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A deep proper-motion survey of the nearby open cluster Blanco 1*†

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ABSTRACT

We provide two comprehensive catalogues of positions and proper motions in the area of open cluster Blanco 1. The main catalogue, CTLGM, contains 6271 objects down to $V\sim 18.5$ and covers a circular ∼11 deg^2 area. The accuracy of CTLGM proper motions, at about 0.3–0.5 mas yr^{-1} for well-measured stars, permits an excellent segregation between the cluster and field stars. The vector-point diagram of proper motions indicates an estimated total of ∼165 cluster members among the stars in our sample, while 314 stars with $\sigma_\mu < 2.5$ mas yr^{-1} have membership probabilities $P_\mu \geq 1$ per cent. We also explored the astrometric potential of the Catalogue of Objects and Measured Parameters from All Sky Surveys (COMPASS) data base in order to obtain additional proper motions for fainter stars in the area of Blanco 1. This effort produced the second catalogue of proper motions, CTLGD, containing 11 598 objects down to $V\sim 21$. A total of 4273 objects are common between the two catalogues. The accuracy of proper motions in CTLGD ranges from 1.0 to 6 mas yr^{-1}. A combination of both proper-motion catalogues was instrumental in confirming that Blanco 1 contains a large population of M dwarfs (∼150 down to M5 V – the limit of our survey). In many respects, Blanco 1 is a scaled down 'twin' of the Pleiades. The noted discrepancy between the distance from a new *Hipparcos* parallax of Blanco 1 and the cluster's photometric distance, at least partially, might be due to the apparent correlation between parallax and proper motion in right ascension for the ensemble of cluster members.

Key words: astrometry – stars: kinematics and dynamics – open clusters and associations: individual: Blanco 1.

1 INTRODUCTION

Blanco 1 (C0001-302) is a nearby ($d\sim 250$ pc) and relatively young (∼100 Myr) open cluster located at the unusually high Galactic latitude of $b = -79°$ which is uncharacteristic for a Galactic thin disc population containing open clusters.

Perhaps, due to the relatively late discovery of this cluster (Blanco 1949) and owing to its location in the Southern hemisphere, no dedicated proper-motion study of Blanco 1 is readily

*All tables with the exception of Table 2 are available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/MNRAS/, and as Supporting Information with this article online.
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available. An attempt has been made to use proper motions for the Blanco 1 cluster membership determination from large sky surveys such as the Guide Star Catalogue II (GSC-II) and the Southern Proper Motion Programme SPM3 (Pillitteri et al. 2003; Carraro et al. 2005). For appropriate selection of stars in these surveys, the cluster is clearly detectable in the proper motion vector-point diagram (VPD). The cluster memberships in these studies appear to be fairly reliable down to $V \sim 14$. At fainter magnitudes, the stated accuracy of proper motions (3–4 mas yr^{-1} or more) apparently is less adequate to separate the cluster stars from field.

Blanco 1 has been studied in a variety of ways, covering its photometric, spectroscopic and kinematic properties as well as measuring the X-ray luminosities of its members. The cluster has been extensively observed by spectroscopic means which have resulted in fairly comprehensive lists of radial velocity measurements (Jeffries & James 1999; Mermilliod et al. 2008; González & Levato 2009). Radial velocities are currently one of the main sources of the cluster's kinematic membership, especially for stars in the outer parts of the cluster. An important step towards a better understanding of Blanco 1 is the high-resolution spectroscopy used to determine reliably its elemental abundances (Ford, Jeffries & Smalley 2005). According to this study, Blanco 1 has a near-solar metallicity at [Fe/H] $= +0.04 \pm 0.04$ dex. In this regard it is similar to the Pleiades, for which the most recent determination of [Fe/H] is $+0.01 \pm 0.02$ dex (Schuler et al. 2010). A few X-ray surveys in the area of Blanco 1 provide extensive lists of X-ray sources, many of which are clearly associated with cluster members (Cargile, James & Platais 2009). X-ray detection can be used as one of the cluster membership criteria, however, caution should be exercised because of a large number of X-ray-active extragalactic sources in the direction of Blanco 1 (Pillitteri et al. 2004).

The astrometric part of our study presented here has its roots in the Southern Proper Motion (SPM) Programme (e.g. Platais et al. 1998). Around circa 1995, we derived preliminary proper motions based on four sets of photographic plates taken with the 51 cm double astrograph of the Cesco Observatory in El Leoncito, Argentina. These proper motions were used to select additional potential cluster members for radial velocity measurements with the CORAVEL spectrophotometer (Mermilliod et al. 2008). They were also used to study Hα emission and abundances of Li I in Blanco 1 (Panagi & O'Dell 1997). At the time it was felt that the accuracy of the preliminary proper motions was insufficient. Therefore, in the following decade additional astrometric observations were collected. Finally, in 2007 new proper motions were derived for 6300 objects in the area of Blanco 1 (Mermilliod et al. 2008). However, even these substantially improved proper motions occasionally are at odds with the cluster membership from radial velocities. The current study of proper motions is an attempt to identify remaining sources of systematic errors and eliminate them. In addition to that, one more recent epoch of CCD observations is included to improve the overall accuracy of proper motions in the area of Blanco 1.

Recently, Moraux et al. (2007) produced two lists of photometrically selected low-mass stars and brown dwarf candidate members of Blanco 1. By virtue of limitations of 'photometric' membership, these lists are expected to be contaminated by M-type field dwarfs. The authors estimated statistically that the sample of low-mass candidate members may contain up to ~55 per cent field stars. Undoubtedly, it would be very helpful to identify such field stars using proper motions. The existing astrographic plates with Blanco 1 are too shallow to effectively cover its low-mass range ($m \lesssim 0.4\,M_\odot$). Therefore, we explored the COMPASS data base of objects derived from the Palomar and UK Schmidt survey plates (Lasker et al. 2008) with the objective of calculating proper motions for faint stars. While Pillitteri et al. (2003) used the proper motions from the GSC-II, we used the lists of positions at a variety of epochs and derived our own proper motions. Our independent analysis was prompted by possible systematic errors in the GSC-II proper motions as hinted by Lasker et al. (2008, section 5.3).

The description of various steps in constructing the catalogues and their properties provided here are in lieu of a paper (Platais et al., in preparation) originally referenced by Mermilliod et al. (2008) and Panagi & O'Dell (1997). An accompanying paper on high-fidelity $UBVI_C$ photometry of Blanco 1 is in the works (James et al., in preparation).

2 MAIN CATALOGUE OF PROPER MOTIONS

The complexity of the observational material required a non-standard approach in the reductions, leading to high-accuracy proper motions, initially not expected considering the relatively poor plate scale. Because of these intricacies, a full account of all steps in the reductions is provided.

2.1 Observational material

Nearly all photographic imaging for the astrometry of Blanco 1 has been obtained at the Cesco Observatory in El Leoncito, Argentina, with the 51-cm double astrograph (scale 55.1 arcsec mm^{-1}). The earliest epoch of that plate material dates back to 1967, while the most recent CCD observations were obtained in 2007. Four sets of photographic plates, each consisting of a blue and a visual plate, were taken as part of the SPM programme. The characteristics of large 17×17 inch SPM plates are given, e.g., in Platais et al. (1998). These plates were measured using the Yale PDS microdensitometer in the object-by-object mode. We also digitized five 5×7 inch plates used by de Epstein & Epstein (1985) in their photometric study of Blanco 1. In 1995 three new exposures of Blanco 1 were taken on the same size plates with the visual lens of the double astrograph. All brighter stars on these plates have haloes around their images, due to the red-sensitive IIIa-F emulsion used in this observing run. Surprisingly, these haloes appear to have no detrimental impact on the astrometric precision. All smaller photographic plates were digitized twice (in direct and reverse orientation) using the Space Telescope Science Institute's (STScI) GAMMA II multichannel scanning microdensitometer (Lasker et al. 2008). Finally, in 1985 three plates were taken with the European Southern Observatory's 40-cm GPO astrograph (scale 51 arcsec mm^{-1}), covering a $2^\circ \times 2^\circ$ coma-free field of view. These plates were digitized using the 2020G PDS microdensitometer in Muenster. Altogether, a total of 19 photographic plates or their equivalents (see Section 2.3) are used for this study of Blanco 1.

The astrometric observations of 2007 were obtained using a Pixel Vision 4 K×4 K CCD camera mounted in the focal plane of the double astrograph's visual optical path. This CCD imager captures $0\overset{\circ}{.}94 \times 0\overset{\circ}{.}94$ of the sky at a resolution of 0.83 arcsec pixel^{-1}. The standard mode of observation is a half-a-chip dither in declination, which provides a twofold overlap over the chosen field of sky (Casetti-Dinescu et al. 2007). In the case of Blanco 1, it required 28 pointings to cover a $3^\circ \times 3^\circ$ area centred on the cluster. In order to compensate for the effects of a rather poor winter–spring seeing, the cluster area was observed three times using this pointing pattern. We note that all SPM observations (the 17×17 inch plates and recent CCD observations) are taken with the wire-grating which provides additional images placed symmetrically with respect to the central image and attenuated by ∼4 mag. For both, the GAMMA-II scans and the CCD observations, we used similar image processing routines; that is the SExtractor for image detection and a two-dimensional Gaussian fit to improve the accuracy of image centres.

2.2 Limitations on target acquisition

As indicated by Cargile et al. (2009), the members of Blanco 1 are spread over about a 3° × 3° area on the sky. Our initial sample of all stars down to $B_J = 16$ was chosen from a circular area with a 3°.8 diameter, centred on RA = $0^h0^m5^s$ and Dec. = −30°5′ (J2000). This sample of 4440 objects was augmented by ancillary stars with $V < 13$ over 6° × 6° which is the angular size of SPM field 455, comprising essentially the entire Blanco 1 cluster. The smaller plates used by de Epstein & Epstein (1985) and the new circa 1995 plates cover a smaller 2°.6 × 1°.8 area. On these plates, all detected objects were measured down to the limiting magnitude $V \sim 17$. The limiting magnitude of the astrograph CCD frames is $V \sim 18$–19. In the advanced stages of this project, it was decided to extend our sample down to $V \sim 17.5$ within the inner circle with radius of 1°. The source of these positions was the measurement of two first-epoch SPM field 455 plates by the Precision Measuring Machine (PMM) at the US Naval Observatory's Flagstaff station. Thus, we selected epoch 1968.64 positions for ∼1800 additional faint objects from an unpublished catalogue which was constructed using the PMM measurements (Platais et al. 2001).

2.3 From pixel to equatorial coordinates

Given the large variety of our plate material supplemented by technologically contrasting CCD observations, it was decided to translate all image centres from pixel coordinates into the International Celestial Reference System (ICRS), represented by the UCAC2 catalogue (Zacharias et al. 2004). As indicated in Section 2.1, each distinctive set of plates has been digitized by a different measuring machine. It is assumed that the measuring accuracy of these machines is better than 1 μm and that they do not produce perceptible systematic errors. The latter, however, is not entirely true for the GAMMA-II measurements but in this case it was possible to calibrate the amount of machine-induced systematics and account for them, using the so-called 'direct' and 'reverse' measurements of each plate. Although systematics in the GAMMA measurements can reach 1–2 μm, the pattern of these systematics is stable and requires only infrequent monitoring and recalibration. The post-correction tests show that these systematics have been eliminated down to the level of 0.2–0.3 μm.

The large 17 × 17 inch SPM plates contain two exposures – a 2 h and an offset 2 min exposure. Throughout the reductions, each of these was handled as an individual 'plate'. In addition, all brighter stars have diffraction images which help to account for the magnitude-dependent systematic errors (Girard et al. 1998). All eight SPM plates were reduced using the SPM pipeline, including the step which deals with transforming grating images on to the central, zero-order image system. Depending on magnitude, we may have up to 16 centre determinations for the same star. The most recent images obtained with the PixelVision CCD camera were reduced using a pipeline similar to that of the photographic plates, which is detailed by Casetti-Dinescu et al. (2007). In this case, on each CCD frame a star may have up to three centres (corrected-for-systematics) related to a central image and first- and second-order diffraction-image pairs. Since the Blanco 1 area was surveyed three times, in the most favourable circumstances a star may have ∼30 centres at most recent epochs.

In order to calculate proper motions, we used a variant of the iterative central-plate-overlap algorithm (e.g. Jones & Walker 1988). The concept of the central-plate-overlap algorithm requires choosing an appropriate reference frame, this often being simply a 'best' plate. Such a choice has a drawback in the form of potential systematic errors in this plate, which then can propagate into the catalogue positions and proper motions. Therefore, we chose an external UCAC2 catalogue of positions and absolute proper motions as our initial reference frame. This catalogue was trimmed down to stars with positional errors less than 75 mas in either coordinate. Then, each set of pixel coordinates was solved into the UCAC2 by using an optimal number of polynomial terms in the equatorial solution. Normally, linear plus quadratic tilt terms were sufficient, while the large SPM plates required the inclusion of the main cubic terms as well. We noticed that the standard error of equatorial solutions has a tendency to increase for the plates and CCD frames taken at the extreme epochs. Usually, this is an indication that the proper motions in the reference catalogue are inaccurate (see Section 2.4).

2.4 Calculating proper motions and positions

Once all image centres are transformed into a common reference frame such as the ICRS, the positions and proper motions for each object can be easily derived from the relationship 'weighted individual positions versus time', which is fitted with a straight line. The uncertainties of individual positions, which provide the weights, are estimated from equatorial solutions and calibrated as a function of instrumental magnitude. At this stage, we also added to our data sets the UCAC2 itself, transformed to the mean epoch of its observations in the region of Blanco 1. The subsequent reductions include the following four steps.

(i) All sets of equatorial coordinates were translated into tangential coordinates, having a zero-point at the nominal centre of the cluster adopted at RA = 1°.0292 and Dec. = −29°.8333, exactly.

(ii) A total of 123 017 values of tangential coordinates were sorted and, within a $r = 5$ arcsec circle, all potentially related positions found for each blindly identified object. All such positions are tagged and excluded from being assigned to another object. At this point the first-cut proper motions and positions are calculated and the discordant data points are eliminated.

(iii) Proper motions are corrected for magnitude- and coordinate-related systematics using a preliminary list of cluster members. The detection of a star is confirmed if at least four data points can be identified, separated by at least 20 years in time. These restrictions eliminate the vast majority of false or dubious detections, mainly due to defects in the photographic emulsions.

(iv) Then, the UCAC2 positions and proper motions are replaced with the newly calculated values and the updated catalogue is used to recalculate all equatorial solutions. Residuals from these solutions are used to calibrate the remaining magnitude-related systematics for each set of coordinates which then are corrected accordingly. On the second iteration, we try to identify additional missing image centres outside the 5-arcsec circle by applying the calculated proper motions to all detections within a 10-arcsec-circle and then recalculating proper motions and positions only for the well-clumped detections. Because of our initial positional restriction at 5 arcsec, we miss proper motions exceeding ∼300 mas yr^{-1}.

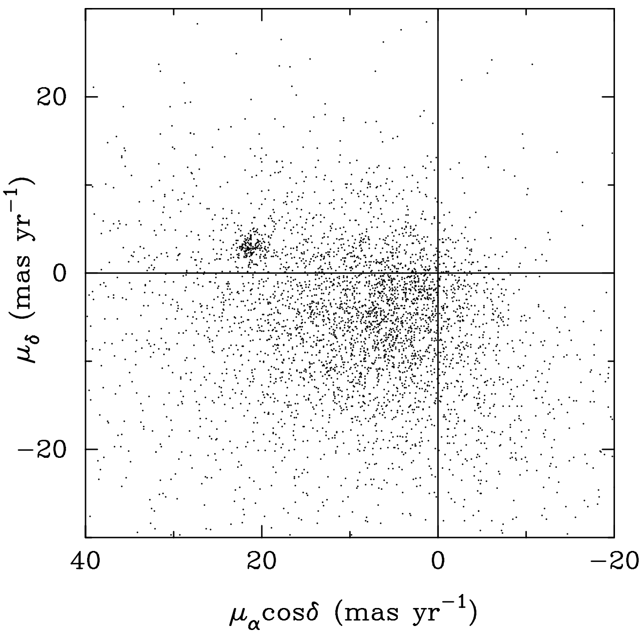

Figure 1. VPD of proper motions from the CTLGM catalogue. A tight clump at $\mu_\alpha \cos\delta = +21.3$ and $\mu_\delta = +2.9$ mas yr^{-1} indicates the location of Blanco 1.

(v) The final step includes a small correction for magnitude-related systematics to all proper motions. These systematics are calibrated using the probable cluster members.

The main catalogue, named CTLGM, contains 6271 objects. The highest formal accuracy of calculated proper motions is 0.3 mas yr^{-1}. None of the objects was deleted because of poor proper motions. Nevertheless, for practical purposes any star or galaxy with a proper motion error exceeding ~3 mas yr^{-1} should be considered with caution. In addition to large proper motion errors, a very small number of detections and/or some deleted detections for brighter stars are usually the telltale signs of a close visual binary. A VPD for 4678 objects with proper-motion errors less than or equal to 2.5 mas yr^{-1} and to within a range of ±30 mas yr^{-1} in either coordinate is given in Fig. 1. The majority of stars with $\sigma_\mu > 2.5$ mas yr^{-1} are fainter than $V = 16.5$ mag. Among these stars might be a few cluster members, however, additional membership criteria must be invoked in order the ascertain their true identity. We note that the distribution of proper motions of likely cluster members is slightly asymmetric. Apparently, some small residual systematics are still left in the proper motions.

The main catalogue CTLGM is given in Table 1 (for the complete catalogue, see the Supporting Information with the electronic version of the article). It contains the running number (ID), estimated V magnitude, right ascension and declination in decimal deg (epoch and equinox J2000), semi-absolute (i.e. on the system of UCAC2) proper motion and its errors in mas yr^{-1}. According to our techniques, $\mu_\alpha^* = \mu_\alpha \cos\delta$ and μ_δ are aligned with the system of equatorial coordinates at a single point only. For certain applications, proper motions may need to be corrected to account for a small rotation at all other points on the sky. The cluster membership probability, P_μ, is given in per cent. The final number of used positions ($N_{\rm obs}$), the number of deleted positions ($N_{\rm del}$) and the span of epochs in years (ΔT) are useful ancillary information. Tangential coordinates, ξ and η, are given in radians. Finally, the cross-ID number, ID2, with the deeper catalogue CTLGD (see Section 3) is provided, if it is not equal to zero.

We do not provide individual positional uncertainties because of our cautionary experience with a similar data set for NGC 188 (Platais, Wyse & Zacharias 2006) where a formal uncertainty did not represent well the positional accuracy. A direct comparison with 19 *Hipparcos* stars from the inner 2° × 2° area around Blanco 1 indicates that the offset of CTLGM coordinates does not exceed 20 mas and the rms scatter of our coordinates is 18 mas. Assuming that there is no perceptible increase of the coordinate offset at fainter magnitudes, we adopt a conservative 50–100 mas accuracy for our positions down to the limiting magnitude.

3 DEEP PROPER MOTIONS

A large number of photometrically selected low mass candidate cluster members reported by Moraux et al. (2007) motivated us to expand the proper-motion survey to fainter magnitudes. Our main catalogue CTLGM reaches $V \sim 18.5$ which in the context of Blanco 1 corresponds to the main-sequence stars of spectral class M2-M3V or a mass of ~0.4 M$_\odot$. In fact, even brighter stars with $V > 17$ have rather large proper-motion errors, not very conducive for a reliable cluster membership analysis. Therefore, we explored the Catalogue of Objects and Measured Parameters from All Sky Surveys (COMPASS; Lasker et al. 2008) data base for its potential to derive deep proper motions. The results of this work are presented in this section.

3.1 Positional catalogues

The COMPASS data base is a repository for the reduced data originated from the Schmidt plate digitization efforts at the STScI. These plates (more than 8000) taken through various photographic bandpasses cover the entire sky multiple times, starting from the 1950s and ending in 1999. From this data base, we selected the sets of precise equatorial coordinates in the area of Blanco 1 derived from the measurements of seven Schmidt plates, listed in Table 2. More information about these plates is given in Lasker et al. (2008) and

Table 1. Main catalogue CTLGM of positions and proper motions in the area of Blanco 1. Listed are the first five entries only. The full table is available as Supporting Information with the electronic version of the article.

ID[a]	V	RA	Dec.	μ_{α^*}	$\sigma_{\mu_{\alpha^*}}$	μ_δ	σ_{μ_δ}	P_μ	$N_{\rm obs}$	$N_{\rm del}$	ΔT	ξ	η	ID2
1	13.61	357.658 3422	−32.738 6798	48.0	10.9	−37.7	4.9	0	5	2	22	−0.049 584 56	−0.051 542 01	0
2	11.97	358.874 8701	−32.739 6806	11.1	3.7	−5.2	5.0	0	8	5	22	−0.031 676 49	−0.051 091 99	0
3	10.92	357.072 3975	−32.681 9865	67.9	5.8	28.1	8.4	0	5	3	22	−0.058 252 99	−0.050 847 88	0
4	9.13	0.208 4496	−32.735 9343	−11.9	3.0	−7.7	5.5	0	9	3	22	−0.012 065 59	−0.050 750 70	0
5	8.39	2.077 7564	−32.700 9251	69.6	3.2	−44.2	3.5	0	9	1	22	0.015 420 46	−0.050 167 66	0

[a]See Section 2.4 for details on the table header and units.

Table 2. Basic data on Schmidt plates.

Survey	Field ID	Plate ID	Band	Epoch	Depth
POSS-I	936	A2TS	E	1954.75	19.1
POSS-I	936	A3WZ	O	1954.75	20.7
POSS-I	881	A2L2	E	1954.90	19.6
POSS-I	881	A2MK	O	1954.90	20.8
SERC J	409	G4IN	B_J	1976.88	22.5
AAO-SES	409	A04G	R_F	1990.79	20.5
SERC I	409	A2RM	I_N	1990.90	18.5

the MAST [1] home page. The last column in this table shows the cut-off magnitude which is about a magnitude brighter than the actual limiting magnitude of these plates. We chose this cut-off magnitude in order to avoid large numbers of less precise coordinates for very faint objects and also artefacts.

In general, the plate measurements on the GAMMA machines have been already processed at the STScI through a similar pipeline to that of our measurements of the SPM plates (Section 2.3). Here, we recap the main functions of the STScI pipeline. Astrometry of the Schmidt plates is more complicated than that of the SPM plates because the latter are obtained with an astrograph which by design is optimized for astrometry, with all geometric distortions minimized. First, for the majority of Schmidt plates, the astrometric reference frame was the Tycho-2 Catalogue (Høg et al. 2000), so that the plate positions are tied directly into the ICRS. Its limiting magnitude is $V \sim 11.5$ and, as such, it provides a relatively sparse reference frame. Secondly, each series of Schmidt plates was corrected by a custom-made empirical astrometric mask. This mask eliminates a systematic pattern in the residuals that a global polynomial plate model cannot remove. Another systematic effect, specific to the Schmidt plates, is the radial 'magnitude equation' reported by Morrison et al. (2001). At the plate edges the positional displacement of faint stars with respect to bright reference stars can reach 0.9 arcsec. A more detailed account of the Schmidt plate astrometric reductions is given in Lasker et al. (2008), describing the properties of the GSC 2.3 catalogue. The estimated average positional accuracy for well-exposed stellar images in GSC 2.3 is 0.28 arcsec. For the Southern hemisphere, the authors report significant systematic errors in the proper motions. While this seems to be discouraging in terms of cluster membership, we attempted to identify and eliminate systematic errors in the positions from individual plates and then to derive new proper motions.

3.2 Proper motions in CTLGD

The new reduction of proper motions started out with tables of positions for each plate listed in Table 2. We chose a circular area with a radius of 1°.5 around the centre, RA= 0^h5^m Dec. = $-30°5'$. There are a total of 192 659 registered detections on seven plates. This extraction of positions was supplemented with the entire catalogue CTLGM at the epoch 2000.0 and the positions of 763 low-mass candidate members from Moraux et al. (2007). The rationale for adding in these two lists was our desire to improve proper motions for stars fainter than $V = 17$, whose proper motions in CTLGM on average are not better than $\sim$3 mas yr^{-1}. Our main catalogue also served as a test bed for systematic errors in the positions from the Schmidt plates. All seven plates needed significant corrections in both right ascension and declination. The largest corrections (up to 0.7 arcsec) were required in right ascension; corrections in declination did not exceed 0.3 arcsec. That approximately follows the pattern of systematic offsets found by Lasker et al. (2008). The magnitude-related systematics were detected and corrected in five plates (only plates A2TS and G4IN appear to be free of this effect). This correction, however, never exceeded 0.2 arcsec in either coordinate.

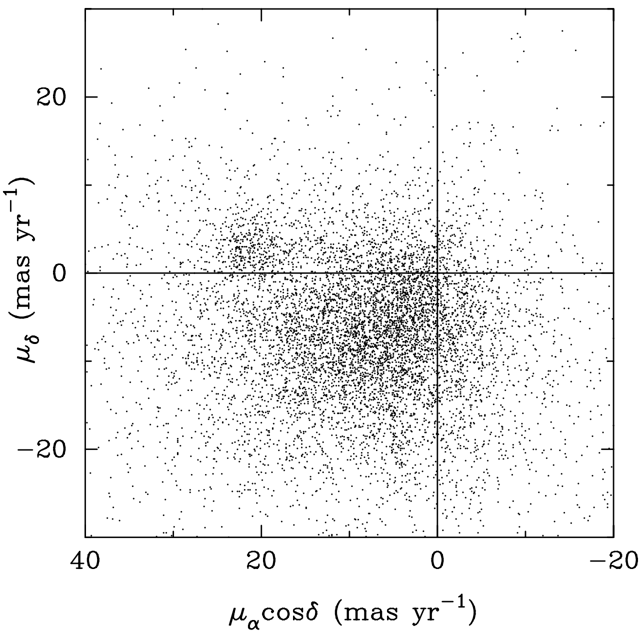

Figure 2. VPD of proper motions from the deep CTLGD catalogue. The cluster centroid (see Fig. 1) appears to be less concentrated owing to substantially lower accuracy of proper motions in CTLGD. The cluster centroid is dominated by faint K–M spectral-type dwarfs.

Once the positions were corrected for systematic offsets, calculating the proper motions was straightforward. As with the main catalogue, we fitted individual positions as a function of time (Section 2.4). A conservative estimate of a 70 mas uncertainty was adopted for all positions. Since we were primarily looking for new cluster members, a smaller ($r = 2.5$ arcsec) search radius for potentially related positions was chosen. To qualify as a catalogue entry, at least three detections of an object were required, separated by at least 20 years. An object was deleted if its proper-motion error exceeded 6 mas yr^{-1}. The resulting catalogue CTLGD contains 11 598 objects down to $V \sim 21$. Among these, 4273 are common with the main catalogue CTLGM.

The V magnitudes in both catalogues are calculated from the empirical relationship: $V = R_F + 0.4283(B_J - R_F) - 0.0463$, where R_F and B_J magnitudes are found from the counterparts in the GSC 2 catalogue. All Tycho stars have their magnitude V_T translated into the Johnson V, which then is listed in CTLGM or CTLGD.

In order to distinguish between our two catalogues, in the following tables and discussion we have added 100 000 to the identification numbers in CTLGD. The catalogue itself is given in Table 3. Its structure is identical to that of Table 1, except no cross-identifications are provided. The VPD of proper motions drawn from CTLGD is given in Fig. 2. Owing to larger proper-motion errors, the spread of cluster centroid in this diagram is also larger.

4 CLUSTER MEMBERSHIP

Cluster membership probabilities are calculated separately for our main catalogue CTLGM and the deep catalogue CTLGD. Here, we

[1] http://gsss.stsci.edu/SkySurveys/Surveys.htm

describe in detail the procedure of calculating membership probabilities and its application to the main catalogue CtlgM.

A list of 108 preliminary cluster members in Blanco 1 was assembled by selecting radial-velocity members from Mermilliod et al. (2008) and González & Levato (2009). Our new proper motions for these cluster stars provided the centre of proper-motion distribution at $\mu_\alpha^c \cos\delta = +21.3$ and $\mu_\delta^c = +2.9\,\mathrm{mas\,yr^{-1}}$. The Gaussian dispersion of this distribution is estimated to be $\epsilon_c = 0.9\,\mathrm{mas\,yr^{-1}}$ down to $V = 14$. This is about twice higher than the formal errors of proper motions and is justified by the presence of small residual systematics (see Section 2.4). At fainter magnitudes it gradually increases up to $1.5\,\mathrm{mas\,yr^{-1}}$. The centre of field star proper-motion distribution is at about $\mu_\alpha^f \cos\delta = +8$, $\mu_\delta^f = -6\,\mathrm{mas\,yr^{-1}}$ with a dispersion of $\epsilon_f \sim 10\,\mathrm{mas\,yr^{-1}}$. Although the cluster and field proper-motion distributions are separated by $\sim 16\,\mathrm{mas\,yr^{-1}}$, they are only $1.6\epsilon_f$ apart. In other words, there is a significant population of field stars with the kinematic parameters close to those of the cluster. Armed with this knowledge, we also calculated formal cluster membership probabilities for all stars in the catalogue using the so-called local sample method (Kozhurina-Platais et al. 1995). Similarly to that paper, we used a symmetric 2D Gaussian for the cluster and a sloping flat distribution to approximate the field star distribution near the cluster centroid in the VPD. A 4-mag-wide interval was used to define the local sample, except nearing the extreme values at $V = 8$ and 18 when it gradually narrows down to a 2-mag interval. Only those proper motions were considered which are within a $8\sigma_\mu \times 8\sigma_\mu$ box centred on the cluster centroid. The actual spatial distribution of cluster stars across the field of view was ignored. The change of cluster centroid dispersion in the VPD is externally estimated as a function of magnitude and then incorporated in the calculations of membership probabilities. In this way apparently, individual uncertainties of proper motions are ignored. Therefore, caution is advised while considering probable cluster members with proper-motion error in either coordinate exceeding 3–4 $\mathrm{mas\,yr^{-1}}$. The formal proper-motion membership probabilities P_μ were calculated using the probability definition formulated by Vasilevskis, Klemola & Preston (1958):

$$P_\mu = \frac{\Phi_c}{\Phi_c + \Phi_f}, \quad (1)$$

where Φ_c and Φ_f are the cluster and field proper-motion frequency functions, deduced from the VPD.

A formal summation of membership probabilities indicates that there should be a total of 165 cluster members among the 314 stars with $P_\mu \geq 1$ per cent (Fig. 3). The distribution of stars with $P_\mu \geq 1$ per cent as a function of magnitude shows the characteristic decline of a maximum probability at fainter magnitudes. This is because the ratio of cluster to field stars steadily tapers towards these magnitudes which our local sample method diligently accounts for. We suggest to use a conservative cut-off at $P_\mu \geq 5$ per cent below which it is not reasonable to expect a tangible number of cluster members. It is inadvisable to use a *single* high P_μ cut-off (e.g. $P_\mu = 80$ per cent) for our proper motions because such a choice will inevitably eliminate the faint cluster members. We caution that a few stars with relatively high proper-motion errors and/or with several deleted data points could still be cluster members despite their marginal membership probability. This situation may arise if, for example, there was an image confusion due to secondary exposures and grating images on the SPM plates and CCD frames. The spatial distribution of 218 stars having $P_\mu \geq 5$ per cent and $\sigma_\mu \leq 2.5\,\mathrm{mas\,yr^{-1}}$ (Fig. 4) indicates that the cluster's kinematic members can be found all over the $d = 3.°8$ field of view. The core of Blanco 1 is confined within the circular area with diameter of $d \sim 70$ arcmin.

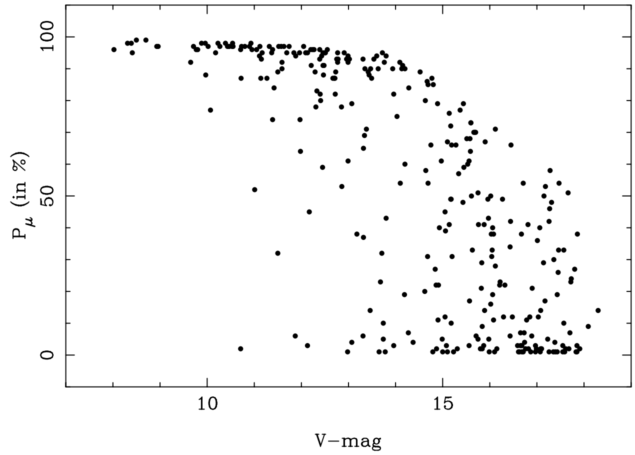

Figure 3. Distribution of cluster membership probabilities $P_\mu \geq 1$ per cent drawn from the CtlgM catalogue as a function of V magnitude. The decline of maximum P_μ at fainter magnitudes reflects the effect of growing contamination by field stars, which is accounted for in the local sample method.

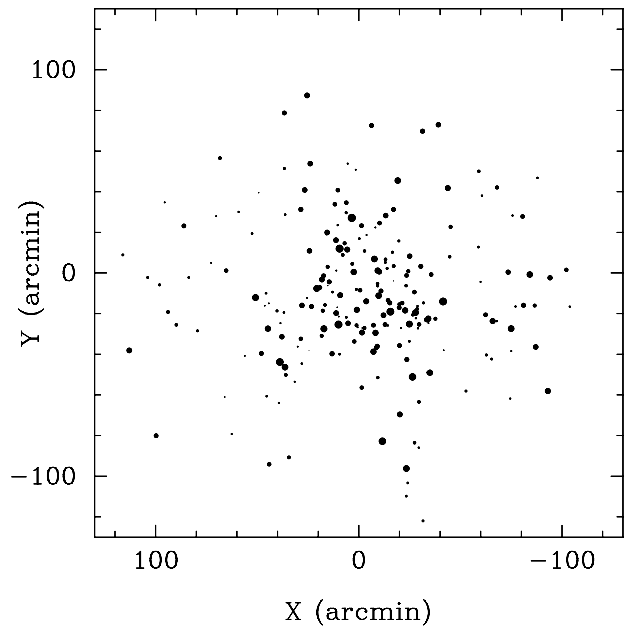

Figure 4. Spatial distribution of probable cluster members from CtlgM with $P_\mu \geq 5$ per cent and $\sigma_\mu \leq 2.5\,\mathrm{mas\,yr^{-1}}$. The symbol size indicates the brightness of the star. Cluster members can be found over the entire 11 $\mathrm{deg^2}$ field of view.

We calculated P_μ for the deep catalogue CtlgD using the same formalism and functional form of parameters of proper-motion distribution functions as for CtlgM. However, the proper-motion errors in CtlgD are significantly higher and, as indicated by the increased dispersion of the cluster centroid (Fig. 2), they reach 3 $\mathrm{mas\,yr^{-1}}$ near $V = 20$. A question may arise whether, for our deep catalogue with lower-accuracy proper motions and a larger VPD area to consider, a sloping flat distribution is adequately representing field stars. To test this, we replaced the sloping flat distribution with a 2D Gaussian. The resulting membership probabilities do change but in such a way that seems problematic. Thus, with a Gaussian distribution of field stars, the membership probabilities for fainter probable cluster members are inflated by ∼20 per cent but are lower for the brighter members. This is counterintuitive because it is a sloping flat distribution that tends to inflate membership probabilities over a larger VPD area. Apparently, a Gaussian is less successful in representing field stars near Blanco 1.

A lower accuracy of proper motions draws in more field stars among the likely cluster members. For instance, there are 13 stars common between the two catalogues, brighter than $V = 16$ and having $P_\mu = 0$ per cent in CTLGM but $P_\mu > 50$ per cent in CTLGD. Most of these high P_μ stars are field stars but it cannot be ruled out that a few of them might be genuine cluster members. In such cases additional arguments (the estimated errors of proper motion, radial velocity and photometric properties) should be used to make a decision on their cluster membership status.

5 COMPARISON WITH PREVIOUS STUDIES

There are several frequently cited studies of Blanco 1 which now warrant another look in terms of cluster membership. In most cases we provide a cross-identification table with our astrometric catalogues. It should be noted that if a star is present in both CTLGM and CTLGD, only a number from our main catalogue is given. In such cases, however, the membership probability can be from CTLGD, if that catalogue has $P_\mu \geq 5$ per cent but CTLGM indicates $P_\mu < 5$ per cent. The substituted membership probability is limited to $P_\mu =$ 70 per cent, although it could be higher in CTLGD.

5.1 Photometric lists

5.1.1 *Eggen (1970)*

This study provides photoelectric *UBV* photometry for 20 bright stars ($5.0 < V < 10.7$). A total of 18 stars are cluster members, i.e. their $P_\mu \geq 5$ per cent (Table 4).

5.1.2 *Perry, Walter & Crawford (1978)*

This study provides multicolour photoelectric Strömgren $uvby\beta$ and Johnson *UBV* photometry for 23 bright stars ($5.0 < V < 10.2$). A total of 17 stars are cluster members which is in nearly perfect agreement with a cluster membership assignment by these authors (Table 5).

5.1.3 *de Epstein & Epstein (1985)*

This study provides an extensive selection of probable cluster members using *BV* photographic photometry down to $V = 15.8$, although spatially limited by the size of 5 × 7 inch plates. Following the authors' wishes, we are now in a position to check how many kinematic cluster members are in their sample of 262 objects (Table 6). In the category of confirmed main-sequence stars (dubbed 'm.s.'), out of 18 only one appears to be a field star. Among the probable main-sequence stars, 'p.m.s.', there are 53 proper-motion members and 77 field stars. Another 25 proper-motion members are among the unmarked stars – presumable field stars. As already pointed out by Panagi & O'Dell (1997), ZS 51, 59, 86 and 87 are galaxies and ZS 250 and ZS 255 are identical stars. We reassigned the original star ZS 30a to a new entry ZS 262. The only unindentified star is ZS 133 = LHS 1012, which is a known large proper-motion star. We note that our coordinates of ZS stars and galaxies supersede the epoch 1967.6 and equinox B1950 coordinates provided by Panagi & O'Dell (1997).

5.1.4 *Westerlund et al. (1988)*

This study is widely cited but is not easy to cross-correlate with the other lists because of the lack of published coordinates. Our Table 7, conjointly with the astrometric catalogues, are now filling this void. We note that star W33 is not marked correctly in the finding chart. Our identification of W33 is based on the provided Cordoba Durchmusterung number. The study by Westerlund et al. (1988) provides photoelectric $UBVRI_C$ and Strömgren $uvby\beta$ for a total of 139 stars, although only *UBV* photometry is complete for this selection of stars in the range $5.0 < V < 13.8$ mag. These authors identify 32 cluster members. According to our astrometric data, there are five field stars among their likely cluster members. In addition, we were able to identify 21 cluster members in the midst of purported field stars. This illustrates the degree of bias/incompleteness using the photometric membership alone (Table 7).

5.1.5 *Moraux et al. (2007)*

A deep and wide photometric *Iz* survey by these authors provides valuable information about the lower main-sequence and substellar domain of Blanco 1. The total area covered by this survey is 2.3 $\deg^2$ and down to $I \sim 24$. Although the selection of cluster members is based entirely on the colour–magnitude diagram (CMD) and the associated 100 and 150 Myr isochrones, it is shown convincingly that Blanco 1 contains numerous candidate low-mass stars and brown dwarf cluster members. We are able to find 409 counterparts to these candidate stars (Table 8). A total of 146 of them have astrometric membership probability $P_\mu \geq 5$ per cent. Even if we assume that all of them are true cluster members, it makes only 35 per cent of stars considered by Moraux et al. (2007) of being proper-motion cluster members. The actual frequency of bona fide cluster members might be lower than this upper limit.

5.2 Radial velocity lists

5.2.1 *Mermilliod et al. (2008)*

A decade long effort of identifying the Blanco 1 cluster members using radial velocities is summarized in this paper. For convenience, we provide cross-identifications with our catalogue CTLGM (Table 9). We note that some cases in which earlier proper motions conflicted the membership from radial velocities now have been resolved or an updated membership information is available (new P_μ values from CTLGM and CTLGD are given in parentheses): M108 = 5509(84,95), M338 = 5852(45,0), M351 = 4590(0,92), M1013 = 2773(0,67). Star M108 is a bona fide astrometric member while the remaining three cases are less convincing. We note that the proper motions and membership probabilities given in Mermilliod et al. (2008) are superseded by the current catalogues.

5.2.2 *González & Levato (2009)*

This paper provides new radial velocities for 45 stars. The numbering system in this study is from Westerlund et al. (1988). Three stars, however, require a clarification as to their identity: E54 = 2529, E57 = 649, E51 = 3603. The match of cluster membership from radial velocities and proper motions is excellent. The cluster membership of an interesting shell-spectrum star HIP 345 = HD 225200 = 4922 is not supported by our proper motions.

5.3 X-ray lists

5.3.1 Micela et al. (1999) and Pillitteri et al. (2003)

Blanco 1 has been observed with the *ROSAT*-HRI at two adjacent pointings covering a total of $\sim$0.9 deg^2 area in the central parts of the cluster. Unfortunately, Micela et al. (1999) chose not to provide the *ROSAT* positions for their selection of cluster members nor give details of their *ROSAT* astrometry. We note that the X-ray source near star ZS 155 could match two probable cluster members: 3330 and 106475. Their other table of unidentified X-ray sources has a large 6 arcsec offset in right ascension. Pillitteri et al. (2003) have used unpublished proper motions from the GSC-II to calculate cluster membership probabilities in these *ROSAT* fields. The authors rightly indicate that the photometrically selected cluster members are likely to be heavily contaminated by field stars. However, a corollary – that samples of X-ray selected cluster members are polluted by field stars – is also possible. Thus, according to our proper motions, in a list of such members of Blanco 1 (Table 2; Micela et al. 1999) there are at least 30 per cent of field stars (up to 43 per cent, if a sum of formal probabilities is used). We made our own attempt (Table 10) to find additional cluster members among the unidentified X-ray sources in Micela et al. (1999). Our selection broadly matches that by Pillitteri et al. (2003).

5.3.2 Pillitteri et al. (2004)

This study represents deep *XMM–Newton* X-ray observations at the same pointing as in Micela et al. (1999) but over a smaller $\sim$0.25 deg^2 field. We successfully identified 17 probable cluster members in the list of X-ray sources with counterparts in optical catalogues (Table 11). For some unknown reason, this list appears to indicate the presence of the following relatively bright and known stars from de Epstein & Epstein (1985): ZS 44, 60, 70, 86, 87 and 105.

6 SELECTED APPLICATIONS OF NEW CLUSTER MEMBERSHIPS

We provide a brief analysis of the latest values of *Hipparcos* parallax and absolute proper motion for Blanco 1. The presence of numerous measured external galaxies allows us to update the ground-based estimate of absolute proper motion for the cluster. Our newly derived comprehensive cluster memberships are well-suited to derive the luminosity function for Blanco 1, thus supplementing the earlier estimated mass function (Moraux et al. 2007). Due to the relatively large angular size of this cluster, the high-precision photometric data are available only for a fraction of likely cluster members (e.g. Moraux et al. 2007; Cargile et al. 2009). Therefore, we limit our photometric analysis to a selection of probable members of Blanco 1 from Two-Micron All-Sky Survey (2MASS) (Cutri et al. 2003). The best-to-date *BV* CMD of Blanco 1 is provided by Mermilliod et al. (2008).

6.1 Absolute proper motion of Blanco 1

In our earlier paper on cluster membership in Blanco 1 (Mermilliod et al. 2008), we provided the extant values of absolute proper motion from four sources: SPM programme (Platais et al. 1998), Tycho-2, UCAC2 and *Hipparcos* (Robichon et al. 1999). Here, we can add two more, both produced by F. van Leeeuwen as the result of a major, bottom-up rework of the entire *Hipparcos* raw data (van Leeuwen 2007, 2009). In the monograph (van Leeuwen 2007), the listed parallax and absolute proper motion of Blanco 1 are: π = 4.14 ± 0.17 mas, $\mu_\alpha \cos\delta = +18.44 \pm 0.17$ and $\mu_\delta = +1.27 \pm 0.09$ mas yr^{-1}. The latest determination of these parameters (van Leeuwen 2009), however, differs significantly: $\pi = 4.83 \pm 0.27$ mas, $\mu_\alpha \cos\delta = +20.11 \pm 0.35$ and $\mu_\delta = +2.43 \pm 0.25$ mas yr^{-1}. Because the latter values are based on the final global iterative solution for the entire *Hipparcos* data set, all prior preliminary solutions for the parameters of individual stars and clusters should be ignored (F. van Leeuwen, private communication). The new *Hipparcos* catalogue is available through VizieR (Ochsenbein, Bauer & Marcout 2000).

Our catalogue contains all 13 *Hipparcos* stars used by Robichon et al. (1999) in their calculation of the cluster's mean astrometric parameters. All of these are kinematic cluster members, typically with membership probabilities ranging from 95 to 99 per cent. One star, HIP 512 = 5191, has P_μ = 32 per cent. However, a closer scrutiny of individual data points shows a small group of slightly deviating positions in the CCD data, which our data culling threshold at 2.5σ could not detect. Star HIP 512 is undoubtedly a bona fide member of Blanco 1.

We note that van Leeuwen (2009) has used a somewhat different selection of *Hipparcos* stars in Blanco 1. His analysis excludes two faintest stars, HIP 212 and HIP 477 (as judged from fig. 16), and includes a new potential cluster member HIP 1830 = HR 89 based on its *Hipparcos* kinematic parameters. This star, however, deserves a closer look. At V = 6.55 (spectral type B9 IV) it would be the brightest member of Blanco 1, followed by a bona fide brightest cluster member HIP 328 (V = 7.07, B8 V). The angular distance of HIP 1830 from the centre of cluster is 4°.3, which is a factor of 3 farther out than the most angularly remote star in the Robichon et al. sample. HIP 1830 is a known HgMn double-lined spectroscopic binary with metallicity [Fe/H] = +0.11 dex (Adelman, Davis Philip & Adelman 1996; Wahlgren, Hubrig & Dolk 2002), which is close to the metallicity estimate of Blanco 1 by Ford et al. (2005). The estimated γ-velocity from 19 high-resolution spectra is +4.7 km s^{-1} (J. F. Gonzalez, private communication), which is again close to the cluster's mean radial velocity at +5.5 km s^{-1} (Mermilliod et al. 2008). Despite a considerable body of evidence in favour of cluster membership, at least two parameters rule out this possibility. First, the estimated tidal radius of Blanco 1 is $r_t \sim 6$ pc, assuming a generous total mass of $\sim$300 M$_\odot$ and using equation (11) from Kozhurina-Platais et al. (1995). Hence, HIP 1830 is located at least 3r_t away from the cluster centre. Secondly, the new parallax of HIP 1830, $\pi = 5.79 \pm 0.47$ mas versus the expected cluster's photometric $\pi \sim 4$ mas, implies that it is a foreground star (see also the following discussion on *Hipparcos* parallax of Blanco 1). We note that according to the calibration of absolute magnitude M_V with spectral type (Straizys 1992), stars HIP 328 and HIP 1830 have the same absolute magnitude ($M_V = +0.1$) and hence, the same brightness, if both of them are cluster members. However, HIP 1830 is by $\sim$0.5 mag brighter and therefore could be considerably closer to the Sun than the Blanco 1 itself, in line with the star's higher *Hipparcos* parallax. To what degree binarity could be the reason for a higher brightness of HIP 1830 may answer a future analysis of the spectroscopic data. We surmise that HIP 1830 could actually be an escaped former member of Blanco 1.

We note that all *Hipparcos*-related studies neglect HIP 571 = 1750 – a cluster member according to our proper motions, radial velocity (González & Levato 2009) and 2MASS JK_S photometry. It appears that the astrometric parameters for HIP 571 and the nearby HIP 570 = 1741 are severely biased, in both the original *Hipparcos* Catalogue (ESA 1997) as well as in its revised version (van Leeuwen 2007).

Our main proper-motion catalogue CTLGM contains numerous background galaxies. By cross-correlating it with the SPM 1.0 catalogue (Platais et al. 1998), we were able to identify 127 galaxies. Among them, 37 galaxies can be used to calculate the relative proper motion of galaxies, $\mu_\alpha^g \cos\delta = +1.7 \pm 0.3$ and $\mu_\delta^g = -0.8 \pm 0.2\,\mathrm{mas\,yr^{-1}}$, which provides the correction to absolute proper motions. Thus, the absolute proper motion of Blanco 1, calibrated against the background galaxies, is $\mu_\alpha \cos\delta = +19.6$ and $\mu_\delta = +3.7\,\mathrm{mas\,yr^{-1}}$. The formal uncertainty of our absolute proper motion is matching the uncertainty of the correction itself. However, true uncertainty should be larger (likely $\sim$0.5 mas yr^{-1} in each coordinate) owing to unaccounted systematic errors in the galaxy proper motions. We stress that proper motions in our catalogues are not corrected using this calibration and, thus, are not strictly absolute. Considering all estimates of absolute proper motions listed here and in Mermilliod et al. (2008), our current independent estimate is closest to the values provided by Robichon et al. (1999).

6.2 *Hipparcos* parallax of Blanco 1

We note that the most recent *Hipparcos* parallax (van Leeuwen 2009) yields a 207 pc distance for Blanco 1, contrasted to the longer photometric distance of 250 pc from a CMD fit (Mermilliod et al. 2008). This is reminiscent of the Pleiades' 'short' *Hipparcos* distance issue discussed, e.g. by van Leeuwen (2009), but this time the disparity in distance modulus reaches a conspicuous 0.4 mag, equivalent to $\Delta\pi = 0.8$ mas or equal to a $3\sigma_\pi$ offset.

Among the nearby ($d < 250$ pc) open clusters, the *Hipparcos* group parallax for Blanco 1 has the highest formal error – a factor of $\sim$2 higher than that for the other clusters with similar number and brightness of *Hipparcos* stars, such as IC 2391, IC 2602 and NGC 2451. The main reason for an elevated parallax errors appears to be a poor observational coverage of the parallactic ellipse (Fig. 5), indicated by uneven timing distribution of stellar transits and their tendency to clump at certain dominating scanning angles. This unfortunate arrangement of observations is due to the intricacies in *Hipparcos* scanning pattern at the cluster's ecliptic latitude of $\beta = -27\overset{\circ}{.}6$.

The calculated new *Hipparcos* parallax of Blanco 1 (van Leeuwen 2009) appears to be biased at a level of $\sim$0.2 mas solely by inclusion of HIP 1830 in the solution. We argue that gravitationally HIP 1830 might not be bound to the cluster and, hence, should not be used in calculating the group parallax. The remaining discrepancy between the *Hipparcos* and cluster's photometric parallax at the level of $\Delta\pi \sim 0.6$ mas is less understood. However, we call attention to the fact that among the *Hipparcos* cluster members there is a significant correlation between parallax and proper motion in right ascension (Fig. 6). The formal correlation factor is 0.7 for the new data and 0.8 for the original *Hipparcos* data (ESA 1997). A similar correlation between parallax and proper motion in declination is twice smaller. In contrast, for individual stars from the new solutions, the mean correlation factor between parallax and proper motion in either coordinate is essentially negligible (not exceeding $\sim$0.1). The uncovered significant correlation in right ascension cannot be attributed to the depth effect because an amplified dispersion of cluster's proper motions is observed only in the *Hipparcos* data. Thus, for the 13 *Hipparcos* cluster members, proper motions from CTLGM show the extreme differences of only 1.7 and 2.4 mas yr^{-1} (corresponding dispersions 0.5 and 0.8 mas yr^{-1}) in right ascension and declination, respectively, while in the new *Hipparcos* catalogue the same differences and dispersions are 4.6 and 2.6 (1.3 and 0.8) mas yr^{-1}. We suspect that this correlation at least partially accounts for a higher value of group parallax for Blanco 1 reported by van Leeuwen (2009). Notably, the new re-reduction of *Hipparcos* data has not reduced this correlation despite a significant reduction in the correlations between parallax and proper motion in right ascension for individual cluster stars.

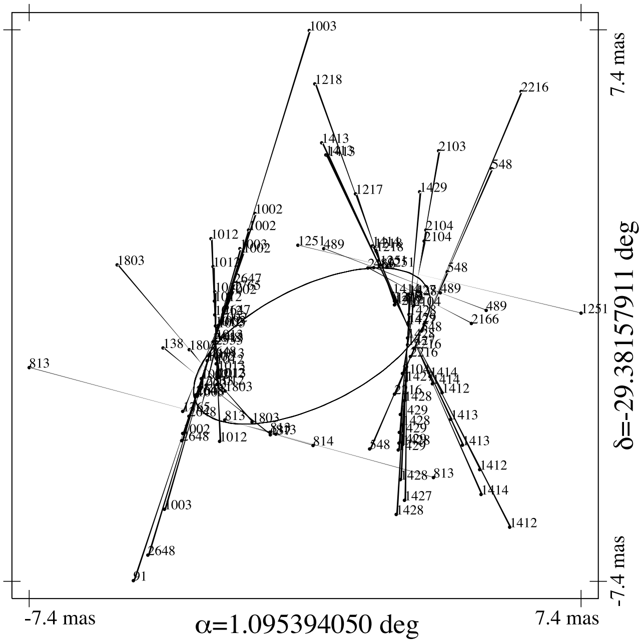

Figure 5. Distribution of new intermediate astrometric data (abscissa residuals) for star HIP 349, after adding the calculated parallactic displacement, shown by an ellipse. Its centre is slightly displaced for a better visibility of residuals. The axes show tangential coordinates in mas, calculated using the indicated epoch 1991.25 equatorial coordinates. The length of each residual represents the formal error. The orbit number is given for each observation. Although the transits cluster around the phase of a maximum parallactic factor, crossing the parallactic ellipse is rarely close to a normal. Minimization of the abscissa residuals is strictly one dimensional and, hence, the crossing angle plays a significant role in the accuracy of kinematic parameters.

6.3 Luminosity function

Our catalogues provide the first ever comprehensive astrometric survey of Blanco 1. Their coverage is complete over 7 deg^2 and down to $V = 21$. Over a larger 11 deg^2 area the coverage is complete down to $V \sim 16.5$. Thus, the spatial extent of our survey exceeds the areal coverage of other studies (Pillitteri et al. 2003; Carraro et al. 2005; Moraux et al. 2007) by a factor of 3–4. Blanco 1 has often been compared with the nearby Pleiades cluster (e.g. Jeffries & James 1999; Cargile et al. 2009; Stauffer et al. 2010). Recently, Stauffer et al. (2007) compiled a comprehensive catalogue of all registered Pleiades candidate members. This catalogue contains 1416 candidate cluster members down to $V \sim 23$ over a circular area with radius $\sim$5°. We used this catalogue as a convenient reference system in order to examine and compare with the properties of Blanco 1.

First, the spatial distribution of Pleiades members was scaled to the distance of Blanco 1, which, based on the photometric distances, is roughly twice farther away. If we assume that the spatial

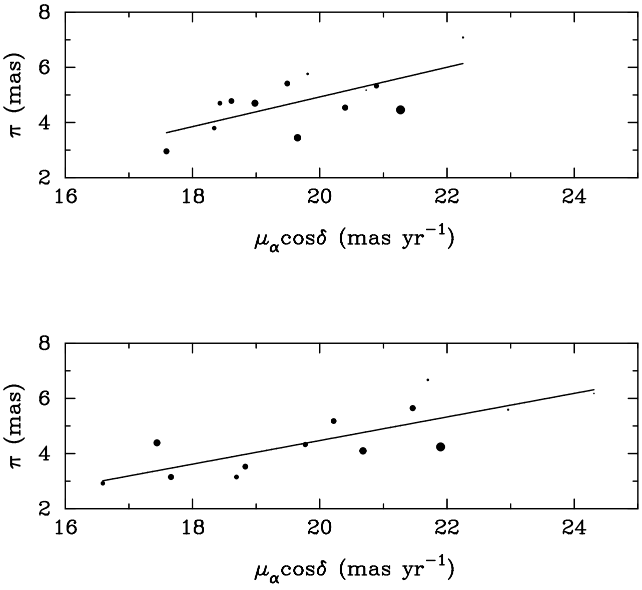

Figure 6. *Hipparcos* parallax versus proper motion in right ascension for the initial 13 *Hipparcos* stars in Blanco 1 (Robichon et al. 1999). Upper panel shows the most recent data from van Leeuwen (2007); lower panel displays the original data (ESA 1997). The line represents an unweighted least-squares fit. The symbol size indicates the brightness of stars ($7 < H_p < 10$). New proper motions have improved by a factor of ∼2 but there appears to be limited improvement on individual parallaxes.

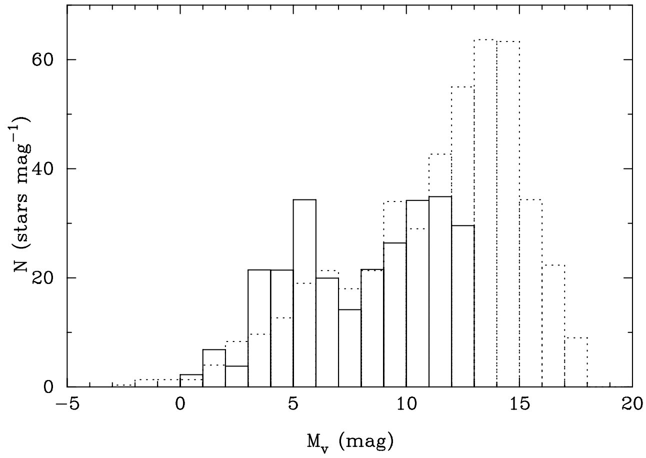

Figure 7. Luminosity function of Blanco 1 (solid line). For comparison, a scaled luminosity function of the Pleiades is overplotted (dashed line). Similarities in the luminosity functions are apparent down to $M_V \sim 12$. Some incongruities are discussed in Section 6.3.

distributions of these two clusters are similar, then our survey of Blanco 1 misses only 6 per cent of cluster members potentially located outside the 11 deg^2 area. Secondly, we derived absolute M_V for all probable members of both clusters using the distance modulus of 5.6 and 7.0, accordingly. The Pleiades catalogue contains complete sets of 2MASS JHK_S magnitudes but is sparsely supplied with BV photometry. In order to obtain V magnitudes for all stars, we used converted J magnitude into V using a fifth-order polynomial derived from the common stars. Then, the M_V versus mass relationship from a solar metallicity 100 Myr isochrone (Marigo et al. 2008), expressed in the form of cubic splines, was used to obtain estimated masses for all probable members of the Pleiades and Blanco 1. Recall that according to Ford et al. (2005) and Schuler et al. (2010) both clusters have essentially solar metallicity.

With all necessary ingredients in hand, we can confidently relate one cluster to the other. The Blanco 1 membership is complete to $M_V = +13$ with the caveat that the outer ring covering ∼4 deg^2 is complete only to $M_V \sim +9.5$ mag. A sum of membership probabilities for 757 stars with $P_\mu \geq 5$ per cent yields a total number of likely members equal to 298. If we adopt an $M_V = +13$ limit in the Pleiades catalogue, then we find 838 cluster members. Hence, down to the spectral type M5 V (0.2 $M_\odot$) the Pleiades is by a factor of ∼2.8 more populated. This should be regarded an upper limit, considering the potentially missing stars in the Blanco 1 outer ring and our implicit assumption that all Pleiades candidate members are genuine cluster members. The luminosity function of Blanco 1 (Fig. 7) is derived by summing the membership probabilities in the corresponding absolute magnitude bins. A total of 76 stars with $P_\mu \geq 5$ per cent were not used to construct the luminosity function owing to their location in the JK_S CMD, well under the main sequence of the cluster. Overplotted is the Pleiades luminosity function, scaled down by a factor of 3. Over the range $0 < M_V < +13$ the luminosity functions of both clusters are fairly similar. However, there is a clear excess of Blanco 1 members near the solar luminosity $+3 < M_V < +6$ and the previously noted lack of Blanco 1 members at $M_V < 0$. The sharply rising number of Pleiades members at $M_V > +12$ might be partially reflecting the degree of field star contamination at these faint magnitudes.

The sum of individual stellar masses added proportionally to the corresponding P_μ and ignoring binaries yields a total mass of Blanco 1 of 197 $M_\odot$. A similar summation for the Pleiades cluster gives a total mass of 690 $M_\odot$ (Adams et al. 2001). Hence, the total mass ratio of 3.5 is reasonably close to the ratio of cluster member totals estimated above.

6.4 JK_S colour–magnitude diagram

To construct a JK_S CMD of Blanco 1, we used 724 stars with $P_\mu \geq 5$ per cent that have counterparts in the 2MASS All-Sky Point Source Catalogue (Cutri et al. 2003). The CMD of Blanco 1 (Fig. 8) shows a fairly clean main-sequence stretching from its brightest member, a B8V star (2918 = HIP 328), down to numerous M dwarfs. The broadening of the main sequence at $J > 14$ is almost entirely due to the 2MASS measuring errors, which at the bottom of CMD can reach ∼0.3 mag in $J - K_S$ colour index. Two stars, 2186 and 105995, according to their $J - K_S$ colours and J magnitudes, could be member white dwarfs as indicated by the 2MASS colours of spectroscopically confirmed white dwarfs (Hoard et al. 2007). We caution though that the cluster membership probabilities of these two stars are marginal and the proper-motion determination of star 2186 is inconsistent.

It is revealing trying to match the main sequences of Blanco 1 and the Pleiades. We ignored the slight difference in the reddening between the clusters, which is expected to be of the order of $\Delta E(J - K_S) = 0.01$ (Blanco 1 being less reddened). We used 105 main-sequence stars of Blanco 1 in the range $7.2 < J < 12.5$ to match 238 Pleiades members by minimizing the cumulative distance of a nearest neighbour along the J-axis. This technique produces $\Delta J = 1.38 \pm 0.02$ which clearly justifies our choice of photometric distance modulus for these clusters. The *Hipparcos* observations indicate a difference in the distance moduli of $\Delta \mathrm{mod} = 1.18 \pm 0.12$ (van Leeuwen 2009).

One unexpected finding while comparing the clusters' JK_S photometries is a colour offset for the early M stars (where the 2MASS

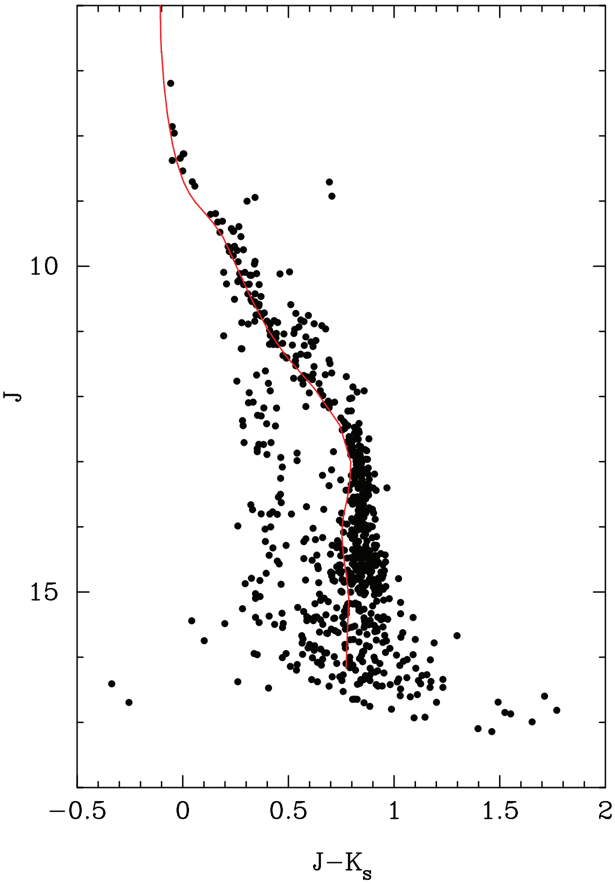

Figure 8. JK_S CMD of Blanco 1. A total of 724 stars with $P_\mu \geq 5$ per cent from combined catalogues CTLGM, CTLGD are plotted. A large number of M dwarfs are evident at $J > 12.5$ mag. Overplotted is a 100 Myr solar metallicity isochrone from Marigo et al. (2008). A poor match between observed and theoretical colours of M dwarfs is clearly noticeable.

measuring errors are still low for both clusters). On average, the Pleiades $J - K_S$ colour of these stars are 0.04 mag *redder*. This is substantially larger than the expected difference in the reddening. The normal 2MASS colours of field M dwarfs (Straizys & Lazauskaite 2009) essentially match the colours of M stars in Blanco 1. Could it be an instrumental problem due to observing from different hemispheres?

For illustrative purpose only we overlay the CMD with a 100-Myr solar metallicity isochrone from Marigo et al. (2008), applying a colour shift of 0.01 mag and adopting a distance modulus of $(V_0 - M_V) = 7.0$ mag (Fig. 8). The isochrone fits well the main sequence, although it fails to match the domain of late K through M stars. The normal colours of field main-sequence stars (Straizys & Lazauskaite 2009) suggest that the mismatch is due to the bias in the isochrone's colour–$T_{\rm eff}$ calibration.

The lack of B-stars in Blanco 1 as opposed to the ostensibly coeval Pleiades containing several B-stars is puzzling. If these stars in Blanco 1 have already gone through the red giant branch phase, then Blanco 1 should be older than 100 Myr and would have left a few bright dwarfs in the wake. None of them has been detected yet. An alternative view might be an assumption that Blanco 1 never had stars more massive than $\sim 3\,M_\odot$. The history of star formation in the Blanco 1 natal molecular cloud may not necessarily have followed the standard path yielding a normal initial mass function (e.g. Kroupa, Aarseth & Hurley 2001). Credence for such a scenario is provided by the recent *Herschel* observations of the Polaris Flare molecular cloud (Heithausen & Thaddeus 1990) which show that the mass distribution of starless cores in this cloud appears to be cut short at $\sim 0.2\,M_\odot$ (André et al. 2010; Men'shchikov et al. 2010). It is conceivable that more observations might eventually unravel an analogue of the hypothetical Blanco 1 natal molecular cloud.

7 SUMMARY AND CONCLUSIONS

We provide two comprehensive catalogues of positions and proper motions in the region of Blanco 1. From the union of the two catalogues, there are 794 stars with membership probabilities $P_\mu \geq$ 5 per cent. A sum of formal P_μ yields $\sim$300 cluster members down to $V = 21$ equivalent to M5 spectral class or $0.2\,M_\odot$. We confirm that Blanco 1 contains a large population of M dwarfs ($\sim$150 down to M5 V). While we have not reached the terminus of the main sequence, it is clear that the cluster is more populous than previously thought. It is now established that Blanco 1 is only three times less populous than the Pleiades. The total mass of Blanco 1 is at least $200\,M_\odot$.

Our findings include a new estimate of the absolute proper motion for Blanco 1: $\mu_\alpha \cos\delta = +19.6$ and $\mu_\delta = +3.7$ mas yr^{-1}. We point out a large discrepancy (0.4 mag) between the photometric and *Hipparcos*-based distance modulus of Blanco 1 and suggest a possible source of its origin. Our comparison of Blanco 1 and the Pleiades revealed a surprising $\Delta(J - K_S) = 0.04$ mag colour offset for the Pleiades early M dwarfs. The origin of this offset is a mystery and warrants further study. We propose two candidate white dwarfs in Blanco 1. Whether or not there are any white dwarfs in this cluster is the key to understanding the star formation history in its natal molecular cloud.

Our proper motions are useful in cleaning up various lists of probable cluster members. This should help to better constrain the basic properties of Blanco 1 using existing measurements. We also encourage the execution of a wide-field, multicolour and deep photometric survey of Blanco 1. In the M dwarf region, 2MASS photometry is essentially 'colour-blind' because of miniscule variations, e.g. in the $J - K_S$ colour index as a function of $T_{\rm eff}$. It effectively rules out this colour as a potential discriminator between field and cluster stars. A relatively large proper motion of Blanco 1 at $\sim$20 mas yr^{-1} should enable reliable cluster membership just within a few year span of observing epochs.

Blanco 1, as the fourth nearest young open cluster in the Southern hemisphere (after IC 2391, IC 2602 and NGC 2451A) offers an opportunity for future studies of M dwarfs and the substellar constituents in this age group. Blanco 1 is also a reasonably rich star cluster and is projected against a low-density Galactic star background owing to its high galactic latitude. Hence, it is much less troubled by issues of field star contamination.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Main catalogue CtlgM of positions and proper motions in the area of Blanco 1.
Table 3. Deep astrometric catalogue CtlgD.
Table 4. Cross-identifications with Eggen (1970).
Table 5. Cross-identifications with Perry et al. (1978).
Table 6. Cross-identifications with de Epstein & Epstein (1985).
Table 7. Cross-identifications with Westerlund et al. (tables 3 and 4, 1988).
Table 8. Cross-identifications with Moraux et al. (2007).
Table 9. Cross-identifications with Mermilliod et al. (table 1, 2008).
Table 10. Cross-identifications with Micela et al. (table 4, 1999).
Table 11. Cross-identifications with Pillitteri et al. (table A.1, 2004).

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