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: stars: individual: HV2112 – techniques: photometric: proper motion – 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 super giant 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 ten or so, would mean that HV2112 is not sufficiently luminous to be a red super giant, 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 PROPER MOTION 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 $2.8 \pm 2.9 \: \text{mas} \: \text{yr}^{-1}$ in right ascension and $-9.8 \pm 2.3 \: \text{mas} \: \text{yr}^{-1}$ 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 $1.8 \pm 2.9 \: \text{mas} \: \text{yr}^{-1}$ in right ascension and $-3.3 \pm 2.7 \: \text{mas} \: \text{yr}^{-1}$ 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...
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 $\xi$ and $\eta$ are in the RA and Dec orientations respectively. Cross hairs are derived from the measurement errors.

Figure 2. Extinction-corrected colour–magnitude diagram from 2MASS for all point sources (black) lying within 1 degree 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.
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. Proper motion estimates for HV2112 from several independent 2012 VISTA measurements show a negligible scatter of ±0.1 mas yr⁻¹.

### 3 LITERATURE PROPER MOTIONS

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, with our analogous not available, it would be necessary to resort to published catalogue proper motions. In the following section, we consider such an approach for HV2112.

We have reviewed all HV2112 PMs available through VizieR¹ (Ochsenbein et al. 2000). The catalogues and associated PMs are listed in Table 1. Column 1 is the coordinate distance between the catalogue and SIMBAD for HV2112. The PMs accepted for the SMC are 0.772 ± 0.063 mas yr⁻¹ in RA and −1.117 ± 0.061 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 proper motion 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:

- NOMAD is a duplicate of UCAC2;
- UCAC2 has been superseded by UCAC4;
- PPMX PM has a large offset in coordinate distance (r = 1.4112°);
- IGSL is a duplicate of UCAC4;
- AllWISE PM has excessive errors.

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 (°) | PM RA (mas yr⁻¹) | σ_PMRA (mas yr⁻¹) | PM Dec (mas yr⁻¹) | σ_PMDec (mas yr⁻¹) |
|----------------|------|------------------|-------------------|-------------------|-------------------|
| *NOMAD*        | 0.0004 | 8.00             | 6.30              | -8.10             | 5.90              |
| *UCAC2*        | 0.0004 | 8.00             | 6.30              | -8.10             | 5.90              |
| *PPMX*         | 1.4112 | 8.78             | 20.10             | 4.34              | 20.10             |
| PPMXL¹         | 0.0013 | 14.40            | 14.20             | -1.30             | 14.20             |
| XPM(PSC)²      | 0.0003 | 10.94            | 5.00              | 3.56              | 5.00              |
| XPM(XSC)²      | 0.0003 | 9.14             | 5.00              | 4.52              | 4.50              |
| SP²            | 0.0027 | 2.80             | 2.27              | -9.78             | 2.30              |
| UCAC4³         | 0.0003 | 1.80             | 2.90              | -3.30             | 2.70              |
| *IGSL*         | 0.0003 | 1.80             | 2.90              | -3.30             | 2.70              |
| APOP²          | 0.0018 | 0.00              | 10.10             | 2.60              | 0.40              |
| *AllWISE*³     | 0.0005 | -2.00            | 30.00             | 28.00             | 33.00             |
| IoA:UKV        | 0.0010 | 1.48             | 2.49              | -1.55             | 3.57              |
| IoA:2MV        | 0.0010 | 1.48             | 2.49              | -1.55             | 3.57              |
| M&dM2016⁴      | 2.40   | 1.80             | -6.80             | 1.80              |

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

When comparing to the SMC directly, as shown in Fig. 4, both UCAC4 and the IoA PMs are in good agreement with the SMC PM within 1σ. Also the SPM PM agrees with the SMC PM to 2σ. 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 generally consistent with the SMC PM although their distribution is quite scattered.

It is clear that several of the catalogues have PMs

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1 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 semi-minor and semi-major 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
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 3kpc would be $-8.94 \text{ mas yr}^{-1}$ in RA and $9.21 \text{ mas yr}^{-1}$ in Dec. However for a halo star at 3kpc 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 $\Delta RA = 261.5'$ and $\Delta Dec = 11.1'$. While located in the outer edges of the angular extent of the SMC (major axis = 309.0' and minor axis = 204.1') 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 50 – 200 Myr ago (Irwin et al. 1990) and is populated by young massive stars akin to HV2112.

The measured radial velocity of HV2112 (approximately $157 \text{ km s}^{-1}$, Levesque et al. 2014) is in good agreement with the accepted radial velocity of the SMC (145.6$\text{ km s}^{-1}$, McConnachie 2012). The Galactocentric line-of-sight radial velocity for HV2112 of approximately $13 \text{ km s}^{-1}$ is consis-

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 semi-minor and semi-major 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 ($\sigma$) in the SMC field PM distribution as shown in Fig. 3 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.

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tent with both a halo star and membership of the SMC. However the velocity dispersion of the SMC is narrower ($\sigma_{\text{SMC}} = 27 \text{ km s}^{-1}$, Harris & Zaritsky 2006) than that of the halo ($\sigma_{\text{halo}} > 85 \text{ km s}^{-1}$, 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 degree 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 co-ordinate 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 TZO 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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