

# Stellar twins determine the distance of the Pleiades <sup>★</sup>

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## ABSTRACT

Since the release of the Hipparcos catalog in 1997, the distance to the Pleiades open cluster has been heavily debated. The distance obtained from Hipparcos and those by alternative methods differ by 10 to 15%. As accurate stellar distances are key to understanding stellar structure and evolution, this dilemma puts the validity of stellar evolution models into question. Using our model-independent method to determine parallaxes based on twin stars, we report individual parallaxes of 15 FGK type stars in the Pleiades in anticipation of the astrometric mission Gaia. These parallaxes give a mean cluster parallax of  $7.42 \pm 0.09$  mas corresponding to a mean cluster distance of  $134.8 \pm 1.7$  pc. This value agrees with the current results obtained from stellar evolution models.

**Key words.** Distance scale – Pleiades

## 1. Introduction

Open clusters like the Pleiades are of vital importance for our understanding of stellar evolution theory because of the assumption that stars form in groups within a common molecular cloud. Since clusters are composed of many stars, which are assumed to have the same chemical composition, distance and age, but different initial masses and therefore residing at different evolutionary stages, they are ideal laboratories for testing stellar evolution models. An important output from these models is the intrinsic luminosity of a star. Given the theoretical luminosity and the observed flux, the model can be calibrated to a star once the distance of the star is known. This is because the observed flux of a star is proportional to the luminosity and inversely proportional to the distance.

The Hipparcos mission (ESA 1997) measured to a high accuracy trigonometric parallaxes of about 120 000 stars in the solar neighbourhood. In fact, one must be aware that the concept of ‘stellar distance measurements’ from Hipparcos or Gaia is incorrect, as the distance is not a true astrometrical observable. The measured quantity is the parallax,  $\varpi$ , which is an annual angular variation of an object with respect to distant stars and the parallax is related to the distance  $d$  of that object by  $d = 1/\varpi$ .

For most of the nearby open clusters, such as the Hyades, the distances obtained from Hipparcos parallaxes agree well with those inferred from stellar evolution models. For the Pleiades, however, the Hipparcos parallax is  $8.32 \pm 0.13$  mas corresponding to a distance of  $120.3 \pm 1.5$  pc (van Leeuwen

2007; Perryman 2008; van Leeuwen 2009; Palmer et al. 2014) while other methods mainly using theoretical modelling estimate a distance of approximately 134 pc, i.e. a parallax of about 7.46 mas. These methods include: isochrone fitting (Pinsonneault et al. 1998; Percival et al. 2005; An et al. 2007), empirical main sequence fitting (Stello & Nissen 2001), astrometric solutions that are alternative to Hipparcos (Makarov 2002; Soderblom et al. 2005), analysing spectroscopic binaries (Munari et al. 2004; Zwahlen et al. 2004; Valls-Gabaud 2007; Groenewegen et al. 2007; Pan et al. 2004) and long baseline interferometry (Melis et al. 2014). A recent comparison between them can be found in Melis et al. (2014) while an extensive discussion on the Pleiades distance controversy is in Perryman (2008).

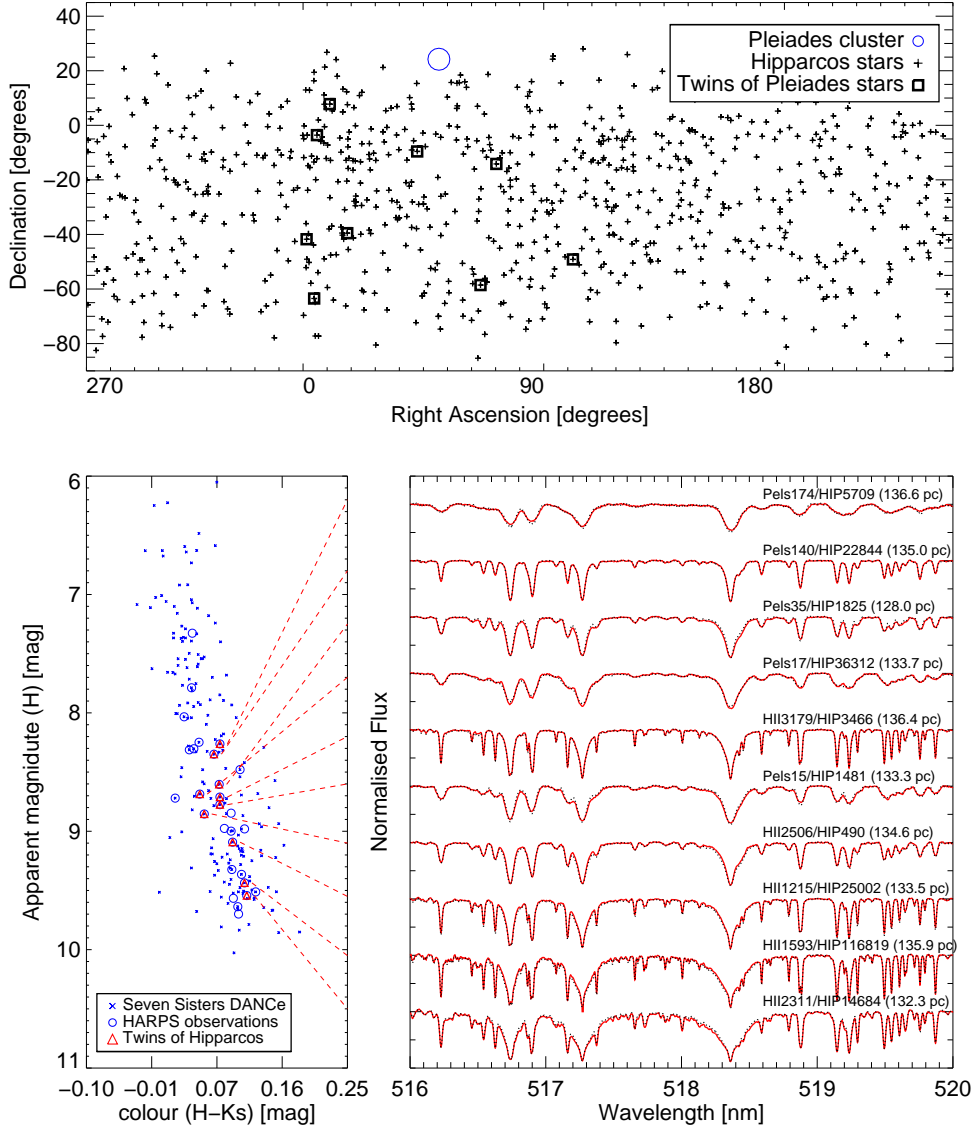
Recently, we proposed the twin method as a robust method for determining stellar distances (Jofre et al. 2015b) that is independent of stellar modelling. It assumes that if two stars at different locations in the sky have identical physical properties, then they are stellar twins. The difference in their apparent brightnesses is directly related to the difference in their distances. By knowing the distance of one star (e.g. from a Hipparcos parallax), it is then possible to know the distance of its twin. As the underlying assumption is that twin stars are physically identical, therefore both stars must have the same spectra. The twin method involves only observational quantities (the apparent brightness and the observed spectra) in the distance determination. This is a great advantage compared to non-astrometric distance determination methods relying on stellar evolution models and is therefore a powerful independent technique for estimating the distance of this important open cluster, provided spectra of Pleiades member stars are identical to spectra of field stars with accurate parallaxes.

A summary of this idea is illustrated in Fig. 1, in which the spectra of some of the field stars with accurate parallaxes located at different parts of the sky is identical to some of the spectra of Pleiades stars located at different parts of the HR diagram. One

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\* Based on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 096.D-0402(A). Table 3 is only available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>



**Fig. 1.** An illustration of the twin method applied to the Pleiades cluster. The coordinates of the stars used in this work are shown in the upper panel. The blue circle represents the location of the Pleiades cluster, the black crosses are the reference Hipparcos field stars and the black squares are the twins of the Pleiades stars found in the field. The bottom left panel shows the color-magnitude diagram of the Pleiades, including the stars of the Seven Sister DANCe catalogue (Bouy et al. 2015) for reference with crosses. Circles correspond to the stars for which we took HARPS spectra, and the red triangles correspond to stars with twins in the field. A selection of Pleiades members with different spectra are shown around the Mg I triplet in red in the right bottom plot, together with a spectrum of a twin in the field as a dotted black line. The name of the Pleiades star and its corresponding twin are indicated, as well as its distance. Fast rotators are Pels 17, Pels 35 and Pels 174 which is seen in the greater broadening of their lines.

can measure the distance of each of the Pleiades spectroscopic twins independently. In this paper we present in detail our procedure and discuss our results for the distance of the Pleiades.

## 2. Data

The spectra used in this work were taken by the HARPS instrument, which is fibre-fed by the Cassegrain focus of the 3.6m telescope in La Silla (Mayor et al. 2003). The spectra were reduced by the HARPS Data Reduction Software (version 3.1). A combination of data taken from ESO public archive and obser-

vations taken by ourselves during 4 nights November 2015 were considered in this analysis.

The new observations contain spectra of 23 stars in the Pleiades field, which have spectral types FGK. This spectral type is important for enhancing the chances to find twins in the sample of field Hipparcos stars available in the HARPS archive, which is composed mostly by FGK solar-type stars. Among these 23 stars, 11 have Hipparcos parallaxes. The apparent magnitudes of these stars vary from  $V = 7$  to 11 mag and in order to achieve a signal-to-noise (SNR) above 50 required for an accurate analysis, the exposure times of these stars were in the range of 1-2 hours. In several cases, shorter exposures of

star name 1	star name 2	$\alpha_{2000}$	$\delta_{2000}$	$m_V$ mag	$RV$ [kms <sup>-1</sup> ]	$\varpi$ [mas]	$e_\varpi$ [mas]	SNR
† Pels 6	† HIP 16639	03 34 07.31	+24 20 40.0	9.61	1.03	6.58	1.38	29
Pels 15	HIP 16979	03 38 22.57	+22 29 58.86	9.81	6.52	6.08	1.82	84
Pels 17	HIP 17091	03 39 41.17	+23 17 27.1	9.93	5.44	11.82	1.94	94
Pels 18	HIP 17044	03 39 13.47	+24 27 59.49	10.42	4.93	10.19	2.19	77
† Pels 25	† HIP 17125	03 40 03.08	+27 44 25.83	9.56	-2.59	9.19	1.66	55
† Pels 26	† HIP 17481	03 44 44.85	+20 44 52.81	8.73	-3.88	9.44	1.03	71
Pels 27	† HIP 17289	03 42 04.72	+22 51 30.82	9.16	4.29	7.65	1.50	91
Pels 35	HIP 17316	03 42 23.99	+21 28 24.57	9.85	7.34	7.27	1.59	121
† Pels 42	† BD +25 610	03 45 45.12	+25 35 44.81	10.25	-1.07			80
† Pels 70	† HIP 18154	03 52 53.47	+24 42 56.62	9.48	0.29	10.13	1.66	77
† Pels 86	† HIP 18544	03 58 01.69	+20 40 36.48	9.37	10.34	8.20	1.44	90
Pels 140	HIP 17511	03 44 58.92	+22 01 56.82	9.43	5.80	10.67	1.37	101
Pels 174	HIP 18955	04 03 44.17	+22 56 39.40	9.67	6.71	5.88	1.26	61
HII 430		03 44 43.98	+24 13 52.36	11.4	4.96			59
† HII 948	† BD +22 549	03 46 12.69	+23 07 42.74	8.67	-6.50			37
HII 1215	BD +23 527	03 46 53.75	+23 35 00.81	10.6	6.21			112
HII 1593		03 47 48.08	+23 13 05.11	11.2	7.23			65
HII 1794	BD +23 550	03 48 17.12	+23 53 25.4	10.2	5.63			64
HII 1924		03 48 34.52	+23 26 05.3	10.7	5.83			96
HII 2311		03 49 28.74	+23 42 44.1	11.36	5.65			80
HII 2506	BD +22 574	03 49 56.49	+23 13 07.03	10.2	6.03			80
HII 3179	BD +23 573	03 51 56.86	+23 54 07.08	10.07	5.55			94
	† BD +20594	03 34 36.24	+20 35 57.45	10.85	-20.35			

**Table 1.** Name, coordinates, apparent magnitudes in the visual, iSpec radial velocity, parallax and its standard error according to van Leeuwen (2007) and SNR of the Pleiades stars analysed in this work. Stars with † were rejected.

about 10 minutes were carried out before these long-time observations to reject potential spectroscopic binaries showing double spectral lines. All observations for each star were stacked using iSpec (Blanco-Cuaresma et al. 2014). The basic information of the Pleiades targets can be found in Table 1.

The spectra of Pleiades stars were compared with a reference sample of HARPS spectra of field stars that have accurate Hipparcos parallaxes. Most of the Hipparcos field stars were taken from our previous work on twin distances (Jofré et al. 2015b), which were selected by cross-matching against the HARPS archive. The cross-matched 664 stars were required to have estimates of FGK spectral type (Soubiran et al. 2010). In addition, we requested 62 stars from the ESO archives<sup>1</sup> which matched the photometric properties of the Pleiades targets. Finally, 143 Hipparcos targets that were not observed so far with HARPS were added to the reference sample and observed during the same run as the Pleiades observations. They were selected to have similar photometric properties as the Pleiades targets, as a way to have more opportunities to find twins between both samples. These stars are very bright and as such, exposures times of around 10 minutes were sufficient to achieve high SNR. The two additional requirements of a non-saturated photometry in the  $H$  and  $K_s$  band and a standard error of the Hipparcos parallax smaller than 7% reduced the reference sample to a total 598 stars. The reference sample, which includes the name, coordinates, magnitude and parallax of the stars, as well as SNR, the date of HARPS observation and the programme ID in which the data were taken, can be found in Tab. A.1.

The dataset was prepared for analysis using iSpec functionalities resulting in a homogeneous set of spectra. The spec-

tra were normalised by fitting cubic splines to the pseudo-continuum, corrected for radial velocity by cross-correlation with the solar atlas of Hinkle et al. (2000), cleaned from cosmic and telluric lines, sampled to common wavelength ranges and smoothed with a gaussian kernel to a lower resolution of 70,000. Although reducing the resolution is not imperative, the smooth spectra had fewer data points yet very high resolution allowing us to resolve the key spectral lines under study and perform a faster pixel-by-pixel comparison of the entire dataset.

### 2.1. Selection of Pleiades members

We assess the question on the cluster membership of the stars in the Pleiades field by comparing their radial velocities, which are listed in Table 1. We considered the radial velocities determined with iSpec, which was also used to process the spectra of the reference dataset. The Pleiades cluster has a radial velocity of approximately 5.7 kms<sup>-1</sup> (van Leeuwen 2009). According to this value, the stars Pels 6, Pels 25, Pels 26, Pels 42, Pels 70, Pels 86, HII 948 and BD +20594 are not considered members of the cluster and were rejected from further analysis. After this membership classification we have in total 15 Pleiades members for the twin distance determination.

### 2.2. Summary

The twin method was applied to a sample of 613 FGK stars having high-resolution spectra and non-saturated 2MASS photometry (Skrutskie et al. 2006) in the near infrared  $K_s$  and  $H$  bands. The sample contained 15 Pleiades members and 598 field stars distributed over the whole sky each with a Hipparcos parallax

<sup>1</sup> request number 192955

with an accuracy of better than 7%. The Pleiades spectra were compared to the entire sample of field stars to search for potential stellar twins.

### 3. Method

In order to analyse homogeneously the slow and fast rotating stars in the Pleiades, we adopted a procedure to determine twin distances by comparing the spectra pixel-to-pixel rather than using equivalent widths as in [Jofré et al. \(2015b\)](#). The use of equivalent widths for high precision studies of solar twins for the determination of chemical abundances ([Meléndez et al. 2006](#); [Datson et al. 2014](#); [Nissen 2015](#); [Spina et al. 2016](#)) is very common and has shown to be very powerful, but it reaches its limitation for fast rotators ( $v \sin i > 20$  m/s). In our sample we have such fast rotators and therefore we developed a new procedure for this purpose. Key to this method is to take the difference of two spectra and evaluate the standard deviation  $\sigma$  of these differences. In this section we explain in detail our procedure.

#### 3.1. Twin distance determination

In the absence of interstellar extinction, there is the well-known relation between the apparent brightness,  $m$  and fluxes,  $F$ , between two stars 1, 2:

$$m_1 - m_2 = -2.5 \log_{10} \left( \frac{F_1}{F_2} \right) \quad (1)$$

As the flux is a function of the luminosity  $L$  and the distance  $d$  of a star, i.e.  $F \propto L/d^2$ , we have

$$m_1 - m_2 = 5 \log_{10} \left( \frac{d_1}{d_2} \right) - 2.5 \log_{10} \left( \frac{L_1}{L_2} \right) \quad (2)$$

The main assertion of the twin distance determination is that twins have the same intrinsic physical properties. Therefore twin stars must have the same intrinsic luminosity and consequently the second term on the right hand side of Eq. (2) vanishes. Another further consequence is that twin stars must have the same intrinsic colour, allowing us to use the difference in observed colour as a proxy for interstellar extinction on the observed magnitudes

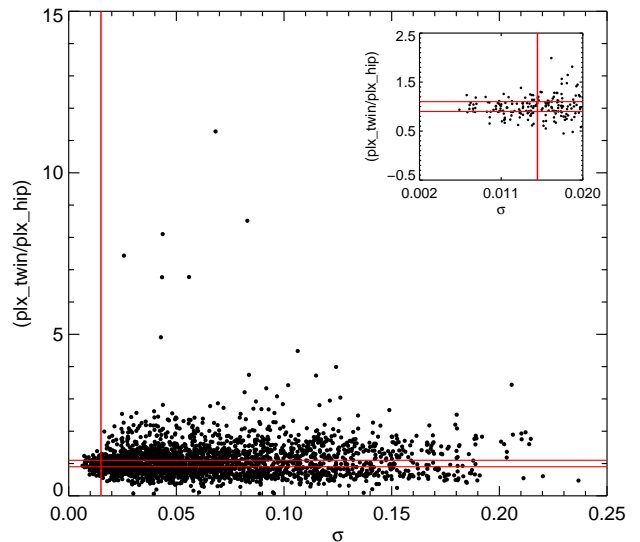
$$E(B - V)_1 - E(B - V)_2 = R_V [(B - V)_1 - (B - V)_2], \quad (3)$$

where  $R_V$  is ratio of the of total-to-selective extinction in filter  $V$ , and  $E(B - V)$  is the de-reddening. Part of the Pleiades cluster is known to be obscured by the Merope Nebula, producing a reddening that is not constant to all stars ([Stauffer & Hartmann 1987](#)). Such errors due to extinction can be minimised by utilising apparent brightnesses in the  $H$  and  $K_s$  filters of 2MASS while having the further advantage of employing a fully homogeneous sample for the photometry. In these filters, we considered  $R_{K_s} [(H - K_s)_1 - (H - K_s)_2]$  as a proxy for extinction, with  $R_{K_s} = 0.3$  according to [Yuan et al. \(2013\)](#). Including this colour correction, twin distances can be determined from the following equation

$$H_1 - H_2 - R_{K_s} [(H - K_s)_1 - (H - K_s)_2] = 5 \log_{10} \left( \frac{d_1}{d_2} \right), \quad (4)$$

Since for the reference stars we have direct measurements of the parallax  $\varpi = 1/d$ , we write Eq. 4 as

$$H_1 - H_2 - R_{K_s} [(H - K_s)_1 - (H - K_s)_2] = 5 \log_{10} \left( \frac{\varpi_2}{\varpi_1} \right). \quad (5)$$



**Fig. 2.** The behaviour of the ratio of twin parallax and Hipparcos parallax as a function of  $\sigma$  using the Hipparcos reference sample. The inlet shows a zoom of the region of the plot at low  $\sigma$ . The horizontal lines represent the range of 10% difference in parallaxes while the vertical line the value of  $\sigma = 0.015$ .

Note that the last equation only involves observable quantities. Thus, our expression to determine twin parallaxes has the form

$$\varpi_2 = \varpi_1 \times 10^{\frac{1}{5} \left( H_1 - H_2 - R_{K_s} [(H - K_s)_1 - (H - K_s)_2] \right)} \quad (6)$$

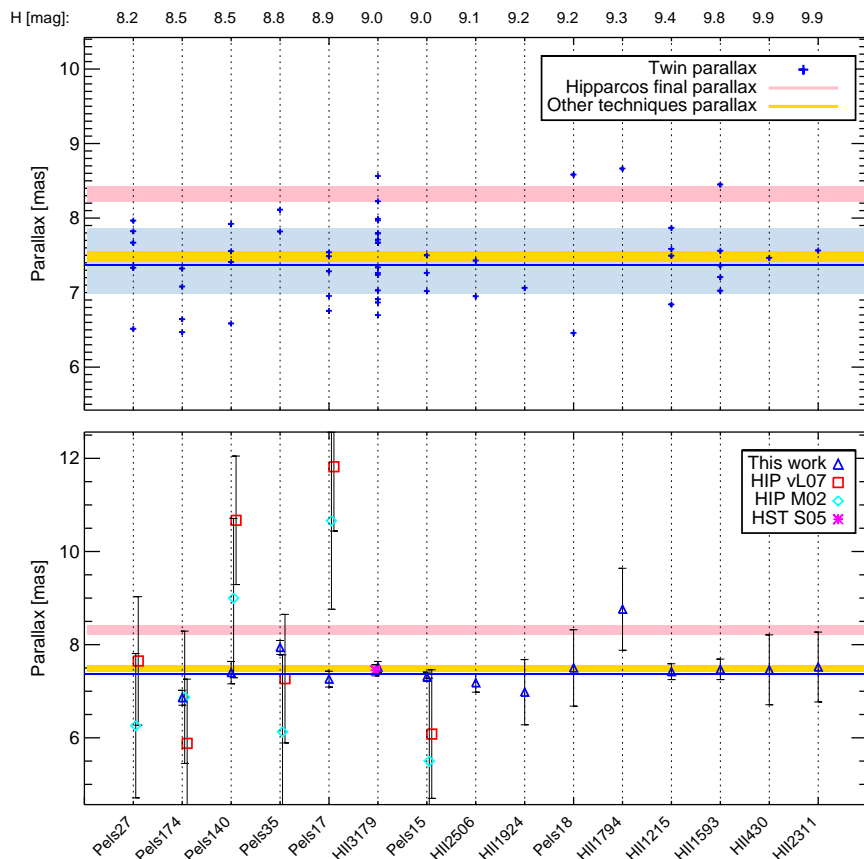
where we determined the unknown parallax  $\varpi_2$  given the knowledge of the reference parallax  $\varpi_1$  and photometry in the  $H$  and  $K_s$  bands of the stars labelled with 1 and 2, respectively.

#### 3.2. Spectral analysis: Assessment of spectral similarity

We compared each spectrum of the reference sample with each of the 15 Pleiades spectra around 423 atomic transitions listed in [Jofré et al. \(2014\)](#) for Fe and in [Jofré et al. \(2015a\)](#) for Mg, Si, Ca, Ti, Sc, V, Cr Mn, Co and Ni, which have been used for the abundance determination of the Gaia benchmark stars (see also [Heiter et al. 2015](#); [Hawkins et al. 2016](#)). Furthermore, the strong features of the wings of the Mg I b triplet and the Balmer lines  $H\alpha$  and  $H\beta$  were also taken into account. These spectral regions are known to contain information on the stellar atmospheric parameters and therefore are well suited to assess the overall equality of spectra of FGK stars.

In theory, twin stars have identical spectra. In practice, this does not happen because the spectra have noise and are observed under different conditions for different stars ([Katz et al. 1998](#); [Soubiran et al. 2003](#)). Thus, critical to this work is a parameter, which we call  $\sigma$ , to address the similarity of the spectra such that the twin parallax formula of Eq. (6) is satisfied within an accepted error in stellar distance. We define  $\sigma$  as the standard deviation of the pixel-to-pixel difference between the spectra in the regions mentioned above. The smaller the value of  $\sigma$ , the more similar are the two spectra.

We investigated the threshold for  $\sigma$  such that we obtain 10% error for the twin parallax. This threshold was found by comparing the spectra with the twin distances of the entire dataset of reference field stars with known Hipparcos parallaxes. That is, the ratio between the Hipparcos parallax  $\varpi_{\text{HIP}}$  and the twin



**Fig. 3.** In both panels, the pink band represents the values of the Hipparcos solution within its margin of error while the yellow band represents the range of the alternatives to Hipparcos. The upper panels shows the parallaxes of the 57 field twins of each Pleiades member sorted by decreasing brightness, while the median and dispersion of the final twin parallaxes are illustrated with the blue line and band, respectively. The lower panel displays the averaged individual twin parallaxes (blue triangles), Hipparcos parallaxes (red squares, HIP vL07), the alternative astrometric solution of (Makarov 2002) (cyan diamonds, HIP M02) and the parallax measurement with the Hubble Space Telescope of (Soderblom et al. 2005) (pink star, S05).

parallax  $\varpi_{\text{twin}}$  was related to  $\sigma$  for each pair of spectra in the data set. This can be seen in Fig. 2, where we plot the ratio of the parallaxes obtained from Eq. 4 and the Hipparcos parallax as a function of  $\sigma$  for the set of field stars. We found that when a pair had very different spectra then the value of  $\sigma$  was high and the value ( $\varpi_{\text{HIP}}/\varpi_{\text{twin}}$ ) was also very different from unity. In the same way, if the spectra were very similar,  $\sigma$  had a low value and the ratio between Hipparcos and twin parallax was close to unity.

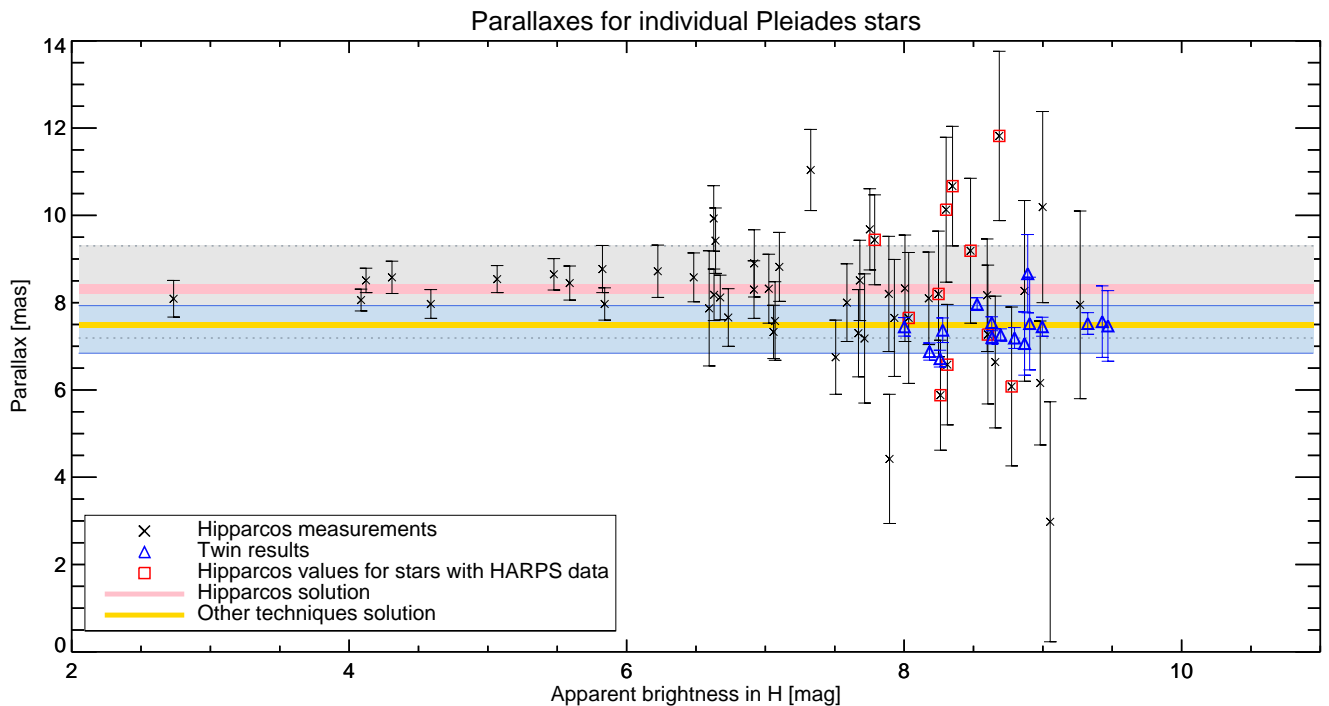
Figure 2 shows that for  $\sigma < 0.015$ , a typical error in parallax does not exceed 10%. We refer to this parallax error  $\Delta\varpi_{\sigma}$  as the error of the twinning, i.e. the relative error  $\Delta\varpi_{\sigma}/\varpi < 0.1$  for  $\sigma = 0.015$  (see below). This error is competitive to typical errors estimated using isochrone fitting when internal systematic errors on the models are neglected. The advantage here is that no stellar evolution models are required.

Hence, requiring  $\sigma < 0.015$  for the Pleiades-field pairs yields individual parallaxes to the Pleiades targets with expected errors of 10%. Note that this includes both the twin assumption error and the errors of the Hipparcos parallax.

### 3.3. Uncertainties

Below we summarize the sources of uncertainties involved in this work regarding our distance determinations.

1. *Reference parallax* : Our reference sample is comprised of only parallaxes with accuracies better than 7% and typically of 3.5%, therefore the traditional law of error propagation can be approximately applied in our case. An uncertainty in the parallax associated to the reference star was propagated to the twin parallax following Jofré et al. (2015b). As discussed in that paper, typical propagated errors are of the order of 5%.
2. *Photometry* : In our sample, the median errors in the photometry of the stars for the  $H$  and  $K_s$  band are of 0.03 and 0.02 mag, respectively. In Jofré et al. (2015b) we showed that this introduces a negligible error in the final results of less than 1%.
3. *twinness*: The error of the twinning  $\Delta\varpi_{\sigma}/\varpi$  arises because the stars may not be exact twins and because the spectra have noise due to different observational condition. The



**Fig. 4.** The parallaxes of 54 Pleiades stars of the Hipparcos solution are indicated with black crosses. The mean and standard deviation of these Hipparcos parallaxes is shown by the grey band enclosed by a dotted line. Eleven of the Hipparcos stars have HARPS spectra and have been analysed in this work (red squares). Our results are indicated with blue triangles. The standard deviation of these values are shown with the blue band enclosed by the blue line. The pink band represents the values of the Hipparcos solution within its margin of error while the yellow band represents the range of the alternatives to Hipparcos.

latter was minimised by requiring high SNR of the observed spectra. As explained in the previous section the error of the twinning is less than 10% when choosing  $\sigma < 0.015$  in the comparison of the spectra.

4. *Multiple twins:* If one star has more than one twin, different values for its parallax can be estimated using each of these twins as reference. This gives a distribution of almost independent parallax measurements, with an associated mean with its standard error. This uncertainty is dependent on the number of twins found for a given star, where the larger the number of twins, the more accurate the distance.

In summary, if several twins are found for a target (which applies to the case of the Pleiades) the reported standard errors correspond to the statistical error (Point 4). If only one twin is found, then the reported standard error corresponds to the square root of the quadratic sum of the uncertainties explained in Points 1, 2 and 3.

## 4. Results

Applying the cut of  $\sigma < 0.015$  to the difference of the spectra of the 8970 Pleiades-field-star-pairs<sup>2</sup> resulted in 57 twin pairs which are listed in Table 2. These pairs were used to determine the individual parallaxes of the Pleiades members, which are indicated in Table 3. Most of the Pleiades targets have more than one partner in the field. As multiple twins to an individual Pleiades star must then share the physical properties, these

<sup>2</sup> The number is the product of the number of 15 Pleiades stars and 598 field stars.

multiple partners should also be twins with each other. We compared their Hipparcos and twin parallax and found an agreement of better than 10%, which is consistent with the uncertainty obtained from the selection of  $\sigma$ . This comparison between the Hipparcos field stars implies that the reference parallax of the field twins are accurate. It further confirms the analysis of Kim et al. (2016) who found that Hipparcos parallax to FGK field stars similar to Pleiades member stars are in good agreement with stellar models.

### 4.1. Parallax of individual Pleiades stars

Figure 3 shows the parallax of individual Pleiades stars, in which our results are compared with the literature (Makarov 2002; Soderblom et al. 2005; van Leeuwen 2007). The star HII 3179 has been analysed by Soderblom et al. (2005) who performed parallax measurements using the Hubble Space Telescope. Our twin parallax and the parallax from Soderblom et al. (2005) are in excellent agreement at 2%. This is encouraging given that these works are independent.

It is important to remark that not all the Hipparcos parallax measurements have the large error bars of the Hipparcos stars shown in Fig. 3. Indeed, several brighter Pleiades members have significantly more accurate measurements. We show in Fig. 4 our Pleiades twin parallax with Hipparcos parallaxes of 54 Pleiades stars that are usually considered for the astrometric solution (e.g. Makarov 2002; van Leeuwen 2007; Palmer et al. 2014). The bright stars ( $H < 7$  mag) have accurate Hipparcos parallaxes with a low star-to-star scatter of 0.5 mas with an averaged parallax of  $8.36 \pm 0.09$  mas (Fig. 4), suggesting that these may be better candidates for comparison. However, this

is currently not possible, since these stars are mainly of A and B spectral type, to which the twin method is much more difficult to apply. First, the HARPS public archive contains mainly FGK stars spectra due to the bias towards searching for exoplanets around solar-like stars. Indeed, for the AMBRE project (De Pascale et al. 2014) 70% of the HARPS archive were found to be FGK stars while the remaining 30% were either binaries, had too low signal-to-noise or were outside the FGK-parameter space. Second, 20% of the brighter Pleiades stars are either variable or binary stars, so their photometry could not be used to determine their distance with the twin method. Furthermore, AB stars are more massive than FGK stars and so have faster evolution implying that there are much fewer AB stars in the sky compared to FGK stars. However, the twin method can potentially be applied to any spectral-type, provided a good reference sample is available, as was recently shown for twin supernovae (Fakhouri et al. 2015).

For fainter stars ( $H > 7$  mag) the situation in Fig. 4 is very different. The Hipparcos parallaxes have large star-to-star scatter of up to 1.8 mas while the twin parallax show a scatter of around 0.4 mas. For further comparison we calculate the weighted mean parallax of the Hipparcos stars with  $H > 7$  mag. Taking the weighted mean is preferred because the parallax estimates of Hipparcos correlate with the errors of the measurements for fainter stars (van Leeuwen 2007, 2009). The weighted mean parallax obtained for the faint Hipparcos stars is  $8.07 \pm 0.20$  mas, which still agrees within the errors of the value obtained from the bright stars. In turn, calculating the weighed mean of the 15 twin parallaxes gives a value of  $7.42 \pm 0.09$  mas.

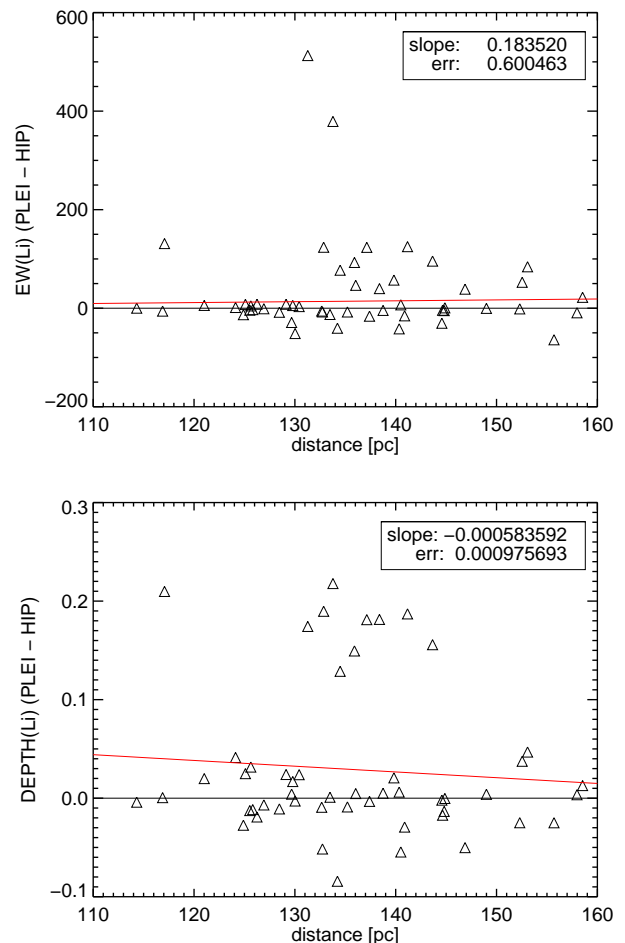
Since the literature regarding the Pleiades controversy is more commonly discussed in terms of distances in parsecs, we transform our results of the individual parallaxes and mean parallax of the cluster to distance using  $d = 1/\varpi$ . Due to this non-linear relation it is clear that a parallax with a symmetric error results in a distance with an asymmetric error. A recent discussion on how parallaxes, distances and their errors are related can be found in Bailer-Jones (2015), where the standard error propagation law of

$$d \pm \Delta d = \frac{1}{\varpi} \pm \frac{\Delta\varpi}{\varpi^2}, \quad (7)$$

for translating errors in parallax to errors in distance can only be used when the error of the parallax is less than 20%. As both the derived twins parallaxes and the weighted mean parallax have relative errors well below 20% we can apply (7). The individual distances of the Pleiades members and their errors are displayed in Table 3. Our main result is thus that the weighed mean parallax of the 15 stars obtained with the twin method yields a distance of  $134.8 \pm 1.7$  pc to the Pleiades.

#### 4.2. Lithium

In our comparison of Pleiades and field stars the issue of age differences adding systematic uncertainties in the distance determination arise, because the cluster stars are all young while the field stars have different ages. In van Leeuwen (2009) it was shown that the colour-colour diagrams of the Pleiades and other young clusters were different with respect to the Hyades, suggesting an intrinsic difference in the luminosity and therefore distance modulus due to age. In order to study this potential systematic difference with our method, we looked at the Li  $\lambda 6707\text{\AA}$  line in our spectra, taking into account that Li abundances can be used as an age-proxy (Jackson & Jeffries 2014; Kim et al. 2016), namely



**Fig. 5.** The difference of the Li equivalent widths and depth as a function of distance for the Pleiades-field twins. The red line indicated the linear fit to the data, with the slope and error of slope indicated in the legend. No correlation between difference of Li abundance and distance has been found.

that a strong Li line indicates young stars. Using *iSpec*, we measured the equivalent width and the depth of the Li  $\lambda 6707\text{\AA}$  line in our sample of twins and correlated their difference with distance (see Fig. 5). A linear fit to the data was performed, showing no indication of systematic difference in distance for stars presenting same or different Li abundances (see also Kim et al. 2016, for a discussion on Li abundances of field stars with same photometric properties as Pleiades member stars). Thus both young and older twins give the same result, showing that differential age effects are not significant in the method.

## 5. Conclusions

In this paper we have applied the twin method to determine distances of the Pleiades in a model-independent way. Our result of  $134.8 \pm 1.7$  pc, based on Hipparcos parallaxes of field stars, disagrees with the value directly derived from Hipparcos parallaxes of Pleiades members (van Leeuwen 2007; Perryman 2008; van Leeuwen 2009; Palmer et al. 2014) but it is in good agreement with the value provided by the model-based methods mentioned earlier (Pinsonneault et al. 1998; Percival et al. 2005; Valls-Gabaud 2007; Groenewegen et al. 2007; Pan et al. 2004; Melis et al. 2014). Since most of these methods (except

star name 1 Pleiades member	Hipparcos name of twin candidate in the field
Pels15	HIP43299, HIP1481, HIP3924
Pels17	HIP43299, HIP36312, HIP2751, HIP3924, HIP2724
Pels18	HIP6572, HIP95149
Pels35	HIP1481, HIP1825
Pels 27	HIP5099, HIP41282, HIP17838, HIP18658, HIP29932, HIP19877
Pels140	HIP22844, HIP1427, HIP37844, HIP46934
Pels174	HIP41282, HIP5709, HIP7443, HIP20350
HII430	HIP14684
HII1215	HIP3203, HIP41587, HIP109110, HIP25002
HII1593	HIP116819, HIP48141, HIP38041, HIP91700, HIP107805
HII1794	HIP95149
HII1924	HIP490
HII2311	HIP14684
HII2506	HIP490, HIP1825
HII3179	HIP33212, HIP112117, HIP72134, HIP45685, HIP38765, HIP413, HIP5280, HIP26722, HIP4747, HIP5806, HIP23128, HIP108859, HIP115803, HIP116106, HIP3466, HIP53094

**Table 2.** Pleiades member stars and their twins in the field.

star name	Hipparcos name	$\varpi$ [mas]	$e_\varpi$ [mas]	$d$ [pc]	$e_d$ [pc]	# twins
Pels15	HIP 16979	7.31	0.10	136.80	+1.89 -1.94	3
Pels17	HIP 17091	7.26	0.17	138.13	+3.08 -3.22	5
Pels18	HIP 17044	7.50	0.82	136.69	+13.15 -16.39	2
Pels 27	HIP 17289	7.53	0.19	133.46	+3.28 -3.45	6
Pels35	HIP 17316	7.94	0.15	126.00	+2.36 -2.45	2
Pels140	HIP 17511	7.40	0.24	135.75	+4.22 -4.51	4
Pels174	HIP 18955	6.86	0.16	146.10	+3.41 -3.57	4
HII430		7.46	0.84	134.06	+13.53 -16.95	1
HII1215		7.42	0.17	135.09	+2.96 -3.09	4
HII1593		7.47	0.22	134.48	+3.83 -4.07	5
HII1794		8.75	0.98	114.23	+11.53 -14.44	1
HII1924		6.98	0.78	143.23	+14.45 -18.11	1
HII2311		7.52	0.84	133.04	+13.43 -16.82	1
HII2506		7.18	0.20	139.53	+3.76 -3.98	2
HII3179		7.52	0.12	133.47	+2.09 -2.15	16

**Table 3.** Our determinations of parallaxes and distances together with their error of the individual Pleiades members with twin candidates in the field. The Hipparcos name is given if known.

Stello & Nissen 2001; Makarov 2002; Soderblom et al. 2005; Melis et al. 2014) use stellar evolution models in their distance determination and because our observed stars are FGK stars, our derived value implies that the current stellar evolution models for FGK stars in the Pleiades are accurate.

Very soon the parallaxes from Gaia will confirm whether our prediction for the individual distances of the 15 Pleiades stars is correct, showing the power of the twin method in complementing Gaia and calibrating distance scales. The Gaia Data Release 1 will probably also show if the star-to-star dispersion for the fainter Pleiades targets remains. It will further confirm whether the Pleiades distance controversy is a matter of individual distance accuracies, cluster morphology, astrometry, or the approximations in stellar evolution models. In this study, a distance estimate to some of the most difficult Hipparcos targets within the Pleiades has been determined. At the end of the Gaia mission, accurate parallaxes will be available for almost every star

for which there is a high resolution spectrum. Nevertheless, new larger telescopes are being constructed, such as the 40-meter E-ELT, will give us high resolution spectra of very faint stars at the outskirts of our Galaxy and beyond. These ground-based instruments will provide new opportunities for complementing Gaia's astrometric solutions and so to continue to climb the cosmic distance ladder with stellar twins.

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## Appendix A: Data of field stars

The information of the Hipparcos field stars used in this work is contained in Tab. A.1. The name and coordinates of the stars are given, as well as the 2MASS photometry with its quality flag, the Hipparcos parallax from van Leeuwen (2007), the SNR of the spectra, the date in which the spectra were taken and the program ID.

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star	RA [deg]	DEC [deg]	H [mag]	K [mag]	$\varpi$ [mas]	e_ $\varpi$ [mas]	SNR	date-obs	Program ID	2MASS Flag
HIP100233	304.938589	-25.228242	5.86	5.76	24.85	0.65	240.30	2005-07-25	072.C-0488(E)	AAA
HIP101345	308.097964	-9.8536410	3.91	4.00	40.98	0.33	352.30	2011-09-16	183.C-0972(A)	DDE
HIP101346	308.099775	6.51751652	7.17	7.10	10.07	0.84	127.90	2004-09-17	072.C-0488(E)	AAA
HIP101785	309.431044	-22.442887	6.35	6.31	19.27	0.67	144.25	2011-05-29	087.C-0831(A)	AAA
HIP101806	309.466397	-60.634323	6.12	6.03	20.01	0.66	234.35	2006-05-28	072.C-0488(E)	AAA

**Table A.1.** Properties of reference field Hipparcos stars used in this sample. A full version of this table can be found in electronic format.