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The proper motion of HV2112: a TŻO candidate in the SMC

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ABSTRACT

The candidate Thorne–Żytkow object (TŻO), HV2112, is becoming a well-studied if enigmatic object. A key point of its candidacy as a TŻO is whether or not it resides in the Small Magellanic Cloud (SMC). HV2112 has detections in a series of photometric catalogues which have resulted in contradictory estimates of its proper motion and, therefore, its membership within the SMC. This letter seeks to resolve the issue of the SMC membership of HV2112 through a reanalysis of extant photometric data. We also demonstrate the difficulties and downfalls inherent in considering a range of catalogue proper motions. We conclude that the proper motion, and associated ancillary radial velocity, positional and photometric properties, are fully consistent with HV2112 being within the SMC and thus it remains a candidate TŻO.

Key words: techniques: photometric – proper motions – stars: individual: HV2112 – galaxies: individual: SMC.

1 INTRODUCTION

HV2112 has recently been proposed (Levesque et al. 2014) as a likely candidate for a Thorne–Żytkow object (TŻO), a red supergiant with a neutron star core (Thorne & Żytkow 1975; Thorne & Żytkow 1977). This candidacy depends on HV2112 being a member of the Small Magellanic Cloud (SMC). Maccarone & de Mink (2016) propose an estimate of a proper motion (PM) for HV2112 which, if in the SMC, corresponds to a space motion of 3000 km s^{-1}, exceeding the escape velocity of SMC. The PM of Maccarone & de Mink (2016) implies a reasonable assumption of HV2112 being a Milky Way halo star at a distance of 3 kpc. Residence in the halo, at a closer distance by a factor of 10 or so, would mean that HV2112 is not sufficiently luminous to be a red supergiant, let alone a TŻO.

HV2112 has also been found to have a strong calcium line in its spectrum (Levesque et al. 2014). Calcium is potentially a key discriminator between the proposed sites of origin for this star. However, the detected calcium is more in line with levels expected for halo stars, rather than the SMC. If, as we support here, HV2112 is indeed a luminous SMC giant, the strong calcium line may well be key to understanding its evolution (Tout et al. 2014; Sabach & Soker 2015).

2 THE PM OF HV2112

A range of photometric catalogues contain images of HV2112. Maccarone & de Mink (2016) investigated the PM of HV2112 from the Southern Proper Motion (SPM) survey (Girard et al. 2011). Observations were made in two different epochs, the first in the B band in 1972 and the second in the V band in 2007, providing a 35 yr baseline between epochs. A PM of 2.8 ± 2.3 mas yr^{-1} in right ascension and -9.8 ± 2.3 mas yr^{-1} in declination was obtained from the SPM catalogue indicating a space motion of 3000 km s^{-1} if HV2112 is an SMC member. As noted by Maccarone & de Mink (2016) there is a significant discrepancy in the direction of declination between the SPM PM and that provided in the UCAC4 catalogue (Zacharias et al. 2013). The UCAC4 PM estimate is 1.8 ± 2.9 mas yr^{-1} in right ascension and -3.3 ± 2.7 mas yr^{-1} in declination. The available literature PMs are explored more in Section 3.

To further investigate the PM of HV2112 we made two additional independent studies. The first compared images in the R band from a UK Schmidt sky survey plate (Cannon 1975), taken in 1989, to images in the near-infra red (NIR) Y-band from VISTA (Emerson et al. 2004) taken in 2012. Secondly NIR J-band images from VISTA, also from 2012, were directly compared with the 2MASS Point Source Catalog (PSC, Skrutskie et al. 2006) of the same region taken in 1998.

Both sets of data were used to generate PM estimates for HV2112 and the surrounding field stars. This was limited to a 5 arcmin × 5 arcmin region centred on HV2112, for the photographic plate – VISTA comparison, to minimise the effects of differential refraction given the different passbands used. For the VISTA – 2MASS comparison, a larger region approximately $1^{\circ} \times 1^{\circ}$ in size could be used given the similar NIR passbands.

The photographic plate catalogue was directly matched to the VISTA Y-band catalogue with a six-constant linear mapping in standard coordinates (ξ, η) with tangent point at the nominal position of HV2112. The direct match between the photographic plate

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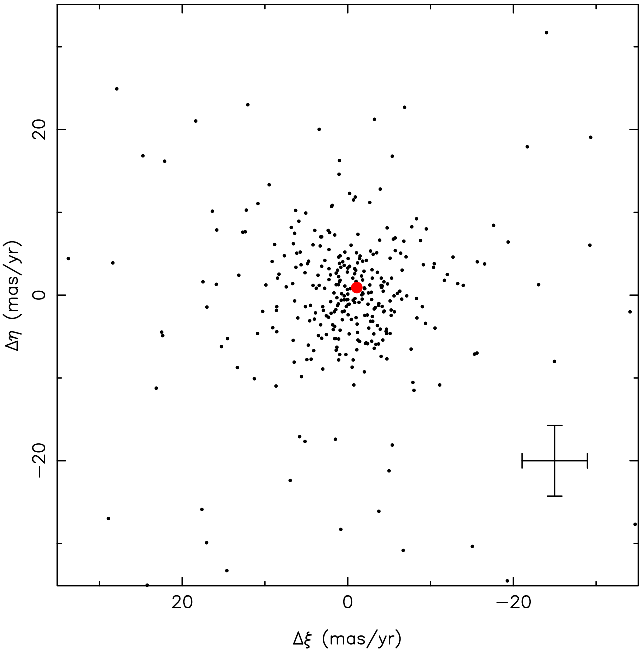

Figure 1. Derived PM from UK Schmidt *R* Band (1989) and VISTA Y (2012) for SMC field stars in black and HV2112 in red. Standard coordinate notation is used where ξ and η are in the RA and Dec orientations, respectively. Cross hairs are derived from the measurement errors.

and the VISTA NIR data benefits from the vastly increased number of objects detected (599 and 1550 to R and Y with limiting magnitudes of approximately 19 and 20, respectively), compared to the 72 suitable 2MASS PSC sources in the 5 arcmin × 5 arcmin region.

In this relatively deep data SMC stars dominate the field population. Therefore the effective PM reference frame is defined by the mean heliocentric PM of the SMC. The measured PM for HV2112 based on the resulting 23 yr baseline is -1.09 ± 4.27 mas yr^{-1} in right ascension and 0.92 ± 4.40 mas yr^{-1} in declination as shown in Fig. 1. The errors here are dominated by the photographic plate rms error. For well-measured stars like HV2112, the rms is typically 100 mas, corresponding to 4.3 mas yr^{-1} over the 23 yr baseline. This is on the order of the scatter in the SMC field in Fig. 1.

The VISTA catalogues are astrometrically calibrated with 2MASS stars for each pointing. This enables direct PM measurements. The procedure is illustrated in Figs 2 and 3. Fig. 2 shows an extinction-corrected 2MASS colour–magnitude diagram for the region. The selection box for the PM estimates shown in Fig. 3 is highlighted by the blue dashed lines and the location of HV2112 shown in red. The giant and supergiant populations of the SMC are prominent and HV2112 sits (notably) at the top of the M-supergiant locus. The selection box has a two-fold purpose. First it ensures that SMC stars dominate the PM collection (rejecting the blueward foreground dwarfs) and secondly limits the 2MASS stars used to those with the lowest rms positional errors (see for example fig. 20 of Skrutskie et al. 2006). The SMC field stars cluster tightly near the origin in Fig. 3 and the PM of HV2112 is highlighted in red.

The reference frame is again defined by the mean heliocentric PM of the SMC, in this case over a 14 yr baseline and yields a PM for HV2112 of 1.48 ± 2.49 mas yr^{-1} in right ascension and -1.55 ± 3.57 mas yr^{-1} in declination. The errors here are dominated by the 2MASS positional uncertainties which are consistent with the rms errors derived from the locus of SMC points in the

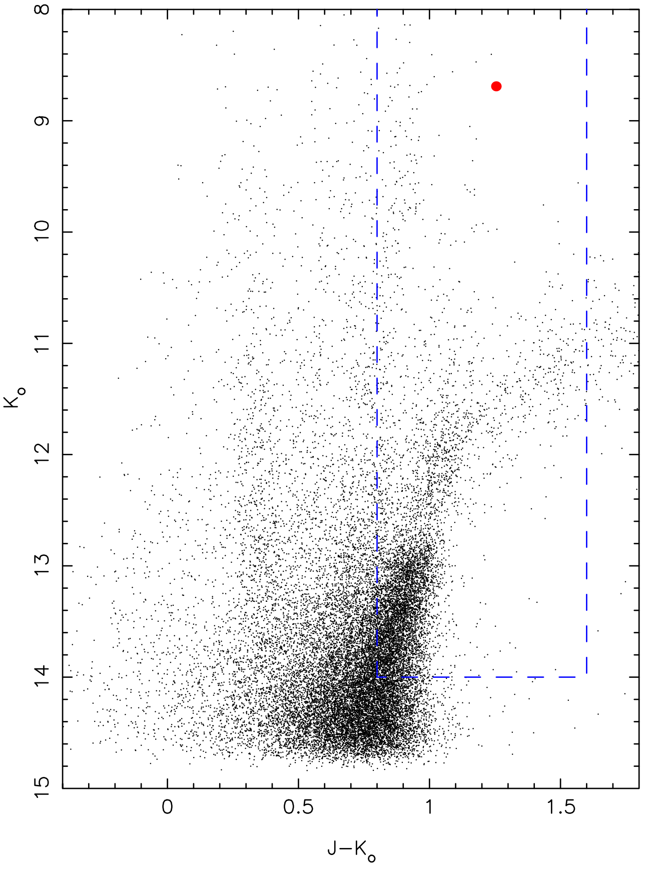

Figure 2. Extinction-corrected colour–magnitude diagram from 2MASS for all point sources (black) lying within 1° of HV2112 (red). The blue box selects a field dominated by SMC member stars, rejecting blueward foreground dwarfs.

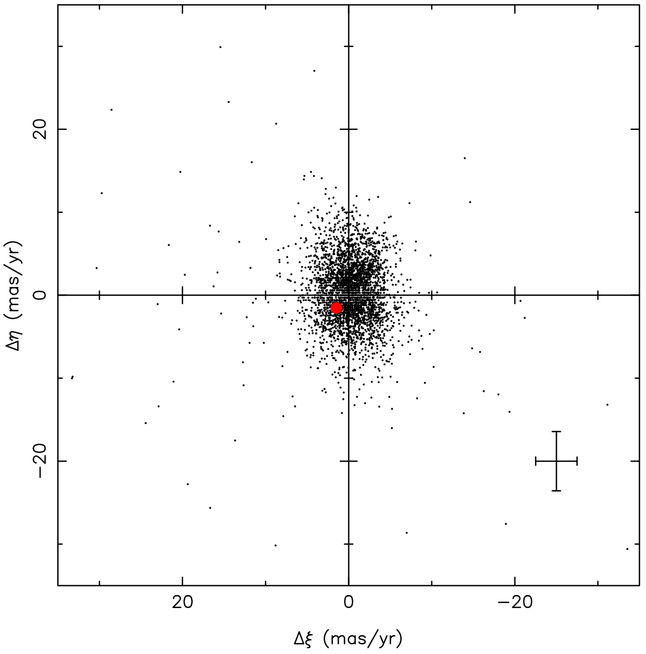

Figure 3. Derived PM from 2MASS (1989) and VISTA J (2012) for SMC field stars in black, selected from within the blue box in Fig. 2, and HV2112 in red. Cross hairs indicate the measurement errors which are dominated by the 2MASS position.

Table 1. Literature PMs for HV2112 taken from catalogues listed in VizieR plus the Maccarone & de Mink (2016) (M&dM2016) weighted mean PM and the two measurements presented here, IoA:UKV (UKSchmidt+VISTA) and IoA:2MV (2MASS+VISTA).

Catalogue	r (arcsec)	PM RA (mas yr^{-1})	σ_{PMRA} (mas yr^{-1})	PM Dec (mas yr^{-1})	σ_{PMDec} (mas yr^{-1})
*NOMAD[a]	0.0004	8.00	6.30	− 8.10	5.90
*UCAC2[b]	0.0004	8.00	6.30	− 8.10	5.90
*PPMX[c]	1.4112	8.78	20.10	4.34	20.10
PPMXL[d]	0.0013	14.40	14.20	− 1.30	14.20
XPM(PSC)[e]	0.0003	10.94	5.00	5.36	5.00
XPM(XSC)[e]	0.0003	9.14	5.00	4.42	5.00
SPM[f]	0.0027	2.80	2.27	− 9.78	2.30
UCAC4[g]	0.0003	1.80	2.90	− 3.30	2.70
*IGSL[h]	0.0003	1.80	2.90	− 3.30	2.70
APOP[i]	0.0018	0.00	10.10	2.60	0.40
*AllWISE[j]	0.0005	− 2.00	30.00	28.00	33.00
IoA:UKV	0.0040	− 1.09	4.27	0.92	4.40
IoA:2MV	0.0010	1.48	2.49	− 1.55	3.57
M&dM2016[#]		2.40	1.80	− 6.80	1.80

Notes. [a]Zacharias et al. (2004a); [b]Zacharias et al. (2004b); [c]Röser et al. (2008); [d]Röser, Demleitner & Schilbach (2010); [e]Fedorov, Akhmetov & Bobylev (2011); [f]Girard et al. (2011); [g]Zacharias et al. (2013); [h]Smart & Nicastro (2014); [i]Qi et al. (2015); [j]Wright et al. (2010).
[#]Weighted mean of the SPM and UCAC4 PMs.
*Discarded from the literature comparison.

figure. PM estimates for HV2112 from several independent 2012 VISTA measurements show a negligible scatter of $\pm 0.1\,\mathrm{mas\,yr^{-1}}$.

3 LITERATURE PMS

As discussed in this letter, the association of HV2112 with the SMC depends largely on the measurement and interpretation of its PM. We have derived an accurate PM for HV2112 based on a re-analysis of the best available imaging data. However, were our analysis not available, it would be necessary to resort to published catalogue PMs. In the following section, we consider such an approach for HV2112.

We have reviewed all HV2112 PMs available through VizieR[1] Ochsenbein, Bauer & Marcout (2000). The catalogues and associated PMs are listed in Table 1. Column r is the coordinate distance between the catalogue and SIMBAD for HV2112. The PMs accepted for the SMC are $0.772 \pm 0.063\,\mathrm{mas\,yr^{-1}}$ in RA and $-1.117 \pm 0.061\,\mathrm{mas\,yr^{-1}}$ in Dec (Kallivayalil et al. 2013).

No error columns are provided for the XPM catalogue but the catalogue description provides an estimate of the random errors of the absolute PMs for Southern hemisphere objects of between 5 and 10 mas yr^{-1}. Thus the errors were assumed to be 5 mas yr^{-1} for both measurements.

The PM calculated by Maccarone & de Mink (2016) as a weighted mean of the SPM and UCAC4 PMs is also included in Table 1. However, as it is a combination of two of the catalogue PMs, we do not include it in the comparison of the literature PMs.

Five entries (indicated by * and shown in red in Table 1) are discarded from the discussion for the following reasons.

(i) NOMAD is a duplicate of UCAC2;
(ii) UCAC2 has been superceded by UCAC4;
(iii) PPMX PM has a large offset in coordinate distance ($r =$ 1.4112 arcmin);
(iv) IGSL is a duplicate of UCAC4;
(v) AllWISE PM has excessive errors.

Fig. 4 displays the remaining six HV2112 literature PMs with those presented here (IoA). The weighted mean of the literature PMs with and without the IoA PMs are also displayed, as well as the accepted SMC PM. Also shown are a series of three ellipses, where the semiminor and semimajor axes are integer multiples of the IoA:2MASS+VISTA RA and DEC PM uncertainties, respectively. These uncertainties are derived from the SMC field as described above and illustrated in Fig. 3 and therefore can be considered as the uncertainty (σ) in the SMC field PM distribution.

One option for us is to define a PM for HV2112 by taking a weighted mean of the literature PMs, accounting for the range in the magnitudes of the associated PM errors. Excluding the IoA results from the weighted mean causes us a small shift in the RA direction as shown in Fig. 4. But both weighted means are within 1σ of the SMC PM within their errors. When we consider the literature PMs and IoA PMs together, five agree with the SMC PM to 1σ within their errors. Two agree to 2σ and one agrees to 3σ.

However, making a simple comparison between literature PMs, as above, ignores whether or not the PM reference frames are consistent and therefore comparable. Certainly calculating a mean PM is not valid if the reference frames are not consistent.

As noted above, the IoA measurements are basically heliocentric with respect to the SMC PM. For the two measurements used by Maccarone & de Mink (2016), the PMs determined for the SPM catalogue use galaxies to establish a PM zeropoint. Likewise UCAC4 is based on the Tycho2 ICRS (Høg et al. 2000) linkage and so is also zeropointed with an extragalactic reference frame. Thus these two PMs are also heliocentric and are based on an extragalactic reference frame.

Comparing these four PMs, the two results that agree most are UCAC4 and IoA:2MASS+VISTA to $0.1\sigma_{\mathrm{PMRA}}$ and $0.4\sigma_{\mathrm{PMDec}}$. Here σ_{PMRA} and σ_{PMDec} are the respective PM errors summed in quadrature. SPM and UCAC4 agree to $0.3\sigma_{\mathrm{PMRA}}$ and $1.8\sigma_{\mathrm{PMDec}}$. The greater disagreement in the PM in declination is evident in Fig. 4 where the SPM PM in declination is a clear outlier.

When comparing to the SMC directly, as shown in Fig. 4, both UCAC4 and the IoA PMs are in good agreement with the SMC

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[1] http://vizier.u-strasbg.fr/viz-bin/VizieR

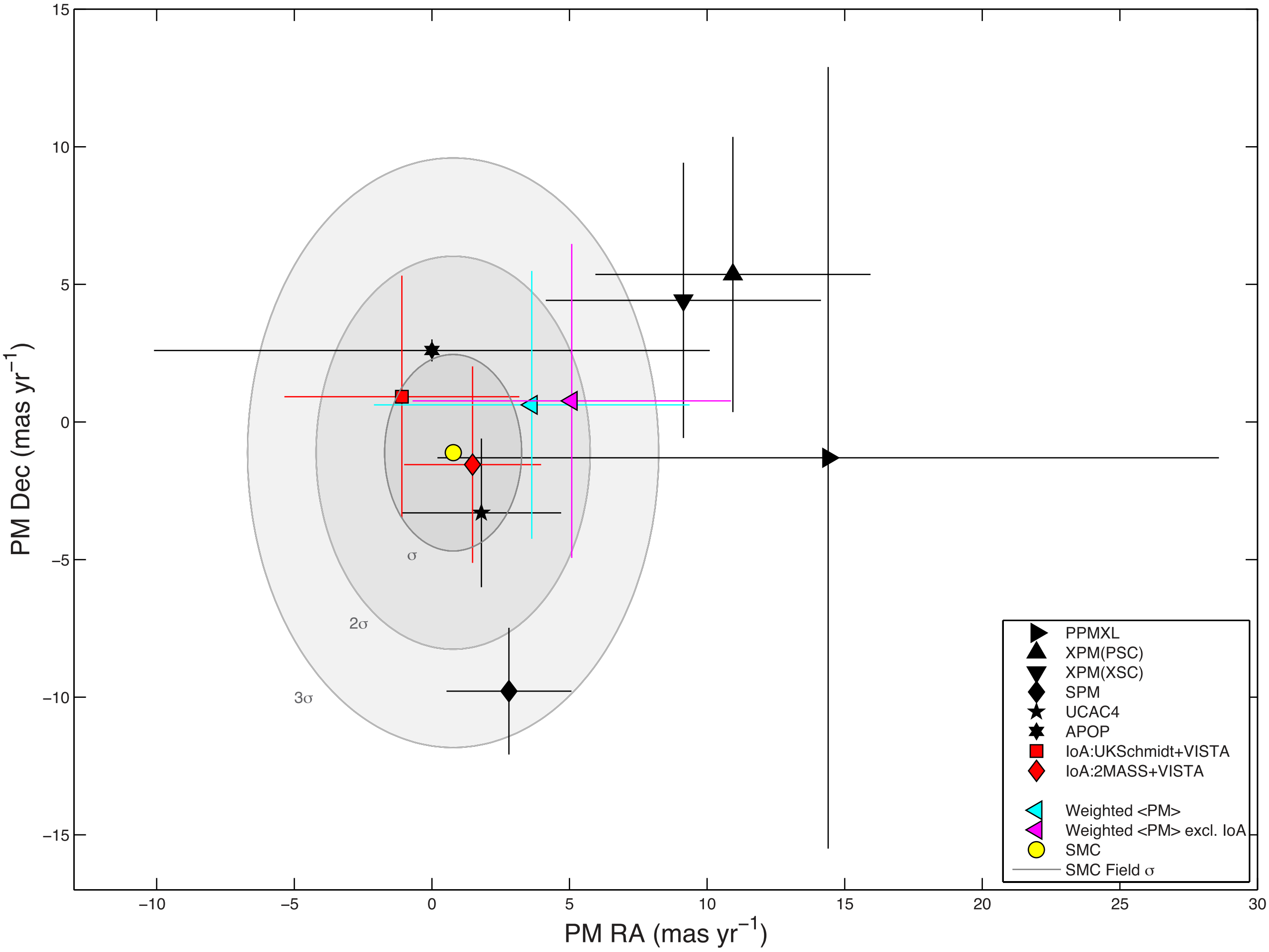

Figure 4. HV2112 literature PMs selected from VizieR, plus the IoA measurements presented here, plus the weighted mean of the literature measurements (with and without the IoA PMs), and the SMC PM. The SMC field PM distribution is also shown as a series of ellipses. The semiminor and semimajor axes are integer multiples of the IoA:2MASS+VISTA RA and Dec PM uncertainties, respectively. IoA:2MASS+VISTA RA and Dec PM uncertainties represent the uncertainty (σ) in the SMC field PM distribution as shown in Fig. 3.

PM within 1σ. Also the SPM PM agrees with the SMC PM to 2σ. Thus Fig. 4 shows that the literature PMs are generally consistent with the SMC PM although their distribution is quite scattered.

It is clear that several of the catalogues have PMs for HV2112 which are in disagreement by more than their quoted uncertainties. Furthermore, it can be unclear which catalogues to include in a comparison and one must be wary of cherry-picking the data by rejecting unfavourable measurements. We also note that many catalogues rely on overlapping data sets (e.g. SPM and UCAC4 share a common first epoch from SPM), and so these should not be considered as independent measurements of the true PM.

In light of such issues, HV2112 provides an excellent example of the potential pitfalls associated with extracting PMs from the literature. We argue that the new measurements we present here are the best PM measurements to-date for HV2112. In the very near future positions, and later PMs and parallaxes, will be available from the Gaia Mission (Perryman et al. 2001). These will provide the definitive answer on the true location of HV2112.

4 DISCUSSION

The two PM analyses carried out here strongly suggest that HV2112 is a member of the SMC. In this study, as shown in Fig. 3, HV2112 is located well within the cluster of SMC points whereas the PM proposed by Maccarone & de Mink (2016) would put HV2112 outside of the SMC field population.

The reflex solar PM for a stationary halo star at 3 kpc would be −8.94 mas yr^{-1} in RA and 9.21 mas yr^{-1} in Dec. However for a halo star at 3 kpc a high transverse motion is expected and so the Maccarone & de Mink (2016) PM would not be unreasonable.

Other types of measurements should be considered alongside the PM determination to provide a broader picture. For example, the difference in RA and Dec of HV2112 from the SMC positional centroid is ΔRA = 261.5 arcmin and ΔDec = 11.1 arcmin. While located in the outer edges of the angular extent of the SMC (major axis = 309.0 arcmin and minor axis = 204.1 arcmin) as shown Fig. 5, HV2112 lies coincident with the substructure of the east wing of the SMC. The east wing is evidence of star forming events that occurred between 50and200 Myr ago (Irwin, Demers

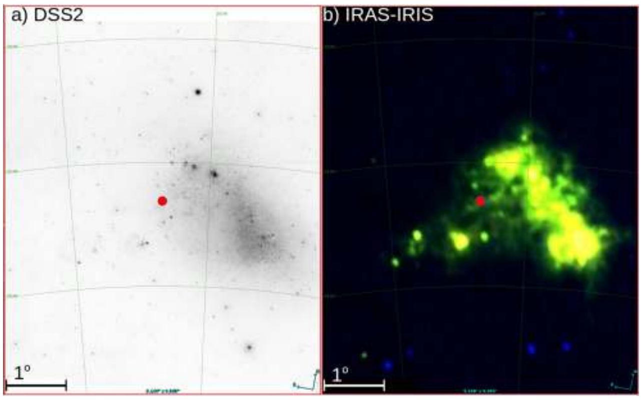

Figure 5. Location of HV2112 (red circle) in the SMC generated using Aladin (Bonnarel et al. 2000) with (a) DSS2; (b) *IRAS*-IRIS (Miville-Deschênes & Lagache 2005) images. HV2112 not only lies in the direction of the SMC but appears close to a region of relatively recent star formation.

& Kunkel 1990) and is populated by young massive stars akin to HV2112.

The measured radial velocity of HV2112 (approximately $157\,\mathrm{km\,s^{-1}}$, Levesque et al. 2014) is in good agreement with the accepted radial velocity of the SMC ($145.6\,\mathrm{km\,s^{-1}}$, McConnachie 2012). The Galactocentric line-of-sight radial velocity for HV2112 of approximately $13\,\mathrm{km\,s^{-1}}$ is consistent with both a halo star and membership of the SMC. However the velocity dispersion of the SMC is narrower ($\sigma_{\rm SMC} = 27\,\mathrm{km\,s^{-1}}$, Harris & Zaritsky 2006) than that of the halo ($\sigma_{\rm halo} > 85\,\mathrm{km\,s^{-1}}$, Brown et al. 2010). Both encompass HV2112 thus favouring membership of neither population in particular.

Finally, in the 2MASS colour–magnitude diagram of point sources lying within 1° of HV2112 shown in Fig. 2, HV2112 lies clearly on the SMC M supergiant locus. If HV2112 is a halo star at 3 kpc, that it has an absolute magnitude at the 2MASS epoch which places it exactly on the SMC supergiant locus would be intriguingly coincidental.

When considered in combination, that an object has coordinate position, PM and radial velocity in good agreement with the SMC and has photometry placing it clearly on the SMC supergiant locus, is strong evidence for HV2112 being a member of the SMC. To have all these in agreement but to not be an SMC member seems unlikely.

5 CONCLUSION

This letter summarises independent analyses of the PM of HV2112. These PM analyses as well as the coordinate position, radial velocity and photometric measurements of HV2112 are all consistent with and strongly support the assumption that HV2112 is a member of the SMC. Therefore HV2112 is not excluded as a candidate TŻO or a luminous, super-AGB star (Tout et al. 2014).

The study of HV2112 is ongoing with high and medium resolution spectroscopic observations. Spectral energy distribution and chemical abundance analyses may reveal the crucial characteristics that can discriminate between the various proposed origins of this enigmatic star.

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