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VVV IR HIGH PROPER MOTION STARS

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RESUMEN

En este trabajo hemos usado el sondeo VISTA de Variables en la Vía Láctea (VVV) para buscar objetos de movimiento propio grande (PM) en la zona oscura del Bulbo de la Vía Láctea y al sur del disco galáctico. Este sondeo es multi-época y ya se extiende sobre un período de más de cuatro años, dándonos una excelente oportunidad para estudios de paralajes y movimientos propios. Encontramos alrededor de 1700 objetos PM con PM>30 mas yr^{-1}. La mayoría de ellos son enanas tempranas y medias tipo M. Hay también algunos pocos objetos de tipo espectral tardío, así como también numerosas enanas tipo K y G. 75 estrellas tienen PM>300 mas $^{-1}$ y 189 tienen PM>200 mas $^{-1}$. Solamente 42 estrellas con PM>200 mas $^{-1}$ eran previamente conocidas en el área explorada por VVV. También encontramos tres binarias dM+WD y nuevos miembros de la vecindad solar inmediata dentro de 25 pc. Generamos un catálogo el cual complementará los ya existentes fuera de la zona estudiada.

ABSTRACT

We used the VISTA Variables en Vía Láctea (VVV) survey to search for large proper motion (PM) objects in the zone of avoidance in the Milky Way bulge and southern Galactic disk. This survey is multi-epoch and already spans a period of more than four years, giving us an excellent opportunity for proper motion and parallax studies. We found around 1700 PM objects with PM>30 mas yr^{-1}. The majority of them are early and mid M-dwarfs. There are also few later spectral type objects, as well as numerous new K- and G-dwarfs. 75 of the stars have PM>300 mas $^{-1}$ and 189 stars have PM>200 mas $^{-1}$. There are only 42 previously known stars in the VVV area with proper motion PM>200 mas $^{-1}$. We also found three dM+WD binaries and new members of the immediate solar vicinity of 25 pc. We generated a catalog which will be a complementary to the existing catalogs outside this zone.

Key Words: infrared: stars — proper motions — stars: low-mass — surveys

1. INTRODUCTION

It is very important to know the complete census of stars within the solar neighborhood out to a specified distance. A complete volume-limited sample will inform us about the stellar mass function, stellar formation and the kinematics of the Galaxy, as well as those of the nearby stellar clusters and young moving groups for which we are able to identify members. The main difficulty in constructing a volume-limited sample is to identify nearby, low-mass, low-luminosity objects and to obtain accurate distances to them. Currently, the most straightforward method to identify potentially nearby stars is from proper motion surveys. Proper motion surveys continually improve, as longer time base lines increase the accuracy of the measurement. A uniform census of nearby stars allows the characterization of the relative occurrence rates of different types of stars, by plotting relationships between intrinsic properties of those stars, including absolute magnitude and color. Early attempts at conducting large surveys for high proper motion stars began in the early 20th century with van Maanen (1915) subsequently expanded by Wolf (1919) and Ross (1939), pushing the detection limit to 0.20 arcsec yr^{-1}. As these surveys progressed, it became apparent that there existed a large population of high proper mo-

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tion, low luminosity objects that were previously undetected due to their faintness. Later, additional surveys were completed: e.g. Giclas et al. (1971,1978) and the New Luyten Catalogue of Stars with Proper Motions Larger than Two Tenths of an Arcsecond (the NLTT catalogue; Luyten 1979), which contains 58,845 objects. More recently, Lépine & Shara (2005) compiled a list of 61977 stars in the northern hemisphere with proper motions larger than 0.15 arcsec yr^{-1}, identifying over 90% of those stars down to a limiting magnitude of V≈19.0, excepting the Galactic plane. Recently, Lépine & Gaidos (2011) published an all-sky catalogue of M-dwarfs with apparent infrared (IR) magnitude J<10. The 8889 stars were selected from the on-going SUPERBLINK survey of stars with proper motion μ >40 mas yr^{-1}, supplemented on the bright end with the Tycho-2 catalogue. Completeness tests suggest that this catalogue represents ≈75% of the estimated ∼11900 M dwarfs with J<10 expected to populate the entire sky. This catalog is, however, significantly more complete for the northern sky (≈90%) than it is for the south (≈60%).

M-dwarfs are the most abundant inhabitants of our galaxy and also are probably the most common sites of planet formation (Lada 2006). They account for over 70% of stellar systems in the solar neighborhood (Henry et al. 1997). In addition, the single star fraction – a crucial statistic for giant planet formation (e.g., Kraus et al. 2012) – decreases from ∼60-70% for M-dwarfs (Fischer & Marcy 1992; Bergfors et al. 2010) to ∼54% for solar-type stars (Duquennoy & Mayor 1991; Raghavan et al. 2010) to near 0% for the most massive stars (Preibisch et al. 1999), further separating M-dwarfs from AFGK stars as the most numerous potential planet hosts of all the stellar classes (Lada 2006). In recent years there has been an increasing interest in low-mass stars and especially in M-dwarfs due to the discovery that they too host exoplanets. About 25% of all Doppler-confirmed planets with M $\sin i$ <30M$_\oplus$ are orbiting M-dwarfs. Large exoplanet surveys have now started to monitor sizable numbers of M-dwarfs, such as the M2K program which is targeting some 1600 M dwarfs for radial velocity (RV) monitoring (Apps et al. 2010) and the MEarth project (Irwin et al. 2009, 2010) which is designed to detect exoplanet transits in nearby late-type M dwarfs. The principal methods of exoplanet detection, radial velocity and transits, are both more sensitive to planets around stars of lower and substellar mass. In fact, inactive K and early M stars have weaker P-mode oscillations and lower Doppler noise (jitter) than their F or G counterparts. The above-mentioned factors make searches for new, nearby, and eventually young low-mass stars or substellar objects highly valuable.

All optical surveys avoid or are at least substantially incomplete near the Galactic plane. This region is referred to as the zone of avoidance, as it contains the highest stellar densities down to faint limiting magnitudes in addition to regions of dark molecular clouds, nebulosities, and current star formation, producing substantial confusion. Nevertheless, the Galactic plane and the Galactic bulge offer considerable latent potential for new discoveries of nearby low-mass stars and ultra-cool dwarfs (UCDs) from deeper searches. Such discoveries may contain young, unusual, and nearby/bright examples, and will also complement those made at higher Galactic latitudes. Good recent examples of nearby (<10 pc) interesting discoveries at low Galactic latitude are those of UGPS J0722-05 (T9: Lucas et al. 2010), DENIS J081730.0-615520 (T6.5: Artigau et al. 2010), and the amazing discoveries of the nearest brown dwarfs WISE J085510.83-071442.5 and WISE J104915.57-531906.1 at ∼2pc from the Sun. These discoveries near the Galactic plane highlight the serendipitous nature in which new IR surveys (e.g., "Vista Variables in Vía Láctea" (VISTA-VVV)) can help to improve the incomplete Solar neighborhood census of low-mass stellar and sub-stellar systems.

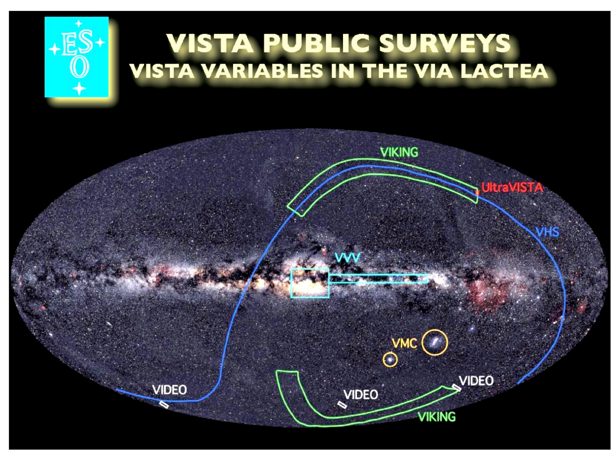

Fig. 1. Vista approved public surveys. The VVV is in the center and covers the bulge ($-10^\circ < l < +10^\circ$ and $-10^\circ < b < +5^\circ$) and plane survey areas ($65^\circ < l < 10^\circ$ and $-2^\circ < b < +2^\circ$).

The VISTA-VVV near-IR ($ZYJHK_{\rm s}$) survey (Minniti et al. 2010, Saito et al. 2012) covers the Galactic bulge and the Southern Galactic disk (see Fig. 1) and provides accurate photometry, and multi-epoch $K_{\rm s}$-band imaging, enabling us to discover a meaningful sample of new nearby cool and ultra-cool dwarfs (UCDs: spectral types >dM6) with a completeness higher than has previously been achieved in the low southern galactic latitudes (e.g., from 2MASS and DENIS), from a proper motion (PM) search. For our initial UCD search we limited our sample selection to the brightest ($K_s < 13.5$ magnitude) objects only.

A positive aspect of the high stellar densities encountered in the Galactic plane and bulge is the plethora of bright reference stars for a good follow up and monitoring, using adaptive optics (AO) tip-tilt low-order correction. This will facilitate high-Strehl imaging measurements to identify very low-mass brown dwarf/planetary-mass, companions for studying multiplicity, and also measuring dynamical masses. Moreover, high-Strehl AO studies of newly identified binary moving group members will also provide good age and composition constrains, as well as dynamical masses, enabling direct feed-back to evolutionary models.

Here we present our first (partial) results of a proper motion survey using the VVV database which will be the basis of a complete catalog published later.

2. SEARCH METHODS AND PROCEDURES

The searching method we used is based on our custom IDL routines and SHELL scripts and cross-matching, K_s-band photometric catalogues obtained for 4 different VVV epochs including the first and the last presently available. The steps in this procedure, listed below, are diagramed in Fig. 2. For the bright subsample ($K_s < 13.5$) the searching routines were applied on all stars in the catalogues (without color cuts) in order to include any saturated stars with uncertain photometry. 2MASS was used as a first epoch for almost all stars of this bright subsample as well as a final visual check.

• Download the latest (new) FITS VVV catalogue epoch file(s) from Cambridge Astronomy Survey Unit – CASU, (http://casu.ast.cam.ac.uk) (e.g., Kv1 . . . Kv6), and then convert them to ASCII using our version of the CASU FORTRAN code.

• Run the *vvv-Kv-mltepch-stilts-prep.pro* IDL code to calculate the epoch differences and the X-correlation search radius to use. This code uses the first "Z, " and "J, H, Ks" FITS catalogue files, and also the FITS catalogue file of the latest Kv epoch. The results are output and appended to the tile log file.

• Run the shell script to X-correlate the new epoch catalogue ASCII file data into the main dataset (script *stlts-Kvx-Xcorr-dsktop.sh*).

• Run the RPM IDL routine called: *vvv-mltepch-PM-finder-STILTS.pro* to find PM candidates between these two epochs just X-correlated together. This routine requires a parameter which is the VVV RMS astrometric error for the dataset (∼0.07 arcsec.

• Repeat this procedure above for at least 3 separate epochs of data to make the next final stage below give the most reliable results (each about 5-6 months apart).

• Run the next IDL routine, *vvv-mltepch-refine-PM-STILTS.pro*, to find the refined PM candidate dataset (by testing for consistent motion).

• The main results file lists all the RPM candidates sorted by a confidence or quality parameter.

• Visually check the candidates using the last available epoch VVV image and the 2MASS position of the stars or the first epoch VVV image.

The final visual check is mandatory because the stellar density in the Galactic plane and especially in the bulge is very high and there are many false candidates (near neighbors). The other reason is that the brightest ($K_s \leq 11.5$) stars are saturated and frequently simulate a proper motion shift.

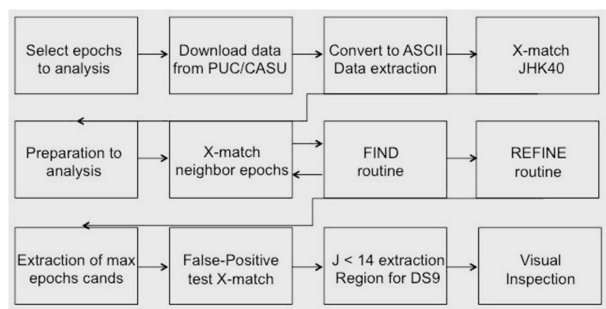

Fig. 2. The routine sequence of our searching package.

3. RESULTS

3.1. *The PM Catalog*

At the moment we have performed a visual check of about 60% of the bright PM candidates. We found about 1700 stars with proper motion PM >30 mas yr^{-1} in the zone of avoidance of the Galactic bulge and southern disk. We generated a catalogue, which will be published when all the VVV area is fully searched for PM objects. We expect to have a complete catalog of about 3000 PM stars until $K_s \leq 13.5$. The catalog itself will be published in a forthcoming paper (Kurtev et al. 2015). Our catalogue contains information of the RA and DEC coordinates for the first and last VVV epochs and 2MASS, PM(RA), PM(DEC), PM, parallactic angle (PA), 2MASS and VVV IR magnitudes, optical SUPERCOSMOS magnitudes where the optical counterpart is cross identified, as well as photometric distances. This catalog

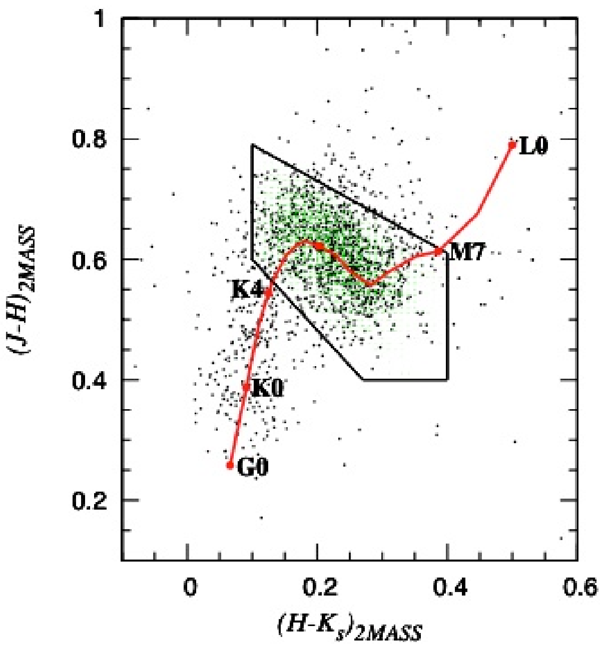

Fig. 3. The $J-H$ vs. $H-K_s$ color-color diagram of the sample stars. Stars from the Lepine and Gaidos (2011) catalog are plotted in green. The main sequence from G0 to L0 is in red. The area enclosed is the region of M-dwarfs.

will be a complement to existing PM catalogues outside the zone of avoidance.

The lower limit of the proper motion for our sample is about 20-30 mas yr^{-1}. The incompleteness of our sample becomes significant at proper motion PM$\leq$100 mas yr^{-1} (Fig. 4a). The vector distribution of the proper motion given on Fig. 4b shows that the majority of the objects belong to the galaxy disk population but there are also objects with typical halo and thick disk kinematics.

The proper motions are obtained in two ways a) using the equatorial coordinates in the first VVV epoch and the last available VVV epoch with a typical separation in time of about four years, and b) comparing the equatorial coordinates of the last available VVV epoch and 2MASS. Practically all of the targets have a 2MASS counterpart. The time separation between the epochs in this second case is always more than 10 years, reaching in some cases 14 years. The precision of the proper motion and the parallactic angle is similar using both methods because, in the first case, the precision of the VVV coordinates is much better but the time difference is less, and, in the second case, the lower precision of the 2MASS coordinates is compensated by 2 to 3 times longer time base. The comparison is given on Fig. 5ab. The coincidence of the results is very good. In the case of the parallactic angle, the small differences produce the two groups of points around the upper left and lower right corners. There are very few errors (point far from the main diagonal lower – left upper right). All of these objects should be checked individually, since these errors are likely due to a match with the wrong neighboring star from the 2MASS catalog.

3.2. *Reduced Proper Motion. Giants vs. Dwarfs*

When the distance to an object is not known, we use the reduced proper motion, H, for the purpose of separating dwarfs from giant stars, where H is used as a proxy for absolute magnitude.

$$H = m + 5 \log \mu + 5 \quad ,$$

where m is the observed magnitude and μ is the observed proper motion in arcsec yr^{-1}. Since the reduced proper motion is analogous to absolute magnitude, a plot of H along with a color index is pseudo-equivalent to a Hertzprung-Russel diagram, where giants are separated vertically from dwarfs. Frith et al. (2013) found a clear separation between the dwarf and the giant populations at $H_{K_s} = 6.0$. The giants populate the region above and the dwarfs below this limit on the RPM diagram. In our catalogue we have only two objects, which lie in the region of the giants and few ones near the border. This is an expected result because high proper motion objects in general should be nearby, if they were giants then they should be extremely bright. There are a few interesting objects near the Galactic center which deserve individual verification and follow up. If they are giants they could be excellent examples of hyper-velocity stars ejected from the central regions of the Milky Way.

3.3. *Nearby M-dwarfs*

The majority of the PM objects in our catalog are early- and mid-type M-dwarfs as can be seen in Fig. 3. There are also few later spectral type objects, as well as numerous new K- and G-dwarfs. 75 of the stars have PM>300 mas yr^{-1} and 189 stars have PM>200 mas yr^{-1}. There are only 42 previously known stars in the VVV area with proper motion PM>200 mas yr^{-1} (Ivanov et al. 2013, A&A, 560, 21). At least 14 (4 new) stars in the immediate solar vicinity of 25 pc are found in the VVV area. We have not done a thorough investigation of binary fraction of our sample, but we have found 35 common proper motion binaries during the verification process. The search for more such systems is still pending. Three systems are dM+WD binaries.

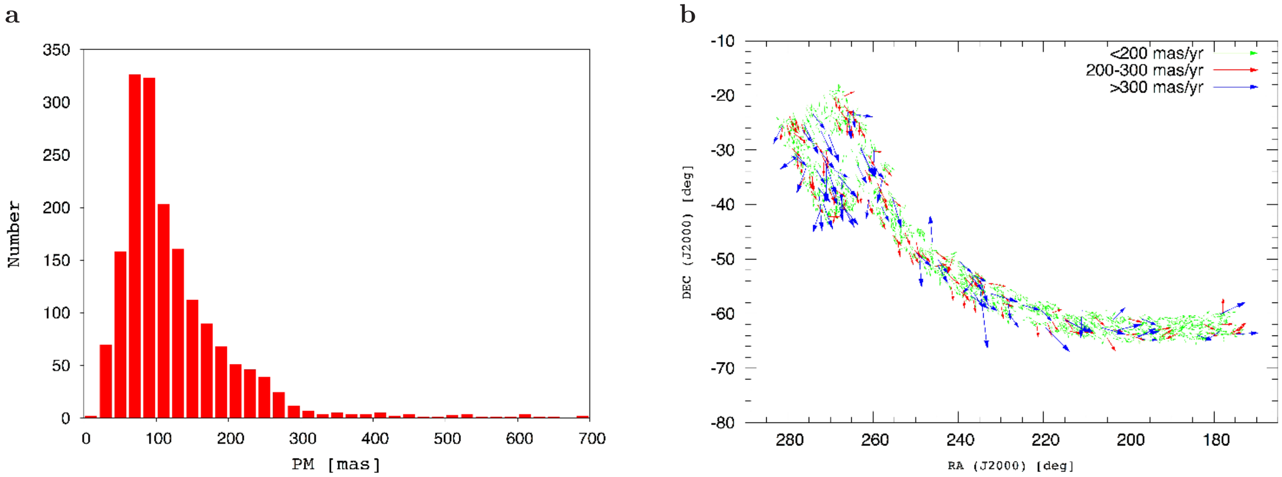

Fig. 4. (**a**) A histogram distribution of the modulus of the proper motions. The sample is significantly incomplete below PM∼100 mas yr^{-1} (**b**) The distributions of the PM vectors over the VVV area. The stars with PM>300 mas yr^{-1} are given in blue, with PM 200-300 mas yr^{-1} with red and with PM<200 mas yr^{-1} with light green.

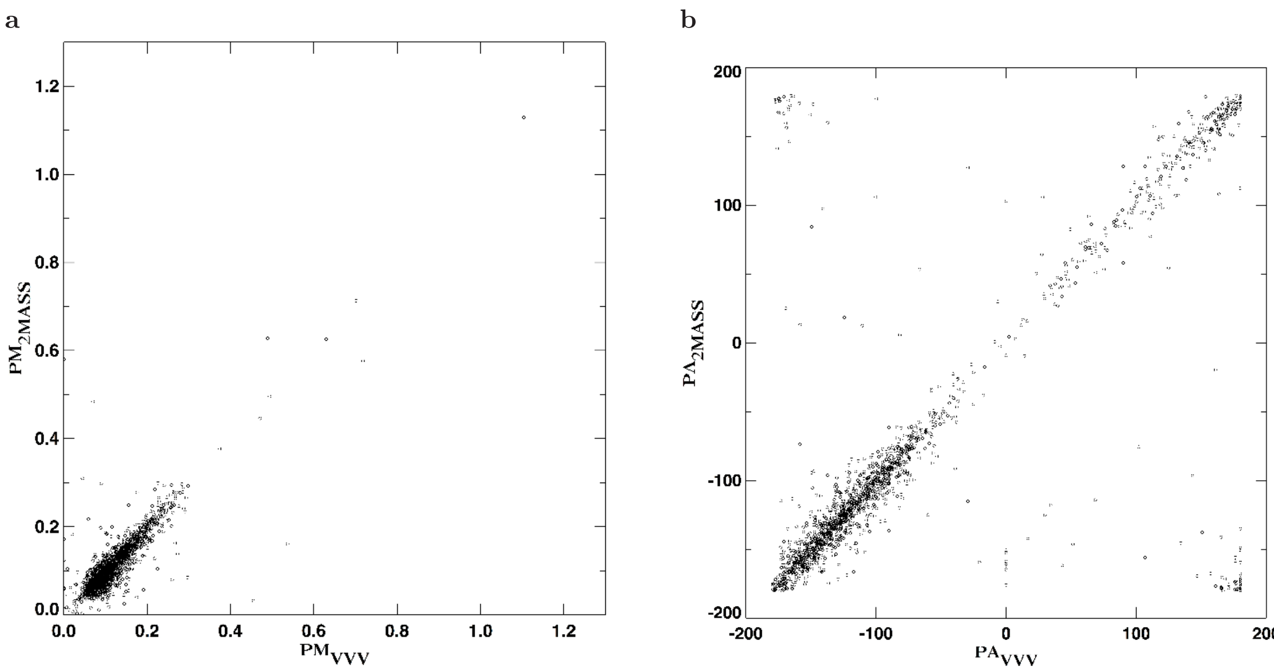

Fig. 5. (**a**) PM obtained from the VVV-2MASS vs. VVV1-VVV2. (**b**) PA obtained from the VVV-2MASS vs. VVV1-VVV2.

3.4. *Parallaxes*

As we showed in Beamin et al. (2013) the VVV survey catalogs are ideal for obtaining parallaxes of nearby objects. More than 80 epochs in K_s and the high precision of the VVV catalog coordinates allow this. To obtain the parallax of the targets, we use the equatorial coordinates from CASU $ZYJH$ along with all K_s epochs available. Usually, bright (13–14 mag), isolated stars without proper motion are used to obtain the corrections to a common field center for each epoch. Using the averaged value of the shifts, we correct the individual epoch coordinates of the target. For each epoch, the mean of the positions measured in individual frames is taken and its uncertainty determined from the dispersion of values in each spatial direction. In this way positional errors were reduced to internal errors only (∼7 mas). Aver-

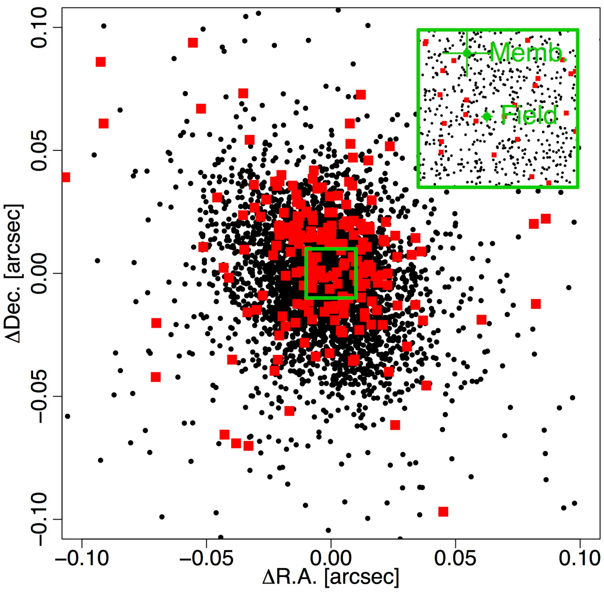

Fig. 6. PM obtained from the VVV for NGC 6530 cluster members (red) and field stars (black). Insert: the blown-up region of plot indicated by the green box. The mean PM for members and field stars are indicated by the green points with error bars.

aging date-by-date, finally, we produced sequences of less but more precise positions to obtain proper motions and parallaxes. In the best cases, a parallax precision of about 2 mas could be reached (Figs. 4 and 5).

3.5. *VVV and Proper Motions Farther Away*

We "pushed the VVV to the limit" and tried to obtain the proper motion of the stars in a star forming region around the Lagoon nebula, at a distance of 1250 pc. Our field is centered on the young stellar cluster NGC 6530 which is part of this region. We have at our disposal a list of confirmed members of the complex – from Chandra MYStIX X-ray/IR-excess selection (Feigelson et al. 2013; Broos et al. 2013). This allows the proper motion of members to be compared with the proper motion of background (field) sources. For this we used two positions, one from 2010 and the other from 2014. The time difference is 3.6 years. Each position is averaged from five individual positions taken from the nearest VVV epochs in order to increase the precision. Both distributions (member and field stars) are shifted with 8.3 ± 1.5 mas, which corresponds to tangential velocity of 14 ± 2.5 km/s. The result is presented on Fig. 6. The members are in red and the field stars in black.

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