, up to the limits of our Galaxy and up to the closest Local Group galaxies (for the brightest stars) will be provided. A few illustrative numbers are given in Table 1. It is noticeable that, up to significant distances (functions of the apparent magnitude), the major contribution to the error of the intrinsic luminosities will no more be the error of the parallax but errors coming from the uncertainties in the extinction, metallicity, stellar rotation, unsolved binarity or variability of the considered stars. This underlines the major importance of the parallel photometric and spectroscopic observations to be performed with *Gaia*, and how crucial is the choice of the passbands and spectral range.

Hipparcos showed that many distances were previously underestimated and that even stars within 25 pc from the Sun were not well known: some 40 % of CNS3 stars (Catalogue of Nearby Stars, Gliese & Jahreiss 1991) are further than 25 pc from *Hipparcos* observations (Turon & Perryman 1999). *Gaia* will provide the accuracy, given by *Hipparcos* within 25 pc, up to distances of more than 6000 pc for stars brighter than $V = 15$ mag, up to 2500 pc for stars brighter than $V = 18$ mag and even up to 125 pc for stars brighter than $V = 20$ mag.

Table 1. Basic information from ground-based, *Hipparcos* and *Gaia* trigonometric parallaxes.

	Ground-based	Hipparcos	Gaia
V_{max}	20	12.4	23 (^{a})
$\sigma_\pi/\pi \leq 1\%$			
Number of stars	a few	442	$\sim 18\times10^6$ (^{b})
d_{max}	25 pc	25 pc	2500 pc
$M_{V,min}$		0 (^{c})	-9
$M_{V,max}$		15 (^{d})	20
$\sigma_\pi/\pi \leq 10\%$			
Number of stars	1000 ?	22 396	$\sim 150\times10^6$ (^{b})
d_{max}	200 pc	200 pc	25 000 pc
$M_{V,min}$	-2	-5.5 (^{e})	-9
$M_{V,max}$	19	15 (^{d})	20
Error on M_V (^{f}) at $V = 10$		0.03 mag at 10 pc 0.3 mag at 100 pc –	10^{-4} mag at 10 pc 10^{-3} mag at 100 pc 10^{-1} mag at 10 kpc

N o t e s:
^{a} for the reddest stars
^{b} Lindegren (1998)
^{c} most stars fainter than absolute magnitude +1
^{d} most stars brighter than absolute magnitude +12
^{e} most stars fainter than absolute magnitude -3
^{f} only due to the error on π

2. LUMINOSITY CALIBRATIONS

Up to the publication of the Hipparcos Catalogue, luminosity calibrations were almost exclusively indirect, based on an extremely small number of stars with accurate trigonometric parallaxes, representative of a very restricted range of spectral types, luminosity classes, stellar populations and evolutionary status. The most widespread method was the use of spectroscopic and/or photometric data to place a star in the HR diagram, and deduce its absolute magnitude from its spectral type or color and its supposed luminosity class.

Hipparcos results have considerably enlarged the direct distance observational basis on which such calibrations rely (Turon 1998). They have also shown that the definition of the presently used luminosity classes have to be revised: most luminosity classes are spread over a large range in absolute magnitudes (up to one or two magnitudes) and there is no clear separation between many of them in some zones of spectral types (Gómez et al. 1997, Jaschek & Gómez 1998, Paunzen 1999). Moreover, *Hipparcos* results have also shown that spectroscopic parallaxes may be strongly underestimated: some 40 % of 5610 stars classified as dwarf stars in the Michigan Spectral Survey (Houk et al. 1975–1988), and estimated to be at distances smaller than 80 pc, are shown by *Hipparcos* to be at distances larger than 80 pc (Binney et al. 1997).

Studies dedicated to specific spectral types confirm the two general conclusions reached above. For example, Oudmaijer et al. (1999) show that a sample of stars selected from the Michigan Spectral Survey to be K0 V stars were (1) shown by *Hipparcos* observations to be 0.2 mag brighter than given previously (Schmidt-Kaler 1982) and (2) were contaminated by about 20 % of K0 IV stars. Domingo & Figueras (1999) use a sample of main-sequence A3–A9 stars, normal and chemically peculiar Am stars, to revise the calibration of absolute magnitudes with respect to temperature, evolution and metallicity effects as obtained from Strömgren photometric indices, and to rotational velocities. They derive the Zero-Age Main Sequence (ZAMS) 0.2–0.3 mag brighter than the ZAMS previously obtained (Crawford 1979, Guthrie 1987). Moreover, they show the difficulty of calibrating the various effects inferred by metallicity, evolution or rotational velocity differences between stars: metallicity and velocity differences were under-corrected by Crawford (1979), but over-corrected by Guthrie (1987).

With *Gaia*, the situation would be drastically modified by the much higher accuracy, leading to the possibility of investigating a much larger volume, up to the outermost of the Galaxy and, for the brightest stars to the closest galaxies of the Local Group. Moreover, the much fainter magnitudes observable lead to the possibility of investigating the bottom of the main sequence down to brown dwarfs, the branch of white dwarfs and non-local stars of medium luminosity.

As a result, samples of stars of any type would be numerous enough to test all possible effects affecting stellar luminosity, with no a priori restriction to a very local sampling. For example, in the paper quoted above, the authors had to restrain themselves to a sample of only 179 normal A-type stars and 127 Am stars to only keep stars with a relative parallax error smaller than 0.2. These are very small numbers for testing the effects of four different parameters. With *Gaia*, A3–A9 stars would be observable with a relative parallax error better than 10 % up to about 5000 pc (taking a mean visual absolute magnitude of 3 mag for this range of spectral types).

The limits reachable for all luminosities are given in Table 2. For stars brighter than $M_V = -5$ mag, the limiting factor is the precision in the parallax, 4 μas for stars apparently brighter than $G = 12$ mag. At the other end, for stars fainter than $M_V = 14.5$ mag, the limiting factor is the apparent magnitude ($G \leq 20$ mag): for all these stars the relative parallax error is always smaller (or even much smaller) than 10 %. For all other stars the limit comes from a combination of the distance and the apparent magnitude (of which depends σ_π).

It is especially remarkable that extremely accurate absolute luminosities will be reached for all stars in the 50 pc radius sphere around the Sun, brown dwarfs included. On the end of the absolute magnitude range, a relative parallax error smaller than 10 % will be obtained for all stars of the bright end of the main sequence, and for nearly all types of galactic supergiants, up to 25 kpc.

3. THE COSMIC DISTANCE SCALE

The impact of *Hipparcos* results on the cosmic distance scale have been reviewed by Turon & Perryman (1999). The only very firm result is the complete three-dimensional study of the Hyades open cluster for which more than 200 members were individually observed with a good accuracy (Perryman et al. 1998). The number of other stellar candles, observed with high accuracy, was not large enough to avoid further divergent analysis, and to reliably explore, for example, the effect of metallicity on the position of open cluster main sequences (van Leeuwen 1999, Robichon et al. 1999, Pinsonneault et al. 1998) or on period-luminosity relations for pulsating variable stars (Feast & Catchpole 1997, Oudmaijer et al. 1998, Luri et al. 1998, Fernley et al. 1998, Tsujimoto et al. 1998, van Leeuwen et al. 1997, Whitelock et al. 1997 and Bergeat et al. 1998).

Table 2. *Gaia* observations: limiting apparent magnitude and distance for stars with a relative parallax error smaller than 10 %, obtained from precisions and $V–I$ given by Lindegren (1998), for the zones with no extinction.

M_V [mag]	Stellar type	$<V–I>$ [mag]	$V_{\rm lim}$ [mag]	$G_{\rm lim}$ [mag]	$d_{\rm lim}$ [pc]
	O V	–0.3	12.0	12.0	
–5	B0–G0 Ib	to			25 000
	all Ia and Ia0	4.7	12.0	8.3	
0	A0 V	0.01	14.6	14.6	8300
	K3 III	0.99	14.8	14.4	9100
5	G5 V	0.8	17.3	17.0	2800
10	M2 V	2.0	19.8	18.7	900
	DB	0.0	19.2	19.2	700
15	M7 V	3.0	21.9	20.0	240
	DG	2.6	21.6	20.0	210
17	M8 V	3.2	22.1	20.0	170
20	brown dwarfs	4.5	23.5	20.0	50

Gaia would provide such accurate distances (and proper motions) for such huge numbers of each category of stellar candles that, again in this domain, the analysis methods should have to be drastically changed. Some illustrative figures are given in Table 3. The sampling of open and globular clusters in age, metal, oxygen or helium content will be complete all over the Galaxy. Parallel improvement in the transformation between observational and theoretical HR diagram will be required to take full benefit of these accuracies in terms of stellar evolution and age determination: photometric and/or spectroscopic data should allow the determination of the bolometric magnitude and of the effective temperature from the observed magnitudes and colors.

For pulsating variables, the sampling versus period, populations, colors and metallicities will be as good as possible, since accurate distances will be obtained for all observable galactic stars, and a first reliable estimation of the intrinsic dispersion of the period-luminosity

Table 3. *Gaia* observations of stellar candles.

Candle	*Gaia* observations
Open clusters	3-D observations up to ~1000 pc
	all mean distances to better than 1 %
	many new clusters to be discovered
Globular clusters	~ 20 with $\sigma_\pi/\pi < 10\,\%$ per star
	~ 40 with $\sigma_\pi/\pi < 20\,\%$ per star
for 1000 stars and 10 kpc	mean distance to better than 1 %
for 4000 stars in LMC	mean distance to better than 10 %
Cepheids	$\sigma_\pi/\pi < 1\,\%$ up to 2500 pc
	$\sigma_\pi/\pi < 4\,\%$ for all galactic Cepheids
	$\sigma_\pi/\pi \sim$ 15–20 % in LMC
	membership to clusters all over the Galaxy
RR Lyrae stars	$\sigma_\pi/\pi < 1\,\%$ up to 2500 pc
	$\sigma_\pi/\pi < 10\,\%$ for most galactic RR Lyrae
Mirae	$\sigma_\pi/\pi < 1\,\%$ up to 2500 pc
	$\sigma_\pi/\pi < 6\,\%$ for all galactic Mirae

relations will be possible. Moreover, a first check of the universality of these relations (not only the slopes, but also the zero-points) will be possible, directly for LMC Cepheids, or using the *Gaia* mean distances – for the closest galaxies of the Local Group, at least for LMC, SMC and the Sagittarius dwarf spheroidal galaxy. Parallel improvement in the determination of metallicity and of interstellar extinction/reddening will be required.

Direct mean distances of the closest galaxies of the Local Group will be within reach and, for example, the controversy between the LMC distances determined from Cepheid (mainly located in the bar) and RR Lyrae (mainly in globular clusters) will be outdated: a sufficiently large number of Cepheids and RR Lyrae will be observed by *Gaia* to obtain directly the mean distance without use of intermediate objects or indirect methods. For example, by using the restricted sample of Cepheids with V photometry from Tanvir (1997) and *Gaia* accuracy as a function of apparent magnitude from Lindegren (1998), the mean distance with a relative accuracy of 4 % is obtained. Adding to these bright Cepheids about 1500 new Cepheids discovered in the microlensing surveys (and *Gaia* will certainly discover many others), a relative accuracy better than 2 % will be obtained.

The use of the nearly 8000 RR Lyrae stars discovered in the microlensing surveys (Alcock et al. 1996), with mean V magnitudes between 18.7 and 19.7, lead to the mean distance accuracy better than 10 %, and the *Gaia* epoch sampling will lead to the discovery of many new RR Lyrae stars.

In the Sagittarius galaxy, at distances estimated to be between 22±1 kpc (Alcock et al. 1997) and 24 or 25±2 kpc (Alard 1996, Ibata et al. 1997), and with a small extent along the line of sight (half-brightness depth of 1.2 kpc, Ibata et al. 1997), the mean V magnitude of the red clump is about 18.2, with V–I around 1.1. With a hundred such stars observed by *Gaia*, a mean distance known to better than 10 % would be obtained, with 2000 stars, 2 %.

In both cases, the determination of the extinction/reddening, very patchy, is essential. The determination of metallicity would provide the possibility to compare the period-luminosity relations of pulsating variables in our Galaxy and in its neighbors.

4. CONCLUSION

Gaia is a unique opportunity for an extended survey of absolute luminosities of stars of all ages, evolutionary phases, populations, all over the Galaxy and for the intrinsically brightest stars, to make comparisons between our Galaxy and the closest galaxies of the Local Group. The other missions aiming at similar astrometric accuracies (SIM or FAME) built for a restricted number of stars, will be required to make a selection of the stars to be observed, with a bias toward solving known problems. With *Gaia*, all types of objects will be equally observed, and all existing systematics will be completely explored.

For the extragalactic distance scale, *Gaia* will provide consistent and homogeneous astrometric and photometric data for a huge number of each type of stellar candles, open and globular clusters, pulsating variables, supergiants, central stars of planetary nebulae, etc., along with a parallel determination of the extinction/reddening and metallicity for a large range of stellar types thanks to suitable spectroscopic/photometric data.

Conclusions with respect to *Gaia* observing requirements:

• keep as high as possible the astrometric accuracy for bright stars for calibrating stellar candles in our Galaxy, down to $V \sim 4$ mag for Cepheids and stars in open clusters, less stringent for the other candles (6 mag for supergiants and 8 mag for RR Lyrae stars);

• obtain a good astrometric and photometric accuracy for faint stars: up to $V \approx 19$ mag for observing the turn-off of distant globular clusters or RR Lyrae stars in the Large Magellanic Cloud;

• select the spectroscopic/photometric system to obtain:

– the best possible determination of the extinction/reddening to be consistent with the accuracy reachable on the absolute magnitude from the distance uncertainty only;

– the best possible determination of metal abundance for the largest range of stellar types to be able to investigate the systematic effects due to metallicity;

– a good comparison with stellar evolution models and reliable age determinations, to be able to transform the observed magnitudes and colors to bolometric magnitudes and effective temperature.

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