Searching for Faint Comoving Companions to the α Centauri system in the VVV Survey Infrared Images

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ABSTRACT
The VVV survey has observed the southern disk of the Milky Way in the near infrared, covering 240 deg$^2$ in the $ZYJHK_S$ filters. We search the VVV Survey images in a ~19 deg$^2$ field around α Centauri, the nearest stellar system to the Sun, to look for possible overlooked companions that the baseline in time of VVV would be able to uncover. The photometric depth of our search reaches $Y$ ~19.3 mag, $J$ ~19 mag, and $K_S$ ~17 mag. This search has yielded no new companions in α Centauri system, setting an upper mass limit for any unseen companion well into the brown dwarf/planetary mass regime. The apparent magnitude limits were turned into effective temperature limits, and the presence of companion objects with effective temperatures warmer than 325 K can be ruled out using different state-of-the-art atmospheric models. These limits were transformed into mass limits using evolutionary models, companions with masses above 11 $M_{\text{Jup}}$ were discarded, extending the constraints recently provided in the literature up to projected distances of $d < 7000$ AU from α Cen AB and ~1200 AU from Proxima. In the next few years, the VVV extended survey (VVVX) will allow to extend the search and place similar limits on brown dwarfs/planetary companions to α Cen AB for separations up to 20000 AU.

Key words: (stars:) brown dwarfs – (stars:) planetary systems – infrared: planetary systems

1 INTRODUCTION
The nearest stellar system α Centauri (including the close binary α Cen AB and Proxima) allows us to probe to unprecedented depth the vicinity of three stars for planets. α Cen AB is three times closer than any other FGK star offering unique conditions for detection and characterization of earth-like planets around sun-like stars in terms of brightness and angular separation of a hypothetical habitable planet. However, the system has not been considered in the target list of exoplanet imaging missions because of light contamination of the environs of each binary component by the other. Recent advances in binary star light suppression and wavefront control (Thomas et al. 2015) has enabled the creation of dark zones around binary systems. As a result, dedicated mission concepts to observe α Centauri has been proposed (Bendek et al. 2015) with telescopes as small as 40 cm in aperture. Scientists and engineers (Sirbu et al. 2017) are also studying whether the WFIRST coronagraph would be able to observe binaries and include α Cen in the target list.

It is worth mentioning that detecting an earth-like
planet in the habitable zone (HZ) of \(\alpha\) Cen AB with a 40 cm aperture telescope is equivalent, in terms of photon flux and angular separation, to performing the same detection around a star at 10 pc with a 4-m class NASA’s “HABEX” flagship exoplanet mission.

This system will be an important target to be further explored with the next generation of space telescopes and missions and of the Breakthrough Starshot project\(^1\).

A planet on a 3.2 day orbit was reported to exist around \(\alpha\) Cen B Dumusque et al. (2012) but more recent studies cast doubts on the existence of this planet, arguing that the signal reported by Dumusque et al. (2012) “arise from the window function of the observed data” (Rajpaul et al. 2016). Demory et al. (2015) looked for evidence of \(\alpha\) Cen Bb using HST/STIS photometry. They found no evidence of the proposed \(\alpha\) Cen Bb, but on the other hand reported the presence of a transit like feature in the light curve of \(\alpha\) Cen B, that might be produced by a earth mass planet in a \(~15-20\) day orbit. Kervella et al. (2006) studied \(\alpha\) Cen AB, with the NACO instrument at VLT, and set upper limits for a possible co-moving companion in the \(H\) and \(K\) band, corresponding to \(-20-30\) \(M_{\text{Jup}}\) with separations between 7 and 20 AU. Later, Kervella & Thévenin (2007) using optical imaging \((V, R, I\) and \(Z\) bands) complemented this search and determined that there were no co-moving companions to this system with masses \(\gtrsim\)15-30 \(M_{\text{Jup}}\) at separations between 100-300 AU

Quarles & Lissauer (2016) investigated numerically if stable planetary orbits exists around one of the stars or around the \(\alpha\) Cen AB binary, and arrived at a positive answer (see their Fig. 11).

Recently, Pourbaix & Boffin (2016) and Kervella et al. (2016) performed a detailed astrometric study of the \(\alpha\) Cen AB system, and derived not only precise proper motion and parallaxes, but also orbital parameters and in the latter case predictions of microlensing events in the following years, that would allow to probe an unexplored parameter space for the presence of exoplanets around those stars.

Regarding Proxima: Benedict et al. (1999) found no companions with masses above 0.8\(M_{\text{Jup}}\) in the period range \(1 \leq P\) [days] \(\leq1000\), using HST Guide Sensor data. Endl and Kürster (2008), based on nearly 7 years of radial velocity measurements found no evidence of planets with masses larger than \(M \sin i \geq 1 M_{\text{Neptune}}\) at periods \(\leq 2.7\) yr.

Lurie et al. (2014) using ground based astrometric measurements constrained the presence of planets with masses down to 2\(M_{\text{Jup}}\) with periods \(2 \leq P\) [years] \(\leq5\), and down to 1\(M_{\text{Jup}}\) for 5 \(\leq P\) [years] \(\leq12\). As pointed by Lurie et al. (2014), these studies eliminate the possibility of finding any Jupiter like planet around Proxima for orbital periods out to 12 years. Recently a rocky planet in a 11 day orbit was reported by Anglada-Escudé et al. (2016) making Proxima b the closest exoplanet known.

Mesa et al. (2017) searched for the presence of giant exoplanets around Proxima using high contrast imaging with SPHERE instrument at the Very Large Telescope, no objects were found with masses above 6-7 \(M_{\text{Jup}}\) at 0.5-1 AU, and 4 \(M_{\text{Jup}}\) at distances larger than 2.5 AU, using the AMES/COND models (Baraffe et al. 2003).

We have investigated the presence of substellar companions with separations up to 7 000 AU from \(\alpha\) Cen and up to 1 200 AU from Proxima. This paper is organized as follows: Section 2 describes the observations, section 3, the manual and automated search for faint companions. Section 4 is dedicated to discussion of the limits imposed by our search and the final section 5 gives the conclusions.

2 SAMPLE SELECTION AND OBSERVATIONS

2.1 VISTA/VIRCAM

The VVV survey (Minniti et al. 2010; Saito et al. 2012; Hempel et al. 2014) was one of the six ESO public surveys carried out with the 4.1m Visual and Infrared Survey Telescope for Astronomy (VISTA) telescope and VIRCAM camera (Dalton et al. 2006; Emerson & Sutherland 2010) at cerro Paranal Chile. The VIRCAM detector has sixteen chips of 2048\(\times\)2048 pixels with a pixel scale of 0.34\(\arcsec\). The total area covered after six overlapping pointings (known as “pawprints”) is 1x1.5 deg (hereafter a “tile”). VVV had a multicolour campaign in 5 NIR bands \((ZYJK_s)\) the first year (2010), and then 5 years of monitoring in the \(K_s\) band, where the total number of epochs differed from field to field from almost 300 epochs in some bulge fields to 54 epochs in the least observed disk field. Additionally, during the last year of the survey (2015) one/two extra epochs were obtained in the \(ZJ\) bands. The main goal of VVV was to trace the 3-D structure of the Milky Way, mainly through the study of variable stars (Dékány et al. 2013) but also using Red clump stars (Gonzalez et al. 2011) and NIR multiwavelength studies (Minniti et al. 2014). This survey is useful for accurate measurements of proper motions (PMs) and parallaxes, as demonstrated previously by Beamin et al. (2013); Ivanov et al. (2013); Beamin et al. (2015); Smith et al. (2015); Kurtev et al. (2017); Beamin et al. (2017); Smith et al. (2017 subm.).

The data used in this study, were reduced at the Cambridge Astronomy Survey Unit (CASU) with pipeline v1.3. In this study we considered 13 different tiles, two epochs in the \(Y\) and \(J\) bands and three epochs for the \(K_s\) band.

3 METHODS

3.1 Visual inspection of images

We created false colour images for 13 tiles using \(K_s\) images taken at 3 epochs separated in time by approximately 2 years from each other. The total area covered by the images was \(\sim19\deg^2\) (See Fig. 1). A source with the same motion of the \(\alpha\) Cen system would have left an easily recognizable colour trace with the same position angle as the proper motion of the \(\alpha\) Cen system. All non-variable sources would appear white, variables of high amplitude would have a point-like shape and the colour skewed to the colour assigned to the epoch at maximum brightness. Very high proper motion sources like solar system objects would only be detected in one image and be detected as a point-like source with only

\(^1\) http://breakthroughinitiatives.org/Initiative/3
Search for companions around α Centauri

Figure 1. Field of view analyzed in this study, each rectangle corresponds to one VVV tile. The position of the α Cen AB system is marked in yellow-orange (separation not to scale) stars and Proxima as a red star. The grey ellipse shows an approximate orbit of Proxima around the AB pair, from Kervella et al. (2017). The green arrow shows the proper motion of the system. The total area covered by this search is ∼19 sq. degrees. The limiting distance of 7 000 AU (and 1 200 to Proxima) is given by the distance to the South-East limit of the tile 'd015' (and 'd014' for Proxima). To the North-East and North-West the limiting separation almost reach 20,000 AU from α Cen AB.

With this method we can reject the presence of an extra component to the system down to $K_S \sim 17-17.5$ mag, which is the 5σ point source magnitude limit detection per epoch, and mainly discard sources around very bright and saturated stars.

3.2 Source catalog cross matching

Following the visual inspection, we retrieved catalogs for 13 different pointings (tiles) from two epochs separated by ∼5 years in the $Y$ and $J$ band from the VVV survey. We choose to use the images in $Y$ and $J$ band because these images are deeper than $H$ and $K_S$ and also more sensitive to ultra cool ($T_{eff} \leq 500$ K) brown dwarfs (BD) in the NIR, than the $K_S$ band (Morley et al. 2014; Beamín et al. 2014; Luhman & Esplin 2016; Zapatero Osorio et al. 2016; Schneider et al. 2016; Leggett et al. 2017). $H$ band is also sensitive to UCDs, but in our survey is shallower than $Y$ and $J$ bands, so this would not improve the detectability of a UCD.

The total time span between the two $Y$ and $J$ band observations is 5 years (2010-2015). Additionally, $Y$ and $J$ band epochs are usually not taken simultaneously. Images from the same year for the $Y$ and $J$ bands for 8 out of the 13 tiles were obtained with a time difference larger than 20 days at least in one epoch, 20 days is the required time for a source co-moving with the α Cen system to move ∼0.6 pixels in the VIRCAM camera, and hence produce a shift in the centroid of 0.1" of the background source, assuming both sources have similar fluxes. This implies that we effectively had 3 or 4 epochs, decreasing significantly the already low chance of an alignment between a possible companion of α Cen system and a background source. The dates of each individual image in $Y$ and $J$ bands are given in the Table A1 in the appendix.

The first epoch was observed usually between March and April 2010, and the second epoch around May-June 2015. For these catalogs the 5σ limiting magnitudes are $Y \sim 19.3$ and $J \sim 19.0$ mag. A list of the values per tile is given in Table 1.

A typical colour magnitude diagram in the $Y$ and $J$ bands is shown in Fig. 3, in this case we selected sources from Tile d053 (containing α Cen) which is the least detection-favoring tile due to the saturation, spikes and “image ghosts”. Nevertheless, over 700,000 sources were cross-matched between the two bands. Additionally, we included the histogram in $Y$ magnitude and the 5σ photometric detection limit ($Y=19.3$ mag) as a dashed line in the colour magnitude diagram (CMD) and solid black line and in the histogram. The remaining 12 tiles analyzed in this study share similar number counts and overall shape of the CMD, with a very strong disk sequence and a less populated sequence of giant
Table 1. 5σ limiting magnitude for the Tiles analyzed in this work.

| Tile name | Y2010 [mag] | Y2015 [mag] | J2010 [mag] | J2015 [mag] |
|-----------|-------------|-------------|-------------|-------------|
| d013      | 19.55       | 19.34       | 19.24       | 19.14       |
| d014      | 19.50       | 19.30       | 18.71       | 19.05       |
| d015      | 19.48       | 19.44       | 18.92       | 18.92       |
| d016      | 19.44       | 19.41       | 18.77       | 19.03       |
| d052      | 19.86       | 19.54       | 19.57       | 19.33       |
| d053      | 19.97       | 19.61       | 19.29       | 19.17       |
| d054      | 20.13       | 19.69       | 19.43       | 19.26       |
| d090      | 20.01       | 19.72       | 19.53       | 19.4         |
| d091      | 19.91       | 19.57       | 19.55       | 19.45       |
| d128      | 19.85       | 19.64       | 19.42       | 19.25       |
| d192      | 19.62       | 19.51       | 19.41       | 19.39       |
| d130      | 19.53       | 19.42       | 19.32       | 19.25       |

Adopted 19.3 19.

Table 2. Astrometry of α Cen system.

| Star name | μα cosδ [mas yr⁻¹] | μδ [mas yr⁻¹] | π [mas] |
|-----------|--------------------|----------------|--------|
| α Cen Aa  | -3619.9            | 693.8          | 747.17 |
| α Cen Ab  | -3619.9            | 693.8          | 747.17 |
| α Cen Cb  (Próxima) | -0773.84   | 770.54        | 768.7  |

a. Kervella et al. (2016), b. Benedict et al. (1999)

The cross-match (Taylor 2005). A 0.7″ tolerance radius (2 pixels) was defined for the match, and we kept only sources that do not have a counterpart in the other epoch, effectively removing the low proper motion sources.

To the remaining stars, we applied the proper motion and parallax motion corresponding to each member of the α Cen system separately (α Cen AB barycentric motion from Kervella et al. (2016) and Proxima from Benedict et al. (1999), to the catalog from year 2010 and performed a new cross-match with the remaining sources in the 2015 catalog (we used the python jplephem² software to calculate the parallax factors at each epoch). The values of proper motion and parallax used to shift the catalogs are available in Table 2 ³.

For the cross-match between the catalogs, we used a 0.35″ tolerance radius and a allowed a difference of up to 0.3 magnitudes for the corresponding band, which is the photometric uncertainty in the J band at the 5σ detection limit. Given the high density of sources towards the galactic inner disk (∼900 000 objects per sq. degree for the VVV limiting magnitude of J ∼19.5) after the cross-match we obtained nearly 50 sources per tile per band, per α Cen stellar member.

A match between these co-moving candidates sources

² https://pypi.python.org/pypi/jplephem
³ Repeating the process with the older values from Hipparcos astrometry from van Leeuwen 2007 and newer astrometry for Proxima from Lurie et al. 2014 does not give positive results either
in the $Y$ and $J$ bands was performed, but not a single object was detected in the two bands, which was expected if there were no additional companions.

Nevertheless we explore if there might be one real source detected in a single band. Most of the sources that passed the first cut were flagged as noise detections. So we decided to apply one more filter, selecting only sources that are flagged as stellar in the CASU catalogs (flag for stellar objects is -1), the last criterion rejected most sources around spikes of saturated stars, or near the edge of the detectors, and blended objects. The remaining candidates per tile, per band and per stellar member of the $\alpha$ Cen system now were reduced to five. We did a visual inspection of these sources in $1' \times 1'$ images, and searched for the source in the original $Y$ and $J$ band images simultaneously \(^{4}\). We eliminated all these candidates, because in at least one of the bands we could see faint sources in both positions, but one of them not being detected by the finding/photometry routine, because of sensitivity or contrast issues caused by artifacts. For a handful of objects where we had doubts in both the $Y$ and $J$ bands we looked at $Z$, $H$ and $K_S$ band images, and we were able to confirm that there was a background source in each expected position. We did not find any source that passes all the matching criteria and the final visual inspection check.

We considered the possibility that at the epoch of observation a faint source might remain undetected because it was projected on the same position of a brighter background star. In Fig. 4 the number of sources per square arc minute per 0.5 magnitude bin is plotted, and also the cumulative fraction of the pixels on the image occupied by sources brighter at each given magnitude. We only show here the information for tiles d053 and d130 which are the worst case scenario, containing $\alpha$ Cen AB and the highest number of sources in the $J$ band respectively. It can be seen that below $JY \sim 16$ mag there is less than 10% chance of alignment, but it reaches almost 30% at the limiting magnitude in $J$ band and 19% at the $Y$ band limit. Thus, the completeness of this search is at least 80%, considering the results in the $Y$ band. Nevertheless, all the fields were observed at different times in $Y$ and $J$ band as explained above, which will decrease the effective area of occupied pixels and hence increase the completeness. Simply multiplying the covered fraction of the independent images would be the easiest way to calculate the final covering fraction, but most of the brightest sources will be detected over the same pixels, and introduce a strong correlation, therefore the simple multiplication would be over optimistic, we adopt then a conservative 85-88% of completeness for the worst case scenario of tile d130, and $\gtrsim$90% for the remaining tiles.

4 DISCUSSION

For the $\alpha$ Cen system, there is a plethora of previous studies, and several properties are well constrained, a parallax of 747.17±0.60 mas (1.338±0.001 pc) \(^{5}\) (Kervella et al. 2016), a metallicity ([Fe/H]) 0.23±0.05 dex \(^{6}\) (Ramírez et al. 2013), and an age range between 4 and 7 Gyr \(^{7}\) (Eggenberger et al. 2004; Mamajek & Hillenbrand 2008; Boyajian et al. 2013; Bazot et al. 2016). The most stringent constraint on the presence of an extra companion in our study comes from the $Y$ and $J$ photometry. No source is detected up to a magnitude $19.3$ and 19.0 mag in $Y$ and $J$ respectively, within separations up to of 7 000 AU from $\alpha$ Cen AB system. The same photometric limits apply for Proxima, no companions to Proxima were found up to separations of 1 200 AU. To transform these magnitude limits to physical parameters, i.e. effective temperatures and masses, we used different atmospheric and evolutionary models.

First we used the BD cloudy models from Morley et al. (2012) and Morley et al. (2014)\(^{5}\). The first one only reaches up to $T_{\text{eff}}=400$ K and considers $\text{Na}_2\text{S}$, $\text{MnS}$, $\text{ZnS}$, $\text{Cr}$, $\text{KCl}$ condensate clouds. The latter models assumes a 50 % cloud covered atmosphere, composed of $\text{H}_2\text{O}$ ice in addition to the $\text{Na}_2\text{S}$, $\text{KCl}$, $\text{ZnS}$, $\text{MnS}$, and $\text{Cr}$. These models reach $T_{\text{eff}}=200$ K. Based on these models we were able to discard objects with $T_{\text{eff}}>325 K$ for any given combination of sedimentation factor and surface gravity, these results can be seen in Fig 5, where we plot $Y - J$ color, against absolute $Y$ magnitude.

Second, we tested with the atmospheric models of Saumon et al. (2012). These models include an improved line list of the NH$_3$ molecule, and of the collision-induced absorption of molecular hydrogen (H$_2$), no clouds opacities were considered for these temperatures. The colours were calculated using the Saumon & Marley 2008 cloud-free evolution model grids. The limits for this model are shown in the upper panel of Fig. 6. Doing a simple linear interpolation of the data in the $Y$ and $J$ bands against effective temperature, considering values of $\log(g)$ between 4 and 4.5, and evaluating the limits obtained in $Y$ and $J$ bands (19.3 and 19.0 mag respectively) we derived upper limits for the effective temperature of 326 K and 322 K, for the $Y$ and $J$ bands respectively.

Finally, we tested the BT-Settl models (Allard et al. 2012)\(^{6}\), which uses the updated solar abundances from Caffau et al. (2011), also account for a calibration of the mixing length based on Radiation Hydrodynamics simulations by Freytag et al. (2010) and adjustments to the MLT equations. To transform between the absolute magnitudes given at the surface of the BD provided by models, we assumed a radius of 0.1 $R_\odot$ which is the expected for these kind of objects at ages around 4-7 Gyr (Burrows et al. 2001). Unfortunately, only objects with low surface gravities are available in the public grid of models at these low temperatures ($\log(g)$ 3.0 and 3.5), for higher gravities ($\log(g)$ 4.0 and 4.5) models are available for effective temperatures above 500 K. In the bottom panel of Fig. 6 it can be seen that the models with higher gravity and $T_{\text{eff}}>500$ K are far above from our limit, and indeed an extension of the models to higher gravities is required to compare the temperature limits with the other set of models. We also plot the lower gravity models.

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\(^{5}\) The models from Morley et al. (2012, 2014) and Saumon et al. (2012) were taken from http://www.ucolick.org/~cmorley/Models.html

\(^{6}\) https://phoenix.ens-lyon.fr/Grids/BT-Settl/CIFIST2011/COLORS/
5 CONCLUSIONS

We have carried out a deep and wide search for other members of the $\alpha$ Cen system using the VVV near-IR images. No additional companions were found around the $\alpha$ Cen AB system. In total we explored a ~19 sq. degree region around the $\alpha$ Cen AB system, ranging up to 7 000 AU to the south east direction and nearly 20 000 AU to the North-

East and North-West direction. Also, no companions were found around Proxima within 1 200 AU.

Our search considered a visual inspection in the $K_S$ band and using photometric 5$\sigma$ limits in the $Y$, $J$ bands. The final limit excludes the presence of a BD/planet with a mass above 9.5-14.5 $M_{\text{Jup}}$, model and age dependent. Our search extended the limits on possible co-moving companions to...
the \( \alpha \) Cen AB system and also Proxima, to greater distances than previous attempts, complementing previous studies using radial velocities (Dumusque et al. 2012; Anglada-Escudé et al. 2016), higher spatial resolution imaging (Kervella et al. 2006; Mesa et al. 2017), deep optical imaging (Kervella & Thévenin 2007) and astrometric searches (Benedict et al. 1999).

An extended search will be possible in the following 2-3 years making use of the on-going VVV extended survey (VVVX), which will extend the observed area 2.2 degrees more in galactic latitude (positive and negative), this will allow us to place limits up to separations of \( \sim 18,000 \) AU in every direction.

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REFERENCES

Allard, F., Homeier, D., & Freytag, B. 2012, Royal Society of London Philosophical Transactions Series A, 370, 2765
Anglada-Escudé, G., Amado, P. J., Barnes, J., et al. 2016, Nature, 536, 437
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 2003, A&A, 382, 563
Baraffe, I., Chabrier, G., Barman, T. S., Allard, F., & Hauschildt, P. H. 2003, A&A, 402, 701
Bazot, M., Christensen-Dalsgaard, J., Gizon, L., & Benomar, O. 2011, A&A, 536, 4054
Beamin, J. C., Minniti, D., Gromadzki, M., et al. 2013, A&A, 557, LL8
Beamin, J. C., Ivanov, V. D., Bayo, A., et al. 2014, A&A, 570, L8
Beamin, J. C., Ivanov, V. D., Minniti, D., et al. 2015, MNRAS, 454, 4054
Beamin, J. C., Mendez, R. A., Smart, R. L., et al. 2017, arXiv:1705.05817
Bendek, E. A., Belikov, R., Lozi, J., et al. 2015, Proc. SPIE, 9605, 960516
Benedict, G. F., McArthur, B., Chappell, D. W., et al. 1999, AJ, 118, 1086
Boyajian, T. S., von Braun, K., van Belle, G., et al. 2013, ApJ, 771, 40
Burrows, A., Hubbard, W. B., Lumine, J. I., & Liebert, J. 2001, Reviews of Modern Physics, 73, 719
Caffau, E., Ludwig, H.-G., Steffen, M., Freytag, B., & Bonifacio, P. 2011, Sol. Phys., 268, 255
Dalton, G. B., Caldwell, M., Ward, A. K., et al. 2006, Proc. SPIE, 6269, 62690X
Dékány, I., Minniti, D., Catelan, M., et al. 2013, ApJ, 776, LL19
Demory, B.-O., Ehrenreich, D., Queloz, D., et al. 2015, MNRAS, 450, 2043
Dumusque, X., Pepe, F., Lovis, C., et al. 2012, Nature, 491, 207
Dupuy, T. J., & Liu, M. C. 2012, ApJS, 201, 19
Eggenberger, P., Charbonnel, C., Talon, S., et al. 2004, A&A, 417, 235
Emerson, J., & Sutherland, W. 2010, The Messenger, 139, 2
Endl, M. & Kürster, M. 2008, A&A, 488, 1149
Freytag, B., Allard, F., Ludwig, H.-G., Homeier, D., & Steffen, M. 2010, A&A, 513, A19
Gonzalez, O. A., Rejkuba, M., Minniti, D., et al. 2011, A&A, 534, LL14
Hempel, M., Minniti, D., Dékány, I., et al. 2014, The Messenger, 155, 29
Ivanov, V. D., Minniti, D., Hempel, M., et al. 2013, A&A, 560, AA21
Ivanov, V. D., Vaisanen, P., Kniazev, A. Y., et al. 2015, A&A, 574, A64
Kervella, P., Thévenin, F., & Lovis, C. 2017, A&A, 598, L7
Kervella, P., Mignard, F., Mérand, A., & Thévenin, F. 2016, A&A, 594, A107
Kervella, P., Thévenin, F., & Lovis, C. 2016, arXiv:1611.03495
Kervella, P., & Thévenin, F. 2007, A&A, 464, 373
Kervella, P., Thévenin, F., Coudé du Foresto, V., & Mignard, F. 2006, A&A, 459, 669
Kurtev, R., Gromadzki, M., Beamin, J. C., et al. 2017, MNRAS, 464, 1247
Leggett, S. K., Tremblin, P., Esplin, T. L., Luhman, K. L., & Morley, C. V. 2017, arXiv:1704.03573
Luhman, K. L., & Esplin, T. L. 2016, AJ, 152, 78
Lurie, J. C., Henry, T. J., Jao, W.-C., et al. 2014, AJ, 148, 91
Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1246-1293
Minniti, D., Lucas, P. W., Emerson, J. P., et al. 2010, New Astronomy, 15, 433
Minniti, D., Saito, R. K., Gonzalez, O. A., et al. 2014, A&A, 571, AA91
Marley, M. S., Seager, S., Saumon, D., et al. 2002, ApJ, 568, 335
Morley, C. V., Fortney, J. J., Marley, M. S., et al. 2012, ApJ, 756, 172
Morley, C. V., Marley, M. S., Fortney, J. J., et al. 2014, ApJ, 787, 78
Mesa, D., Zurlo, A., Milli, J., et al. 2017, MNRAS, 466, L118
Pourbaix, D., & Boffin, H. M. J. 2016, A&A, 586, A90
Quarles, B., & Lissauer, J. J. 2016, AJ, 151, 111
Rajpaul, V., Aigrain, S., & Roberts, S. 2016, MNRAS, 456, L6
Ramírez, I., Allende Prieto, C., & Lambert, D. L. 2013, ApJ, 764, 78
Saito, R. K., Hempel, M., Minniti, D., et al. 2012, A&A, 537, AA107
Saumon, D., & Marley, M. S. 2008, ApJ, 689, 1327-1344
Saumon, D., Marley, M. S., Abel, M., Fromhold, H., & Freedman, R. S. 2012, ApJ, 750, 74
Schneider, A. C., Cushings, M. C., Kirkpatrick, J. D., & Gelino, C. R. 2016, ApJ, 823, L35
Sirbu, D., Thomas, S., & Belikov, R. 2017, arXiv:1704.05441
Smith, L. C., Lucas, P. W., Contreras Peña, C., et al. 2015, MNRAS, 454, 4476
Smith, L. C. subm
Taylor, M. B. 2005, Astronomical Data Analysis Software and Systems XIV, 347, 29
Thomas, S., Belikov, R., & Bendek, E. 2015, ApJ, 810, 81
van Leeuwen, F. 2007, A&A, 474, 653
APPENDIX A: INDIVIDUAL OBSERVATION DATES

We list here all the epochs used to obtain the magnitude limits in this study for the $Y$ and $J$ bands.

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| Table A1. VVV individual tile frames used in this study. |
|----------------------------------------------------------|
| Tile name Filter Date                                    |
| d013 Y 2010-03-27T09:15:8423                            |
| d013 J 2010-04-02T06:55:128                               |
| d013 Y 2015-05-03T02:50:8657                             |
| d013 J 2015-06-08T05:23:57:134                            |
| d014 Y 2010-03-27T03:38:22:178                            |
| d014 J 2010-04-01T08:10:18:437                            |
| d014 Y 2015-05-03T07:13:05:467                            |
| d014 J 2015-06-07T05:55:04:05                             |
| d015 Y 2010-03-27T07:29:17:121                            |
| d015 J 2010-04-03T06:11:37:039                            |
| d015 Y 2015-05-02T08:31:57:020                            |
| d015 J 2015-05-04T07:29:17:121                            |
| d016 Y 2010-03-27T05:54:26:590                            |
| d016 J 2010-04-05T06:20:45:691                            |
| d016 Y 2015-05-03T06:33:53:83                            |
| d016 J 2015-05-09T07:28:21:944                            |
| d016 J 2015-05-14T06:57:05:149                            |
| d052 Y 2010-03-27T05:53:31:888                            |
| d052 J 2010-04-02T07:01:43:579                            |
| d052 J 2015-05-03T07:24:07:882                            |
| d052 J 2015-06-08T06:16:15:733                            |
| d053 Y 2010-03-28T05:23:19:580                            |
| d053 J 2010-04-03T06:36:25:697                            |
| d053 Y 2015-05-02T08:41:46:933                            |
| d053 J 2015-05-04T07:33:33:687                            |
| d054 Y 2010-03-28T05:36:12:492                            |
| d054 J 2015-03-03T07:25:944                               |
| d054 J 2015-05-02T08:52:42:769                            |
| d054 J 2015-05-04T08:24:04:814                            |
| d090 J 2010-03-27T04:43:39:047                            |
| d090 Y 2010-03-28T04:39:26:094                            |
| d090 Y 2015-04-29T07:41:48:8063                            |
| d090 J 2015-05-09T04:52:36:383                            |
| d091 J 2010-03-27T05:48:09:395                            |
| d091 Y 2010-06-25T03:28:45:574                            |
| d091 Y 2015-05-03T07:34:18:524                             |
| d091 J 2015-05-29T04:31:46:786                            |
| d091 J 2015-06-24T02:50:02:516                            |
| d092 J 2010-03-29T05:16:06:889                            |
| d092 Y 2010-06-16T04:52:10:577                            |
| d092 Y 2015-04-16T09:08:36:166                            |
| d092 Y 2015-04-16T09:18:28:562                            |
| d092 J 2015-06-01T04:10:11:8593                           |
| d128 J 2010-03-27T05:04:24:036                            |
| d128 Y 2010-03-28T04:54:23:8370                           |
| d128 Y 2015-04-29T07:52:16:4593                           |
| d128 J 2010-03-29T05:29:48:4227                           |
| d129 J 2010-03-27T06:10:27:3904                           |
| d129 Y 2010-06-25T03:45:04:0264                           |
| d129 Y 2015-05-03T07:36:03:737                            |
| d129 J 2015-06-24T03:29:36:1733                           |
| d130 J 2010-03-27T06:32:28:5134                           |
| d130 Y 2010-06-25T03:59:50:6191                           |
| d130 Y 2015-05-03T07:56:15:7642                           |
| d130 J 2015-06-24T04:03:23:2328                           |