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Pseudomagnitudes and differential surface brightness: Application to the apparent diameter of stars

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ABSTRACT

The diameter of a star is a major observable that serves to test the validity of stellar structure theories. It is also a difficult observable that is mostly obtained with indirect methods since the stars are so remote. Today only ~600 apparent star diameters have been measured by direct methods: optical interferometry and lunar occultations. Accurate star diameters are now required in the new field of exoplanet studies, since they condition the planets' sizes in transit observations, and recent publications illustrate a visible renewal of interest in this topic. Our analysis is based on the modeling of the relationship between measured angular diameters and photometries. It makes use of two new reddening-free concepts: a distance indicator called pseudomagnitude, and a quasi-experimental observable that is independent of distance and specific to each star, called the differential surface brightness (DSB). The use of all the published measurements of apparent diameters that have been collected so far, and a careful modeling of the DSB allow us to estimate star diameters with a median statistical error of 1.1%, knowing their spectral type and, in the present case, the *VJHKs* photometries. We introduce two catalogs, the JMMC Measured Diameters Catalog (JMDC), containing measured star diameters, and the second version of the JMMC Stellar Diameter Catalog (JSDC), augmented to about 453 000 star diameters. Finally, we provide simple formulas and a table of coefficients to quickly estimate stellar angular diameters and associated errors from (*V*, *K*s) magnitudes and spectral types.

Key words. stars: fundamental parameters – methods: data analysis – astronomical databases: miscellaneous – catalogs – techniques: interferometric

1. Introduction

Most of our knowledge of the Universe still comes from, either directly or indirectly, an analysis of starlight. Stellar physics is used, implicitly or explicitly, in every astrophysical research field, and must be continually tested against observations. One of the most fundamental and dimensioning parameters of the physics of a star is its size, measured through its distance and its apparent angular size. The original interest in measuring stellar angular sizes was to get precise estimates of the stellar effective temperature, T_{eff}, which is pivotal to, for example, determining ages and metallicities. But there is renewed interest, such as the precise stellar radii now needed to measure transiting exoplanets' sizes and densities, which can eventually fall into the host star's so-called habitable zone (von Braun et al. 2014).

Primary distance measurements are the realm of the space missions HIPPARCOS (ESA 1997) and *Gaia* (de Bruijne 2012). The most straightforward method to measure the angular sizes of stars is interferometry (Michelson & Pease 1921; Hanbury Brown & Twiss 1958; Labeyrie 1975), and in a less measure, more historically, lunar occultations (Cousins & Guelke 1950). Modern interferometric techniques – combining adaptive optics, mononode fibers, cophasing, fast and low noise near-infrared cameras – are today able to measure stellar diameters with a precision better than 1% (Cruzalèbes et al. 2013; Boyajian et al. 2012a,b). However the ultimate precision is often dominated by the calibration process. To reach very high precision, it is mandatory to know and to observe with the state of the art procedures, together with the object of interest, a star called calibrator. In other words, a single star, as close as possible to the object, with similar magnitude, with a known angular diameter and associated error, that is used to measure the transmission of the observing system. This underlines the importance of angular diameter predictions for calibration purposes. The angular diameter predictions are based on two kind of methods: the first are based on a polynomial fit of measured angular diameters as a function of colors, from Wesselink (1969) to Boyajian et al. (2013, 2014); the second, like the Infrared Flux Method (Blackwell et al. 1979; Casagrande et al. 2010), are based on a subtle mix of experimental data and modeling. Other methods, like Asteroseismology (Brown & Gilliland 1994; Chaplin & Miglio 2013), provide linear diameters that must be converted to angular diameters using a distance estimate.

Our initial motivation for this work was to optimize the calibrator-finding utility SearchCal[1] (Bonneau et al. 2006, 2011), an angular diameter estimator of the first kind described above, with a rigorous treatment of error propagation. The aim was to produce a more robust version of the catalog of ~40 000 star diameters, the JMMC Stellar Diameter Catalog

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[1] `http://www.jmmc.fr/searchcal`

(JSDC; Lafrasse et al. 2010). This led us to reconsider the general problem of deriving the polynomial coefficients that are used in such estimators, which usually come from star magnitudes that need to be de-reddened before use. We solved the visual extinction problem by introducing two new concepts: a distance indicator called pseudomagnitude, and the differential surface brightness (DSB), both reddening-free. The DSB is an observable specific to each star, independent of distance, which depends only on measured quantities: the stellar diameter and the observed magnitudes.

Our approach to predict stellar diameters, definitely experimental, consists of a polynomial fit of the DSB as a function of the spectral type number for a database of stars with known diameters. It allows us to by-pass the knowledge of visual extinction and that of intrinsic colors. The polynomial coefficients are then applicable to any star with a known spectral type and magnitudes to provide an apparent diameter value. As an illustration of our method, we compiled a catalog of ~600 measured star diameters and photometries that we used to compute the DSB polynomial fit. Using these polynomials and all the stars in the ASCC catalog (Kharchenko 2001) that have an associated spectral type, we are able to give the apparent diameter of ~453 000 stars with a median diameter precision of 1.1%, as well as possible astrophysical biases up to 2% (due to luminosity classes, DSB fine structures, metallicity, and so on), that is in agreement with the limiting precisions discussed in Casagrande et al. (2014).

Section 2 introduces the new formalism, especially the concepts of pseudomagnitudes and differential surface brightness. Section 3 describes the least squares fit approach. Section 4 describes how we built the database of measured diameters from the literature, discusses their validity, and how we tried to avoid any systematics. The results are presented and discussed in Sect. 5.

2. Pseudomagnitudes and differential surface brightness

In this section, we introduce the concept of pseudomagnitudes and a new experimental observable: the differential surface brightness (DSB). Our starting point is the expression of the surface brightness S_i of a star (Wesselink 1969), see Eq. (9) of Barnes & Evans (1976):

$$\mathrm{S}_i = 5\log(\theta) + m_i^0, \tag{1}$$

where θ is the angular diameter of the star and m_i^0 the unreddened magnitude in the photometric band i. m_i^0 can be written as:

$$m_i^0 = m_i - c_i A_v, \tag{2}$$

where m_i is the observed magnitude, c_i is the ratio between the extinction coefficients R_i and R_v in the i and visible bands, respectively. Given two photometric bands i and j, the interstellar extinction can be writtten as

$$A_v = \frac{m_i - m_j}{c_i - c_j} - \frac{m_i^0 - m_j^0}{c_i - c_j}. \tag{3}$$

Combining the three previous equations, the surface brightness may be expressed as a function of the angular diameter, the measured magnitudes, and the intrinsic color of the star, $C_{ij} = m_i^0 - m_j^0$. That is to say

$$\mathrm{S}_i = 5 \times \left(\log(\theta) + 0.2 \times \frac{c_i\, m_j - c_j\, m_i}{c_i - c_j} \right) + \frac{c_i}{c_i - c_j} C_{ij}. \tag{4}$$

At this point, it is useful to introduce a new stellar observable that we call pseudomagnitude, defined by

$$\mathrm{P}_{ij} = \frac{c_i\, m_j - c_j\, m_i}{c_i - c_j}. \tag{5}$$

The pseudomagnitudes have remarkable properties and applications that will be discussed in a forthcoming paper. Basically, they are reddening free distance indicators:

$$\mathrm{P}_{ij} = \mathrm{P}_{ij}^{10} + d_M, \tag{6}$$

where P_{ij}^{10} is the absolute pseudomagnitude, i.e., the pseudomagnitude at 10 pc distance, $d_M = 5\log(d) - 5$ is the distance modulus and d the distance in parsecs. We note that if one of the coefficients c_i or c_j tends to zero, then the pseudomagnitude tends to the magnitude m_i or m_j. Hence, the absolute pseudomagnitude is, in some way, related to the stellar luminosity.

The surface brightness may simply be rewritten as follows:

$$\mathrm{S}_i = 5 \times \mathrm{DSB}_{ij} + \frac{c_i}{c_i - c_j} C_{ij}, \tag{7}$$

where DSB_{ij} is the DSB between the photometric bands i and j, defined as

$$\mathrm{DSB}_{ij} = \log(\theta) + 0.2\,\mathrm{P}_{ij}. \tag{8}$$

DSB_{ij} is a self-calibrated observable specific to each star. It is reddening-free, independent of the distance, and can be measured via photometry and interferometry. The only a priori is the diameter limb-darkening correction, which induces a diameter error that is generally less than 1%, smaller than the errors managed in this work.

The knowledge of the DSB, as a function of the spectral type, the luminosity class, the metallicity, and so on, is sufficient to predict the angular diameter of a star, given its observed magnitudes. Unfortunately, we do not possess this level of detailed information because of the poor spectral type-sampling owing to the small number of useable measured diameters (~600) available today. To compensate our lack of knowledge, we fit the DSB as a function of the spectral type number n_s (varying from 0 to 69 for spectral types between O0 to M9) with simple polynomial laws. Within the present framework, if the determination of spectral type is robust to reddening (e.g., is not derived from colors), then the intrinsic color, replaced by the spectral type number, is no longer a variable of the diameter prediction problem and our approach is fully reddening-free.

3. Algorithmic approach

This is a two-step process: 1) polynomial estimate based on the DSBs derived from database values; 2) diameter calculations from polynoms and pseudomagnitudes.

3.1. Polynomial

A data point consists in a limb-darkened diameter θ and N_B photometric bands, which provides $N_B - 1$ linearly independent (but statistically dependent) equations. We can build many sets of $N_B - 1$ linearly independent equations, but each set provides the same polynomial solution. We then have to characterize, $N_B - 1$ polynomials of degree m, each associated with a pair of photometric bands. This corresponds to $(m + 1) \times (N_B - 1)$ unknowns, that we evaluate simultaneously via a simple linear least squares fit (see Appendix A.1).

Wherever possible, we used the mean interstellar extinction coefficients of Fitzpatrick (1999) that give: $(c_V, c_J, c_H, c_{K_\mathrm{S}}) = (1.0, 0.28, 0.17, 0.12)$. Strictly speaking, the coefficients c_i depend on the spectral type (McCall 2004). In principle, one can consider variable coefficients, but for the present analysis we restrict ourselves to constant values, since the influence of these variations, with respect to diameter calculation, is smaller than the errors and the biases reported here.

Also, it may be necessary to reject anomalous data points. For example, in the production of the star diameter catalog described in Sect. 5, we use the database described in Sect. 4. From the found polynomial solution, for each entry of our database we can estimate $N_B - 1$ single diameters and a mean diameter. It sometimes occurs that one or various single diameters deviate from the mean diameter by more than 5 times the error on the difference. This may be due to observational biases in the diameter measurements, or that the star is not single, etc. In this case, we excluded the entry from the database that was used. Table 2 lists all the stars and references retained for fitting the polynomials, as discussed in Sect. 5.

3.2. Diameters

A polynomial, together with two magnitudes (pseudomagnitude), provides an estimate of the diameter. Several pairs of magnitudes gives several estimates of the same diameter. These are not statistically independent and we show in Appendix A.2 how to rigorously combine them in a single diameter value and its associated error. Beyond the error improvement, which is generally modest, the main interest of using more than two photometric bands is to produce various diameter estimates that can be recombined and, above all, compared through a quality factor, see Sect. 5.

4. The database of measured angular diameters

4.1. Building the database

The empirical approach used in this paper relies on the knowledge of a statistically significant number of accurately measured angular diameters, ideally obtained with different techniques, such as avoiding as much as possible any technique-related bias. The angular diameters must be prime results, i.e., not the result of a modeling of the observations. Ideally, they should be equally distributed, both in space and in spectral type.

Several star diameter compilations exist that contain a fair amount of published angular diameters values. The CADARS (Pasinetti Fracassini et al. 2001) has entries for 6888 stars and is complete up to 1997. CHARM2 (Richichi et al. 2005) lists 8231 measurements of 3243 stars, up to 2005. However these catalogs mix results from very direct methods, such as intensity interferometry with indirect methods, or spectrophotometric estimates of various kind (always including some model of the star), or linear diameters from eclipsing binaries (1600 entries in CADARS), which need some modelling of the two stars, as well as a good estimate of the distance to be converted into an angular diameter.

Another difficulty is that, the published angular diameters have been obtained at various wavelengths and may include, or not, a compensation for the limb-darkening effect. As a result, we initiated a new compilation of measured stellar diameters that would suit our needs. This database, called JMDC[2], only uses direct methods, merges multiwavelength measurements into one value of limb-darkened diameter (LDD), and aims to be complete up to the most recent publications by being updated on a regular basis through a peer-reviewed submission process.

The JMDC used in this paper gathers 1072 apparent diameter values that have been published since the first experiments by Michelson. Prior to 1997, our bibliography relies only on the reference list of Pasinetti Fracassini et al. (2001). After this date we used NASA's ADS hosted at CDS. We retained only the measurements obtained from visible/IR interferometry, intensity interferometry and lunar occultation in the database. We always retrieved the values in the original text[3] and used SIMBAD to properly and uniquely identify the stars.

The three techniques retained share the same method of converting the measurements (squared visibilities for optical interferometry, correlation of photon-counts for intensity interferometry, fast photometry for lunar occultations) into an angular diameter: fitting a geometrical function into the values, in many cases a uniform disk, which provides a uniform disk diameter (UDD) value. This UDD is wavelength-dependent owing to the limb-darkening effect of the upper layers of a star's photosphere, and JMDC retains the wavelength or photometric band at which the observation was made.

To measure a star's apparent diameter consistently, i.e., with the same meaning as our Sun's well-resolved apparent diameter, it was necessary for the authors of these measurements to take into account the star's limb-darkening, for which only theoretical estimates exist as yet. They chose one of the various limb-darkening parameters available in the literature (see Claret 2000, for a discussion on the classical limb-darkening functions used), either by multiplying the UDD by a coefficient function of the wavelength and the star's adopted effective temperature, or directly fitting a limb-darkened disk model in the data. Of course this adds some amount of theoretical bias in the published measurements, which however diminishes as the wavelength increases. An additional difficulty for the lunar occultations is that the result depends on the exact geometry of the occulting portion of the lunar limb, which can, more or less, be correctly estimated.

To deal with the limb-darkening problem as efficiently as possible, in the publications where reported diameters are measured in several optical/IR bands, we retained the measurement with the best accuracy and favored the measurement at the longest wavelength to minimize the effect of limb-darkening correction. Furthermore, we further used the published UDD measurement, or retrieved the original, unpublished UDD measurement from the LDD value and the limb-darkening coefficient used by the authors, and uniformly converted these UDD values into limb-darkened angular diameters using the most recent correction factors published (Neilson & Lester 2013a,b), when possible. This, in our opinion, works towards minimizing the biases of the database, which will be confirmed afterwards by the statistical analysis of our results.

We did not keep any other information from the original references. Instead, we retrieved all the ancillary information such as photometries, parallaxes, spectral types etc, at once by using our `GetStar` service, a specially crafted version of our `SearchCal` server[4] that fetches all relevant information from a dozen CDS-based catalogs (VizieR, Simbad for object and spectral types). This ensures that there is no difference in the origin, thus no added bias, between the database we use to derive our

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[2] `JMMC Measured stellar Diameters Catalog`, available at `http://www.jmmc.fr/jmdc`

[3] With the exception of a few very old references in CADARS that were not easily available at our location.

[4] `http://www.jmmc.fr/getstar`

polynomials (see below) and those that will be used in the reverse process, for any object known by Simbad at CDS.

4.2. Database properties

As of today, the database retains 1072 different measurements on 627 stars from 169 publications. Of them, 204 stars have multiple entries, from 2 (205 stars) to 18 (α Tau). In addition, 1041 measurements have an UDD value, 565 reported an LDD value. After an eventual LDD to UDD conversion and use of the above-mentioned conversion factors (for compatible spectral types), we are left with 853 entries with useable LDD measurements.

With regard to the techniques, data is issued from long-baseline optical/IR interferometry (68%), then lunar occultations (26%), and finally intensity interferometry (6%). Of the measurements retained, 36% are in the K band (around 2200 nm), the rest being equally distributed between the B, V, R, I, and H bands.

4.3. Database final filtering

For the purposes of this work (single stars of classical spectral types), we remove the known multiples or strongly variable stars (cepheids, miras, close doubles[5], spectroscopic binaries, elliptical variables etc) to obtain a set of (apparently) standard stars. In addition, we consider only stars with the following complete information: *VJHK*s magnitudes and errors[6]; SIMBAD spectral types within half a subclass precision; LDD diameters and their errors. Finally, keeping only measurements with an S/N above five for LDDs, we are left with 573 measurements of 404 distinct stars.

The spectral types of the 573 selected measurements range from O5 to M7 in five luminosity classes: 124 dwarves (V), 42 subgiants (IV), 297 giants (III), 38 subsupergiants (II), 56 supergiants (I), and 16 without luminosity class (in the SIMBAD database). The diameter measurements range over more than two decades, from 0.23 to 44 mas.

5. Results and discussion

To derive the polynomial coefficients and their errors, we used the 573 selected measurements of our database (see Sect. 4.3), and simultaneously fitted the DSB of the photometric pairs (V, J), (V, H), and (V, Ks).

The quality of the polynomial fit is evaluated by the associated chi-square, $\chi^2_{\rm p}$ (see Appendix A.1), and that of the reconstructed diameters by the mean diameter chi-square $\langle\chi^2_\theta\rangle$, (see Appendix A.2).

5.1. Influence of luminosity class

To test the influence of the luminosity class (LC), we first computed three sets of polynomials of degree 6 separately, from: 1) LC I, II and III ($\chi^2_{\rm p} = 0.6, \langle\chi^2_\theta\rangle = 0.6$); 2) LC IV and V ($\chi^2_{\rm p} = 0.8, \langle\chi^2_\theta\rangle = 0.7$); and 3) all, including unknown LC ($\chi^2_{\rm p} = 0.7, \langle\chi^2_\theta\rangle = 0.7$). Then in each case, we computed the angular diameters of all stars of the HIPPARCOS (ESA 1997) catalog with known spectral types and magnitudes (93 142 stars). Within an rms bias of 2%, we found no difference between cases 1) and 3), and cases 2) and 3). As a consequence, we decided to use all the selected measurements of our database, irrespective of their luminosity class (or absence thereof), to derive a single set of polynomials that is applicable to all stars.

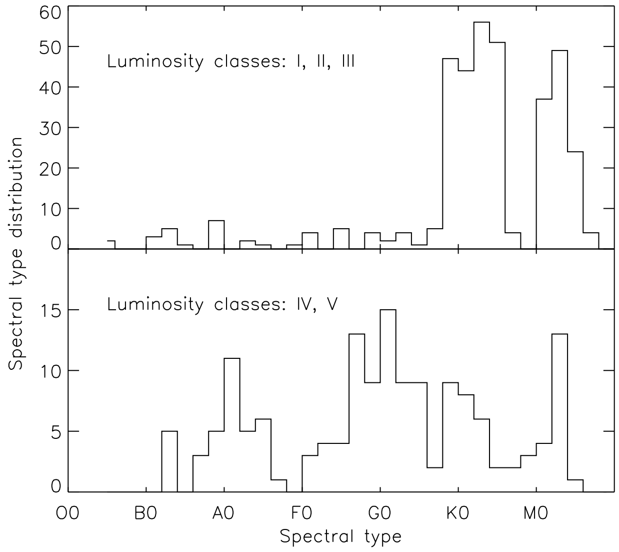

Fig. 1. Histogram of retained stellar diameter measurements for the DSB polynomial fit. *Top*: note the overabundance of luminosity classes I–III (363 entries), around K and M spectral types and the poor sampling for earlier ones. *Bottom*: spectral distribution for luminosity classes IV and V (150 entries).

5.2. Selected database measurements and their DSB

From the initial 573 entries, 526 (92%) filled the fitting condition (see end of Sect. 3.1) and were retained for polynomial calculations (363 entries with LC I, II, and III, 150 with LC IV and V, and 13 with unknown LC). The spectral type distribution for luminosities classes I–III is shown in Fig. 1 (top). There is an overabundance of measurements around K and M spectral types and a poor sampling for earlier ones. Instead, for luminosity classes IV and V (Fig. 1, bottom) the spectral types are quite well distributed between B and M types. Also note that 100% (31 entries) of interferometry intensity data, 92% (407 entries) of classical interferometry data and 87% (88 entries) of lunar occultation data, have been retained.

Figure 2 shows the DSB in the three selected photometric pairs as a function of the spectral type, together with the polynomial fit. The entries were binned, with an interval of one subspectral type, separately for LC I, II and III (filled circles) and LC IV and V (open circles), to understand their similarity. Figure 3 shows the same DSB with all entries binned with an interval of 2.5 subspectral type. It is clear that the spectral metric is not smooth, especially for the (V, J) pair. It presents a period of about one spectral type plus some possible fine structures. In fact no polynomial of reasonable degree is able to reproduce the exact structure of the DSB and we must always keep in mind the 2% rms bias on the diameter.

5.3. Comparison of diameter predictions with recent measurements

To test the diameter predictions of our model, we computed the diameter of eight stars, which had recently been measured

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[5] Of separation less than one arc second.

[6] Our GetStar service is used to retrieve Johnson V magnitudes from the ASCC (Kharchenko 2001) and HIPPARCOS (ESA 1997) catalogs, and JHKs from 2MASS (Skrutskie et al. 2006). GetStar makes a careful cross-match on the stellar properties reported in these catalogs, comparing them with Simbad values, and takes into account proper motions in its cross-matching.

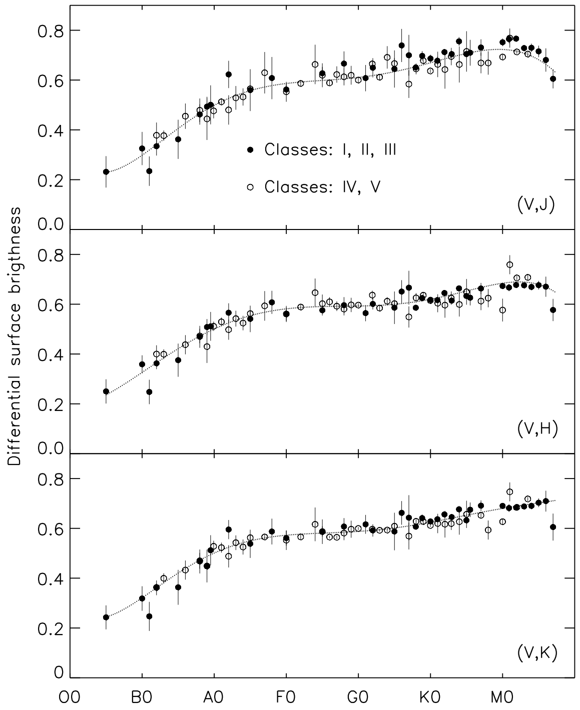

Fig. 2. DSB values in the three selected photometric pairs, together with polynomial fits of degree 6 (dotted lines), as a function of the spectral type. The entries were binned separately, with an interval of one subspectral type, for LC I, II, and III (filled circles) and LC IV and V (open circles), to understand their similarity.

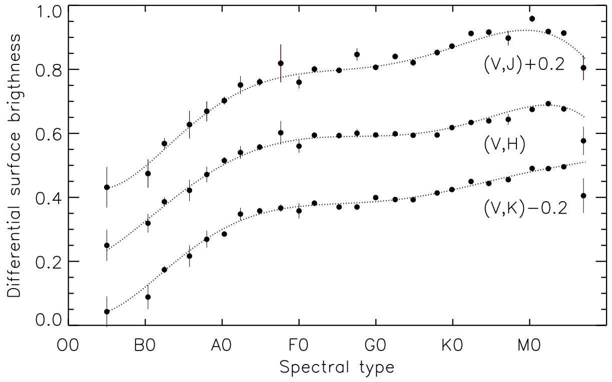

Fig. 3. Differential surface brightness for (from top to bottom) the (V, J), (V, H) and (V, Ks), photometric pairs versus spectral type. The (V, J) and (V, Ks) curves have been shifted by ±0.2 for clarity. The entries were binned, with an interval of 2.5 subspectral type. The dotted lines represent the best fit with polynomials of degree 6. Note that the spectral metric is not smooth (see text).

by interferometry and not used for the polynomial fit. Figure 4 shows the computed diameters as a function of the measured ones. The agreement is excellent, with a mean-squared difference between measured and computed diameters that is expressed in noise units of about 0.5.

5.4. The JMMC stellar diameter catalogue

We used the present formalism to compute the angular diameters of stars in the Tycho2 catalog[7] (Høg et al. 2000) with known

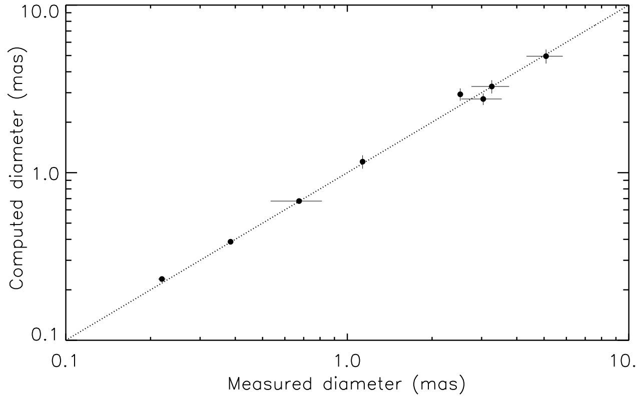

Fig. 4. Computed diameters as a function of measured diameters, for eight stars recently observed with interferometry and not used for the polynomial fit. Stars with increasing diameter, HD numbers: 209458 (G0V), 189733 (K1.5V), 69830 (G8), 185351 (G9III), 190658 (M2.5III), 183589 (K5I), 95687 (M3I), 97671 (M3I), (Johnson et al. 2014; Boffin et al. 2014; Tanner et al. 2015; Boyajian et al. 2015; Arroyo-Torres et al. 2015). The agreement is excellent, with a mean-squared difference between measured and computed diameters expressed in noise units of 0.5. The straight dotted line corresponds to $x = y$.

Table 1. Differential surface brightness polynomial values p and associated errors $\sigma_{\rm p}$ for stars measured in the (V, Ks) photometric pair.

SP type	p	$\sigma_{\rm p}$	SP type	p	$\sigma_{\rm p}$
O5	0.2432	0.0443	F6	0.5810	0.0025
O6	0.2534	0.0337	F7	0.5822	0.0024
O7	0.2670	0.0255	F8	0.5835	0.0023
O8	0.2830	0.0192	F9	0.5850	0.0022
O9	0.3009	0.0147	G0	0.5867	0.0021
B0	0.3201	0.0116	G1	0.5888	0.0020
B1	0.3401	0.0096	G2	0.5912	0.0020
B2	0.3603	0.0085	G3	0.5939	0.0019
B3	0.3805	0.0077	G4	0.5971	0.0019
B4	0.4003	0.0071	G5	0.6006	0.0019
B5	0.4195	0.0067	G6	0.6045	0.0019
B6	0.4378	0.0062	G7	0.6088	0.0019
B7	0.4551	0.0059	G8	0.6134	0.0020
B8	0.4712	0.0055	G9	0.6183	0.0020
B9	0.4862	0.0053	K0	0.6235	0.0021
A0	0.4998	0.0051	K1	0.6289	0.0021
A1	0.5121	0.0050	K2	0.6345	0.0022
A2	0.5231	0.0049	K3	0.6402	0.0023
A3	0.5329	0.0048	K4	0.6460	0.0025
A4	0.5414	0.0047	K5	0.6518	0.0026
A5	0.5488	0.0046	K6	0.6575	0.0028
A6	0.5551	0.0045	K7	0.6632	0.0029
A7	0.5604	0.0043	K8	0.6686	0.0030
A8	0.5648	0.0041	K9	0.6739	0.0031
A9	0.5684	0.0039	M0	0.6790	0.0029
F0	0.5714	0.0037	M1	0.6838	0.0026
F1	0.5738	0.0034	M2	0.6884	0.0023
F2	0.5757	0.0032	M3	0.6928	0.0025
F3	0.5773	0.0030	M4	0.6971	0.0039
F4	0.5786	0.0028	M5	0.7012	0.0065
F5	0.5798	0.0026	M6	0.7054	0.0104

Notes. The angular diameter (mas) and its statistical relative error may be obtained from Eqs. (9) and (10), replacing X by Ks.

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[7] See the JSDC catalog at `http://www.jmmc.fr/jsdc`. The Tycho2 catalog is used here as a list of star positions and photometries are retrieved through GetStar, as described in Sect. 4.3.

Table 2. List of stars and associated references of angular diameter measurements that have been retained to calibrate the DSB in this work.

Name	Ref(s)	Name	Ref(s)	Name	Ref(s)	Name	Ref(s)	Name	Ref(s)	Name	Ref(s)
GJ411	59	GJ412A	75	GJ649	82	GJ687	75	HD 100029	57, 63, 83	HD 100920	19
HD 1013	83	HD 10144	9	HD 101501	74	HD 102212	43, 57, 63, 83	HD 102328	72	HD 102647	9, 66
HD 102870	74	HD 103605	72	HD 10380	36, 56	HD 10476	77	HD 104985	69	HD 106574	72
HD 106625	9	HD 10697	69, 77	HD 107383	82	HD 10780	70, 74	HD 108907	83	HD 109358	74, 83
HD 112300	63	HD 113049	72	HD 113226	56, 63, 83	HD 113996	83	HD 114710	74	HD 114961	36, 43
HD 115617	82	HD 115659	80	HD 117176	69	HD 117675	83	HD 118904	72	HD 119149	23
HD 11964	69, 77	HD 11977	73	HD 119850	75	HD 120136	69	HD 120477	56, 83	HD 121130	83
HD 121370	57, 63, 67	HD 123139	61	HD 123934	14, 16, 22	HD 12479	14, 37, 50, 54	HD 12533	32, 63	HD 126660	74
HD 127665	83	HD 128167	74	HD 12929	40, 46, 48, 56, 63	HD 129712	83	HD 130948	77	HD 131156	74
HD 131873	40, 63	HD 13189	69	HD 131977	65	HD 132112	36, 43	HD 1326	58, 59, 75	HD 132813	63
HD 133124	83	HD 133208	57, 63, 83	HD 133774	23	HD 135722	56, 63	HD 136202	77	HD 136726	72, 83
HD 137443	72	HD 137759	83	HD 138265	72	HD 139357	72	HD 139663	12	HD 140538	77
HD 140573	57, 63, 83	HD 141795	74	HD 142804	36	HD 142860	74	HD 143107	83	HD 143761	69, 82
HD 144690	50	HD 145675	69	HD 146051	63, 78	HD 146233	74	HD 148387	57, 63, 83	HD 148478	47, 63
HD 149661	75	HD 150383	49	HD 150680	57, 63	HD 150798	78	HD 150997	56, 63, 83	HD 1522	83
HD 152786	78	HD 154345	71	HD 156283	46, 56, 63	HD 157214	77	HD 157681	72	HD 158633	77
HD 159181	63	HD 159561	9	HD 160290	72	HD 161096	83	HD 16141	71	HD 16160	58, 59, 75
HD 161797	63	HD 162003	74	HD 163770	63	HD 163917	83	HD 164058	40, 41, 44, 46, 63	HD 164259	74
HD 167042	72	HD 16765	77	HD 168151	77	HD 16895	74	HD 168988	36	HD 169022	9
HD 170693	72, 83	HD 172167	1, 9, 63	HD 172816	17, 23, 29, 34, 36, 37, 55	HD 17361	56	HD 173667	74	HD 17506	63
HD 175588	51, 63	HD 175726	76	HD 175775	18	HD 175823	72	HD 175865	51, 63	HD 176124	36
HD 176408	72	HD 176411	56	HD 176437	79, 81	HD 176524	83	HD 176678	83	HD 17709	63
HD 177153	76	HD 177724	74	HD 177756	81	HD 177830	69	HD 180540	34, 55	HD 180610	83
HD 180711	40, 57, 63	HD 180809	46, 56	HD 181276	56, 83	HD 181420	76	HD 18191	16, 35	HD 182572	74
HD 183439	46, 63, 83	HD 184171	81	HD 185144	70, 74	HD 185395	74	HD 186408	77	HD 186427	69, 77
HD 186791	56, 63	HD 186815	72	HD 186882	81	HD 187082	23	HD 187637	76	HD 188512	56
HD 190228	69	HD 190360	69	HD 190406	76	HD 19058	44, 51, 63	HD 192781	72	HD 19373	74
HD 193924	1, 9	HD 194093	56, 63	HD 195564	77	HD 195820	72	HD 196777	4, 30, 36	HD 197345	32, 63
HD 19787	56	HD 197989	48, 63	HD 198149	56	HD 199305	75	HD 199665	71	HD 19994	69
HD 200205	72	HD 200905	56, 63	HD 201092	68	HD 202109	63	HD 202850	79	HD 203504	83
HD 204724	63	HD 205435	56	HD 20630	74	HD 206778	57, 63	HD 206860	77	HD 206952	83
HD 207005	12	HD 20902	32, 56, 63	HD 209100	65	HD 209750	56, 63	HD 209950	29	HD 209952	1, 9
HD 210027	76	HD 21019	77	HD 210418	74	HD 210702	71, 82	HD 210745	63	HD 212496	56, 83
HD 213306	53, 56	HD 213558	74	HD 214868	56, 72	HD 214923	81	HD 215648	74	HD 215665	56, 63
HD 216032	43	HD 216131	56, 63	HD 216386	2, 63	HD 216956	1, 9, 66	HD 217014	69, 77	HD 217906	44, 46, 48, 51, 52, 63, 80
HD 218329	83	HD 218356	63	HD 218396	76	HD 219080	79	HD 219134	75	HD 219576	36
HD 219615	83	HD 219623	77	HD 221115	56	HD 221345	71	HD 222368	74	HD 222603	77
HD 224062	19, 37	HD 22484	74	HD 224935	64	HD 23249	67	HD 23319	73	HD 23596	69
HD 24398	81	HD 24512	78	HD 25025	63	HD 25604	56	HD 25705	78	HD 27256	73
HD 285968	82	HD 29139	8, 24, 25, 26, 27, 28, 33, 38, 41, 42, 44, 48, 51, 63	HD 30959	78	HD 31398	63	HD 31767	63	HD 31964	63
HD 32518	72	HD 32630	79	HD 33564	82	HD 3360	79	HD 33793	59	HD 34085	1, 9

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Table 2. continued.

Name	Ref(s)	Name	Ref(s)	Name	Ref(s)	Name	Ref(s)	Name	Ref(s)	Name	Ref(s)
HD 34411	74	HD 3546	56	HD 35468	1, 9, 81	HD 3627	48, 57, 63	HD 36389	31, 36, 37, 39, 78	HD 36395	59, 75
HD 3651	69	HD 36673	56	HD 36848	73	HD 3712	32, 46, 48, 56, 63	HD 37128	1, 9	HD 38529	69
HD 38858	77	HD 38944	83	HD 39983	43, 54	HD 40239	51, 63	HD 4128	78	HD 42995	60
HD 432	56	HD 44478	6, 7, 10, 11, 21, 35, 41, 44, 51, 63	HD 45348	1, 9, 78	HD 45410	71	HD 4628	75	HD 4656	50
HD 48329	13, 43, 45, 50, 56, 63	HD 48915	1, 9, 62, 63	HD 49933	76	HD 49968	30	HD 5015	74	HD 52089	1, 9
HD 5395	56	HD 5448	79	HD 54605	9	HD 54719	83	HD 56537	74	HD 57423	35
HD 5820	23	HD 58350	9	HD 58946	74	HD 59686	69	HD 60294	72	HD 6210	77
HD 62345	83	HD 66141	83	HD 66811	3, 9	HD 6860	32, 41, 44, 46, 48, 51, 63	HD 69267	56, 63	HD 69897	77
HD 70272	46	HD 7087	56	HD 73108	72	HD 74442	36	HD 76294	57, 83	HD 76827	63
HD 79211	75	HD 7924	82	HD 80007	9	HD 8019	23	HD 80493	46, 57, 63	HD 81797	63, 78
HD 81937	74	HD 82308	83	HD 82885	74	HD 83618	83	HD 84194	83	HD 84441	57, 63
HD 8512	83	HD 85503	83	HD 86663	18, 23, 56	HD 86728	74	HD 87837	13, 15, 21, 29, 56	HD 87901	1, 9
HD 88230	58, 59, 75	HD 89449	76, 79	HD 89758	57, 63	HD 90839	74	HD 91232	43	HD 9138	45
HD 9408	56	HD 95418	74	HD 95608	79	HD 95735	58, 58, 75, 75	HD 96833	57, 63, 83	HD 97603	74
HD 97633	79	HD 9826	69	HD 98262	63	HD 9927	46, 56	HD 99998	5, 20, 56	HR4518	56
HR9045	56										

spectral type. The resulting median diameter error is 1.1%. About 453 000 stars have an associated internal diameter χ^2_θ less than 5, and 393 000 less than 2.

5.5. Simplified formula

For a star which could be absent in the JMMC catalog and for which two tycho-like magnitudes and a spectral type are known, it is easy to derive a diameter estimate using the formula below.

Knowing the DSB polynomial values p and their errors $\sigma_{\rm p}$, the stellar diameter (mas) and its relative error may quickly be computed using the following formulas:

$$\log(\theta) = -0.2 \times \frac{c_V\, m_X - c_X\, m_V}{c_V - c_X} + p \tag{9}$$

and

$$\frac{\sigma(\theta)}{\theta} = \ln(10)\,\sqrt{0.04 \times \frac{c_V^2 \sigma^2(m_X) + c_X^2 \sigma^2(m_V)}{(c_X - c_V)^2} + \sigma_{\rm p}^2}, \tag{10}$$

with $X = J, H$ or Ks. Table 1 provides the pair $(p, \sigma_{\rm p})$ for the $(V, K{\rm s})$ photometries and stars of spectral type O5 to M6.

It is also possible to estimate angular diameters without a precise knowledge of the spectral type, but with a degraded precision. For a star whose spectral type is known within some range, it suffices to replace in Eqs. (9) and (10), the pair $(p, \sigma_{\rm p})$ by the pair (a, σ_a), where a is the mean value of p, and σ_a its dispersion over the spectral range. If the spectral type is in the range O5–M6, then for any X, $(a, \sigma_a) = (0.56,\ 0.12)$, for the range A0–M6, $(a, \sigma_a) = (0.62, 0.05)$, which respectively provides 28% and 12% diameter error.

6. Conclusion

Our approach to predict stellar angular diameters is based on the modeling of the relationship between angular diameters and photometries. We developed a new methodology that is based on two reddening-free observables: 1) a distance indicator called pseudomagnitude and 2) the differential surface brightness, a handy quasi-experimental observable, that is independent of distance and specific to each star. This, together with our new database of measured angular diameters, allows us to provide estimates of star diameters with statistical errors of ~1.1%, plus possible biases of ~2%. It permits us to upgrade the JSDC catalog of stellar diameters to about 453 000 stars, a tenfold improvement in number of stars and diameter precision.

The polynomial method developed in this work may be used with any photometric system, selecting optical bands that best represent the stellar continuum. However, the exercise has severe limits because the DSB is not smooth. The only way to reduce the biases and to go beyond 1% error is to measure its structure for all spectral types and luminosity classes. This emphasises this importance to get precise photometry with biases smaller than 1% and above all the importance of optical interferometry to get precise and numerous angular diameters.

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Appendix A: Linear least squares fit

The data consist of a set of N_S stars that are characterized by their measured diameter θ (corrected for limb-darkening) and N_B observed magnitudes. Each star provides $N_B - 1$ linearly independent pseudomagnitude, which combined with the diameter θ, give $N_B - 1$ correlated measurements (differential surface brightness) per star. Each measurement is fitted as a function of the stellar spectral type number (from 0 to 69 for O0 to M9) with a polynomial of degree m. The problem is then to evaluate $(m + 1) \times (N_B - 1)$ polynomial coefficients, which we do via a simple linear least squares fit, described below.

A.1. Polynomials calculation

We align the $(N_B - 1) \times N_S$ measurements in a vector $\boldsymbol{M}$, and we define the transition matrix $\mathbf{T}$ of dimensions $(N_B - 1).N_S \times (m + 1).(N_B - 1)$ as the derivative of $\boldsymbol{M}$ with respect to the unknowns. For simplicity, we assume that the N_S stars are distinct, implying no correlations between the measurements of different stars. This allows us to define N_S independent covariance matrices $\mathbf{C}_i, i = 0, 1, ..., N_S - 1$, of dimension $(N_B - 1) \times (N_B - 1)$. Given the photometric pairs that were selected in this work (V, J), (V, H), $(V, K\mathrm{s})$, the generic expression of the covariance matrix is

$$\mathbf{C} = \frac{\sigma_\theta^2}{\theta^2 \ln(10)^2} + 0.04 \times \begin{bmatrix} \frac{c_J^2\sigma_V^2 + c_V^2\sigma_J^2}{(c_V - c_J)^2} & \frac{c_J c_H \sigma_V^2}{(c_V - c_J)\times(c_V - c_H)} & \frac{c_J c_{K\mathrm{s}} \sigma_V^2}{(c_V - c_J)\times(c_V - c_{K\mathrm{s}})} \\ \frac{c_J\, c_H \sigma_V^2}{(c_V - c_J)\times(c_V - c_H)} & \frac{c_H^2\sigma_V^2 + c_V^2\sigma_H^2}{(c_V - c_H)^2} & \frac{c_H c_{K\mathrm{s}} \sigma_V^2}{(c_V - c_H)\times(c_V - c_{K\mathrm{s}})} \\ \frac{c_J c_{K\mathrm{s}} \sigma_V^2}{(c_V - c_J)\times(c_V - c_{K\mathrm{s}})} & \frac{c_H c_{K\mathrm{s}} \sigma_V^2}{(c_V - c_H)\times(c_V - c_{K\mathrm{s}})} & \frac{c_{K\mathrm{s}}^2\sigma_V^2 + c_V^2\sigma_{K\mathrm{s}}^2}{(c_V - c_{K\mathrm{s}})^2} \end{bmatrix}, \quad \text{(A.1)}$$

where θ is the measured diameter and σ_θ its error, $(\sigma_V, \sigma_J, \sigma_H, \sigma_{K\mathrm{s}})$, and $(c_V, c_J, c_H, c_{K\mathrm{s}})$ are the magnitude errors and the interstellar extinction coefficients in the corresponding bands. Next we place the inverse of the covariance matrices $\{\mathbf{C}_i^{-1}\}$ along the diagonal of a matrix $\mathbf{D}$ of dimensions $(N_B - 1).N_S \times (N_B - 1).N_S$. The solution for the polynomial coefficients is contained in a vector $\boldsymbol{A}$ of dimensions $(m + 1) \times (N_B - 1)$, given by

$$\boldsymbol{A} = \left[{}^t\mathbf{T} \times \mathbf{D} \times \mathbf{T}\right]^{-1} \times^t \mathbf{T} \times \mathbf{D} \times \mathbf{V}. \quad \text{(A.2)}$$

The covariance matrix $\mathbf{C}_a$ of the solution $\boldsymbol{A}$ is

$$\mathbf{C}_a = \left[{}^t\mathbf{T} \times \mathbf{D} \times \mathbf{T}\right]^{-1}. \quad \text{(A.3)}$$

The reconstructed measurement vector writes: $\boldsymbol{M}_r = \mathbf{T} \times \boldsymbol{A}$, and the reduced χ^2_p of the fitting process is

$$\chi^2_\mathrm{p} = \frac{{}^t(\boldsymbol{M} - \boldsymbol{M}_r) \times \mathbf{D} \times (\boldsymbol{M} - \boldsymbol{M}_r)}{N_S \times (N_B - 1)} \cdot \quad \text{(A.4)}$$

A.2. Diameter calculation

For a given star with a spectral type number n_s and an associated pseudomagnitude vector $\boldsymbol{P}$ of dimension $N_B - 1$, the reconstructed *iest* $(i = 0, ...N_B - 1)$ diameter θ_i is given by

$$\log(\theta_i) = \sum_{k=0}^{k=m} \mathbf{A}[\boldsymbol{k} + i \times (m + 1)] \times n_\mathrm{s}^k - 0.2 \times \mathbf{P}(i). \quad \text{(A.5)}$$

The covariance matrix $\mathbf{C}_\mathrm{d}$ between log diameter estimates writes

$$\begin{aligned} \mathbf{C}_\mathrm{d}[\log(\theta_i), \log(\theta_j)] &= 0.04\,\mathrm{cov}[\mathbf{P}(i), \mathbf{P}(j)] \\ &+ \sum_{k=0}^{k=m}\sum_{l=0}^{l=m} \mathbf{C}_a[k + i \times (m + 1), l + j \times (m + 1)] \times n_\mathrm{s}^{k+l}. \quad \text{(A.6)} \end{aligned}$$

Let us range the $N_B - 1$ log diameter estimates within a vector $\boldsymbol{R}$. The mean log diameter $\overline{\log(\theta)}$ and the associated error are

$$\overline{\log(\theta)} = \frac{\sum \mathbf{C}_\mathrm{d}^{-1} \times \boldsymbol{R}}{\sum \mathbf{C}_\mathrm{d}^{-1}} \quad \text{(A.7)}$$

$$\sigma[\overline{\log(\theta)}] = \left[\sum \mathbf{C}_\mathrm{d}^{-1}\right]^{-0.5}, \quad \text{(A.8)}$$

where $\sum$ stands for the sum of all the matrix elements. The mean diameter $\overline{\theta}$ and its error are computed as follows:

$$\overline{\theta} = 10^{\overline{\log(\theta)}} \quad \text{(A.9)}$$

$$\sigma(\overline{\theta}) = \ln(10)\,\sigma[\overline{\log(\theta)}] \times \overline{\theta}. \quad \text{(A.10)}$$

At last, we define the chi-square χ^2_θ associated with the reconstructed log diameter (from the database) by

$$\chi^2_\theta = \frac{{}^t\boldsymbol{B} \times [\mathbf{C}_\mathrm{d} + \sigma_\theta^2]^{-1} \times \boldsymbol{B}}{N_B - 1}, \quad \text{(A.11)}$$

where $\boldsymbol{B}$ is the vector of the difference between the log of the diameter estimates ($\boldsymbol{R}$) and that of the measured diameter, and σ_θ is the error of the measured log diameter. In the case of a catalog of stars with no measured diameter, we can define an internal χ^2_θ, replacing the measured diameter and its error with the mean computed diameter and its error.