2017.09.02 the dropbox links changed to website

2015.10.16 **DRAFT** With comments by Matthias Steinmetz in Appendix C and info on APASS in Appendix D.

2015.09.09 With comments by Ulrike Heiter and Paul McMillan in Appendix B.

Previous version of 2015.07.03 with updates in red**:**
http://www.astro.ku.dk/~erik/xx/GaiaMag4.pdf
Section 3: How good is 4Most for photometric distances? See
the crucial questions in Section 4.
Section 5 on extinction.
To be discussed: The role of knowing the stellar mass for predicting absolute magnitude from spectra and photometry.

Previous version of 2015.05.28 with updates in red**:**
http://www.astro.ku.dk/~erik/xx/GaiaMag20150528.pdf

Previous version of 2015.05.14 with updates in red**:**
http://www.astro.ku.dk/~erik/xx/GaiaMag20150514.pdf

An overview of photometric distances

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ABSTRACT

Context. The use of Gaia proper motions for kinematic studies depends crucially on knowing the distances to the stars. They can be obtained from Gaia parallaxes for the same stars, but only for a small part of all the stars for which accurate proper motions will be obtained. Distances for the more remote stars can only be obtained by multi-colour photometry and/or spectra from which the absolute magnitudes, the apparent magnitudes, the interstellar extinction, and the distance are derived. Such distances are here called "photometric distances" for the sake of brevity.

The present time. We give an overview of luminosity calibration and derivation of distances, as found in the literature and from correspondence with several colleagues. We focus on surveys covering the whole sky or large parts of it, not just on clusters or other small parts of the sky. Estimates of the accuracy of photometric distances obtained by various authors have so far been found in three cases: 0.40, 0.41 and 2 mag for the distance moduli. For surveys of giants with limited sky coverage 2% accuracy of distances, i.e. 0.04 mag for the moduli has been reported.

An accuracy for photometric distances of 20% i.e. 0.40 mag for distance moduli for normal, constant single stars seems to be a conservative estimate for the present. This is based on present day stellar structure models and Hipparcos parallaxes

The future. The millions of accurate Gaia parallaxes becoming available will lead to improved knowledge of stellar structure and evolution. Combined with these millions of stellar distances for calibration, much better photometric distances will be the result. Photometric distances for hundred millions of stars with an accuracy of 10% will perhaps be common standard by 2025. An accuracy of 1 or 2 % may even be obtained for giants and some other types of stars.

Messages agreeing with my conclusions in Sect.8 have been received from: Tansel Ak, Selcuk Bilir, and Arne Henden.

Preamble

Distances of stars are needed to derive tangential velocities from proper motions. Distances may be obtained from the parallaxes observed with Gaia, but they must be supplemented by distances for remote stars derived from photometry because 80% of the stars in Gaia are expected to have parallax errors worse than 20%.

Proper motions and tangential velocity, however, can be obtained with good accuracy for many more stars, especially if a Gaia successor mission in twenty years is considered, as shown in Table 2 of Høg (2015). This table shows e.g. that a tangential velocity with a very useful accuracy of 2 km/s is obtained for a star of G=16 mag at a distance d=19.5 kpc from Gaia and at d=195 kpc from Gaia1+2 data provided the distance is known. The accuracy of trigonometric distances from Gaia is given in Table 1 of Høg (2015) showing e.g. 41 muas error for the parallax of a G=16 star. Since the parallax at 20 kpc is 50 muas the trigonometric distance is practically useless having nearly 100 % error.

It thus appears that photometric distances are very much needed. The present overview is meant to be a help to further work on this matter in spite of its deficiencies: It is far from complete and in some respects not self-consistent, it contains no tables and no figures, it gives references but few descriptions of the methods. The version owes much to comments by Regner Trampedach (Space Science Institute, Boulder, USA and Stellar Astrophysics Centre, Aarhus University) to a previous version of 2015.05.28. Some of these comments are taken into account in the following main text, others are contained in Appendix A. Further comments by Ulrike Heiter and Paul McMillan are contained in Appendix B, and comments by Matthias Steinmetz in Appendix C.

1 Introduction

Photometric distances are in principle derived from the apparent magnitude *m* and the spectral energy distribution (*SED*) of the star using the Pogson law. The photometric distance *d* is a function of *m*, *M* and *A*, which are functions of the particular wavelength band considered. Thus, *d* is a function of *m* and *SED*:

$$d = d\,(m, M, A) = d\,(m,\ SED)$$

These quantities follow Pogson's law: $M = m - 5\log(d) + 5 - A$,

with the usual symbols of respectively *M, m, d, A* for the absolute magnitude, the apparent magnitude, the distance (in pc) and the interstellar extinction. The absolute magnitude *M* and the interstellar extinction *A* must be obtained from the observed *SED* and these observations and the data analysis have required great efforts and given results which are subject of the following overview.

In other words: The absolute (bolometric) magnitude of a star depends on its T_{eff} and radius: $M(T_{eff}, R)$, and T_{eff} is derived from photometry and spectroscopy with some dependence on atmosphere models. Surface gravity can be found from spectroscopy with sizable uncertainty. Radius and mass is found (presumably) with the various methods listed in Sect. 4. More briefly: T_{eff}, *log g,* and the metallicities [Fe/H] and [alpha/Fe] give together the absolute magnitude *M.* When the extinction and the apparent magnitude *m* are known, the distance *d* can be obtained.

Observations are obtained in the optical wavelength interval 300-2500 nm by spectra and photometry as illustrated in, e.g., Fig. 1 of Henden & Munari (2014). This figure shows the spectral energy distributions of a G0 main sequence and of a Red Clump star (the typical field stars in any magnitude limited sky survey), over plotted with the transmission profiles of Landolt *BV* and Sloan *g'r'i'* bands adopted by APASS. The infrared 2MASS *JHK* bands at 1.1-2.3 µm (including telluric absorptions) are also plotted. A thick horizontal dash at 860 nm marks the wavelength range covered by RAVE and Gaia spectra.

Analyses of observations are based on astrophysical assumptions with various degrees of sofistication on especially stellar evolution, interstellar extinction, and galactic populations.

According to the following messages from Santiago and Henden, the problems for distances are: 1) how well can giants be separated from dwarfs and 2) how well can the extinction be determined; The extinction is discussed in Section 5.

Bilir & Ak say below that giants and dwarfs can be distinguished by means of V and 2MASS photometry. We could ask specifically, how well can it be done by Gaia photometry and spectroscopy. In the Appendix B Paul McMillan proposes to use Gaia parallaxes for the distinction. How well can it be done by 4MOST spectroscopy? Answers as function of magnitude are wanted.

2 Calibration with parallaxes

The photometric distance method requires a calibration of the absolute magnitudes for the classes of stars being considered. This has so far been done with trigonometric parallaxes form the Hipparcos satellite which obtained parallaxes for about 100,000 stars with typically 1 milliarcsec (1 mas) accuracy, and 719 stars have an accuracy of 1% for the distance.

Calibration will be much strengthened by Gaia. The trigonometric distances from Gaia will have, e.g., better than 1.0 percent accuracy for 10 million stars, most of these will be dwarfs. For giants of luminosity class III, the sample within 2 kpc from the sun will contain stars brighter than *V* about 11.5 mag if we assume an absolute magnitude about zero to be typical. With σ_π=7.1 µas a relative accuracy better than 7.1/500 or 1.4 percent is then obtained for distances of giants. These several hundred thousand giants will be available for luminosity calibration and they will have excellent photometry in G, BP, and RP and spectra from RVS (Radial Velocity Spectrometer) so that physical characteristics can be derived. Gaia photometry is obtained in a broad band, G, and from two low dispersion spectra, BP and RP, in respectively blue and read, all in the wavelength interval 330-1050 nm, see details at Gaia (2015).

More precise estimates of the number of stars may be obtained from the population synthesis Galaxy star count model TRILEGAL (TRIdimensional modeL of thE GALaxy[1], Girardi et al. 2005, 2012) as described in Sect.3.1 of Perryman et al. (2014).

In Sect.6 we focus on the derivation of distances to RGB (Red Giant Branch) stars since they play a crucial role in the paper by Helmi et al. (2012) about dark matter substructures in the Galaxy Halo.

3 Surveys

Some of the surveys considered in the distance determination in the following Section 4 are

1) The RAVE survey, see RAVE (2013) and Appendix C.

RAVE (RAdial Velocity Experiment) is a multi-fiber spectroscopic astronomical survey of stars in the Milky Way using the 1.2-metre UK Schmidt Telescope of the Australian Astronomical Observatory (AAO). The CaII triplet at 840 – 875 nm is observed.

2) The APASS survey, see Munari et al. (2014) (Appendix D) and earlier Henden & Munari (2014).

The APASS photometric survey covers the whole sky, from Pole to Pole, and has measured in Landolt B, V and Sloan g’,r’,i’ bands all stars in the range 10.0<V <17.0 over about four distinct epochs between 2009 and 2013. The photometry is accurate to 0.02 mag and the astrometry to 0.17 arcsec. At the time of writing (2013) 8

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[1] At http://stev.oapd.inaf.it/trilegal

incremental Data Releases have been issued covering about 50 million stars. The final survey products will be ready by the end of 2014 and will include 100 million stars. Extension to brighter stars (7.5<V<10.0) and additional bands (u', z' and Y) is underway.

The authors Henden & Munari write on p.519: "In addition to filling in a wide magnitude gap in the photometric coverage of the sky not to be addressed by future surveys, APASS is also filling in the time gap with Pan-STARRS and LSST from which data will not be available for probably another decade. Scientific exploitation of APASS data has already begun, examples being: derivation of photometric temperatures…"

I am suggesting that photometric distances with an accuracy of 20% for the 100 million stars of APASS could be obtained by the method described by Santiago et al. (2015).

3) The Gaia satellite survey, see Sect. 2.

The errors of Gaia astrometry, photometry etc. as expected before launch have most recently been given by Luri et al. (2014). It appears from Fig.17 that the photometric errors at G=19 are about 3 mmag for G and 8 mmag for the low-dispersion red GRP, but much larger for the blue band GBP. Absolute magnitudes may therefore perhaps be obtained from the spectra of faint red stars. But the main source for accurate absolute magnitude of faint Gaia stars would probably be other photometric surveys and the 4MOST spectra, after luminosity calibration with the Gaia parallaxes.

4) The 4MOST survey by VISTA – the 4-metre Multi-Object Spectroscopic Telescope.

Spectra for radial velocities and photometry for classification and distances of faint stars may be obtained in great number with the 4MOST facility of ESO (de Jong et al. 2012, Fig.1) which will be running spectroscopic Public Surveys on VISTA nearly full time from about 2020. Radial velocities are required to obtain space velocities for unambiguous dynamical studies. Radial velocities of ≤ 2 km/s accuracy of the faintest stars observed by Gaia may be obtained with 4MOST, and the Table 2 of Høg (2015) compares the performance of Gaia and 4MOST.

The 4MOST spectra should be uniquely suited for deriving photometric distances to the stars, which is very much needed since no other distances are available for the majority of stars observed. But I have not found any discussion of this possibility yet. **How good is 4Most for photometric distances?**

5) Further surveys are mentioned in Santiago et al. (2015): The photometric data cover both the optical and near infra-red wavelengths. The spectroscopic parameters are also based on spectra taken at various wavelengths, with varying spectral coverage and resolution: the Radial Velocity Experiment (RVS) of Gaia, the Sloan Digital Sky Survey programs SEGUE and APOGEE, and the ESO HARPS instrument.

4 Distances

RAVE: Distance determinations by Zwitter et al. (2010) and Binney et al. (2014) from observations with the RAVE survey are outlined. Hanson & Bailer-Jones (2014) describe a method to derive distance moduli using multi- band photometry from SDSS and UKIDSS.

Bilir et al. (2013) have derived an M_V absolute magnitude calibration in terms of the B-V colour and [Fe/H] metallicity using the RC (Red Clump) stars, in the globular and open clusters with a wide range of metallicities. The standard error of the resulting absolute magnitude is 0.036 mag, corresponding to an error in the distance of 1.8%, provided the error on extinction can be neglected. This distance error is valid for a single RC star.

Because the RC stars are bright objects and can be easily identified in the stellar clusters, they can be used as indicators either for Galactic distances and distances of the galaxies in the local group. Bilir et al.'s (2013) calibration gives an error in the distance of up to 5% for the local group galaxies.

As for the separation of the giants from the dwarfs, this separation can be obtained by using magnitudes in the wide photometric bands located in the two different parts of the electromagnetic spectrum. Bilir et al. (2006a) showed that V and 2MASS magnitudes can be effectively used for such a separation. Their method has been confirmed using the data from the photometric data of the stellar clusters (Bilir et al., 2006b) and RAVE data (Bilir et al., 2011).

Tansel Ak and Selcuk Bilir agree with my conclusions.

Zwitter et al. (2010) determine distances from spectra of the CaII triplet based on assumptions on a standard stellar evolution scenario as described in sect. 2 of the paper. The method is applied to observations from the RAVE survey, described in RAVE (2013) and Appendix C.

The derived distances of both dwarfs and giants match within ~ 21% to the astrometric distances of Hipparcos stars and to the distances of observed members of open and globular clusters. This corresponds to an accuracy of 0.41 on the distance modulus.

Henden & Munari (2014) and Munari et al. (2014) describe the APASS photometric survey covering the whole sky, from Pole to Pole, with the Landolt B, V and Sloan g',r',i' bands, see more in section 3.

Arne Henden: "I have reviewed your paper and agree with your conclusions. The hardest part of estimating distances through photometry/spectroscopy is in fully characterizing the observations. Extinction must be included properly, and determining an accurate spectral type is necessary (not easy with wide-band photometry, and getting spectroscopy of a statistically large sample of faint stars is difficult). Direct distance measurements through parallax will thus dramatically change our knowledge of the local universe."

Binney et al. (2014) also determine distances for stars in the RAVE survey. The authors use improved data compared with those used by Zwitter et al. (2010) and they use a more advanced method. Regrettably, they do not give any accuracy for the derived distance explicitely as did Zwitter et al.

The authors determine probability density functions (pdf) from new stellar parameters for the distance moduli of stars for which the RAVE has obtained spectra with S/N ≥ 10. Single-Gaussian fits to the pdf in distance modulus suffice for roughly half the stars, with most of the other half having satisfactory two-Gaussian representations.

Quotation from p.2 of the paper: "We use the Bayesian framework described by Burnett & Binney (2010) but modified to allow for the impact of interstellar dust. Two other significant novelties are (i) the production of multi-Gaussian fits to each star's probability density function (pdf) in distance modulus and (ii) the use of the kinematic correction factors introduced by Schönrich et al. (2012) to check for systematic errors in our distances.We have derived distances for all stars that have spectra to which the new pipeline assigns a signal-to-noise ratio of 10 or higher. When a star has more than one spectrum in the database, the catalogued distance is that derived from the highest S/N spectrum."

Hanson & Bailer-Jones (2014) describe a method to derive distance moduli from multi-colour photometry to approximately 2 mag.

They write: "We present a method to simultaneously infer the interstellar extinction parameters $A0$ and $R0$, stellar effective temperature Teff, and distance modulus μ in a Bayesian framework. Using multi-band photometry from SDSS and UKIDSS, we train a forward model to emulate the colour-change due to physical properties of stars and the interstellar medium for temperatures from 4000 to 9000 K and extinctions from 0 to 5 mag. We introduce a Hertzsprung-Russel diagram prior to account for physical constraints on the distribution of stars in the temperature-absolute magnitude plane. This allows us to infer distances probabilistically. Influences of colour information, priors and model parameters are explored. Residual mean absolute errors (MAEs) on a set of objects for extinction and temperature are 0.2 mag and 300 K, respectively, for *R*0 fixed to 3.1. For variable *R*0, we obtain MAEs of 0.37 mag, 412.9 K and 0.74 for *A*0, *T*eff and *R*0, respectively. Distance moduli are accurate to approximately 2 mag."

Coryn Bailer-Jones answered in Feb. 2015 my question about photometric distances. He has not looked specifically into the issue of photometric distances, and he does not know who yet has (if anyone within the context of Gaia and Gaia data), but they do plan to estimate distances to stars using the estimation of the astrophysical parameters they are doing based on the BP/RP spectra. This will be important, because 80% of the stars in Gaia are expected to have parallax errors worse than 20%.

Coryn Bailer-Jones in March 2015 answers my question about his large error of 2 mag on the modulus compared with 0.4 mag by others:

His quick answer is that at large distance it is very hard to estimate distances with any accuracy: "Our distance modulus accuracy does vary with distance, I seem to recall. Furthermore, we are estimating four parameters (Teff, A_r, R_0, and distance modulus) from a prior very large initial range, using just a handful (5 to 8) of measurements, not all of which are informative about these parameters. I put the first author of that paper, Richard Hanson, in cc, in case he wants to add more."

Richard Hanson added: "as Coryn correctly summarized, the key issue is that we derived distance moduli as one of four parameters simultaneously, whilst making only few assumptions about the prior parameter space. As we do not infer metallicity (and cannot with reasonable accuracy do so with the data employed), we find that changes to the HRD prior can introduce significant uncertainty with respect to distance estimation (see Sec. 4.1 and Fig. 6)."

Rodrigues T.S. et al. (2014) report on accuracies of 2 per cent for giants in surveys with limited sky coverage: "The first 1989 giants targeted by APOKASC are found at typical distances between 0.5 and 5 kpc, with individual uncertainties of just about 1.8 per cent."

Cristina Chiappini, coauthor of Rodrigues et al. wrote that she will contribute.

Santiago et al. (2015) describe a general-purpose Bayesian approach. They have developed a procedure that estimates distances to stars using measured spectroscopic and photometric quantities. It employs a Bayesian approach to build the probability distribution function over stellar evolutionary models given the data, delivering estimates of expected distance for each star individually. The method provides several alternative distance estimates for each star in the output, along with their associated uncertainties. The photometric data cover both the optical and near infra-red wavelengths. The spectroscopic parameters are also based on spectra taken at various wavelengths, with varying spectral coverage and resolution: the Radial Velocity Experiment, the Sloan Digital Sky Survey programs SEGUE and APOGEE, and the ESO HARPS instrument. For Hipparcos and CoRoT samples, the typical random distance scatter is 20% or less, both for the nearby and farther data. There is a trend towards underestimating the distances by < 10%. – A 20% relative distance error corresponds to a 0.40 mag error in the distance moduli.

Basilio Santiago, brief comment in March 2015: "I agree that luminosity calibration is an essential step towards improving the accuracy of photometric parallaxes. And GAIA's parallaxes will greatly improve the size of calibrating samples for all stellar classes. On the other hand, identifying to which class a star belongs using photometry alone is equally important to infer its distance. It is often very hard to disentangle dwarfs from giants with photometry alone, since they tend to be more efficiently separated if log *g* is available and this latter only weakly correlates with photometric measurements. I believe that this is likely to be the main difficulty in achieving accurate photometric distances (even to 20%). As I understand, however, GAIA will also produce spectra for a sizeable sample, from which spectrophotometric distances can be inferred. - I will get back to you as soon as I can.”

5 Extinction - section added in March-May 2015

Interstellar extinction may be obtained from photometry and/or spectroscopy of every star individually. An overview of the present and future accuracy of such determination is wanted and of the effect on photometric distances.

Photometric extinctions are generally determined from the dust maps of Schlegel et al. (1998) who gives extinction up to the edge of the disc in any Galactic direction. These extinctions must be reduced according to the distance of the object in question. Precision of the extinctions depends on the distance and the Galactic latitude. For the Galactic disc, extinctions obtained from these maps are not reliable. For the stars whose distances found from the Hipparcos parallaxes, extinctions obtained from the dust maps can be reduced using Bahcall & Soneira's (1980) formulae. Appendix B of that paper describes how reddenings and extinction in different optical and infrared filters can be related.

Comments by Trampedach: ”Add a description of the work Schlegel at al.. That would be a good foundation for the rest of this section. Also explain what is meant by "reducing" the extinction "...according to the object in question.". The sentence mentioning Bahcall & Soneira's (1980) formula seems incomplete. What does that formula do (related to what "reduction" means here)?”

This method may be supplemented by means of a three-dimensional map of interstellar clouds including the absorbing characteristics of each cloud. Such a map can be constructed when Gaia has delivered a three-dimensional map of the expected millions of stars, 100 million stars will obtain an accuracy of better than 5% on distances. An overview of the capability of this idea is wanted. My guess would be that these tools together, individual photometry and a map of all clouds, will provide extinction values in most of the sky which will contribute only little to the uncertainty of photometric distances.

Distances to neutral and ionized clouds as well as dust clouds can be bracketed by stars observed along the line of sight as pointed out on p.51 in ESA (2000). The method has been used by Knude & Høg (1998) to estimate distances of molecular clouds by combining Hipparcos parallaxes, Tycho-2 colour indices, and spectral classification data. In Knude & Høg (1999) 21 cm emission data were also taken into account resulting in distances of intermediate- and high- velocity clouds. Gaia will provide distances within 10 per cent to hundreds of clouds in the halo and disk, according to ESA (2000).

The use of a 3-D map of the clouds as a tool to improve the extinction and thus the photometric distance to stars in general is not mentioned in ESA (2000), but this is our proposal here.

It is similar to a method used for recent studies, according to information received from Tansel Ak & Selcuk Bilir. Ak & Bilir added: ”… we do not know how Gaia's extinction calibration is and what method will be use for estimation of the extinction. Thus, we cannot know the future precision of the extinction.”

Jens Knude wrote that main sequence stars may be better than giants for estimation of extinction because the main sequence colder than turn off is much sharper than the giant branch(es) and may be empirically calibrated using nearby targets with negligible extinction. The main sequence earlier than the turn off has a much smaller logg variation than star in the giant band. Knude has also seen that the BP/RP validations show the smallest success rate for giants. Knude is referring to the recovery of the astrophysical parameters for possible "best" extinction tracers (those with A_G,est - A_G,true < 0.1 or 0.03 mag). A reference for estimating A_r for a band of M dwarfs is e.g. Knude and Lindstrøm (2012).

This was discussed with Tansel Ak and Selcuk Bilir when we met in Istanbul on 22 April and they maintain their prediction of the possible accuracy for giants.

6 Why RGB stars?

I have asked Amina Helmi and the coauthor Andrew Cooper why RGB stars were chosen as tracers in the study of dark matter substructures by Helmi et al. (2011) and not some other type of star. **Helmi answered** very concisely: ”There are plenty of RGB stars for every (old) stellar population and they are bright, so one can probe large distances, far out in the galactic halo. MSTO (main sequence turnoff) are more common, and hence even more useful but one is restricted to remain in the inner 20-30 kpc down to V ~ 20 – 22 mag.”

Andrew Cooper elaborated in his mail on 18 Dec. 2014: “To create mock observations from the coarse sampling of the stellar mass density in the Cooper 10 simulations, Helmi et al. converted each single stellar population 'tag' into a number of tracer stars of an assumed type, having particular values magnitude and abundance by number.” - By 'abundance' in this context is meant the number of stars of a particular type per unit mass of all stars in a population.

Cooper continued: “We adopted two fiducial tracer magnitude/abundance combinations, labelled, somewhat loosely, 'turn-off' (faint and numerous) and 'RGB' (bright and sparse). The fiducial number of stars and magnitude for these two tracer types are reasonable at the back-of-the-envelope level, but they are empirical rather than predictions of a particular stellar evolution model. I'm not sure the paper even specifies what the assumed magnitude of the 'RGB' tracers is, just that they are visible to a certain large distance (of course, real RGB stars have a relatively wide range of magnitudes and the term itself is not all that well defined from an operational point of view).”

“It might be most appropriate to just think of the paper as talking about 'bright tracers' (i.e. a tracer visible to ~100 kpc or so) and 'faint tracers' (visible to ~35 kpc). We could equally well have called the bright tracers 'K giants' or some such -- most of the points in the paper don't depend on which specific type of star is used. (That said, since we didn't weight these distributions by the metallicity or age of the stellar tags, it wouldn't have been appropriate to have called the bright tracers 'horizontal branch' stars, since HB stars have stronger number-per-unit-mass biases than giant branch stars in those two parameters.)”

“If you're interested in these issues, you might like to look at Lowing et al. (2015) where we used isochrones specific to each stellar population to generate much more realistic mock catalogues.

Cheers, Andrew .” – End of quotation from Cooper.

7 Calibration according to Max Palmer

Palmer (2014) has studied luminosity calibrations with Gaia data, see the abstract at Palmer (2014a). Palmer has developed a general method which can be used to determine absolute magnitudes of any kind of stars. In his thesis, Max Palmer has so far addressed RR-Lyrae and Cepheid variables and calibrated their period-luminosity relation.

Other types of stars could be treated in the same way, according to Palmer in our correspondence. But this requires that the absolute magnitudes of the considered class or group of stars obey a relation so that the quantity to be calibrated has a narrow distribution function. This would be the case if the absolute magnitude is a function of measurable spectral features, which brings us to the tasks mentioned in Sect. 1.

Max Palmer answered my question about the calibration of RGB stars with his method on 19 Dec. 2014:

“I have not specifically studied RGB stars in relation to this method but provisionally I think that it would be possible. In Sec. 4 you will find the example for the basic method. By constructing a (multi colour) model for the expected absolute magnitude of RGB stars to replace the simple magnitude distribution given in the example, you can fit the absolute magnitude (and distance) by including Gaia parallaxes and other multicolour photometry measurements.

Including more information into the fitting (e.g. extinction estimates, kinematics) could also constrain the distances further.

If you or anybody else is thinking of attempting this I would be happy to help.
- Max” –End of quotation from Palmer.

Trampedach has commented: “His method needs to also be described, not merely mentioned. Specifically what is the difference between a "...(multi colour) model for the expected absolute magnitude..." versus "...a simple magnitude distribution..."? ”

These questions have been passed on to Palmer. The answer will be taken into account. But the correspondence with Palmer has not continued since he has not become available by June 2015.

8 Conclusion

An accuracy for photometric distances of 20% i.e. 0.40 mag for distance moduli for normal, constant single stars seems to be a conservative estimate for the present. This is based on present day stellar structure models and Hipparcos parallaxes

The millions of accurate Gaia parallaxes becoming available will lead to improved knowledge of stellar structure and evolution. Combined with these millions of stellar distances for calibration, much better photometric distances will be the result. Photometric distances for hundred millions of stars with an accuracy of 10% will perhaps be common standard by 2025. An accuracy of 1 or 2 % may even be obtained for giants and some other types of stars.

Further contributions from Cristina Chiappini and Basilio Santiago have been announced, but are no longer truely *expected* . Arne Henden wrote in May 2015: ”… I looked through the paper, and have no further comments. Thanks for letting me see the evolution of this important topic!”

Acknowledgements: I am grateful for inform ation and comments from Tansel Ak, Coryn Bailer-Jones, Selcuk Bilir, Andrew Cooper, Richard Hanson, Ulrike Heiter, Amina Helmi, Arne Henden, Jens Knude, Paul McMillan, Max Palmer, Basilio Santiago, Matthias Steinmetz and Regner Trampedach.

9 References Some hyperlinks are incomplete!

Bahcall, J. N.; Soneira, R. M. 1980, The universe at faint magnitudes. I - Models for the galaxy and the predicted star counts. Astrophysical Journal Supplement Series, vol. 44, Sept. 1980, p. 73
`http://esoads.eso.org/abs/1980ApJS...44...73B`

Bilir, S.; Karaali, S.; Güver, T.; Karataş, Y.; Ak, S. G.,2006a, AN, 327,72

Bilir, S.; Güver, T.; Aslan, M., 2006b, AN, 327, 693

Bilir, S.; Karaali, S.; Ak, S.; Onal, O.; Coskunoglu, B.; Seabroke, G. M., 2011, MNRAS, 418, 444

Bilir, S., Ak, T., Ak, S., Yontan, T., Bostancı, Z.F. 2013, A New Absolute Magnitude Calibration for Red Clump Stars. New Astronomy, 23, 88. `http://de.arxiv.org/pdf/1303.3292v1`

Binney J., Burnett B. et al. 2014, New distances to RAVE stars. Mon. Not. R. Astron. Soc. 000, 1–21 (2012) Printed 12 February 2014. `http://arxiv.org/abs/1309.4270`

Cooper A.P., Cole S., Frenk C.S. et al. 2010, Galactic stellar haloes in the CDM model. Mon. Not. R. Astron. Soc. **406,** 744–766 (2010). `http://mnras.oxfordjournals.org/content/406/2/744`

de Jong Roelof S., Olga Bellido-Tirado, Cristina Chiappini, et al. (>60 additional authors) 2012, 4MOST - 4-metre Multi-Object Spectroscopic Telescope. `http://arxiv.org/abs/1206.6885`

ESA 2000, GAIA – Composition, Formation and Evolution if the Galaxy. Concept and Technology Study Report. ESA-SCI(2000)4.

Gaia 2015, Gaia photometric instrument. `http://www.cosmos.esa.int/web/gaia/photometric-instrument`

Girardi, L., Groenewegen, M. A. T., Hatziminaoglou, E., et al. 2005, A&A, 436, 895

Girardi, L., Barbieri, M., Groenewegen, M. A. T., et al. 2012, in ASSL, 165

Hanson R.J. and Bailer-Jones C.A.L 2013, 3D Galactic dust extinction mapping with multi-band photometry. Mon. Not. R. Astron. Soc. http://www2.mpia-hd.mpg.de/~calj/ or `http://arXiv.org/abs/1312.3424`

Helmi, A., Cooper, A. P., White, S. D. M., Cole, S., Frenk, C. S., Navarro, J. F., 2011, Substructure in the Stellar Halos of the Aquarius Simulations. ApJL 733, L7. `http://esoads.eso.org/abs/2011ApJ...733L...7H`

Henden A. &. Munari U. 2014, The APASS all-sky, multi-epoch BVgri photometric survey. Contrib. Astron. Obs. Skalnate Pleso 43, 518 { 522, (2014). See p.518 at: *http://www.astro.sk/caosp/Eedition/Abstracts/2014/Vol_43/No_3/index.html*

Høg E. 2015, Absolute astrometry in the next 50 years. Draft report: 2015. `http://arxiv.org/abs/1408.2190`

Høg, E. 2015a, Gaia6 – a large Gaia successor. `http://www.astro.ku.dk/~erik/xx/Gaia6.pdf`

Knude, J.; Høg, E. 1998, Interstellar reddening from the HIPPARCOS and TYCHO catalogues. I. Distances to nearby molecular clouds and star forming regions. Astronomy and Astrophysics, v.338, p.897 `http://esoads.eso.org/abs/1998A%26A...338..897K`

Knude, J.; Høg, E. 1999, Interstellar reddening from the HIPPARCOS and TYCHO catalogues. II. Nearby dust features at the NGP associated with approaching HI gas. Astronomy and Astrophysics, v.341, p.451 `http://esoads.eso.org/abs/1999A%26A...341..451K`

Knude J., Lindstrøm H.E.P. 2012, MBM 12 and MBM 16 distances. Accepted for publication in MNRAS 2012. `http://arxiv.org/pdf/1202.3600v1.pdf`

Lowing, B. et al. 2015, Creating mock catalogues of stellar haloes from cosmological simulations. Monthly Notices of the Royal Astronomical Society, Volume 446, Issue 3, p.2274-2290. Only the abstract is available at the link: `http://adsabs.harvard.edu/abs/2015MNRAS.446.2274L`

Luri, X.; Palmer, M.; Arenou, F.; Masana, E.; de Bruijne, J.; Antiche, E.; Babusiaux, C.; Borrachero, R.; Sartoretti, P.; Julbe, F.; and 6 coauthors 2014, Overview and stellar statistics of the expected Gaia Catalogue using the Gaia Object Generator. Astronomy & Astrophysics, Volume 566, id.A119, 15 pp. `http://adsabs.harvard.edu/abs/2014A%26A...566A.119L`

Munari U., Henden A., Frigo A. and further 24 coauthors 2014, APASS Landolt-Sloan BVgri photometry of RAVE stars. I. Data, effective temperatures and reddenings. The Astronomical Journal, 148:81 (15pp), 2014 November `http://arxiv.org/abs/1408.5476`

Palmer M. 2014, Astrostatistics for luminosity calibration in the Gaia era. A dissertation presented to the Department of Astronomy and Meteorolog y for the degree of Doctor of Physics in the subject of astrophysics, University of Barcelona, Barcelona, Spain, November 2014. 211 pages. `https://www.dropbox.com/s/9bknygq8wtvgc47/MaxPalmerThesis.pdf?dl=0`

Palmer M. 2014a, Abstract of Palmer's thesis. `http://www.astro.ku.dk/~erik/xx/GaiaMagPalmer.pdf`

RAVE 2013, See overview and references in http://en.wikipedia.org/wiki/RAVE_(survey)

Rodrigues T.S. et al. 2014, Bayesian distances and extinctions for giants observed by Kepler and APOGEE. `http://arxiv.org/abs/1410.1350`

Santiago, B.. 2015, Spectro-photometric distances to stars: a general-purpose Bayesian approach. Astron. Astrophys. Submitted on 22 Jan. 2015. `http://arxiv.org/abs/1501.05500`

Schlegel, David J.; Finkbeiner, Douglas P.; Davis, Marc 1998, Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds. The Astrophysical Journal, Volume 500, Issue

2, pp. 525-553 `http://esoads.eso.org/abs/1998ApJ...500..525S`

Zwitter et al. 2010, Distance determination for RAVE stars using stellar models . II. Most likely values assuming a standard stellar evolution scenario. Astronomy and Astrophysics, Volume 522, id.A54, 15 pp. `http://esoads.eso.org/abs/2010A%26A...522A..54Z`

Appendix A

Extensive comments were received from Regner Trampedach on 2 June 2015. Some of the suggested additions or corrections to my text have been introduced in the present above version while the remaining comments follow hereafter.

Regner Trampedach commented:

Dear Erik,

Hereby my comments to your report, "An overview of photometric distances". This is a very interesting topic, that certainly deserves some careful analysis. Considering Gaia's launch and start of science operation, this report is indeed timely.

It is also rather hard to read, as there is little information about the actual methods envisioned, save for the references. The references are, of course, indispensable for finding all the background information, but the reader might be more sympathetic to your cause if faced with a convincing case that is also self-contained.

The fundamental problem is that, although Teff can be determined rather well from spectroscopic observations, surface gravity is much less well determined, and R (or equivalently M) cannot be obtained from spectroscopy or photometry, alone. But nothing is said in the report about how R is to be constrained, except for in the case of Hanson & Bailer-Jones (2014)'s work, mentioned on p.5. Please mention for each method, how this gap is bridged.

I have been working on an absolute calibration of synthetic photometry of my grid of 3D radiation-coupled hydrodynamics simulations of deep convective solar metallicity, stellar atmospheres (Trampedach et al. 2013), against the sample of solar twins by Casagrande et al. (2010). I have not had time to finish that calibration and have yet to find the best method for dealing with the unknown radius of the observed solar twins.

I will be happy to review an updated version of your report, and will keep you posted as to my progress on my absolute calibration of photometry.

Sincerely Yours,
Regner

Some specific comments by Trampedach:
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p.3, Surveys, 2) APASS:
What kind of telescope(s) is employed by APASS? What does APASS stand for?
The status report of 2013 needs to be updated - is the survey now complete?
Note by EH: These questions have been answered by Henden & Munari in Appendix D.

The eclipses after "derivation of photometric temperatures" need to be replaced by more examples.
The suggestion "...that photometric distances with an accuracy of 20% for the 100 million stars of APASS could

be obtained by the method described by Santiago et al. (2015).", needs to be substantiated and the method needs at least a cursory description.

p.6, Distances, Rodrigues T.S. et al. (2014):

The reason the APOKASC survey has a "limited sky coverage", is that it provides classic observations (photometry and spectroscopy) of Kepler targets, that have seismically determined surface gravity and radius, and both with high precision. The very small error-bars on their distances are therefore contingent on years of dedicated, very stable, very precise, continuous, half hour cadence photometry.

Appendix B

Summary: Ulrike Heiter and Paul McMillan have sent the following comments which I hope others will make full use of but this is regrettably beyond my present capacity.

Ulrike Heiter wrote on 27.8.2015:

Hi Erik,

Thanks for sending a reminder.
This is a timely review.

I have not been working on the topic of photometric distances myself, but I can give you some general comments and refer to a colleague who has recently submitted a paper related to the topic.

1) Section 1 Introduction

Where you introduce the photometric distance d, I agree with Trampedach:
The expression simply corresponds to the definition of parsec (the units of d should be added here). The important points are to determine the absolute magnitude at a specific wavelength which depends on the stellar properties, and the extinction which is independent of stellar physics. These points should be stressed and discussed here (as already started). - This has been done on 2015.10.16 - Erik.

The general discussion of "crucial questions" and extinction could be moved here from Section 4 - (The "crucial questions" have now been moved, but not the extinction in Section 5 - Erik.) - Sections 4 and 5 then describe concrete solutions and applications related to these questions.

2) Section 3 Surveys

You should add a paragraph about the Gaia-ESO survey.
References:
Gilmore et al. 2012Msngr.147...25G
Randich et al. 2013Msngr.154...47R
Webpage:
http://www.gaia-eso.eu

3) Section 4 Distances

You could add a description of the method presented by Jofré et al:
http://arxiv.org/abs/1505.07806v1
This is a purely empirical method based on spectroscopically-identified twin stars. Extinction is determined from differential magnitudes and does not depend on extinction maps.

You can contact Paula Jofré about the status of the paper and with any further questions:
Paula Jofre <pjofre@ast.cam.ac.uk>

Best regards,
Ulrike

> **Paul McMillan** wrote:
> Erik,

I'm afraid I have been very busy since the meeting in Cambridge, and have not had the opportunity to give these issues the time and attention they need. I'm still rather busy but hope to have the time in the next month.

The one comment I can offer now is that it must be emphasised that a major difficulty in finding a photometric distance to a star is determining whether it is a dwarf or a (sub-) giant. Some studies (e.g. SDSS, Juric et al 2008) get around this problem because the stars they observe are so faint that they can reasonably be assumed to be (mostly) giants.

In the case of RAVE this was not the case, hence the use of multi-Gaussian pdfs by Binney et al (which was something I urged and implemented). Parallaxes from Gaia (even rather uncertain ones) will often allow one to make this determination with high confidence, thus allowing one to take would be a very uncertain photometric distance, and a very uncertain distance from the parallax, and combining them to provide a very accurate distance estimate.

Yours,

Paul

Appendix C

Summary: On 2015.09.27 Matthias Steinmetz sent the following information on the RAVE survey.

Dear Erik,
for an overview of RAVE, please have a look at
(i) the RAVE webpage: www.rave-survey.org
(ii) the RAVE data release papers:

\bibitem[Kordopatis et al.(2013)]{2013AJ....146..134K} Kordopatis, G.,
Gilmore, G., Steinmetz, M., et al.\ 2013, \aj, 146, 134
\bibitem[Siebert et al.(2011)]{2011AJ....141..187S} Siebert, A., Williams,
M.~E.~K., Siviero, A., et al.\ 2011, \aj, 141, 187
\bibitem[Zwitter et al.(2008)]{2008AJ....136..421Z} Zwitter, T., Siebert,
A., Munari, U., et al.\ 2008, \aj, 136, 421

\bibitem[Steinmetz et al.(2006)]{2006AJ....132.1645S} Steinmetz, M.,
Zwitter, T., Siebert, A., et al.\ 2006, \aj, 132, 1645

for chemical abundances:
\bibitem[Boeche et al.(2011)]{2011AJ....142..193B} Boeche, C., Siebert, A.,
Williams, M., et al.\ 2011, \aj, 142, 193

for distances
\bibitem[Binney et al.(2014)]{2014MNRAS.437..351B} Binney, J., Burnett, B.,

Kordopatis, G., et al.\ 2014, \mnras, 437, 351
\bibitem[Zwitter et
al.(2010)]{2010A&A...522A..54Z} Zwitter, T., Matijevi{\v c}, G., Breddels, M.~A., et al.\ 2010, \aap, 522, A54

\bibitem[Breddels et
al.(2010)]{2010A&A...511A..90B} Breddels, M.~A., Smith, M.~C., Helmi, A., et al.\ 2010, \aap, 511, A90

A few proceedings that give a nice summary:
\bibitem[Steinmetz(2014)]{2014EAS....67..161S} Steinmetz, M.\ 2014, EAS
Publications Series, 67, 161

\bibitem[Kordopatis(2014)]{2014sf2a.conf..431K} Kordopatis, G.\ 2014,
SF2A-2014: Proceedings of the Annual meeting of the French Society of

Astronomy and Astrophysics, 431

\bibitem[Steinmetz(2012)]{2012AN....333..523S} Steinmetz, M.\ 2012,
Astronomische Nachrichten, 333, 523

all the best

Matthias

Appendix D

Summary: On 2015.10.08 the following information on the APASS survey, copied from Munari et al. 2014 in arXiv

APASS Landolt-Sloan BVgri photometry of RAVE stars. I. Data, effective temperatures and reddenings.

We provide APASS photometry in the Landolt BV and Sloan g'r'i' bands for all the 425,743 stars included in the latest 4th RAVE Data Release. The internal accuracy of the APASS photometry of RAVE stars, expressed as error of the mean of data obtained and separately calibrated over a median of 4 distinct observing epochs and distributed between 2009 and 2013, is 0.013, 0.012, 0.012, 0.014 and 0.021 mag for B, V, g', r' and i' band, respectively. The equally high external accuracy of APASS photometry has been verified on secondary Landolt and Sloan photometric standard stars not involved in the APASS calibration process, and on a large body of literature data on field and cluster stars, confirming the absence of offsets and trends. Compared with the Carlsberg Meridian Catalog (CMC-15), APASS astrometry of RAVE stars is accurate to a median value of 0.098 arcsec. Brightness distribution functions for the RAVE stars have been derived in all bands. APASS photometry of RAVE stars, augmented by 2MASS JHK infrared data, has been chi2 fitted to a densely populated synthetic photometric library designed to widely explore in temperature, surface gravity, metallicity and reddening. Resulting Teff and E(B-V), computed over a range of options, are provided and discussed, and will be kept updated in response to future APASS and RAVE data releases. In the process it is found that the reddening caused by an homogeneous slab of dust, extending for 140 pc on either side of the Galactic plane and responsible for E(B-V,poles)=0.036 +/- 0.002 at the galactic poles, is a suitable approximation of the actual reddening encountered at Galactic latitudes |b|>=25 deg.